þÿSupplemental Guidance on the Application of FHWA s Traffic Noise Model (TNM)

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 791

Supplemental Guidance on the Application of FHWA's Traffic Noise Model (TNM)

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Grant S. Anderson was the lead author for the research topics *Topography, Ground Zones,* and *Tree Zones.*

Douglas E. Barrett was the lead author for the research topic *Area Sources*.

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FOREWORD

By Lori L. Sundstrom
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This report provides state departments of transportation (DOTs) staff and other transportation professionals with technical guidance on using the FHWA Transportation Noise Model (TNM) to model traffic-generated noise in a variety of settings that have not been addressed by TNM. This report should be of immediate use to experienced users of TNM by helping them to improve the accuracy and precision of their modeling results and inform decision-making related to the design of noise abatement measures.

Noise is an important environmental consideration for highway planners and designers, and through 2007, state highway agencies have spent $4.5 billion to abate the noise generated by federal-aid highway projects. Transportation agencies assess different aspects of highway noise to determine or predict community impacts during transportation planning, although procedures have varied from program to program and agency to agency. To aid states in complying with FHWA's noise policies and regulations, FHWA developed and improved a series of computerized noise prediction models beginning in the 1970s. FHWA's TNM is a computer program used for predicting noise levels and therefore impacts in the vicinity of highways, and it uses advances in personal computer hardware and software to improve upon the accuracy and ease of modeling highway noise, including the design of effective, cost-efficient highway noise barriers.

FHWA has provided substantial guidance for the routine application of TNM but scenarios exist for which there is no technical guidance. Out of necessity and without technical guidance, TNM users have independently developed techniques to assemble and input data into the TNM to analyze these scenarios. Typically these techniques have not been validated with field measurements, and the accuracy of their results is unknown. Accurate results are necessary to help DOTs make consistent and cost-effective noise abatement decisions and provide reliable modeling results to the public.

Under NCHRP Project 25-34, Harris Miller Miller & Hanson Inc. was asked to identify best practices and to supplement existing guidance on applying TNM to accurately, consistently, and efficiently model (1) structure-reflected noise; (2) bridge expansion joints; (3) signalized interchanges; (4) intersections; (5) area sources, e.g., weigh stations, park and ride lots, toll facilities, and service plazas; (6) median barriers; and (7) roundabouts. This research determined the sensitivity and accuracy of methods to model (1) multilane highways, (2) rows of buildings, (3) topography, (4) ground zones, and (5) tree zones, and identified best practices for input parameters. The research also synthesized the state of practice for analyzing the effects of wind direction and temperature inversion on sound propagation. The report is organized by scenario, and experienced transportation analysts, modelers, and designers should find this guidance immediately useful in using TNM to model noise impacts under these scenarios.

Practitioners interested in the information, studies, modeling practices, and results that were evaluated to develop the guidance provided in *NCHRP Report 791* may wish to consult Appendices A through L of the contractor's final report, which were prepared to accompany each of the research topic areas and are available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986.

CONTENTS

SUMMARY

Supplemental Guidance on the Application of FHWA's Traffic Noise Model (TNM)

The FHWA has provided substantial guidance for the routine application of the Traffic Noise Model (TNM); however, scenarios exist for which there remains limited or no technical guidance. The objectives of NCHRP Project 25-34 were the following:

- First, to supplement existing guidance on applying the TNM by identifying best practices to accurately, consistently, and efficiently model (1) structure-reflected noise; (2) bridge expansion joints; (3) signalized interchanges; (4) intersections; (5) area sources, e.g., weigh stations, park-and-ride lots, toll facilities, and service plazas; (6) median barriers; (7) roundabouts; (8) parallel barriers; and (9) tunnel openings.
- Second, to determine the sensitivity and accuracy of methods to model (1) multilane highways, (2) rows of buildings, (3) topography, (4) ground zones, and (5) tree zones, and identify best practices for input parameters. These five research topics represent parameters that already exist within the TNM.
- Third, to synthesize the state of practice for analyzing the effects of (1) wind direction and (2) temperature on sound propagation. Although considerable data exist on the effects of meteorology on sound propagation, thus far these results have not been applied directly to use within the TNM.

NCHRP Report 791 is intended primarily as a guidance document for TNM users and highway noise analysts. As a result, it does not attempt to fully justify or document how the guidance was developed; nor does the report list all of the information, studies, modeling practices, and results that were evaluated to develop the guidance. Instead, those details are included in Appendices A through L of the contractor's final report, which were prepared to accompany each of the research topic areas and which are available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986.

Sixteen different research topic areas were investigated in detail as part of this study, and significant guidance has been provided on modeling and interpreting results in each of the areas in this report. Even concise summaries of such guidance for each area would require one or more pages of text. Therefore, it is not practical to provide such guidance summaries for each research topic area in this report summary. For summaries of the guidance, the reader is referred to the research topics identified in the chapter titles of this report and to the sections of those chapters describing best modeling practices and guidance.

CHAPTER 1

Introduction

1.1 Introduction to NCHRP Project 25-34

Although the FHWA has provided substantial guidance for routine application of the Traffic Noise Model (TNM), scenarios exist for which there remains limited or no technical guidance. The objectives of NCHRP Project 25-34 were the following:

- First, to supplement existing guidance on applying the TNM by identifying best practices to accurately, consistently, and efficiently model (1) structure-reflected noise; (2) bridge expansion joints; (3) signalized interchanges; (4) intersections; (5) area sources, e.g., weigh stations, park-and-ride lots, toll facilities, and service plazas; (6) median barriers; (7) roundabouts; (8) parallel barriers; and (9) tunnel openings.
- Second, to determine the sensitivity and accuracy of methods to model (1) multilane highways, (2) rows of buildings, (3) topography, (4) ground zones, and (5) tree zones, and identify best practices for input parameters. These five research topics represent parameters that already exist within the TNM.
- Third, to synthesize the state of practice for analyzing the effects of (1) wind direction and (2) temperature on sound propagation. Although considerable data exist on the effects of meteorology on sound propagation, thus far these results have not been applied directly to use within the TNM.

Together, these three objectives cover 16 research topics. Some of the research topics are related or have similar research approaches. Those have been grouped and addressed together. In conduct of the research, the topics were addressed in parallel through a seven-step process. Each step, or task, built upon the previous steps, ultimately forming the final report. The seven steps were as follows:

1. Determine the existence of any useful information, either modeling techniques or measurement data useful for validation purposes. This was conducted by surveying AASHTO Standing Committee on Environment's Environmental Process Subcommittee, the NCHRP Project 25-34 research team, and the TRB ADC40 Committee members. Where appropriate and necessary, a literature search was conducted.
2. Compile modeling techniques and existing validation data for each research topic.
3. Identify candidate modeling techniques.
4. Prepare the interim technical report.
5. Process existing validation data and/or collect additional data.
6. Test and evaluate modeling techniques and identify best practices.
7. Prepare final technical report.

1.2 Purpose and Content of *NCHRP Report 791* and Supporting Appendices

The purpose of the research herein was to develop guidance for TNM users and highway noise analysts to address situations where guidance has not been provided in the past. Therefore, this report is intended and structured primarily as a guidance document. As a result, it does not attempt to fully justify or document how the guidance was developed; nor does this report list all of the information, studies, modeling practices, and results that were evaluated to develop the guidance. Instead, those details are included in Appendices A through L of the contractor's final report, which were prepared to accompany each of the research topic areas and which are available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986.

CHAPTER 2

Structure-Reflected Noise and Expansion-Joint Noise

2.1 Introduction

When modeling noise levels at receptors located adjacent to an elevated roadway on a structure (bridge or viaduct), FHWA TNM is capable of predicting the noise generated by vehicles traveling on the highway structure, taking into account direct noise paths and diffracted noise influences of any noise-blocking features (parapets, noise barriers, etc.). However, FHWA TNM Version 2.5 does not enable the direct modeling of noise reflected off of barriers or retaining walls on the opposite side of the roadway nor noise reflected off of the underside of the structure itself. While Version 3.0 of FHWA TNM will be capable of modeling reflected noise, the treatment of such reflections will be limited to vertical or nearly vertical surfaces such as far-side barriers and retaining walls. Reflections will not be applicable to horizontal surfaces such as the underside of bridges and viaducts.

In addition to the noise that can be reflected off of the underside of structures, vibrations of a structure can be created by vehicles traveling on a bridge, and these vibrations result in noise being radiated from/by the bridge superstructure. Vehicles traveling over bridge expansion joints also create noise that can travel to adjacent receivers located above and below the elevation of the structure roadway as well as to receivers directly underneath the structure.

In the majority of instances, the structure-related noise conditions described above occur simultaneously, and their individual noise level contributions cannot be segregated. Therefore, the NCHRP Project 25-34 research team has evaluated several candidate modeling techniques and has considered the conditions identified above both individually and in combination. Based on these evaluations, several best modeling practices for the development of adjustments to the basic FHWA TNM predictions have been developed to account for these structure-reflected and structure-radiated noise conditions that cannot be modeled directly. It is envisioned that such practices will be applied similarly to the basic (modeled) noise levels generated by either FHWA TNM Version 2.5 or Version 3.0.

This chapter provides a summary of the evaluations performed and the resultant suggested best modeling practices for determining adjustments to FHWA TNM values to account for structure-related noise contributions. A more detailed discussion, including the development of the suggested practices, is included in Appendix A (available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986).

2.2 Modeling Techniques Evaluated

Candidate modeling techniques evaluated for modeling structure-reflected noise primarily focused on addressing noise reflected from the underside of bridge structures to adjacent receivers located below (lower in elevation) elevated portions of a highway. Sound paths to adjacent receivers located level with or above a highway are generally influenced by reflections off of the pavement, which are accounted for in FHWA TNM. The evaluations of noise reflections off of roadway features such as safety barriers, median barriers, and retaining walls are discussed in Chapter 5. For above-road receivers, structure-radiated noise is not believed to be a major issue since it is masked by direct path vehicle noise predicted by FHWA TNM and tire-pavement interaction variations (not a part of this research project). However, in certain situations, receivers located above the roadway are influenced by noise from expansion joints. The techniques developed to address expansion-joint noise for receivers located below the elevation of the roadway were also evaluated for application to receivers elevated above the roadway.

2.2.1 Best Modeling Practices #1A and #1B

Best Modeling Practice #1A, an image-source technique that constructs an image of any receptor influenced by noise

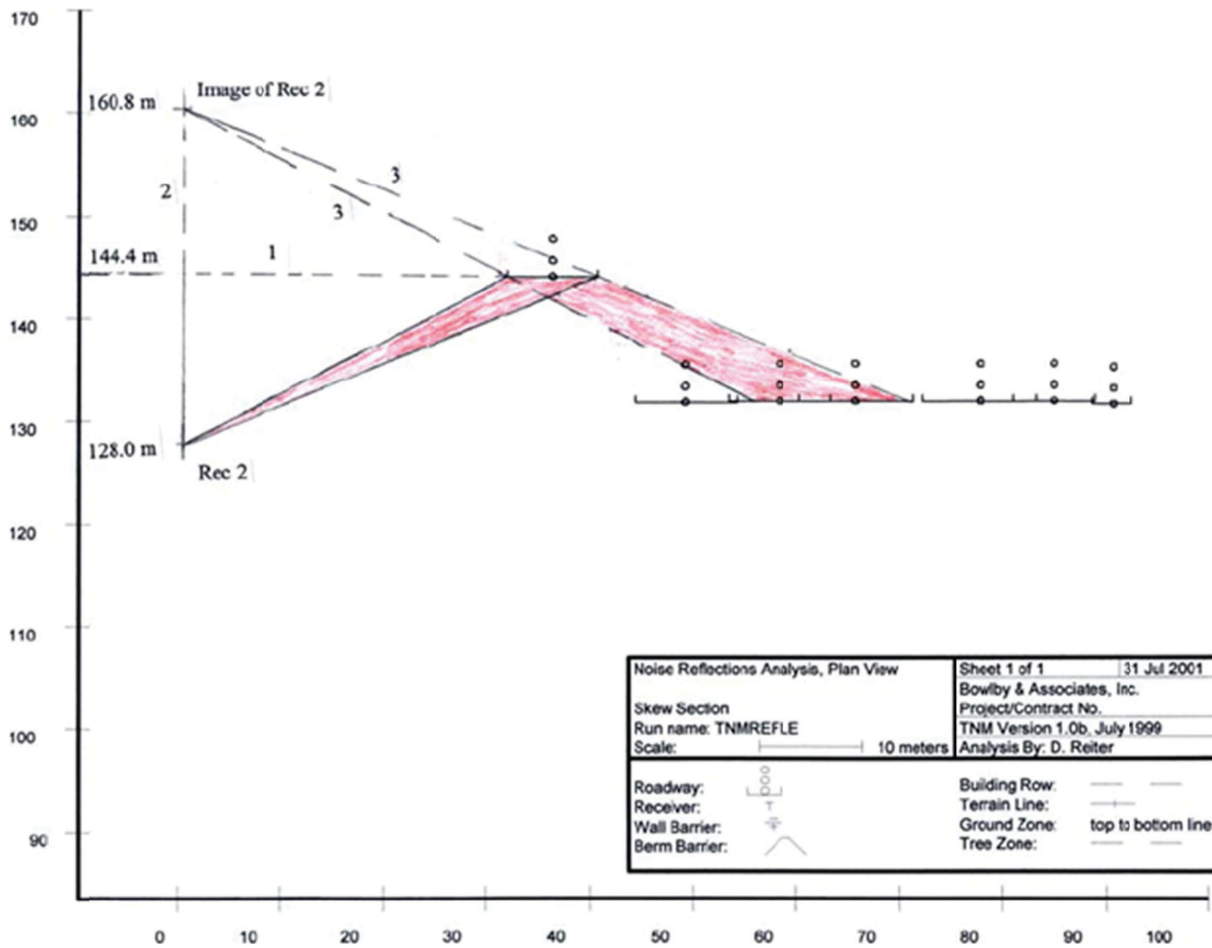


Figure 1. TNM skew section showing roadways contributing to reflected sound.[2]

reflecting off of the undersides of structures, was evaluated and tested for several projects. A complete description of this technique can be found in a 2002 paper by Reiter and Bowlby.[1] Additional discussion of this technique is contained in Appendix A. This technique starts with FHWA TNM skew section views to help identify which sections of roadways and which vehicle types are involved in the reflections that may reach individual receptors. Figure 1 from the 2002 Reiter and Bowlby paper is an example. For any receptor affected by noise reflections, its associated "reflection-contributing" sources are then modeled at that receptor's image location. For each affected receptor, its noise level from reflected sources is then added to the noise level generated in the base FHWA TNM run to obtain its total noise level.

This technique was utilized as a screening process by NCHRP Project 25-34 research team members during the noise evaluation of a Tennessee Department of Transportation (TDOT) project that involved the proposed widening of Interstate 40 (I-40) and a proposed four-level interchange reconstruction in Nashville. The reflecting structure was a ramp with relatively low traffic volumes, so structure-radiated and joint noise were not concerns.

Since the time that the screening analysis was completed, the project has been constructed. The team tested and evaluated this technique from the 2002 paper using Best Modeling Practice #1B, which involved limited simultaneous measurements at three sites that were identified as being affected by reflected noise. For comparison, simultaneous measurements were also taken at three additional sites where traffic characteristics were similar, but where the elevated ramp structure is not present and where reflected noise is not an issue. The reflected noise component estimated by Best Modeling

[1] Reiter, D. D. and W. Bowlby, "Assessing Noise Reflections off the Underside of Elevated Bridge Structures: Procedures Using the FHWA Traffic Noise Model," *Transportation Research Record: Journal of the Transportation Research Board, No. 1792*, Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 50–56.

[2] Reiter, D. D. and W. Bowlby, "Assessing Noise Reflections off the Underside of Elevated Bridge Structures: Procedures Using the FHWA Traffic Noise Model," *Transportation Research Record: Journal of the Transportation Research Board, No. 1792*, Transportation Research Board of the National Academies, Washington, D.C., 2002, Figure 4, p. 53.

Practice #1A was compared to the estimated reflective noise component derived from Best Modeling Practice #1B. Details related to this comparative analysis are contained in Appendix A. While Best Modeling Practice #1B indicated a wider variation of the reflective noise values (3 to 8 dB range) than the 4 to 5 dB range estimated via Best Modeling Practice #1A, the average value was approximately 5 dB using both practices. This indicated that either practice (image-source modeling or comparative measurements) appears to represent a viable Best Modeling Practice for estimating the contribution of structure-reflected noise.

Best Modeling Practice #1A was also used by the research team in its noise analysis of the widening and reconstruction of the Interstate 95 (I-95) Section Girard Avenue Interchange (GIR) project in Philadelphia, Pennsylvania, and by the Washington State Department of Transportation (WSDOT) to evaluate the effects of noise reflections on communities adjacent to the two-level bridge carrying Interstate 5 over the Ship Canal in Seattle.

The processes, applications, and limitations associated with Best Modeling Practices #1A and #1B are described below.

2.2.1.1 Best Modeling Practice #1A: FHWA TNM Modeling of Reflected Noise by Developing Image Receptors

The process of Best Modeling Practice #1A is the following:

1. Model direct highway noise contributions from all roadways using FHWA TNM.
2. Use the technique described in Reiter and Bowlby 2002 (see footnote 1) to estimate adjustments due to reflections off of the underside of structures.
3. Apply adjustments to obtain structure-noise-adjusted predicted noise level.

The applications and limitations of Best Modeling Practice #1A are the following:

1. Since Best Modeling Practice #1A is solely based on noise modeling, it can be applied to any type of highway project, i.e., construction on new location or reconstruction of an existing highway.
2. Use requires detailed geometric and traffic information.
3. Use does not account for the variation of reflected noise associated with different types of superstructures, i.e., spread box beams, adjacent box beams, segmental bridges, steel I-beams, steel deck pans, etc.
4. Best Modeling Practice #1A deals only with structure-reflected noise and does not account for any other structure-related noise.

2.2.1.2 Best Modeling Practice #1B: Comparing Noise Measurements at a Site Containing Reflections with a Site without Reflections

The process of Best Modeling Practice #1B is the following:

1. Model direct highway noise contributions from all roadways using FHWA TNM. Model for each traffic condition at all receivers associated with each measurement period.
2. Conduct multiple sets (minimum of three) of noise measurements at selected setback locations where reflected noise is believed to be a contributing factor.
3. Conduct multiple sets (minimum of three) of simultaneous measurements at locations with similar setbacks that have similar traffic and topographic features, but where reflections from the underside of a structure are not a contributing factor.
4. For each measurement setback distance, calculate the difference between the values for Items 2 and 3, above. This is the reflected noise adjustment factor.
5. For each measurement setback distance, apply the reflected noise adjustment factor (Item 4) to the FHWA TNM noise level from Item 1 to obtain the structure-noise-adjusted predicted noise level.

The applications and limitations of Best Modeling Practice #1B are the following:

1. Use requires detailed geometric and traffic information.
2. Use inherently accounts for the type of superstructure.
3. Use requires exclusion of extraneous noise sources.
4. Use requires sufficient equipment and personnel to perform simultaneous measurements and to collect simultaneous traffic data, which are required to normalize the measured levels to one set of traffic conditions.
5. Use requires finding a location without reflections that has similar traffic and topography for comparison with the reflective location.

2.2.2 Best Modeling Practice #2: Using Noise Measurement Data to Develop Combined Structure-Related Predicted Noise Levels

Development of a best modeling practice that relies on noise measurements to establish adjustment factors associated with structure-related noise to apply to basic FHWA TNM values involved a multistep approach. This multistep approach was a refinement of an approach used by NCHRP Project 25-34 research team members during a 2011 noise analysis of an adjacent section of I-95.

Table 1. Structure-radiated and expansion-joint noise under I-95.

Date	Beginning Time of Measurement	Measured Noise Level L_{eq} in dB(A)		
		Position 1: Near Joint, within 5 ft of Bottom of Deck	Position 2: Away From Joint, within 5 ft of Bottom of Deck	Position 3: 5 ft Above Ground between Positions 1 and 2
		L_{eq}	L_{eq}	L_{eq}
4/15/2013	3:47 pm	63.6	63.2	63.1
	4:08 pm	64.4	64.1	64.2
	4:24 pm	No Data	64.2	64.2

For the multistep approach, the research team initially conducted noise measurements directly underneath a span of the I-95 viaduct at Schiller Street in Philadelphia where other highway noise sources do not exist. Three sets of simultaneous measurements were taken underneath the viaduct at three positions:

- Site 1: Within 5 ft of the bottom of the deck near an expansion joint.
- Site 2: Within 5 ft of the bottom of the deck at a point midway between expansion joints.
- Site 3: At 5 ft above the ground at a location midway between Positions 1 and 2.

These measurements were performed using American National Standards Institute (ANSI) Type I noise meters and compatible microphone cables. Commonly available and relatively inexpensive equipment (connected pieces of half-inch electrical conduit costing less than $25.00 supported by speaker stands) was used to position the microphones at locations close to the underneath of the viaduct superstructure. Results of the measurements are included in Table 1.

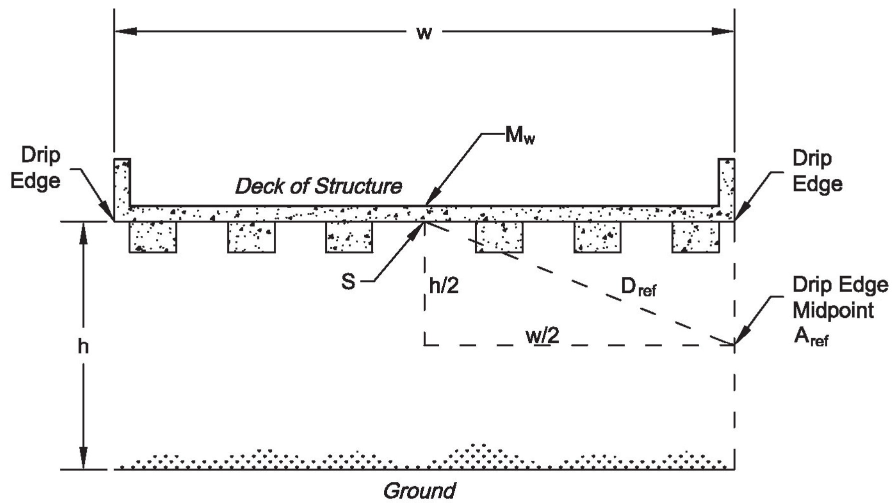
The measurements show very little difference in noise levels at positions underneath the structure, illustrating that, at this location, ground level noise levels resulted from a combination of joint and deck noise, with neither of these noise sources predominating. In addition, there was little difference between noise levels measured just below the deck and those measured 5 ft above the ground. Based on these observations, it was assumed that a measurement taken at a point below the outside of the viaduct (drip edge location) would represent the combined noise level due to deck and joint noise at that location. To estimate the combined contribution of deck and joint noise at points at various distances (setback locations) from the structure, drop-off equations associated with various drop-off rates were developed.

For the purpose of establishing an initial reference distance for calculating structure-related noise at setback locations, it was assumed that the noise emanates from the underside of the deck at the centerline of the structure, midway between the drip edges. In establishing structure-related noise levels at setback locations, the location of drip edge noise was assumed to be midway between the bottom of the bridge deck and the ground. The input parameters illustrated in Figure 2 were used to determine the reference distance (D_{ref}) and the distance from the assumed midpoint source of structure-related noise (S) to the drip edge location (A_{ref}) using the following procedure:

- Measure the height of the structure from the underside of the deck to the ground (h). Divide the distance by two (h/2) to calculate the midpoint between the ground and the underside of the deck. This is designated the drip edge midpoint (A_{ref}).
- Measure the width of the structure from drip edge to drip edge (w). Divide the distance by two (w/2) to calculate the midpoint or centerline of the structure (M_w). The underside of the deck at M_w is the assumed location of the source of the structure-related noise (S).
- To calculate D_{ref}, the distance from the source of the deck noise (S) to the drip edge midpoint A_{ref}, the formula $D_{ref} = \sqrt{\left(\frac{w}{2}\right)^2 + \left(\frac{h}{2}\right)^2}$ was employed.

Figure 3 illustrates the relationship between D_{ref} and the location of the analysis points at various setback distances from the drip edge. The height, width, and measured noise level at the drip edge of the structure are entered into the Structure-Related-Noise Calculation Worksheet (see Table 2). The spreadsheet calculates A_{ref}, M_w (or S), and D_{ref}. Setback distances from the drip edge of the structure are included in Table 2 for standard distances of 25, 50, 100, 200, and 400 ft. A blank row (A_{xxx}) is provided for inserting an additional setback distance if desired. The spreadsheet also calculates the structure-related noise at the analysis points based on the three drop-off rates of 3.0, 4.5, and 6.0 dB per double distance (dB/DD) using the following formula:

$$L_{A_x} = L_{DE} - 10Log_{10}\left(D_{AP}/D_{ref}\right)$$



h = Height of structure, from ground to underside of deck

A_{ref} = Midpoint between ground and underside of deck at drip edge (h/2)

w = Width of structure from drip edge to drip edge

M_w = Midpoint of Structure (w/2)

S = Assumed source of structural noise

D_{ref} = Source reference distance calculated by:

$$(D_{ref})^2 = (w/2)^2 + (h/2)^2$$

Note: Drawing used for graphical purposes only; not to scale.

Figure 2. Input parameters.[3]

where

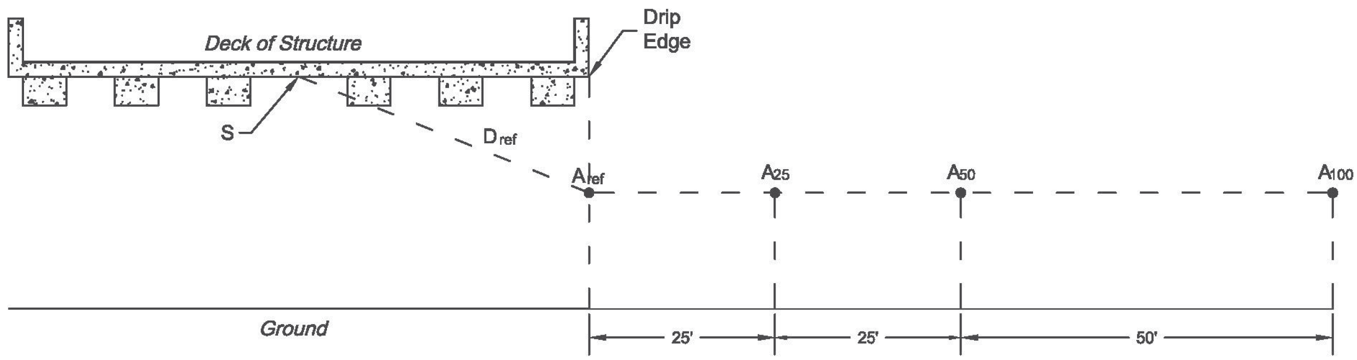
L_{DE} = Equivalent sound level ($_{Leq}$) noise measurement in dB(A) taken at 5 ft above ground under structure drip edge.
L_{A_x} = Calculated structure-related-noise level at an analysis point A_x, located *x* feet from the drip edge.
D_{AP} = Distance from point S to the analysis point A_x.
D_{Ref} = Distance from point S to Point A_{Ref}.

The value of "10" in the formula represents a drop-off rate of 3 dB per doubling of distance (dB/DD). For the 4.5 dB/DD calculation, this value is 15 in the formula. For a 6 dB/DD drop-off rate, the value in the formula is 20.

A detailed discussion of the development of this worksheet-based methodology can be found in Appendix A. In testing the appropriateness of this methodology at setback locations related to the following projects, the research team found the practice to yield reasonable results:

- I-95 projects in Philadelphia, Pennsylvania: Section AFC (nine sets of measurements at Schiller Street) and five Section GIR measurement sets taken at Eyre Street, Sergeant Street, Susquehanna Avenue (two sets of measurements), and Cambria Street.
- Pennsylvania Turnpike Susquehanna River Bridge project in Highspire, Pennsylvania: (four sets of measurements).
- Indiana Department of Transportation (DOT) project: (two sets of measurements).
- Arkansas I-40: (two sets of measurements).

[3] Source: Environmental Acoustics



Note: Drawing used for graphical purposes only; not to scale.

Figure 3. The relationship between D_{ref} and the location of the analysis points. [4]

Detailed information associated with the testing process is included in Appendix A.

The processes, applications, and limitations associated with Best Modeling Practice #2 are given below.

2.2.2.1 *Best Modeling Practice #2: Process, Applications, and Limitations*

The process of Best Modeling Practice #2 is the following:

1. Model direct highway noise contributions from all roadways using FHWA TNM. Model under a variety of free-flow traffic conditions at all receivers associated with each measurement period.
2. Conduct multiple (minimum of three) sets of noise measurements at the drip edge ground level location and at a minimum of two setback distances for the purpose of validating the FHWA TNM runs and determining the extent of structure-related noise contributions. If third-octave band measurements were conducted, review frequency graphs for setback locations to help verify the limits of structure-related-noise contributions. See Appendix A for frequency graphs associated with one-third-octave band measurements for the tested projects.
3. Apply the adjustments from the Table 2 worksheet to levels at setback locations to determine total modeled noise levels at each setback location.
4. If expansion-joint noise is the predominant source of structure-related noise, assume that the noise emanates from the joint above the measurement point rather than at the midpoint of the structure and adjust the worksheet D_{ref} value to be the distance from the drip edge microphone to the bottom of the structure's deck.
5. Apply the values from the Table 2 worksheet to FHWA TNM predicted levels for the proposed project using the drop-off rates that best correlate with the measured levels.

The applications and limitations of Best Modeling Practice #2 are the following:

1. Use requires detailed geometric and traffic information.
2. Use inherently accounts for the type of superstructure.
3. Use requires exclusion of extraneous noise sources.
4. Use requires sufficient equipment and personnel to perform simultaneous measurements and to collect simultaneous traffic data.
5. It does not account for any reflected noise from other sources of highway noise that affect setback locations unless such reflected noise reaches the ground level drip edge location.
6. Since this best modeling practice was developed based on actual existing conditions and tested against these conditions, it is likely to be most applicable to projects that involve reconstruction and/or widening of existing highways as opposed to highways on new locations. In any case, measurements should be taken at structures that resemble the structure type and configuration planned for the proposed highway improvement project.
7. While measurements conducted during the development of the Table 2 worksheet did not indicate substantial variation of expansion-joint and/or deck noise levels due to the variety of observed traffic conditions, users may want to

[4] Source: Environmental Acoustics

Table 2. Structure-related-noise calculation worksheet.

PennDOT I-95 at Schiller Street 4/16/2013 11:11am Northbound Side at 25 feet and 50 feet				
Input Data:				
h: Height of structure, from ground to underside of deck				27
A_{ref}: Center point between ground and underside of structure (h/2).				13.5
w: Width of structure				132
M_w: Midpoint of structure (w/2). The underside of the deck at this point is the assumed source of structural noise (S).				66
D_{ref}: Reference distance - from S to A_{ref}				67
Measured Noise Level at Drip Edge, dB(A)				66.0
Set-back Calculations:				
Analysis Point	Distance from Drip Edge (ft.)	Distance from S to Analysis Point (ft.)	Measured Noise Level at Drip Edge L_{eq} in dB(A)	Calculated Noise Level, Drop-off Rate = 3.0 dB/DD
A_{ref}	06766.0			
A_{25}	25	92		64.6
A_{50}	50	117		63.6
A_{100}	100	167		62.0
A_{200}	200	267		60.0
A_{400}	400	467		57.6
A_{XXX}		67		66.0
Analysis Point	Distance from Drip Edge (ft.)	Distance from S to Analysis Point (ft.)	Measured Noise Level at Drip Edge L_{eq} in dB(A)	Calculated Noise Level, Drop-off Rate = 4.5 dB/DD
A_{ref}	06766.0			
A_{25}	25	92		63.9
A_{50}	50	117		62.4
A_{100}	100	167		60.1
A_{200}	200	267		57.0
A_{400}	400	467		53.4
A_{XXX}		67		66.0
Analysis Point	Distance from Drip Edge (ft.)	Distance from S to Analysis Point (ft.)	Measured Noise Level at Drip Edge L_{eq} in dB(A)	Calculated Noise Level, Drop-off Rate = 6.0 dB/DD
A_{ref}	06766.0			
A_{25}	25	92		63.3
A_{50}	50	117		61.2
A_{100}	100	167		58.1
A_{200}	200	267		54.0
A_{400}	400	467		49.2
A_{XXX}		67		66.0

test this methodology under different traffic conditions as well as test the characteristics of their project's specific structure type, employing techniques used by the research team in developing the worksheet drop-off methodology (see Appendix A).

2.2.3 Best Modeling Practice #3: Using a Combination of Best Modeling Practices

As illustrated in the testing of the various candidate modeling techniques, several of the projects evaluated were affected by contributions of structure-reflected noise additional to deck-radiated and/or expansion-joint noise. This required the incorporation of Best Modeling Practices #1A and #2. If appropriate, Best Modeling Practice #1B could also be employed in such a situation.

In addition, there may be situations where two different practices may be considered for application. For example, WSDOT used Best Modeling Practice #1A to adjust FHWA TNM modeled noise levels to account for structure-reflected noise on the two-level Ship Canal Bridge in Seattle, Washington. At the same time, the research team applied Best Modeling Practice #2 to several selected setback receptors to determine this practice's potential to account for structure-related noise for such a project. This comparison indicated that these two best modeling practices produced similar values for the selected receptors. The selection of the appropriate methodology for a project such as this would most likely depend upon whether the structure-related noise is associated with reflections, deck-radiated noise, expansion-joint noise, or some combination of these sources. Where structure-reflected noise is the predominant source, Best Modeling Practice #1A is probably most appropriate, whereas Best Modeling Practice #2 could be considered where all sources are present, but where sources of deck and/or joint noise predominate.

CHAPTER 3

Signalized Interchanges, Intersections, and Roundabouts

3.1 Introduction

Four of the 16 research topics covered in this report are related in that they involve "interrupted flow," that is, the deceleration, acceleration, and possible stopping and idling of vehicles. The topics are signalized interchanges, intersections, roundabouts, and area sources. The first three topics are covered in this chapter because they have many features and components in common. Guidance on modeling accelerating and decelerating traffic associated with the special situations of toll facilities, service areas, weigh stations, and park-and-ride lots is given in Section 4.2 of Chapter 4 of this report.

3.1.1 Signalized Interchanges

The two main types of signalized interchanges addressed in this research are the traditional diamond interchange and the single point urban interchange (SPUI), shown in Figure 4.

The main issue with interchanges of all types, including unsignalized ones such as clover leafs, is over-modeling or micro-modeling without any improvement in the accuracy of the results. The converse issue would be under-modeling and thus ignoring potentially important effects, particularly the effects of accelerating vehicles, where noise-sensitive receptors are nearby.

Given that so much deceleration and acceleration occurs near the center of an SPUI, an important question is how much influence the interrupted flow has on overall levels at receivers near the interchange. This influence is more likely to be important at a diamond, where sensitive receptors could be very close to the changing-speed traffic. However, the influence can be small depending on parameters such as the dominance of mainline traffic noise if the crossing road passes over the highway (so that the ramp embankments shield the mainline noise) and the proximity of the receptors to the ramps and the mainline.

3.1.2 Intersections

This task area includes both signalized and unsignalized intersections. The main issue with intersections of all types is over-modeling or micro-modeling without any improvement in the accuracy of the results. As with signalized interchanges, the converse issue would be under-modeling and missing potentially important effects on received sound levels when noise-sensitive receptors are nearby.

3.1.3 Roundabouts

Roundabouts have become a more and more common design feature for regular intersections and for highway entrance and exit termini in the last 15 years. As noted in the Foreword of *NCHRP Report 672: Roundabouts: An Informational Guide, Second Edition*,[5] there were only about 38 "modern" roundabouts in the United States in 1997, but by 2010, there were over 2,000. A modern roundabout differs from the older, large, high-speed rotaries still in use in the country and also from the smaller traffic circles typically used to calm traffic in suburban neighborhoods. As illustrated in Figure 5 (Exhibits 1-1 and 6-2 from *NCHRP Report 672*), a modern roundabout is characterized by

- A generally circular shape with counterclockwise flow.
- A single lane or multiple lanes with signing and pavement markings that eliminate the need to change lanes to exit from the roundabout.
- Use of splitter islands between the approach and departure lanes that creates entry geometries that force slow speeds, positively direct the motorist in the correct direction, and provide a refuge for crossing pedestrians.

[5] Rodegerdts, L. A., J. Bansen, C. Tiesler, J. Knudsen, E. Myers, M. Johnson, M. Moule, B. Persaud, C. Lyon, S. Hallmark, H. Isebrands, R. B Crown, B. Guichet, and A. O'Brien, *NCHRP Report 672: Roundabouts: An Informational Guide, Second Edition*, Transportation Research Board of the National Academies, Washington, D.C., 2010.

Figure 4. SPUI.[6]

- Use of yield signs at the entries rather than stop signs or signals.

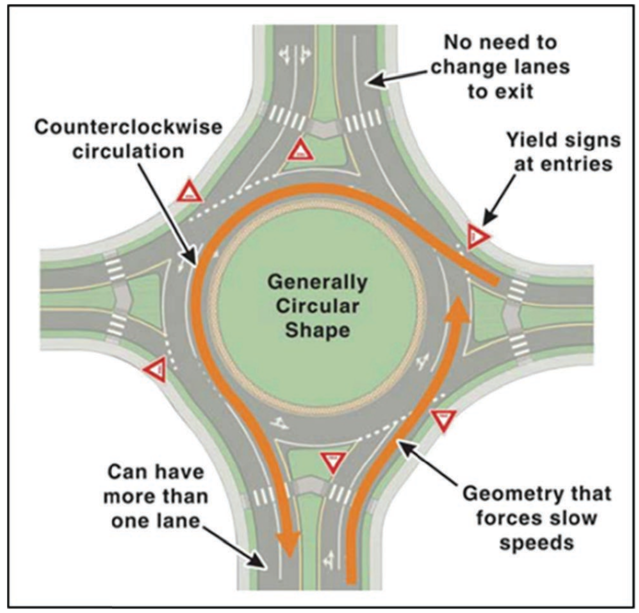
The goal of modern roundabout design is to slow, but not stop, the vehicles, achieving smooth and safe functioning of the intersection.

As with signalized interchanges and intersections, the main issue with roundabouts is finding a level of detail in modeling that achieves accurate results while avoiding over-modeling that does not improve the results.

3.2 Modeling Acceleration and Deceleration

3.2.1 Acceleration

FHWA TNM computes the acoustical effect of acceleration as vehicles pull away from traffic-control devices such as stop signs, toll booths/barriers, and traffic signals, and also along highway entrance ramps. FHWA TNM calls roadways with traffic-control devices "flow control" or "interrupted flow" roadways. As vehicles accelerate on these roadways, vehicle reference energy mean emission levels (REMELs) are higher than the REMELs of cruising vehicles at the same speed, according to field research done as part of the FHWA TNM development.[7] That research developed a "full throttle" emission-level database and speed-distance-grade algorithms for computing the speed of vehicles as they accelerate along an interrupted flow roadway. Collection of deceleration data was not within the scope of that work.



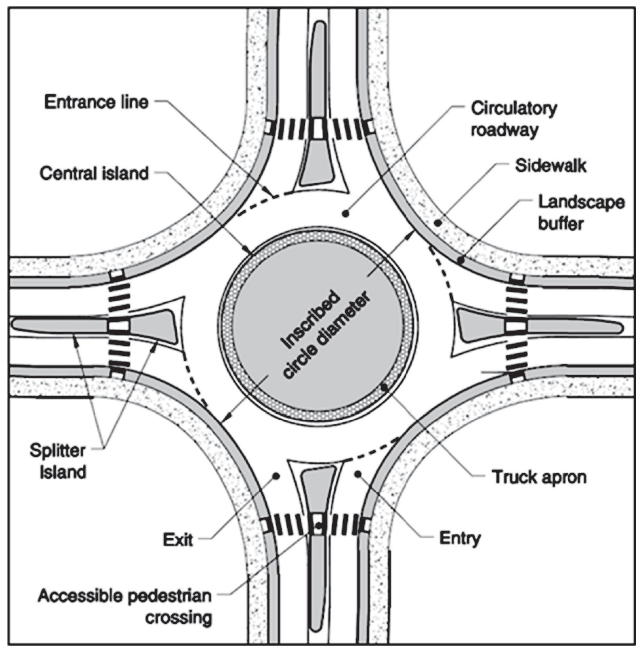


Figure 5. Modern roundabout characteristics.[8]

An interrupted flow roadway is designated by choice of a "Control Device" in the FHWA TNM Roadway Input dialog box. When this choice is made, the modeler-supplied speeds

[6] Imagery © 2014 Google, Map data © 2014 Google.

[7] Bowlby, W., R. L. Wayson, S. Chiguluri, M. Martin, and L. A. Herman, *Interrupted Flow Reference Energy Mean Emission Levels (REMELs) for the FHWA Traffic Noise Model*, U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center, Report No. DOT-VNTSC-FHWA-97-1 and FHWA-PD-97-019, January, 1997.

[8] The schematics shown in Figure 5 are, on the top, Exhibit 1-1 (p. 1–3), and on the bottom, Exhibit 6-2 (p. 6–9), from Rodegerdts, L. A., et al., *NCHRP Report 672: Roundabouts: An Informational Guide, Second Edition*, Transportation Research Board of the National Academies, Washington, D.C., 2010. ©National Academy of Sciences 2010.

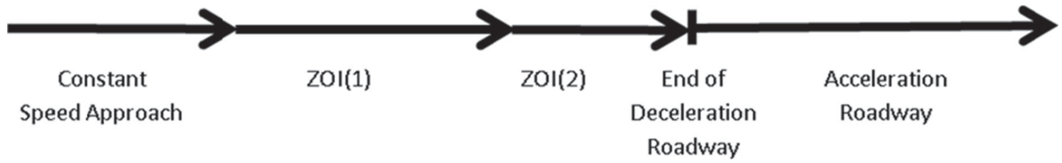


Figure 6. ZOIs for a deceleration roadway as defined in **NCHRP Report 311.**

on the traffic tab of the roadway input dialog box are treated by FHWA TNM as the final speeds that vehicles will try to reach during their acceleration. The modeler provides a starting speed for all traffic on the roadway, called the "speed constraint," which would be zero for a stop sign, but which could be non-zero for an entrance ramp, as an example. The modeler also provides a percentage from 0 to 100% for "vehicles affected," which, in the case of a control device such as a traffic signal, results in a percentage of the traffic to experience acceleration, while the remaining percentage is modeled as cruising along the roadway at the modeler-provided speeds.

The *FHWA TNM Technical Manual*[9] states that FHWA TNM computes accelerating speeds for each vehicle type along a roadway's length as a function of roadway grade until the final speed is attained or the end of the roadway is reached. Research conducted under NCHRP Project 25-34 identified a problem with the condition of reaching the end of the roadway and proposes a solution. The *FHWA TNM Technical Manual* also notes that FHWA TNM tracks speeds from one roadway segment to the next for a given roadway, but not from one roadway to the next.

3.2.2 Deceleration

FHWA TNM has no built-in function for modeling deceleration. For deceleration conditions, *NCHRP Report 311: Predicting Stop-and-Go Traffic Noise Levels*[10] gives a foundation from which to work. That research project developed a methodology for using the constant-speed STAMINA 2.0 program (FHWA TNM's predecessor) in acceleration and deceleration situations that occur on interrupted flow facilities or on ramps. The work included measurement and analysis of both accelerating and decelerating vehicle sound levels and a series of sensitivity tests using STAMINA 2.0.

NCHRP Report 311 defined two "zones of influence" (ZOIs) to represent the last two segments of a roadway being used to model deceleration, as illustrated in Figure 6. As shown in Table 3, which is modified from Table 7 of *NCHRP Report 311*, guidelines are given on the lengths of these segments, as a function of approach speed, and "equivalent speeds" to use for each vehicle type on each segment. Both the segment lengths and speeds were empirically derived from field measurements reported in *NCHRP Report 311*. An issue is that those speeds are based on the circa-1975 emission levels in the STAMINA 2.0 model, not the circa-1994 emission levels in FHWA TNM.

3.2.3 Questions on Modeling Acceleration and Deceleration

For acceleration, as noted above, FHWA TNM includes REMEL equations and changing-speed algorithms that were derived empirically from field-measured sound-level and speed data. There was no identified or expected need to question that data or collect new data.

There are several issues with modeling an acceleration:

- What roadway segment length should be used to minimize errors in the predicted level?
- What starting speed, or Speed Constraint, should be used for an acceleration roadway?
- Where should the interrupted flow roadway start in the presence of a queue of traffic at a signal, whether that signal is at the end of a ramp or at the intersection of two through roads?
- How does the choice of percentage of traffic to use for the Vehicles Affected parameter affect the results?
- To what level of detail should the traffic movements be modeled?
- How far should an acceleration roadway such as an entrance ramp be extended to properly account for the noise from the accelerating traffic, especially heavy trucks?

The issues for modeling a deceleration situation are the following:

- Should a deceleration roadway be modeled by a series of decreasing-speed roadway segments, or should it be modeled by a constant-speed segment?
- If using decreasing-speed roadway segments, over what distance should deceleration be modeled, and what should the speeds be?
- Once vehicles have decelerated to a stop at a signal, should there be some accounting of the time spent stopped and

[9] Menge, C. W., C. F. Rossano, G. S. Anderson, and C. J. Bajdek, *FHWA Traffic Noise Model®, Version 1.0—Technical Manual*, U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center, Report No. DOT-VNTSC-FHWA-98-2 and FHWA-PD-96-010, Cambridge, MA, February 1998.

[10] Bowlby, W., R. L. Wayson, and R. E. Stammer, Jr., *NCHRP Report 311: Predicting Stop-and-Go Traffic Noise Levels*, Transportation Research Board, National Research Council, Washington, D.C., 1989.

Table 3. *NCHRP Report 311* guidelines for modeling deceleration roadways with a final speed of 0 mph.[11]

Deceleration Range (mph)		Length (ft)		Speed ZOI(1) (mph)			Speed ZOI(2) (mph)		
$S_{initial}$	S_{final}	ZOI(1)	ZOI(2)	Automobiles	MT	HT	Automobiles	MT	HT
30	0	150	100	29	26	24	18	13	10
40	0	275	100	34	30	28	18	13	10
50	0	400	100	38	34	31	18	13	10
60	0	500	100	41	36	33	18	13	10

MT = Medium trucks. HT = Heavy trucks.

idling while the signal is red before acceleration begins when the signal turns green?

- When is this entire effort worth doing? In other words:
  - For a one-way road, what is the effect of an acceleration roadway starting at the stop line on levels for receivers on the deceleration side of the stop line?
  - For a one-way road with a traffic signal, what is the effect of a percentage of the traffic on the deceleration side on the signal traveling at cruise speed?
  - For a two-way road with a traffic signal, what is the effect of the accelerating and cruising traffic on the far roadway on the levels for receivers along the deceleration side of the near roadway?

3.3 Research Tasks

The research began with a survey of practitioners. Information was obtained on the modeling approaches used on a number of previous highway project noise studies, including several that were conducted by members of the research team.

Following an analysis of previous modeling approaches, a sensitivity analysis was conducted to examine the size of the effects on the wayside L_{eq} caused by varying the different input parameters for acceleration roadways. A single TNM interrupted flow roadway was created with an array of receivers along its length and offset to the side. Separate runs were made for automobiles and heavy trucks. Multiple runs were made for varying vehicle speeds (the final cruise speed after acceleration), Speed Constraint, and the percentage of Vehicles Affected. Constant speed runs were also made for comparison to the acceleration roadway runs.

The next step was to address deceleration, initially through a sensitivity analysis. Test scenarios were developed using the deceleration roadway segment lengths and equivalent speeds for automobiles, medium trucks, and heavy trucks developed in the *NCHRP Report 311* research. These scenarios were for the different approach speeds used in *NCHRP Report 311* and, again, for an array of receivers.

Then, scenarios of decreasing speed were developed based on the modeling approaches presented in the reviewed studies—an incremental decreasing of speeds from one segment to the next. In addition, the scenarios were then re-run without any deceleration modeling at all to determine the effect, if any, of leaving out deceleration completely.

Then, more realistic situations for interchanges were examined such as (1) a diamond interchange ramp in the presence of a mainline highway and (2) an SPUI. For the diamond interchange, a scenario was created with a mainline and exit ramp and an array of receivers to test the effects of various multipliers of the ramp traffic volume on the mainline roadways. The goal was to gain insight on when the mainline traffic dominates the received levels. For the SPUI, cases of detailed and simplified modeling were tested and compared.

The research included limited field measurements and model validation along the exit ramp of a diamond interchange to refine the findings from the sensitivity testing. Some individual vehicle pass-by sound exposure levels (SELs) were also measured for prediction of an SEL-based $L_{eq}(h)$ for comparisons to the TNM modeling results.

Much of the sensitivity analysis discussed for the signalized interchange also applies to regular intersections. The sensitivity analysis was expanded to include the effect of adding traffic moving in the opposite direction—acceleration on a roadway in one direction alongside deceleration on the roadway in the opposite direction. A second consideration was the presence of cruising traffic in addition to the accelerating and decelerating traffic for signalized intersections where a certain percentage of the traffic cruises through the intersection on a green signal. The third consideration was the needed level of detail for the modeling.

The initial work done for interchanges and intersections was also applied to roundabouts. In particular, the sensitivity analysis provided important information on the variation in

[11] Bowlby, W., R. L. Wayson, and R. E. Stammer, Jr., *NCHRP Report 311: Predicting Stop-and-Go Traffic Noise Levels*, Transportation Research Board, National Research Council, Washington, D.C., 1989. Table 7 (adapted), p. 32.

sound levels that can be expected with changes in the FHWA TNM Flow Control input parameters for acceleration and the *NCHRP Report 311* guidelines for deceleration. From these results, initial guidelines were developed on the modeling of components of roundabout approach and departure legs and inner circulatory roadway.

Limited field validation noise measurements were also made at a one-lane roundabout site. The site was modeled in FHWA TNM (and used in the above-described sensitivity testing) with the traffic counted during the measurements, allowing comparison of the measured and predicted levels. Some deceleration and acceleration individual vehicle pass-by SELs were also measured for comparison to the measured and modeled L_{eq}(h).

3.4 Outcomes of the Research—Best Practices and How to Implement Them for a Noise Study or TNM Model

3.4.1 Signalized Interchanges—Diamond

There are two main components to the diamond interchange: the entrance ramps and the exit ramps. Modeling of the crossing road can also be important.

3.4.1.1 Entrance Ramp

The ramp should be modeled as a flow control acceleration roadway that starts at the beginning of the ramp, with 100% Vehicles Affected. The Speed Constraint should be 10 mph, based on *NCHRP Report 311*. If the ramp carries more than 3% heavy trucks, the Speed Constraint could be increased to 15 or 20 mph because automobiles can make the turn onto the ramp at a higher speed before beginning the acceleration along the ramp.

Figure 7 shows the predicted L_{eq}(h) for separate runs of 1,000 automobiles/hr and 1,000 heavy trucks/hr accelerating up to a cruise speed of 60 mph for Speed Constraints of 0 and 10 mph. The receivers are along the side of the roadway, offset 100 ft from it, beginning at the start line and proceeding downstream. These runs show the effect of the 10-mph Speed Constraint over the first several hundred feet of acceleration and also show the large difference in L_{eq}(h) by vehicle type if the volumes of the two vehicle types are equal. If the heavy truck percentage was only 3% of the total volume, the automobile and heavy truck curves would be roughly equal at the close-in distance and the automobile L_{eq}(h) would dominate the total L_{eq}(h) beyond about 1,000 ft downstream. Figure 8 shows this case for a Speed Constraint of 0 mph. The range in predicted L_{eq}(h) over the entire

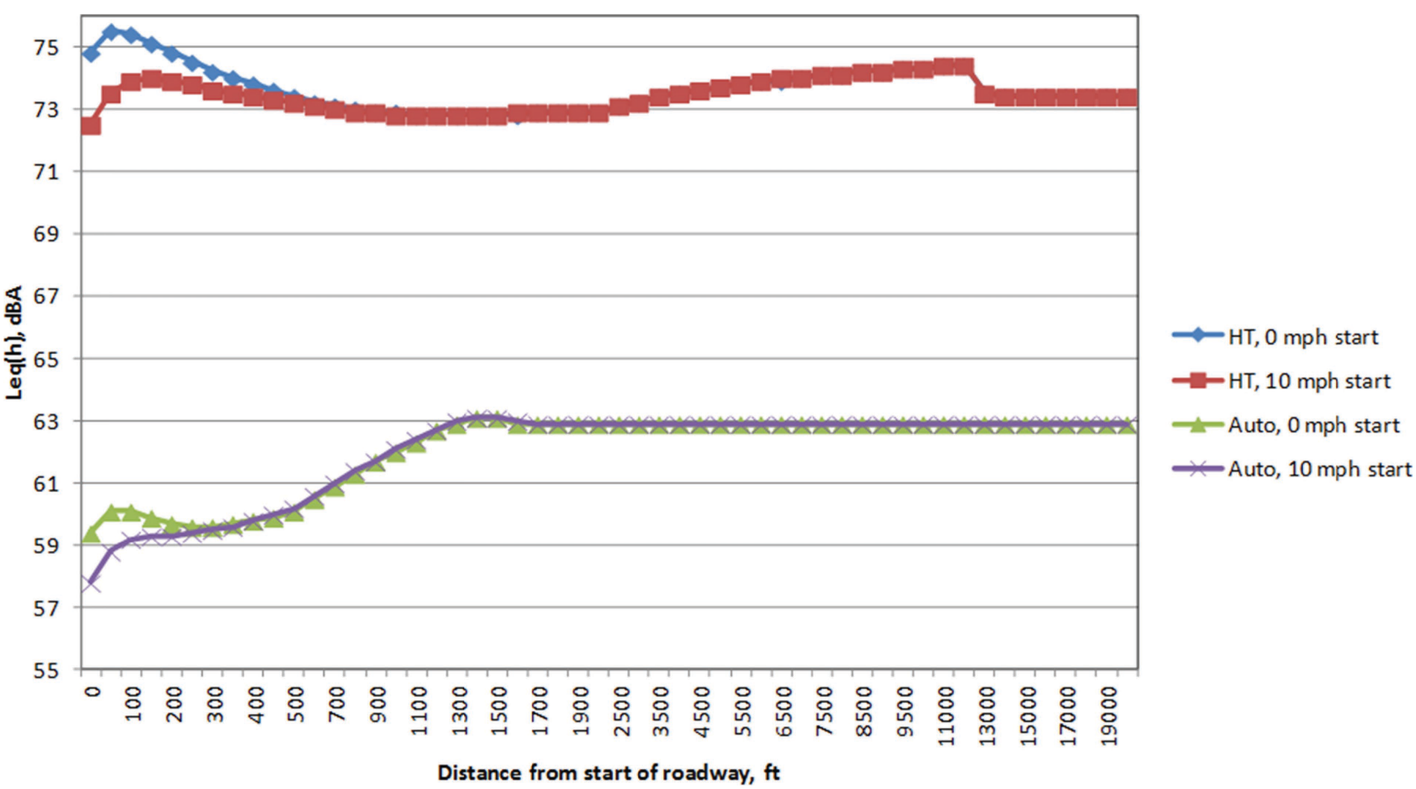


Figure 7. L_{eq}(h) for 1,000 automobiles and 1,000 heavy trucks, plotted separately, accelerating from 0 mph to 60 mph with 100% of the Vehicles Affected and Speed Constraint of 0 and 10 mph for a series of receivers offset 100 ft from the roadway.

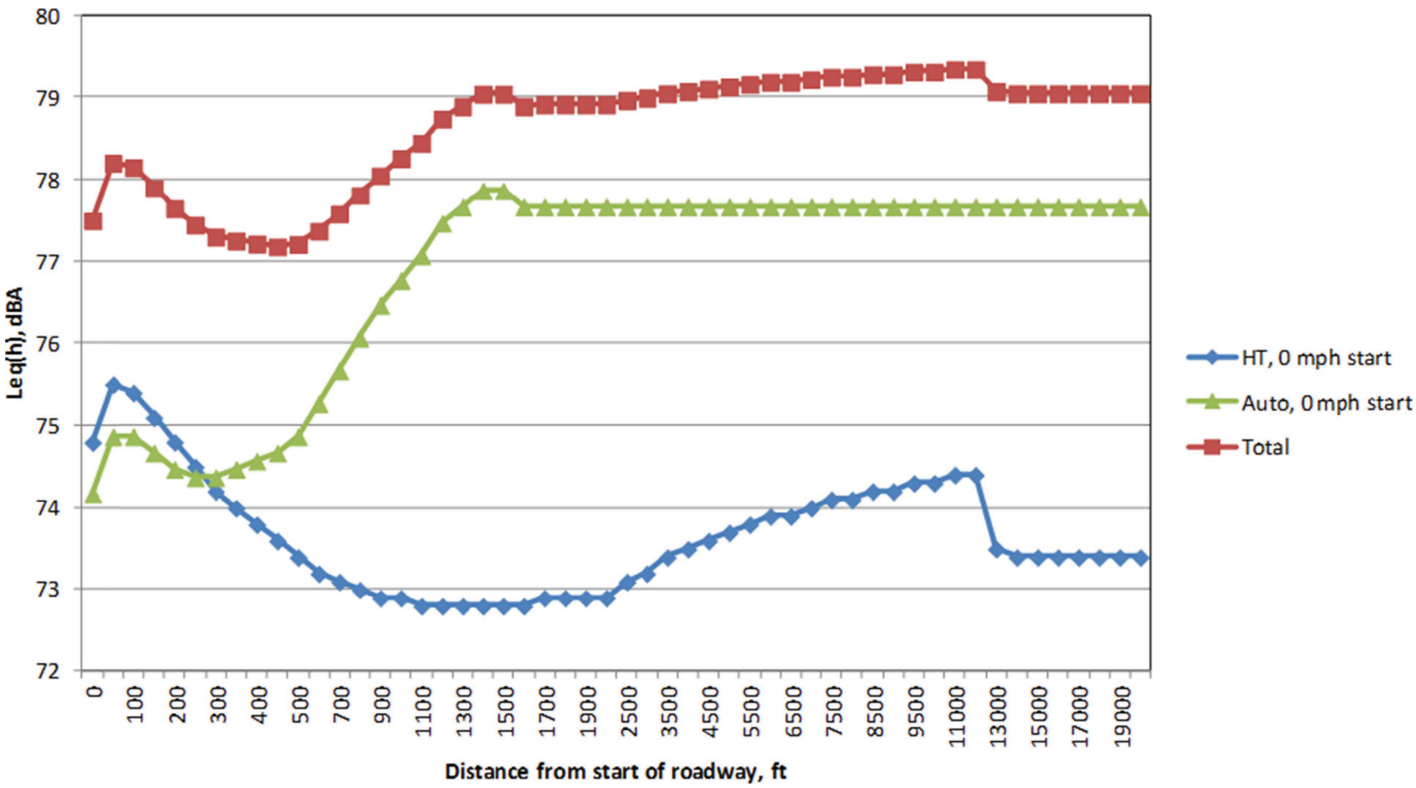


***Figure 8.** L_{eq}(h) for 97% automobiles and 3% heavy trucks (31,000 vehicles), accelerating from 0 mph to 60 mph with 100% of the Vehicles Affected and a Speed Constraint of 0 mph for a series of receivers offset 100 ft from the roadway.*

acceleration region and on into the cruise speed region is only about 2 dB.

The FHWA TNM roadway segment lengths should not exceed 50 ft if the final cruise speed is 30 mph, 100 ft for 45 mph, and 500 ft for 60 mph or higher.

In the process of doing the sensitivity analysis for acceleration, an apparent error in the FHWA TNM speed algorithm was found. The FHWA TNM Technical Manual indicates that speed along an interrupted flow roadway segment is computed on a subsegment basis as the program subdivides user-specified segments for its sound-level computations. Then, when the vehicle reaches the "target" or final speed that has been input by the user, FHWA TNM is supposed to stop accelerating the vehicle, revert back to the cruise emission levels, and continue computing levels along the roadway at the target speed. Instead, it was found that once TNM accelerates the vehicle to the target speed, it does not revert back to the cruise emission levels until the beginning of the next roadway segment. The result is that the user's choice of the segment lengths can result in very different predicted sound levels at a receiver instead of being independent of the user-specified segment length. The problem was studied, and guidance to avoid incorrect sound-level calculations was developed. Appendix B documents the analysis (available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986.)

There are several options on the modeled length of the ramp roadway. Two of these options are the following:

- Option 1 is to model the roadway past the physical merge point and then parallel to and offset by a foot from the outer mainline roadway until the end of the modeled mainline roadway. One advantage of this option is that the analyst does not have to determine where to stop the ramp roadway in terms of its effects on the total wayside sound level. A second advantage is that the analyst does not have to adjust the mainline roadway traffic volumes past the merge point to add in the ramp traffic.
- Option 2 is to end the ramp at the physical merge point. Because of the difference in the cruise and "full throttle" REMELs in FHWA TNM, unless the ramp truck traffic is a very large percentage of the mainline truck traffic (40% at 50 mph and 16% at 70 mph), the consequence of ending the ramp before the cruise speed is attained and modeling all of the trucks beyond that point at the cruise speed is slight (±0.5 dB) over-prediction of level (less than 0.5 dB). As a guide, it is sufficient to have FHWA TNM only accelerate the heavy trucks up to a speed of 30 mph—a distance of about

700 ft on a 0% grade—for the above-cruise speeds and truck percentages. Appendix B provides details on this analysis.

3.4.1.2 Exit Ramp

The need to model deceleration along the ramp in detail is moderated by several factors. First, while 100% of traffic will either have to stop at the signal or decelerate down to about 10 to 20 mph to make a turn at the end of the ramp, the traffic may then be modeled as accelerating away from the end of the ramp. If there is a queue on the ramp for the signal, that acceleration will occur along the ramp. Acceleration from the end of ramp or the queue will affect levels at upstream receivers; as a result, precise modeling of end of deceleration is not needed. Second, the mainline noise may be the dominant contributor to the total sound level for receivers along the ramp; the effect is a function of the receiver offset distance from the ramp, the distance upstream along the ramp, and the amount of traffic on the ramp compared to the mainline traffic.

Figure 9 compares the wayside L_{eq}(h) for receivers at an offset distance of 100 ft along the deceleration roadway for a deceleration roadway alone and the deceleration roadway with an acceleration roadway heading downstream from the stop line away from the upstream receivers. The stop line is on the left of the chart and upstream is to the right. Separate predictions are shown for 1,000 automobiles and 1,000 heavy trucks with 100% of the Vehicles Affected and a Speed Constraint of 0 mph for the acceleration. The deceleration roadway was modeled using the *NCHRP Report 311* guidelines for 60-to-0-mph deceleration. The effect of the downstream acceleration away from the upstream receivers is large. The levels are higher than the deceleration-only case as far upstream as 300 ft from the stop line. In real-world terms, the acceleration of the vehicles away from the stop line is heard upstream at a level high enough to affect the total upstream level. The greater the offset distance, the greater the influence will be, as shown in Appendix B.

When an acceleration roadway is modeled at the end of a deceleration roadway, precise modeling of at least the last 100 ft of the deceleration roadway is not needed—the total level will be largely influenced by the acceleration roadway.

Field noise measurements along an exit ramp of a diamond interchange on Briley Parkway in Nashville, Tennessee, demonstrated this upstream effect from acceleration away from the stop line. Figure 10 shows the measured L_{eq}(15 min) at a 50-ft offset from the ramp centerline at distances of 50, 100, 200, and 400 ft upstream from the stop line at the end of the ramp. The elevated measured L_{eq} at the 50-ft point, and to some degree at the 100-ft point, show the effects of noise from traffic accelerating away from the ramp and passing local road traffic. Also shown are the FHWA TNM predictions with the

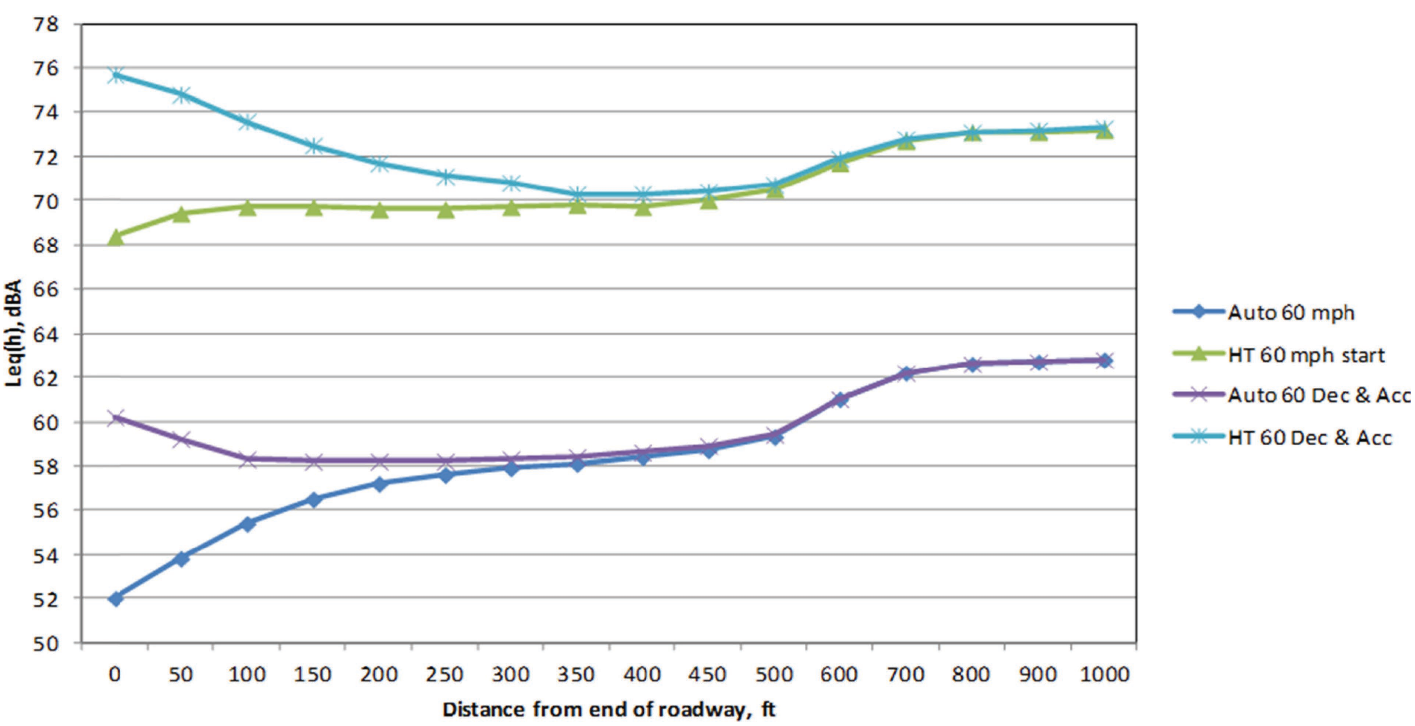


Figure 9. Separate L_{eq}(h) for 1,000 automobiles and 1,000 heavy trucks decelerating from 60 mph to 0 mph using NCHRP Report 311 roadway segment lengths and speeds and then accelerating downstream from 0 mph to 60 mph for a series of receivers offset 100 ft from the deceleration roadway.

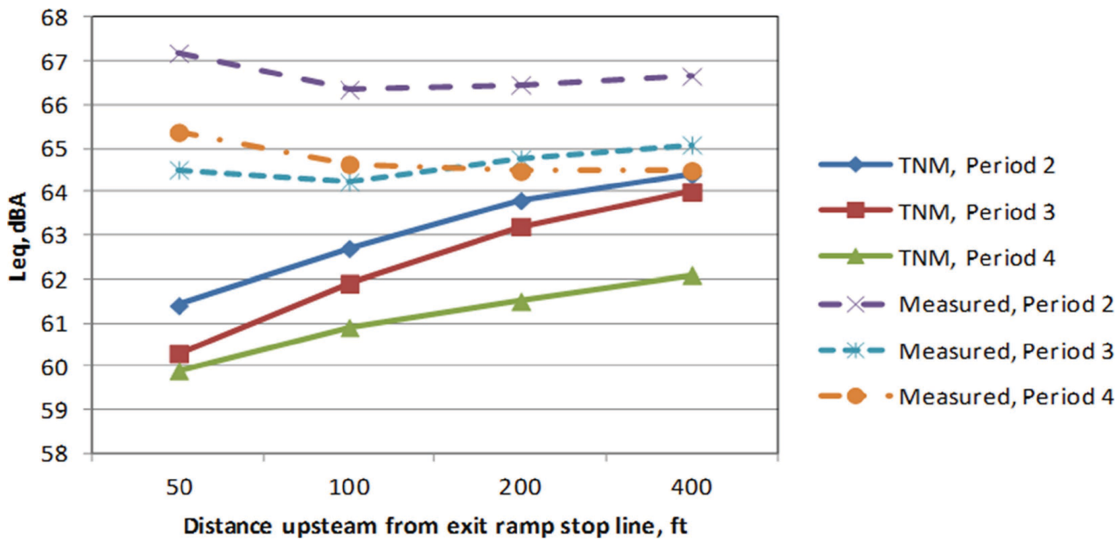


Figure 10. Comparison of measured traffic noise and modeled noise excluding mainline heavy trucks, Briley Parkway exit ramp site.

ramp traffic counted during three of the four measurement periods factored up to hourly volumes. The deceleration was modeled using the *NCHRP Report 311* segment lengths and speeds for deceleration from 60 to 0 mph acceleration at the end of the ramp, and local road traffic are not modeled. The model under-predicts the most at the 50- and 100-ft upstream points. Measurements of individual vehicle sound levels during deceleration along the ramp showed a trend similar to that of the modeled levels.

Testing was then done to improve the prediction of the deceleration L_{eq} by FHWA TNM in comparison to an $L_{eq}(h)$ computed based on the measured SEL data. The results for the exit ramp suggest that the *NCHRP Report 311* segment lengths remain valid when modeling deceleration from 60 mph, but with revised speeds:

- Roadway Segment ZOI(1): 500 ft long with speeds of 50, 40, and 35 mph for automobiles, medium trucks, and heavy trucks, respectively.
- Roadway Segment ZOI(2): 100 ft long with a speed of 20 mph for each vehicle type.

However, the results also show that the L_{eq} at the 50-ft and 100-ft upstream distances from the stop line are heavily influenced by the noise of the vehicles accelerating away from the stop line.

The influence of mainline traffic noise on levels for receivers along a deceleration ramp can be seen in the results of some additional modeling at another diamond interchange. A receiver array was set up with offsets of 50, 100, 200, and 400 ft from the ramp and spacing upstream along the ramp at distances from 50 to 800 ft from the stop line. The end of the ramp is approximately 520 ft from the outermost mainline travel lane.

Tests were made for several ratios of mainline traffic to ramp traffic: mainline traffic equal to 2, 4, 8, and 16 times the ramp traffic, translating to ramp traffic percentages of the mainline traffic of 50%, 25%, 12.5%, and 6.3%, respectively. Only automobiles and heavy trucks were modeled, with a mix of 9% heavy trucks on both the mainline and the ramp.

Figure 11 shows an example of results for receivers close to the ramp (offset 50 ft from the ramp centerline) for a high percentage of ramp traffic—25% of the mainline traffic. In this case, the ramp traffic is an important contributor to the total $L_{eq}(h)$, especially at the shorter distances upstream.

Figure 12 shows the results for receivers farther from the ramp (offset 200 ft) and for a lower ramp traffic percentage—12.5% of mainline). For these receivers, the ramp only affects the total $L_{eq}(h)$ by 0.5 dB or less regardless of the distance upstream from the ramp stop line.

Not included in the results are the effects of acceleration away from the ramp or traffic on the cross street. If these conditions were modeled in the runs, the need for accurate modeling of the deceleration ramp would decline, even for receivers closer to the ramp and closer to the stop line. More results are available in Appendix B.

3.4.2 Signalized Interchanges—Folded Diamond

The folded diamond has one pair of entrance and exit ramps in the traditional diamond layout and the other pair as loop ramps onto and off of the mainline, as shown in

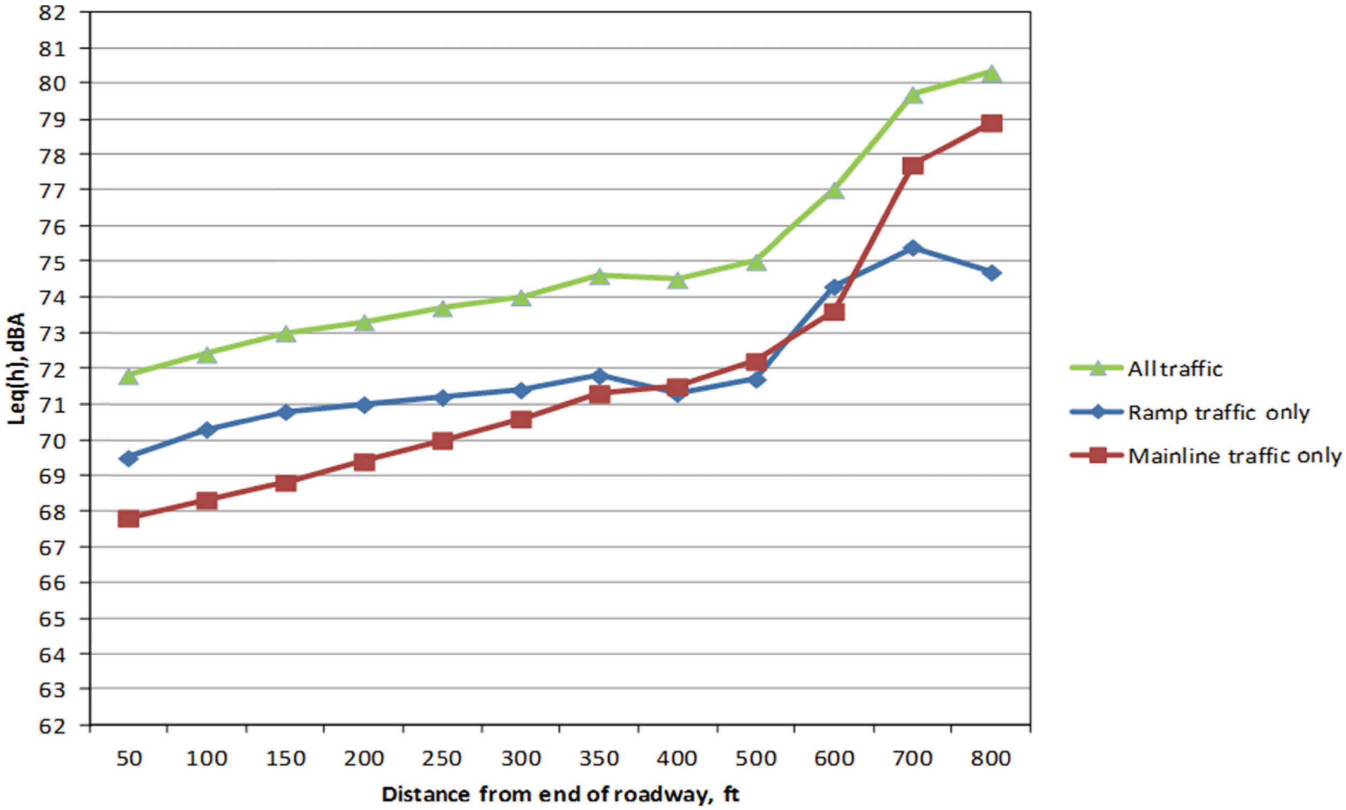


Figure 11. Diamond interchange $L_{eq}(h)$ for ramp traffic equal to 25% of mainline traffic using NCHRP Report 311 deceleration roadway segment lengths and speeds, for a series of receivers offset 50 ft from the ramp centerline.

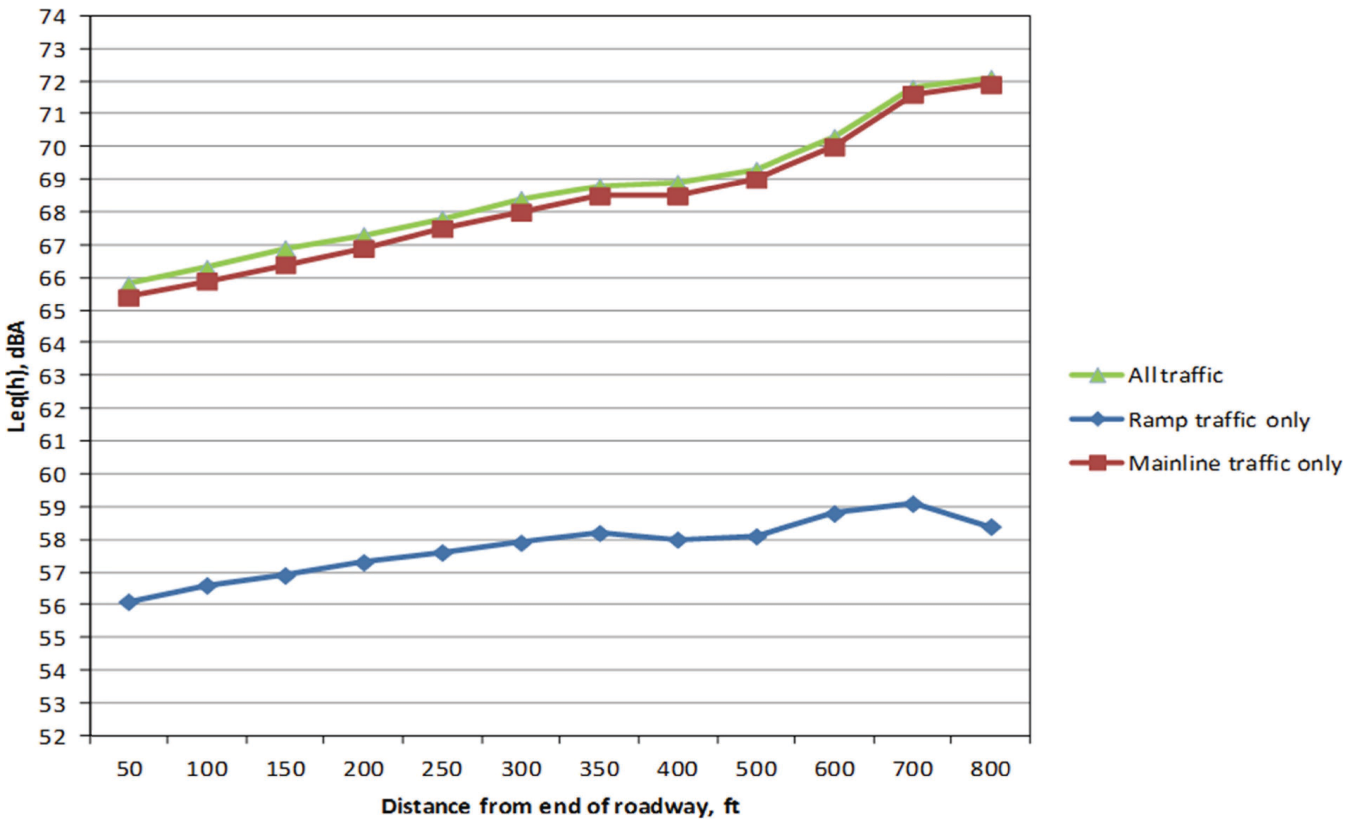


Figure 12. Diamond interchange $L_{eq}(h)$ for ramp traffic equal to 12.5% of mainline traffic using NCHRP Report 311 deceleration roadway segment lengths and speeds, for a series of receivers offset 200 ft from the ramp centerline.

Figure 13. Folded diamond interchange.[12]

Figure 13. Traffic signals control the flow on either side of the interchange. The end of the exit ramp and start of the entrance ramp at each signal resemble a two-way road intersection with approach and departure roadways on one leg only.

3.4.2.1 Entrance Loop Ramp

The FHWA TNM roadway would start at the beginning of the ramp, just past the traffic signal. It would be designated as a flow control roadway with 100% Vehicles Affected and a Speed Constraint of 10 mph (based on *NCHRP Report 311* for heavy trucks) until the loop curve is reached. Then, a new roadway of cruise segments would be used to model the loop at the posted ramp speed. Then, an acceleration roadway would be modeled with 100% Vehicles Affected and a Speed Constraint equal to the ramp loop speed up to final mainline speed.

The FHWA TNM roadway segment lengths should not exceed 50 ft if the final cruise speed is 30 mph, 100 ft for 45 mph, and 500 ft for speeds of 60 mph or higher.

3.4.2.2 Entrance Diamond Ramp

This ramp would be modeled in the same manner as described for the regular diamond interchange.

3.4.2.3 Exit Loop Ramp

The FHWA TNM roadway would start at the beginning of the ramp. It would be modeled by a series of segments along the loop at the posted speed. A final 100-ft segment could be modeled at a speed of 20 mph, ending at the stop line. The immediately adjacent entrance ramp with accelerating traffic and the local crossing road would dominate the levels for any nearby receivers.

3.4.2.4 Exit Diamond Ramp

This ramp would be modeled in the same manner as described for the regular diamond interchange. The immediately adjacent entrance ramp with accelerating traffic and the local crossing road would dominate the levels for any nearby receivers; precise modeling of the deceleration is much less important.

3.4.3 Signalized Interchanges—Single Point Urban Interchange

SPUIs present potentially complex modeling scenarios. The mainline can be designed to pass over or under the turning movements. When passing under, the mainline traffic is largely shielded from the receivers by the ramp embankments or retaining walls. When the mainline traffic passes over the crossing road, mainline noise will dominate the exit ramp traffic's deceleration noise even more than at diamond interchanges because the SPUI ramp is closer to the mainline due to geometry of the interchange design. Also, in this configuration, the interchange movements are under the mainline deck and are shielded from the receivers.

3.4.3.1 Full Modeling

Full modeling is generally not necessary, but the details of the center intersection movements will be briefly described as a basis for understanding the partial modeling. Figure 14 shows the TNM plan view (assuming north is at the top of the figure) for full modeling of a SPUI studied in this research, where the mainline passes under the interchange deck. Figure 15 shows a detail of the modeling of the top of the ramp deck. In the detail:

- The thick solid line is the eastbound crossing road street section going across the deck, represented by a flow control roadway that accelerates traffic from the traffic signal.
- The dotted line is a flow control roadway representing southbound exiting traffic that accelerates to the east away from the signal at the end of the ramp.
- The dashed line is a flow control roadway representing entering traffic from the eastbound cross street accelerating to the north away from the signal at the start of the ramp lane.

The flow control parameters for each of the three indicated roadways are a speed constraint of 0 mph and an assumed 50% of the traffic affected by the signal. There are three

[12] Imagery © 2014 Google, Map data © 2014 Google.

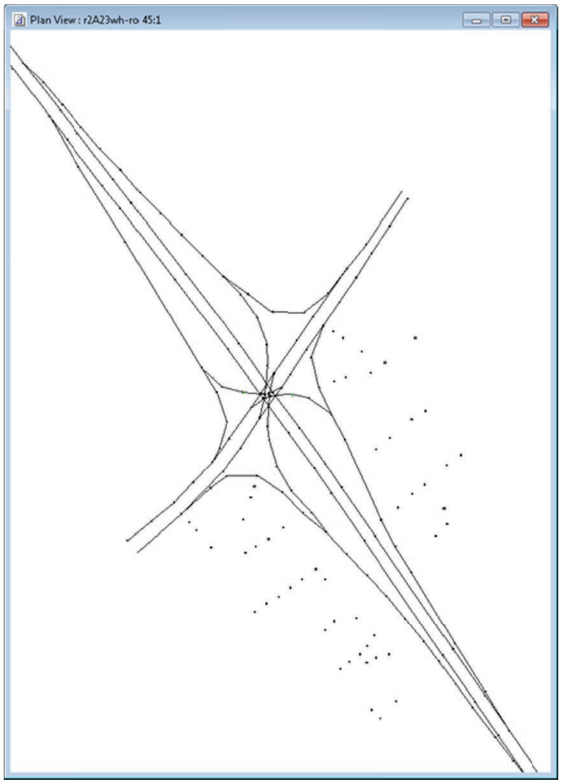


Figure 14. FHWA TNM plan view for full modeling of an SPUI (north is to the top).

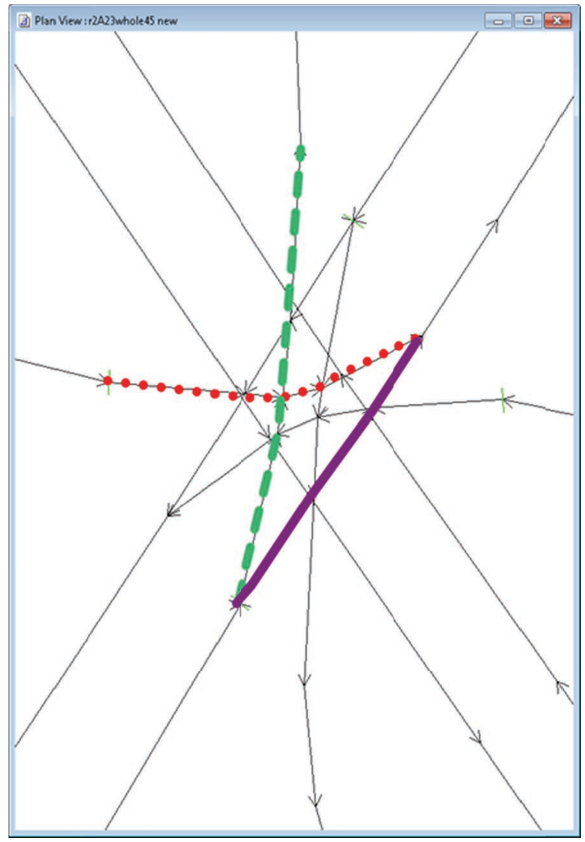


Figure 15. Detail of the modeling of the top of the ramp deck for the full modeling case.

similar flow control roadways for traffic moving in the opposite direction on the crossing road. A disadvantage of this detailed modeling is that it requires modeling of 12 intersecting points of the ramp sections and the cross street roadways, all set as "on structure" segments to allow the mainline roadways to pass under them.

3.4.3.2 Partial Modeling

Partial modeling of the interchange turning movements has the advantages of avoiding micro-modeling of all segments of all turning movements and avoiding modeling of 12 roadway segment intersecting points in the center deck area. A disadvantage is that partial modeling may slightly underestimate sound levels for receivers very close to the end of the exit ramp because the acceleration away from the signal for the left leg of the ramp is not modeled.

Figure 16 shows the TNM plan view for the partial modeling. This partial modeling method requires only four flow control roadways for accelerating traffic on the deck: eastbound crossing road (A), westbound crossing road (B), northbound entrance ramp (C), and southbound entrance ramp (D), and two more flow control roadways not on the deck—the eastbound-to-southbound entrance ramp (E) and the westbound-to-northbound entrance ramp (F). Partial modeling also eliminates all of the otherwise needed roadway intersection points (FHWA TNM requires that crossing roadways share a common point with identical x, y, and z coordinates).

Entrance Ramps. There is one entrance ramp in each mainline direction—northbound (G) and southbound (H)—with each ramp consisting of two acceleration roadway sections. The dashed line toward the center of Figure 16 and the interchange is the eastbound-to-northbound entrance ramp roadway (C). It is modeled as a flow control roadway starting at a point that is past the crossing points in the center of the deck; its branch on the right is the westbound-to-northbound entrance ramp roadway (F), which has no flow control device.

The FHWA TNM roadway segment length for the flow control roadways will depend on the final desired cruise speed, as described for the diamond interchange.

The right-turn (e.g., westbound-to-northbound) entrance ramp roadway (F, shown as a dashed line) starts at a point beyond the crossing points on the deck. It is modeled as a flow control acceleration roadway with 100% Vehicles Affected. The Speed Constraint should be 10 mph if this movement is a full right turn at a signal and can be 20 to 25 mph for channelized flow that eliminates the full right turn.

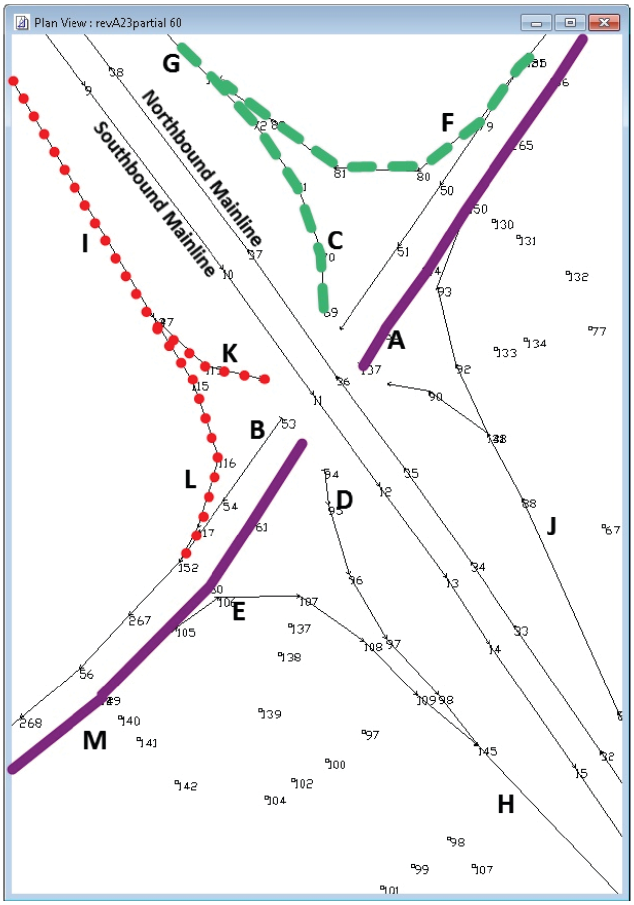


Figure 16. Detail of the SPUI modeling for the partial modeling case.

For the left-turn movement (C), the flow control acceleration roadway is started past the center of the interchange with 50% Vehicles Affected due to the presence of the signal, which is on the entrance (western) side of the deck and a Speed Constraint of 20 mph because the vehicles are already moving forward from the signal.

The southbound entrance ramp (H) is modeled in the same way as the northbound entrance ramp (G). Both ramps are extended to their physical merge points with the mainline, which provides sufficient length for acceleration of the heavy trucks to minimize any under-prediction caused by not extending the ramp until the final cruise speed is actually reached.

Exit Ramps. There is one exit ramp in each mainline direction—southbound (I) and northbound (J)—with each ramp consisting of two branches near its end. The southbound exit ramp (I) is represented in the figure by dotted lines. The branch to the left (in the direction of travel) is the southbound-to-eastbound exit ramp roadway (K) and is modeled as ending at a traffic signal. The branch to the right (in the direction of travel) is the southbound-to-westbound exit ramp roadway (L), which may or may not end at a signal, depending on the design.

Precise deceleration modeling is not critical because of the acceleration at the end of the ramp toward the outside of the interchange (L)—not the movement across the center of the interchange (K)—and acceleration of the adjacent crossing road's through traffic (B).

The exit ramps may be modeled as a series of segments with decreasing speeds. The mainline speed is carried well along the ramp. *NCHRP Report 311* ZOI(1) and ZOI(2) segment lengths may be used for the left branch (K) to the signal leading onto the center deck. The speeds for those segments can be the speeds derived from the diamond interchange noise measurements and modeling.

For the branch to the right (L), the speed will depend on whether the branch is channelized for smooth merging into the crossing road or signalized. If channelized, speeds of 25 to 35 mph could be used depending on the geometrics. The right branch of the ramp (L) would end at the physical merge point with the crossing road (B). If signalized, the last segment (ZOI[2]) would be at 20 mph, in which case the crossing then starts as an acceleration roadway.

Crossing Road. For the crossing road, each travel direction should be modeled separately. The thick solid line in Figure 16 is the eastbound crossing roadway, broken into two modeling sections. The one on the left is the eastbound approach leg (M) and is modeled as ending at a traffic signal at the "entrance" to the deck. It may be modeled at cruise speed because of the acceleration on the nearby southbound entrance ramp legs (D and E) and acceleration in the opposite direction by the westbound crossing road's departure traffic.

The thick solid line on the right of the figure is the eastbound crossing roadway's departure leg (A). It is modeled as starting past the center of the deck as a flow control roadway with 50% of Vehicles Affected and a Speed Constraint of 20 mph because vehicles have already been moving forward from the signal at the entrance to the center deck.

3.4.3.3 Discussion

To illustrate the effect of the acceleration of far lane traffic in the opposite direction and adjacent to the decelerating near lane, Figure 17 compares results for modeling the approach leg with decelerating vehicles using the *NCHRP Report 311* recommendations against modeling the approach at a cruise speed of 30 mph and for heavy trucks only. The accelerating traffic in the other direction was modeled on a flow control roadway for Vehicles Affected values of 25%, 50%, and 75%. Both roadways represent single lanes separated by 12 ft. In this particular case, the stopping points in each direction were offset 80 ft to simulate their separation

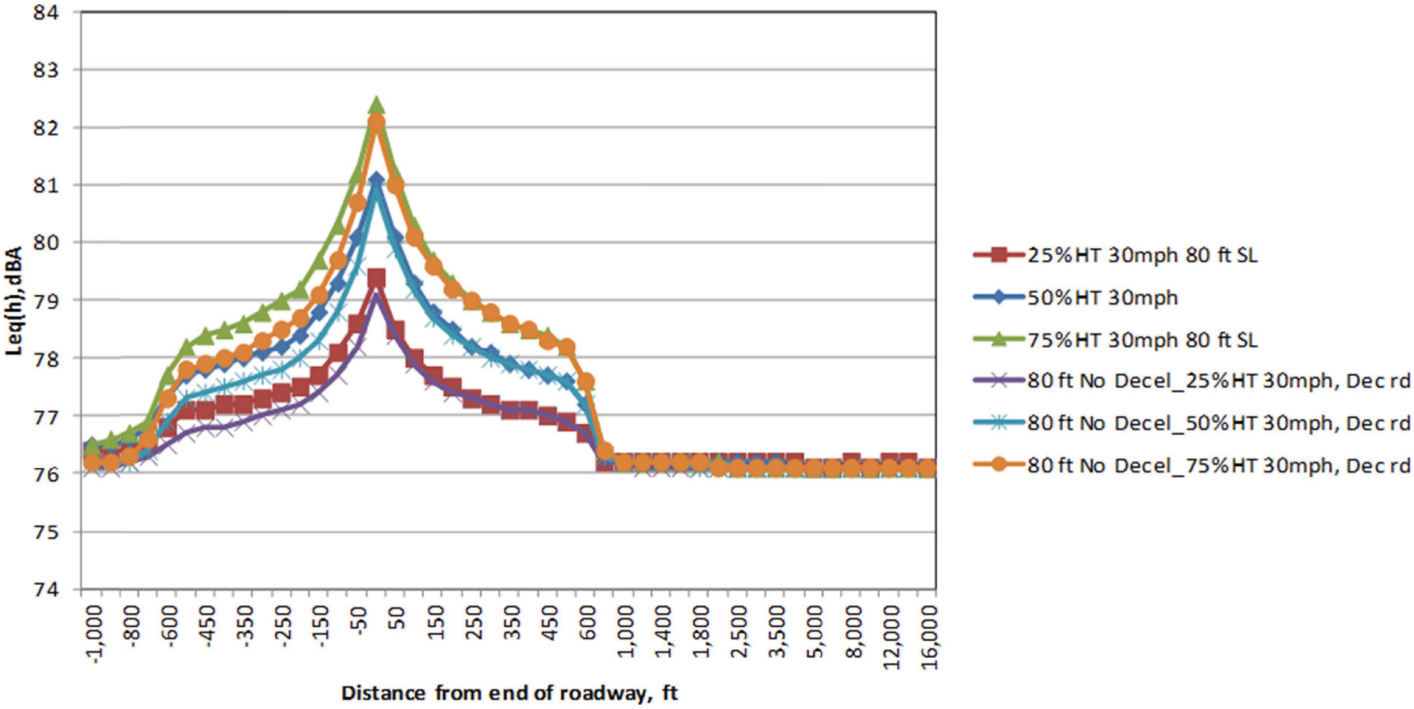


Figure 17. L_{eq}(h) for 1,000 heavy trucks for two-way "Deceleration + Cruise" compared to "All Cruise" on the upstream deceleration side for a 30-mph cruise speed and an array of receivers at a 50-ft offset distance from the roadway.

at a typical intersection of two two-lane roads. The separation would be greater for the SPUI. In this situation, receivers on the upstream deceleration side of the near roadway are exposed to the noise of accelerating vehicles on the downstream side of the acceleration roadway directly across from them. The results are for a string of receivers along the near road, offset from it by 50 ft. When comparing the cases for each percentage of Vehicles Affected, the modeling of the deceleration conditions on either side does little to reduce the total received level, due to the dominance of the acceleration roadways' noise on both sides of the intersection. Modeling the approach roadway at the 30 mph cruise speed is sufficient. The key is to model the acceleration roadway in each direction. As the receiver offset distance increases, the differences decrease, meaning that there are fewer cases in which it may be necessary to model deceleration in the presence of cruising traffic. More details on this analysis are in Appendix B.

As a conservative worst case, modeling on the deceleration side could be done with all cruising traffic first, and if levels were within 1 dB of causing impacts, more precise modeling might be needed to demonstrate that no impacts are predicted to occur.

The results of the comparisons of the full and partial modeling of a SPUI where the mainline passes under the cross street indicate the following:

- Partial modeling of the interchange on the deceleration ramp side is sufficient if there are no receivers within 300 ft of the intersecting road or 400 ft of the deceleration ramp. Even then, detailed modeling is not needed if the partial modeling shows the levels are more than 1 dB below the noise impact criteria in the state highway agency noise policy.
- Partial modeling of the interchange on the acceleration ramp side is sufficient even if there are receivers very close to the intersecting road or ramp.
- When partially modeling the SPUI deck, the speed constraint for both the cross street and the entrance ramp should be 20 mph, with 50% of the Vehicles Affected. For the entrance ramp not crossing the deck, the Speed Constraint should be based on the geometrics of the ramp (20 mph was used in the testing).

Where the mainline passes over the cross street, the partial interchange modeling should be sufficient in almost all cases because of the shielding of the interchange movement beneath the mainline and the greater exposure of the receivers to the mainline noise. Details of the testing of the various scenarios and the results are in Appendix B.

3.4.4 Intersections—Unsignalized

3.4.4.1 Two-Way Stop

This situation would involve a more heavily traveled main road and a lower volume cross street. The main road should be modeled by FHWA TNM roadways in each direction at cruise speed with no acceleration or deceleration. The cross street probably does not need to be modeled because if even a four-way stop is not warranted to control traffic on the main road, then intersecting road volumes and speed are both likely to be low. However, the cross street could be modeled if there are adjacent receivers by a flow control acceleration roadway starting just past the mainline roadways using 100% Vehicles Affected and a Speed Constraint of 20 mph to represent speed as the vehicle exits the intersection. The local road approach leg should be modeled at the posted speed for that road; no modeling of reduced speeds for deceleration is needed if the approach speeds are 40 mph or less.

3.4.4.2 Four-Way Stop

The four-way stop may require more complete modeling if there are receivers adjacent to each road. One would model the acceleration away from the stop line in each of the four directions.

Total modeling would require many intersecting points for the crossing roadways because FHWA TNM does not allow two roadways to cross without sharing a point with the same x, y, and z coordinates and may not be needed:

- If the scenario is modeled with one FHWA TNM roadway in each direction, there would be four points of intersection.
- If the scenario is modeled as two FHWA TNM roadways per direction of travel on one road and one FHWA TNM roadway per direction of travel on the other road, there would be eight intersecting points.
- If the scenario is modeled as two FHWA TNM roadways in each direction for each road, there would be 16 intersecting points.

In all cases, the flow control roadway would start at the stop line with 100% Vehicles Affected and a Speed Constraint of 0 mph. As illustrated in the SPUI discussion, the approaching traffic could be modeled as the posted speed. If the posted speed were as high as 60 mph, there would be over-prediction by 1–3 dB by not modeling the deceleration.

A simpler approach is to partially model the movements of one of the roads and avoid all of the intersecting FHWA TNM points. In this case, model the road with the most traffic (or perhaps the most adjacent receivers) as continuous, with an FHWA TNM cruise speed roadway on the upstream side connected at the stop line to a flow control acceleration roadway that crosses through the intersection and proceeds downstream on the departing leg. The flow control roadway would have a Speed Constraint of 0 mph and 100% Vehicles Affected.

The lesser road would be modeled as described above for the two-way stop: (1) on the departing leg, by a flow control acceleration roadway starting just past the main roadways using 100% Vehicles Affected and a Speed Constraint of 20 mph to represent speed as the vehicles exit the intersection, (2) on the approach leg, by a constant-speed roadway at the posted speed for that road. No modeling of reduced speeds for deceleration is needed unless the posted speed is high and the simpler modeling did not result in levels within a couple of dB of causing noise impacts.

3.4.5 Signalized Intersections

3.4.5.1 One-Way Roadways

Model the departing leg as a flow control acceleration roadway starting halfway back along the upstream queue. Use 50% Vehicles Affected, a Speed Constraint of 0 mph, and a final speed of the operating or posted speed.

Model the approaching leg as a constant-speed roadway at the operating or posted speed to halfway back in the queue. The low-speed deceleration does need to be modeled unless the posted speed is high because of the dominance of noise from the percentage of traffic cruising through the signal and the percentage of traffic accelerating from a stopped condition on the upstream side of the intersection.

The effect of the accelerating traffic on the upstream receiver levels was shown in the discussion on diamond interchanges. The effect of two-way traffic with acceleration in each direction was shown in the SPUI discussion. Figure 18 and Figure 19, shown here, are similar to what was shown for the two-way road, except that they represent a single road. Cruise speeds of 30 and 60 mph were tested for Vehicles Affected values of 25%, 50%, and 75% for the acceleration roadway, with those same percentages applied to the deceleration side of the intersection. Because prior analysis showed the dominance of heavy truck noise over automobile noise except at very high percentages of automobiles, only heavy truck cases were run.

Figure 18 illustrates the results for 1,000 heavy trucks for a cruise speed of 30 mph and at a receiver offset distance of 50 ft. For all three percentages of Vehicles Affected, there is very little difference in the levels for the “Deceleration + Cruise” case compared to the “All Cruise on the Deceleration Side” case. At a low speed, the combined presence of the cruise traffic on the upstream deceleration side and accelerating traffic on the downstream acceleration side dominates the total level for upstream receivers.

Figure 19 shows the results for the cruise speed of 60 mph. The levels on the upstream side of the intersection for the “Deceleration + Cruise” are lower than the levels for the “All Cruise on the Deceleration Side” cases from the

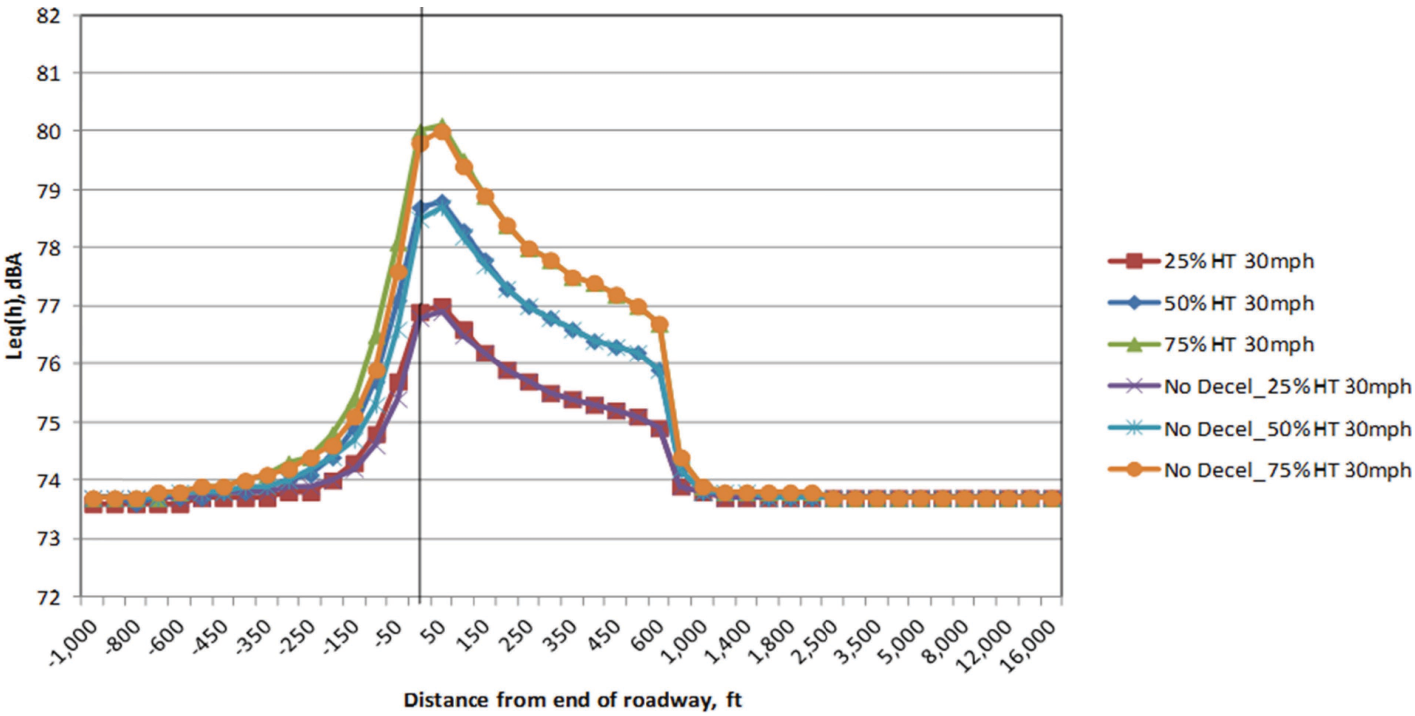


***Figure 18.** L_{eq}(h) for 1,000 heavy trucks for one-way "Deceleration + Cruise" compared to "All Cruise" on the upstream deceleration side for a 30-mph cruise speed and an array of receivers at a 50-ft offset distance from the roadway.*

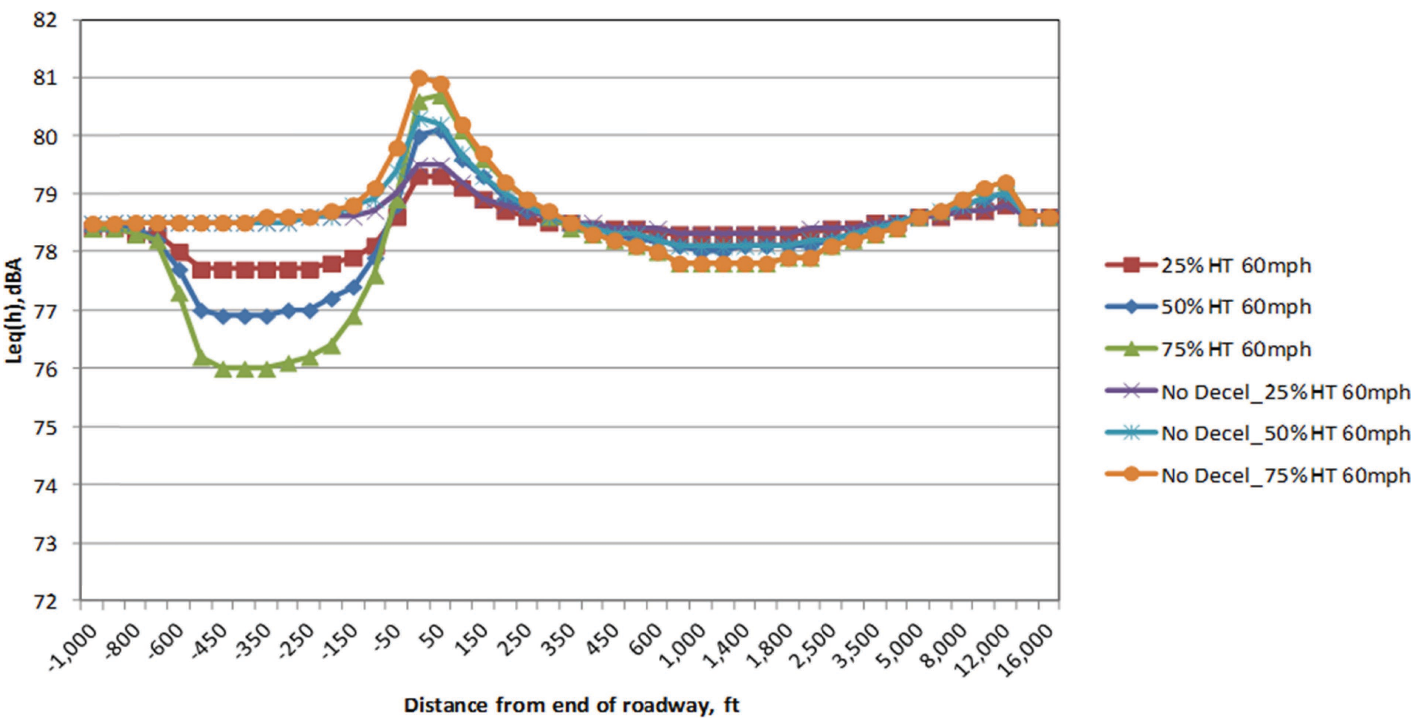


***Figure 19.** L_{eq}(h) for 1,000 heavy trucks for one-way "Deceleration + Cruise" compared to "All Cruise" on the upstream deceleration side for a 60-mph cruise speed and an array of receivers at a 50-ft offset distance from the roadway.*

stopping point back to an upstream distance of 600 ft by the following:

- 25% Affected: 0.4 to 0.8 dB.
- 50% Affected: 0.6 to 1.6 dB.
- 75% Affected: 0.9 to 2.6 dB.

As the offset distance to the receivers increases beyond 50 ft, the differences decrease (as shown in Appendix B), meaning there are fewer cases in which it may be necessary to model deceleration in the presence of cruising traffic. Thus, for a 30-mph case, the approach side of the intersection may be modeled by a cruise roadway at the desired speed. For the higher speed, as a conservative approach, the deceleration side may initially be modeled by a cruise roadway at the cruise speed. If the predicted $L_{eq}(h)$ is high enough to cause noise impacts, then more detailed modeling of the deceleration may be needed to confirm the existence of impacts.

3.4.5.2 Two-Way Roadways

The degree to which a signalized intersection with two-way traffic on all legs needs to be modeled depends on the proximity of the receivers. As described for the four-way stop, total modeling would require many intersecting points for the crossing roadways because FHWA TNM does not allow two roadways to cross without sharing a point with the same x, y, and z coordinates and may not be needed.

A simpler approach is similar to what was described for the four-way stop—partially model the movements of one of the roads and avoid all of the intersecting FHWA TNM points. The road with the most traffic (or perhaps the most adjacent receivers) would be modeled as continuous in each direction. A constant speed FHWA TNM roadway (or multiple roadways for multiple lanes) would be modeled on the approach, connected to a flow control acceleration roadway (or roadways) that crosses through the intersection and proceeds downstream on the departing leg. The joining point would be halfway up the expected queue, which could be several hundred feet from the stop line. The flow control roadway would have a Speed Constraint of 0 mph and 50% Vehicles Affected.

The intersecting road would be modeled as not crossing through the intersection. On the departing leg, a flow control acceleration roadway would start just past the main roadways to avoid the intersecting points. This flow control roadway would have 50% Vehicles Affected and a Speed Constraint of 20 mph to represent the speed as the vehicles exit the intersection.

On the approach leg, a constant-speed roadway would be modeled at the posted speed for that road; no modeling of reduced speeds for deceleration is needed. Unlike the one-way road case illustrated above, even at higher approach speeds, the difference between modeling a combination of deceleration and cruise and all cruise is small.

Figure 20 shows the results for the two-way situation at 60 mph at a receiver offset distance of 50 ft. As with the

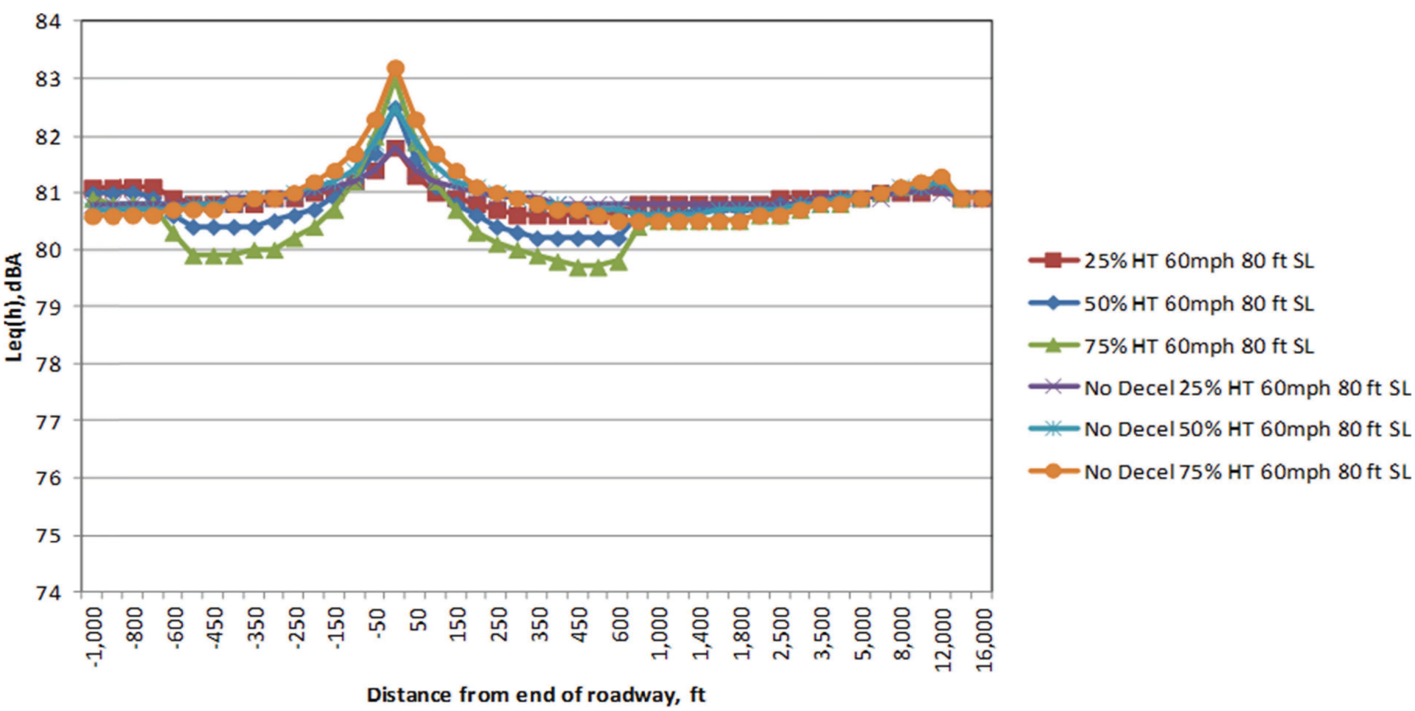


***Figure 20.** $L_{eq}(h)$ for 1,000 heavy trucks for two-way "Deceleration + Cruise" compared to "All Cruise" on the upstream deceleration side for a 60-mph cruise speed and an array of receivers at a 50-ft offset distance from the roadway.*

30-mph cases, there is symmetry on the approach and departure legs caused by the accelerating traffic in each direction. The largest differences at the 50-ft receiver offset distance are on the order of 1 dB. As shown in Appendix B, as the receiver offset distance increases, the differences decrease, meaning that there are fewer cases in which it may be necessary to model deceleration in the presence of cruising traffic.

As a conservative worst case, modeling on the deceleration side could be done with all cruising traffic first and, if levels were within 1 dB of causing impacts, the more precise modeling might be needed to demonstrate that no impacts are predicted to occur.

3.4.6 Roundabouts

Roundabout design is largely governed by guidance in *NCHRP Report 672.* Key design factors are the entry, circulation, and exit speeds, which are determined by the radii of the curves leading into, going around, and leaving the roundabout. For a single-lane roundabout with a center radius on the order of 90 ft or less, the typical entry and circulation speed is 20 mph. For a multilane roundabout with a larger radius, the typical entry and circulation speed is approximately 25 mph.

This research focused on the slower-speed roundabout with a one-lane inner circulatory road, but tests were also made for higher speeds and have been generalized to the larger two-lane inner circulatory road.

This research showed that detailed noise modeling of all of the roundabout movements is generally not needed. However, if one chooses to model all of the movements, the methodology illustrated in Figure 21 for the eastbound "through" movement of the east-west roadway is a good way to represent speeds and assign traffic volumes for the deceleration, constant-speed, and acceleration components.

Figure 21 shows an approach FHWA TNM roadway (thick solid line) that models (1) constant speed to the beginning of deceleration (not shown); (2) deceleration with two decreasing speed segments (only ZOI[2] is shown); (3) a final constant-speed approach segment ("Entry"); (4) two segments representing the east-west portion of the circle (which, as described below, do not necessarily have to be modeled with traffic on them); and (5) a constant-speed "Exit" segment with the circle speed out to where acceleration away from the round-

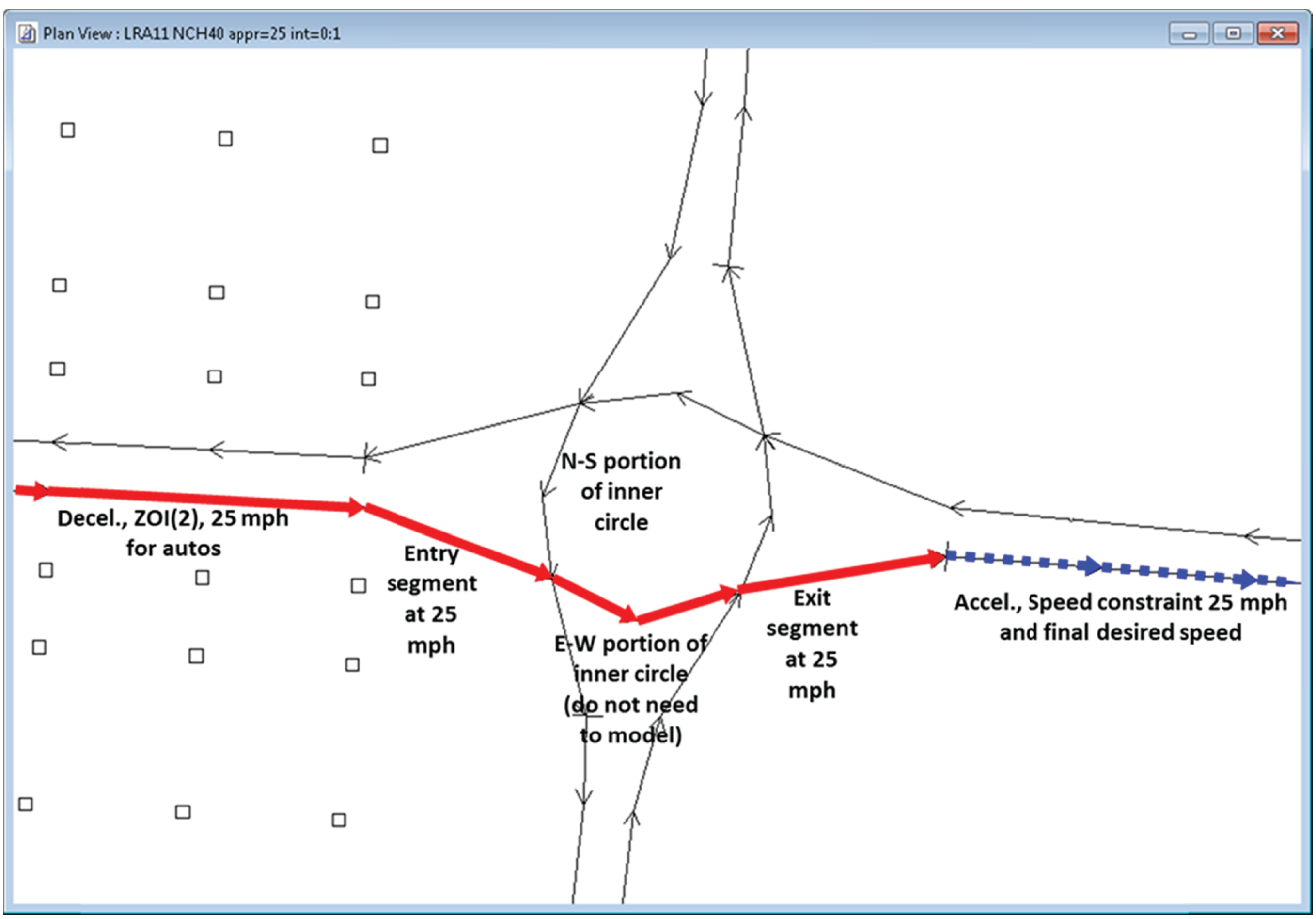


Figure 21. Modeling methodology for eastbound approach and departure legs and center circle of roundabout.

about would begin. Figure 21 also shows a departure FHWA TNM roadway (dotted line), modeling acceleration with a flow control device of "Onramp," a Speed Constraint equal to the speed on the last segment of the approach roadway, and a final desired cruise speed (in these runs equal to the approach speed).

3.4.6.1 One-Lane Inner Circulatory Road

Approach Leg. The approach to the roundabout may be modeled by a constant speed equal to the posted speed up to the beginning of the splitter island/crosswalk. Then, one 25-mph segment would be used to represent the entry leg, ending at the entry point to the circulatory road.

Inner Circulatory Road. The traffic on the inner circulatory road does not need to be modeled. The noise from the accelerating traffic departing the roundabout will dominate the overall sound levels.

Departure Leg. For the departure leg, a one-segment constant-speed roadway would be modeled at a speed of 25 mph. It would start at the exit point from the inner circulatory road and end at the end of the reverse curve typically at the end of the splitter island/crosswalk. Then, a flow control acceleration roadway would be modeled from the point downstream to the end of the modeled site. The roadway would have a Speed Constraint of 25 mph and 100% Vehicles Affected with the posted or operating speed as the final desired speed.

3.4.6.2 Discussion

Sensitivity testing was based on an actual single-lane roundabout that was modeled in FHWA TNM and was also studied in the field. The location was the western side of the Liberty Pike roundabout at Turning Wheel Lane in Franklin, Tennessee. Most of the runs were made for cruise speeds of 40 mph. Additional runs were also made for 30 and 50 mph. Because most roundabouts appear to carry predominantly automobile traffic, the runs were made for automobiles only. The analysis showed that the accelerating noise of traffic on departure from the roundabout dominated sound levels close in. As a result, little, if any, change was seen in leaving the traffic off of, or not modeling, the inner circulatory road. Figure 22 presents a sample of the results for 40 mph for the 50-ft receiver offset distance, comparing two cases—Case 1 and Case 9:

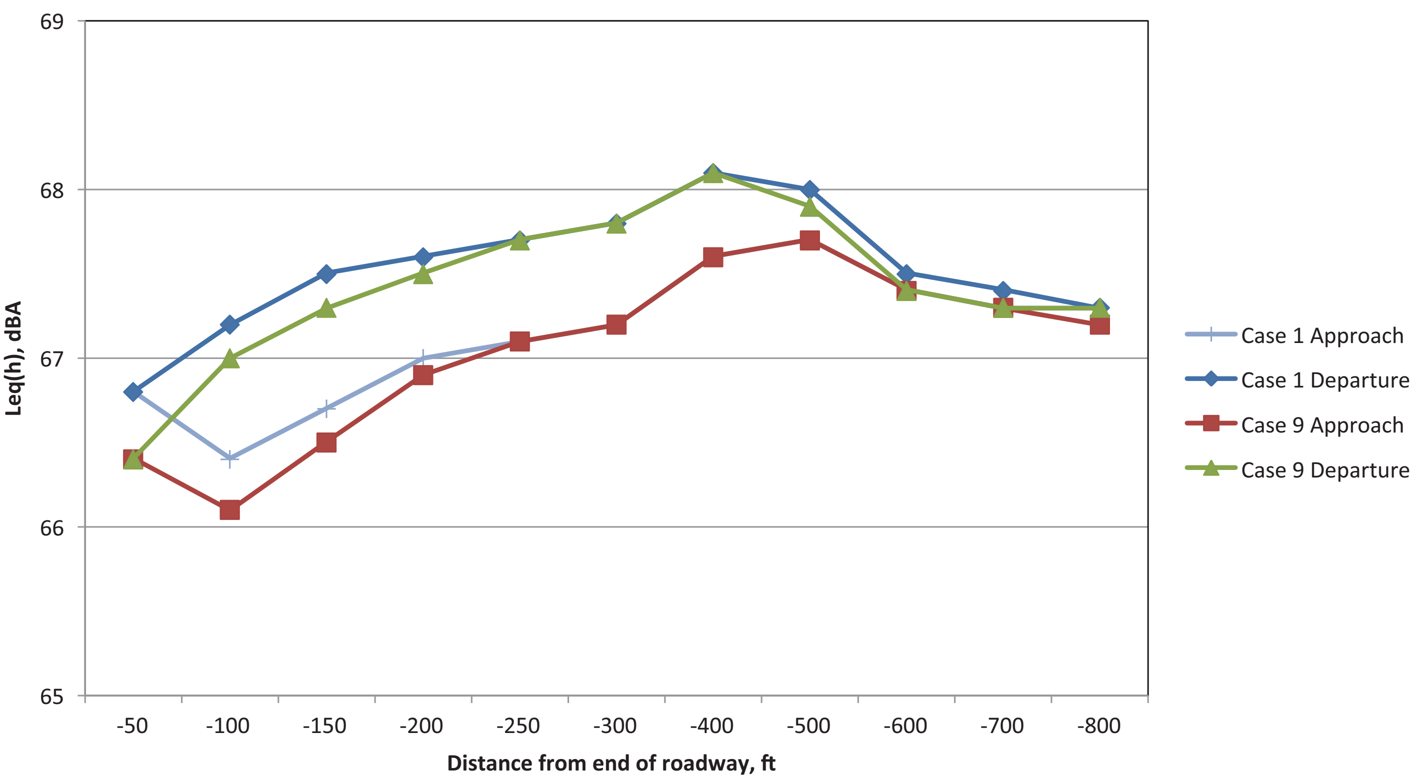


Figure 22. Comparison of L_{eq}(h) for Cases 1 and 9 for a series of receivers offset 50 ft from the western leg roadways for 1,000 automobiles approaching and departing roundabout at 40 mph.

- Case 1 included full modeling of all four legs of the roundabout using *NCHRP Report 311* deceleration segment lengths and speeds for 40 to 0 mph on the approaches, a circulatory road speed of 15 mph, and FHWA TNM acceleration on the departures.
- Case 9 included the same deceleration modeling as Case 1 for the western, northern, and southern legs, but no traffic on the eastern legs or the circulatory road.

Considering Case 1 or Case 9 individually, the levels on the (westbound) departure side are about 1 dB higher than on the (eastbound) approach side because those receivers are closer to the louder accelerating traffic. In comparing Case 9 to Case 1, not modeling traffic on the eastern leg and the circulatory road affected levels by only fractions of 1 dB, even at the closest receiver, located 50 ft from the entry/exit points in the circle.

Figure 23 compares the same two modeling cases at 40 mph for a receiver offset distance of 200 ft. Again, there is very little difference between the Case 1 and Case 9 results along both the eastbound approach and westbound departure legs. The reason the levels are high at the points closest to the roundabout for the 200-ft offset distance is that these points are actually much closer to the modeled northbound and southbound approach and departure legs. For the 200-ft receiver offset distance along the western leg of the roundabout, the traffic on the circulatory road and on the eastern leg does not need to be modeled.

Similar results were found for 30- and 50-mph scenarios. For both speeds, there is very little difference in the two cases, meaning the circulatory road and the eastern leg roadways do not need to be modeled.

Thirty-minute measurements of the A-weighted L_{eq} and individual vehicle SELs were made at four points along each western leg (approach and departure) of this roundabout at 50, 100, 200, and 400 ft from the entry/exit points and an offset distance of 25 ft from the edge of the travel lane. Traffic was almost entirely automobiles.

Figure 24 shows the measured L_{eq}(30 min) at each point for the approach-side measurement and the departure-side measurement. Also shown are the measured average SELs for automobiles for deceleration and for acceleration. The deceleration SEL values decrease by about 6 dB going from 400 ft to 50 ft upstream. In contrast, the acceleration SEL on the departure leg only increases by about 2 dB going from 50 ft downstream to 200 ft downstream, and then decreases 1 dB from 200 ft to 400 ft. The L_{eq} data along each side tend to match the pattern of the acceleration SEL data—there is a relatively small increase from 50 ft to 400 ft.

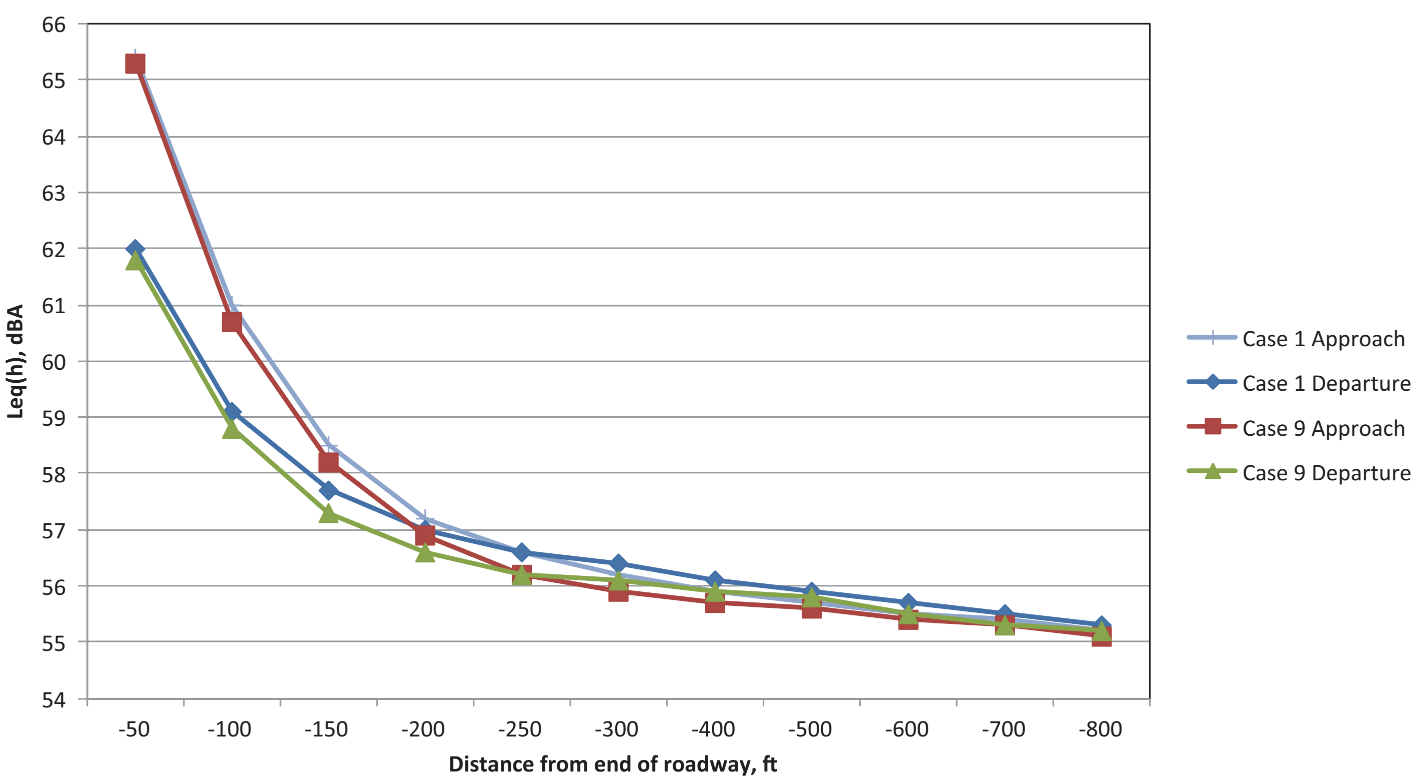


Figure 23. Comparison of L_{eq}(h) for Cases 1 and 9 for a series of receivers offset 200 ft from the western leg roadways for 1,000 automobiles approaching and departing roundabout at 40 mph.

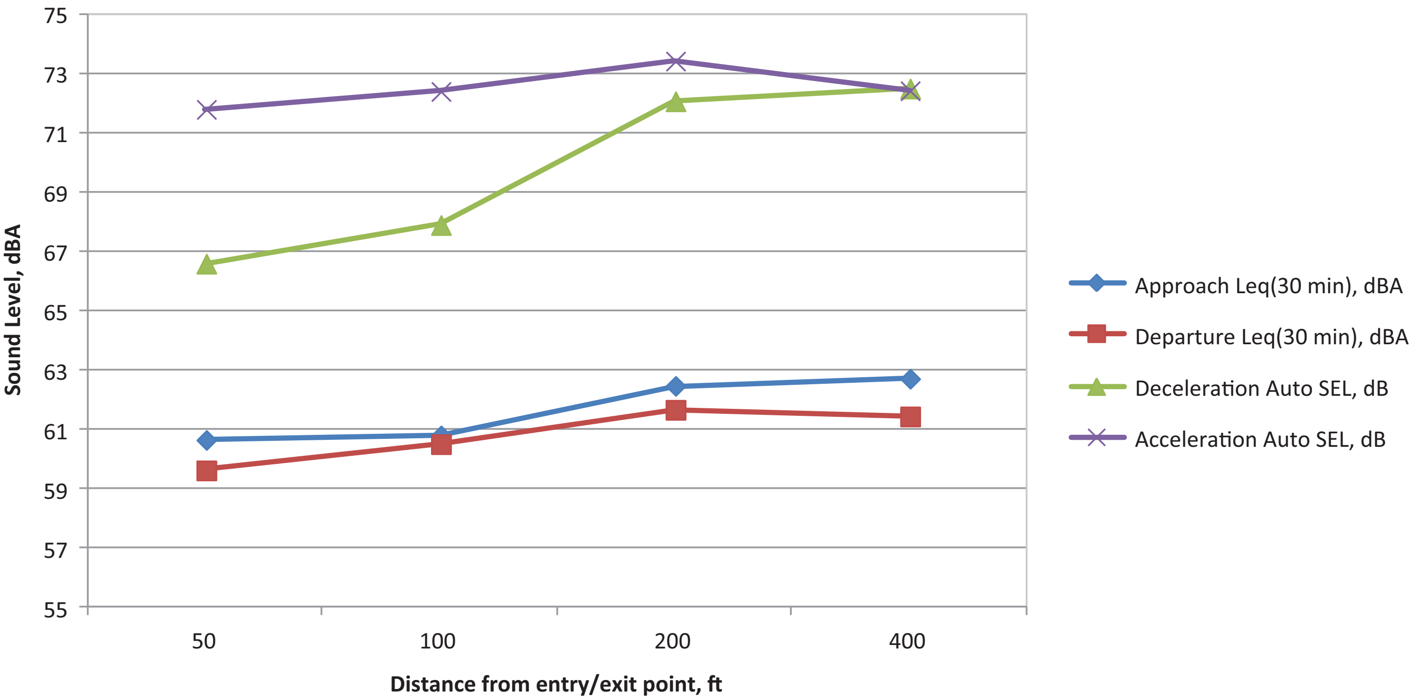


Figure 24. Measured L_{eq} (30 min) at 25-ft offset from edge of travel lane, Liberty Pike roundabout.

Essentially, the noise of accelerating traffic on the departure side of the roundabout dominates the measured L_{eq} on both sides of the road, supporting the sensitivity analysis conclusion.

3.4.6.3 Two-Lane Inner Circulatory Road

A roundabout with a two-lane inner circulatory road may be modeled in essentially the same way as a one-lane inner circulatory road.

Because of the slightly higher speed typical of the two-lane case (20 to 25 mph instead of 15 to 20 mph on the smaller diameter one-lane road and the greater circumference), there might be a desire to model the inner circulatory road, especially if receivers are immediately adjacent. However, if the inner road's entry and approach legs are each modeled, then it is unlikely that the inner road itself needs to be modeled, especially because of the noise of vehicles accelerating away from the roundabout.

CHAPTER 4

Area Sources

Area sources include weigh stations, park-and-ride lots, toll facilities, and service plazas. Typical noise sources near these facilities include low-speed and stop-and-go traffic, accelerating vehicles, decelerating vehicles, and idling trucks. While noise levels related to these facilities often are no louder than mainline traffic, they can cause annoyance for nearby residents, particularly when the facility is located closer to residences than the mainline traffic.

Typical issues encountered in FHWA TNM modeling of area sources include the following:

- FHWA TNM has no provision for modeling stop-and go traffic.
- FHWA TNM has no provision for modeling decelerating traffic.
- FHWA TNM has no provision for modeling stationary sources such as idling trucks at service plazas or buses at park-and-ride facilities.
- FHWA TNM assumes that all noise sources are line sources, although point sources or area sources, along with related propagation mathematics, may be more appropriate in these situations.

The issues described above can be divided into these categories: modeling of stationary point or distributed point sources, accelerating/decelerating vehicles under free-flow conditions, and stop-and-go traffic. The best practices described here include FHWA TNM modeling techniques for (1) area sources involving stationary sources such as idling vehicles at service plazas, weigh stations, and park-and-ride lots, and (2) accelerating/decelerating vehicles under both free-flow and stop-and-go conditions, such as at toll plazas and approaching service plazas and weigh stations.

4.1 Stationary Sources

4.1.1 Overview

Stationary, idling vehicles typically are quieter than moving traffic because they do not produce the tire-pavement noise that generally dominates traffic noise levels. As a result, when facilities such as service plazas and weigh stations are located adjacent to highways with moving traffic, the mainline roadway often dominates noise levels. Therefore, in many cases, detailed modeling of these facilities is not required. In some cases, however, facilities are located immediately adjacent to noise-sensitive receptors and/or between the receptors and the main roadway; in these cases, idling vehicles have the potential to make a significant contribution to overall noise levels, and modeling may be appropriate.

The suggested modeling practice for stationary sources such as idling vehicles at service plazas, weigh stations, and park-and-ride lots uses TNM roadway segments to represent either point sources (such as a single idling truck) or larger line or area sources (such as a line of idling buses or a large overnight parking area for trucks at a service plaza). The practice provides two possible approaches. The *standard* approach utilizes existing components within TNM, including REMELs for standard TNM vehicle types. The *advanced* approach uses a procedure for creating a user-defined vehicle type within TNM based upon emission-level measurements conducted by the practitioner according to accepted practices. The two approaches are described below in greater detail.

4.1.2 Standard Approach

The standard approach for modeling stationary sources uses a straightforward procedure that can be implemented without any special field measurements or modifications to TNM. This approach is appropriate for most situations

Table 4. Suggested parameters for modeling stationary sources.

Roadway Length (ft)	Modeled Speed (mph)	Volume Factor
10	1	528.0
20	1	264.0
30	1	176.0
40	1	132.0
50	1	105.6
60	1	88.0
70	1	75.4
80	1	66.0
90	1	58.7
100	1	52.8
150	1	35.2
200	1	26.4
300	1	17.6
400	1	13.2
500	1	10.6
Note: Volume factors for other roadway lengths may be calculated as follows: Volume factor = (10/L) * 528, where L = Roadway length in ft. Always set modeled speed to 1 mph.		

involving standard TNM vehicle types, although it is expected to be most commonly used for heavy trucks idling either at weigh stations or for extended periods at service plazas.

4.1.2.1 Roadway Segments

The standard approach utilizes TNM roadway segments to represent stationary noise sources. The length of the roadway segment may vary depending upon the size and distribution of the stationary source being modeled. For example, a single heavy truck cab may be modeled as a 10-foot long roadway segment. A line of several idling heavy trucks or buses may be modeled as a longer roadway segment. Multiple queues or distributed parking areas may be modeled as a combination of roadway segments of appropriate length. In each case, the roadway segment(s) should be selected to demonstrate the geometric distribution of the stationary sources as opposed to the number of sources. Table 4 lists suggested roadway segment lengths ranging in length from 10 ft to 500 ft.

4.1.2.2 Volume Factors

Table 4 also indicates a "volume factor" that depends upon the length of each modeled roadway segment. Because TNM defaults to compute a 1-hour equivalent sound level (LA_{eq1h}), the volume factor is necessary to represent the presence of a stationary source throughout the entire hour. TNM does not accept input speeds of 0 mph. Instead, the speed for the modeled segments is set to 1 mph, resulting essentially in the 0 mph emission level. The volume factor may be thought of as the number of vehicles, each moving at 1 mph, that would be required to traverse the roadway segment one at a time so that an average of one vehicle is present at all times throughout the 1-hour period. For example, because a 10-ft roadway segment is 1/528 of a mile (10 ft divided by 5,280 ft), the time required for a vehicle moving at 1 mph to traverse this segment would be 1/528 of an hour. Consequently, 528 vehicles, each traversing the 10-ft segment in turn at 1 mph, would be required for an average of one vehicle always to be present on the roadway segment throughout the hour. The resulting LA_{eq1h} for the 528 slowly moving vehicles is the same as one stationary vehicle for the entire hour. *Note that the volume factor for a roadway segment is dependent only on the length of the modeled segment.*

Volume factors for other roadway segment lengths scale up and down in an inverse linear relationship to the segment length. For example, the volume factor for a 100-ft roadway segment is 1/10 that of the volume factor for a 10-ft segment (52.8 versus 528). The volume factor for a roadway segment of any length may be calculated as follows:

$$\text{Volume Factor} = (10/L) * 528$$
$$L = \text{Roadway Length in feet}$$
$$\text{Modeled Speed} = 1 \text{ mph}$$

Once the roadway length and volume factor have been determined for each segment, the practitioner multiplies the volume factor by the average number of stationary noise sources present during the modeled time period. The resulting traffic "volume" then is entered on TNM's "LA_{eq1h} Hourly" Roadway-Input tab, with a speed of 1 mph. (See Example 1 in Section 4.1.4.)

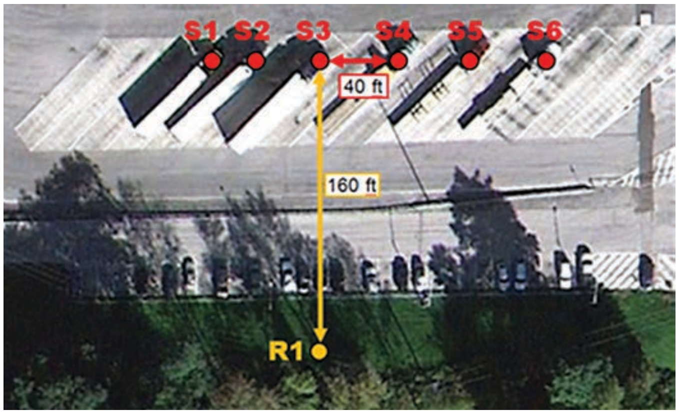


Figure 25. Geometry for comparing array of individual noise sources to a single line source.[13]

4.1.2.3 Line Sources

In some cases, it may be unnecessary or impractical to model each stationary noise source as a separate TNM roadway. For example, different spaces within a row of parking slots at a truck stop may be used at different times throughout the modeled time period. In these situations, it can be advantageous to model multiple source locations with one TNM roadway. The methodology used to model an array of individual sources as a line source is the same as described above, except that the length of the TNM roadway is determined by the extent of the area where the noise sources are located. Table 4 is then used to determine the correct volume factor for the appropriate roadway length. As the final step, the volume factor is multiplied by the average number of sources present during the modeled hour. (See Examples 2, 3, and 4 in Section 4.1.4.)

In cases where receivers are located in close proximity to individual noise sources, use of a line source may provide different results than would modeling each individual source separately. As a rule of thumb, *when the distance from the closest receiver to the nearest noise source is equal to or greater than the spacing between the individual noise sources, a line source may be substituted for the array of individual sources.* Use of this guidance typically will limit discrepancies between a modeled line source and the corresponding array of individual sources to less than 1 dB. Conversely, if the practitioner desires to accurately portray the specific locations of individual noise sources, then the sources should be modeled individually when the distance from the closest receiver to the nearest noise source is equal to or less than the spacing between the individual noise sources.

Figure 25 shows a receiver (R1) and a row of six idling trucks (S1 through S6). The trucks could be modeled as six individual noise sources using six short roadway segments or, alternatively, as one line source using a longer roadway segment spanning the entire row. Because the source-to-receiver distance (160 ft) is greater than or equal to the average spacing of the noise sources (40 ft), substituting a single line source for the six individual sources would introduce a discrepancy of less than 1 dB.

[13] Imagery © 2011 Google, Map data © 2013 Google.

4.1.2.4 Noise Barriers with Stationary Sources

Noise barriers, either fixed-height or perturbable, may be used in conjunction with modeling stationary sources in the same way they may be used in conjunction with modeling roadways. In some cases, a practitioner may contemplate modeling objects associated with the noise sources themselves (e.g., truck trailers) as noise barriers (See Examples 5 and 6 in Section 4.1.4). It is worthwhile for the practitioner to carefully consider the following issues if modeling moveable objects, such as a row of parked trucks, as a noise barrier:

- Would the entire "barrier" be intact with no gaps throughout the modeled time period?
- Are flanking paths, such as gaps beneath or between objects, present?
- Is there the possibility of reflected sound paths, as between parked parallel truck trailers?
- Would the moveable barriers also provide shielding from mainline traffic noise? If so, is it appropriate to include them in the noise model even though they may not always be present?
- Does the local agency or State DOT provide any guidance or restrictions regarding modeling temporary objects as noise barriers?

4.1.3 Advanced Approach

In some cases, practitioners may need to model a stationary noise source that is different than one of TNM's five standard vehicle types. For these situations, the advanced approach may be used. This approach requires the practitioner to conduct emission-level measurements in accordance with the procedures used for the development of TNM's REMELs.[14] The emission-level measurements then may be used to create a user-defined vehicle type within TNM. For most user-defined vehicles, TNM requires the development of three coefficients (denoted A, B, and C) to define the emission-level regression curve.[15] For a stationary vehicle, A and B are both zero (A=B=0),

[14] Lee, C. S. Y., and G. G. Fleming, *Measurements of Highway-Related Noise*, Report No. FHWA-PD-96-046 and DOT-VNTSC-FHWA-96-5, Cambridge, MA, U.S. Department of Transportation, John A. Volpe National Transportation Systems Center, Acoustics Facility, May 1996.

[15] Anderson, G. S., C. S. Y. Lee, G. G. Fleming, and C. W. Menge, *FHWA Traffic Noise Model®, Version 1.0 User's Guide*, Report No. FHWA-PD-96-009 and DOT-VNTSC-FHWA-98-1, Final Report, January 1998, p. 91.

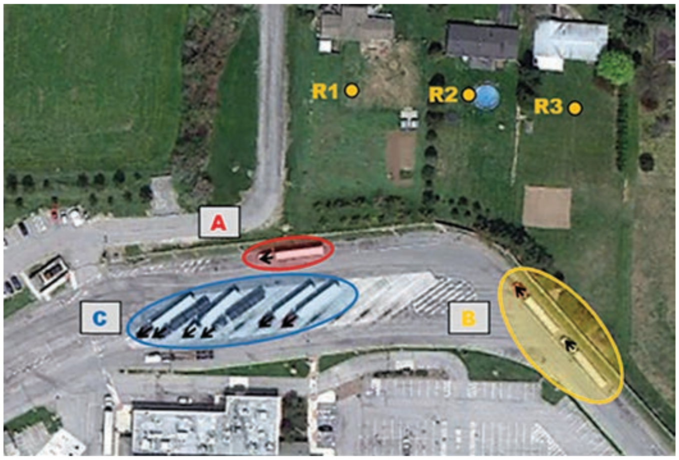


Figure 26. Example 1—idling trucks at service plaza modeled individually.[16]

and C (the minimum emission level at very low speeds) is set to the measured emission level at 50 ft. Once the user-defined vehicle has been defined, the practitioner may proceed using the standard approach described above.

4.1.4 Stationary Source Examples

The following examples illustrate various aspects of the practices described above.

4.1.4.1 Example 1

A practitioner needs to model noise levels at three residences because of several trucks idling at a nearby service plaza. During the modeled hour, up to nine trucks may be parked at the service plaza, as shown in Figure 26. Three trucks are parked along the perimeter of the service plaza in Areas A and B; six additional trucks are parked in angled slots at Area C. Due to the relatively small number of trucks, the practitioner chooses to model each parked truck as a separate 10-ft long TNM roadway segment. The black arrows on Figure 26 located over the cab of each truck indicate the modeled TNM roadways. Consulting Table 4, a volume factor of 528 and speed of 1 mph is used for each 10-ft roadway segment. Because one truck will be present for 100% of the modeled hour at each location, the volume factor is multiplied by 1, and the resulting "volume" of 528 heavy trucks per hour is input on the "LAeq1h Hourly" tab for each of the nine modeled roadway segments. As shown on Table 5 for Example 1, the resulting hourly L_{eq} sound levels range from about 67 to 68 dBA at the three receivers.

[16] Imagery © 2011 Google, Map data © 2013 Google.

4.1.4.2 Example 2

As shown in Figure 27, a practitioner chooses to model the service plaza from Example 1 by using a smaller number of TNM roadways to represent multiple idling trucks. Area A, with just one truck, is modeled, as in Example 1, using a single 10-ft roadway segment. The two trucks in Area B are modeled with one 85-ft long roadway segment. The length is determined by the distance encompassing the two noise sources (in this case, the distance between, and including, the two truck cabs). Because Table 4 does not include a pre-computed volume factor for an 85-ft roadway segment, the appropriate volume factor must be calculated:

$$\text{Volume Factor} = (10/L) * 528 \text{ where } L = \text{Roadway Length in ft}$$

$$\text{therefore, Volume Factor} = (10/85) * 528 = 62.1$$

Since this roadway segment represents two trucks for 100% of the modeled period, the volume factor is multiplied by two and the resulting "volume" of 124 heavy trucks per hour is input on the "LAeq1h Hourly" tab at a speed of 1 mph. The six trucks in Area C are modeled similarly, using a roadway segment of length 175 ft. The volume factor for Area C is

$$\text{Volume Factor} = (10/175) * 528 = 30.2$$

Because this roadway segment represents six trucks for 100% of the modeled period, the volume factor is multiplied by six for a modeled "volume" of 181 heavy trucks per hour.

Note that the distance from any of the three receivers to the closest noise source is greater than either the distance between the two trucks in Area B or the distance between any of the six trucks in Area C. Based on the guidance for using line sources provided above, one would expect the difference between the computed sound levels in Example 1 versus Example 2 to be less than 1 dB. As shown in Table 5, the computed differences between the two examples are no more than 0.3 dBA at any of the three receivers.

4.1.4.3 Example 3

In some cases, a practitioner may model multiple noise source locations that are not used for 100% of the modeled time period. Figure 28 shows the same service plaza as above; however, Area A has been expanded to include three truck parking spaces and Area C has been expanded to include all 11 available spaces. Area B remains at two parking spaces. Accordingly, the length of the modeled roadway segments increases to represent the larger spatial distributions. Thus the Area A roadway segment increases

Table 5. Computed sound levels for stationary source service plaza examples.

Example	Computed Sound Level (LA_{eq1h}, dBA)			Comments
	R1	R2	R3	
1	68.2	68.0	67.1	9 trucks modeled as 9 individual sources
2	68.5	67.9	67.1	9 trucks modeled as 3 line sources
3	68.9	68.5	67.7	9 trucks modeled as 3 line sources, but with greater spatial dispersion
4	71.6	70.9	69.8	16 trucks modeled as 3 line sources, same spatial dispersion as Example 3
Note: See accompanying text for additional discussion.				

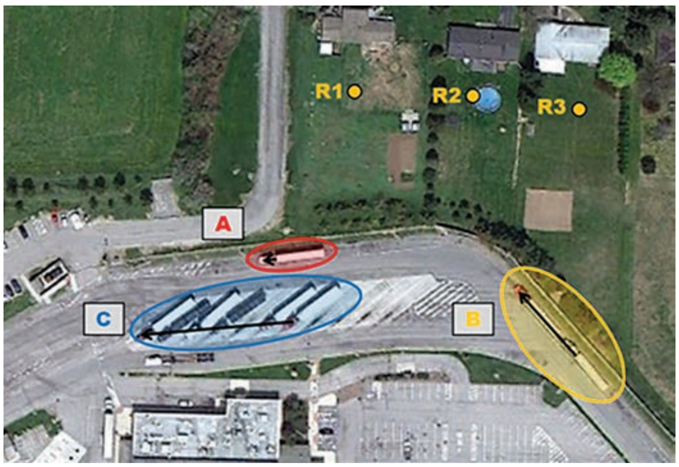


Figure 27. Example 2—multiple idling trucks at service plaza modeled as line sources.[17]

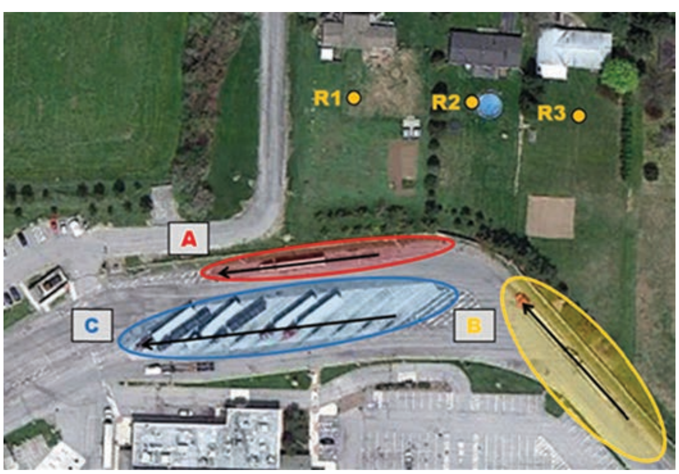


Figure 28. Examples 3 and 4—multiple idling trucks at service plaza with increased spatial distribution.[18]

[17] Imagery © 2011 Google, Map data © 2013 Google.
[18] Imagery © 2011 Google, Map data © 2013 Google.

in length from 10 ft to 180 ft, and the Area C roadway segment grows from 175 ft to 280 ft. As a result, the volume factors also change:

$$\text{Area A: Volume Factor} = (10/180) * 528 = 29.3$$

$$\text{Area C: Volume Factor} = (10/280) * 528 = 18.9$$

Despite the 16 available spaces, the practitioner has determined that on average only nine trucks are present during the modeled hour, as in Example 2. Therefore, for Area A, the new volume factor still is multiplied by one to determine the modeled "volume" because only one truck will be present in one of the three spaces. Similarly, the new volume factor for Area C is multiplied by six because six trucks will occupy some combination of the 11 spaces. Area B is modeled the same as it is modeled in Example 2. As shown in Table 5, the computed sound levels increase slightly at all three receivers (less than 1 dBA), primarily because of the newly modeled use of the Area C parking slots closest to the receivers.

4.1.4.4 Example 4

A practitioner wishes to model a worst-case condition for the same service plaza as the previous examples. For this scenario, all truck parking spaces are occupied by idling vehicles for 100% of the modeled time period. The roadway segment lengths and accompanying volume factors are the same as they are in Example 3. In this case, however, the volume factor for Area A is multiplied by three to determine the modeled "volume" since all three parking spaces will be occupied. The volume factor for Area C is multiplied by 11 to represent full occupancy of the 11 spaces in this area. Area B is modeled the same way that it is modeled in Examples 2 and 3. As shown in Table 5, due to the greater number of trucks present in this worst case, computed sound levels increase by about 2 to 3 dBA at all three receivers.

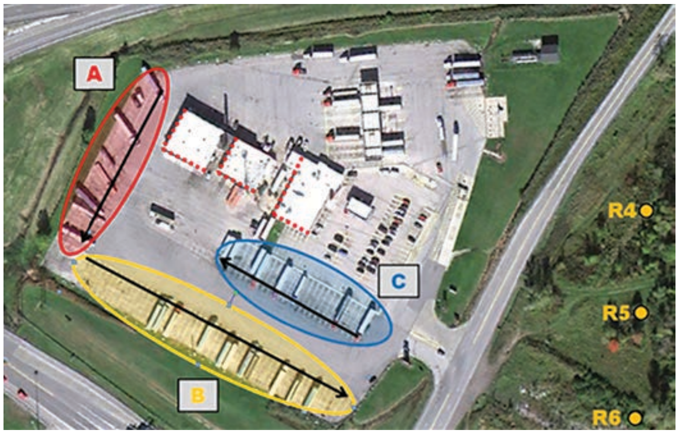


Figure 29. Example 5—truck stop with buildings as fixed-height noise barriers.[19]

4.1.4.5 Example 5

A practitioner needs to model the truck stop shown in Figure 29. With all delineated spaces full, the facility has a capacity of 98 heavy trucks. As a worst-case condition, the practitioner models all 98 spaces as occupied with idling trucks. The three different rows of parking slots (Areas A, B, and C) are modeled with three line sources ranging in length from 320 to 580 ft. Volume factors and modeled "volumes" are computed as described in the examples above. The three largest buildings at the facility are modeled as fixed-height noise barriers ranging in height from 20 ft to 30 ft (indicated by dashed lines on Figure 29). As shown in Table 6, the resulting hourly L_{eq} sound levels at the three receivers range from about 67 to 68 dBA. If the practitioner had determined that all parking spaces were full, but that on average only 50% of the trucks were idling throughout the modeled period, the modeled "volumes" would decrease by 50%, and the resulting sound levels would be 3 dBA lower.

4.1.4.6 Example 6

A practitioner wishes to model the same truck stop shown in Example 5 with the row of trucks designated as Area C included as a noise barrier. Because of the orientation of the truck trailers relative to the sound propagation paths from the various truck parking rows to the nearby residences, the practitioner concludes that significant flanking paths between and under the trailers are unlikely to exist. Furthermore, the practitioner concludes that reflected sound between the Area C trucks is not likely to be significant at the receivers. A 13-ft high noise barrier is modeled in the location indicated by the additional dashed line in Figure 30. Note that the modeled noise barrier reflects the condition when all spaces in Area C are occupied. As shown in Table 6, the modeled noise barrier reduces sound levels by about 3 to 4 dBA at R4 and R5, but only by about 1 to 2 dBA at R6.

[19] Imagery © 2011 Google, Map data © 2013 Google.

4.2 Accelerating and Decelerating Traffic

Note that additional guidance on modeling accelerating and decelerating traffic in TNM is given in Chapter 3 of this report, Signalized Interchanges, Intersections, and Roundabouts.

4.2.1 Decelerating Vehicles

Decelerating vehicles associated with weigh stations, park-and-ride lots, and service plazas consist of vehicles slowing to enter the facility, typically on an exit ramp from a limited-access roadway. At toll plazas, vehicles decelerate from mainline cruise speeds when approaching the toll barrier. In the case of a toll-ticket system, all vehicles decelerate to a full stop; in the case of an electronic tolling system, vehicles typically decelerate to some reduced speed that is dependent on the specific facility. The suggested modeling approach for decelerating vehicles is based upon methodology previously developed under *NCHRP Report 311: Predicting Stop-and-Go Traffic Noise Levels*[20] and also is consistent with the guidance on modeling signalized interchanges, intersections, and roundabouts described in Chapter 3 of this report.

4.2.1.1 Exit Ramps

Under free-flow conditions, traffic exiting from mainline roadways and decelerating to enter weigh stations, park-and-ride lots, service plazas, and other similar facilities may be modeled as follows:

- Divide the exit ramp into two deceleration ZOIs. The length of each ZOI is dependent on both the initial and final speeds, but for highway traffic, ZOI(1) typically will be 500 ft long and ZOI(2) will be 100 ft long (see Table 7). Note that the locations of the ZOIs are determined by working backwards from the endpoint of ZOI(2), the point where the final speed is reached, upstream toward the mainline.
- In situations where a queue forms along the exit ramp (e.g., trucks waiting in a queue to enter a weigh station), the endpoint of ZOI(2) is located at the average location of the end of the queue. See Section 4.2.3, "Stop-and-Go Traffic in Queues," for further guidance.

[20] Bowlby, W., R. L. Wayson, and R. E. Stammer, Jr., *NCHRP 311: Predicting Stop-and-Go Traffic Noise Levels*, Transportation Research Board, National Research Council, Washington, D.C., 1989.

Table 6. Computed sound levels for stationary source truck stop examples.

Example	Computed Sound Level (LA_{eq1h}, dBA)			Comments
	R4	R5	R6	
5	67.7	68.0	67.5	98 trucks modeled as 3 line sources, buildings modeled as noise barriers
6	63.5	64.5	66.1	98 trucks modeled as 3 line sources, buildings and Area C trucks modeled as noise barriers
Note: See accompanying text for additional discussion.				

- Using Table 7, determine the appropriate modeled speed for each ZOI roadway. Note that although each ZOI does not need to be modeled as a separate roadway, care must be exercised to ensure that the appropriate speeds are assigned only to the correct roadway segments.

4.2.1.2 Toll Plazas

Under free-flow conditions, decelerating traffic approaching toll plazas may be modeled as follows:

- Divide the affected roadways into either one or two deceleration ZOIs based upon Table 7. For highway traffic coming to a complete stop at a toll-ticket facility, ZOI(1) typically will be 500 ft long and ZOI(2) will be 100 ft long. However, for traffic passing through electronic toll facilities at speeds of 30 mph or greater, only one ZOI is required. Note that the locations of the ZOIs are determined by working backwards from the point where the final speed is reached.
- In situations where a queue forms at a toll plaza, the endpoint of ZOI(2) is located at the average location of the end of the queue. See Section 4.2.3, "Stop-and-Go Traffic in Queues," for further guidance.
- Using Table 7, determine the appropriate modeled speed for each ZOI roadway. Note that although each ZOI does not need to be modeled as a separate roadway, care must be exercised to ensure that the appropriate speeds are assigned only to the correct roadway segments.
- In toll facilities with a combination of toll-ticket and electronic lanes, the different types of lanes must be modeled separately. Multiple lanes of the same type, however, may be modeled with one TNM roadway. See Section 4.2.4, "Combining Electronic Toll and Ticket Lanes at Toll Plazas," for further guidance.

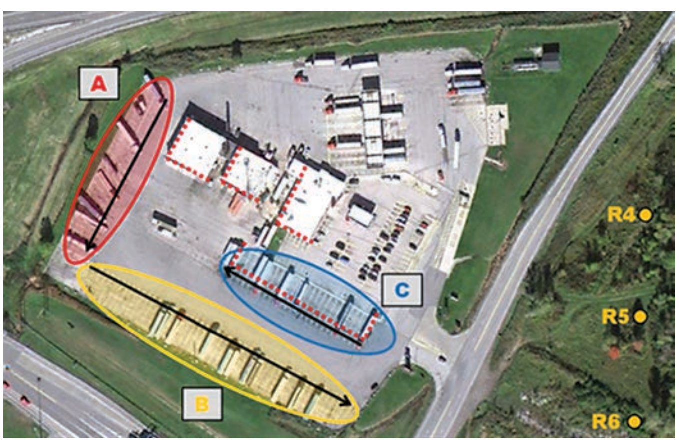


Figure 30. Example 6—truck stop with buildings and truck trailers as noise barriers.[21]

[21] Imagery © 2011 Google, Map data © 2013 Google.

4.2.2 Accelerating Vehicles

Accelerating vehicles associated with weigh stations, park-and-ride lots, and service plazas consist of those departing from the facility, typically on an entrance ramp to a limited-access roadway, and accelerating to rejoin traffic on the mainline roadway. At toll plazas, vehicles accelerate back to cruise speed after passing through the toll barrier. In the case of a toll-ticket system, all vehicles accelerate starting at 0 mph; in the case of an electronic tolling system, vehicles typically accelerate from some reduced speed that is dependent on the specific facility.

The "flow control" feature in TNM (found on its own tab within "Input/Roadways") provides a convenient method for modeling accelerating vehicles in each of these situations. The flow control feature automatically increases the speeds of accelerating vehicles from a user-defined starting speed (sometimes, but not always, 0 mph) to a user-defined ending speed (typically the mainline traffic speed). The feature uses regression equations similar to official performance curves,[22,23] but derived from data collected during measurements of TNM's emission levels. In addition, the flow control feature automatically employs full throttle emission levels, also

[22] American Association of State Highway and Transportation Officials, *A Policy on Geometric Design of Highway and Streets: 1990*, Washington, D.C., 1990.

[23] *Special Report 209: Highway Capacity Manual*, 3rd ed., Transportation Research Board, National Research Council, Washington, D.C., 1985.

Table 7. Deceleration ZOIs and corresponding equivalent speeds.

Deceleration Range (mph)		Length (ft)		Speed ZOI(1) (mph)			Speed ZOI(2) (mph)		
$S_{initial}$	S_{final}	ZOI(1)*	ZOI(2)**	Automobiles	MT	HT	Automobiles	MT	HT
60	0	500	100	50	40	35	20	20	20
60	30	500	none	50	40	35	n/a	n/a	n/a

*Starting from end of ZOI(2).
**Starting from point of S_{final} and proceeding upstream from that point.

determined from field measurements during TNM's development, while vehicles are accelerating.

4.2.2.1 Entrance Ramps

When using the flow control feature to model traffic departing from weigh stations, park-and-ride lots, service plazas, and other similar facilities on entrance ramps to limited-access roadways, the following input parameters are recommended on TNM's flow control tab:

- Control Device: Onramp.
- Vehicles Affected (%): 100.
- Speed Constraint: 10 mph.[24]

4.2.2.2 Toll Plazas

When using the flow control feature to model traffic accelerating away from toll plazas, the following input parameters are recommended on TNM's flow control tab:

- Control Device: Toll.
- Vehicles Affected (%): 100.
- Speed Constraint: 0 mph if toll-ticket lane, average speed through barrier if electronic toll lane.

4.2.3 Stop-and-Go Traffic in Queues

The discussions above regarding decelerating and accelerating vehicles assume free-flow traffic conditions. Under some traffic conditions, however, queues may be expected to form along off-ramps and approaching toll barriers. In these situations, each vehicle does not decelerate smoothly, but instead accelerates and decelerates as it moves up in the queue. Measurements conducted during the *NCHRP Report 311* project indicated that this stop-and-go behavior may increase emission levels for heavy trucks by approximately 3 dBA compared either to free-flow deceleration conditions or to stationary idling heavy trucks.[25] This section provides guidance for modeling heavy trucks in stop-and-go queues.

Because the emission levels for other vehicle types at stop-and-go speeds are significantly lower than for heavy trucks, typically it is not necessary to model vehicles other than heavy trucks in queues. *In general, when the percentage of heavy trucks is at least 1% of the total traffic volume, heavy trucks will dominate the overall L_{eq} sound level generated by vehicles in the queue.* Exceptions would include queues that form in facilities such as parkways without heavy trucks. In that case, similar methodology could be applied to automobiles. Even in this case, however, the practitioner may find that it is not necessary to model a stop-and-go queue of automobiles because the emission levels will be lower than on other nearby roadways with traffic moving at higher speeds.

The suggested approach for modeling queues is similar to the methodology in discussed in Section 4.1.2, which covers the standard approach to modeling stationary sources, with the addition of an adjustment to account for the higher emission level of stop-and-go traffic as opposed to stationary idling vehicles. The procedure is as follows:

- **Determine the average length of the queue.** For traffic conditions that typically occur during the period modeled, measure or compute the distance from the front of the queue (e.g., the toll barrier or the scales at a weigh station) "upstream" to the end of the queue (the point where traffic ceases free flow and begins stop-and-go conditions). Model the queue as a separate TNM roadway of this length.
- **Determine the volume factor.** Using Table 4 (suggested parameters for modeling stationary sources), determine the correct volume factor for the length of the queue. Note that the volume factor is dependent only on the length of the TNM roadway representing the queue.
- **Determine the average number of vehicles in the queue.** With existing facilities, the average number of vehicles in

[24] This recommendation is consistent with *FHWA Traffic Noise Model®, Version 1.0 Technical Manual*, p. 64.

[25] Bowlby, W., R. L. Wayson, and R. E. Stammer, Jr., *NCHRP 311: Predicting Stop-and-Go Traffic Noise Levels*, Transportation Research Board, National Research Council, Washington, D.C., 1989, p. 18.

the queue may be determined by direct observation. For future facilities, the number in the queue may be computed based on the average length of the queue[26] or upon projected traffic volume combined with the average waiting time in the queue.[27]

- **Compute the modeled volume.** Following the guidance for stationary sources, compute the modeled traffic volume for the queue by multiplying the volume factor by the average number in the queue. Note that if the queue includes mixed vehicle types (as at a toll facility), in most cases one may ignore all vehicle types other than heavy trucks.
- **Include 3-dBA stop-and-go adjustment.** The traffic volume computed above would represent a line of stationary idling vehicles. To account for the stop-and-go heavy trucks being approximately 3 dBA louder than a similar line of stationary idling vehicles, multiply the computed volume by 2 (doubling the traffic volume increases the modeled L_{eq} by 3 dBA). Input this volume on the "LAeq1h Hourly" tab for the TNM roadway representing the queue with a speed of 1 mph. In summary: *Input Traffic Volume = Volume Factor × Average Number in Queue × 2.*

4.2.4 Combining Electronic Toll and Ticket Lanes at Toll Plazas

Some toll plazas include both electronic toll lanes and traditional toll-ticket lanes. While all vehicles must come to a complete stop in the ticket lanes, vehicles typically pass through the electronic lanes at moderate speeds. In other cases, referred to as "open road tolling," vehicles pass beneath an electronic sensor array without decelerating from highway cruise speeds.

Due to the higher speeds, traffic in electronic toll lanes may dominate overall sound levels near a combined electronic toll/toll-ticket plaza. As a result, detailed modeling as described in the preceding sections may not always be necessary. The relative contribution of electronic lanes and ticket lanes at a combined toll plaza to the overall sound level depends on many factors including the following:

- The traffic volume in each type of lane.
- The traffic mix in each type of lane, and, especially the heavy truck percentage.
- The average speed of vehicles passing through the electronic lanes.
- The overall distance of prediction sites from the toll plaza.
- The relative distance of the different types of lanes to prediction sites.

Because of these variables, it is difficult to provide guidance for modeling every possible case; however, the following guidelines are offered:[28]

- **Toll plazas with full-stop ticket lanes and reduced-speed electronic lanes.** When the typical minimum speed in the electronic toll lanes is 30 mph or less and the volume of vehicles in the electronic lane(s) equals or exceeds the volume in the ticket lane(s), all vehicles may be modeled as if in the electronic lanes. The typical error introduced by this approximation will be less than 1 dBA. For higher ratios of electronic lane to ticket lane traffic and/or for speeds lower than 30 mph in the electronic lanes, the error will be lower.
- **Toll plazas with full-stop ticket lanes and high-speed open road tolling lanes.** In toll plazas combining open road toll lanes with full-stop ticket lanes, all vehicles may be modeled as if in the electronic lanes when the volume of vehicles in the electronic lane(s) is at least twice the volume in the ticket lane(s). The typical error introduced by this approximation will be less than 1 dBA. For higher ratios of electronic to ticket lane traffic and/or for speeds lower than 60 mph in the electronic lanes, the error will be lower.

When in doubt, the practitioner should model traffic in the different types of lanes separately using the guidance in the preceding sections. As noted above, multiple lanes of the same type (i.e., multiple electronic toll lanes or multiple ticket lanes) may be combined into a smaller number of TNM roadways.

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[26] For example, the average length of a queue along the entrance ramp to a weigh station is 500 ft. Heavy trucks at a similar existing facility are observed to be spaced at approximately 100-ft intervals (including both the trucks and gaps between). The average number of trucks in the queue is five.

[27] For example, 2,000 vehicles per hour, including 4% heavy trucks (80 trucks) are projected to pass through a particular lane at a toll barrier. Average waiting time during the modeled hour is projected to be 90 seconds; therefore heavy trucks will be in the queue for a cumulative total of 7,200 seconds each hour (80 trucks × 90 seconds each). On average, two heavy trucks will be in the queue at any particular time throughout the hour (7,200 truck-seconds/3,600 seconds). Note that it is not necessary to model queued automobiles in this case even though they share the same lane as the heavy trucks.

[28] This guidance was developed for heavy truck percentages ranging from 4 to 10%. In addition, vehicle mix was assumed to be the same in both electronic and ticket lanes, and both types of lanes were assumed to be equidistant from the prediction points. Substantial deviations from these parameters may provide different outcomes.

CHAPTER 5

Median Barriers

5.1 Introduction

Typical issues encountered in FHWA TNM modeling of roadway sections that contain median barriers include the following:

- FHWA TNM Version 2.5 has a component that addresses single reflections; however, this component is "turned off" and not available for use.
- The parallel barrier module within the FHWA TNM is not intended for use with lower-height barriers such as median barriers.
- It is envisioned that the FHWA TNM Version 3.0 will be capable of modeling single reflections; however, this version is not yet available for use and its limitations and graphic functionality are still being evaluated. Therefore, evaluations using FHWA TNM Version 3.0 were not conducted.

It is recognized by some noise practitioners that median barriers can have an effect on noise levels at adjacent receptors. The effect may be related to a variety of factors, including the following:

- Horizontal and vertical relationship of the median barrier to adjacent lanes.
- Elevation of adjacent receptors with respect to roadways and the median barrier.
- Distances between the roadways and median barrier and adjacent receptors.
- Height and shape of the median barrier.

While other factors such as ground type, topography, and noise barriers affect noise levels, for purposes of testing and evaluating the influences of median barriers, the research team focused on the four bulleted items listed above. Therefore, traffic and noise measurement data associated with locations with relatively simple topography and features were selected for testing and evaluation. While various ground types exist for the selected sites, no attempts were made as part of this investigation to address ground type variability in developing best modeling practices for median barriers. In addition, the team focused on collecting measurement data from sites located at elevations level with the highway, higher than the highway, and lower than the highway.

The techniques associated with FHWA TNM Version 2.5 were evaluated and tested using measurement data from the five selected projects described in Section 5.2 of this report. Suggested best modeling practices for median barriers were developed based upon this evaluation and testing. More detailed information is included in Appendix D, which is available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986.

5.2 Measurement Locations Evaluated

By far, the highest quality noise measurement and validation data exist in recent studies conducted by the Volpe Center. The following three locations in the Volpe measurement studies had median barriers and were evaluated in this investigation:

- **Volpe Site 3C.** This measurement location in Arizona was part of Volpe's Arizona Quiet Pavement Program evaluation project. The location is relatively flat, and the eight-lane divided highway (four lanes in each direction plus a ramp lane in one direction) is relatively level. The median barrier is in the center of a 32-ft wide paved median.
- **Volpe Site 18PA.** In 2001, measurements were taken at this location adjacent to the Pennsylvania Turnpike west of Carlisle, Pennsylvania, for use by Volpe in its FHWA TNM Validation Project. The topography is relatively flat and the four-lane divided highway (two lanes in each direction)

is relatively level. The median barrier is in the center of a 10-ft wide paved median.

- **Volpe Site 22PA.** Measurements were taken at this location adjacent to PA Route 581 in Camp Hill, Pennsylvania, as part of Volpe's FHWA TNM Validation Project. In this area, an earth berm extends along a length of the highway. It then ends, and an unprotected (no berm) length of highway exists. For the unprotected section, three measurements were taken at distances equal to those in the berm section. With the exception of the berm, the topography for both areas is relatively level. The four-lane divided highway (two lanes in each direction) is also relatively level. The median barrier takes up the majority of the narrow paved median.

In addition to the evaluation and testing of the high-quality noise measurement and traffic data available from the Volpe studies described above, the team evaluated and tested each modeling technique identified in Section 5.3 using several measurement data sets from the following two projects:

- **Pennsylvania Turnpike Noise Analysis Project, Butler, Pennsylvania.** In the early to mid-2000s, members of the research team conducted a variety of noise measurements for a section of the Pennsylvania Turnpike in Butler, Pennsylvania, as part of a noise evaluation for the Turnpike's proposed Warrendale Mainline Toll Plaza project. An existing public park exists within the project area immediately adjacent to the Turnpike. The majority of the park is approximately 15 to 20 ft lower in elevation than the Turnpike. For this park area, team members used a grid of receivers for analyzing equivalent residential units. During the time of the noise measurements, a median barrier existed in the area and the volume of heavy trucks was significant.
- **Ohio DOT Interstate 71 (I-71) Noise Analysis, Columbus, Ohio.** In 2006, research team members conducted extensive noise measurements for a six-lane (three lanes in each direction) section of I-71 in Columbus, Ohio. During the model validation process, the team evaluated various measurement locations where specific attention was directed toward consideration of the effects of median barriers. Locations existed where receptors were located level with, above, and below the roadway elevation.

5.3 Modeling Techniques Evaluated

Based on a review of data collected by the team and input from team members and other noise specialists contacted, modeling techniques were identified by the team for evaluation and testing. For evaluation of each one of these candidate modeling techniques, the team utilized the measurement and traffic information from the projects described in Section 5.2. This process resulted in the development of methodologies to adjust the basic FHWA TNM output data to appropriately incorporate the effects of median barriers.

Receptors located at various distances from the highway were evaluated using each of the techniques discussed below. In its evaluation of each of these modeling techniques, the team utilized the measurement and traffic information associated with 49 individual measurements taken at distances ranging from 46 to 1,000 ft from the center of the near traffic lane. Measurements were taken at points where the topography at the measurement site ranged from below the elevation of the highway to near level with the highway to above the highway.

While the FHWA TNM Version 2.5 does not have the ability to model low-height reflective surfaces or their shapes, the team did evaluate the relative effects of median barriers using FHWA TNM and varying median barrier heights (from 2.5 to 4.5 ft) for each of the five projects identified in Section 5.2. From this evaluation, the team determined that the relative differences in noise levels associated with the range of median barrier heights evaluated was relatively insignificant.

For each modeling technique described below, median barriers were assumed to be the same height as existed at the time of the measurements for each respective project. Vertical median barrier faces that are 100% reflective were assumed. In addition, each roadway lane was input as a separate roadway within the FHWA TNM, with its own geometry, traffic volumes, and speeds.

5.3.1 Image Roadway Technique *Approximation* Using "Seen" Travel Lanes

This technique developed an image roadway to represent the noise reflected from the median barrier from the near travel lanes. This roadway was constructed in an FHWA TNM run by "flipping" the eastbound travel lanes (shown in Figure 31) to the far side of the barrier, as shown in Figure 32. Where different traffic volumes are assigned to each travel lane in the base FHWA TNM run (such as in the Volpe projects), these travel lane volumes were also flipped to place them at similar distances from the median barrier. When calculating the reflected noise values using this technique, only the image roadways (eastbound flipped travel lanes) were modeled and only the eastbound vehicles that were "seen" (and heard) by a particular receptor were modeled in their "flipped" position. To provide an approximation of which vehicles would be seen, a line was drawn from the receptor to the top of the median barrier. Any vehicle sources falling on or below this line were assumed to be seen by the receptor, unless the line of sight is blocked by some ground or roadway feature. The research team also looked at skew sections representing flanking noise in the identification

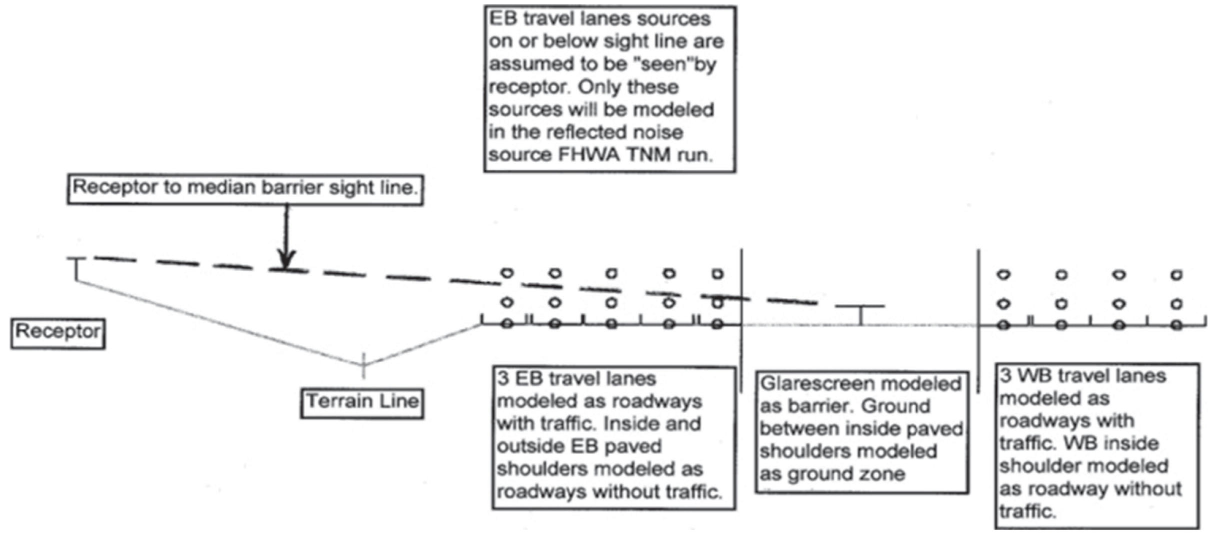

Figure 31. Skew section of base FHWA TNM run.

of seen traffic sources. For the example used, this sight line is shown in Figure 31, with the seen sources indicated by solid circles in Figure 32.

In modeling the flipped roadway, the default ground type within the FHWA TNM run was the same as that of the base FHWA TNM run and all other topographic features (ground zones, terrain lines, etc.) were the same as in the base FHWA TNM run. The areas occupied by the roadway median and the eastbound roadways and shoulders were input as ground zones having their respective surface properties. Noise levels generated by this reflected noise run were calculated at the actual receptor locations. Any adjustments determined to be appropriate based on this reflected noise run were applied to values generated by the base FHWA TNM run, which was modeled with the median barrier input as a barrier.

Because of the many ray paths and multiple reflections that actually occur between the various sources, the median barrier, and the roadway surfaces, the team recognizes that this technique is, at best, an approximation of the reflected noise. However, the use of a more complex ray-tracing technique is beyond the scope of this research.

An alternative approach explored by the team was to model the eastbound lanes and shoulder areas but to delete all traffic from the eastbound lanes. In modeling flipped roadways, the team compared reflected noise levels generated by the following two approaches for several of the projects described in Section 5.2:

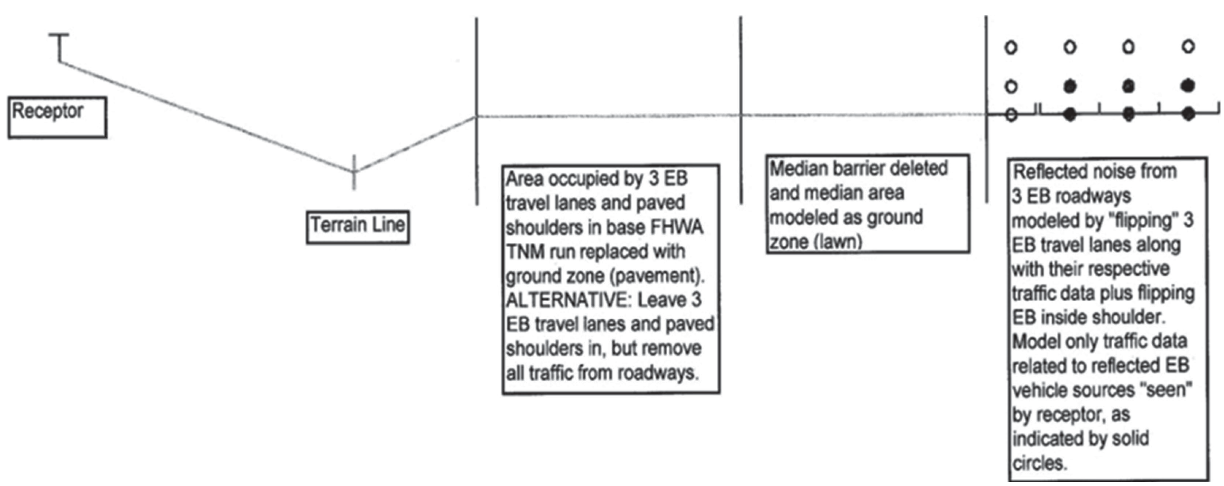

Figure 32. Skew section of reflected (flipped) FHWA TNM run.

- Modeling flipped roadways and using ground zones to represent the intervening ground occupied by deleted near roadway lanes.
- Modeling flipped roadways and retaining the pavement surface geometry of the near roadway lanes, but deleting traffic from these near roadway lanes.

The comparison indicated that the "ground zone" approach results in slightly higher values for the reflected noise component than does the "pavement" approach. However, when the reflected component is added to the direct noise component (FHWA TNM modeled noise levels from all lanes with a median barrier in place), the difference in total noise levels ranged from 0.1 to 0.4 dB, which is relatively small. The team chose to use the slightly more conservative ground zone approach in its estimations of reflected noise component values.

5.3.2 Image Roadway Technique *Approximation* Using All Travel Lanes

A more conservative approach evaluated by the team was to model all "flipped" roadway sources as being reflected by the median barrier. This typically resulted in higher reflected noise levels than generated by the "seen" vehicle source technique described in Section 5.3.1.

5.3.3 Ignoring Median Barrier

This technique simply ignored the presence of any median barrier in the base FHWA TNM run and did not assume any noise reflections.

5.3.4 Ignoring Median Barrier Reflections

This technique included the barrier in the base FHWA TNM run, but made no adjustments to account for reflections off of the barrier.

5.4 Best Modeling Practices

The team recognizes that any one of its best modeling practices may not be appropriate for all modeling scenarios. For example, one practice may be appropriate for elevated receptors, but not for receptors located lower than the roadway. One practice may work for nearby receptors, but not for more distant receptors. Review of the trends in the results of the research resulted in suggestions for best management practices for modeling median barriers:

- For receptors located within 500 ft of the highway (center of nearest travel lane) and located below the elevation of the highway, model the median barrier and ignore reflections off of the median barrier.
- For receptors located beyond 500 ft of the highway and located below the elevation of the highway, model the median barrier and consider reflections off of the median barrier using the appropriate reflected barrier technique.
- For receptors that are located from 50 ft to 500 ft from the highway and are level with or less than 6 ft above the highway, model the median barrier and ignore reflections.
- For receptors that are located 6 ft or more above the elevation of the highway and within 500 ft of the highway, model the median barrier and account for reflections.

The majority of the median barriers evaluated were intentionally located in areas with relatively simple terrain containing no intervening noise barriers or berms. However, the research team recognizes that median barriers often exist in conjunction with these other features, and therefore the team selected one area to test the various modeling techniques against such features. High-quality measurement and validation data were obtained by the team for Volpe Site 22PA. This location offered the opportunity to test and evaluate each of the median barrier analysis techniques at two receptor locations behind an earth berm. The analysis of these sites based on FHWA TNM runs for the receptors indicated that it is probably appropriate to ignore the effects of the median barrier. While this can provide some guidance for similar types of projects, the best modeling practice for projects having median barriers located in areas containing noise berms or noise walls should consider the specifics of the project area.

5.5 Conclusions

Suggested best modeling practices were developed for adjusting FHWA TNM predictions to account for the effects of noise reflections off of median barriers. The team recognizes that any one of its suggested best modeling practices may not be appropriate for all modeling scenarios. However, certain trends were observed that enabled the development of the generalized suggestions, shown in Table 8, related to incorporating the effects of noise reflections off of median barriers. Such suggestions relate to situations where receptors were generally unaffected by intervening objects between the median barrier and the receptor, as well as areas where receptors were located behind a noise abatement feature. Based on the team's evaluation and testing, it is suggested that median barriers be modeled in all cases, even if the effects are slight. An exception to this suggestion could occur where receptors are located behind noise abatement features.

Table 8. Suggested modeling techniques for median barriers by receptor location.

Distance from Middle of Near Travel Lane (ft)	Height of Receptor with Respect to Roadway	
	Receptor Below to 6 ft Above Roadway	Receptor More Than 6 ft Above Roadway
50	Model Median Barrier and Ignore Reflections	Model Median Barrier and Consider Reflections
100		
200		
500		
1000	Model Median Barrier and Consider Reflections	

CHAPTER 6

Multilane Highways

6.1 Introduction

Based upon the extensive FHWA TNM modeling experience of research team members and the review of data obtained from the literature search, a number of candidate modeling techniques for multilane highways have been identified.

Typical issues encountered in FHWA TNM modeling of roadway sections that contain more than one travel lane in each direction include the following:

- Modeling groups of lanes versus modeling each lane as its own roadway.
- How much to overlap lanes.
- How to represent shoulders and median areas.
- How to represent edge of roadway section diffraction points.
- Shielding of one roadway by another roadway, such as with a bifurcated roadway section.
- Modeling super-elevated roadways.
- It is envisioned that FHWA TNM Version 3.0 will be capable of modeling multilane highways via its multilane tool; however, this version is not yet available for use and its limitations and graphic functionality are still being evaluated. Therefore, evaluations using FHWA TNM Version 3.0 were not conducted.

In evaluating modeling techniques related to multilane highways, the research team focused on the bulleted items listed above, addressing traffic and noise measurements associated with locations with relatively simple topography. The evaluation and testing reinforced the team's knowledge that factors such as pavement type, ground type, topography, noise barriers, and so forth affect noise levels. The influences of these factors were determined to often be more significant than the variations of noise levels associated with the different techniques for modeling roadway lanes, shoulders, and median areas. While various pavement and ground types exist for the selected sites, no attempts were made as part of this investigation to address their variability in developing best modeling practices for multilane highways.

In selecting measurement and validation data related to multilane highways, the team focused on collecting information for receptors located on adjacent land at elevations level with the highway, above the highway, and below the highway. Sites without median barriers were also selected, to eliminate this variable from the other variables examined. No data could be obtained for bifurcated highway projects without median barriers or outside parapets. Note that the topic of median barriers is addressed in Chapter 5.

The techniques associated with FHWA TNM Version 2.5 were evaluated and tested using measurement data from the six selected projects described in Section 6.2 of this report. Suggested best modeling practices for modeling multilane highways were developed from this evaluation and testing. More detailed information is contained in Appendix E, which is available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986.

6.2 Measurement Locations Evaluated

By far, the highest quality measurement and validation data exist in recent studies conducted by the Volpe Center. The following three locations in the Volpe measurement studies were selected for the evaluation of multilane highways:

- **Volpe Site AZ3B.** This site is located in Arizona and is part of Volpe's Arizona Quiet Pavement Program evaluation project. The site is relatively flat and the six-lane divided highway (three lanes in each direction) is relatively level. In 2008, three sets of measurements were taken at three primary locations—50, 95, and 246 ft from the center of the near lane. The reference (50-ft) microphone was positioned 5 ft above the roadway elevation, while the microphone heights at the 95-ft and 246-ft locations were positioned at 5 ft above the ground.

- **Volpe Site 01MA.** In 2008, measurements were taken at this site, located adjacent to Route 24 in Massachusetts for use by Volpe in its FHWA TNM Validation Project. The site is relatively flat and the four-lane divided highway (two lanes in each direction) is relatively level. The paved shoulders were modeled as 10-ft wide roadways with no traffic. Measurements were obtained at 5 ft and 15 ft above the ground at distances of 50, 100, and 200 ft from the center of the near lane.
- **Volpe Site 20PA.** This site is located adjacent to Interstate 81 (I-81) west of Harrisburg, Pennsylvania, and is part of Volpe's FHWA TNM Phase 2 Validation Project. In 2001, noise measurements were taken at four sites adjacent to the four-lane divided highway (two lanes in each direction) with a wide grass median. The sites were located at 90, 200, 400, and 600 ft on generally level terrain, except for the 600-ft site, which was approximately 14 ft higher than the others.
- **Volpe Site 19PA.** This site is located adjacent to US Route 30 in Coatesville, Pennsylvania, and is part of Volpe's FHWA TNM Phase 2 Validation Project. In 2001, noise measurements were taken at seven sites adjacent to the four-lane divided highway (two lanes in each direction) with a grass median. The sites were located at 50, 200, 400, 500, and 700 ft along a center offset row of microphones.

In addition to the evaluation and testing of the noise measurement and traffic data available from the Volpe studies, the research team also evaluated and tested modeling techniques using four data sets from the following project, which used a simplified technique in modeling a multilane highway:

- **U.S. Route 35 Noise Analysis Project, Dayton, Ohio.** In 2005, research team members conducted a variety of noise measurements for a section of US 35 as part of a preliminary noise evaluation for a proposed reconstruction and widening project. Numerous measurement sites were located along this four-lane highway (two lanes in each direction) at locations level with the highway and above and below the elevation of the highway. Lanes were grouped and represented by a single roadway in each direction, with the edge of shoulder diffraction edge defined by the outside edge of the modeled roadway closest to the measurement sites.

In addition to evaluating measurements obtained at the above locations, the team considered measurements taken at an additional location adjacent to Interstate 95 in Philadelphia, Pennsylvania, in a limited evaluation of a multilane highway section where each roadway lane's profile was independently modeled. Receptors at this location were located approximately 50 and 100 ft from the highway and approximately 15 ft below roadway grade.

6.3 Evaluation of Modeling Techniques

Based on a review of data collected by the team and input from team members and other noise specialists contacted, candidate modeling techniques were previously identified by the team. For evaluation and testing of each of these techniques, the team used the measurement and traffic information from the projects listed and described in Section 6.2. This process resulted in the development of best modeling practices to apply when modeling multilane highways using the FHWA TNM.

Receptors located at various distances from the highway were evaluated using each of the techniques discussed below. In its evaluation of each of these modeling techniques, the team used 67 individual measurements and related traffic information associated with the five projects listed in Section 6.2. These measurements were taken at distances ranging from 50 to 700 ft from the center of the near traffic lane at points where the measurement site (microphone) ranged from approximately 20 ft below the elevation of the highway to approximately 29 ft above the highway.

6.3.1 Description of Modeling Techniques

Candidate modeling techniques have been selected for basic FHWA TNM input elements related to roadways, shoulders, and diffraction edges, with consideration given to the bulleted issues listed in Section 6.1. For all projects, the ground type for any area existing between the inside shoulders was defined by the default ground type designated in the project's FHWA TNM run. The three basic modeling techniques are described below.

6.3.1.1 Dummy Lane Technique

This technique involves representing a shoulder in FHWA TNM by entering it as a roadway with a defined width and elevation and no traffic. The width of any designated outside dummy lane is typically set so as to also define the roadway section's diffraction point.

6.3.1.2 Ground Zone Technique

This technique involves defining a shoulder in FHWA TNM by representing the area of the shoulder with a ground zone. When representing a shoulder with a ground zone, the outside edge of the shoulder must be defined by a terrain line unless its elevation is the same as the adjacent topography.

6.3.1.3 Adjacent Lane Width Technique

This technique involves defining a shoulder in FHWA TNM by establishing the outside of the shoulder by designating an appropriate width for its adjacent roadway lane. This width can also be used to define the outside diffraction edge of the roadway section.

6.3.2 Application of Techniques to Projects

Various technique subcategories were also evaluated. They included modeling roadways (grouped lanes, individual lanes, and four options for overlapping lanes); modeling shoulders (dummy lanes, ground zones, adjacent lane width methods); and establishing roadway section diffraction edges (dummy lane, ground zone, and adjacent lane width methods).

6.3.3 Comparison of Modeling Techniques for Selected Projects

Results of the comparison of the various modeling techniques addressed the difference between the measured noise levels and modeled noise levels for each of the three primary modeling techniques previously described—dummy lane, ground zone, and adjacent lane width. For each of these techniques, values are provided for four options for overlapping lanes plus a grouped-lane option.

In applying the various modeling techniques to the projects listed in Section 6.2, several conclusions were drawn. These conclusions are listed and discussed below and relate to the evaluation of these specific projects.

- While there were a few outlier values, the vast majority of analysis sites showed little variation between the techniques in terms of the difference between measured values and modeled values. The average measured versus modeled absolute differences for each technique were approximately 0.6 dB.
- Even including the outlier values, the average measured versus modeled absolute differences for all techniques were each approximately 0.8 dB. The data suggested that the measured-modeled differences for sites located significantly lower than the elevation of the highway could be greater for techniques employing grouped roadway lanes versus those modeling individual lanes. However, sufficient receptors did not exist in the selected projects to verify this possibility.
- Evaluation of the best modeling techniques in terms of differences between modeled and measured values suggested that it may be best to keep lane overlap distances in the 0.1-to-1.0-ft range and that using the dummy lane technique may be the best. The ground zone technique employing grouped lanes gave similar results, however. Most of the best results for the ground zone technique were associated with sites that were elevated with respect to the roadway. However, these ground zone trends are not sufficient to formulate a best modeling practice.

For the projects described in Section 6.2, factors such as pavement type, ground type, distribution of traffic between lanes, measurement period variations, and vehicle speed identification methods have the potential to create greater variation between measured and modeled values than do the different multilane modeling techniques evaluated. This potential, plus the fact that only a few insights into the development of a best modeling practice could be gleaned from the evaluation of the selected sites, prompted the team to consider a generic site where most of these factors could be normalized and where differences associated with the analysis techniques could be better determined.

6.3.4 Comparison of Modeling Techniques for a Generic Project

In the construction of a project-validated model, the specific effect of any individual input factor is not usually evident. This was true in the team's evaluation of the selected projects. For that reason, a generic project was developed and analyzed in an attempt to isolate the relative influences and differences between the multilane modeling techniques.

The generic project considered a 4,000-ft-long, four-lane, divided highway with level grade and containing 10-ft-wide, paved, inside and outside shoulders and a paved median. Receptors were placed at setback distances of 50, 100, 200, 300, 400, and 500 ft from the center of the near lane at heights related to the highway of −15 ft, −5 ft, +5 ft, and +15 ft. For each of the primary modeling techniques, grouped lanes were modeled and compared to the use of individual lanes with 0.1-ft overlaps.

The evaluation resulted in insignificant differences between individual- and grouped-lane modeling techniques with the four-lane generic project. This confirmed the general findings from the evaluation of the selected projects previously discussed. This finding was further validated by evaluation of the I-95 GIR project in Philadelphia. That project has super-elevated roadway lanes, but showed no significant differences between the individual- and grouped-lane modeling techniques.

The results of the four-lane generic project evaluation led to the development and evaluation of a wider, eight-lane generic project that included additional receptors at elevations of 25 and 35 ft below roadway grades. The results of the eight-lane evaluation showed that the grouped-lane technique under-predicted noise levels relative to the individual-lane technique at receptors located close to and significantly lower than the highway. Presuming that individual-lane modeling is more precise because the noise sources are more precisely located, this result illustrates the importance of modeling individual lanes in areas where certain lanes may be shielded and others may be exposed, or where certain vehicles in certain lanes are shielded and some are not. While this situation most often exists in locations close to and/or below the grade of the highway, it could also exist at other locations that may be shielded or partially shielded by features that are either manmade (structures, barriers, etc.) or natural (undulating terrain, natural berms, etc.).

To gather additional data related to the causes of the grouped-lane under-prediction of noise levels for the eight-lane generic project, FHWA TNM was run individually for automobiles, medium trucks, and heavy trucks, with results illustrating the predominance of the heavy truck noise component. This indicated that truck stack noise is a major component and a factor that must be considered in modeling roadway travel lanes in multilane highway situations. This will be of particular significance for roadways with high truck volumes because trucks are predominant in the outside lanes, where they are close to the nearest receptors and will be less shielded by the edge of pavement where the roadway is elevated.

6.4 Best Modeling Practices

Based on the evaluation of the analysis techniques reported, the research team has compiled a list of suggestions for modeling of multilane highway projects. This list represents the team's best managing practices. The following two suggestions are deemed to be most important:

- Model each travel lane separately when receptors are located below the elevation of the highway.
- Regardless of the receptor's relationship to the highway, model each travel lane separately when there are any intervening manmade or natural features that block the line of sight between any receptor and any travel lane. Consider roadway super-elevation and all perpendicular and flanking noise paths in making such determinations. If in doubt, model individual lanes.

The following modeling techniques are suggested by the research team based upon the reported evaluations:

- Set FHWA TNM default ground type to "Pavement" to minimize any possible effects created by inadvertently leaving gaps between roadways when modeling complex roadways with features such as ramp gores, curved roadway sections, and super-elevated roadways. Model median areas between paved shoulders and surfaces outside of the roadway section by use of the appropriate FHWA TNM ground zone(s).
- Provide travel lane overlap distances in the 0.1-to-1.0-ft range.
- Use the dummy lane technique to model shoulders, especially outside shoulders. It presents less potential for illegal intercepts within FHWA TNM and does not require the addition of a contour line that is required with the ground zone technique. The dummy lane technique also allows for a smaller lane overlap than that resulting from use of the adjacent lane width technique and is more compatible with modeling super-elevated roadway sections.
- When modeling super-elevated roadways, model the profile elevations associated with each roadway lane if such data are available.

CHAPTER 7

Building Rows

7.1 Research Approach

7.1.1 Basic Concepts

A row of small buildings such as the detached houses in Figure 33 acts as a series of small noise barriers with gaps in between them, which reduces sound levels at receivers behind the row. In FHWA TNM 2.5, one could choose to model each house as a barrier object. With some exceptions, this approach is generally not used except for model comparison to field measurements. Even then, when each house is modeled as a barrier, the TNM algorithms do not account for the reflection of sound from the highway off the sides of the buildings to receivers behind them.

The FHWA TNM building row object simulates a row of houses as a single long barrier with a low uniform transmission loss, something akin to a porous noise barrier. TNM diffracts a portion of the sound energy over the top of the row and allows a portion to pass uniformly through the row. The specific locations of the gaps between the buildings are not defined and thus the effect of their exact location in the row is not computed. Unlike FHWA TNM Barriers, building rows cannot be perturbed up and down from the average height.

The building row may be defined as series of connected straight line segments, defined by x, y, and z coordinates of the segment endpoints. The base of the building row defines the terrain over which the sound passes from source to receiver and thus affects the computation of the interactions with the ground in the propagation calculations. Because a building row defines the location of the ground and because it causes sound to be diffracted over it, its location relative to the roadway and receiver is also important, as are the elevations of the ground at the roadway and receiver, and the height above ground of the receiver. The closer the building row is to the source or receiver, all else remaining the same, the greater the diffraction attenuation will be.

Other needed input parameters are the following: (1) average height of the buildings above the user-specified ground elevations; and (2) building percentage, which is the percentage of the line defined by the row that is blocked by the row (or 100% minus the percentage of gaps [gap fraction] between the houses). The allowable range is 20% to 80%.

TNM computes sound-level reductions based on user-defined location, length, average height, and percentage of area blocked. More than one building row may be modeled in a run.

Where there is more than one row of buildings between the highway and the receivers, a simplified calculation is used. As described in the "Traffic Noise Model: Frequently Asked Questions FAQs" section on the FHWA noise web site:[29]

> TNM first identifies all building rows that interrupt the effective source-receiver path. Rows that do not interrupt the propagation path are ignored. For each row that interrupts the path, TNM determines which building row has the most effective attenuation at the 630 Hz frequency band. For this building row, the actual attenuation is calculated for all ⅓-octave frequency bands. For each remaining row that interrupts the propagation path, an attenuation of 1.5 dB is applied to each ⅓-octave band. The maximum attenuation for any number of building rows has been set to 10 dB. For a listing of maximum attenuation for each ⅓-octave band please refer to Table 13 on Page 100 in the TNM Tech Manual.

Table 13 from the FHWA TNM *Technical Manual*[30] is presented in Appendix F, which is available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986.

As with many of the other FHWA TNM objects, there are always concerns about over-modeling of building rows that does not improve accuracy. As noted above, detailed ⅓-octave band attenuations are only calculated for the most effective

[29] *Traffic Noise Model: Frequently Asked Questions FAQs*, FHWA website: www.fhwa.dot.gov/environment/noise/traffic_noise_model/tnm_faqs.

[30] FHWA Traffic Noise Model, *Technical Manual*, FHWA No. FHWA-PD-96-010, February 1998.

Figure 33. Detached houses in front of a highway on an embankment.[31]

building row, with other building rows simply adding 1.5 dB attenuation per ⅓ octave band. Nonetheless, the FHWA TNM building row object is a very important parameter in noise impact assessment, affecting how quickly sound levels drop off with distance from the road. The building row object is also, possibly, an important parameter in noise barrier reasonableness assessment, potentially affecting the number of residences benefited by a noise barrier because of the interplay between building row attenuation and noise barrier attenuation.

Unfortunately, the noise reduction calculated by FHWA TNM for building rows cannot be easily field validated because building rows do not spatially locate the real-world gaps through which sound passes. In addition, as one gets deeper into a community, background noise and refractive meteorological effects caused by wind shear, wind direction, and temperature lapse rate—none of which are modeled in FHWA TNM 2.5—become much more important in determining the overall sound level measured at a site, making model validation difficult and often impossible.

The goals of this research were to test and refine current FHWA guidelines on modeling building rows, specifically as related to

- Height.
- Building percentage.
- Use of an FHWA TNM building row or individual building barrier objects.
- Effect of receiver location behind a row of houses.

Two other items were considered:

- How does the presence of a building row affect the calculated noise reduction from a noise barrier along the edge of the road?
- How much noise reduction is computed when the building rows are perpendicular to the modeled roadway?

[31] Source: Bowlby & Associates, Inc.

7.1.2 Research Tasks

There are two basic candidate modeling techniques that were evaluated:

- Use of the FHWA TNM building row object for rows parallel to the highway and rows perpendicular to the highway through sensitivity testing and use of the available validation data sets.
- Use of the FHWA TNM barrier object for modeling rows of houses or other small building as individual building barriers.

The work began with a survey of practitioners, which identified one very well-documented field validation study of modeling detached houses as individual barriers, conducted by and for the Maryland State Highway Administration. Four other field validation studies previously conducted by the NCHRP Project 25-34 research team were also identified.

These studies all had very good sets of validation data—measured sound levels with concurrent traffic classification counts and speed measurements. The FHWA TNM runs were also made available to the research team. The Maryland State Highway Administration project was different from the others in that it used the approach of modeling each house as an FHWA TNM barrier object.

Following a review of the surveyed material, a sensitivity analysis was conducted for generic situations to examine the variation in the modeled wayside sound-level results due to variations in the different TNM building row input parameters, specifically the percentage of a row that is blocked by the buildings, the average height of the buildings, and the number of rows that are modeled. Situations were studied both with and without barriers, and with rows that are both parallel and perpendicular to the roadway.

The next step was to analyze the available TNM validation data sets. For two older studies, the FHWA TNM 1.0b runs were converted to FHWA TNM 2.5 format. For the other studies, the original modeling had been done with FHWA TNM 2.5. Separate model runs were made using building rows and building barriers, and, in two cases, for specific pavement types. The modeled levels were compared to the measurement results, keeping in mind that any differences in measured and modeled results could not be solely attributed to the use of the FHWA TNM building row object.

Further, the TNM building row object is, by its nature, an approximation because it does not account for the actual locations of the gaps between the buildings. Some of the runs were modified to study the calculated effects of varying the receiver positions behind the building row.

The building row modeling guidelines were refined based on the research results.

7.2 Outcome of the Research—Best Practices and How to Implement Them for a Noise Study or TNM

7.2.1 Distance from Building Rows and Percentage of Blockage

The results showed the following:

- As the distance from the building row (and the roadway) increases, the amount of noise reduction decreases.
- As the building percentage increases, the amount of noise reduction increases.
- As a result of the above two findings, simple guidance may not be sufficient.

7.2.2 Sensitivity to Building Row Height

Table 9 shows the *change* in noise reduction (not the actual noise reduction) behind a single building row as a function of building height for different building percentages. The table may be used to decide how precise the modeling of the height needs to be for a given situation.

The shaded values are for differences of half a dB or more. *The values should be viewed as indicators of the effect, not as absolute noise reduction differences. The effects will be specific to the situation being modeled.* Also, Table 9 is for a receiver in the middle of the building row. Near the ends of the row, the sound coming from the unshielded area beyond the end of the row will reduce the effect of changes in the building row parameters.

The results show the following:

- For 20% to 40% blockage, a change in height of 5 ft causes little change in the noise reduction regardless of how far back the receiver is behind the building row.
- For higher building percentages, the change in noise reduction is dependent on the distance behind the building row. The maximum difference for a 5-ft height change—from 20 to 25 ft and from 25 to 30 ft—is less than 2 dB in these modeled cases.

Sensitivity runs were completed for one building row parallel to an eight-lane road (four lanes in each direction) with shoulders and a 30-ft-wide grassy median. Each lane was modeled with mixed traffic traveling at 60 mph. The building row was 70 ft from the edge of the near travel lane. Three building heights were chosen (20, 25, and 30 ft) to represent one-story and two-story buildings with an intermediate height. The percentage of blockage was varied from 20% to 80% in 10% increments, along with a 0% case (no row). Receivers were modeled up to 1,000 ft from the road. Full details are in Appendix F.

Figure 34 shows the noise reductions as a function of building percentage for the 20-ft height, and Figure 35 shows results for the 30-ft height.

In both cases, up close to the building row, the noise reduction varies from about 1 dB for 20% blockage to over 6 dB for 80% blockage. Up close, the path of sound through the building row is more dominant than the diffracted sound over the top of the row, hence the greater sensitivity to building percentage. As the distance back from the building row increases, the amount of diffraction attenuation over the top of the building row decreases, such that the path over the top of the row begins to dominate the total received level:

- For the 20-ft-high building row, by just over 330 ft behind the row, the noise reduction is 1 dB or less regardless of the building percentage.
- In contrast, for the 30-ft-high building row, there is a more gradual decrease in the noise reduction as the distance away from the building row increases. For example, at 330 ft behind the row, the noise reduction for 80% blockage is 3.7 dB, roughly 2.7 dB greater than that for a 20-ft-high building row.

7.2.3 Sensitivity to Building Percentage

7.2.3.1 One Building Row

The building row noise reduction is also a function of the building percentage. Table 10 compares the *change* in the noise reduction from one building percentage to a value that is 10% greater (e.g., from 20% to 30%) for single building row heights of 20, 25, and 30 ft. Table 10 may be used to assess how precise the modeling of the building percentage needs to be for a given situation.

The values given in Table 10 are not the noise reductions, but the changes from one case to the next. Shading identifies differences of 0.5 dB or more. *The values provided in Table 10 should be viewed as indicators of the size of the effect, not as absolute noise reduction differences.* The effects will be specific to the situation being modeled. Also, Table 10 is for a receiver in the middle of a building row. Near the ends of the row, the sound coming from the unshielded area beyond the end of the row will reduce the effect of changes in the building percentage.

The results show that the greater the building row height, the greater the difference in going from one building percentage to another percentage that is 10% higher or lower.

For building percentages of 20 to 60%, a variation of ±10% around a given percentage will produce a noise reduction difference of less than 1 dB at all of the studied distances

Table 9. Change in noise reduction behind a single building row as a function of building height for different building percentages.

Distance to Building Row, ft	Noise Reduction Differences between Different Building Percentages, dB						
	20%	30%	40%	50%	60%	70%	80%
Building Row Height Change from 20 ft to 25 ft							
10	0.0	0.0	–0.1	–0.1	–0.1	–0.2	–0.3
30	–0.1	0.0	–0.2	–0.2	–0.2	–0.3	–0.5
50	–0.1	–0.1	–0.2	–0.3	–0.5	–0.7	–0.9
70	–0.2	–0.2	–0.2	–0.4	–0.5	–0.7	–1.0
90	–0.1	–0.2	–0.3	–0.5	–0.6	–0.8	–1.2
110	–0.2	–0.3	–0.3	–0.5	–0.6	–0.9	–1.2
130	–0.2	–0.2	–0.4	–0.5	–0.8	–1.0	–1.4
170	–0.2	–0.3	–0.5	–0.7	–1.0	–1.4	–1.7
210	–0.3	–0.4	–0.6	–0.8	–1.1	–1.4	–1.8
250	–0.3	–0.4	–0.6	–0.8	–1.1	–1.4	–1.8
290	–0.2	–0.4	–0.6	–0.8	–1.1	–1.3	–1.7
330	–0.2	–0.4	–0.6	–0.8	–1.0	–1.3	–1.6
430	–0.3	–0.3	–0.5	–0.7	-0.9	–1.1	–1.3
530	–0.2	–0.3	–0.5	–0.6	–0.8	–1.0	–1.3
730	–0.2	–0.4	–0.5	–0.7	–0.9	–1.0	–1.3
930	–0.2	–0.4	–0.5	–0.6	–0.8	–1.0	–1.2
Building Row Height Change from 25 ft to 30 ft							
10	0.0	–0.1	0.0	0.0	0.0	0.0	–0.1
30	0.0	–0.1	0.0	0.0	–0.1	–0.2	–0.2
50	0.0	–0.1	–0.1	–0.1	–0.1	–0.2	–0.3
70	0.0	0.0	–0.1	–0.1	–0.2	–0.3	–0.5
90	0.0	0.0	–0.1	–0.1	–0.2	–0.3	–0.5
110	0.0	0.0	–0.1	–0.2	–0.3	–0.4	–0.7
130	0.0	–0.1	–0.2	–0.3	–0.3	–0.6	–0.8
170	–0.1	–0.2	–0.2	–0.3	–0.4	–0.6	–0.9
210	–0.1	–0.1	–0.2	–0.3	–0.5	–0.6	–0.9
250	–0.1	–0.1	–0.2	–0.4	–0.5	–0.7	–1.0
290	–0.2	–0.2	–0.2	–0.4	–0.5	–0.8	–1.1
330	–0.1	–0.2	–0.3	–0.4	–0.6	–0.8	–1.1
430	–0.1	–0.3	–0.4	–0.5	–0.7	–1.0	–1.3
530	–0.2	–0.3	–0.4	–0.6	–0.8	–1.0	–1.3
730	–0.2	–0.2	–0.4	–0.5	–0.7	–1.0	–1.3
930	–0.1	–0.2	–0.3	–0.5	–0.7	–0.9	–1.2
Building Row Height Change from 20 ft to 30 ft							
10	0.0	–0.1	–0.1	–0.1	–0.1	–0.2	–0.4
30	–0.1	–0.1	–0.2	–0.2	–0.3	–0.5	–0.7
50	–0.1	–0.2	–0.3	–0.4	–0.6	–0.9	–1.2
70	–0.2	–0.2	–0.3	–0.5	–0.7	–1.0	–1.5
90	–0.1	–0.2	–0.4	–0.6	–0.8	–1.1	–1.7
110	–0.2	–0.3	–0.4	–0.7	–0.9	–1.3	–1.9
130	–0.2	–0.3	–0.6	–0.8	–1.1	–1.6	–2.2
170	–0.3	–0.5	–0.7	–1.0	–1.4	–2.0	–2.6
210	–0.4	–0.5	–0.8	–1.1	–1.6	–2.0	–2.7
250	–0.4	–0.5	–0.8	–1.2	–1.6	–2.1	–2.8
290	–0.4	–0.6	–0.8	–1.2	–1.6	–2.1	–2.8
330	–0.3	–0.6	–0.9	–1.2	–1.6	–2.1	–2.7
430	–0.4	–0.6	–0.9	–1.2	–1.6	–2.1	–2.6
530	–0.4	–0.6	–0.9	–1.2	–1.6	–2.0	–2.6
730	–0.4	–0.6	–0.9	–1.2	–1.6	–2.0	–2.6
930	–0.3	–0.6	–0.8	–1.1	–1.5	–1.9	–2.4

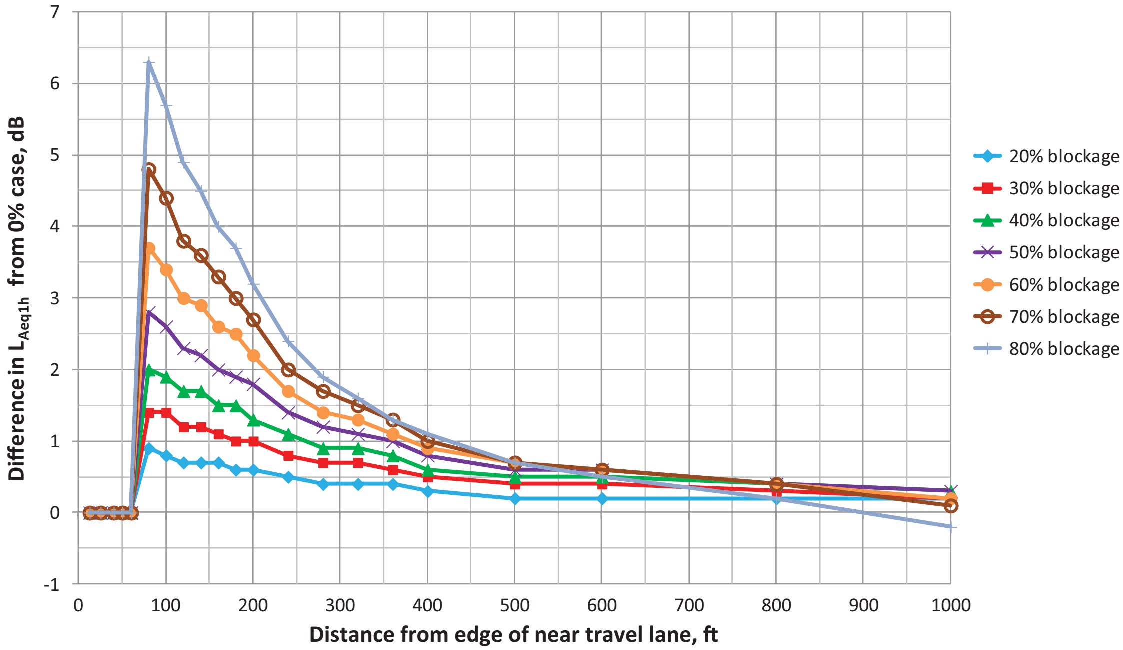

Figure 34. Noise reduction as a function of building percentage for a single 20-ft-high building row 70 ft from edge of an eight-lane roadway.

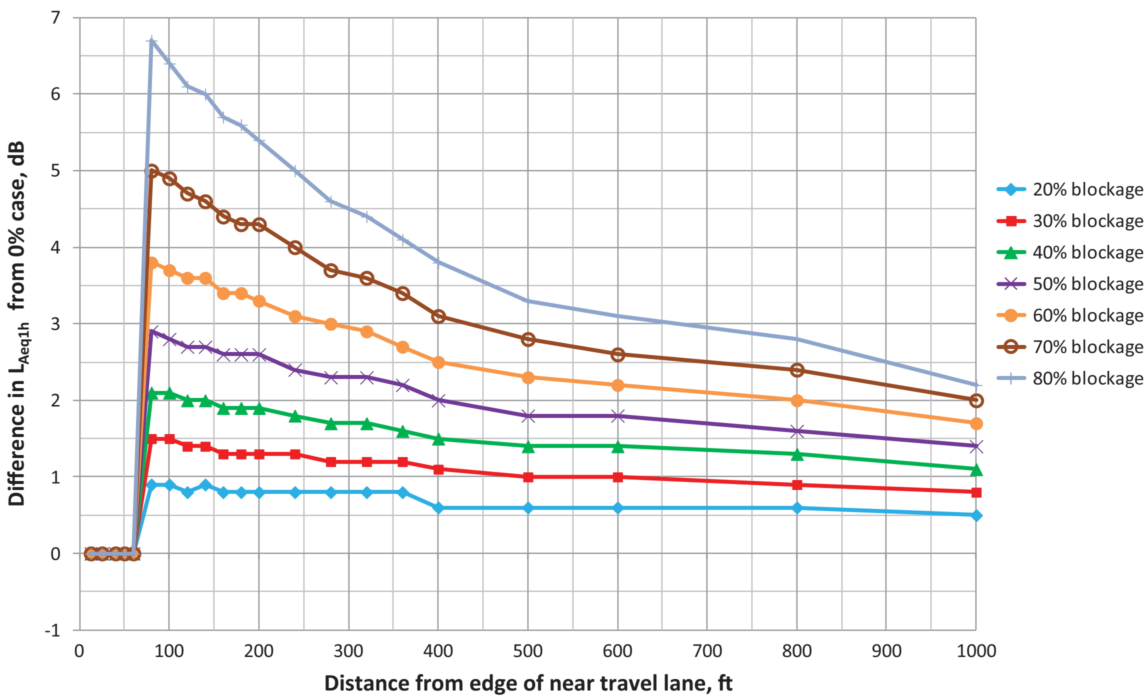

Figure 35. Noise reduction as a function of building percentage for a single 30-ft-high building row 70 ft from edge of an eight-lane roadway.

Table 10. Changes in noise reduction for 10% changes in building percentages for a single building row.

Distance Behind Building Row, ft	Noise Reduction Differences between Different Building Percentages, dB					
	From 20 to 30%	From 30 to 40%	From 40 to 50%	From 50 to 60%	From 60 to 70%	From 70 to 80%
Building Row Height of 20 ft						
10	0.5	0.6	0.8	0.9	1.1	1.5
30	0.6	0.5	0.7	0.8	1.0	1.3
50	0.5	0.5	0.6	0.7	0.8	1.1
70	0.5	0.5	0.5	0.7	0.7	0.9
90	0.4	0.4	0.5	0.6	0.7	0.7
110	0.4	0.5	0.4	0.6	0.5	0.7
130	0.4	0.3	0.5	0.4	0.5	0.5
170	0.3	0.3	0.3	0.3	0.3	0.4
210	0.3	0.2	0.3	0.2	0.3	0.2
250	0.3	0.2	0.2	0.2	0.2	0.1
290	0.2	0.2	0.2	0.1	0.2	0.0
330	0.2	0.1	0.2	0.1	0.1	0.1
430	0.2	0.1	0.1	0.1	0.0	0.0
530	0.2	0.1	0.1	0.0	0.0	–0.1
730	0.1	0.1	0.0	0.0	0.0	–0.2
930	0.0	0.1	0.0	–0.1	–0.1	–0.3
Building Row Height of 25 ft						
10	0.5	0.7	0.8	0.9	1.2	1.6
30	0.5	0.7	0.7	0.8	1.1	1.5
50	0.5	0.6	0.7	0.9	1.0	1.3
70	0.5	0.5	0.7	0.8	0.9	1.2
90	0.5	0.5	0.7	0.7	0.9	1.1
110	0.5	0.5	0.6	0.7	0.8	1.0
130	0.4	0.5	0.6	0.7	0.7	0.9
170	0.4	0.5	0.5	0.6	0.7	0.7
210	0.4	0.4	0.5	0.5	0.6	0.6
250	0.4	0.4	0.4	0.5	0.5	0.5
290	0.4	0.4	0.4	0.4	0.4	0.4
330	0.4	0.3	0.4	0.3	0.4	0.4
430	0.2	0.3	0.3	0.3	0.2	0.2
530	0.3	0.3	0.2	0.2	0.2	0.2
730	0.3	0.2	0.2	0.2	0.1	0.1
930	0.2	0.2	0.1	0.1	0.1	–0.1
Building Row Height of 30 ft						
10	0.6	0.6	0.8	0.9	1.2	1.7
30	0.6	0.6	0.7	0.9	1.2	1.5
50	0.6	0.6	0.7	0.9	1.1	1.4
70	0.5	0.6	0.7	0.9	1.0	1.4
90	0.5	0.6	0.7	0.8	1.0	1.3
110	0.5	0.6	0.7	0.8	0.9	1.3
130	0.5	0.6	0.7	0.7	1.0	1.1
170	0.5	0.5	0.6	0.7	0.9	1.0
210	0.4	0.5	0.6	0.7	0.7	0.9
250	0.4	0.5	0.6	0.6	0.7	0.8
290	0.4	0.4	0.6	0.5	0.7	0.7
330	0.5	0.4	0.5	0.5	0.6	0.7
430	0.4	0.4	0.4	0.5	0.5	0.5
530	0.4	0.4	0.4	0.4	0.4	0.5
730	0.3	0.4	0.3	0.4	0.4	0.4
930	0.3	0.3	0.3	0.3	0.3	0.2

behind the building row. For a difference of less than 0.5 dB, the needed distance behind the building row is a function of building row height:

- 20 ft high—beyond 130 ft behind the building row.
- 25 ft high—beyond 250 ft behind the building row.
- 30 ft high—beyond 430 ft behind the building row.

For building percentages of 60 to 80% and for building row heights of 20 to 30 ft, the accuracy of the estimated building percentage is a bit more important than at the lower building percentages. Differences in noise reduction for a variation of ± 10% are as large as 1.5 dB close behind the building row, but drop down to under 1 dB at distances from 70 to 210 ft as the building row height increases from 20 to 30 ft.

Another way to use the results is to determine the error in simply using a building percentage of 50% regardless of the actual percentage. Figure 36 shows the differences in noise reduction for various building percentages compared to 50% blockage for a 20-ft-high building row:

- The error is less than 1 dB for 40% and 60% blockage at all distances behind the building row.
- For 30% and 70%, the receiver has to be about 170 ft or farther behind the building row for the error to be under 1 dB.
- At about 330 ft back and beyond, the 20% and 80% cases could be represented as 50% with an error of under 1 dB.

Appendix F includes the results for the 25- and 30-ft-high building rows. The patterns are similar to the 20-ft case, except that the differences are somewhat greater, especially as one moves farther behind the row.

7.2.3.2 Two Building Rows

A second building row should be modeled if a second row is present in the study area. Modeling a second building row will have important effects in reducing the predicted level at a receiver compared to modeling only a single row. Care should be used in approximating the height and building percentage of both rows because FHWA TNM will determine which row is more effective and use it as the primary basis for its noise reduction calculations. That choice can vary by receiver-roadway pair.

Cases were studied for a single 12-ft-wide roadway, with the first building row 70 ft from the edge of the travel lane and the second building row 150 ft back from the first, a typical distance in going across a residential street with houses on relatively small lots.

Figure 37 shows the predicted noise reductions for both rows at a height of 20 ft for building percentages varying from 20 to 80%. Notice how the noise reduction decreases with increasing distance from the first building row, steps back up for receivers behind the second row, and then decays again with increasing distance behind the second row.

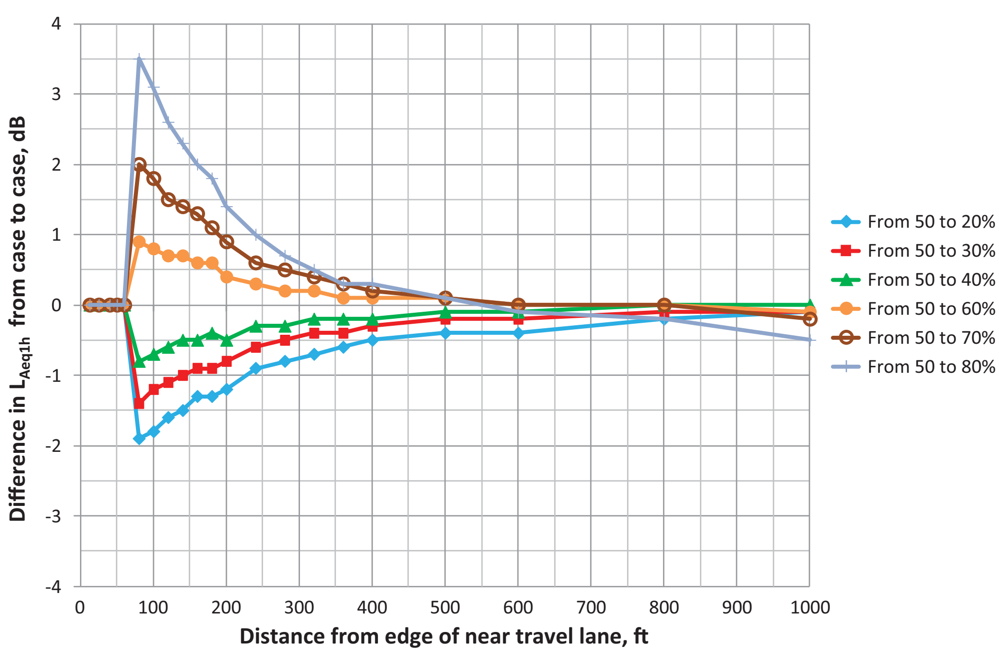

Figure 36. Differences in noise reduction for various building percentages compared to 50% blockage for a single 20-ft-high building row 70 ft from the edge of an eight-lane roadway.

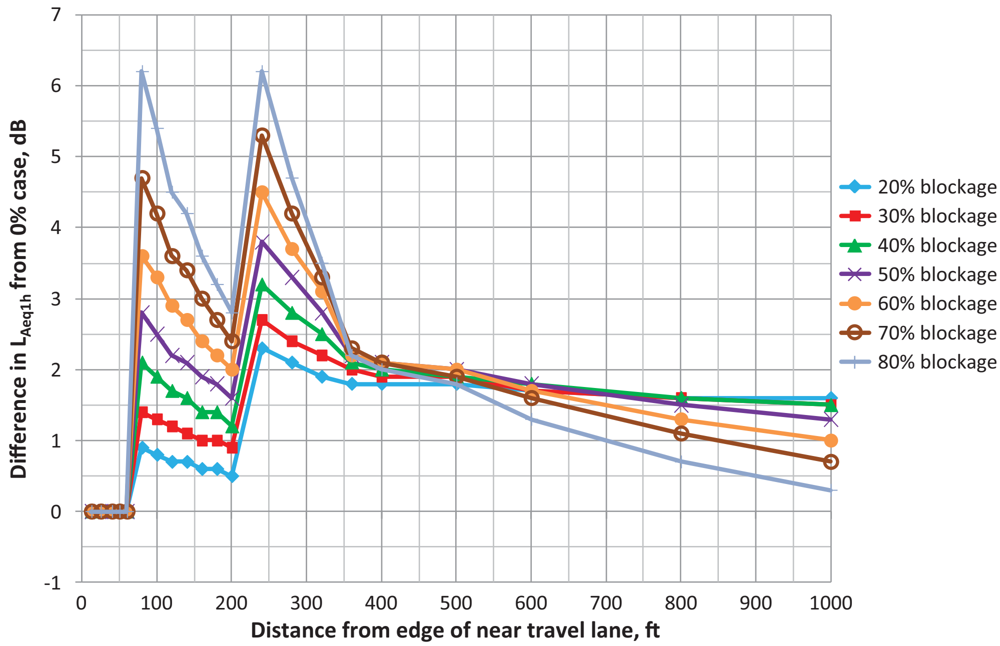

Figure 37. Noise reduction as a function of building percentage for two 20-ft-high building rows near a single 12-ft-wide roadway.

For two building rows, the noise reductions are sensitive to building row height as the distance back from the second row increases. Close in behind the second row, the differences in noise reduction are generally small for the different heights except for the high building percentages.

Of interest is the amount of the increase in the noise reduction when going behind the second row—nearly 3.5 dB for the 80% blockage case. The FHWA FAQ states that when two rows are present, the program computes the attenuation for each building row on a ⅓-octave band basis, chooses the more effective one, and then adds simply 1.5 dB to the A-weighted level for the less effective one. These results illustrate that when the receiver is moved behind the second row, the program is choosing the second row as more effective than the first row because the receiver is directly behind the second row with an associated very large diffraction angle. The change in level is not as simple as subtracting 1.5 dB from the level computed for the first building row.

Building percentage also affects the amount of noise reduction and the step-up in that noise reduction when going behind the second row. Both values decrease as building percentage decreases. For example, the step-up in noise reduction for the 20% blockage case is only 1.8 dB compared to 3.5 dB for 80% blockage.

Beyond 400 ft, the total noise reduction for the two-row case drops below 2 dB, which is still 1 to 1.5 dB greater than the single row case at these distances.

Figure 38 presents the differences in noise reduction between building percentages that differ by 10% for the two-row case with the 20-ft building row height. A 10% change in the first-row blockage results in a change in the noise reduction from 0.4 dB for the low building percentages to 1.5 dB for the highest building percentages. The changes behind the second row (which is located at 220 ft from the edge of the roadway) range from 0.4 to 0.9 dB right behind the row, but quickly drop to under a 0.5 dB at greater distances back.

Appendix F provides the results for the 25- and 30-ft-high building rows. For these greater heights, the decay in the noise reduction is not as rapid as for the 20-ft height, both in front of and behind the second row.

7.2.3.3 Three Building Rows

Modeling a third building row will have important effects in reducing the predicted sound level at a receiver compared to modeling only a single row or two rows and should be done if a third row is present in the study area. Care should be used in approximating the height and building percentage of each row because FHWA TNM will determine the most effective row and use it as the primary basis for its noise reduction calculations. That choice can vary by receiver-roadway pair.

For the tests for the three-row case, the third building row was located at a distance of 150 ft back from the second row in the previous tests, or 370 ft from the edge of the travel lane.

Figure 39 shows the predicted noise reductions (differences from the 0% blockage case) for the three-row scenario. This figure is for 20-ft building row heights for building percentages varying from 20 to 80%. The pattern described for

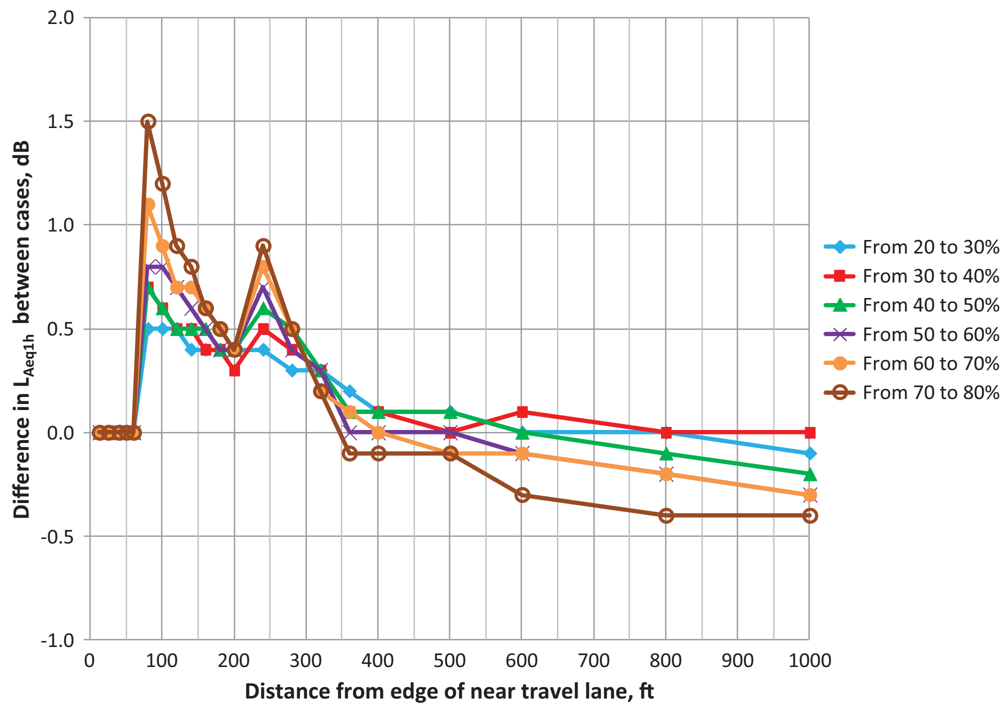

Figure 38. Differences in noise reduction for 10% incremental increases of building percentage for two 20-ft-high building rows near a single 12-ft-wide roadway.

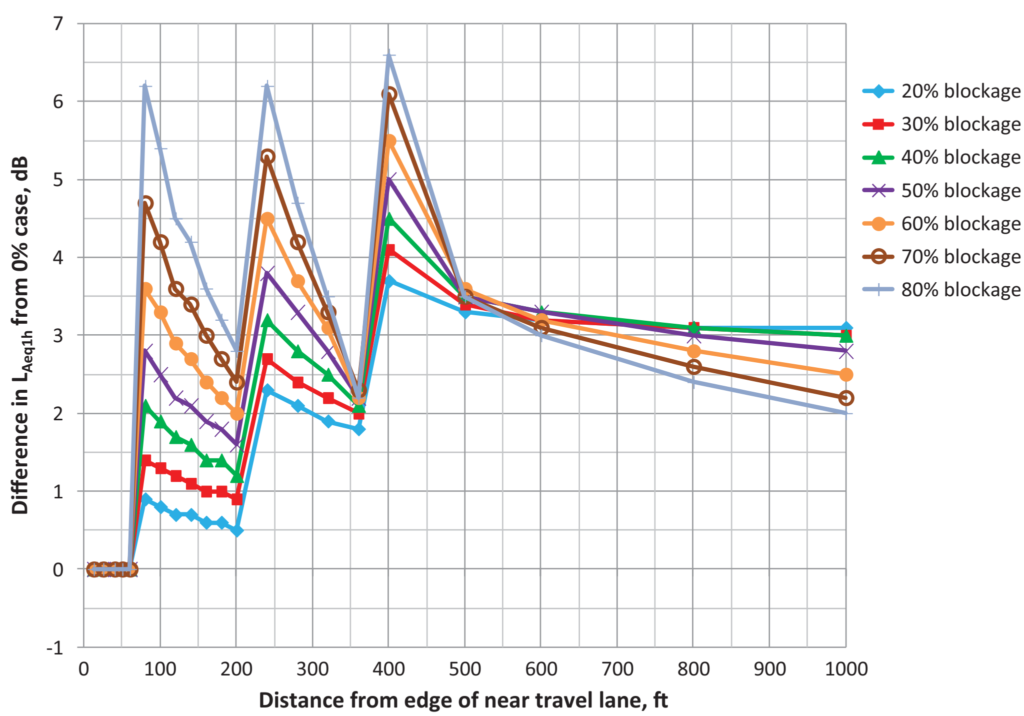

Figure 39. Noise reduction as a function of building percentage for three 20-ft-high building rows near a single 12-ft-wide roadway.

the two-row case is present: the noise reduction decreasing with increasing distance from the first building row. The noise reduction then steps back up for receivers behind the second row, and then decays again with increasing distance from the second row until it steps back up again for receivers behind the third row.

As with the two-row case, there is a large increase in the noise reduction when going behind the second row—nearly 3.5 dB for the 80% blockage case. There is also a 4 dB increase when going behind the third row. As the building percentage decreases, the noise reduction decreases, and the stepping up when going behind the second and third rows decreases as well.

Beyond 500 ft, the total noise reduction for the three-row case varies between 2 and 3.5 dB across all of the building percentages.

Appendix F includes the results for the 25- and 30-ft-high building rows. For the greater heights, the decay in the noise reduction is not as rapid as it is for the 20-ft height, both in front of and behind the second row.

7.2.4 Building Row Effect on Noise Barrier Noise Reduction

The predicted sound level behind a noise barrier decreases in the presence of an intervening building row, in addition to the "no-barrier" level decreasing. The noise reduction provided by that barrier may increase or decrease slightly over the case without a building row, depending on the barrier height and the building row parameters. A 1.5-dB difference was modeled in the noise reduction for a 20-ft-high noise barrier between the 30% and 70% blockage cases for a 30-ft-high building row.

The change in the barrier noise reduction could change the barrier acoustical design and decisions on barrier feasibility and reasonableness depending on whether or not receptors behind the building row(s) were impacted and/or benefited in accordance with the criteria in a state highway agency's traffic noise policy.

The eight-lane road scenario was modified to include a noise barrier just off the shoulder. Barrier heights of 12 to 28 ft were tested in addition to a "no-barrier" case. A single building row was located 70 ft from the edge of the near travel lane. For these tests, building row heights of 20 and 30 ft and building percentages of 30, 50 and 70% were used.

Figure 40 shows the predicted sound levels for one of the cases: the 20-ft-high noise barrier and the 30-ft-high building row. Note that both the no-barrier and with-barrier levels decrease as the building percentage increases. In the no-barrier cases, the with-building-row levels are roughly 4 to 5 dB lower than the no-building-row case. In the with-barrier cases, the with-building-row levels are 2 to 3 dB lower than the no-building-row levels.

Figure 41 is the companion graph of the differences in the no-barrier and with-barrier levels—the noise reduction provided by the 20-ft barrier. The no-building-row noise reductions are very similar to the 50% blockage case for this particular example.

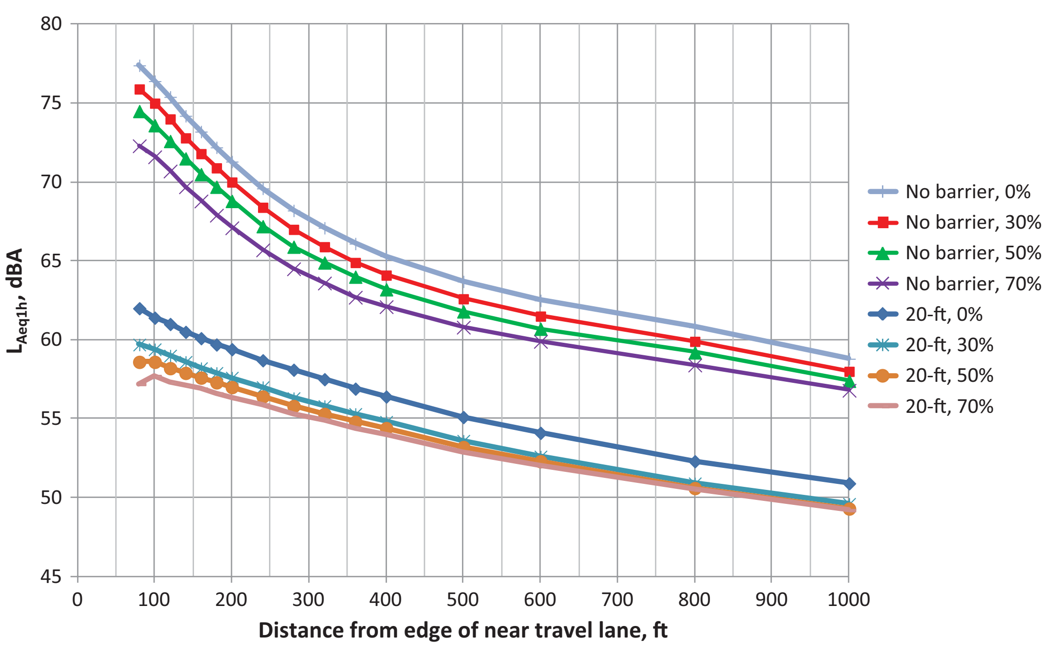

Figure 40. Sound level with and without a 20-ft-high noise barrier along the edge of the shoulder of an eight-lane roadway with a 30-ft-high building row located 70 ft from the edge of the near travel lane, for various building percentages.

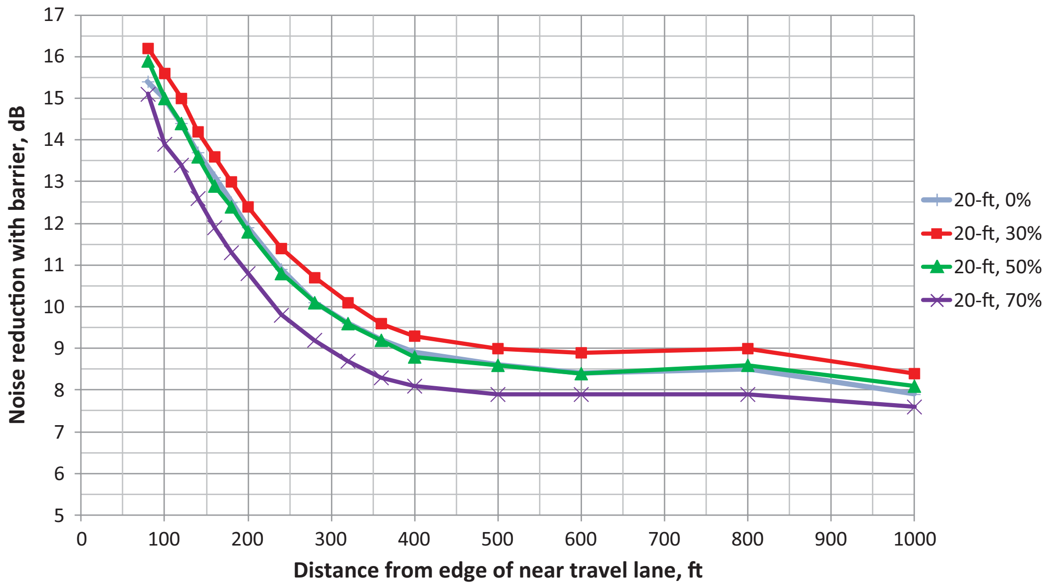

Figure 41. Noise reduction for a 20-ft-high noise barrier along the edge of the shoulder of an eight-lane roadway with a 30-ft-high building row located 70 ft from the edge of the near travel lane, for various building percentages.

The other cases are in Appendix F and show similar effects on both the with-barrier and no-barrier levels and the resultant overall noise reductions.

7.2.5 Building Rows Perpendicular to the Roadway

Rows of houses can also be perpendicular to the highway—along streets that end at the highway right-of-way, in a cul-de-sac, or intersecting with a collector road that is parallel and adjacent to the highway.

The noise reductions for perpendicular building rows are not as large as reductions for building rows parallel to the highway. Exposure to noise coming from beyond the ends of the rows and coming through the gaps for local streets or adjoining back yards appears to dominate the modeled levels.

Another option to modeling the scenario where rows of houses are perpendicular to the road is to model FHWA TNM building rows parallel to the highway, cutting across the local streets and front and back yards instead of running along them. The building percentage for such building rows parallel to the highway would most likely be substantially lower than for the perpendicular rows in order to accommodate the depth of yards reaching from the local streets to the rear property lines.

Figure 42 shows a case in a TNM plan view of four building rows representing rows of houses on both sides of two perpendicular streets. In this scenario, the building rows are modeled 150 ft apart on either side of the streets, and the distance across the backyards between the two "interior" rows is 200 ft. Front yard receivers are located 30 ft in front of the building row, and backyard receivers are located 50 ft behind the building row. The modeling of both front yard and backyard receivers for the same houses would not typically be done, but was used in this analysis to test the differences. The receivers are spaced assuming lot widths of 100 ft. Thus, a building percentage of 50% would mean a 50-ft-wide house with 25 ft of yard on either side. Building percentages of 30, 50, and 70% were tested for building row heights of 20 ft and 30 ft.

For the outermost backyard receivers exposed to upstream or downstream noise the greatest noise reduction was only 1.3 dB for 20-ft-high building rows and 1.7 dB for 30-ft-high building rows, both for 70% blockage. For the two sets of internal front yard receivers, the greatest noise reduction was 2.2 dB for the 20-ft-high building rows and 3.3 dB for the 30-ft-high building rows, both for 70% blockage.

7.2.6 Modeling as Individual Building Barriers Instead of as Building Rows

Some noise analysts prefer to model each house as an individual noise barrier rather than using the FHWA TNM building row object. As a standard procedure, the Maryland State Highway Administration models rows of houses as individual noise barriers, which it calls "building-barriers." Figure 43 shows a portion of a noise study area for one Maryland State Highway Administration project.[32] Figure 44

[32] Rummel, Klepper & Kahl, LLP, and Maryland State Highway Administration Noise Abatement Design & Analysis Team, "HO317A21 US 29 Widening, Type I, Technical Noise Analysis Report," 2010.

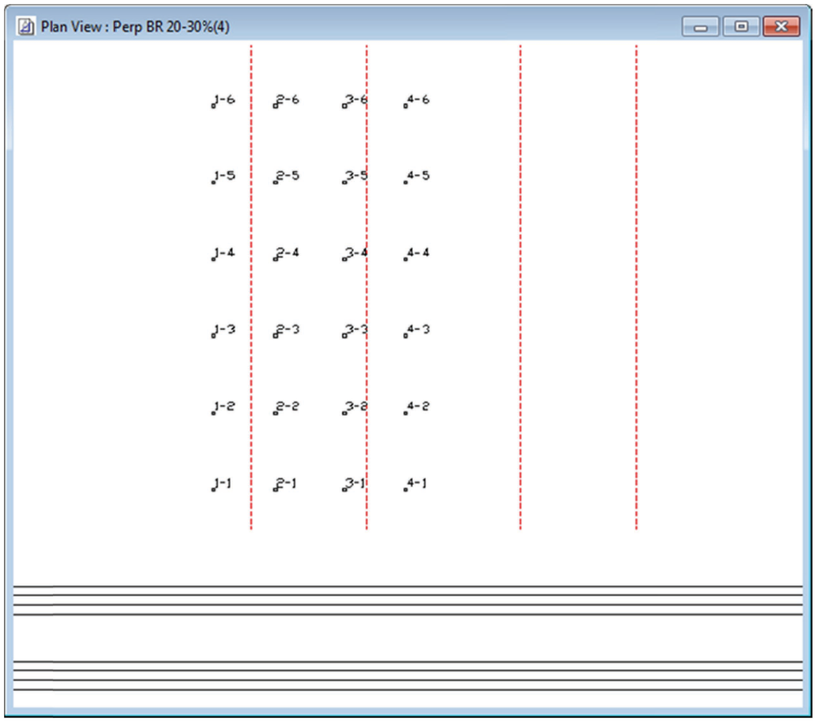

Figure 42. FHWA TNM plan view of four perpendicular building rows adjacent to an eight-lane highway.

Figure 43. Portion of Noise Study Area G for US 29 study.[33]

[33] Schematic in Figure 43 is from Rummel, Klepper & Kahl, LLP, and Maryland State Highway Administration Noise Abatement Design & Analysis Team, "HO317A21 US 29 Widening, Type I, Technical Noise Analysis Report," 2010.

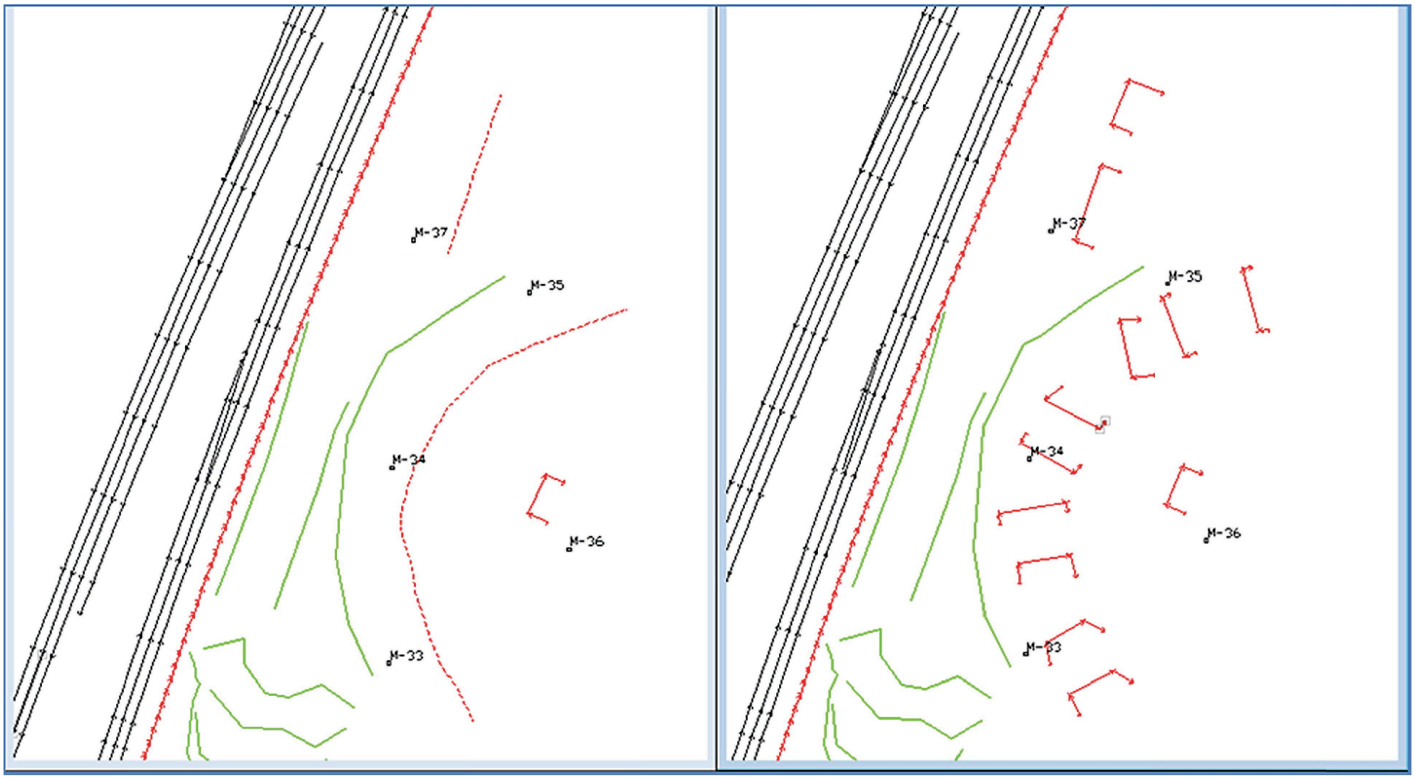

Figure 44. TNM plan view with building rows (left) ***and building barriers*** (right)***, Noise Study Area G of US 29 widening.***

shows the corresponding Maryland State Highway Administration modeling of the houses as building barriers on the right and the comparative modeling of the houses as FHWA TNM building rows on the left.

In the case shown in Figure 44, the analyst chose to model three sides of each house as barrier segments. Choice of sides is usually dictated by which sides appear to offer the most noise reduction to receivers behind them. For a receiver close to the "rear" side, that side may be most effective. For a building close to the roadway, the side facing the roadway may be the most effective.

One option is to model all four sides and let FHWA TNM compute the combined effect using its double diffraction algorithms. However, if more than two "highest path points" are detected by FHWA TNM for any given receiver-to-roadway path (including noise abatement barriers and terrain), only the two most effective points will be considered for that path. In addition, since FHWA TNM does not compute the effects of sound reflections off the sides of the buildings, detailed modeling of all four sides of a row of buildings will not necessarily mean a more accurate sound-level prediction behind the modeled buildings. Further, the accuracy of the modeling is not improved by modeling every small turn in the façade of a building; straight line segments for each façade are sufficient.

Modeling as barriers does take more time than modeling as building rows. Useful guidance on how to model houses as building barriers, working in Bentley's InRoads© roadway design computer-aided design (CAD) program, was provided by an in-house Maryland State Highway Administration consultant,[34] summarized as follows:

> Houses are represented by either three-sided barriers or two-sided barriers, considering which orientation would likely provide the best shielding. The house shape is outlined and then "lifted" above the ground elevations on the surface. Sometimes, roof elevations (if available) are used to help define the height. Other times, an estimated height is used to create either an irregular top or a level one. The primary interest is in modeling the most massive part of the structure (below the roof line) to be conservative, as opposed to modeling a sloped roof. Finally, the preference is to place receptors in the gap spaces between the houses for greatest exposure to the modeled traffic noise.

If modeling only two sides of a building, the modeler needs to choose the two sides carefully so as not to expose the receiver to a greater view of the roadway (and thus, more noise) than would occur in the real world.

[34] Based on email from Matthew G. Mann, Sr., P.E., in-house consultant from The Wilson T. Ballard Company on the Maryland State Highway Administration Noise Abatement Design & Analysis Team.

7.2.6.1 Case Study Comparisons of Measured and Modeled Data

For this analysis, five different projects with a total of eight noise study areas were examined for a comparison between modeling detached houses using building rows and modeling using building barriers. Sound-level measurement results with concurrent traffic counts were available. The counts were used in modeling the sites to allow comparison to the measured levels. Building height and percentage of blockage were site specific. There were a total of 34 receivers in the models that were at least partially shielded from roadway noise by intervening houses. For one project, three repetitions of the measurements were made. Each receiver had predictions run with the "Average" pavement type in FHWA TNM. For two of the projects with portland cement concrete (PCC) pavement, predictions were also run with PCC pavement and normalized to a reference microphone's measured levels.

From the five cases, 138 discrete comparisons were made between measured levels and (1) levels from a model using building rows and (2) levels from a model using building barriers. A detailed presentation on the projects and the measurement and modeling results is provided in Appendix F. In general, the overall results and comparisons seemed reasonable for three of the projects. However, for two of the projects, generally poor agreement was found between the measured levels and levels predicted by both modeling methods.

With the broad range of site conditions and results, it is difficult to generalize. However the following observations are made:

- Modeling each house as a barrier generally gave lower predicted sound levels than modeling a building row, ranging from an increase of less than 1 dB to a 5 dB decrease. The average reduction in sound level across all cases was 1.5 dB.
- In over 80% of the 138 comparisons of measured and modeled levels using the building barrier approach, the modeled level was within 3 dB of the measured level. In contrast, roughly 67% of the modeled building row comparisons were within 3 dB of the measured levels.
- For the non-normalized results, neither of the two modeling methods was substantially better than the other in terms of producing FHWA TNM results that were closer to the measured sound levels.
- In the cases where normalizing to a reference microphone was done, the building barrier approach provided better agreement with the measurements than the building row approach.

This last finding supports the idea of modeling rows of houses as building barriers, but not to the point of being recommended instead of using building rows. Modeling using barriers should be considered if the modeler is attempting to validate an FHWA TNM to measured levels. However, the need for validation can be questioned for receivers that have one or more rows of houses between them and the road. One instance in which such validation might be more important would be where a state highway administration's traffic noise policy includes criteria for determining the feasibility and reasonableness of a noise barrier that are based on a percentage of all of a study area's impacted receptors and benefited receptors, as compared to only the *first-row* receptors. Even then, the reliability of that validation can be questioned, given the greater distance from the road for such receivers and the effects of meteorological conditions and other sources of noise on the measured levels.

What is apparent from the results is that if a state highway administration decides to model shielding by rows of houses with building barriers instead of building rows, it should do so consistently on all projects and should have carefully defined procedures for the modeling in terms of the individual barriers, placement of the receiver points, and possibly the terrain elevation between the barriers. The latter two factors are described in the following sections.

7.2.6.2 Effect of Receiver Location Behind Building Barriers

Receiver placement can be an important factor for the predicted sound level when using building barriers, but it also may not be critical, depending in part on how close the receivers are placed to the houses, the size of the houses, and the amount of blockage provided by the houses. Differences as small as 0.3 dB and as large as 4 dB were seen in shifting the receiver location laterally in the tested cases.

One concern is that the predicted sound level can be sensitive to a receiver location near the gap between two building barriers or directly behind one of the barriers. In particular, variations in the modeling technique—building rows versus building barriers, distance back from the houses, height of the houses, and receiver location relative to the gaps between the houses—can change findings in an analysis. A typical state highway administration policy value for defining noise impact for a proposed project is 66 dBA. The levels in the tests fell on either side of that criterion, meaning that the receptors represented by these FHWA TNM receivers would be found as impacted in one analysis and not impacted in another.

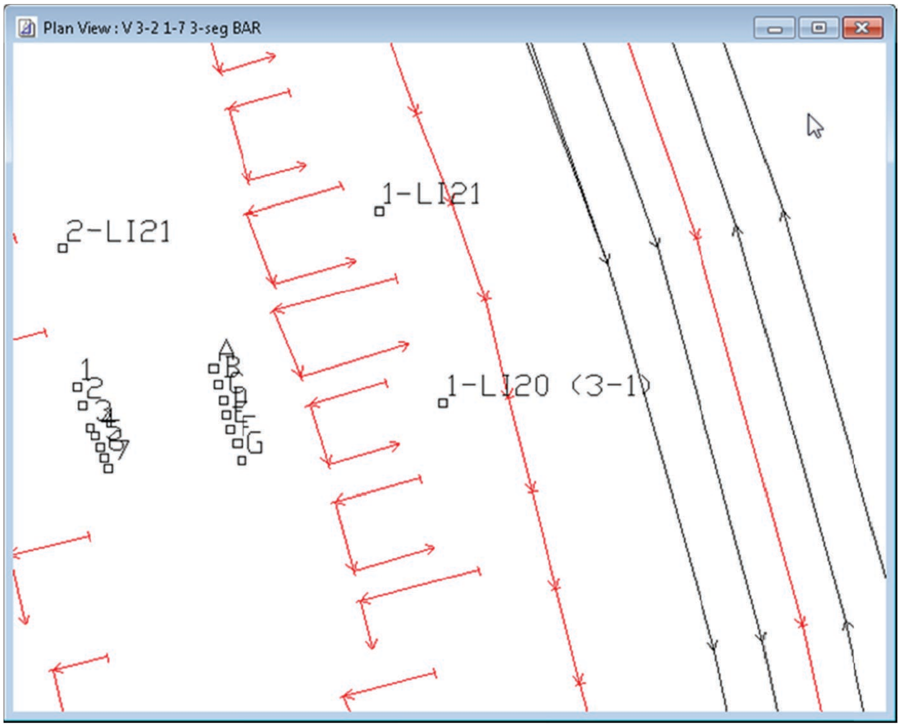

Figure 45. I-65 south with two sets of receivers at different distances behind the row of buildings.

This effect was tested using four FHWA TNM runs based on three of the modeled sites from the analysis of modeling houses as building rows versus modeling them as building barriers. Figure 45 shows two of the tested cases, with one set of receivers (labeled 1 through 7) farther from the intervening row of houses and the second (labeled A through G) closer to the row. In this case, the analyst chose to model the walls of the houses facing away from the road (to the left in the figure) as the more effective facades because the houses were closer to the receivers than to the roadway.

The results varied. For the two cases shown in Figure 45, there is only a 0.3 dB variation in levels for the more distant receivers, but a 4 dB range for the closer receivers. The highest sound level is in front of the gap between the houses and the lowest sound level directly in front of one of the houses. For the other two tested cases, the levels varied by only 0.4 dB in one case and 1.1 dB in the other.

For the cases shown in Figure 45, the building percentage was 70% and the houses were relatively long (deep into the lot) relative to their width. Farther back, it was much less likely that a receiver would be placed where there was not blockage of the line of sight through the gaps. Closer in, it was more likely that there would be a direct line of sight of the roadway through a gap, causing a larger variation in the predicted levels than farther back.

7.2.6.3 Effect of Terrain Elevation in the Gaps between Building Barriers

As a final note, in certain situations care needs to be taken to properly model the ground elevation in between the individual building barriers. With a building row, the ground elevation is defined along the entire row based on the user-input elevations of the segment points for the building row. However, in defining individual barriers, FHWA TNM is only provided with the ground elevations of the barrier segment points, not the ground elevation in the gaps between the individual barriers.

Figure 46 shows two “skew section” views of paths from a receiver to the highway, one that passes through the building and captures the elevation of the base of the building and one that passes through the gap and misses that ground elevation information. The result could be incorrect calculations of the amount of terrain shielding or excess ground attenuation for sound paths in the gaps and, thus, an incorrect total predicted sound level at a receiver behind the buildings.

In those cases where the terrain does vary, it might be necessary to model short FHWA TNM terrain line objects connecting between each building barrier. Alternatively, a separate terrain line could be defined slightly in front of or behind the building barriers that properly models the ground elevation of the adjacent building barriers’ ground points.

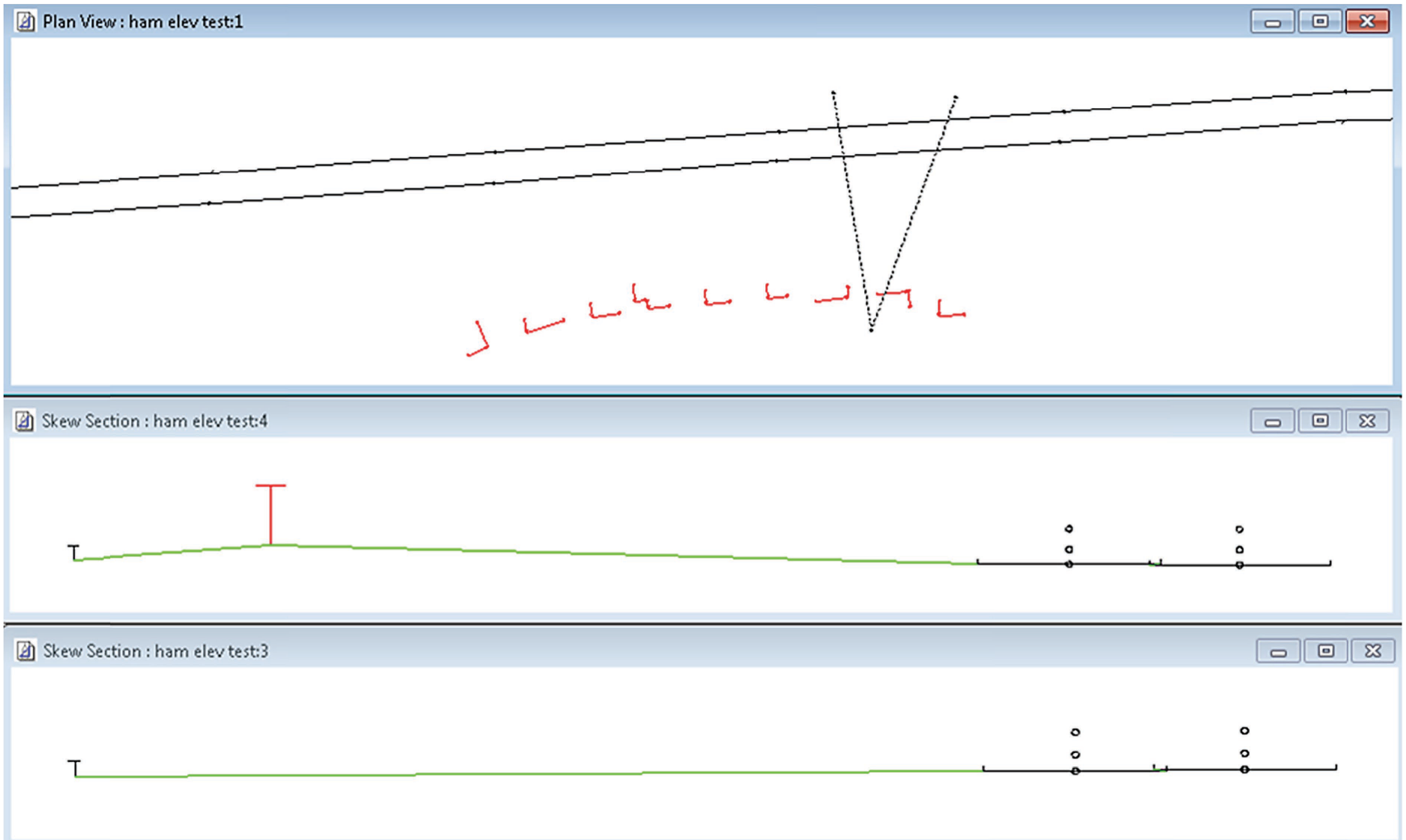

Figure 46. FHWA TNM plan view (top) *and skew section views through a building barrier* (middle) *and through a gap* (bottom) *where the ground elevation has not been defined.*

CHAPTER 8

Topography

This chapter focuses on guidance on the use of topographic features within FHWA TNM. Appendix G (available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986) provides substantial detail on the methods and test cases that were used to develop the guidance.

8.1 Outside Edge of Pavement: Horizontal Precision

8.1.1 Guidance for TNM Input

The research team suggests the following best practices for entering the near edge of pavement (or "equivalent" terrain line) into TNM:

- First, analysts should be on the lookout for intervening ground that is flat and level (no intervening hills or ridges) out to the nearest receivers (or "equivalent" barrier) or that slopes gently up or down (±1 to 2 degrees or so) toward them.
- Where such situations exist, analysts should determine the vertical angle in degrees, at the near edge of roadway (or "equivalent" terrain line), subtended by the receiver (or "equivalent" barrier) height.
- The reciprocal of that angle is an upper bound on the change in L_{eq} produced by a 4-ft horizontal shift in the position of the edge of pavement (or "equivalent" terrain line).
- If that sound-level uncertainty is too large for modeling purposes, then extra input effort should be spent to model that edge with more horizontal precision:
  - For edge of pavement—a "shoulder" roadway is suggested, with width that overlaps the nearest travel lane and weaves left and right to precisely position the edge of shoulder.
  - For "equivalent" terrain line—a closer look at roadway plans to more precisely locate the terrain line is suggested.

This guidance applies to (1) traffic of all mixes, (2) roadways of all widths, (3) receiver distances up to 1,000 ft, (3) receivers or "equivalent" barriers up to 15 ft above the terrain.

The research team suggests that analysts not model the near edge of pavement with a pavement ground zone. Instead, it should be modeled with a "shoulder" roadway—that is, a roadway without traffic that weaves right/left to best match the near edge of pavement.

8.1.2 Further Explanation

To develop the guidance above, the actual analysis was augmented with other "equivalent" situations (based upon an understanding of roadway noise acoustics) beyond the exact cases computed. In particular, the augmentation takes the following into account:

- The likelihood that an "equivalent" terrain line—that is, one located somewhat outside the roadway pavement and at pavement height—would experience the same location sensitivity as the near edge of pavement actually computed. This equivalence is based upon the belief that the sensitive TNM behavior discussed above is due to very small grazing angles when sound diffracts from the near edge of pavement toward the receiver.
- The belief that this same sensitivity would accrue when an "equivalent" barrier substitutes for the computed receivers. In this situation, the sensitivity "trigger" is the barrier top. The resulting sensitivity would likely accrue to most receivers in the barrier's shadow zone.

8.2 Required Terrain Lines along Elevated Roadways

8.2.1 Background

When roadways are elevated, getting the most accurate sound-level predictions requires a terrain line along the

Table 11. Approximate under-predictions with omitted terrain line.

Under-Prediction	Conditions			
	Receiver Height	Receiver Distance	Predominant Vehicle(s)	Height of Roadway-Edge Barrier
2 to 3 dB	5 and 15 ft	100 ft and greater	Automobiles and medium trucks	7 ft or less, or no barrier
3 to 4 dB	5 and 15 ft	200 ft and greater	Automobiles and medium trucks	3 ft or less
4 to 5 dB	5 ft	300 ft and greater	Automobiles	3 ft or less

roadway—either (1) along the toe of slope for roadways on fill or (2) at ground level just off the edge of structure, for roadways on structure. That terrain line serves to pull the ground downward to its proper elevation, thereby properly modeling the height of lines of sight above the ground.

For example, with a roadway on 20-ft fill or on 20-ft structure, omission of such a terrain line can result in under-prediction of sound levels by the amounts shown in Table 11.

8.2.2 Resulting Guidance for TNM Input

When modeling roadways on fill, analysts should always include a terrain line along the toe of slope of the roadway fill. Similarly, when modeling roadways on structure, a terrain line should always be included at ground level just off the edge of the structure.

8.3 Minimum Terrain Line Spacing

8.3.1 Background

The diffraction mathematics within TNM assumes that sound waves are spherically shaped when approaching a diffraction edge. This is normally true; however, when two diffracting edges are spaced very closely together, the first of these edges distorts the wave shape so that it is no longer spherical when it approaches the second edge. As a result, terrain line spacing of less than 4 ft produces an abrupt, anomalous increase in sound level of

- Approximately 6 dB when the terrain lines are near the top of an intervening hill or berm.
- As large as 6 dB when the terrain lines are on intervening flat ground.
- Between 0 dB and 6 dB when the terrain lines lie in an intervening gully.

When digital terrain models approximate undulating terrain, they often divide that terrain into a large collection of triangles. If the edges of those triangles are used as terrain lines within TNM, then the terrain line spacing reduces to 0 ft near the vertex of all those triangles. Although not tested in this research, such a set of terrain lines could produce these 6-dB anomalies throughout.

8.3.2 Resulting Guidance for TNM Input

Analysts should never input terrain lines less than 4 ft apart, especially on an intervening hill or intervening flat ground. In addition, terrain lines should not be input to duplicate the triangular topography regions that are produced by digital terrain models.

8.4 Terrain Lines: Vertical Precision

8.4.1 Background

As part of NCHRP Project 25-34, the research team solicited and received a number of noise studies and/or TNM runs for actual highway projects around the United States. Input for two of these included an interesting assortment of terrain lines. Of concern to this research project is TNM's sensitivity to the input Z coordinates of these modeled terrain lines. To that end, these two TNM cases were re-run with all the terrain lines moved upwards by 2 ft.

In addition, a sensitivity analysis was performed with offset terrain line elevations under three geometries: (1) intervening flat ground, (2) intervening 40-ft hill, and (3) intervening 20-ft gully.

8.4.2 Resulting Guidance for TNM Input

Resulting guidance for TNM input is the following:

- **Guidance from the Highway Projects.** Analysts should attempt to keep the vertical precision of all terrain lines to ±1 ft—especially for barrier design projects, for which accuracy of ±1 to 2 dB is generally the goal.
- **Guidance from the Sensitivity Analysis.** Table 12 provides the appropriate guidance. No additional guidance is needed for situations not shown in Table 12. In particular, no guidance is needed when the terrain lines are in intervening gullies of significant depth.

8.5 Barrier Tops: Vertical Precision

8.5.1 Background

When a barrier just grazes the source-receiver line of sight, the resulting path length difference for the barrier is nearly

Table 12. Guidance for elevation of intervening terrain lines.

Intervening Terrain	Dominant Vehicle Type	Receiver Heights	Receiver Distances	Roadway Width	Guidance: Match Actual Terrain Elevation within This Amount
Flat within ± 10 ft Gullies less than 10 ft deep	Heavy trucks	5 ft	All	All	± 2 ft
	Medium trucks Automobiles	5 ft	Less than 450 ft	All	± 2 ft
			450 to 750 ft	More than 50 ft	± 0.5 ft
				30 to 50 ft	± 1 ft
				Less than 30 ft	± 2 ft
			750 to 1000 ft	More than 50 ft	± 1 ft
				Less than 50 ft	± 2 ft
			More than 1000 ft	All	± 2 ft
Hills more than 10 ft high	All	All	Actually on the hill	All	± 2 ft
			Within 100 ft behind the hill	All	± 1.5 ft
			Farther than 100 ft behind the hill	All	± 1 ft

zero. For this condition, the barrier attenuation can be highly sensitive to barrier height.

More specifically, when the path length difference (from the upper subsource height) is less than 0.04 ft:

- A 2-ft shift in barrier height can result in 2-to-8 dB shifts in barrier attenuation and therefore in receiver L_{eq}.
- Within this range, the shift is worse for small source-receiver distances:
  - 4-to-6 dB shifts are possible for source-receiver distances less than 300 ft.
  - 6-to-8 dB shifts are possible for source-receiver distances less than 100 ft.
- This L_{eq} sensitivity occurs for all vehicle types.
- Over flat ground, such small path length differences occur only for low barrier heights (generally 8 to 10 ft). However, rolling terrain might lower barrier tops of tall barriers relative to source and receiver elevations, thereby producing this high sensitivity even for taller barriers.

8.5.2 Resulting Guidance for TNM Input

When any lines of sight from upper vehicle subsources to receivers closely graze a barrier top or berm top, the research team suggests taking extra care with TNM barrier input so as to precisely match (within 1 ft) barrier heights with physical reality (for existing barriers) and with intended construction heights (for future barriers).

In addition, where uniform-height barriers are planned on undulating terrain, the same input care is suggested for the terrain just under the barrier, that is, for the Z coordinates of the barrier's baseline input points. When providing guidance on barriers to roadway designers, it is better to recommend specific "barrier-top elevations" than to recommend "barrier heights above the ground."

Also, the thousands of test case comparisons conducted with TNM in this research have shown very large L_{eq} sensitivity to the exact location of diffracting edges, whenever sound paths just graze across those edges. For those grazing situations, L_{eq} is also very sensitive to the slightest wind in the direction of propagation, which TNM does not account for. Chapter 11 provides information on the effects of wind on sound levels behind barriers.

8.6 Flat-Top Berms

8.6.1 Background

During TNM validation studies, the U.S. DOT Volpe National Transportation Systems Center acoustics group determined that TNM sometimes miscomputes sound levels behind flat-top berms by 5 dB or more. To avoid this miscomputation, TNM 2.5 currently prevents entry of a berm object's top width—thereby restricting berm objects to "wedges," without flat tops. Nonetheless, TNM users can bypass berm objects entirely by using terrain lines to manually input berm shapes, including shapes with flat tops, and, unfortunately, such manually input berms produce the same miscomputations.

8.6.2 Resulting Guidance for Highest Precision (Generally for Project "Design Phase")

Recently the Volpe Center has devised (but not published) the following work around for TNM's flat-top berm problem. To avoid miscomputation, the top edges of flat-top berms should be "rounded-off" (see Figure 47), as follows:

1. The original top-edge terrain line should be moved toward the center of the berm top by 1/10th of the

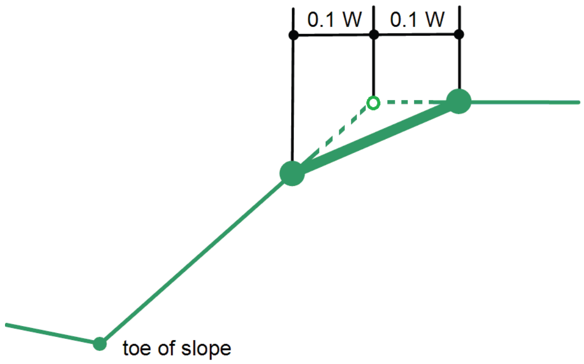

Figure 47. Section view of flat-top berm shape including the suggested "rounding off" of the top edge.

berm-top width (W), keeping its original elevations from point to point.

2. A second terrain line should be added down the berm slope, positioned outward by 1/10th the berm-top width and downward by the amount needed to keep it approximately on the original berm slope.
3. As the toe-of-slope terrain line moves in/out and up/down along the length of the berm, that might change the slope along the berm. For such situations, the new terrain line can be positioned vertically so the new piece's slope (the thick line in Figure 47) is approximately one-half the original berm slope.
4. This process should be repeated for the other top edge of the berm as well.

8.6.3 Resulting Guidance for Moderate Precision (Generally for Project "Location Phase")[35]

For a flat-top berm, a wedge-shaped berm of the same height can be used as a substitute. Such substitution might be slightly conservative, that is, it might compute slightly lower noise reduction than actually achieved by the flat-top berm.

[35] This recommendation is a paraphrased condensation of the TNM FAQ on the web at www.fhwa.dot.gov/environment/noise/traffic_noise_model/tnm_faqs/faq07.cfm.

CHAPTER 9

Ground Zones

This chapter focuses on guidance on the use of ground zones within FHWA TNM. Appendix H (available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986) provides substantial detail on the methods and test cases that were used to develop the guidance.

9.1 Size and Location of Ground Zones

9.1.1 Background

When ground surfaces other than the default ground intervene between roadway and receivers, ground zones are used to model those other ground surfaces. Several questions arise concerning the location and size of these ground zones:

- **General size.** Are ground zones needed for very small patches of non-default ground—patches such as suburban sidewalks and driveways?
- **Precise coordinates.** How precisely must ground zone coordinates be input to achieve reasonably precise sound levels?
- **Location.** Are ground zones needed more (1) toward the middle of the propagation path or (2) toward the ends near the roadway and receivers?

The following section answers these questions with resulting guidance for TNM input.

9.1.2 Resulting Guidance for TNM Input

9.1.2.1 General Size

Ground zones are not needed for small patches of non-default ground such as suburban sidewalks and driveways. In general, a ground zone must cover about 20% of the source-receiver distance to have more than a 1-dB effect.

9.1.2.2 Coordinate Precision

It is not necessary to be precise when entering X and Y coordinates for ground zones. Ground zone effects are very *insensitive* to the precise size and location of the zone. For example, it might take a change in width of 30 ft to cause a 1-dB change in the ground zone's effect, and even then the change might only occur under the most critical input geometry.

9.1.2.3 Location

Ground zones are needed more toward the middle of the propagation path, generally in the area where the sound ray bounces off the ground toward the receivers. In general, ground zones are needed in this central area as long as they cover more than 10 to 20% of the source-receiver distance. If in doubt, it is best to include them to determine their effect.

A sense of the effects of ground zones can be gained by examining the figures and graphs included in Appendix H.

9.2 Expanded List of Ground Types

9.2.1 Background

During validation measurements for TNM 2.5, the U.S. DOT Volpe National Transportation Systems Center investigated modifications to current TNM practice concerning ground types—for both ground zones and default ground—with the aim of improving the match between computed and measured sound levels.[36]

The Volpe Center found the best match between computed and measured sound levels when an expanded set of effective flow resistivity (EFR) values was used in place of TNM's standard ground types (see next section).

[36] Hastings, A. L. and J. L. Rochat, *Ground and Pavement Effects Using FHWA's Traffic Noise Model 2.5*, DOT-VNTSC-FHWA-10-01 and FHWA-HEP-10-021, John A. Volpe National Transportation Systems Center, Environmental Measurement and Modeling Division, Acoustic Facility, Cambridge MA, April 2010.

9.2.2 Resulting Guidance for TNM Input

9.2.2.1 Expanded Set of EFR Values

The Volpe Center's expanded set of EFR values for various ground types is collected mostly from the acoustics literature (see Table 13). Note that Volpe actually measured the 5,800 EFR for hard-packed dirt. Also note that TNM's built-in ground zone types are also included in Table 13.

For best computation (especially for barrier design projects), the use of EFR values from this table is suggested:

- **Ground zones.** Ground zones should be designated as "Custom" with the appropriate EFR value from the table entered.
- **Default ground.** A built-in ground type can be selected from TNM's pull-down list. Otherwise, the full default ground area can be overlaid with one or more new ground zones and with custom EFRs from Table 13. TNM does allow a ground zone to completely enclose another as long as their boundaries do not touch.

9.2.2.2 Distances beyond 500 ft

In addition, Volpe validation showed that TNM's built-in ground effects were too extreme for receiver distances beyond 500 ft or so. In particular

- Acoustically soft TNM ground types provide too much absorption, thereby under-predicting sound levels at large distances.
- Acoustically hard TNM ground types provide too much reflection, thereby over-predicting sound levels at large distances.

Table 13. Expanded set of EFR values.

Ground Type Description	Additional Detail	Average EFR
Powder snow (built into TNM)	-----[a]	10
Dry snow	4 in of newly fallen snow, on top of 16 in of older snow	20
Sugar snow	-----	38
Granular snow (built into TNM)	-----	40
Forest floor	Pine or hemlock	50
Lawn	With 11.9% to 16.5% moisture content	58
Field (meadow) grass (built into TNM)	-----	150
Lawn root layer in loamy sand	Volume porosity between 43.5% and 59.8%	188
Lawn	Rough pasture, around public buildings	212
Lawn (built into TNM)	-----	300
Lawn	Various ratios of dirt and vegetation	375
Soil	Various types	278
Sand	Various types	473
Loose soil (built into TNM)	-----	500
Roadside dirt	Various small rocks up to 4-in mesh	550
Dirt	Roadside with rocks smaller than 4-in diameter	550
Sandy silt	Hard packed by vehicles	1650
Limestone chips	0.5-in to 1-in mesh	2750
Old dirt road	Filled mesh	3000
Hard soil (built into TNM)	------	5000
Hard-packed dirt	Including some gravel—EFR measured by Volpe	5800
Exposed dirt	Rain packed	6000
Asphalt	New, various particle size	10,000
Water[b]	Especially with wave roughness	10,000
Quarry dust	Hard packed	12,500
Pavement and water (built into TNM)	------	20,000
Asphalt	Old, sealed with dust	27,500
Concrete	Depends on finish	65,000
Concrete	Painted	200,000

[a]----- = no additional detail.
[b] This water entry derives from text in the Volpe report, rather from the actual Volpe table.

TNM users will want to be aware of this tendency when computing sound levels at distances beyond 500 ft.

9.3 Bodies of Water

9.3.1 Background

Large bodies of water often require a TNM ground zone as input. This is especially important when (1) the body of water is toward the middle of the propagation path and (2) when it covers more than 10 to 20% of the source-receiver distance (both input criteria per Section 9.1.2.3 of this document).

9.3.2 Resulting Guidance for TNM Input

When entering a ground zone for a body of water in TNM, analysts should recall that the ground zone includes no elevation information, so they must enter a terrain line that completely encloses the ground zone to define the water elevation. Because water surfaces are always horizontally flat, all points on that terrain line should have the same Z coordinate, that is, the water's elevation.

Sometimes surrounding land does not slope gradually to the water. Instead, it sometimes drops abruptly down to the water from the water's so-called "bank." Where this is the case, analysts must enter a second terrain line that lies close to the first terrain line.

CHAPTER 10

Tree Zones

This chapter focuses on guidance on the use of tree zones within FHWA TNM. Appendix I (available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986) provides substantial detail on the methods and test cases that were used to develop the guidance.

10.1 Overlaid Loose-Soil Zone Not Needed with Tree Zones

Prior to this current research, it was believed that TNM would incorrectly compute attenuation for tree zones placed on ground types other than loose soil. Were this true, then a loose-soil ground zone would need to be input, overlaid on each tree zone, for TNM to compute correct tree attenuation.

No overlaid ground zone of any type is needed for TNM input to properly compute tree attenuation. However, it is important to use default ground type or a ground zone type for the tree zone that is consistent with the actual ground present under the vegetation.

10.2 Guidance for Narrow Tree Zones

Figure 48 shows a narrow tree belt that intervenes between roadways and a receiver. As the text in Figure 47 indicates, an observer at the receiver position can see some traffic when looking perpendicular to the roadway, toward its closest portions. However, when looking at a significant skew angle, no traffic is generally visible due to the much longer path through the trees.

Computations conducted for such narrow tree belts show that belts of trees up to 25 ft thick (and marginally up to 50 ft thick) provide no attenuation to the nearest portions of a roadway. Therefore, it may seem unnecessary to include narrow tree zones as TNM input. Further, TNM guidance is that vegetation must be "sufficiently dense to completely block the view along the propagation path."

Nevertheless, these computations also show that attenuation down the roadway from the receiver is significant, automatically per TNM, because of the extra depth of trees in those skew directions. Therefore, with narrow vegetation zones, less sound energy will reach receivers from more distant sections of a highway than will if such zones are not included.

As a result, omitting narrow vegetation belts (up to 50 ft in width) as TNM inputs could result in a noise barrier that was longer than necessary, thereby increasing noise barrier costs at each end of the barrier. Appendix I provides some examples from test cases run with TNM.

10.3 Attenuation Dependence on Visibility through Tree Zones

An especially useful article by Fang and Ling examines the dependence of tree/shrub attenuation on degree of visibility through a wide variety of different kinds of vegetation.[37] The measurements conducted and described in the article were compared with TNM's built-in tree attenuation to develop guidance for TNM users who are (1) comparing TNM computations with field measurements at tree/shrub locations along a project roadway or (2) deciding when to include TNM tree zones in TNM computations for a project roadway.

Fang and Ling developed the equation below to summarize their extensive measurements of attenuation through vegetation:

[37] Fang, C.-F., and D.-L. Ling, "Investigation of the Noise Reduction Provided by Tree Belts," *Landscape and Urban Planning*, Vol. 63, pp. 187–195 (2003). Available at http://ir.lib.ncut.edu.tw/bitstream/987654321/2472/1/2003-Investigation+of+the+noise+reduction+provided+by+tree+belts.pdf.

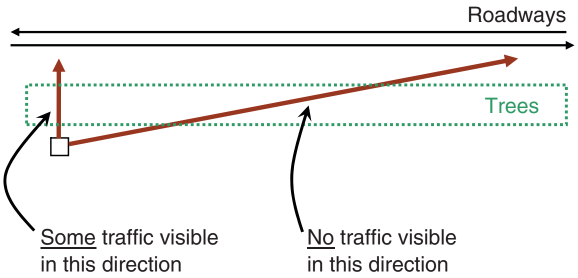

Figure 48. Roadway visibility through a narrow tree belt.

$$\frac{A_{\text{Veg}}}{\text{dBA}/50\text{ ft}} = \left[4.08 - 2.87\log\left(\frac{D_{\text{Vis}}}{1\text{ ft}}\right) + 2.32\log\left(\frac{L_{\text{VegProp}}}{1\text{ ft}}\right)\right]$$

where

A_{Veg} is the vegetation attenuation (in dBA per 50 ft).
D_{Vis} is the visibility distance into the vegetation (in ft), which was measured by walking into the vegetation until no longer visible from the outside and then averaging this visibility distance over three tries at each of two locations.
$L_{VegProp}$ is the vegetation path length (in ft).

Whenever vegetation intervenes at a TNM measurement site, analysts should measure visibility into the vegetation at that site perpendicular to the roadway. This is measured by walking into the vegetation until no longer visible from the outside and then averaging this visibility distance over three tries at each of two locations.

To interpret the measurements, analysts should do the following:

1. Determine TNM's vegetation attenuation by computing TNM with and without an intervening tree zone.
2. Compute a visibility-based attenuation using Fang and Ling's equation (above).
3. Compare the two attenuations:
   – If they are both nearly zero, then a tree zone is not needed.
   – If they are not zero but are nearly the same, then the TNM tree zone is computing well enough.
   – If they are not zero and are not the same, analysts should compare the TNM-computed attenuation and the visibility-based attenuation, and, based on this comparison, an appropriate tree-attenuation value should be chosen. Accurate computation at specific sites may require combined use of TNM tree zones and an additional negative adjustment factor to compensate for TNM's under-prediction of tree attenuation.

CHAPTER 11

Wind and Temperature Gradients

11.1 Introduction

As sound travels from its source, the speed and direction of wind can increase or decrease the amount of sound energy that arrives at the receiver relative to a calm condition. This is primarily due to the refraction of the sound toward the ground in a downwind case or upward in the upwind case, as illustrated in Figure 49. This refraction is caused by a gradient in the wind speed (which affects net sound speed), with lower wind speeds near the ground due to drag and higher air speeds above ground. In downwind propagation, the higher wind speed farther above the ground would cause a higher net sound speed farther above the ground because the speed of sound would add to the wind speed, causing downward refraction. In the upwind direction, the wind is in the opposite direction of the propagation and the wind speed would be subtracted from the speed of sound for the net sound speed. Thus the increase in wind speed with height above the ground would cause a lower net sound speed and upward bending of the sound path.

Like wind gradients, temperature gradients cause sound speed to vary with distance from the ground. This gradient in sound speed causes refraction of the sound, which increases sound levels through the reduction of ground effect or the reduction of barrier attenuation or decreases sound levels by the creation of shadow zones. Negative temperature gradients, where the temperature decreases with height above the ground, are referred to as lapse conditions. Positive temperature gradients, where the temperature increases with height above the ground, are referred to as inversion conditions. Sound propagation paths for the typical daytime lapse condition and a temperature inversion are shown in Figure 50.

TNM does not currently incorporate the effect of wind speed and direction or temperature gradients. It is the research team's understanding that there is no plan for implementation in the near future. Instead, measurements, modeling, and an understanding of current literature can help in evaluating these effects on sound propagation. Armed with effective tools, TNM users and state highway agencies can address concerns and questions about the effect of wind and temperature effects on noise levels in communities.

Further, evidence of a prevailing wind condition or a daily inversion scenario and an understanding of its effects could inform local officials and residents of long-term trends in sound levels. A synthesis of the state of practice for analyzing the effects of wind speed and direction and temperature gradients on sound propagation would help to establish sound-level adjustments that may be appropriate based on various parameters (such as effect in relation to varying wind speed and direction, effect in relation to varying temperature gradients, distance from the road, effect in relation to shielding objects [e.g., noise barriers], etc.) and when to apply the adjustments.

11.2 Research Approach

There is an extensive literature covering meteorological effects on sound propagation, but only a limited number of studies examine the effect on highway noise in a quantitative way. Examples of such studies are the Caltrans *I-80 Davis OGAC Pavement Noise Study*,[38] the Arizona Department of Transportation's *Atmospheric Effects Associated with Highway Noise Propagation*,[39] and the Volpe Center's *Validation of*

[38] Illingworth & Rodkin, Inc., *I-80 Davis OGAC Pavement Noise Study 12 Year Summary Report*, prepared for the California Department of Transportation Division of Environmental Analysis, May 2011.

[39] Saurenman, H., J. Chambers, L. C. Sutherland, R. L. Bronsdon, and H. Forschner, *Atmospheric Effects Associated with Highway Noise Prediction—Final Report 555*, FHWA-AZ-05-555, prepared for the Arizona Department of Transportation, October 2005.

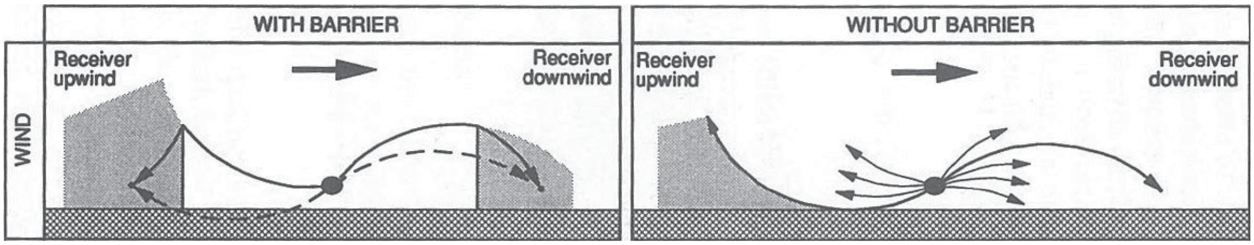

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Figure 49. Sound propagation under downwind and upwind conditions.[40]

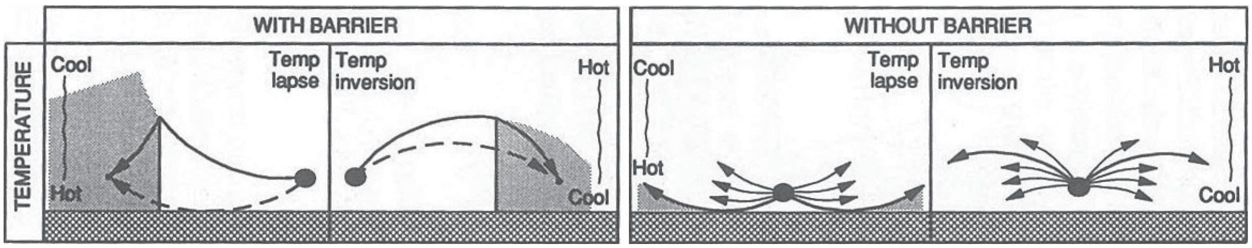

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Figure 50. Sound propagation under temperature inversion and lapse conditions.[41]

FHWA's Traffic Noise Model (TNM): Phase 1.[42, 43] These studies provide measured sound levels under various meteorological conditions. In addition, Part C of the Caltrans report, *Additional Calibration of Traffic Noise Prediction Models*,[44] describes a method of empirically determining a function to adjust measurement results to a calm wind condition. These studies are discussed in greater depth in Appendix J, which is available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986.

A sound propagation model other than TNM can easily help determine the effects of wind speed and direction and temperature inversion or lapse conditions for highway sites of interest. (For a brief and readable comparison of how the models mentioned here deal with weather conditions and noise barrier mathematics, see *Barriers to Consistent Results: the Effects of Weather.*[45]) The SoundPLAN[46] computer program was used to run test scenarios using the Nord2000[47] sound propagation model, which accounts for detailed meteorological effects. This model has been selected for this evaluation because of its ability to compute sound levels under a variety of wind and temperature conditions and because its calculations are validated with published studies. It is discussed in further detail in Appendix J.

Other well-established sound propagation models such as ISO 9613-2[48] and the General Prediction Method[49] assume a moderate downwind condition in order to replicate an equivalent long-term average. Wind and temperature effects can be entered in these models only as a user-specified decibel

[40] Beranek, L., Vér, I., *Noise and Vibration Control Engineering: Principles and Applications*, John Wiley & Sons, Inc., 1992.

[41] Beranek, L., Vér, I., *Noise and Vibration Control Engineering: Principles and Applications*, John Wiley & Sons, Inc., 1992.

[42] Rochat, J. L. and G. G. Fleming, *Validation of FHWA's Traffic Noise Model® (TNM): Phase 1*, DOT-VNTSC-FHWA-02-01 and FHWA-EP-02-031, Acoustics Facility, John A. Volpe National Transportation Systems Center, Cambridge MA, August 2002.

[43] Rochat, J. L. and G. G. Fleming, *TNM Version 2.5 Addendum to Validation of FHWA's Traffic Noise Model® (TNM): Phase 1*, DOT-VNTSC-FHWA-02-01 Addendum and FHWA-EP-02-031 Addendum, Acoustics Facility, John A. Volpe National Transportation Systems Center, Cambridge MA, July 2004.

[44] Hendriks, R., *Additional Calibration of Traffic Noise Prediction Models—Technical Advisory, Noise TAN-03-01*, California Department of Transportation, Division of Environmental Analysis, Hazardous Waste, Noise & Vibrations Office, August 2003.

[45] Smith, M., *Barriers to Consistent Results: the Effects of Weather*, paper for Acoustics 2008 Geelong, Victoria, Australia, November 2008.

[46] Braunstein + Berndt GmbH, SoundPLAN® User's Manual, January 2012 (including update information for Version 7.2—November 2012).

[47] Delta, *Proposal for Nordtest Method: Nord2000—Prediction of Outdoor Sound Propagation*, January 2010.

[48] Technical Committee ISO/TC 43, Acoustics, Subcommittee SC1, Noise, ISO 9613-2:1996(E), International Organization for Standardization, Geneva, Switzerland, 1996.

[49] Kragh, J., B. Andersen, J. Jakobsen, *Environmental Noise from Industrial Plants General Prediction Method*, Danish Acoustical Laboratory, Danish Academy of Technical Sciences, Report No. 32, 1982.

adjustment. Although like Nord2000, the Concawe[50] model can compute the effects of wind speed and direction, it was not selected because no equivalent measurement validation studies were identified for it.

The Nord2000 modeling was utilized to predict sound levels over a range of cases. Output from the various predictions has been described in terms of potential input for adjustments in TNM or simply as offsets from a condition with calm winds and neutral atmosphere with no temperature gradient in order to better understand potential variation in community noise levels and field measurements.

11.3 Research Tasks

A SoundPLAN model of a typical highway geometry was created to document the effect of different meteorological conditions at various receiver distances and heights. The model assumed flat ground with a four-lane (two lanes traveling in each direction) highway with a typical mix of automobiles and trucks traveling at 60 mph. A string of receivers was placed at heights of 5 ft and 15 ft at the following distances from the roadway: 50 ft, 100 ft, 200 ft, 400 ft, 800 ft, and 1,600 ft. A noise barrier (height of 17 ft) was included in some runs. Multiple runs were computed by varying the presence of the noise barrier, changing the model to assume all hard or soft ground, and by varying the presence of trucks on the roadways. Further details of the model and the Nord2000 validation with measured sound levels under various atmospheric conditions are included in Appendix J.

The combinations of variables described above were run in SoundPLAN with various wind and temperature conditions, and the results were compared to results under calm/neutral atmosphere conditions. Moderate upwind and downwind conditions were modeled by assuming a wind speed of 2.5 m/s (5.6 mph) at a height of 10 m above the ground. (Wind speeds and temperature gradients are reported primarily in metric (SI) units in this chapter because these parameters are nearly always reported in SI units and because the modeling was conducted with SoundPLAN, which is an SI-based model.)

Strong upwind and downwind conditions were modeled by assuming a wind speed of 5 m/s (11.2 mph)[51]. Positive temperature gradients associated with inversion conditions were modeled by assuming +0.1°C/m and +0.5°C/m. Negative temperature gradients associated with lapse conditions were modeled by assuming –0.1°C/m and –0.3°C/m.[52,53,54,55]

While SoundPLAN includes the implementation of the Nord2000 model, it also includes the implementation of TNM algorithms, both with and without "bug fixes" that the SoundPLAN developers have made. As a point of comparison, the results produced using the SoundPLAN implementation of Nord2000 for the test cases using calm weather conditions were also run using the TNM implementation in SoundPLAN. The comparison of the results using Nord2000 and TNM indicated that the two models provide generally consistent results. There is more conformity with hard ground and with the TNM results in general with the "bug fixes" SoundPLAN TNM implementation. These small differences are expected due to the different vehicle source emission levels in Nord2000 and from differences in the sound propagation algorithms. These differences are discussed further in Appendix J. It should be noted that while there are differences between the calculated sound levels in Nord2000 and TNM, the point of the study was to determine the differences between various atmospheric conditions and calm/neutral conditions using a roadway noise source model, and this has been successfully accomplished with Nord2000.

11.4 Outcome of the Research—Effect of Wind Speed and Direction and Temperature Gradients on Highway Noise Sources

Table 14 provides the results of the modeled meteorological conditions relative to calm/neutral atmosphere conditions. Positive numbers indicate sound levels higher than sound levels with calm/neutral conditions, and negative numbers indicate sound levels lower than those with calm/neutral conditions. Table 14 is broken into multiple sections based on various configurations of the variables automobiles/trucks, hard ground/soft ground, with noise barrier/without noise barrier described above. TNM users are encouraged to

[50] Marsh, K. J., "The Concawe Model for Calculating the Propagation of Noise from Open-Air Industrial Plants," *Applied Acoustics* Vol. 15, No. 6, November 1982, pp. 411–428.

[51] Rossing, T., Springer *Handbook of Acoustics*, Springer Science+Business Media, LLC, New York, New York, 2007.

[52] Illingworth & Rodkin, Inc., *I-80 Davis OGAC Pavement Noise Study 12 Year Summary Report*, prepared for the California Department of Transportation Division of Environmental Analysis, 13 May 2011.

[53] Saurenman, H., J. Chambers, L. C. Sutherland, R. L. Bronsdon, and H. Forschner, *Atmospheric Effects Associated with Highway Noise Prediction—Final Report 555*, FHWA-AZ-05-555, prepared for the Arizona Department of Transportation, October 2005.

[54] Ying, S., *Sound Intensity Attributed to Temperature Inversion at Night*, Paper presentation at Noise-Con 87, Pennsylvania State University, State College, PA, June 8–10, 1987.

[55] Kasper, P., R. S. Pappa, L. R. Keefe, and L. C. Sutherland, *A Study Of Air-To-Ground Sound Propagation Using An Instrumented Meteorological Tower*, NASA CR-2617, Prepared for the National Aeronautics and Space Administration, October 1975.

Table 14. Differences in sound levels relative to calm/neutral conditions.[56]

Automobiles and Trucks, Hard Ground, with Noise Barrier

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

Automobiles and Trucks, Soft Ground, with Noise Barrier

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

Automobiles and Trucks, Hard Ground, without Noise Barrier

Receiver Distance (ft)	Receiver Height (ft)	Sound-Level Difference (dB)							
		Wind Condition				Temperature Condition			
		Moderate Upwind (2.5 m/s)	Strong Upwind (5 m/s)	Moderate Downwind (2.5 m/s)	Strong Downwind (5 m/s)	Weak Lapse (–0.1°C/m)	Strong Lapse (–0.3°C/m)	Weak Inversion (+0.1°C/m)	Strong Inversion (+0.5°C/m)
50	5	0	–1	0	0	0	0	0	0
100	5	–1	–2	0	0	0	0	0	0
200	5	–2	–5	0	1	0	0	0	1
400	5	–7	–11	1	1	0	–1	0	1
800	5	–13	–19	1	2	–1	–5	1	2
1600	5	–20	-25	2	2	–4	–11	2	4
50	15	0	0	0	0	0	0	0	0
100	15	0	0	0	0	0	0	0	0
200	15	0	–1	0	0	0	0	0	0
400	15	–1	–4	1	1	0	0	0	1
800	15	–6	–11	1	1	0	–3	1	1
1600	15	–12	–18	1	2	–2	–9	1	3

[56] Source: Harris Miller Miller & Hanson Inc., 2013.

Table 14. (Continued).

Receiver Distance (ft)	Receiver Height (ft)	Moderate Upwind (2.5 m/s)	Strong Upwind (5 m/s)	Moderate Downwind (2.5 m/s)	Strong Downwind (5 m/s)	Weak Lapse (–0.1°C/m)	Strong Lapse (–0.3°C/m)	Weak Inversion (+0.1°C/m)	Strong Inversion (+0.5°C/m)
Automobiles and Trucks, Soft Ground, without Noise Barrier									
		Sound-Level Difference (dB)							
		Wind Condition				Temperature Condition			
50	5	–2	–3	3	3	0	–1	0	2
100	5	–3	–4	6	8	0	–1	1	4
200	5	–4	–6	10	12	–1	–2	2	8
400	5	–7	–9	13	14	–2	–4	3	11
800	5	–11	–14	14	15	–4	–8	4	12
1600	5	–16	–21	14	14	–7	–11	4	13
50	15	–1	–1	1	1	0	0	0	1
100	15	–1	–3	2	2	0	–1	1	2
200	15	–3	–5	4	6	–1	–2	1	4
400	15	–5	–8	8	10	–2	–4	3	8
800	15	–8	–12	11	13	–3	–7	4	11
1600	15	–13	-16	12	13	-7	–12	5	12
Automobiles Only, Hard Ground, with Noise Barrier									
		Sound-Level Difference (dB)							
		Wind Condition				Temperature Condition			
Receiver Distance (ft)	Receiver Height (ft)	Moderate Upwind (2.5 m/s)	Strong Upwind (5 m/s)	Moderate Downwind (2.5 m/s)	Strong Downwind (5 m/s)	Weak Lapse (–0.1°C/m)	Strong Lapse (–0.3°C/m)	Weak Inversion (+0.1°C/m)	Strong Inversion (+0.5°C/m)
50	5	–2	–4	7	12	–1	–1	3	9
100	5	–2	–4	6	11	–1	–2	4	10
200	5	–2	–3	6	11	–1	–2	4	11
400	5	–1	–2	4	10	–1	–2	3	13
800	5	–2	–6	3	9	–1	–4	3	14
1600	5	–5	–10	6	10	–4	–12	6	18
50	15	–3	–5	8	13	–1	–2	3	7
100	15	–3	–4	6	10	–1	–2	4	9
200	15	–2	–3	5	9	–1	–2	4	11
400	15	–1	–3	3	8	–1	–3	4	13
800	15	–1	–2	3	8	–1	–3	4	15
1600	15	–1	–6	6	9	–3	–11	6	18
Automobiles Only, Soft Ground, with Noise Barrier									
		Sound-Level Difference (dB)							
		Wind Condition				Temperature Condition			
Receiver Distance (ft)	Receiver Height (ft)	Moderate Upwind (2.5 m/s)	Strong Upwind (5 m/s)	Moderate Downwind (2.5 m/s)	Strong Downwind (5 m/s)	Weak Lapse (–0.1°C/m)	Strong Lapse (–0.3°C/m)	Weak Inversion (+0.1°C/m)	Strong Inversion (+0.5°C/m)
50	5	–3	–5	8	13	–1	–1	4	10
100	5	–3	–5	7	12	–1	–2	4	10
200	5	–3	–5	7	11	–1	–2	4	11
400	5	–5	–9	6	11	–2	–5	4	13
800	5	–5	–10	5	11	–3	–8	4	16
1600	5	–7	–11	5	9	-6	–13	5	19
50	15	–4	–6	8	13	–1	–1	3	8
100	15	–3	–5	7	11	–1	–2	4	9
200	15	–-2	–4	5	10	–1	–2	3	11
400	15	–2	–3	3	9	–1	–3	3	12
800	15	–2	–5	2	6	–2	–6	3	14
1600	15	-2	–8	3	5	–4	–13	4	17

Table 14. (Continued).

Automobiles Only, Hard Ground, without Noise Barrier									
Receiver Distance (ft)	Receiver Height (ft)	Sound-Level Difference (dB)							
		Wind Condition				Temperature Condition			
		Moderate Upwind (2.5 m/s)	Strong Upwind (5 m/s)	Moderate Downwind (2.5 m/s)	Strong Downwind (5 m/s)	Weak Lapse (–0.1°C/m)	Strong Lapse (–0.3°C/m)	Weak Inversion (+0.1°C/m)	Strong Inversion (+0.5°C/m)
50	5	0	–1	0	0	0	0	0	0
100	5	–1	–2	0	0	0	0	0	0
200	5	–3	–6	1	1	0	0	0	1
400	5	–8	–13	1	1	0	–2	0	2
800	5	–15	–21	2	2	–1	–6	1	3
1600	5	–22	–27	2	3	–5	–11	2	5
50	15	0	0	0	0	0	0	0	0
100	15	0	–1	0	0	0	0	0	0
200	15	–1	–1	0	0	0	0	0	0
400	15	–2	–5	1	1	0	0	1	1
800	15	–7	–12	1	2	0	–4	1	2
1600	15	–13	–19	2	3	–2	–9	2	3
Automobiles Only, Soft Ground, without Noise Barrier									
Receiver Distance (ft)	Receiver Height (ft)	Sound-Level Difference (dB)							
		Wind Condition				Temperature Condition			
		Moderate Upwind (2.5 m/s)	Strong Upwind (5 m/s)	Moderate Downwind (2.5 m/s)	Strong Downwind (5 m/s)	Weak Lapse (–0.1°C/m)	Strong Lapse (–0.3°C/m)	Weak Inversion (+0.1°C/m)	Strong Inversion (+0.5°C/m)
50	5	–3	–4	3	4	0	–1	1	2
100	5	–4	–6	7	9	–1	–2	1	5
200	5	–6	–8	12	14	–1	–3	3	9
400	5	–8	–10	15	16	–2	–5	4	12
800	5	–12	–15	16	17	–5	–8	5	14
1600	5	–16	–21	16	16	–8	–11	6	15
50	15	–1	–1	1	1	0	0	0	1
100	15	–2	–3	2	2	0	–1	1	2
200	15	–4	–7	5	6	–1	–3	2	5
400	15	–7	–10	10	11	–2	–5	4	10
800	15	–10	–13	13	14	–4	–9	5	13
1600	15	–13	–16	14	15	–8	–12	6	14
Note. Positive numbers indicate sound levels higher than those with calm conditions. Negative numbers indicate sound levels lower than those with calm conditions.									

use the data in these tables to explain the difference in sound levels for validation purposes and for explanation of sound levels for agency and public purposes.

11.4.1 Effect of Wind Speed and Direction on Highway Noise Sources

Figures 51 and 52 are sample graphs of the sound-level differences among varying wind speeds and directions and calm conditions. Both figures show the results with automobiles and trucks at a 5-ft receiver height over soft ground. Figure 51 includes a noise barrier, and Figure 52 does not. Similar figures showing the differences relative to calm conditions for all of the various combinations in Table 14 are included in Appendix J, as well as figures showing the computed hourly equivalent sound level (L_{eq}).

11.4.1.1 Effect of Receiver Height on Results

Overall, the results show that sound levels in wind and calm conditions show a similar pattern of variance at 5-ft and 15-ft receiver heights. As would be expected, the variance in the results at the two receiver heights is more pronounced at greater receiver distances and under soft ground conditions.

11.4.1.2 Effect of Noise Barrier on Results

The presence of a noise barrier in the model typically had a large effect on the results. However, the difference between the results with and without a noise barrier was affected more by wind conditions than by temperature conditions.

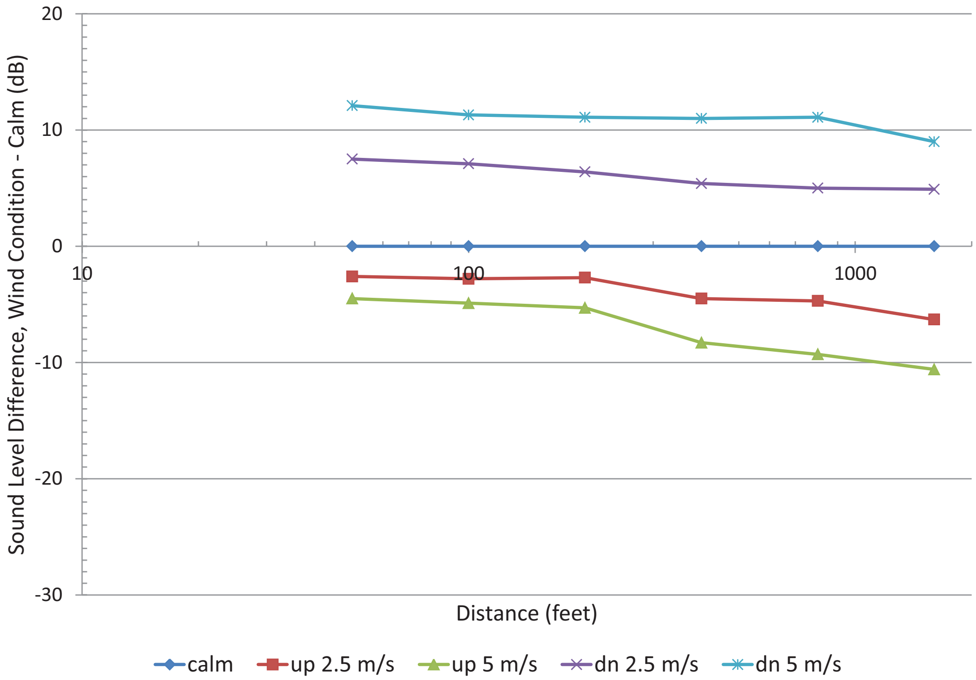


Figure 51. Sound-level difference with noise barrier and varying wind and calm conditions (automobiles and trucks, 5-ft receiver, and soft ground).

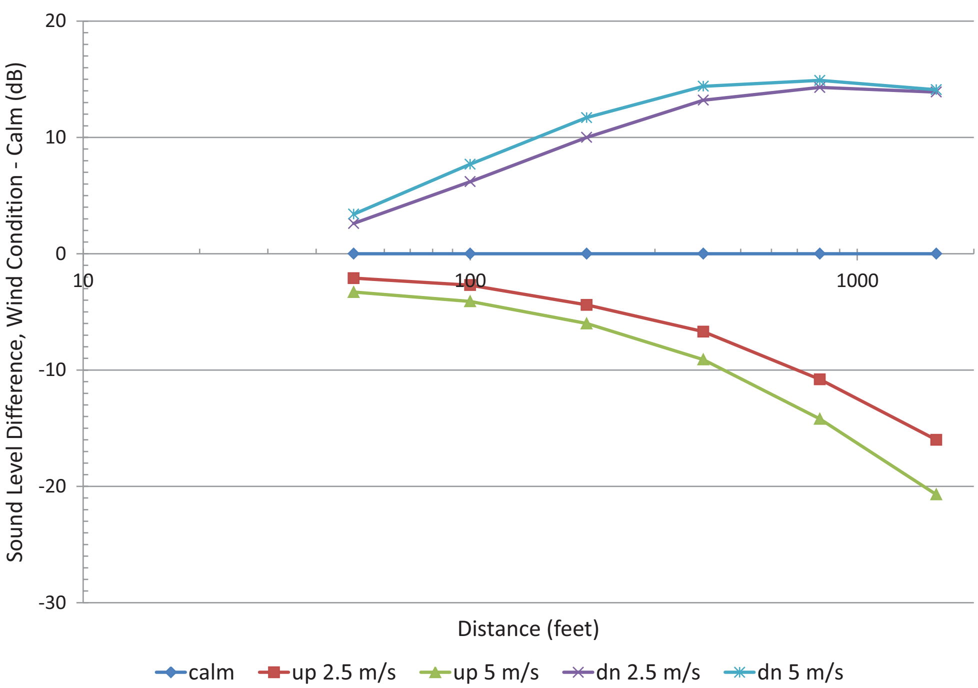


Figure 52. Sound-level difference without noise barrier and varying wind and calm conditions (automobiles and trucks, 5-ft receiver, and soft ground).

11.4.1.3 Effect of Ground Type on Results

The type of ground (either hard or soft) in the model also had a large effect on the results. As would be expected, the differences between the hard and soft ground cases varied much more at the greater receiver distances.

11.4.1.4 Effect of Truck Percentage on Results

Varying the model to include some trucks or assuming no trucks had a relatively small difference on the results. The presence of trucks in the model was not one of the most significant variables.

11.4.2 Effect of Temperature Inversion and Lapse on Highway Noise Sources

Figures 53 and 54 are sample graphs of the variance in sound level at varying temperature gradients under calm conditions. Both figures show the results with automobiles and trucks at a 5-ft receiver over soft ground. Figure 53 includes a noise barrier and Figure 54 does not. Similar figures showing the differences relative to calm conditions for all of the various combinations in Table 14 are included in Appendix J, as well as figures showing the computed hourly equivalent sound level (L_{eq}).

11.4.2.1 Effect of Receiver Height on Results

Overall, the results show that sound levels in wind and calm conditions show a similar pattern of variance at 5-foot and 15-foot receiver heights. As would be expected, the differences in the results at the two receiver heights is more pronounced at the greater receiver distances, and under soft ground conditions.

11.4.2.2 Effect of Noise Barrier on Results

The presence of a noise barrier in the model typically had a large effect on the results. However, the difference between the results with and without a noise barrier was affected more by wind conditions than by temperature conditions.

11.4.2.3 Effect of Ground Type on Results

The type of ground (either hard or soft) in the model also had a large effect on the results. As would be expected, the differences between the hard and soft ground cases varied much more at the greater receiver distances.

11.4.2.4 Effect of Truck Percentage on Results

Varying the model to include some trucks or assuming no trucks had a relatively small difference on the results. The presence of trucks in the model was not one of the most significant variables.

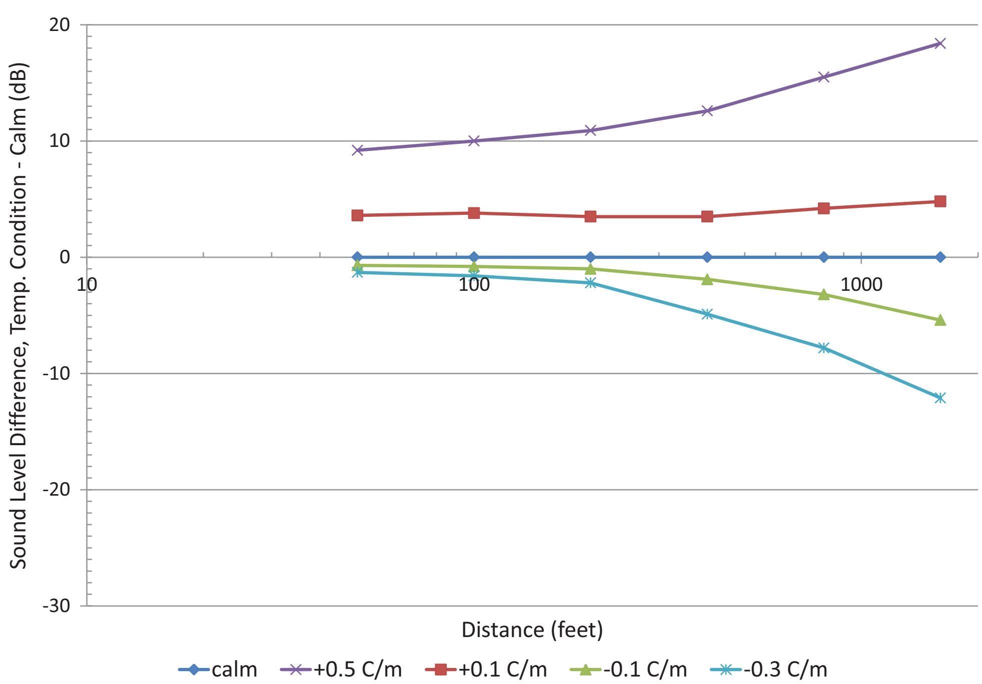


Figure 53. Sound-level difference with noise barrier, varying temperature, and calm conditions (automobiles and trucks, 5-ft receiver, and soft ground).

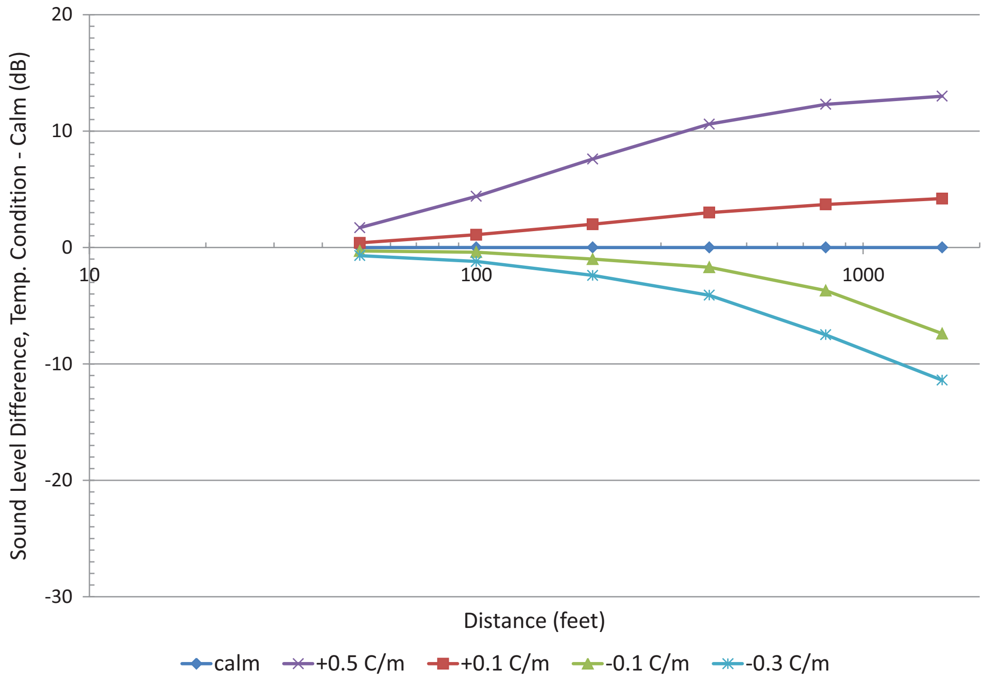


Figure 54. Sound-level difference without noise barrier, varying temperature, and calm conditions (automobiles and trucks, 5-ft receiver, and soft ground).

11.5 Combined Effects of Wind and Temperature Gradients on Highway Noise Sources

The focus of this research was primarily the separate effects of varying wind and temperature conditions on sound levels from highway noise sources. Often, wind and temperature gradients sufficient to affect sound propagation do not occur at the same time.[57] However, it is possible that some moderate wind and temperature conditions may occur simultaneously. These could have the effect of being additive, or in theory, cancel each other out. For example, in the case of downwind sound propagation and a temperature inversion, the sound levels would be greater than in the case of downwind propagation and no temperature gradient.

It was not practical to model all the various combinations of wind and temperature conditions and compare them. However, some combinations of moderate temperature inversion and lapse conditions were modeled with various wind speeds and directions. Those results are included in Appendix J.

[57] Rossing, T., ed., *Springer Handbook of Acoustics*, Springer Science+Business Media, LLC, New York, NY, 2007.

CHAPTER 12

Parallel Barriers

12.1 Research Approach

12.1.1 Basic Concepts and Use of the FHWA TNM Parallel Barriers Module

Sound levels behind a barrier can increase when there are multiple reflections of the sound between the barrier and a second barrier parallel to it on the opposite side of the road, forming a vertical wall "canyon," as shown in Figure 55. Figure 56 shows in a schematic overhead view that these multiple reflections are a three-dimensional phenomenon, with reflected sound reaching the receiver before vehicles pass by it and after they pass as well.

FHWA TNM 2.5 allows modeling of this phenomenon in a separate two-dimensional parallel barrier analysis module within the program. When the analyst selects a cross section to study and initiates a new parallel barrier design by cutting a section line through the plan view of the model, a separate parallel barrier view is opened, as shown in Figure 57. Certain input data are passed to the module from the main part of TNM, including the elevations and horizontal offsets of the following:

- Roadways.
- Analysis locations (receivers with their heights added to their ground elevations).
- Barriers (with the barrier input heights added to their ground elevations).

Traffic volumes and speeds of the roadways are also passed to the parallel barrier module. The analyst then typically refines this cross section to tailor it more specifically to the actual location, as shown in Figure 58, where

- Additional roadways were added to represent individual travel lanes that may not have been modeled in the main part of FHWA TNM.
- Barrier heights were adjusted from the input heights to the analyst's designed heights.
- Additional representative analysis locations were added that were not picked up in the initial cutting of the analysis section.
- Parallel barrier cross-section surface segments outside of the canyon to be studied were deleted (because analysis locations may not be within the extents of the cross section being calculated).

The program then computes sound-level increases over the single barrier "with barrier" L_{Aeq1h} computed during the barrier design in the main part of FHWA TNM. The program does not add these increases to the L_{Aeq1h}. That task is left to the analyst. Then, if the increases are considered significant (typically more than 1 to 2 dB), the analyst can evaluate mitigation using the parallel barrier analysis module such as applying a sound-absorbing surface to the inside faces of the parallel barrier or tilting the barrier outward slightly to eliminate the multiple reflections pattern.

12.1.2 Research Steps

The objective of this research was to investigate the sensitivity of the parallel barrier module to a variety of factors and refine the available guidance on the use of the module. Guidance was needed in a number of areas, in some cases in terms of best modeling practices and in other cases on how to recognize and work around issues with the implementation of the module within FHWA TNM. The areas that were studied relating to the sensitivity of the computed sound-level increase to the input parameters include the following:

- Height-to-width ratio for the barriers and receiver position behind the barrier.
- Number of FHWA TNM roadways used to represent the travel lanes.
- Source position.
- Differences in the heights (top elevations) of the two barriers.

Figure 55. Highway with parallel noise barriers on opposite sides of the road.[58]

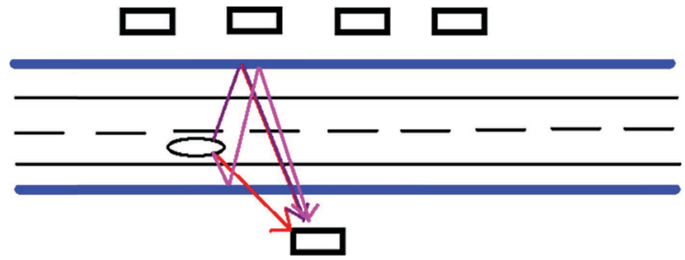


Figure 56. Plan view of multiple reflections off parallel highway noise barriers.

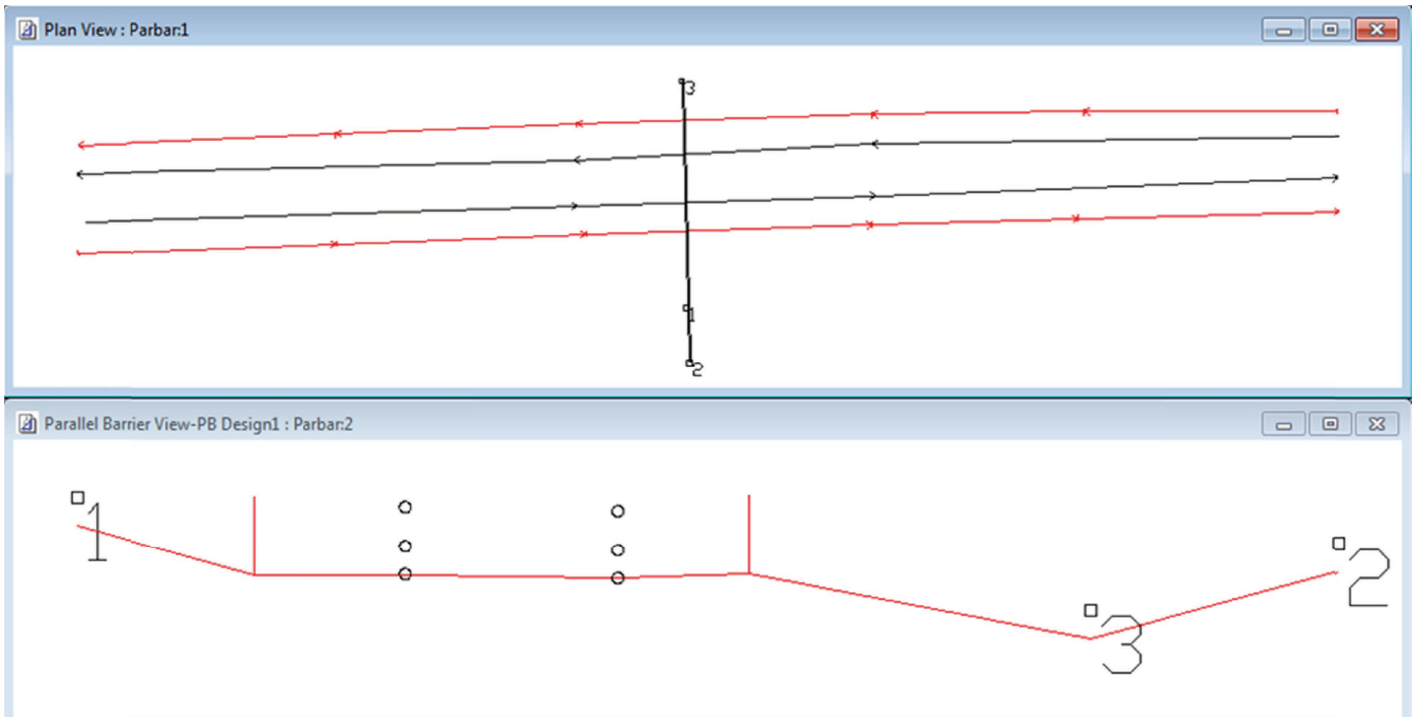


Figure 57. Section line through the plan view of the model.

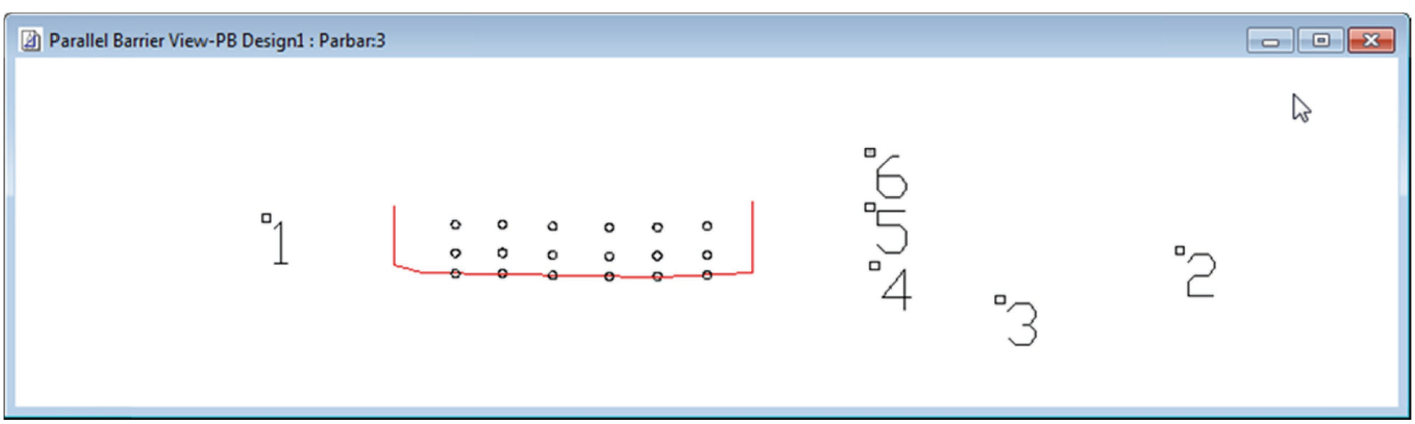


Figure 58. Tailored cross section of actual location.

[58] Source: Bowlby & Associates, Inc.

- Internal vertical reflecting surface.
- Vehicle mix (e.g., automobiles only versus heavy trucks only).
- Hourly volumes of vehicles.
- Vehicle speed.
- Noise reduction coefficient of barrier surfaces.

The research also evaluated two sets of measured and modeled data for a parallel barrier project before and after the addition of sound-absorbing panels to one of the barriers.

12.2 Outcome of the Research—Best Practices and How to Implement Them for a Noise Study or TNM Model

12.2.1 Height–to-Width Ratio for the Barriers and Receiver Position Behind the Barrier

The sound-level increase due to multiple reflections between the parallel barriers is partly a function of the width-to-height ratio for the cross section (distance between the noise barriers divided by their height). In general, the smaller the ratio, the greater the sound-level increase will be.

The current FHWA TNM FAQ states:

> When should I analyze my parallel barriers?
>
> Research has shown that the magnitude of the performance degradation associated with parallel reflective noise barriers is linked to the ratio of the separation (width) between the barriers and the average height of the barriers. Definitely analyze parallel barriers when the cross-section's width-to-height ratio (W: H) is less than 10:1. When the ratio is between 10:1 and 20:1, you may still want to analyze the cross-section with TNM. If the ratio is greater than 20:1, you do not necessarily have to analyze the cross-section. Such a calculation will yield inconsequential sound-level increases. Please refer to the Parallel Barriers Menu section on Page 103 of the TNM Users Guide for more information.

The TNM Users Guide repeats the guidance quoted above and indicates that the maximum expected degradation in the noise reduction provided by a single barrier due to a second barrier (termed "sound level increase" in the FHWA TNM program) will be 0 to 3 dB for W:H ratios of 10:1 to 20:1 and that there will be "no degradation" for a W:H ratio greater than 20:1.

The findings of this research were different in terms of the model results from FHWA TNM.

Tests were run for an eight-lane cross section with a barrier-to-barrier width of 136 ft consisting of eight 12-ft lanes with 10-ft inside and outside shoulders in each travel direction. As illustrated in Figure 59, an array of receivers was modeled for six distances back from the near wall (25, 50, 100, 150, 200, and 300 ft) and at four heights relative to the roadway surface: 15 ft, 5 ft, –5 ft and –15 ft. These heights represent, respectively, an exterior second-story location in an at-grade cross section, a typical exterior receiver in an at-grade cross section, a receiver alongside a 10-ft roadway embankment, and a receiver alongside a 20-ft roadway embankment. In the FHWA TNM parallel barrier module, the points at which the sound-level increases are predicted are called "analysis locations." In this chapter, the word "receiver" will be used, where the height of the receiver is the point at which the sound-level increase is predicted.

It is known that the parallel barrier module has not been validated for receivers above the top of the near wall, which is the case for some of the studied situations.

Barrier heights were varied from 1 to 20 ft, with the resulting W: H ratios ranging down to 7:1 for 20 ft. The barriers are assumed to be sound reflecting, with a noise reduction coefficient (NRC) of 0.05.

Appendix K (available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986) contains graphs of the results of modeling for automobiles only and heavy trucks only. The sound-level increase is a function of not only barrier height (and thus width-to-height ratio) but also receiver height above or

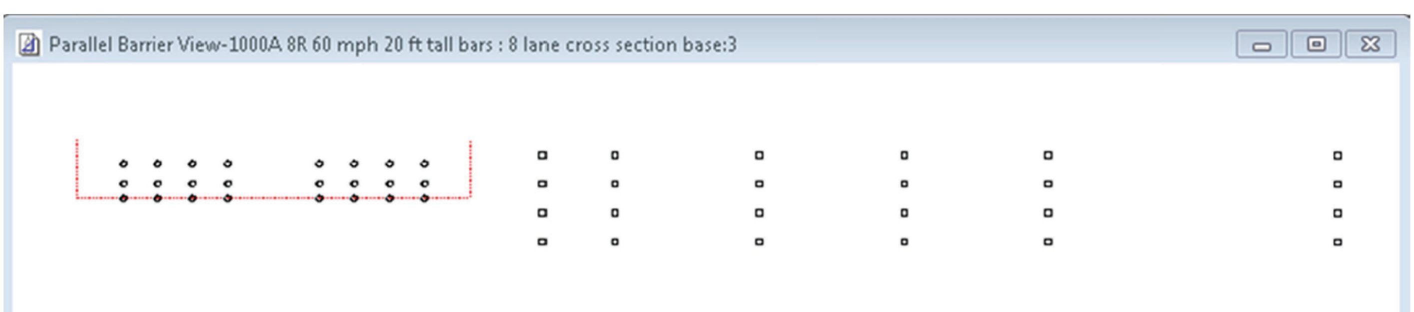


Figure 59. Illustration of receiver array at heights of 15, 5, –5 and –15 ft relative to the roadway surface and distances of 25, 50, 100, 150, 200, and 300 ft from the near wall.

below the road, receiver distance back from the near wall, and vehicle type.

For the studied cross section, a 10:1 width-to-height ratio resulted in sound-level increases for automobiles ranging from 1.0 to 6.5 dB. For heavy trucks, the range was 0.3 to 4.1 dB. In some limited testing of medium trucks, the predicted sound-level increases were within 0.1 to 0.3 dB of those for automobiles. The sound-level increase tends to rise as receiver height increases. For most of the receiver positions, this amount of sound-level increase warrants attention in the barrier design process.

For this same cross section, a 20:1 width-to-height ratio resulted in sound-level increases for automobiles from 0.3 to 3.1 dB, being greatest for the 5-ft receiver. For heavy trucks, the range is 0 to 0.7 dB. Depending on the mix of traffic and the receiver location, the sound-level increase even for this 20:1 width-to-height ratio may warrant attention during barrier design.

For the 5-ft-high receiver located 25 ft from the near wall, the sound level increases very little as barrier height increases from 11 to 20 ft, with a similar pattern for the same receiver 50 ft from the near wall. For heavy trucks, the sound-level increase is also not particularly sensitive to increasing barrier heights at the closer-in distances. These results counter prevailing thought that the sound-level increase rises as barrier height increases because more multiple reflection paths are created as the barriers get taller. This pattern is not consistent across all receiver heights and distances, but suggests that FHWA TNM will show that increasing the barrier heights will overcome the increase in the “with barrier” sound level in a parallel barrier situation, which could lead to increasing heights as an alternative mitigation technique to sound absorption. This report is not recommending such a strategy because of the lack of field validation. Use of sound-absorbing surfaces on the road side of the walls remains the recommended mitigation strategy for minimizing the sound-level increases.

Further tests varied the width-to-height ratio by keeping the barrier heights at 20 ft and increasing the width between the parallel barriers for automobiles-only cases. Even at 20:1, sound-level increases over 2 dB were calculated for the 15-ft-high receiver over all distances and at 100 ft and beyond for the 5-ft receiver. At 20:1, the sound-level increases for the receivers 5 ft and 15 ft below the roadway grade are less than 2 dB.

Untested is whether or not the sound-level increases would occur in the real world. A 20:1 width-to-height ratio for 20-ft high barriers means the barriers are 400 ft apart. Meteorological effects on sound propagation, such as wind shear (changing wind speed with altitude) or temperature lapse rate (changing temperature with altitude) could easily have more effect on sound levels over these distances due to refraction than would the reflected paths.

12.2.2 Number of FHWA TNM Roadways Used to Represent the Travel Lanes

Within the range of the tested cases described above, modeling the eight-lane cross section by a total of two or four FHWA TNM roadways (one or two in each direction) produced results within a 0.5 dB of the eight-roadway model, with a few exceptions where differences up to 1 dB were computed.

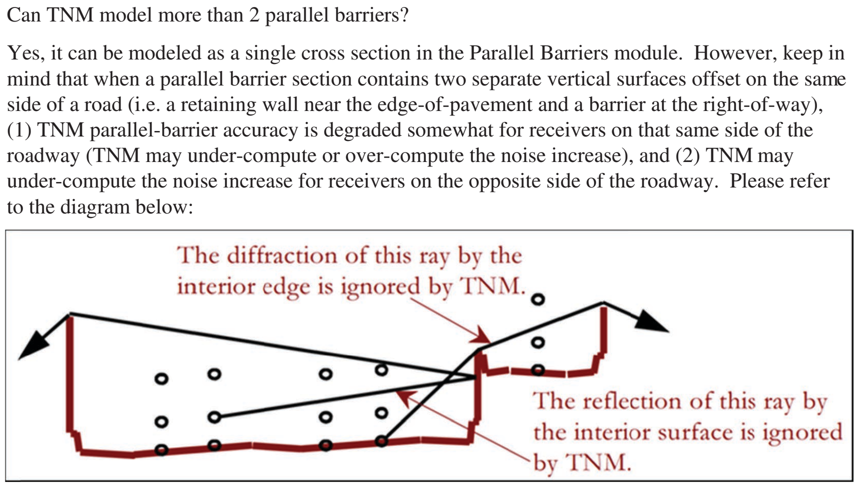
12.2.3 Source Position

The finding of insensitivity to the number of modeled roadways across the entire cross section was tested to see how much source position within the canyon between the two barriers affected the parallel barrier sound-level increases. The eight-lane cross section shown in Figure 59 was broken down into cases consisting of the four “far” lanes only being modeled by four FHWA TNM roadways and then by one roadway centered between them, and then the four “near” lanes only being modeled by four roadways and then one roadway.

Source position has only a small effect on the sound-level increase for the lower receiver positions (1 dB or less), especially within 150 ft of the near wall. Source position has a larger effect, of 2 dB or more, at the more distant receiver positions and for the 15-ft-high receiver. The results were similar for the automobiles-only and heavy trucks-only cases, with the automobiles-only sound-level increases being generally higher.

12.2.4 Differences in the Heights (Top Elevations) of the Two Barriers

As the height of one of the two parallel barriers changes, there is a change in the pattern of sound-level reflection. Conceptually, as the height of the far wall decreases, the potential for many multiple reflection paths decreases, a situation that could then reduce the size of the sound-level increase due to reflections. Tests varying the far wall height from 10 to 22 ft while holding the near wall height at 20 ft for the eight-roadway cross section for automobiles only showed, in general, that the parallel barrier module does compute smaller sound-level increases as the far wall height decreases. The change in the sound-level increase is greater for the higher receivers and the greater distances from the near wall because the actual sound-level increases for the equal wall height cases are larger for these receiver positions. However, even for relatively low far wall heights, the sound-level increases can still be substantial enough to warrant investigation and possible mitigation through the use of sound-absorbing surfaces on one or both walls.


Can TNM model more than 2 parallel barriers?

Yes, it can be modeled as a single cross section in the Parallel Barriers module. However, keep in mind that when a parallel barrier section contains two separate vertical surfaces offset on the same side of a road (i.e. a retaining wall near the edge-of-pavement and a barrier at the right-of-way), (1) TNM parallel-barrier accuracy is degraded somewhat for receivers on that same side of the roadway (TNM may under-compute or over-compute the noise increase), and (2) TNM may under-compute the noise increase for receivers on the opposite side of the roadway. Please refer to the diagram below:

Figure 60. Text and diagram from TNM FAQs on parallel barriers.[59]

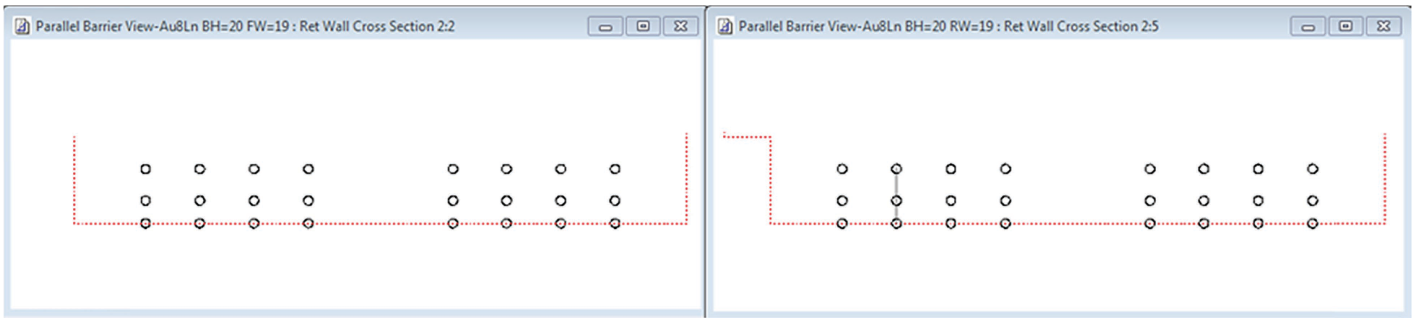


Figure 61. Cross section with 19-ft-high far wall as an external vertical surface (left) and an internal vertical surface with a 1-ft noise barrier offset 10 ft from the top of the internal vertical surface (right).

12.2.5 Internal Vertical Reflecting Surface

The FHWA TNM FAQ for parallel barriers cautions analysts about having an internal, vertical, reflecting surface in the analyzed parallel barrier cross-sectional surface. (See Figure 60.)

The extent of the effect on the results may depend on the source position, the heights of the noise barriers and the internal vertical surface, the offset of the external wall from the internal vertical surface, and the receiver position. A test was created to illustrate the problem of internal surface reflections. As shown in Figure 61, the cross section on the left consisted of a 20-ft-high near wall and a 19-ft-high far wall. The cross section on the right was the same, except that a 1-ft-high noise barrier was added offset 10 ft to the left beyond the far wall. The 19-ft-high far wall thus went from being an external vertical surface to an internal vertical surface.

The parallel barrier module computed sound-level increases in both cases, but there were differences, ranging from 1 dB in close to more than 4 dB farther back. Acoustically, there should be no difference in the calculated sound-level increases. The 1-ft noise barrier offset from the 19-ft vertical section is not in a position to reflect sound back across to diffract over the top of the near wall. This fact was tested by making the 19-ft-high wall highly absorptive: all of the sound-level increases became 0 dB.

In an additional test, the 1-ft noise barrier was deleted so that the cross section ended with a horizontal segment beyond the top of the 19-ft section, which was reset to being highly reflective. All of the sound-level increases became 0 dB.

Because of these inconsistent results, internal vertical reflecting or diffracting surfaces *should not* be analyzed using the parallel barrier module or included in any parallel barrier analysis cross sections.

12.2.6 Vehicle Mix

The FHWA TNM parallel barrier module is not sensitive to changes in vehicle mix (the percentage of automobiles versus trucks in an hourly traffic flow) once trucks are introduced into the flow. In general, a ±5% change in percentage

[59] Source: www.fhwa.dot.gov/environment/noise/traffic_noise_model/tnm_faqs/faq10.cfm#menupara.

of automobiles changes the sound-level increase by only a few tenths of a decibel, except in going from 100% automobiles to 95% automobiles, where the change in sound-level increase is on the order of 0.5 dB.

12.2.7 Hourly Volumes of Vehicles

The FHWA TNM parallel barrier module is only predicting a sound-level increase in the 1-hour L_{eq} and not an actual 1-hour L_{eq}. The module's calculations are independent of the hourly volumes, but are dependent on the vehicle mix, as was just described in Section 12.2.6. Identical sound-level increases were computed for a run of 1,000 each of automobiles, medium trucks, and heavy trucks compared to a run with just one vehicle of each type.

12.2.8 Vehicle Speed

Sound-level increases computed by the FHWA TNM parallel barrier module are independent of speed for each vehicle type. Results will not change as speed changes.

12.2.9 NRC of Barrier Surfaces

When the predicted sound-level increase from reflected sound is determined to be large enough to mitigate, the most common solution has been the use of a sound-absorbing product or material for the surfaces of the walls facing the roadway. Some state highway agencies will also use sound-absorbing barriers in single-wall situations where there are residences on the other side of the road that may or may not be impacted, but do not meet the agency's noise abatement feasibility or reasonableness criteria.

The FHWA TNM parallel barrier module has the capability of testing the effectiveness of changing the NRC of all or parts of one or both of the parallel barriers. The NRC is a frequency-specific quantity, being the average of the sound-absorption coefficients in the 250, 500, 1,000, and 2,000 Hz octave bands. Different products with different sound-absorption coefficients in these bands can have the same NRC, yet perform differently in the field. The FHWA TNM parallel barrier module computes the diffraction attenuation of the sound passing over the near wall at a frequency of 500 Hz. As such, the application of an NRC will give an indication of the general effect of the sound-absorbing material, but not a precise calculation for a specific product.

To test the parallel barrier module's application of the NRC, several cases were studied. The basic case was the eight-roadway cross section for automobiles only with 18-ft barriers on either side. The NRC of both walls varied between 0.05 (a typically used value for concrete) and 0.90 in 0.10 increments (starting from 0.10). Then, just the far wall was made sound-absorbing, with the same NRC variation, and then just the near wall in the same manner. Finally, the heights of both walls were varied in tandem to test the effect of the NRC on different height configurations. Appendix K provides graphs of the sound-level increases as a function of the wall NRC for all of the receivers shown in Figure 59.

For all three cases, the effectiveness of the increased sound absorption is fairly linear, reducing the sound-level increase as the NRC increases. For absorption on both walls, an NRC of 0.7 or higher brings the reflective barriers' sound-level increases down to less than 1 dB for all of the receiver positions except at the 15-ft receiver height, for which the maximum sound-level increase is less than 2 dB.

Sound absorption on the far wall only is also very effective for this cross section in reducing the sound-level increases. For any given receiver position, the sound-level increases with absorption on just the far wall are 0 to 1.3 dB higher than when there is absorption on both walls.

In contrast, absorption on just the near wall is far less effective than absorption on the far wall or both walls. For any given receiver position, the sound-level increases with absorption on just the near wall are up to 3.8 dB higher than when there is absorption on both walls.

The results suggest the importance of the single far wall reflections on the total sound level at a receiver, but also show that the program is calculating multiple reflection paths back and forth between the barriers because near wall absorption also reduces the sound level over the fully reflective case.

12.2.10 Comparison of Measured and Modeled Levels Including Parallel Barrier Sound-Level Increases

A comparison of measured and FHWA TNM predicted sound levels, including parallel barrier sound-level increases, was made for a study that evaluated traffic noise barriers along both sides of a state highway.[60] The walls were both originally sound reflecting. In response to citizen complaints about noise behind one of the barriers, the state highway agency studied the problem[61] and then added absorption panels to the wall on the opposite side of the highway to reduce sound reflections back into the community. The follow-up study was then conducted.

Included in the follow-up study were noise measurements with concurrent traffic and meteorological data collection, noise modeling with TNM 1.0b, and administration of a follow-up survey of the affected citizens. The data sets

[60] Bowlby & Associates, Inc., *SUM-8-6.83 Noise Wall "After Absorption" Study, State Route 8, Silver Lake, Ohio*, for Ohio DOT District 4, 2000.

[61] Bowlby & Associates, Inc., *SUM-8-6.83 Noise Barrier Post Construction Study-State Route 8 - Silver Lake Ohio*, for Ohio DOT Office of Environmental Services, 1996.

from the initial and follow-up studies provide field data and FHWA TNM runs for a reflective parallel wall situation (before absorption) and for a situation with a near side reflective wall and a far-side, sound-absorbing wall (after absorption). FHWA TNM 1.0b runs were converted to run in FHWA TNM 2.5 for use in this research.

The project study area had two analysis sections:

1. A "two-wall" area where both walls were essentially at-grade with the road and of nearly equal heights.
2. A "no-wall" area north of both barriers.

A reference microphone was deployed in each area (0-Ref in the no-wall area, 2-Ref in the two-wall area), and two individual study sites were chosen within each area (0-A, 0-B, 2-A, 2-B), with a third, more distant, site in each area (0-C, 2-C).

The results for the initial measurements with both walls reflective showed FHWA TNM 2.5 predicted well in the no-wall area at sites 0-Ref and 0-B. FHWA TNM 2.5 generally under-predicted the levels at the other sites. However, at 0-A, the FHWA TNM 2.5 over-prediction was 5.4 and 7.0 dB. In the original study in 1996, the FHWA STAMINA 2.0 program over-predicted this same site by 6.1 dB, and when the predictions were redone with FHWA TNM 1.0b, the over-prediction was also large. The reasons for all three models' over-prediction are not clear.

The two-wall sites were then studied with the FHWA TNM 2.5 parallel barrier module. The computed parallel barrier sound-level increases were 0.3 dB at 2-Ref, 2.6 dB at 2-A, 3.4 dB at 2-B, and 0 dB at 2-C. Applying the sound-level increases to the main FHWA TNM 2.5 single-wall predictions improved the model performance slightly at the 2-Ref site, with it still under-predicting by 0.1 to 1.8 dB. The predicted levels at study sites 2-A and 2-B increased. Site 2-A's levels became higher than the measured levels by 0.7 to 1.5 dB, whereas they were lower before adding in the calculated sound-level increase. Site 2-B's over-prediction increased to 4.1 dB. Normalizing the data by the 2-Ref predicted-minus-measured sound-level difference increased the predicted-minus-measured differences at 2-A and 2-B and improved the difference at 2-C.

After the sound-absorption installation, new measurements were made and the modeling was revisited, using a far wall NRC of 0.80. For this research, the modeling was redone using FHWA TNM 2.5. In the no-wall area, FHWA TNM 2.5 predicted within –0.1 to +1.0 dB of the measured levels at 0-Ref. However, at 0-A, 0-B, and 0-C the results were mixed. The measured levels varied substantially between periods at each site, resulting in both good and poor agreement with the modeling. The reasons for the variation in the measured levels were not clear.

In the two-wall area, the computed parallel barrier sound-level increase at 2-Ref was 0.3 dB, the same as for the "both walls reflective" case. One would have expected this value to decrease. At 2-A, the sound-level increase dropped from 2.6 dB to 0.2 dB; at 2-B, it decreased from 3.4 dB to 0 dB; and at 2-C, it remained at 0 dB. Overall, after using the parallel barrier module, FHWA TNM 2.5 predicted within 1 dB of the measured levels at 2-Ref, within 2 dB at 2-A, and within 2.5 dB at 2-B. At 2-C, FHWA TNM 2.5 greatly under-predicted the levels.

Overall, the results of the comparisons of the measured and modeled levels in the reflective and far wall absorptive cases were mixed. Agreement was good at the reference microphone sites for both the no-wall and two-wall sites in each case, and at 2-A, the closest site behind the near wall. At the other study sites, agreement ranged from mixed at 0-B to poor at 0-A and 2-C. One issue was with the range in the measured sound levels at the sites, especially in the far wall absorptive case. Site 2-C was deep into the community, and while care was taken regarding localized noise sources and meteorological effects on sound propagation, these factors could not be ruled out as possible causes of the sound-level differences.

12.2.11 General Notes and Guidance

Finally, several general notes and some guidance are provided here.

Because the algorithms in the parallel barrier module have not been calibrated for receivers at elevations above the elevation of the near barrier, the guidance from the module's developer (G. S. Anderson) is to generally require a minimum barrier height of 6 ft for either barrier.

Additionally, the algorithms are such that the module should not be used for single-wall reflections. There are also occasions where single reflections off a barrier or a vertical retaining wall on the far side of a highway may be important to receivers on the near side of the highway. Studying single-wall reflections was outside of the scope of this research. FHWA TNM 2.5 has a single reflections routine in the main part of the program—separate from the parallel barrier module—that is currently deactivated in the code because of issues during its development. The plan for FHWA TNM 3.0, now under development, is to make this single-wall reflections component functional.

Until then, FHWA TNM 2.5 modelers should consider the use of "image roadways" in a run to model single-wall reflections without actually having the far wall in the run. Careful addition of TNM roadways to the run to represent the reflected images of the "real" TNM roadways in the barrier is an excellent way to study such situations. Care must be taken to ensure that the image roadways in the run represent vehicle sources on "real" roadways, all of which would truly reflect from the barrier to the receivers in the run.

In general, a parallel barrier analysis would begin with a review of the highway plans and proposed noise barriers to identify areas where multiple sound reflections might occur, namely, where there are barriers and/or vertical retaining walls on both sides of the road. Several representative sites or cross sections would then be selected for study, such as the following:

- Different cross section types (e.g., cut, fill, and at grade).
- Different barrier heights (for one or both of the barriers).
- Different barrier offset distances from the roadways.

In cutting parallel barrier analysis sections in the main plan view of FHWA TNM, the analyst does not have to select or cut through modeled receiver points. The receivers can be added in the parallel barrier module as "analysis locations." The elevation for an analysis location is not the ground, but the calculation point above the ground (receiver ear height). Analysis locations may not be placed at the edge or within the boundaries of a cross-section surface.

In the program's parallel analysis location input dialog box, the analysis locations may be named by the analyst as other than the default, but the program-assigned "sequence #" needs to be kept in the name for identification on the parallel analysis location table because the parallel barrier view only displays sequence numbers and not names, and the table only displays names and not sequence numbers.

The "computed increases in L_{Aeq1h}" due to reflections are in this table. The increases are to the "with barrier" L_{Aeq1h} values in the main sound-level results table. However, FHWA TNM does not add these increases to those "with barrier" levels. If new analysis locations have been added to the parallel barrier case that are not among the main FHWA TNM receivers, these new analysis locations will not have L_{Aeq1h} calculated for them in the main TNM run. However, these analysis locations may represent nearby receivers in the main run for which there are results.

The analyst should be wary of computed increases of 0.0 dB, especially in sound-reflecting cases. Sometimes, when the analysis location Z coordinate is below the roadway Z coordinate, the computed increases may be incorrectly computed as zero. This problem appears to be random. Sometimes, "grabbing" all of the graphical objects in the parallel barrier view and moving them up or down very slightly will correct the problem. Alternatively, if the analysis location is slightly below the roadway elevation, the analysis location's elevation could be adjusted to move it slightly above the roadway elevation.

The TNM Users Guide suggests using these L_{Aeq1h} increases as adjustment factors in the main TNM run for those receivers represented by these analysis locations. If this is done after calculation of levels by the main part of FHWA TNM, the calculated levels would be invalidated and have to be recalculated to include these factors. Used in this manner, the "no barrier" and "with barrier" L_{Aeq1h} will be increased, which could lead to designing taller walls to get back down to the pre-reflections "with barrier" levels. However, as seen in this research, raising the wall heights in a parallel barrier situation may increase the multiple reflections sound-level increase for certain receiver positions, negating the effect of the raised wall heights on overall noise reduction, and likely requiring a re-analysis in the parallel barrier module.

The preferred alternative is to not use the parallel barrier sound level increases as adjustment factors, but to use the parallel barrier module as a design tool to analyze the effects of sound-absorbing materials or tilting one or more of the walls outward.

To test sound absorption, changes would be made to the NRC values in the parallel cross section input dialog box. However, if the parallel cross section input dialog box is already open, its data will be for the previously remembered case, as indicated by the name in the input dialog box window banner. This input dialog box must be closed and then reopened before changing data such as the NRC. If this is not done, the computed increases for the new case will be based on the old data (and thus will not change from their previous values), even though the parallel analysis location table will show the new design's name. Note that FHWA TNM will not accept an NRC greater than 0.95 even though some products report higher values. An NRC of 0.05 is typically used for reflective materials such as concrete. An approximate NRC for grassy areas within the cross section would be 0.4.

One final note: after an input check in the parallel barrier module, FHWA TNM will show a message box stating that the "Current data is valid. Discard and recalculate?" Actually, the data are not valid because they were just changed; the case must be recalculated to see the effects of the input data changes.

CHAPTER 13

Tunnel Openings

13.1 Introduction

Tunnel openings produce localized increases in traffic noise levels in relatively close proximity to the opening (or "portal"). The amount of noise radiated from a tunnel opening is dependent on a number of factors including traffic volumes and speeds, the presence of scattering and absorption elements inside the tunnel, the size of the tunnel opening, and the length of the tunnel. To produce best modeling practices, the research team conducted a literature review and evaluated several modeling techniques within TNM using the results from another environmental noise prediction program as a benchmark. The following sections describe the development of the best modeling practices for tunnel openings and present best modeling practices for an approximate calculation of the "tunnel effect" with TNM. Appendix L (available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986) provides a comprehensive discussion of the literature review and data review and also identifies gaps or weaknesses in the studies that have been performed to date by other researchers including Takagi et al.[62] and Probst.[63]

Given the limitations on the types of objects that are available to the user in TNM Version 2.5,[64] the research team has come up with best modeling practices for an approximate calculation of the "tunnel effect." Should users require a more precise evaluation of the tunnel effect, or the effects of variables not addressed in this research, the research team suggests the use of other commercially available environmental noise prediction models to supplement the best modeling practices described herein.

13.2 Modeling Techniques Evaluated

The research team identified several modeling techniques for evaluation and testing based on a comprehensive literature review that is detailed in Appendix L. The team found that the modeling technique presented by Probst appears to provide a relatively precise modeling of the radiated noise from tunnel openings; however, that study does not provide any validation or comparisons with measurement data. Therefore, while the Probst approach is comprehensive, thorough, and based upon well-established methods, and therefore holds significant promise as a model for serious consideration by this research team, the methodology has not been validated with measurements, and this is a weakness.

In comparison, Takagi et al. developed a model of tunnel opening noise emissions for tunnels of both semi-circular and rectangular cross section. The Takagi et al. model derives sound power at the mouth of the tunnel from assumed sound power of vehicular traffic inside the tunnel integrated along the length of the tunnel with an assumed absorption factor. Modeling results were compared with sound-level measurements at 10 locations outside the tunnel of the time-history of a single vehicle traveling in the tunnel and also of the noise from continuous traffic. The Takagi et al. paper cites the methodology of the ASJ Model 1998 as being used to compute the L_{Aeq} values at the tunnel entrance and presents validation data and curve fit results that show good agreement. The Takagi et al. model forms the basis of the tunnel-opening algorithms in the SoundPLAN noise prediction software. The research team chose to use SoundPLAN's tunnel-opening functionality as the benchmark for predicting noise from tunnel openings and for evaluating alternative modeling techniques using TNM.

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[62] Takagi, K., T. Miyake, K. Yamamoto, and H. Tachibana, "Prediction of Road Traffic Noise Around Tunnel Mouth," Paper no. 566, *Inter-noise 2000*, Proceedings of the 29th International Congress on Noise Control Engineering, August 27–31, Nice, France, 2000.

[63] Probst, W., "Prediction of Sound Radiated from Tunnel Openings," *Noise Control Engineering Journal*, Vol. 58, No. 2, 2010, pp. 201–211.

[64] The only type of source within TNM Version 2.5 is a roadway, which is modeled as a line source. TNM does not possess the functionality to model a source of noise as either a point source or an area source.

For the evaluation of these candidate modeling techniques, the team calculated traffic noise levels using SoundPLAN's tunnel-openings objects and algorithms and then used those calculated values as the baseline against which each modeling technique was evaluated. This process resulted in the development of methodologies to adjust the FHWA TNM output data to appropriately incorporate the effects of tunnel openings. The best modeling practices for TNM users are based on the modeling technique that was found to yield the best agreement with the tunnel-openings algorithms in SoundPLAN.

In addition, the team developed a table of results directly from the SoundPLAN-Takagi et al. model that can serve as a quick reference for the tunnel effect given a number of variables. These variables included receiver (receptor) location relative to the tunnel opening, tunnel length, and tunnel-opening size (number of lanes). The SoundPLAN model is based on metric system (SI) units, so the modeling with the Takagi algorithms was conducted in SI units. Since later TNM analysis results were compared directly with the SoundPLAN-Takagi results, the SI units were retained for the TNM analysis as well.

The following parameters were included in each of the modeling techniques that were evaluated by the research team:

- A single TNM road (1,500 m long with 0.0 percent grade) located outside the tunnel with 3,600 automobiles, 150 medium trucks, and 120 heavy trucks per hour, all traveling at a speed of 55 kph.
- Pavement as default ground type everywhere.
- A 5-by-7 matrix of receptors at distances of 10, 25, 50, 100, and 300 m from the road centerline and distances of 1, 5, 10, 25, 50, 100, and 300 m from the tunnel opening.
- Receptor elevations of 1.5 and 4.5 m above ground level (AGL).
- Tall noise barriers at a height of 30 m to represent the side walls of the tunnel (included only in the TNM model of the tunnel opening).
- No added absorptive material in the tunnel.
- Two tunnel opening sizes—5 m wide by 6 m high and 15 m wide by 6 m high.

The research team generally focused the evaluation on tunnels that were 30 and 150 m in length; however, tunnel lengths of 1 m and 1,000 m also were evaluated in an attempt to understand the dependency of the calculated "tunnel effect" upon tunnel length.

Before evaluating and testing the modeling techniques against SoundPLAN's tunnel-opening algorithms, the team tested SoundPLAN's implementation of the TNM algorithms for the road outside the tunnel. Excellent agreement between SoundPLAN's implementation of the TNM algorithms and TNM itself was found for the simple straight road located outside the tunnel—as described in the first bullet above. Calculated traffic noise levels in SoundPLAN ranged from 0.1 dBA less than to 0.2 dBA greater than the noise levels calculated with TNM Version 2.5 at both 1.5 and 4.5 m AGL. On average, SoundPLAN-calculated noise levels were 0.1 dBA higher than TNM-calculated noise levels for the 5-by-7 receptor matrix at 1.5 m AGL. At 4.5 m AGL, SoundPLAN-calculated noise levels were within 0.1 dBA of the TNM-calculated noise levels.

Having demonstrated that SoundPLAN was appropriately implementing TNM's algorithms for the road outside the tunnel, the modeling techniques were evaluated using SoundPLAN's calculated noise levels as a benchmark, as described below. For the evaluation of the following modeling techniques, the contributions from the road outside the tunnel were ignored, and calculated "tunnel-only" noise levels from TNM Version 2.5 were compared to calculated "tunnel-only" noise levels from SoundPLAN.

Initially, the team evaluated a perpendicular road across and just outside the tunnel opening in TNM, as a worst-case source location. This puts noise sources in approximately the right positions, but perhaps too low in cases where tunnels have high ceilings. As described in Appendix L, this modeling technique yielded TNM-calculated results that were in poor agreement with the SoundPLAN-Takagi et al. benchmark. After several iterations, the team selected a modeling technique that placed three or four parallel and evenly spaced roadways in the tunnel for each road outside the tunnel. The traffic volumes on the roads inside the tunnel were adjusted relative to the traffic volume on the road outside the tunnel, depending on the length of the tunnel and the number of roadways in the tunnel. Traffic speeds on the roads inside the tunnel matched the speeds on the road outside the tunnel.

13.2.1 Three Roads Inside the Tunnel (Volume of Each Road = 1 × Volume on the Road Outside the Tunnel)

This modeling technique considered three evenly spaced roads inside the tunnel between two very tall noise barriers that were included in the model to represent the walls of the tunnel. Each road inside the tunnel was modeled with the same traffic volumes and speeds as the road outside the tunnel—so in effect, the traffic volumes inside the tunnel were three times the traffic volumes on the road outside the tunnel. Figure 62 shows a plan view of the modeled geometry for a tunnel measuring 15 by 6 by 30 m in TNM.

The results of the modeling technique depicted in Figure 62 are presented in the graphs of Figures 63 to Figure 65 for receptors at a height of 1.5 m AGL. While the

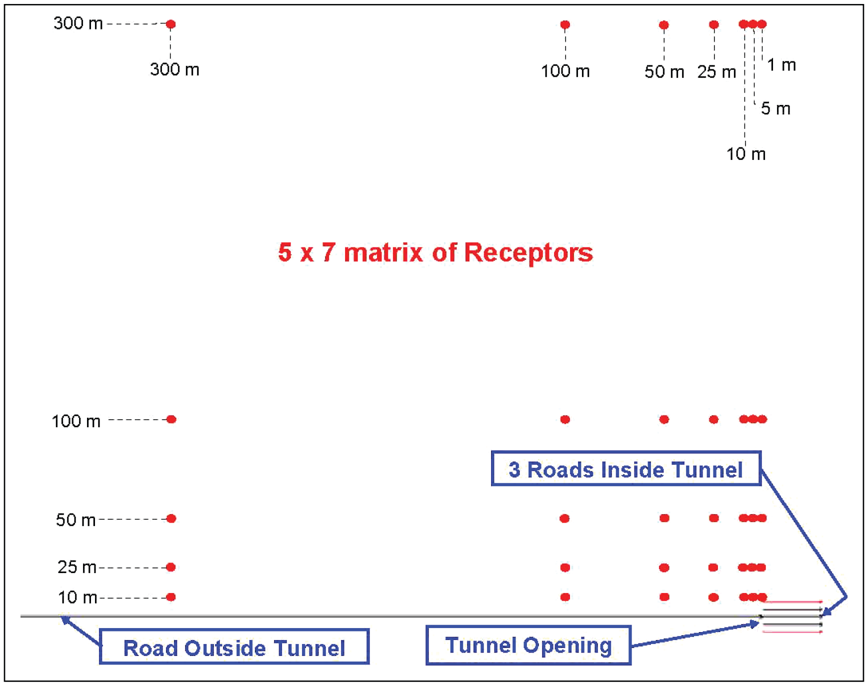

Figure 62. Plan view of modeled geometry for tunnel measuring 15 by 6 by 30 m with three parallel and evenly spaced roads inside (with the 5-by-7 matrix of receptors).

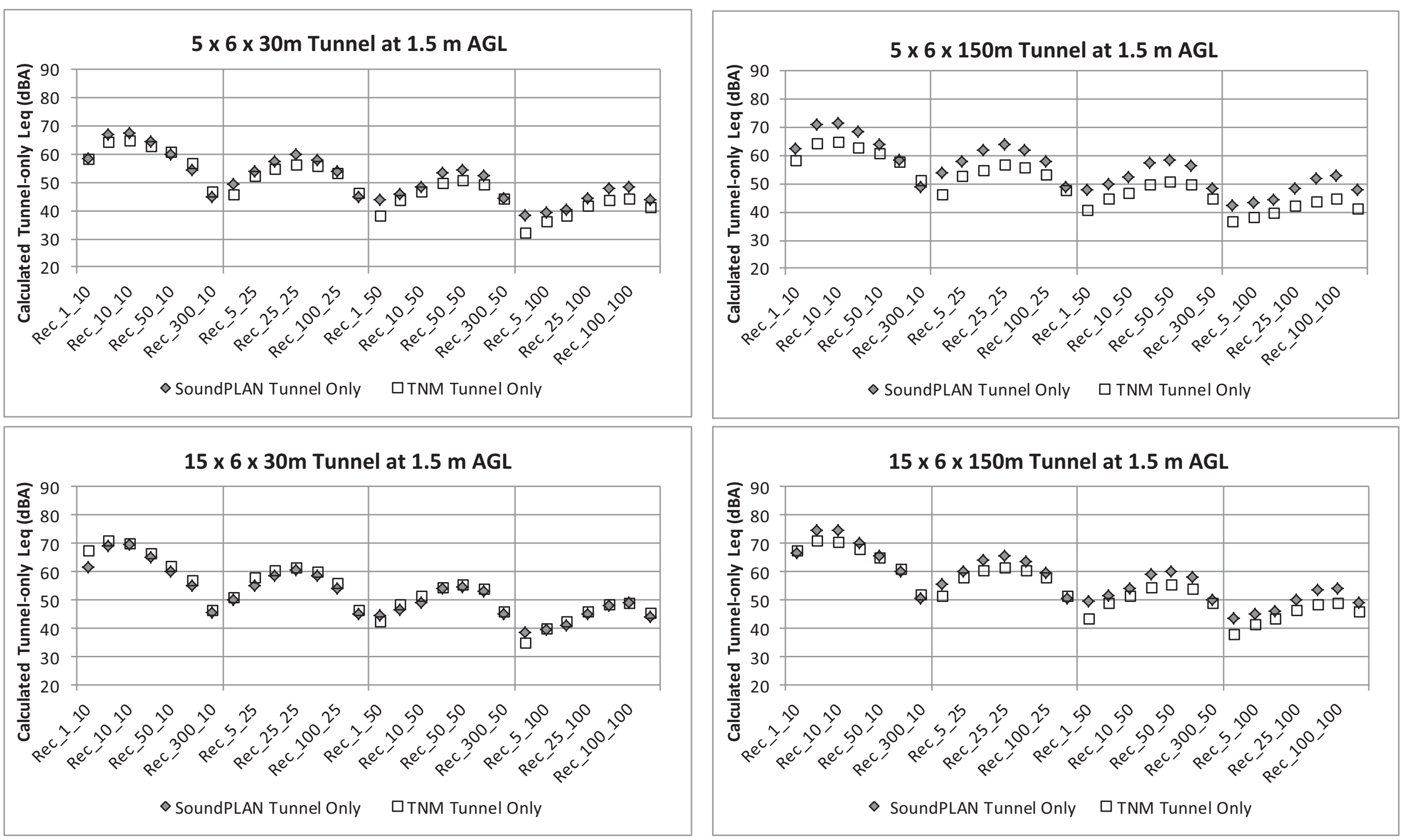

Figure 63. TNM and SoundPLAN tunnel-only noise levels for three parallel roads inside the tunnel, each with 1 × the volume of road outside tunnel—at distances of 1, 5, 10, 25, 50, 100, and 300 m from the tunnel opening and 10, 25, 50, and 100 m from the road centerline and 1.5 m AGL.

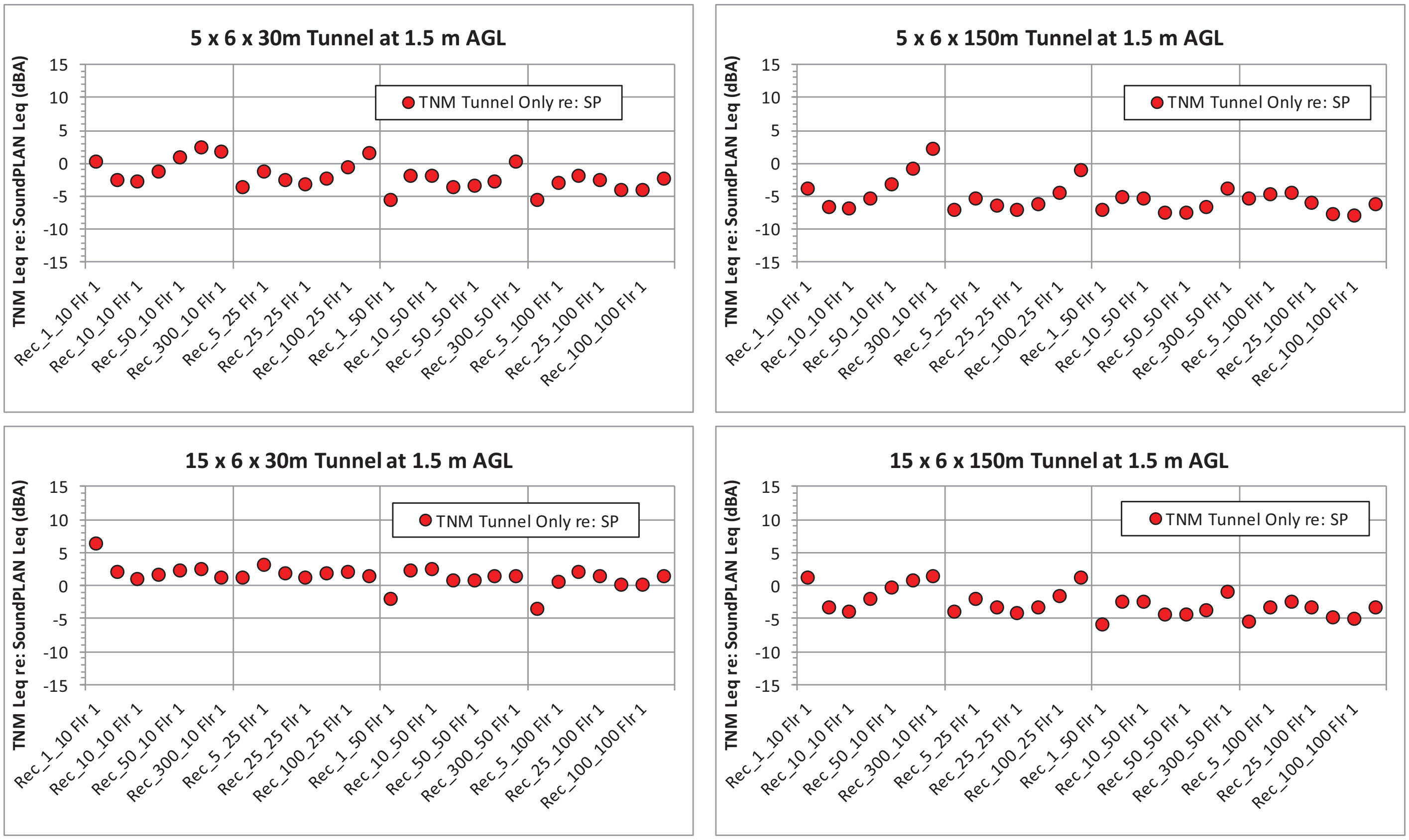

Figure 64. TNM tunnel-only noise level minus SoundPLAN tunnel-only noise level for three parallel roads inside the tunnel, each with 1 × the volume of road outside tunnel—at distances of 1, 5, 10, 25, 50, 100, and 300 m from the tunnel opening and 10, 25, 50, and 100 m from the road centerline and 1.5 m AGL.

results for a receptor height of 4.5 m AGL are not shown herein, they very closely matched the results at the 1.5-m receptor height.

Figure 63 shows TNM and SoundPLAN tunnel-only noise levels for this modeling technique for the 5-by-7 matrix of receptors at 1.5 m AGL. Figure 64 shows the calculated difference between tunnel-only noise levels calculated with TNM and SoundPLAN. Figure 65 plots the calculated TNM tunnel-only noise levels against the SoundPLAN tunnel-only noise levels.

Four tunnel lengths (1, 30, 150, and 1,000 m) were evaluated for this modeling technique to understand the extent to which tunnel length influences the amount of noise radiated from the tunnel opening. The results of this modeling technique were judged to be acceptable for both the 5-m and the 15-m tunnel width at a length of 30 m. However, at a tunnel length of 150 m, the TNM-calculated tunnel effect was approximately 4 dB lower than the tunnel effect calculated with SoundPLAN.

The results for the 30-m-long tunnel were judged to be acceptable. This modeling technique was judged to be suitable for tunnel lengths between 15 and 60 m.

13.2.2 Three Roads Inside the Tunnel (Volume of Each Road = 2.5 × Volume of the Road Outside Tunnel)

This modeling technique was evaluated to address the 4-dB under-prediction that was previously observed for the 150-m-long tunnel. Since the calculated tunnel-only noise levels demonstrated the expected directionality pattern using the previous modeling technique, the 4-dB under-prediction was addressed by increasing the traffic volumes on the three roads inside the tunnel by a factor of 2.5 times the traffic volume on the road outside the tunnel. This upward adjustment effectively increases the traffic volumes inside the tunnel by a total of 7.5 times the traffic on the road outside the tunnel.

The graphs of Figures 66 to Figure 68 show the results of this modeling technique for the 5-by-7 matrix of receptors at a height of 1.5 m AGL. Figure 66 shows TNM and SoundPLAN tunnel-only noise levels for this modeling technique, while Figure 67 shows the calculated difference between tunnel-only noise levels calculated with TNM and SoundPLAN, and Figure 68 plots the calculated TNM tunnel-only noise levels against the SoundPLAN tunnel-only noise levels. As

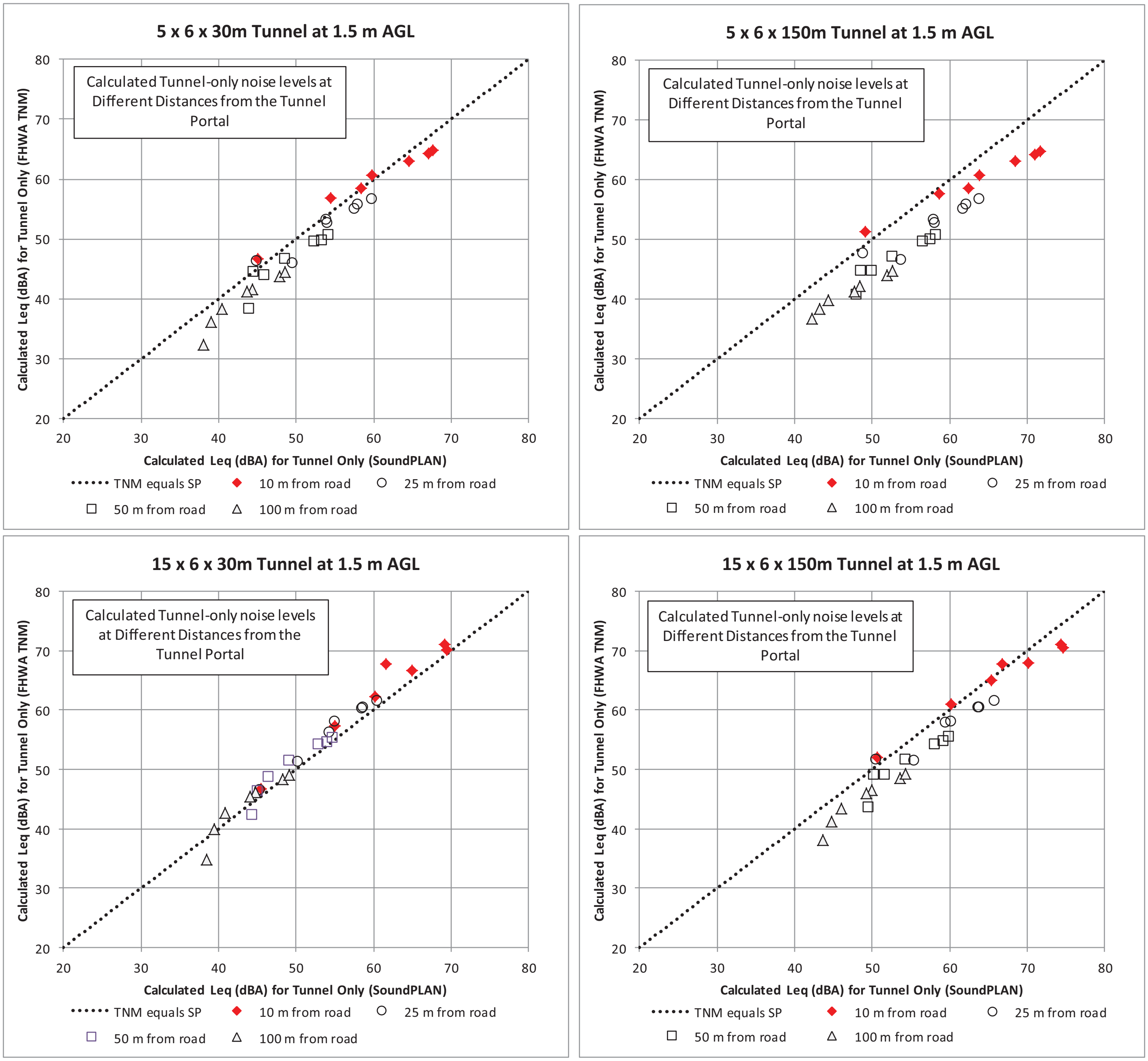

Figure 65. FHWA TNM tunnel-only noise levels compared to SoundPLAN tunnel-only noise levels for three parallel roads inside the tunnel, each with 1 × the volume of road outside tunnel—at distances of 1, 5, 10, 25, 50, 100, and 300 m from the tunnel opening and 10, 25, 50, and 100 meters from the road centerline and 1.5 m AGL.

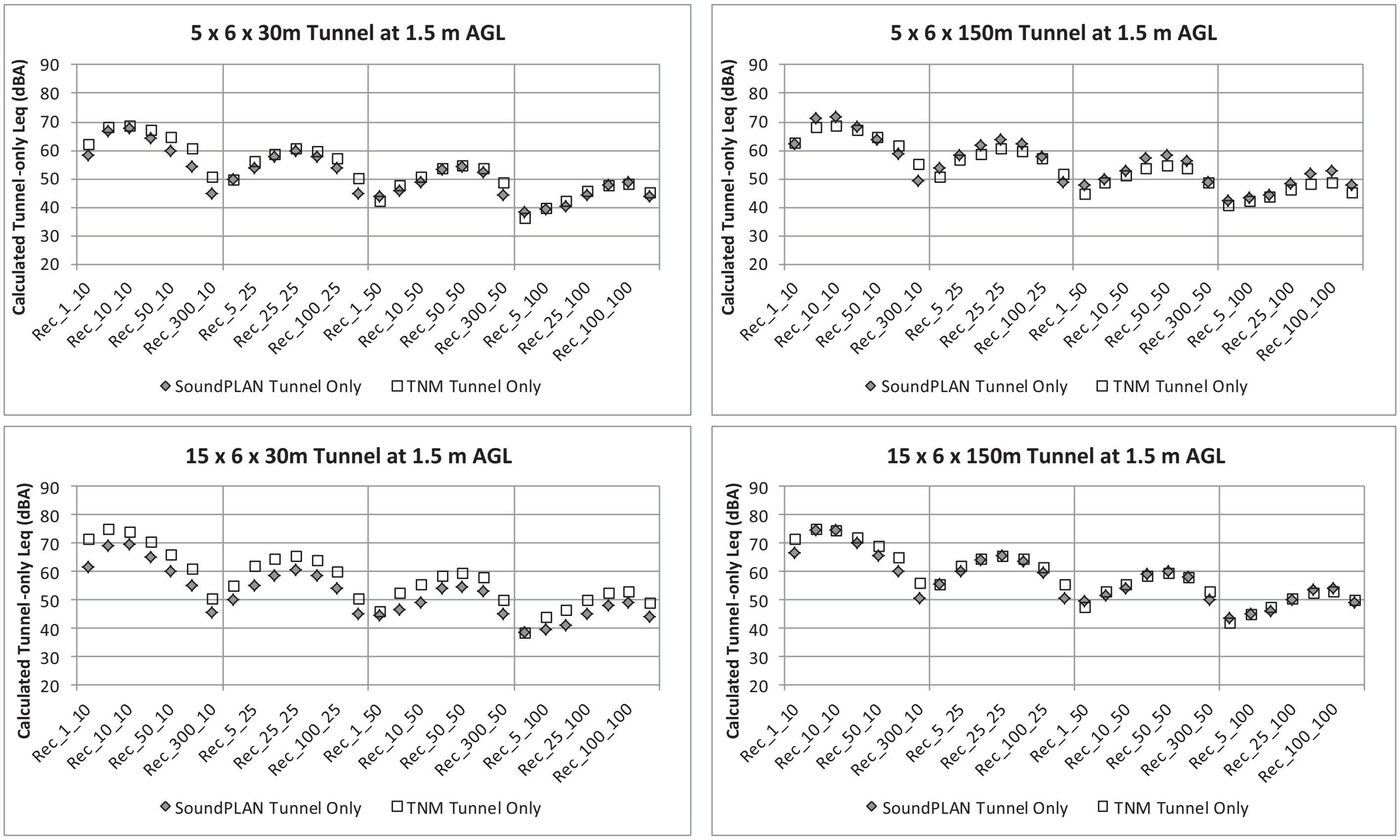

Figure 66. TNM and SoundPLAN tunnel-only noise levels for three parallel roads inside the tunnel, each with 2.5 × the volume of road outside tunnel—at distances of 1, 5, 10, 25, 50, 100, and 300 m from the tunnel opening and 10, 25, 50, and 100 m from the road centerline and 1.5 m AGL.

shown in the two charts on the right-hand side of Figure 68, this modeling technique shows better agreement with SoundPLAN for the 150-m-long tunnel.

The results for the 150-m-long tunnel were judged to be acceptable, and so this modeling technique was judged to be suitable for tunnel lengths greater than 60 m.

13.2.3 Four Roads Inside the Tunnel (Volume of Each Road = 1.9 × Volume of the Road Outside Tunnel)

The previous modeling technique is easily used for cases with a single road on the outside of the tunnel. Realizing that there may be real-world situations for which two roads may be modeled outside the tunnel, e.g., to accommodate two directions of travel, this modeling technique was evaluated to provide the user with a more straightforward method of distributing the traffic volumes across each of the roads inside the tunnel. This modeling technique uses 1.9 times the traffic volume(s) on the road(s) outside the tunnel on each of the four roads inside the tunnel. This technique effectively increases the traffic volumes inside by a total of 7.6 times the traffic on the road outside the tunnel. As expected, the results of this modeling technique closely matched the results of the previous technique that utilized three roads inside the tunnel each with 2.5 times the traffic on the road outside the tunnel. For this reason, the results are not presented in the main body of the report; rather, graphs of the results for this modeling technique many be found in Appendix L.

This modeling technique may be used interchangeably with the previous three-road modeling technique. This four-road modeling technique also was judged to be suitable for tunnel lengths greater than 60 m.

13.3 Best Modeling Practices for Tunnel Openings

The team recognizes that any one of its best modeling practices may not be appropriate for all modeling scenarios. For example, one practice may be appropriate for at-grade receptors, but not for elevated receptors. Even so, based on the team's review of the trends that are described in Appendix L and the following general observations, the research team's best management practices for modeling tunnel openings in TNM Version 2.5 are presented in this section. Based on the desired level of precision and the need to evaluate the effects of different

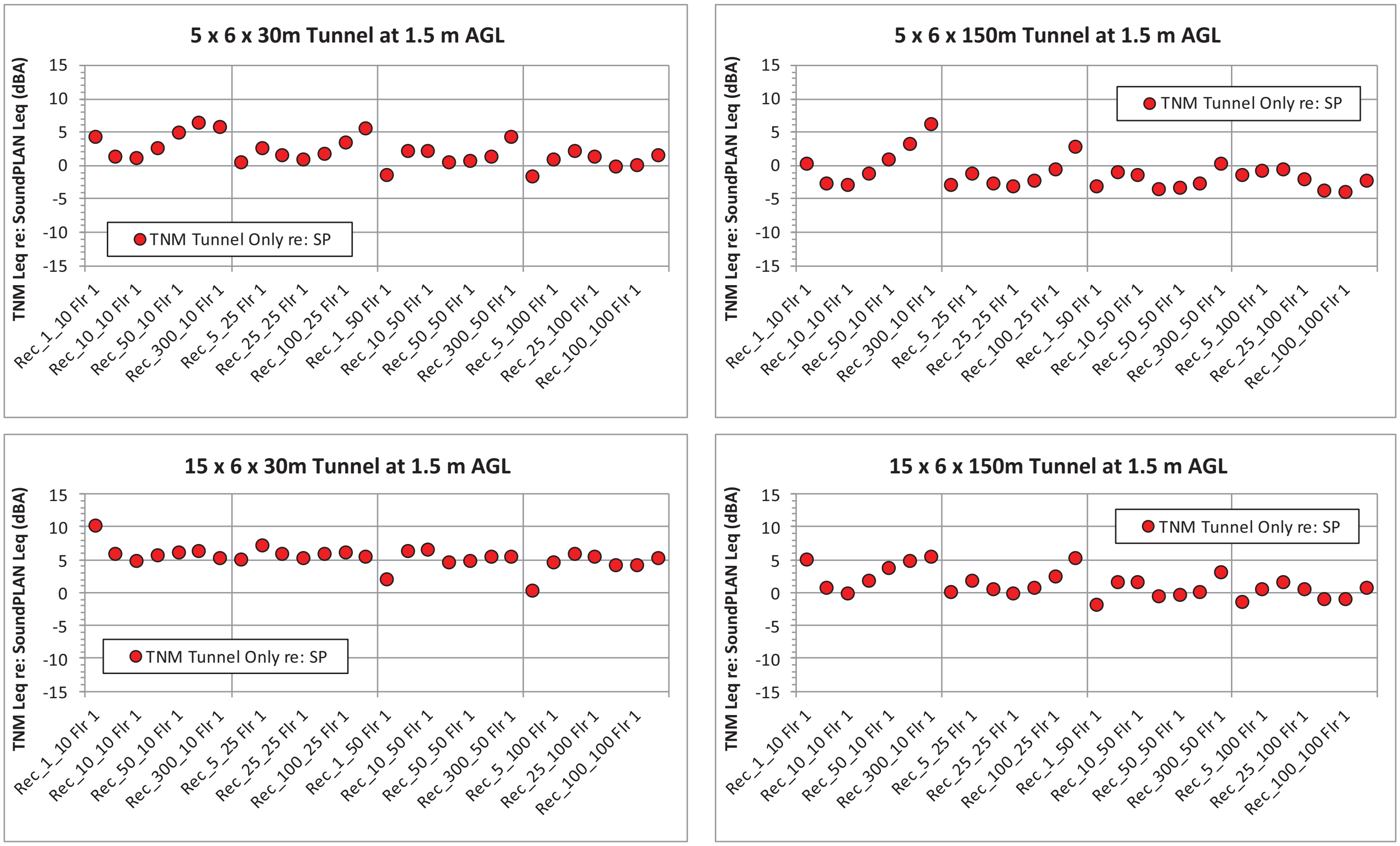

Figure 67. TNM tunnel-only noise level minus SoundPLAN tunnel-only noise level for three parallel roads inside the tunnel, each with 2.5 × the volume of road outside tunnel—at distances of 1, 5, 10, 25, 50, 100, and 300 m from the tunnel opening and 10, 25, 50, and 100 m from the road centerline and 1.5 m AGL.

variables such as noise barriers, two approaches to assessing the effects of tunnel openings are suggested. Before presenting those two approaches, the following observations are given:

- **General Observation 1.** The width of the tunnel opening does not have a strong influence on the amount of noise radiated from the opening. Therefore, no special accommodations are needed for tunnels of different widths.
- **General Observation 2.** The length of the tunnel affects the noise radiated from the tunnel opening. The SoundPLAN calculations show that noise emissions increase with increasing tunnel length up to a point. Over the range of tunnel lengths from 30 to 150 m, the additional tunnel length adds approximately 0.03 dB of radiated noise per meter. At greater tunnel lengths, over the range from 150 to 1,000 m, the additional tunnel length adds only 0.002 dB of radiated noise per m.

13.3.1 Table of Precalculated Adjustments for "Tunnel Effects"

Users may use Table 15 to determine an adjustment to the TNM-computed, A-weighted traffic noise level without any roadways in the tunnel for various receptors based on their proximity to the tunnel opening. As shown in Table 15, the calculated tunnel effects based on the SoundPLAN model are mostly negligible at distances of 100 m from the road. The largest adjustment factors occur close to the opening of long tunnels. This modeling technique would be suitable for an environmental noise study in support of the National Environmental Policy Act process.

13.3.2 Model Tunnel Openings in FHWA TNM Version 2.5

The team has developed the following guidelines for those users who may wish to explicitly model a tunnel opening in TNM Version 2.5. This modeling technique would be suitable for a noise abatement design study. The technique is as follows:

- Radiated noise from tunnel openings should not be modeled for tunnel lengths that are less than 15 m; the sound-level increases are minimal.
- For tunnel lengths between 15 and 60 m, use a minimum of three or four parallel roads in the tunnel. The roads

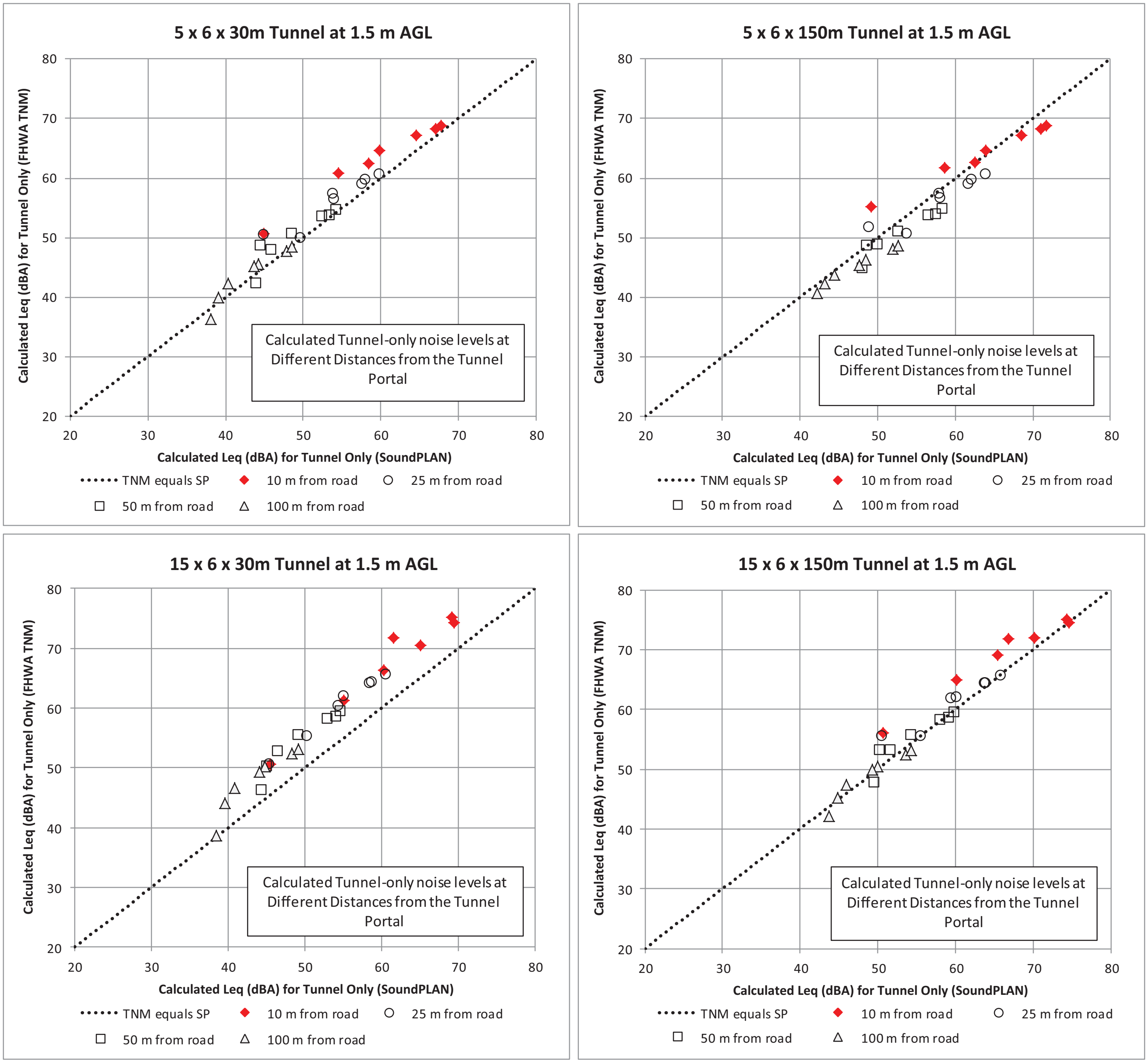

Figure 68. FHWA TNM tunnel-only noise levels plotted against SoundPLAN tunnel-only noise levels for three parallel roads inside the tunnel, each with 2.5 × the volume of road outside tunnel—at distances of 1, 5, 10, 25, 50, 100, and 300 m from the tunnel opening and 10, 25, 50, and 100 m from the road centerline and 1.5 m AGL.

Table 15. A-weighted adjustments to add to TNM-calculated noise levels due to traffic on roads outside a tunnel.

Distance from Road Centerline (m)	Distance from Tunnel Opening (m)	Tunnel Effect (dBA) to Be Added to TNM-Calculated Noise Levels			
		Single Lane (short tunnel)	Single Lane (long tunnel)	2+ Lanes (short tunnel)	2+ Lanes (long tunnel)
10	1	0	1	0	1
	5	1	3	2	5
	10	1	3	2	4
	25	1	1	1	2
	50	0	0	0	1
	100	0	0	0	0
	300	0	0	0	0
25	1	0	0	0	0
	5	0	0	0	1
	10	0	1	1	2
	25	1	1	1	2
	50	0	1	0	1
	100	0	0	0	0
	300	0	0	0	0
50	1	0	0	0	0
	5	0	0	0	0
	10	0	0	0	0
	25	0	1	0	1
	50	0	1	0	1
	100	0	0	0	1
	300	0	0	0	0
100	1	0	0	0	0
	5	0	0	0	0
	10	0	0	0	0
	25	0	0	0	0
	50	0	0	0	1
	100	0	0	0	1
	300	0	0	0	0

should be evenly spaced across the tunnel section along the full length of the tunnel, with two 30-m-tall noise barriers located along the tunnel walls:

– Three roadways are suggested for single-direction tunnels, since most of the published research and the tests in this research were conducted with such a configuration. Each of the three roadways should have all of the traffic that was on the road outside of the tunnel (regardless of the number of lanes that were modeled outside of the tunnel) such that the total traffic volume in the tunnel is three times the traffic volume outside the tunnel.
– Only volumes should be increased, not speeds, and the volumes should be increased for all vehicle types proportionally.
– If the tunnel has two directions of traffic, then use a minimum of four roadways inside the tunnel. If four roads are modeled inside the tunnel, each should have 75% of the traffic volume that is on the road(s) outside the tunnel, such that the total traffic volume inside the tunnel would be three times the volume outside the tunnel.

- For tunnels longer than 60 m, it is not necessary to model roadways the full length of the tunnel. While this was not tested thoroughly in the research, it is expected that only up to approximately 300 m of tunnel length need be modeled to provide the necessary contribution of the reflected sound field to calculated noise levels at the receptors beyond the tunnel opening. However, for longer tunnels, the traffic volumes in the tunnel section need to be increased such that they are approximately seven to eight times the total traffic volume outside of the tunnel. This can be accomplished by either adding more roadways in the tunnel or by increasing proportionally the traffic volumes on the modeled roadways.

13.3.3 Use Other Commercially Available Environmental Noise Prediction Models

The addition of absorptive materials or absorptive cavities inside tunnels, not far from the tunnel opening, will decrease radiated noise from the opening. The team has not attempted to address the use of absorption elements inside the tunnel in this guidance document. If accommodating those characteristics is important, then the team suggests the highway noise analyst make use of the SoundPLAN approach (with the Takagi et al. model) or the Probst approach with Cadna/A. Those environmental noise prediction software packages can model the tunnel noise emissions with and without added absorption inside the tunnel. The differences calculated could then be applied to the results predicted with TNM using this guidance. Alternatively, a potentially more accurate approach would be to compute the tunnel-only emissions with either of the other methods, determine an A-weighted adjustment factor based on the position of a receptor with respect to the tunnel opening, and then apply that adjustment factor to the TNM-calculated noise levels for the road outside the tunnel (only).

13.4 Conclusions

The research team developed best modeling practices that may be used to adjust FHWA TNM predictions to account for the effects of radiated noise from tunnel openings. The team recognizes that any one of its suggested best modeling practices may not be appropriate for all modeling scenarios. This guidance only addresses tunnel-opening contributions to the overall noise levels beyond the end of the opening. Receivers placed behind the tunnel mouth will not receive any contribution from the tunnel opening using the best modeling practices in this document. If the user wishes to quantify the effect of the tunnel opening at such locations, the research team suggests the use of other commercially available environmental noise prediction models. However, the researched studies have shown that the radiated noise from a tunnel opening is close to negligible at locations behind the tunnel opening.

Appendices A through L

Appendices A through L of the contractor's final report for NCHRP Project 25-34 are not published herein but are available on the NCHRP Project 25-34 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2986. Appendix titles are the following:

- Appendix A: Structure Reflected Noise and Expansion Joint Noise
- Appendix B: Signalized Interchanges, Intersections and Roundabouts
- Appendix C: Area Sources
- Appendix D: Median Barriers
- Appendix E: Multilane Highways
- Appendix F: Building Rows
- Appendix G: Topography
- Appendix H: Ground Zones
- Appendix I: Tree Zones
- Appendix J: Wind and Temperature Gradients
- Appendix K: Parallel Barriers
- Appendix L: Tunnel Openings

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation