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TRAFFIC NOISE MODEL 3.1

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13. ABSTRACT (Maximum 200 words)
This technical manual describes the Federal Highway Administration's Traffic Noise Model (TNM) Version 3.1. Chapter 2 describes the process of determining noise emissions and levels at a reference location 15 m (50 ft) from the traffic noise source. This includes: the geometric discretizing of the study in the horizontal plane into elemental triangles, which are the basis for all other computations; the computation of traffic speed based on user inputs and TNM objects; and the determination of noise emissions based on measured levels at 15 m (50 ft), which are then converted to free-field at the same location. Chapter 3 describes how adjustments based on the horizontal geometry are determined. These include adjustments for: traffic volume and speed, and roadway lengths and distance (Ad). User specified adjustment factors are also discussed. Chapters 2 and 3 combined describe the functions that depend on the horizontal geometry. Chapter 4 describes how adjustments for all shielding and ground effects between the roadway and the receiver (As) are determined. Chapter 5 covers additional adjustment factors for parallel and single barrier reflections. Chapter 6 covers the computation of contours. Appendices supplement the discussions as needed and are largely reproductions of the appendices found in the TNM Version 1.0, modified only to reflect changes between TNM 1.0 and TNM 3.1 and to avoid repetition of some materials already presented in the main body.

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This report draws heavily from the previous work that went into the development of the Federal Highway Administration's Traffic Noise Model (FHWA's TNM) Version 1.0 and its technical report. The technical report for version 1.0 was written by: Christopher W. Menge, Christopher F. Rossano, Grant S. Anderson, and Christopher J. Bajdek. Much of the text of this report has been reproduced from this original version; however, since the release of TNM Version 1.0 many updates have been made to TNM so the content has been updated to reflect these changes.

Many people have contributed to TNM's improvements over the years, including staff from the Volpe National Transportation Systems Center, the Federal Highway Administration, multiple State Departments of Transportation, and various contractors. We would like to extend a special thanks to Roger Wayson, Judith Rochat, Cynthia Lee, Eric Boeker, Amanda Rapoza, Aaron Hastings, Adam Alexander, Mark Ferroni, Aileen Varela-Margolles and Cecilia Ho for their work during their time as USDOT staff.

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ABBREVIATIONS

Abbreviation	Term
Auto	Automobile
DGAC	Dense-graded asphaltic concrete
DNL	Day-Night Average Sound Level
EFR	Effective Flow Resistivity
EL	Vehicle Noise Emission Levels
ET	Elemental Triangle
FHWA	Federal Highway Administration
HPP	Highest Path Point
HT	Heavy Truck
L_{10}	Noise level exceeded ten percent of the time
L_{50}	Noise level exceeded fifty percent of the time
$L_{Aeq,1\text{-}hr}$	Hourly equivalent A-weighted sound pressure level
L_{den}	Day-Evening-Night Average Sound Level
L_{dn}	Day-Night Average Sound Level (see also DNL)
MT	Medium Truck
NHHP	Near Highest Path Point
NRC	Noise Reduction Coefficient
OGAC	Open-graded asphaltic concrete
Pa	Pascals, the unit of acoustic pressure
PCC	Portland cement concrete
REMEL	Reference Energy Mean Emission Level
SPL	Sound Pressure Level
TNM	Traffic Noise Model

GLOSSARY

Term	Definition
Elemental Roadway	The roadway segment that forms the base of an elemental triangle.
Elemental Triangle	The smallest unit that TNM evaluates. Each elemental triangle is defined by a receiver and two points on a roadway segment.
Energy Average	An average of noise levels that is computed by averaging the energy associated with the noise levels rather than the levels themselves. Sometimes referred to as a log average.
Horizontal Geometry	The study geometry as represented in the x-y plane. This is the geometry that is viewable in TNM's Plan View.
Level Average	An average of noise levels that is computed by averaging the levels themselves rather than the energy associated with the levels. Sometimes referred to as a linear average.
Reference Energy Mean Emission Level	An energy averaged maximum noise level as a function of speed fifty feet from the vehicle source.
Triangle Base	See elemental roadway.
Triangle Leg	The line that connects one end point on an elemental roadway to the receiver.
Vehicle Noise Emission Levels	An energy average noise level as a function of speed and distance. Note it is not a maximum level.
Vertical Geometry	The study geometry as represented along the z-axis. This defines the height of TNM objects.

PREFACE

This Technical Manual describes the fundamental equations and acoustical algorithms of Version 3.0[1] of the Federal Highway Administration's Traffic Noise Model (FHWA TNM). This is the Federal Highway Administration's software application for highway traffic noise prediction and analysis. A "Getting Started Guide" is available from within the Help Menu in the application itself and can be used to learn the basics of creating a study in TNM and obtaining noise predictions. In addition, a technical report, "Development of national reference energy mean emission levels for the FHWA traffic noise model (FHWA TNM), version 1.0", documenting the vehicle noise-emissions data base (Fleming, Rapoza, & Lee, Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model, 1995) is also available.

TNM Version 1.0 was developed in C++ using a Borland compiler and released in 1998 and replaced FHWA's prior pair of computer programs, STAMINA 2.0/OPTIMA. A Technical Manual for TNM Version 1.0 was also published in 1998 (Anderson, et al., 1998). Since that time there have been several incremental updates to TNM resulting in versions 1.0A, 1.0B, 1.1, 2.0, 2.1, and 2.5 (released in 2004). Each of these updates represented important improvements to TNM, but all utilized the same basic software architecture, which was based on 16-bit code that has several issues when running on modern computers and operating systems. These previous versions were intended to run on Microsoft® Windows 3.1 or later and TNM 2.5 will run on Windows XP but is not able to take advantage of XP's 32-bit architecture fully. It is not recommended to run TNM 1.X or 2.X on Windows 7 or later.

SOFTWARE BASIS OF TNM 3.0 AND TNM 3.1

TNM 3.0 and 3.1 were developed in C# using Microsoft's® Visual Studio and are intended for use on computers running Windows 7 or later because they utilize the 64-bit architecture of these versions of Windows. TNM 3.0 and 3.1 were developed using the following software and protocols:

- Microsoft .NET Framework
- Cesium Viewer/ WebGL 3-D
- C#
- Power Collections
- GeoAPI
- C5
- OxyPlot
- NUnit
- Telerik
- Microsoft Visual Studio 2010 with NET 4.0
- Esri ArcGIS Runtime, only applicable when using the ESRI version

[1] *TNM 3.1 uses the same algorithms as TNM 3.0.*

System Requirements for TNM 3.1

Due to the above architectural and algorithmic enhancements, TNM 3.1 should be run on a PC with:

- **OS:** Windows 7 or higher (not compatible with Mac OS)
- **RAM:** 16 GB, 32 GB RAM is recommended for optimal runtimes
- **Graphics Card:** Intel® HD Graphics (or equivalent)
- **ROM:** 20 GB or more of free hard drive space available for working (2 GB minimum for install)
- **CPU:** Intel® Core i5 or i7 (or equivalent CPU)
- **License:** ArcGIS Standard Runtime 10.2, only applicable when using the ESRI version

Functional Enhancements from TNM 2.5 to TNM 3.1

In addition to the architectural updates to make TNM more compatible with modern computers and operating systems, TNM 3.1 has many functional enhancements and maintains the improvements to the acoustical algorithms that were implemented with TNM 3.0.

- Improvements to the user experience for TNM 3.1 include:
    - Addition of an installer
    - Removal of the database saving structure
    - Ability to import projects with map projects, coordinate systems, and adjustments
    - Stabilization of View Panes and their interaction with the data model
- Improvements to the user interface for TNM 3.1 include:
    - Ability to filter and sort data in the Barrier Design Table
    - Standardization of the colors and symbols to better match previous versions of TNM
- Improvements to the object models for TNM 3.1 include:
    - Miscellaneous bug fixes, including a Ground Zone bug
    - Ability to calculate the full range of noise levels as intended in TNM 3.0
- Improvements to the acoustical algorithms in TNM 3.0 included:
    - Miscellaneous bugs fixed
    - Explicit computation of one-third octave bands below 250 Hz and above 5000 Hz
    - Computation of percentile noise levels (L_{10} and L_{50})
    - Uniform angles subtended by elemental triangles on the same acoustically homogenous section of roadway
    - True, three-dimensional divergence computations for free-field propagation
    - Computation of contribution to overall noise for single reflections due to barriers on opposite side of roadways

1. INTRODUCTION

The Federal Highway Administration Traffic Noise Model (FHWA TNM) is an engineering noise model that is used to predict highway-related noise levels adjacent to highways. These predictions are developed by first determining and then applying a series of adjustments to a reference sound level that is a function of the vehicle type and speed, roadway slope and pavement type. The reference level used by TNM is the Vehicle Noise Emission Level, which refers to the maximum sound level emitted by a vehicle pass-by at a reference distance of 15 m (50 ft). The adjustments account for traffic flow, volume and speed, roadway geometry, and shielding. These factors are related by the following equation:

$$L_{Aeq,1h} = EL_i + A_{traff(i)} + A_d + A_s \tag{1}$$

where, EL_i represents the vehicle noise emission level for the i^{th} vehicle type, $A_{traff(i)}$ represents the adjustment for vehicle volume and speed for the i^{th} vehicle type, A_d represents the adjustment for distance between the roadway and receiver and for the length of the roadway and A_s represents the adjustment for all shielding and ground effects between the roadway and the receiver.

TNM is an integrated model, which means that it computes noise contributions from short segments of roadways (called elemental roadways) due to each vehicle type for a given receiver and then adds up the results from each elemental roadway / vehicle type pair to determine the total noise level at the receiver. **Figure 1** illustrates, at a high level, the process by which noise levels are computed in TNM. Note that this flow chart distinguishes between aspects of the procedure that are based on the model's horizontal geometry (components in blue with a solid border) and a single component in orange with a dashed border that includes aspects of the procedure that are based on the model's vertical geometry.

The general procedure is to start with the entire study[2,3] and then create a list of all receivers to iterate through. For each receiver, all roadways with traffic defined are then iterated through. If traffic control devices exist, e.g. stop signs, or if the grade is greater than 1.5% then a speed flag is set for all affected vehicles to tell TNM that it will need to compute speeds for these vehicles (rather than assuming the user specified speeds). For each roadway segment with traffic, the roadway segment is subdivided into smaller sections such that the path between each end of the segment to the receiver encounters the same TNM objects (e.g. the same barriers, terrain lines, ground zones, etc.). These elemental segments are also selected to guarantee that the angle subtended is no greater than 10 degrees. The triangles formed by these elemental roadway segments and the receiver are called elemental triangles and are the fundamental geometries used in TNM to compute

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[2] *Study, project, run and model are used interchangeably to refer to the user defined geometry, traffic and meta-data that are used to define the parameters that are necessary to compute the noise level at each receiver location. To avoid ambiguity, in most cases, the terms study, project or run will be used in preference to model, since model can be confused with the acoustic model that refers to the algorithms used to compute the noise level at each receiver location.*

[3] *At a minimum, a study consists of at least one receiver and one roadway with traffic volumes and speeds defined on at least one segment. Most studies consist of: many roadways with many segments each and traffic volumes and speeds defined on most of these segments; several receivers representing noise sensitive areas, terrain lines, barriers, building rows, tree zones and ground zones that define the topography and acoustic absorption of the ground.*

noise results.

For each elemental triangle, TNM iterates over all vehicle types, determines vehicle speed, and computes emission levels for two sub-source heights. TNM then computes an adjustment, A_{traff}, that accounts for vehicle volume and speed; computes an adjustment, A_d, that accounts for distance and length of the elemental roadway segment; and computes and adjustment, A_s, that accounts for shielding and ground effects. This last adjustment factor, A_s, is the only one that is computed using the vertical geometry. Once all these adjustments are determined, final metrics are computed and stored. Once TNM iterates through all elemental triangles for a given receiver, the results are aggregated. TNM then moves to the next receiver and continues the process.

Chapter 2 describes the process of determining noise emissions (E) and noise emission levels (EL) at a reference location 15 m (50 ft) from the traffic noise source. This includes: the geometric discretizing of the study in the horizontal plane into elemental triangles, which are the basis for all other computations; the computation of traffic speed based on user inputs and TNM objects; and the determination of noise emissions based on measured levels at 15 m (50 ft), which are then converted to free-field at the same location. Chapter 3 describes how adjustments based on the horizontal geometry are determined. These include adjustments for: traffic volume and speed (A_{traff}) as well as roadway lengths and distance (A_d). User specified adjustment factors are also discussed here. Chapters 2 and 3 combined describe the functions that depend on the horizontal geometry. Chapter 4 describes how adjustments for all shielding and ground effects between the roadway and the receiver (A_s) are determined. Chapter 5 covers additional adjustment factors determined for parallel and single barrier reflections. Chapter 6 covers the computation of contours. Appendices are given at the end to supplement the discussions in chapters as needed and are largely reproductions of the appendices found in (Anderson, et al., 1998), modified only to reflect changes between TNM 1.0 and TNM 3.0 and to avoid repetition of some materials already presented in the main body.

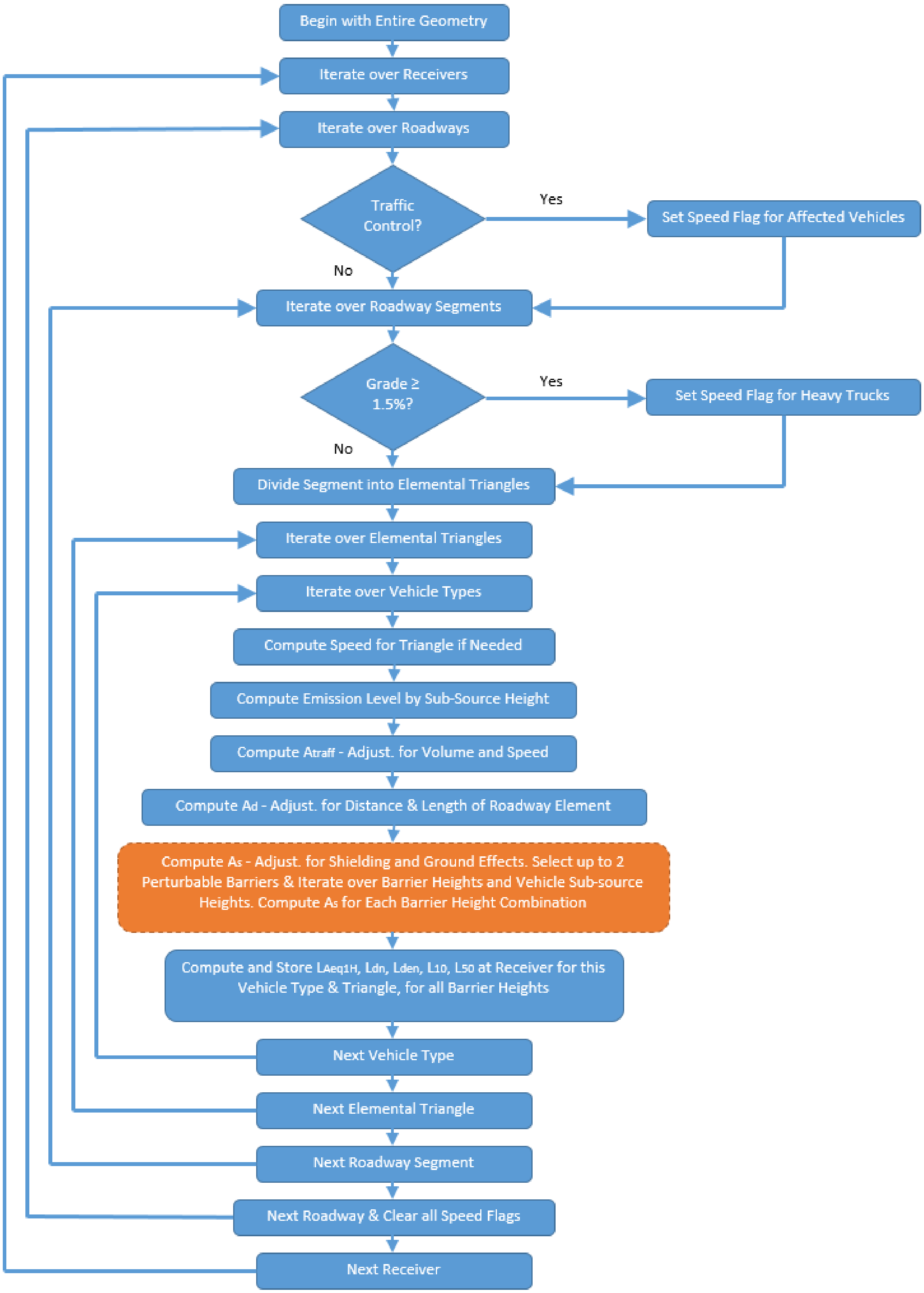

Figure 1 *High-level Flow Chart of TNM Computations (Horizontal Geometry Components are in Blue with Solid Outlines. Vertical Geometry Components are in Orange with Dashed Outlines.)*

2. EMISSIONS

This chapter describes how free-field noise emissions at the reference distance of 15 m (50 ft) are determined for all vehicle types. This includes a description of Elemental Triangles, which are the fundamental unit for all acoustic algorithms, a description of how speeds are determined, and finally the steps taken to compute free-field noise emissions for each elemental triangle using the appropriate speed.

2.1 ELEMENTAL TRIANGLES

This section describes the process of discretizing the study into elemental triangles (ETs), which are composed of elemental roadway segments and a receiver, and are the basis for all other computations.

An elemental triangle is the smallest unit that TNM evaluates. Each elemental triangle is defined by a receiver and two points on a roadway segment. There can be no points inside an elemental triangle. There will be at a minimum three points on its edges (two at the base formed by the roadway and one at it the receiver location) and possibly more. **Figure 2** illustrates the basic elements of an elemental triangle. These include an elemental roadway, which forms the base of the elemental triangle, a receiver, which defines the tip, and two legs, which define the path from the receiver to the roadway.

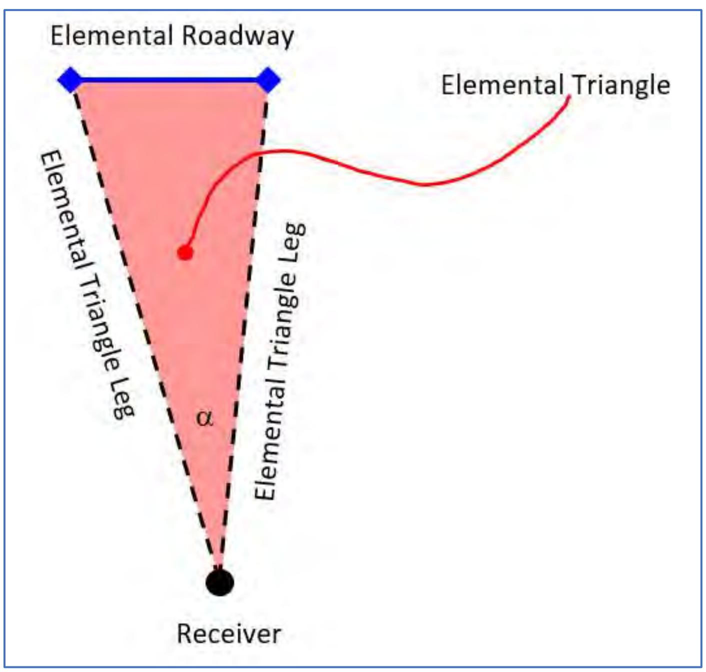

***Figure 2** Archetypal Elemental Triangle*

Line segments from other input objects, such as barriers, terrain lines, buildings, and tree zone lines, may cross the triangle, but may not terminate within it. **Figure 3** provides examples of what may and may not be an elemental triangle.

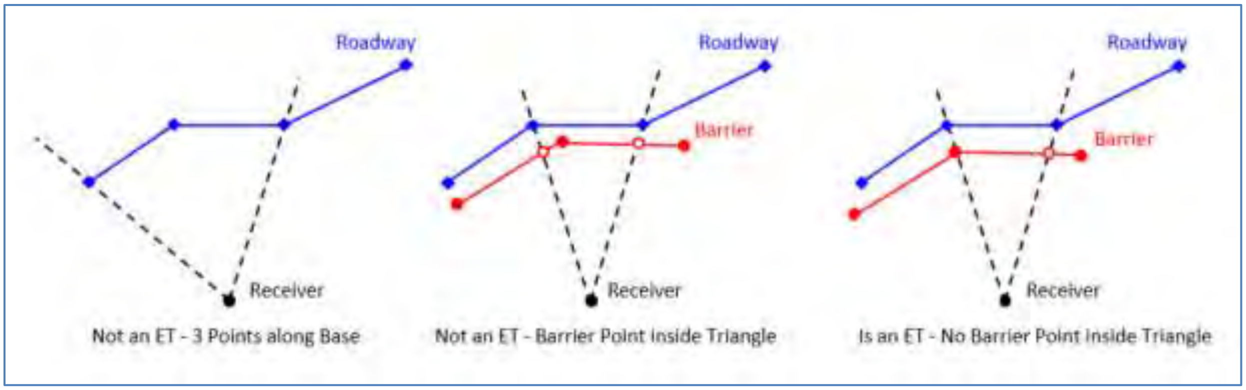

Figure 3 *Examples and Counter Examples of Elemental Triangles*

Procedurally, TNM decomposes the horizontal geometry (as defined by object points in the x-y plane) into elemental triangles before evaluating the vertical geometry. (Acoustical effects of objects whose line segments cross the elemental triangles are considered separately, and are discussed in Chapter 4.) **Figure 4** shows how a preliminary roadway-to-receiver triangle is defined by the closest spacing of the object endpoints in the x-y plane. In this example, the left leg of the triangle is defined by the projection of a line from the Receiver through Barrier Point 2. Since a point is not defined on the roadway at this intersection, this requires that the point on the roadway be inferred based on the geometry of the roadway segment, barrier point and receiver.

To ensure sufficient precision where object endpoints are not closely spaced (as in **Figure 4**), TNM equally subdivides preliminary triangles that subtend angles greater than 10 degrees. **Figure 5** shows **Figure 4** after TNM ensures that all the elemental triangles derived from this preliminary triangle all have the same angle that is also no greater than 10 degrees.

Noise emissions are determined for each elemental triangle and these emissions are then modified based on traffic volume, elemental roadway (the base of the elemental triangle) length and position relative to the receiver, based on shielding and ground effects as well as other adjustment factors (see Chapters 3 through 5.) Note that attenuation due to shielding factors is determined based on the energy average of the attenuation along the two legs of a given elemental triangle.

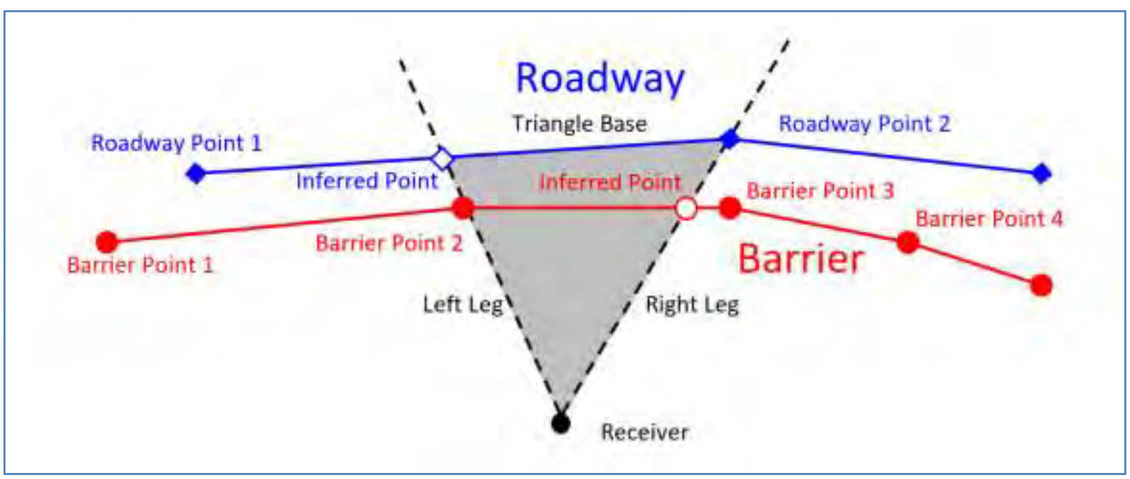

Figure 4 *Preliminary Triangle with no Points within the Geometry*

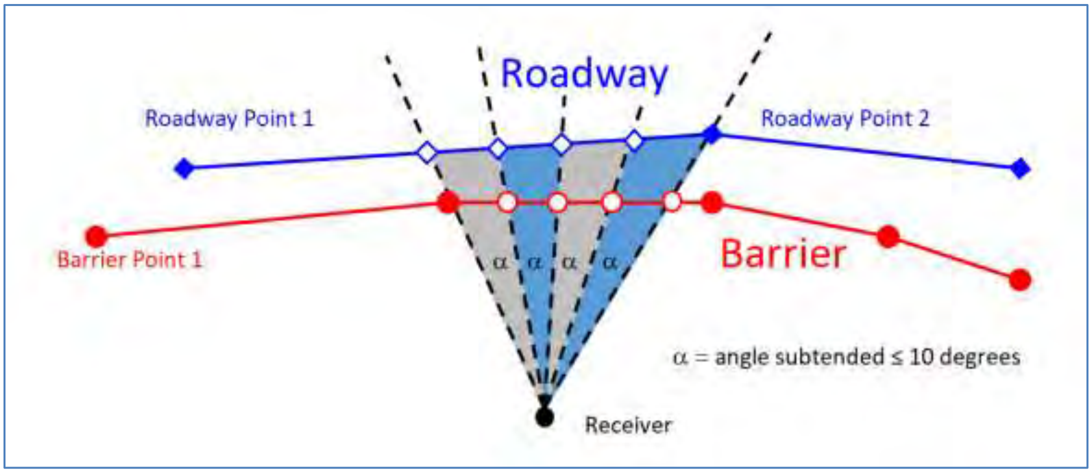

Figure 5 *Set of Elemental Triangles Derived from the Preliminary Triangle*

2.2 Speed Computations

In order to compute noise emissions for a vehicle type traveling along an elemental roadway segment associated with an elemental triangle, TNM needs to determine the speed of the vehicle. Under most conditions, TNM directly uses the vehicle speeds that are input by the user. However, TNM modifies the user input vehicle speeds under two conditions: (1) when traffic speeds are reduced by upgrades; and (2) when they are reduced by traffic-control devices. Under both conditions, TNM begins "tracking" the speed of the vehicle type along this roadway. When the speed changes under these two conditions, as will be explained below, TNM uses the average ($s_{average}$) of the entrance ($s_{entrance}$) and exit (s_{exit}) speeds for noise emission computations as given in Equation (2).

$$s_{average} = \frac{s_{entrance} + s_{exit}}{2} \tag{2}$$

2.2.1 Entrance Speeds

Entrance speeds for a vehicle type will either equal: (1) the speed entered by the user, (2) a traffic-control device's speed constraint, or (3) the exit speed of the previous elemental roadway segment. The first of these options will be used by TNM provided that TNM is not "tracking" the particular vehicle's speed. If TNM encounters a traffic-control device, TNM sets the entrance speed of all vehicle types to the device's speed constraint entered by the user and begins tracking speed for all vehicle types. If the traffic-control device only applies to a percentage of vehicles, TNM accounts for this as well. If TNM is tracking the speed of a vehicle, but it is not at the point of a traffic-control device, then the exit speed of the previous elemental roadway segment will be used for the current segment's entrance speed. This situation can arise for segments "downstream" from the initial traffic-control device and also when roadway upgrades that are equal to or greater than 1.5% have heavy truck traffic (or user-defined vehicles that are linked to heavy trucks).

Whenever a tracked vehicle types entrance speed matches the user input speed, TNM stops tracking that vehicle types speed.

2.2.2 Exit Speeds

Whenever TNM is tracking the speed of a particular vehicle type, it will compute the exit speed for the current elemental roadway segment using a set of regression equations developed for this purpose. TNM contains regression equations for all vehicles to accelerate them when their entrance speed is less than the user input speed. TNM also contains regression equations for heavy trucks to decelerate them when they are on a roadway segment with a grade greater or equal to 1.5%. Details of these regressions are given in Appendix A: Vehicle Speeds.

2.3 Vehicle Noise Emissions

This section describes how the vehicle noise emission levels (EL) are determined for each elemental triangle. This is a function of vehicle type and speed and thus can be affected by flow control devices and roadway grade.

As a single, acoustically isolated vehicle approaches and then passes a microphone that is located 15 m (50 ft) perpendicularly from the centerline of the near travel lane, its sound level rises, reaches a maximum, and then falls as the vehicle recedes from the microphone location. The maximum A-weighted sound level during the passby is called that vehicle's noise-emission level and the energy associated with this is the noise emission. Note that during computations TNM usually works with the energy associated with noise emissions; however, it is often more intuitive to discuss these steps according to the levels associated with the noise emission level. These two values are directly related to one another through the relationships described in Equations (3) and (4).

2.3.1 Noise Emission Database

TNM 3.1 relies on a database of maximum A-weighted sound pressure levels for passby events and corresponding one-third octave-band spectra to determine vehicle noise emission levels. This database includes noise emission levels from approximately 6000 vehicles measured in 9 states (Fleming, Rapoza, & Lee, Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model, 1995). Measurements included in the database were acquired over relatively flat ground, with the microphone at height 1.5 m (5 ft) and with the microphone horizontal distance at 15 m (50 ft). Generally, the ground between the roadway edge and the microphone was acoustically absorptive. The data were collected for cruise and full-throttle conditions over a variety of vehicle and pavement types. Vehicle types included in the database are described in **Table 1**.

TABLE 1: VEHICLE TYPES INCLUDED IN TNM 3.1

Vehicle Type	Description
Automobiles	All vehicles with two axles and four tires -- primarily designed to carry nine or fewer people (passenger cars, vans) or cargo (vans, light trucks) -- generally with gross vehicle weight less than 4,500 kg (9,900 lb)
Medium trucks	All cargo vehicles with two axles and six tires -- generally with gross vehicle weight between 4,500 kg (9,900 lb) and 12,000 kg (26,400 lb)
Heavy trucks	All cargo vehicles with three or more axles -- generally with gross vehicle weight more than 12,000 kg (26,400 lb)
Buses	All vehicles designed to carry more than nine passengers
Motorcycles	All vehicles with two or three tires and an open-air driver/passenger compartment

The database includes noise emission levels for vehicles on the following pavement types:

- Dense-graded asphaltic concrete (DGAC)
- Portland cement concrete (PCC)
- Open-graded asphaltic concrete (OGAC)
- An "Average" composite pavement type consisting of data for DGAC and PCC combined

In addition to cruise noise emission levels, TNM includes full-throttle noise emission levels for vehicles on upgrades and vehicles accelerating away from the following traffic-control devices:

- Stop signs
- Toll booths
- Traffic signals
- On-ramp start points

TNM uses the full-throttle emission levels for heavy trucks where there is an upgrade roadway of at least 1.5 percent or where user-entered traffic control devices indicate an acceleration condition. Refer to (Bowlby, 1997) for details on accelerating vehicles.

2.3.2 REFERENCE ENERGY MEAN EMISSION LEVELS (REMELS)

For each elemental triangle, TNM utilizes the regression functions given in Equation (3) to (5) to predict noise emission levels at the reference distance 15 m (50 ft) from the source as a function of speed, frequency, vehicle type, throttle condition and pavement type. The development of these curves is based on the database described in Section 2.3.1.

$$E_A(\ s_i\ ) = (\ 0.6214\ s_i\ )^{A/10} \cdot 10^{B/10} + 10^{C/10} \tag{3}$$

where,

E_A is the maximum noise emission energy for a vehicle passby, s_i is the vehicle speed in kilometers per hour[4] for the i^{th} vehicle and A, B, C are variables that depend on vehicle type, pavement type, and

[4] *Note, TNM's acoustic algorithms are based on metric units and the equations presented here reflect this convention.*

engine throttle and are defined in Appendix A. The level equivalent of E_A is given by:

$$L_A(s_i) = 10 \cdot \log_{10}\big(E_a(s_i)\big) \tag{4}$$

Because TNM computes various adjustment factors on a one-third octave band basis, the characterization of noise emission levels are further refined using Equation 5.

$$\begin{aligned} L_{emis,\ i}(\, s_i, f\,) = {} & \\ & L_A(s_i) + (\, D_1 + 0.6214\, D_2 s_i\,) + (\, E_1 + 0.6214\, E_2 s_i\,) \left[\log_{10}(\, f\,)\right] + \\ & (\, F_1 + 0.6214\, F_2 s_i\,) \left[\log_{10}(\, f\,)\right]^2 + (\, G_1 + 0.6214\, G_2 s_i\,) \left[\log_{10}(\, f\,)\right]^3 + \\ & (\, H_1 + 0.6214\, H_2 s_i\,) \left[\log_{10}(\, f\,)\right]^4 + (\, I_1 + 0.6214\, I_2 s_i\,) \left[\log_{10}(\, f\,)\right]^5 + \\ & (\, J_1 + 0.6214\, J_2 s_i\,) \left[\log_{10}(\, f\,)\right]^6 \end{aligned} \tag{5}$$

where,

f is the nominal frequency (in Hz) of the one third octave band in question and D_1 to J_2 are variables that depend on vehicle type, pavement type, and engine throttle and are defined in ***TABLE 10*** of Appendix A.

Do to the form of these equations, A, B and C control the overall level while D_1 to J_2 control the spectral shape of the emissions. Note that $L_{emis,\ i}$ is a level term, but can be converted to energy utilizing Equation (6).

$$E_{emis,i}(\, s_i, f\,) = 10^{L_{emis,i}(\, s_i, f\,)/10} \tag{6}$$

$L_{emis,i}$ is the Reference Energy Mean Emission Level (REMEL) and represents the average maximum passby level for a combination of a particular vehicle type, engine throttle, pavement type, speed and frequency.

Figure 6 shows the overall A-weighted noise emission levels as a function of speed for autos, medium trucks, heavy trucks and buses under cruise conditions and traveling over “Average” pavement (DGAC and PCC combined). When speed is sufficiently high or low, the contributions from the various components in Equation (4) can be approximated as:

$$L_A(s_i) \approx C \qquad\qquad s_i \ll 40\ kph \tag{7}$$

$$L_A(s_i) \approx A \cdot \log_{10}(s_i) + B \qquad\qquad s_i \gg 40\ kph \tag{8}$$

Using these approximations, it can be seen that *C* controls the level at low speeds, while at high speeds, *A* gives the level slope as a function of the log of speed and *B* provides an offset. Speeds around 40 kph represent a transition region, where neither of these approximations completely dominate the results.

English unit versions of many equations are given in Appendix G.

The complete set of emission level curves for all vehicle types under all conditions is given in Appendix A. The appendix also shows the vehicle spectra at various speeds. The one-third octave band noise emission level spectra are used by TNM 3.1 for all sound level calculations.

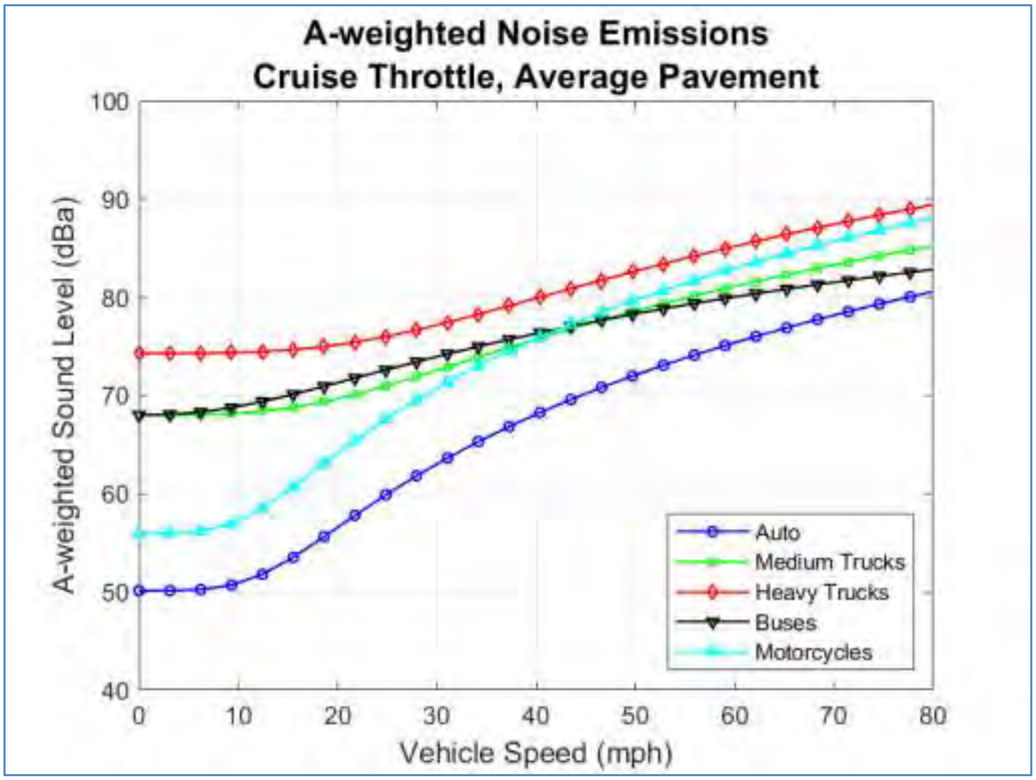

Figure 6 *A-Weighted Vehicle Noise Emission Levels under Cruise Conditions*

2.3.3 Noise Emissions by Sub-Source Height

Road vehicles typically have two main sources of noise. Noise due to the tire-pavement interface tends to dominate at posted highway speeds. Engine or exhaust noise tends to dominate at slower speeds. A field study was undertaken to determine the effective source heights of various vehicles (Coulson, 1996). This study assigned two “sub-source” heights to each vehicle type. They were at 0 m (0 ft) and 1.5 m (5 ft) above the pavement for all vehicles except heavy trucks, where the upper source was 3.66 m (12 ft) above the pavement. The study also determined the ratio of sound energy distributed at the lower and upper heights as a function of frequency, vehicle type, and throttle condition.

For each vehicle type, TNM utilizes Equations (9) to (11) to separate the noise emission level into two sub-source heights. One source will always be the tire / road source at the pavement. For all vehicles except heavy trucks, the second sub-source will be the engine at 1.5 m (5 ft) above the pavement. For heavy trucks, the second sub-source will be the exhaust at 3.66 m (12 ft) above the pavement.

$$r_i(f) = L + (1 - L - M)\left[1 + e^{(N \log_{10}(f) + P)}\right]^{Q} \tag{9}$$

$$E_{emis,i,upper}(s_i, f) = \left(\frac{r_i}{r_i + 1}\right) E_{emis,i} \tag{10}$$

$$E_{emis,i,lower}(s_i, f) = \left(\frac{1}{r_i + 1}\right) E_{emis,i} \tag{11}$$

Here, the *upper* and *lower* subscripts refer to the upper and lower source heights respectively. *L, M, N, P* and *Q* account for the separation of the noise emission level into the two sub-source heights. These constants are given in ***Table 2*** and repeated in Appendix A for convenience. Note that the sub-source height split is also a function of vehicle type and frequency as shown in ***Table 3***.

Table 2: Constants for Sub-Source Height Split

Vehicle type, *i*					Pavement type, *p*				Full throttle		Constants: For a user-defined vehicle, use the TNM-equivalent vehicle to choose the relevant table row for these five constants				
Au	MT	HT	Bus	MC	Avg	DGAC	OGAC	PCC	Yes	No	L	M	N	P	Q
X					X	X	X	X	X		0.37324	0.97638	-13.195596	39.491299	-2.583128
X					X	X	X	X		X	0.37324	0.97638	-13.195596	39.491299	-2.583128
	X				X	X	X	X	X		0.57926	0.87135	-177.24921	558.98028	-0.026532
	X				X	X	X	X		X	0.56693	0.93352	-25.497631	80.239979	-0.234435
		X			X	X	X	X	X		1.33	0.08	-204.844	592.568	-159.344
		X			X	X	X	X		X	0.85	-0.33	163.021	-492.451	-58.005
			X		X	X	X	X	X		0.57926	0.87135	-177.24921	558.98028	-0.026532
			X		X	X	X	X		X	0.5631	0.92809	-31.517739	99.099777	-0.263459
				X	X	X	X	X	X		0.39135	0.97841	-19.278172	60.404841	-0.614295
				X	X	X	X	X		X	0.39135	0.97841	-19.278172	60.404841	-0.614295

Table 3: Sound Energy Distribution between Sub-Source Heights

Vehicle Type	Operating Condition	Percentage of Total Sound Energy at Upper Sub-source Height: 1.5m (5ft), except 3.6m (12ft) for Heavy Trucks: At Low Frequencies (500 Hz and below)	At high Frequencies (2000 Hz and above)
Autos	Full Throttle	27%	4%
Autos	Cruise	27%	4%
Medium Trucks	Full Throttle	34%	11%
Medium Trucks	Cruise	35%	6%
Heavy Trucks	Full Throttle	57%	48%
Heavy Trucks	Cruise	57%	46%
Buses	Full Throttle	34%	11%
Buses	Cruise	36%	7%
Motorcycles	Full Throttle	28%	3%
Motorcycles	Cruise	28%	3%

2.3.4 Free Field Noise Emissions by Sub-Source Height

Because the measured data used to develop the REMELs included ground effects, once the emission energy is separated into upper and lower sources, TNM removes the ground effects using Equation (12) and (13).

$$E_{emis,\ i,\ upper,\ ff}(s_i, f) = m_{upper} \cdot E_{emis,\ i,\ upper} \tag{12}$$

$$E_{emis,\ i,\ lower,\ ff}(s_i, f) = m_{lower} \cdot E_{emis,\ i,\ lower} \tag{13}$$

Here the subscript *ff* indicates that the noise emission has had the ground effects removed, that is, this represents the free-field condition and gives the value as if there was no intervening ground. The values for m_{upper} and m_{lower} are given in ***Table 4***. This gives the reference free-field noise emissions for the i^{th} vehicle's upper and lower source as a function of speed and frequency at 15 m (50 ft).

Table 4: Multiplier, m, for each Built-In Sub-Source Height

Freq (Hz)		50	63	80	100	125	160	200	250	315	400	500	630
Multiplier, *m*	Height: 3.66 m (12 ft)	0.3	0.32	0.36	0.44	0.52	0.69	0.95	1.78	1.00	0.32	0.4	0.25
	Height: 1.5 m (5 ft)	0.26	0.27	0.27	0.28	0.3	0.33	0.38	0.48	0.62	0.79	1.12	1.58
	Height: 0 m (0 ft)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.2

Freq (Hz)		800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
Multiplier, *m*	Height: 3.66 m	0.25	0.25	0.25	0.25	0.32	0.56	1.00	1.00	1.00	1.00	1.00	1.00
	Height: 1.5 m	0.40	0.50	0.32	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Height: 0 m (0 ft)	0.25	0.25	0.22	0.2	0.25	0.27	0.34	0.42	0.47	0.52	0.59	0.67

2.3.5 User-Defined Vehicles

TNM includes five built-in vehicle types, automobiles, medium trucks, heavy trucks, buses and motorcycles. In some cases, a user may wish to use data that are more representative to a specific project. Subject to FHWA policy guidelines, TNM allows user-defined vehicle types to supplement its built-in vehicle types. These user-defined vehicles duplicate the spectral shape and sub-source heights of one of the built-in vehicle types as specified by the user. The overall level, however, is determined directly from data provided by the user.

The FHWA provides instructions on how to measure and analyze field data to be used for user-defined vehicles in (FHWA, 2018). Once the user has collected the requisite data and determined the values of *A*, *B* and *C* associated with Equation (3), the user then determines the reference level at 80 kilometers per hour. This value is entered for the reference level along with *C* for the minimum level and *A* for the slope. Additional details for noise emissions are given in Appendix B: Vehicle Noise

Emission Levels.

3. Horizontal Geometry Adjustments

This chapter describes how adjustments based on the horizontal geometry are determined. These include adjustments for: traffic volume and speed (A_{traff}) as well as roadway lengths and distance (A_d). User specified adjustment factors are also discussed here.

3.1 Traffic Adjustments for Volume and Speed

This section describes how adjustments based on traffic volume and speed (A_{traff}) are determined and applied to the free-field emissions determined in the previous chapter. Consistent with Emissions computed in Chapter 2, these computations are performed independently for each vehicle type on each elemental roadway.

The previous chapter described how maximum free-field noise emissions were determined for a single vehicle passby at 15 m (50 ft). Applying A_{traff} to the reference free-field noise emissions for the i^{th} vehicle's upper $E_{emis,\ i,\ upper,\ ff}$ and lower $E_{emis,\ i,\ lower,\ ff}$ accounts for the number of vehicles (or vehicle volume) of the specified type.

The equivalent volume is determined from user inputs and also depends on the metric being computed as shown in Equations (14) to (17).

$$v_{i,equiv} = v_i \qquad \text{for } L_{Aeqlh}, \text{volume input} \tag{14}$$

$$v_{i,equiv} = \frac{a_h \rho_i}{100} \qquad \text{for } L_{Aeqlh}, \text{percentage input} \tag{15}$$

$$v_{i,equiv} = \frac{a_d\left(\rho_{i,day} + 10\rho_{i,night}\right)}{2400} \qquad \text{for } L_{dn} \tag{16}$$

$$v_{i,equiv} = \frac{a_d\left(\rho_{i,day} + 3\rho_{i,even} + 10\rho_{i,night}\right)}{2400} \qquad \text{for } L_{den} \tag{17}$$

where

- i is the index for the i^{th} vehicle type: including built-in types and user-defined types
- v is the vehicle volume, in vehicles per hour
- v_{equiv} is the equivalent hourly vehicle volume, in vehicles per hour
- a_h is the average hourly traffic, in vehicles per hour, which only applies to computation of L_{Aeq1h}, and only when the user inputs traffic percentages instead of volumes
- a_d is the average daily traffic, in vehicles per 24 hours, which only applies to computation of L_{dn} and L_{den}
- ρ_i is the percentage of total hourly traffic for vehicle type i, which only applies to computation of L_{Aeq1h} , and only when the user inputs traffic percentages instead of volumes

- $\rho_{i,day}$ is the percentage of average daily daytime traffic for vehicle type i, which only applies to computation of L_{dn} (daytime equals 7 am to 10 pm) and L_{den} (daytime equals 7 am to 7 pm)
- $\rho_{i,even}$ is the percentage of average daily evening traffic for vehicle type i, which only applies to computation of L_{den} (evening equals 7 pm to 10 pm)
- $\rho_{i,night}$ is the percentage of average daily nighttime traffic for vehicle type i, which only applies to computation of L_{dn} and L_{den} (nighttime equals 10 pm to 7 am).

With $v_{i,equiv}$ computed and s_i, the vehicle speed, in kilometers per hour, which is determined based on user specifications, flow control, and road grade as described in Section 2.2, the volume and speed correction can be determined by using:

$$A_{traff(i)} = 10 \cdot \log_{10}\left(\frac{V_i}{S_i}\right) - 13.2 \text{ dB} \tag{18}$$

Alternatively, the volume and speed corrected noise emissions can be determined directly by using Equation (19) and (20).

$$E_{traf,\ ref,\ upper}(\ s_i, v_{i,equiv}, f\ ) = 0.0476\left(\frac{v_{i,\ equiv}}{s_i}\right)E_{emis,i,upper,ff} \tag{19}$$

$$E_{traf,\ ref,\ lower}(\ s_i, v_{i,equiv}, f\ ) = 0.0476\left(\frac{v_{i,\ equiv}}{s_i}\right)E_{emis,i,lower,ff} \tag{20}$$

where, f is the one-third octave-band nominal center frequency, in Hz. Note that increasing the equivalent volume increases noise emissions, due to a greater number of sources, while increasing the speed decreases the noise emissions, due to the shorter duration of the sources presence on the road. (Here we can see part of the dual nature of how speed affects the noise emissions. On the one hand, higher speeds are associated with higher maximum noise emissions, as shown in **Figure 6**. On the other hand, higher speeds results in shorter durations, which decrease the emissions associated with metrics that are averaged over time, as is the case for L_{Aeq1h}, L_{dn} and L_{den}.)

Once the noise emissions have been corrected for equivalent volume and speed, TNM's next step is to correct for the length of the elemental roadway and its distance to the source.

3.2 Adjustments for Roadway Length and Distance (A_d)

This section describes how adjustments based on distance between the roadway and receiver and for the length of the elemental roadway (A_d) are determined. Applying this adjustment results in converting the free-field noise emissions at the reference location to the free-field noise energy at the receiver location. Depending on the geometry, see **Figure 7**, TNM uses one of two sets of equations below.

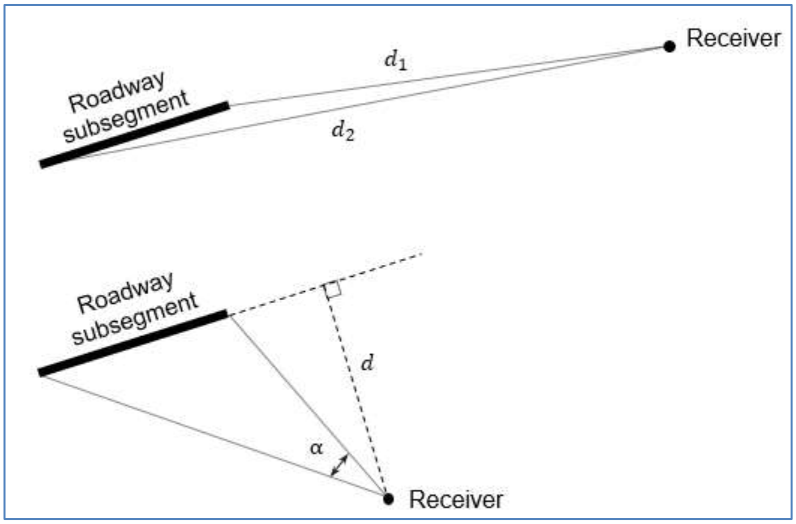

Figure 7 *Definition of Relevant Distances and Angles*

If the perpendicular distance, d, is less than 0.3 m (1 ft) then:

$$A_d = 10 \cdot \log_{10}\left[\frac{|d_2 - d_1|}{d_2 d_1}\right] + 12\ \text{dB} \tag{21}$$

Which can be directly applied to the reference energy by using:

$$E_{traf,upper,ff}(\ s_i, v_{i,equiv}, f\ ) = 15.9\left(\frac{|d_2 - d_1|}{d_2 d_1}\right) E_{traf,ref,upper} \tag{22}$$

$$E_{traf,lower,ff}(\ s_i, v_{i,equiv}, f\ ) = 15.9\left(\frac{|d_2 - d_1|}{d_2 d_1}\right) E_{traf,ref,lower} \tag{23}$$

otherwise,

$$A_d = \log_{10}\left[\left(\frac{15}{d}\right)\left(\frac{\alpha}{180}\right)\right]\ \text{dB} \tag{24}$$

Which can be directly applied to the reference energy by using:

$$E_{traf,upper,ff}(\ s_i, v_{i,equiv}, f\ ) = \left(\frac{\alpha}{180}\right)\left(\frac{15}{d}\right) E_{traf,ref,upper} \tag{25}$$

$$E_{traf,lower,ff}(\ s_i, v_{i,equiv}, f\ ) = \left(\frac{\alpha}{180}\right)\left(\frac{15}{d}\right) E_{traf,ref,lower} \tag{26}$$

where d_1 is the distance from receiver to the first point of elemental roadway, in meters, d_2 is the distance from the receiver to second point of the elemental roadway, in meters, d is the perpendicular distance from the receiver to the elemental roadway, in meters, where the elemental roadway is extended if needed to meet the perpendicular and α is the angle subtended at the receiver by the elemental roadway, in degrees. (See also **Figure 7**.) Note that, in contrast to previous versions of TNM, the values d_1, d_2 and d, although computed within the horizontal acoustic algorithms, use both horizontal and vertical distances to compute the true lengths of these parameters.

3.3 User Entered Adjustment Factors

In most cases, $E_{traf,upper,ff}$ and $E_{traf,lower,ff}$ represent the total free-field noise energy at the receiver location for the given vehicle type on the specified elemental roadway; however, in some cases, users also provided an additional adjustment factor. Although this adjustment is actually applied after the vertical acoustic algorithms have been exercised (see Chapter 4), because these adjustments are often due to features of the model's horizontal geometry, the method of applying these user adjustment factors is shown here. The total noise energy (including vertical adjustments, which will be discussed in the next chapter) is given by:

$$E_{traf,h,atten,barrs}\left(s_i, v_{i,equiv}, f \right) = \left(\phi_{h,f,barrs}\right)\left(10^{\Delta L/10} \right)E_{traf,h,ff} \tag{27}$$

where ΔL is the user-entered adjustment factor for a particular receiver/roadway-segment pair, in dB and $\phi_{h,f,barrs}$ is the vertical geometry adjustment described in Chapter 4 and in Appendix D: Vertical Geometry Acoustics.

4. Vertical Geometry Adjustments

This chapter describes how adjustments for shielding and ground effects between the roadway and the receiver (A_s) are determined. Because the computation of vertical geometry adjustments are very involved, this chapter describes these adjustments at a high level. Detailed descriptions are provided in Appendix D. In this chapter, all references are to the two-dimensional vertical plane (except for brief references to elemental triangles) and all of the computations are based on point-source mathematics.

4.1 Acoustical Model Theory

The acoustical algorithms used by TNM to compute shielding and ground effects are based on research that moved the propagation algorithms from a largely empirical basis to a largely theoretical basis. The research focused on two main areas, ground effects and diffraction.

The ground effects model assumes that sound propagates from the sound source to the receiver along two path types, direct and indirect. Direct paths follow a straight line from a source to the receiver. Indirect paths can be a combination of reflections, diffractions or both. **Figure 8** and **Figure 9** show examples of indirect paths. Note that, while there is only ever one direct path, there can be many reflected and / or diffracted paths.

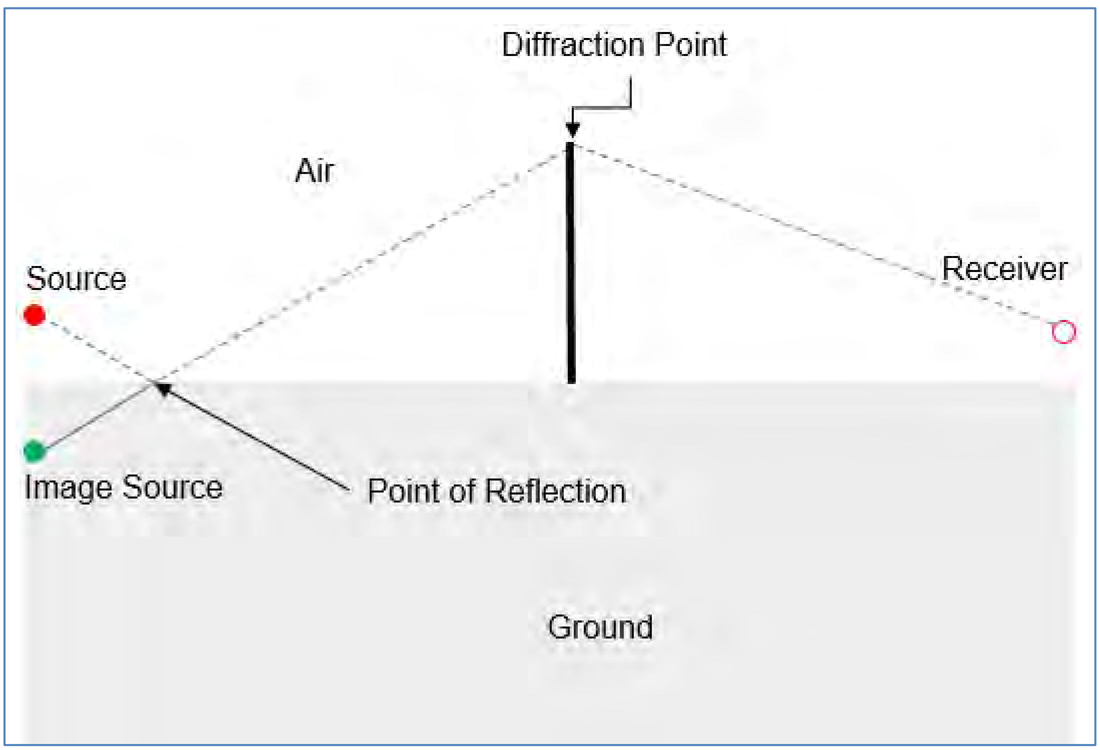

***Figure 8** Example Geometry Showing a Reflection and Diffraction due to Change in Vertical Geometry*

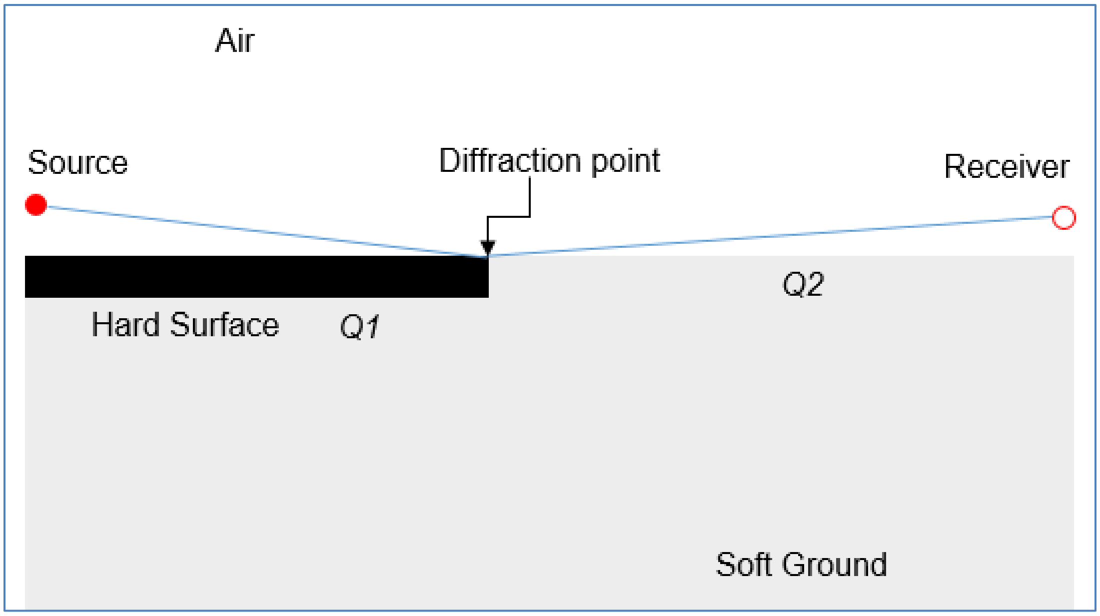

***Figure 9** Example Geometry Showing Diffraction due to an Impedance Discontinuity*

Sound from the reflected and / or diffracted paths combine with sound from the direct path, but because the path is longer and because the ground has an impedance associated with it, the amplitude and phase of the reflected and / or diffracted paths are different than that of the direct path. Thus, the waves sometimes add constructively and sometimes add destructively. The models and data used by TNM to determine the interference patterns associated with these constructive and destructive combinations are based on the work of (Chessell, 1977), (Delaney & Bazley, 1970) and (Embleton, Piercy, & Daigle, 1983).

Figure 10 shows an example of an interference pattern for a simple geometry with a single reflection. The ordinate shows the sound level of the combined direct and reflected paths relative to the direct path, that is, it shows how much the level increases compared to the direct path. At very low frequencies, where the direct and reflected paths combine constructively, the effect is to have the sound level increased by 6 dB or the sound pressure doubled. At other frequencies, such as about 550 Hz in this example, the two paths combine destructively reducing the sound level to –infinity or the sound pressure to zero. Note that the location on the abscissa of the minima and maxima in the interference pattern depend on the ground type and geometry of the source, receiver and ground.

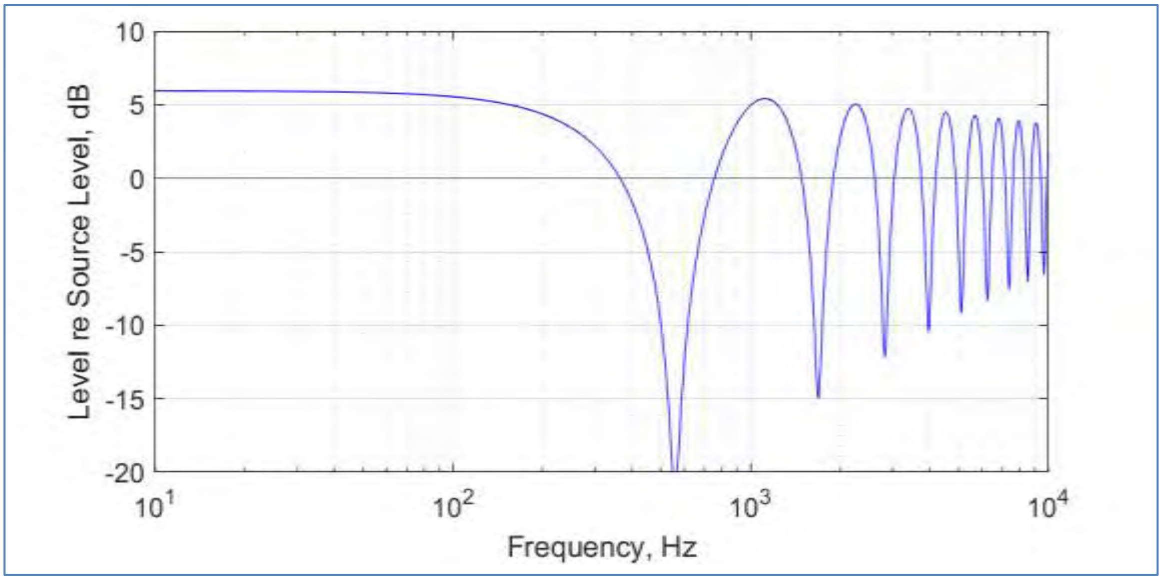

***Figure 10** Example Interference Pattern for Single Reflection over Flat Ground. (Source Height = 1.5 m (5 ft), Receiver Height = 1.5 m (5 ft), Horizontal Distance = 15 m (50 ft), Ground Type = Hard Soil (5000 cgs Rayls))*

Figure 10 illustrates how sound paths can add constructively or destructively for a reflected path. When sound propagates over a path that has vertical peaks (as in **Figure 8**) or impedance changes (as in **Figure 9**), the sound is diffracted. The diffraction model used by TNM is described by (De Jong, Moerkerken, & van der Toorn, 1983). Although this model works well for a limited number of diffraction points, the algorithm does not work well for large numbers of diffraction points, which can occur for highway cross-sections with many impedance discontinuities and vertical changes. To solves this issue TNM applies smoothing algorithms to the vertical geometry and averages some impedance changes as described by (Boulanger, Waters-Fuller, Attenborough, & Li, 1997). Boulanger's method has been validated by using scale model measurements and agrees well with the De Jong model for simpler cases.

4.2 Elemental Triangles

Section 2.1 provided an overview of elemental triangles. With respect to the vertical geometry, shielding effects are computed separately for each leg of the elemental triangle. Note that, although the same objects can be present on each elemental leg (the same roadway, barrier, terrain line segments, etcetera) the points making up the segment can have different heights and different locations along the two legs, for example a barrier segment can be closer to a roadway on the left side compared to the right side. Thus, different values are expected for the two legs. These two values are then energy averaged to determine the shielding for the elemental triangle.

4.3 Propagation Paths

This section describes the individual elements that may be present in the propagation path. A more detailed discussion of how the elements are implemented in TNM is presented in Appendix D.

4.3.1 Ground points and segments:

In TNM, a ground point defines the location of the ground and a set of ground points defines the path in the vertical geometry. Ground points are always placed below the source and receiver (derived from the x, y and z coordinates and the source or receiver height), and at the edge of roadways (derived from the x, y and z coordinates of the road center line and the roadway width). When TNM calculates results, the points that make up terrain lines are converted into ground points directly and berms are converted into either three or four ground points directly for each point defined in the user input for the berm. (The base of the berm is defined by two points, and the top is defined by either one, if the top width is less than 0.1 m, or two points.) Other elements in the geometry are also used to generate ground points but persist as their original type as well since they provide additional information required during the calculations. These other elements include: wall barriers, building rows, tree zones and ground zones. **Figure 11** provides examples of some objects that affect the vertical geometry ground points. **Figure 12** shows these same example objects in a section view to illustrate the effect along the ground point path. Note that ground zones only define points along the horizontal axis of the path. Ground zones do not affect the vertical location of points in the path.

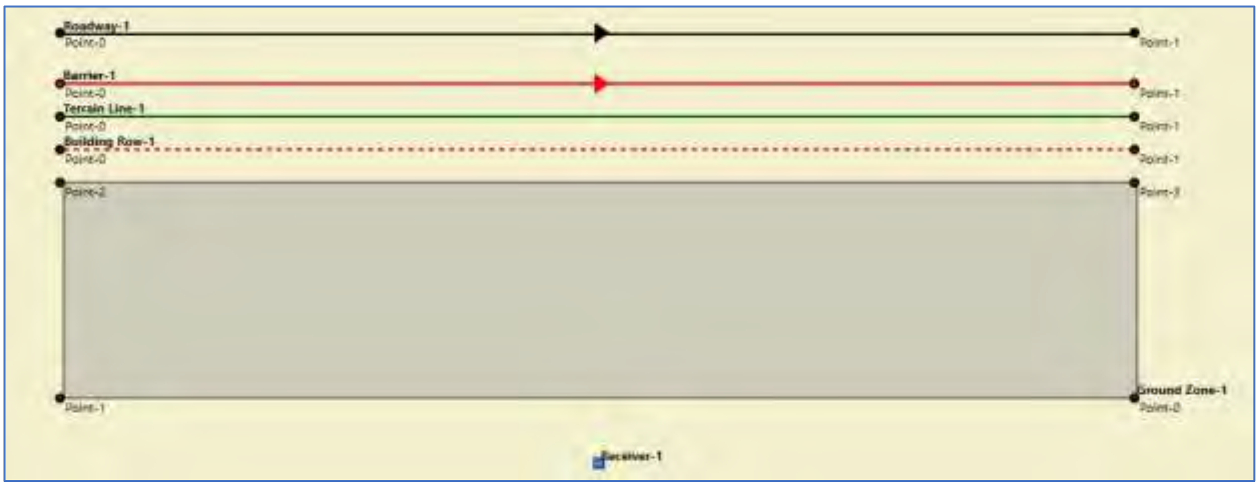

Figure 11 *Example TNM Objects in the Plan Builder*

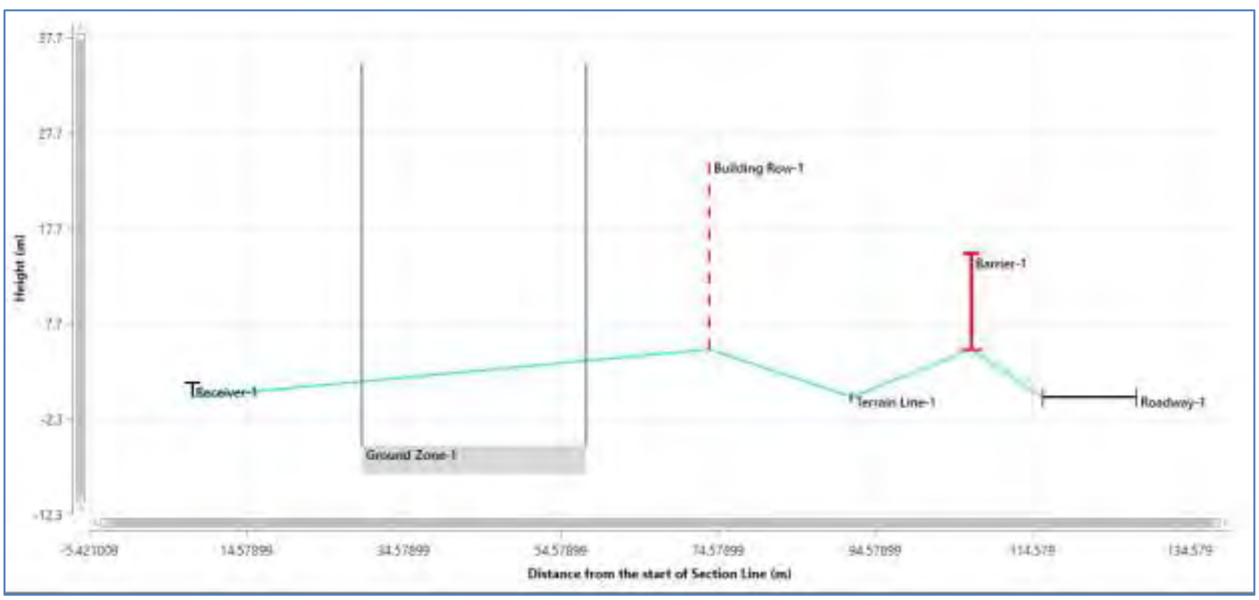

Figure 12 *Example TNM Objects in the Section View*

In the vertical geometry, ground points define ground segments where sound reflections can occur.

Reflections that occur on ground segments with different ground types can be very different. The interference between the direct and reflected paths over soft ground types (low Effective Flow Resistivity or EFR) often creates substantial destructive interference across a broad range of frequencies, typically between 200 Hz and 1000 Hz. This is the “ground-effect” interference that causes excess attenuation over soft ground. The softer the ground is, the greater the ground-effect attenuation is for sources and receivers that are relatively close to the ground. TNM allows users to enter various ground types that are based on the effective flow resistivity measured by (Embleton, Piercy, & Daigle, 1983). The ground types and associated EFR are given in ***Table 5***.

Table 5: Ground Type and Effective Flow Resistivity

Ground Type Name	EFR (cgs Rayls)
Pavement*	20,000
Water	20,000
Hard Soil (& dirt road)	5,000
Loose Soil (& gravel)	500
Lawn	300
Field Grass*	150
Granular Snow	40
Powder Snow	10

**Note: TNM’s Pavement and Water ground types represent a generic acoustically hard ground surface. TNM’s Field Grass ground type represents a generic acoustically soft ground surface.*

4.3.2 Impedance Discontinuities

As mentioned previously, diffractions are often computed at impedance discontinuities. Impedance discontinuities occur where one ground type changes to another, for example pavement to lawn. Because roadways have an EFR of 20,000 cgs Rayls, impedance discontinuities occur at the edge of roadways if the default ground type is not “pavement” or “water” and the roadway is not within a “ground zone” of pavement or water. Impedance discontinuities will also occur where a user has entered a ground zone with a different ground type than the default.

If a reflection occurs near an impedance discontinuity, a diffracted path from the impedance discontinuity must also be computed in order to modify the magnitude and phase of the reflected component. If the diffracted component were to be omitted, the sound field would not remain continuous.

4.3.3 Wall Barriers

The computation of shielding due to barriers is one of the primary purposes of TNM. Wall barriers stand vertically, have a base (ground) point, a height, and Noise Reduction Coefficient (NRC) associated with their sides. Barriers may be specified with multiple heights by defining perturbations in the user interface. TNM can compute diffraction from the barrier top and its base points on both sides.

The De Jong model requires computation of reflections in the barrier surfaces in order to compute single-barrier diffractions properly. This is a logical extrapolation of the wedge model used in developing the De Jong model and is the way that TNM accounts for the pressure doubling that occurs at the barrier top on the source side. In these reflections, the NRC on the barrier's surface influences the diffracted sound energy. The effect is relatively small: approximately 1 dB to 1½ dB additional barrier insertion loss for NRC's in the range of 0.7 to 0.9 for a 4.6-meter (15-ft) barrier and mixed traffic (Menge, Rossano, Anderson, & Bajdek, 1998).

The users specify an NRC for a barrier surface, which is then used to compute a reflection coefficient. To maintain consistency within the model, the barrier's surface impedance is converted to a value of effective flow resistivity. The approach is described in detail in Appendix D, but it is also described briefly here. The absorption coefficient at a given frequency is related to the “reflection factor,” which is a function of the impedance of the surface and the impedance of air. The surface impedance was derived from the EFR values in Delany's empirical fit for fibrous materials (Delaney & Bazley, 1970). Individual values of EFR were found that corresponded to values of NRC (see ***Table 6***). This approach allowed a single parameter to be used for each value of NRC chosen by the user. **Figure 13** shows the absorption coefficients as a function of frequency that are used within TNM for selected values of NRC.

Table 6: Effective Flow Resistivity used for values of Noise Reduction Coefficient (NRC)

NRC	EFR (cgs rayls)
0.00	20000
0.05	5000
0.10	1570
0.15	865
0.20	500
0.25	385
0.30	282
0.35	214
0.40	150
0.45	129
0.50	102
0.55	81
0.60	64
0.65	50
0.70	40
0.75	30
0.80	22
0.85	16
0.90	10
0.95	5.5
1.00	0.1

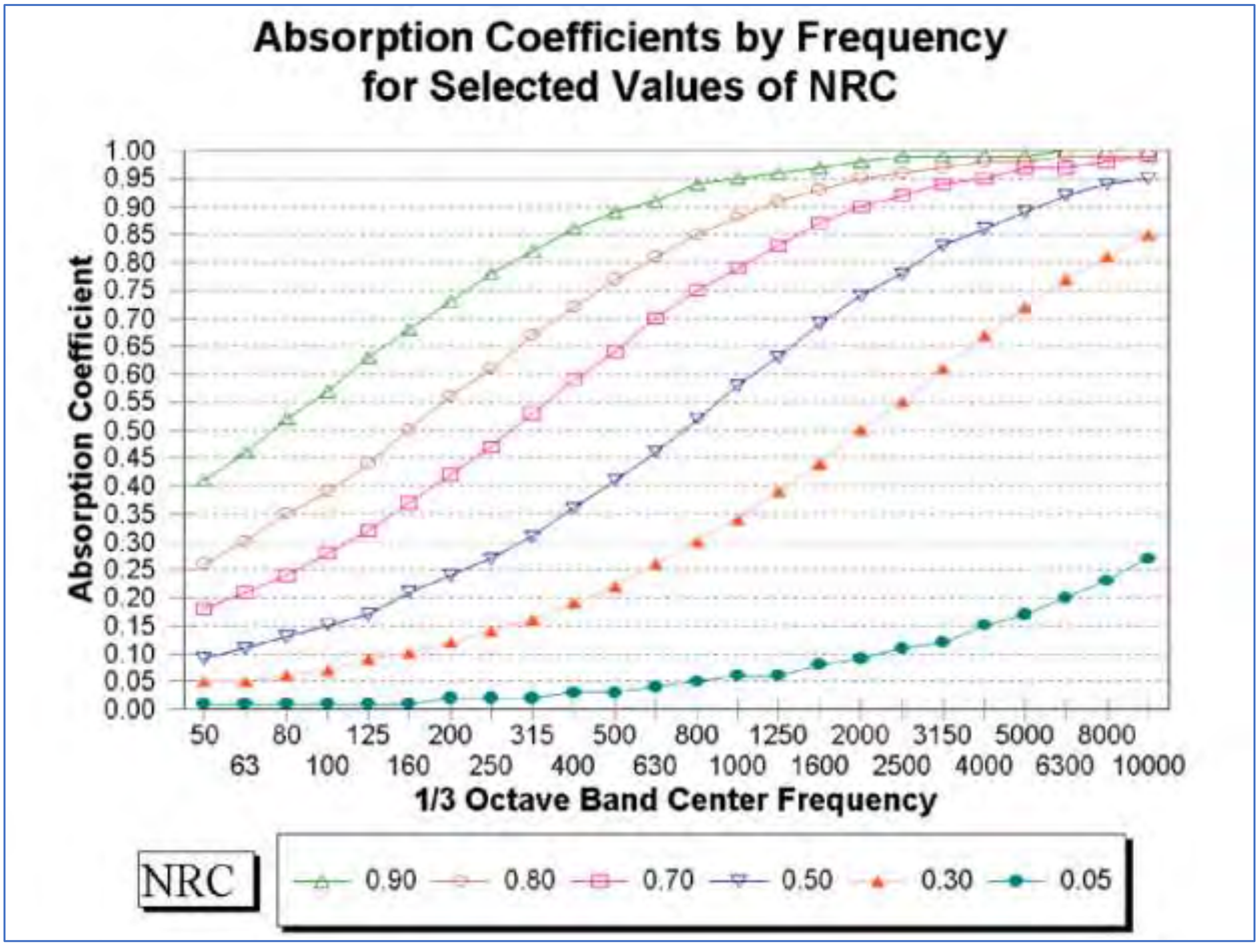

Figure 13 *Absorption Coefficient as a Function of Frequency for Selected Values of NRC*

4.3.4 Berm Barriers

TNM's acoustic algorithms treat berms as a series of ground points. Users can manually create them using a set of terrain lines, or users can create berms as a type of barrier with specified heights, top widths and side slopes. In the latter case, TNM's vertical geometry routines compute the location of the intersections between the bases of the berms and the ground. Those intersections then become ground points in the vertical geometry. Berms that are defined with a finite top width have two diffracting edges. Flattop berms have a slightly greater insertion loss than berms that come to a single point at the top. TNM has shown apparent anomalies in the diffraction algorithms for berms with a top width. Because of these apparent anomalies, TNM maintains a default value of 0 for berm top width; however, the width can be changed.

Berms take on the default ground type or, if a berm is inside a ground zone, the type of ground defined for that zone. Therefore, if the default ground type is "lawn" or "field grass" berms will be earth berms and diffraction will be computed accordingly. If the default ground type is "pavement," the berm will be acoustically hard.

4.3.5 Tree Zones

TNM incorporates tree zones as an optional element in the propagation path. Tree zones have both ground height and top height, and therefore define ground points at their edges. The vertical geometry algorithms compute the distance the propagation paths travel through tree zones as well. TNM uses the ISO 9613-2 standard for attenuation due to dense foliage (ISO, 1996) which is defined as "sufficiently dense to completely block the view along the propagation path." In TNM, the octave-band attenuation values shown in ***Table 7*** are applied to each of the one-third octave bands within the associated octave band.

Table 7: Attenuation through Dense Foliage

Octave-band center frequency (Hz)	63	125	250	500	1K	2K	4K	8K
Attenuation (dB, total) for d_f (distance through foliage) less than 10 meters (33 feet)	0	0	0	0	0	0	0	0
Attenuation (dB, total) for d_f between 10 meters (33 feet) and 20 meters (66 feet)	0	0	1	1	1	1	2	3
Attenuation (dB per meter) for d_f between 20 meters (66 feet) and 200 meters (660 feet)	0.02	0.03	0.04	0.05	0.06	0.08	0.09	0.12
Maximum attenuation (dB) for $d_f \geq$ 200 meters (660 feet)	4	6	8	10	12	16	18	24

4.3.6 Building Rows

TNM incorporates building rows as optional elements in the propagation path. Like tree zones, they have both ground height and top height, but building rows have no width. Building rows are also characterized by a "building percentage," the percentage of area in a single row blocked by buildings. The building percentage and the height are both used in computing the attenuation of the most effective intervening row, according to the equation in the German rail industry standard (Kurze E. J., 1998) (see Appendix D for details). The number of rows of buildings also factors into the total attenuation, adding 1½ dB for each additional row after the most effective. A maximum of 10 dB attenuation is allowed (based on mixed-traffic spectrum: the limits are 8.4 dB at 500 Hz and 10.4 dB at 1000 Hz). Unlike with barriers, propagation paths in TNM are allowed to go through building rows rather than having to diffract over them. TNM restricts users from entering building percentages greater than 80 percent or less than 20 percent. Therefore, users must employ barriers to model building rows without significant gaps between the buildings.

4.3.7 Atmospheric Absorption

TNM incorporates variable atmospheric absorption depending on temperature and relative humidity as specified by the user. The ISO 9613-1 standard is used (ISO, 1993). Details of the equations employed are given in Appendix D.

4.4 Logic Flow and Vertical Geometry Modeling

This section outlines the logic and the modeling approaches incorporated in TNM's vertical geometry algorithms; it describes the process of evaluating a leg of an elemental triangle. Many of the modeling approaches discussed relate to limits placed on TNM's computations to enhance run time or to constrain array sizes. For example, limits have been placed on the number of barriers and the number of ground points that are calculated. All of the topics presented here are covered in greater detail in Appendix D.

4.4.1 Perturbable barriers:

TNM has been designed to handle up to two perturbable barriers in the source-receiver path. If three or more perturbable barriers are encountered, TNM will choose the most effective pair of barriers based on their input heights. This test is performed at the beginning of the evaluation of a given vertical geometry, and TNM then discards all other perturbable barriers for the remainder of the elemental triangle's analysis. This conservative approach allows only two barriers in series, limiting total attenuation. The choice of the most effective pair of barriers is made with the "Foss selection algorithm" (Foss, 1976). This is a relatively simple and quick procedure that computes attenuation for two barriers in series from path length differences. The procedure follows directly from Foss' scale model measurements, which show good agreement with the algorithm. The equations and an illustration are given in Appendix D.

4.4.2 Highest path points, including barriers and ground points:

TNM next determines how many points in the geometry cause the shortest path from the source to receiver to diffract downward. These "highest path points" (HPPs) could be barriers or ground points, which could be associated with berms, terrain lines or roadways. If three or more HPPs are encountered, TNM will not compute diffraction for all of them and will only use the most effective pair. Again, the choice is made with the Foss selection algorithm. The primary reason for excluding more than two HPPs from calculation was that additional points would cause additional diffraction, reducing sound levels, and no empirical data on such multiple diffractions were available for the purpose of validation.

4.4.3 Initial geometry smoothing:

The next step in the process involves the "smoothing" away of multiple ground points that have small effects on the overall shape of the ground. This is performed to reduce computation time, since the effect on the sound level is small. The smoothing algorithm has been designed to make only small changes to the vertical geometry. Only inflection points in terrain of the same ground type are considered for smoothing (including small berms); ground-impedance discontinuities are never smoothed away.

4.4.4 Regression ground and near-highest path points:

TNM next evaluates the complexity of the geometry and if necessary, simplifies it. To enable TNM to handle complex geometries and to improve run times for those cases, straight-line regressions to the ground have been combined with a method of ground-impedance averaging (Boulanger, Waters-Fuller, Attenborough, & Li, 1997). This approach is used where more diffraction points are encountered than the De Jong model can properly handle, such as would be encountered with one or more intervening roadways or hilly terrain. Potential diffraction points occur at each impedance discontinuity and at each ground inflection point that has not been smoothed away by the initial smoothing algorithm (described previously).

The ground regression is performed differently for two different frequency regions. For the potentially most significant diffraction point in the geometry, a test is performed to determine if the point is in the source-to-receiver Fresnel zone for a Fresnel number of *N* > -0.3. If the point is inside that zone, a transition frequency, f_T, at which the point moves outside of the Fresnel zone is computed. Then, for frequencies above f_T, the ground regression algorithm approximates the ground between "source" and "receiver" (either of which can be a highest path point), and the sound propagation paths are generated (see below) based on that representation of the ground. For frequencies below f_T, the point is designated a "near-highest path point" (NHPP) and the ground regression algorithm is used separately to approximate the ground between the source and the NHPP and again between the NHPP and the receiver. A separate set of propagation paths are then generated for the revised geometry, including the NHPP as a diffraction point. By using different representations of the geometry based on the frequency-dependent significance of individual points allows for a more continuous change in the overall sound level as the position of a point in the geometry is gradually changed (such as with a barrier perturbation).

Any impedance discontinuities present in the original geometry are projected onto the regression ground line(s), and the ground-impedance averaging is performed as described below, after the paths are constructed.

4.4.5 PROPAGATION PATH GENERATION:

In the next step, TNM generates all possible direct, reflected and diffracted paths between the true source and receiver. If a near-highest path point is designated in the geometry, the set of sound propagation paths is different for frequencies below and above f_T.

4.4.6 PATH SIGNIFICANCE TEST:

Next, a Fresnel zone test is used for each propagation path generated, to determine if the path is significant enough to be included for computation. Segments of the path that include bright-zone diffraction points are evaluated relative to paths that do not include those points. A path is considered significant and is computed if the receiving point falls into the region where the Fresnel number is greater than -0.3. To maintain continuity of results, the test is performed at a low frequency, 250 Hz. Since $N = 2\delta/\lambda$, the path length difference, δ, must be greater than 0.2 meters (0.7 feet) for a path to be excluded. This quick test was incorporated into TNM to avoid the time-consuming computation of the many possible diffraction paths in the more complex geometries with barriers. For example, the diffraction from the bottom edges of tall barriers will often be eliminated, because the contribution to the total sound level will be insignificant. Note that this test is performed for bright-zone diffractions only, and that all diffraction paths where the receiving point is in the shadow zone are assumed to be significant.

4.4.7 GROUND-IMPEDANCE AVERAGING:

The Boulanger approach to ground-impedance averaging is then used for cases where: (1) more than one impedance discontinuity is present in the local geometry between source and receiver or highest path points; or (2) a single discontinuity has not been chosen to be computed explicitly (as it would if designated a near highest path point). Instead of computing the multiple diffraction paths explicitly, this approach computes a Fresnel ellipse about the reflection point on the ground and computes the area inside the ellipse represented by each type of ground. Then, an average reflection coefficient is computed from the reflection coefficient for each ground type weighted by the ratio of its area to the total area. The average reflection coefficient is used, and no diffraction terms are computed at all. However, the size of the ellipse is a function of frequency, so the average impedance and therefore the reflection coefficient will often change for each one-third octave band. Appendix D explains this approach further.

4.4.8 Sum over propagation paths:

Finally, for each one-third octave band, TNM computes contributions to the acoustic pressure from each propagation path at the receiver. The complex sum (magnitude and phase) of each of these paths represents the combined effect of all of the paths and all of the elements in each path. This sum is then referenced to the free field pressure to determine the adjustment factor, A_s, for shielding and ground effects.

5. Other Adjustment Factors

This chapter covers additional adjustment factors that are determined for single and parallel barrier reflections.

5.1 Single Barrier Reflections

Single barrier reflections are a new addition to the computational capabilities of TNM in version 3.0. Single barrier reflections are accounted for by creating virtual sources that are reflected about the barrier in much the same way that reflections are accounted for in the vertical geometry by creating virtual receivers that are reflected about the ground. **Figure 14** to **Figure 16** illustrate three cases for reflection. In **Figure 14** the reflected path is well below the top of the barrier so the sound is fully reflected by the barrier. In **Figure 15** the reflected path is close to the top of the barrier, so some of the sound is reflected, but some of the sound diffracts over the barrier and away from receiver. In **Figure 16** the reflected path is well above the top of the barrier so the sound is not reflected back toward the receiver. In order to properly account for the diffractions and reflections, the barrier is replaced with a virtual barrier, as shown in these figures. It is the paths from the virtual receivers that go under (or diffract under) the virtual barrier that are used to determine the effect of the single barrier reflections. (For more information about this concept, see also Appendix E.5.2.)

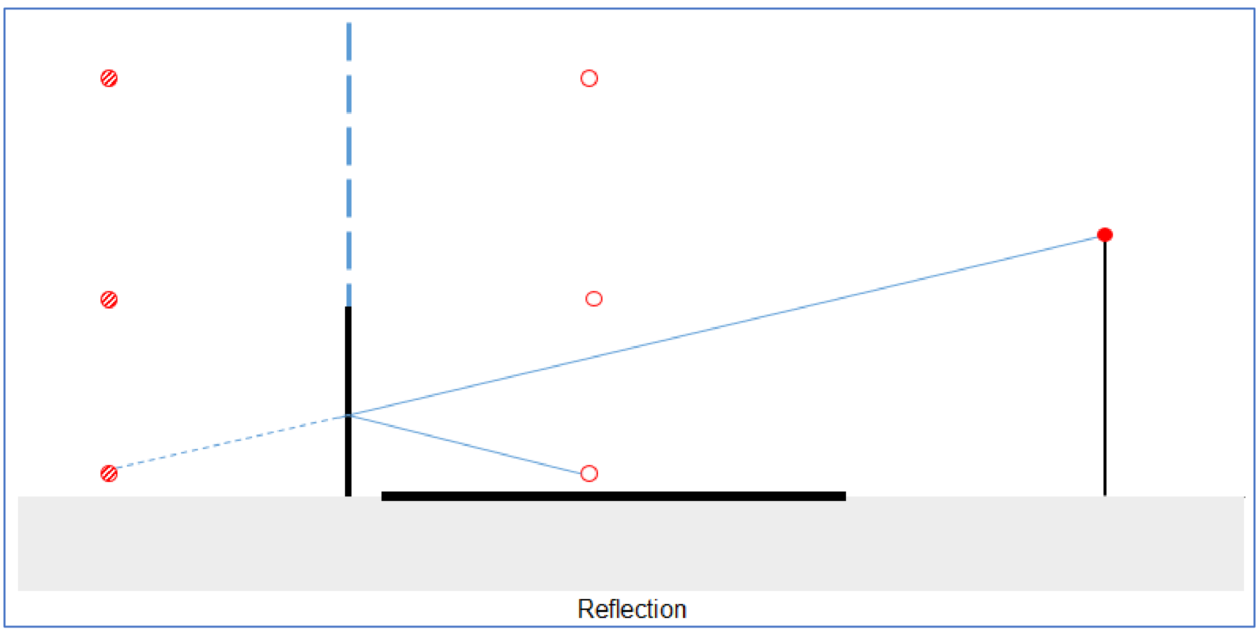

Figure 14 *Example of Source Fully Reflected by Single Barrier*

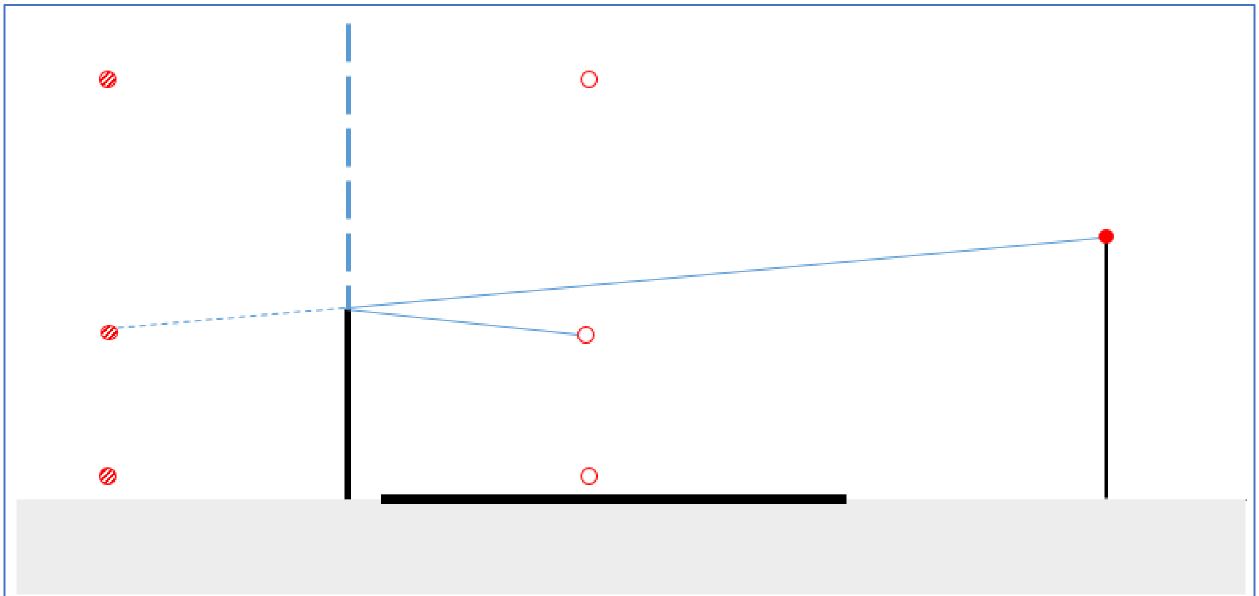

Figure 15 *Example of Source Partially Reflected by Single Barrier*

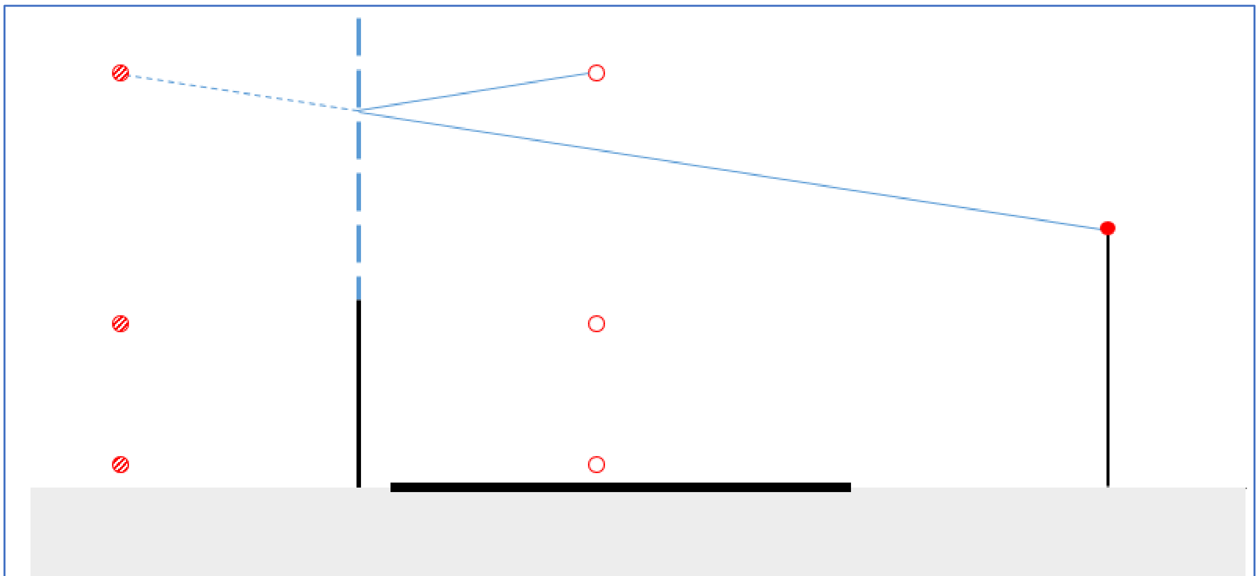

Figure 16 *Example of Source Not Reflected by Single Barrier*

5.2 Parallel Barrier Reflections

Parallel barriers and parallel retaining walls can create reverberations by reflecting sound back and forth across a roadway multiple times for a single source. This reverberation tends to increase noise levels at receivers compared to the case where the barrier or retaining wall on the opposite side is not present; this increase noise levels is called "degradation" of barrier insertion loss.

TNM's regular sound-level computations cannot predict the degradation of barrier performance due to parallel barriers or retaining walls since TNM assumes that sound only propagates from source to receiver and does not allow for propagation in the opposite direction. However, TNM contains a separate, multiple-reflections module that can be used to compute values of degradation due to multiple reflections between parallel surfaces in two dimensions. This module incorporates two-dimensional ray-tracing algorithms for computing multiple sound reflections (Menge C. W., 1991) and is designed to assist users in calculating the acoustical effects of parallel barriers or retaining walls when they are on both sides of a highway.

In previous versions of TNM, a separate user interface was available in order to develop a detailed representation of the vertical-plane cross-section geometry and assign values of NRC to each surface. TNM 3.0 simplifies this process by generating the vertical-plane cross-section using a “cut” from the receiver through the barriers and roadways of interest. The NRC values are still user definable and appropriate values of NRC range from 0.05 for hard surfaces like pavement and concrete walls to 0.30 for grass. Note, that because the multiple-reflections module produces an adjustment factor that is manually applied by the user and because the module has not been modified between TNM 2.5 and TNM 3.1, if a user wishes to develop a more detailed vertical-plane cross-section than TNM 3.1 allows, the adjustment can be computed in TNM 2.5 and manually applied in TNM 3.1.

TNM's multiple-reflections module begins its computation of parallel-barrier degradation by tracing individual acoustic rays outward from each traffic noise sub-source. Some rays come close enough to receivers or diffraction edges to register a “hit” and therefore contribute their portion of sound energy to the total. For these rays, TNM computes the effects of divergence, ground attenuation, absorption upon reflection, and barrier attenuation, to derive two sound levels at each receiver. One level is based on all multiple reflections and the NRCs entered by the user. The second is similar, except that rays that hit one of the flanking barriers or retaining walls are completely absorbed, as if the barrier or wall were not there. Then TNM subtracts the two sound levels at each receiver, to obtain the degradation value. The resulting parallel-barrier degradation is a function of: (1) traffic on each roadway; (2) the location of the roadways; (3) the location, orientation, and NRC of each reflecting surface; (4) the location of the diffracting edges at each side of the cross section; and (5) the location of each receiver.

Further details of TNM’s parallel-barrier computations are given in Appendix E.

6. CONTOURS

In most cases, TNM is used to compute sound levels at user specified locations. In some cases, it is desirable to compute noise metrics over a wide area. To meet this need, TNM allows the user to compute contours[5] within specified contour zones. Three types of contours are available:

- Sound level contours for a specified barrier design, in the user's chosen sound level metric
- Noise reduction contours for a specified barrier design
- Level difference contours between two specified barrier designs

To compute contours, TNM first generates a regular grid of special receivers within the user's contour zone. It then interpolates the ground elevation and computes the sound level at each such receiver, at the receiver height of 1.5 m (5 ft) above the ground. If needed, it subdivides each grid cell and adds additional receivers to obtain the user's requested contour tolerance.

Once TNM obtains computed values at all receivers, it generates a so-called "grid" file with these computed values, the XY coordinates of the receivers, and other miscellaneous data. It then presents these data as a gradient in the plan view.

Contour computations are linked to barrier designs[6]. Through this linkage, TNM sets the height of each barrier segment in the design to one particular value, from among all the possible height perturbations. Barrier designs are linked in the following ways:

- For sound-level contours, the user first chooses a barrier design, with its particular barrier heights. Then TNM uses these heights to compute sound levels at all grid points.
- For noise reduction contours, the user first chooses a barrier design, with its particular barrier heights. TNM uses these heights to compute sound levels, with barriers. Then TNM reduces the height of all perturbable barriers to zero, to compute sound levels without barriers. TNM then subtracts the two sets of grid values, to obtain the barrier insertion loss at all grid points.
- For level difference contours, the user chooses two barrier designs. TNM computes sound levels at the grid points from both, then subtracts them. Note that any two barrier designs in the same TNM run will automatically have the same coordinate system.

TNM determines initial grid spacing automatically, using the dimensions of the user's contour zone. First, TNM determines the smaller contour-zone width, either the X-width or the Y-width as:

$$X - width = x_{max} - x_{min} \tag{28}$$

$$Y - width = y_{max} - y_{min} \tag{29}$$

---

[5] Note, previous versions of TNM created series of contour lines. TNM 3.0 creates color gradients instead of contour lines. The underlying information is the same, only the presentation is changed. For consistency with previous versions, the term contour is used when referring to these gradients.

[6] A barrier design can contain no barriers, as is the case for "All Barriers at Zero Height," for example.

Where, x_{max} is the maximum x-coordinate value in the contour zone, x_{min} is the minimum x-coordinate value in the contour zone, y_{max} is the maximum y-coordinate value in the contour zone, and y_{min} is the minimum y-coordinate value in the contour zone. Then TNM divides the smaller of these two by 10, to obtain the initial grid spacing. This spacing is used in both directions, X and Y, even though it is derived from only one of them.

After computing sound levels at each grid point, TNM then loops back through the grid to decide upon subdivision. The left frame in **Figure 17** shows a grid "cell" composed of four grid points: 1, 2, 3 and 4. TNM has already computed sound levels at these four points. To decide whether or not to subdivide this cell into four smaller cells:

- TNM computes sound levels at three additional points, marked A, B and C in the figure
- TNM subtracts the computed level at point A from the algebraic average at points 1
- TNM subtracts the computed level at point B from the algebraic average at points 1
- TNM subtracts the computed level at point C from the algebraic average at points 1
- If *all* of these differences are within the user's requested precision, then TNM does not subdivide this cell. If any one of these is greater than the user's requested precision, then:
    - TNM subdivides cell 1234, as shown to the right in the figure, to obtain four cells.
    - TNM individually tests and possibly subdivides each of the resulting four cells.

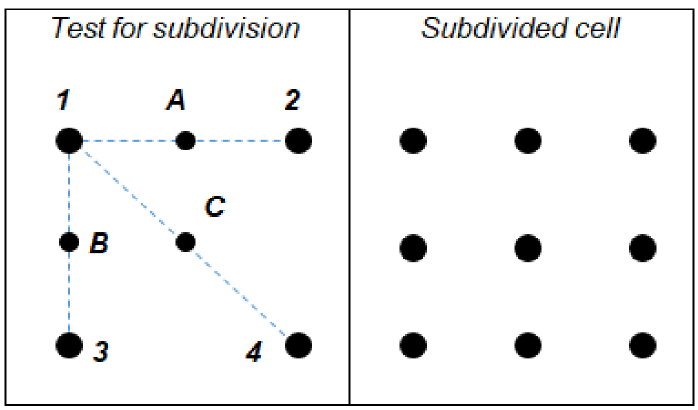

Figure 17 *Subdivision of Grid Cells during Contour Computation*

Subdivision stops when the differences are within the user's requested precision. In addition, subdivision automatically stops when the size of a subgrid falls below the user's "minimum grid spacing." For example, if the user is interested in geographic resolution down to only 10 m (33 ft), then a minimum subgrid size of 10 m (33 ft) would prevent TNM from subdividing any further.

Note that TNM has to contain some limit on the depth of subdivision. Without such a limit, TNM would never stop subdividing in regions with sound-level discontinuities. Such discontinuities occur from front to back of a barrier or a building row. In addition, they occur across roadways, although most users will not include roadways within contour zones.

Also, although contour zones can intersect any other type of TNM input, users are cautioned against the intersection of barriers and roadways (this includes a roadway's width) with contour zones. The reason is that contouring logic can break down in areas of steep noise gradients, such as exist around the ends of barriers and on roadways.

APPENDIX A: VEHICLE SPEEDS

This appendix supplements discussions in Section 2.2 and is largely a reproduction of the portions of Appendix B of (Anderson, et al., 1998), modified only to reflect changes between TNM 1.0 and TNM 3.1 and to avoid repetition of some materials already presented in the main body. Note, for ease of reference, some information originally presented in the main body is still repeated here.

Under most situations, TNM uses vehicle speeds that are input by the user. However, in two situations TNM computes vehicle speeds on its own. These two conditions are: (1) whenever traffic speeds are reduced by upgrades; and (2) whenever they are reduced by traffic-control devices. This appendix details how and when TNM performs its internal speed computations.

A.1 OVERVIEW

Figure 18 illustrates the speed effects of upgrades and traffic-control devices. The upper frame in the figure illustrates the influence of upgrades on heavy trucks and on any user-defined vehicles that mimic heavy trucks. The lower frame illustrates the influence, on all vehicles, of traffic-control devices and subsequent roadway grades.

A single roadway is drawn bold in each frame of the figure. Within TNM's roadway “loop,” this is the “current” roadway being computed. Other roadways are dashed in the figure. In addition, the figure shows grades for each segment of the current roadway and the location of a traffic-control device in the lower frame.

Also shown in the figure are the locations at which TNM starts and stops computing speeds. For upgrades, TNM starts computing heavy-truck speeds where the upgrade equals 1.5 percent or more. In the upper frame, this occurs at the entrance point of the segment labeled "1.7 percent up." It is at this point that the roadway grade begins to affect heavy-truck speeds. For traffic-control devices, TNM starts computing speeds at the location of the device, itself. Traffic-control devices abruptly reduce speeds to the device's "speed constraint," for the device's “percentage of vehicle affected.” Most traffic- control devices affect 100 percent of the vehicles. However, traffic signals affect only a portion of the traffic: that portion stopped at the red signal phase. The remainder of the vehicles progress as if the device was not there.

TNM stops computing speeds at whichever happens first: either (1) the vehicles accelerate back up to the user's input speed; or (2) the vehicles come to the end of the current TNM roadway. TNM never "tracks" vehicles from one roadway to the next when computing speeds. For this reason, speed computations on the current roadway are completely independent of speeds on connecting roadways: before, after, or ramp-like connections in the middle.

For example, in the bottom frame of the figure, TNM does not track accelerating onramp vehicles onto the dashed mainline. Instead, all vehicles on the mainline proceed at mainline vehicle speeds. Traffic on the ramp and the mainline are not “linked” in any sense. If the user wishes TNM to continue accelerating vehicles after they merge with mainline traffic, the user must extend the onramp far enough, parallel to the mainline roadway, and only then connect the onramp into the mainline.

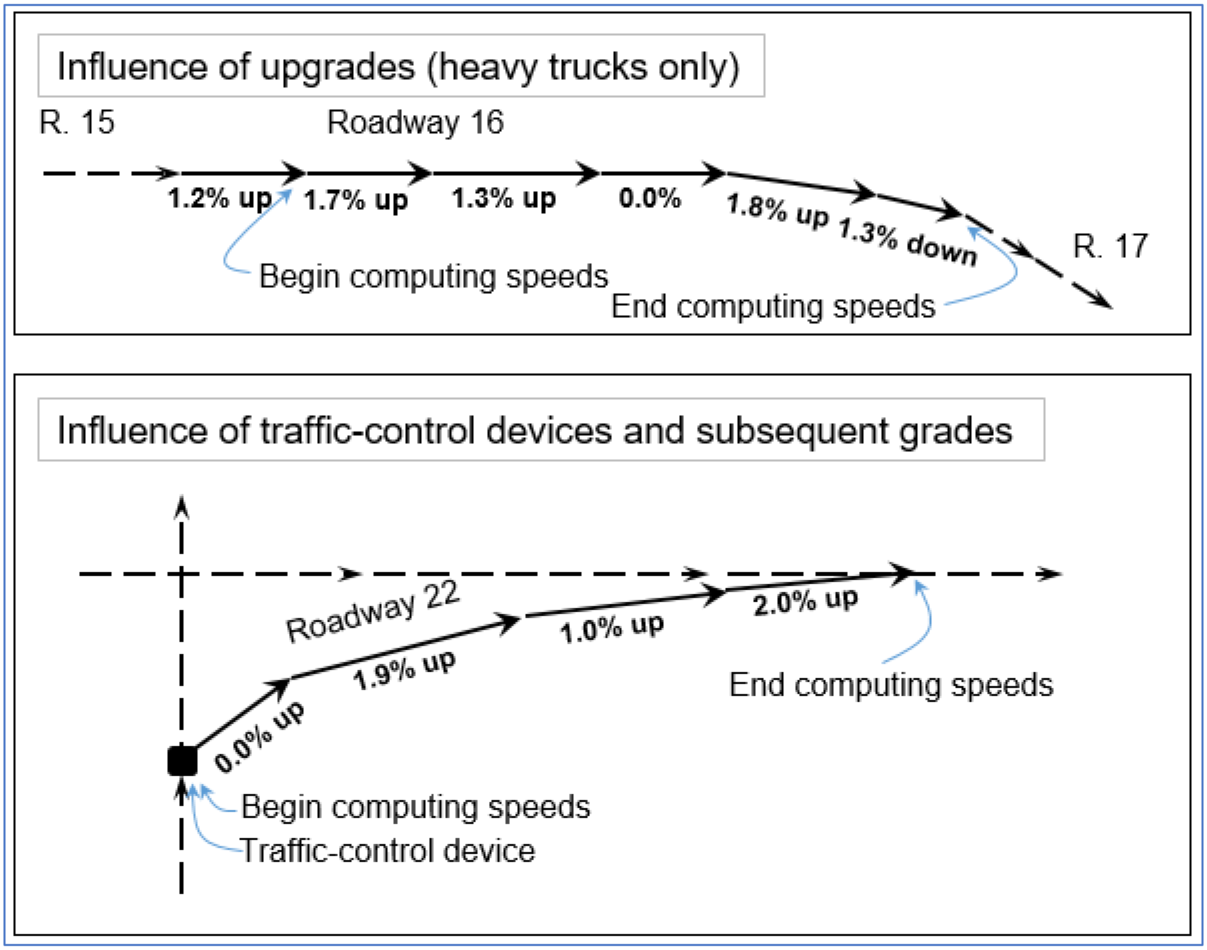

Figure 18 *Geometrics for Speed Effects of Upgrades and Traffic-control Devices*

The following sections of this appendix describe this speed-computation process further, with illustrations.

A.2 Entrance and Exit Speeds: Overview

Figure 19 shows a subdivided elemental triangle, inside the innermost computation "loop" for sound levels. At this point in the acoustical computations, TNM is computing sound levels for a specific receiver from a specific input roadway segment, and has now finished subdividing that roadway segment into the smallest portions (sub-segments) needed for computation.

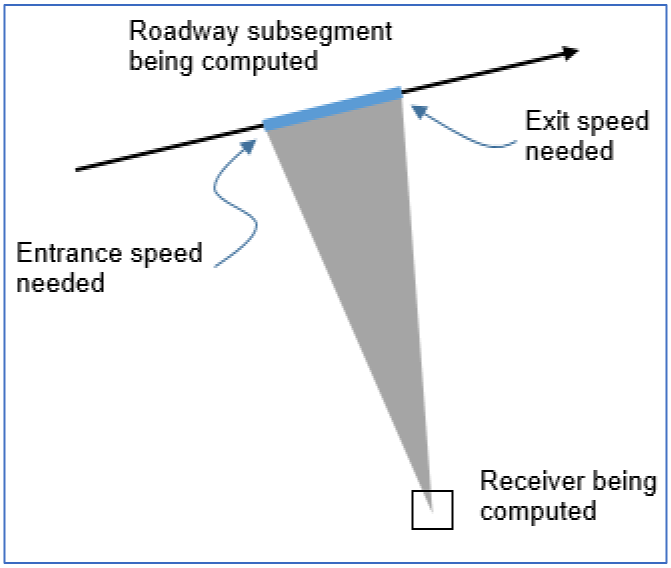

Figure 19 *Entrance and Exit Speeds*

At this point, TNM needs to determine the acoustical energy at the receiver from the traffic on this roadway sub-segment. To determine this, TNM must first know the average vehicle speed, $s_{average}$, for each type of vehicle on the sub-segment.

TNM calculates average speeds from the *entrance* and *exit* speeds of each vehicle type, as follows:

$$s_{average} = \frac{s_{entrance} + s_{exit}}{2} \tag{30}$$

A.3 Entrance Speeds

In general, a vehicle type's entrance speed sometimes equals: (1) the speed entered by the user, sometimes; (2) a control-device's speed constraint; and sometimes (3) the exit speed of the previous sub-segment. The distinction among these depends upon whether TNM is "tracking" that vehicle's speed or not.

In particular:

- **The first entrance speed for upgrades:** When traffic first encounters an upgrade equal to 1.5 percent or more, TNM begins to track heavy-truck speeds, plus the speeds of all user-defined vehicles that mimic heavy trucks. For the first sub-segment, TNM sets entrance speed equal to the user’s input speed.
- **The first entrance speed for traffic-control devices:** If a traffic-control device is located on the first point of a segment, then TNM begins tracking speeds for all vehicles along this segment. For the first sub-segment, TNM sets the entrance speed of all vehicle types to the device’s speed constraint entered by the user. If the device is a traffic signal, TNM also remembers that speed tracking only pertains to the device's "percentage of vehicles affected."
- **Subsequent entrance speeds:** Then as vehicles progress from sub-segment to sub-segment, TNM preserves speed continuity. Specifically, it first computes each vehicle type’s exit speed for the current sub-segment, *i*, as described in the next section. Then it assigns these speeds

as entrance speeds for the next sub-segment, i+1. Level grades and downgrades allow vehicles to accelerate back upwards towards user's input speeds. Once this happens for a particular vehicle type, then TNM stops tracking speed for that vehicle type.

A.4 Exit Speeds

In general, a vehicle type's exit speed sometimes equals its input speed and sometimes is computed from the entrance speed, the roadway grade and the length of the sub-segment.

Whenever TNM is tracking speed for a particular vehicle type, it must compute sub-segment exit speeds. For each vehicle type, TNM requires an equation for:

s_{exit}, vehicle speed at the end of the segment, in kilometers per hour, as a function of the following:

$s_{entrance}$, vehicle speed at the beginning of the segment, in kilometers per hour,

x, length of the segment, in meters,

g, roadway grade, in percent,

i, vehicle type,

plus, whether the vehicle is accelerating or decelerating.

A.5 Regression Equations

For every possible roadway grade (upgrade, level, and downgrade), heavy trucks have a so called "crawl speed." As TNM tracks heavy-truck speeds along a roadway segment, whenever the heavy-truck speed at the beginning of the segment, $s_{entrance}$, is less than $s_{HTcrawl}$ for that grade, then the heavy trucks will accelerate upwards towards their crawl speed. On the other hand, whenever the speed at the beginning of the segment, $s_{entrance}$, is greater than $s_{HTcrawl}$ for that grade, then heavy trucks will decelerate down towards their crawl speed.

In short, heavy trucks

- accelerate when $s_{entrance} < s_{HTcrawl}$,
- decelerate when $s_{entrance} > s_{HTcrawl}$, and
- keep speed constant when $s_{entrance} = s_{HTcrawl}$.

In the last unlikely situation, note that TNM still continues to track speed on the segment, even though this speed is constant, because the heavy truck is not yet up to the user's input speed.

Other TNM vehicles have no crawl speed. TNM does not slow them down due to upgrades. When TNM tracks vehicles other than heavy trucks, it always accelerates them upwards, until they reach the user's input speed.

A.5.1: Regression Equation for Accelerating Vehicles

For vehicles accelerating from an entrance speed of zero,

$$s_x = 1.609A\left\{1 - \exp\left[-\left(\frac{0.3048x}{B}\right)^C\right]\right\} \tag{31}$$

Where, s_x is vehicle speed, in kilometers per hour, at distance x along the roadway sub-segment, in meters. For this equation, A, B and C appear in ***Table 8***.

Note that some of these regression coefficients are functions of roadway grade, g. Also note the distinction between G (a regression coefficient) and g (the roadway grade), in percent.

When the entrance speed is not zero, TNM uses the following equation, which is derived from the previous one:

$$s_x = 1.609A \times \left\{1 - \exp\left[-\left(\frac{\{0.3048x + B[\ln(A) - \ln(A - 0.6214s_{entrance})]^{1/c}\}}{B}\right)^C\right]\right\} \tag{32}$$

Where, $s_{entrance}$ is vehicle speed, in kilometers per hour, at the entrance to the roadway sub-segment.

Table 8: Regression Coefficients for Accelerating Vehicles

Vehicle Type	A	B	C
Automobiles and motorcycles	D exp(-E g), where D = 130.300 E = 0.119	F exp(-G g), where F = 3950.000 G = 0.208	0.482
Medium trucks and all buses	D exp(-E g), where D = 85.714 E = 0.119	F exp(-G g), where F = 1838.149 G = 0.197	0.521
Heavy trucks	D exp(-E g), where D = 70.721 E = 0.137	F exp(-G g), where F = 1849.803 G = 0.231	0.51

A.5.2: Regression Equation for Decelerating Heavy Trucks

For heavy trucks decelerating from an entrance speed of 121 kilometers per hour (75 miles per hour),

$$s_x = 1.609A + (121 - 1.609A)\exp\left[-\left(\frac{0.3048x}{B}\right)^C\right] \tag{33}$$

Where, for this equation, A, B, and C appear in ***Table 9***. Note that some of these coefficients are functions of roadway grade, g, in percent.

Table 9: Regression Coefficients for Decelerating Heavy Trucks

Vehicle Type	A	B	C
Heavy Trucks	D exp(-E g), where D = 64.606 E = 0.196	F exp(-G g), where F = 3996.848 G = 0.121	1.268

When the entrance speed is not 121 kilometers per hour, TNM uses the following equation, which is derived from the previous one:

$$s_x = 1.609\,A + (\,121 - 1.609\,A\,)$$
$$\times\, exp\left[-\left(\frac{\left\{\,0.3048\,x + B\,[\,\ln(\,121 - 1.609\,A\,) - \ln(\,s_{entrance} - 1.609\,A\,)\,]^{\frac{1}{C}}\right\}}{B}\right)^{C}\right] \qquad (34)$$

A.6 Graphs of Acceleration and Deceleration

Figure 20 to **Figure 23** plot Equations 31 to 34. They show TNM's functional relationships between vehicle speed and distance along a roadway sub-segment, starting at zero speed for acceleration and 121 kilometers per hour (75 miles per hour) for deceleration.

These functional relationships resemble the official performance curves used for highway geometric design (American Association of State Highway and Transportation Officials, 1990) (Transportation Research Board, 1985). The curves here have been regressed to the same functional form as the official performance curves, but from vehicle acceleration and deceleration data during measurement of TNM’s emission levels for full-throttle vehicles (heavy trucks on upgrades and all vehicles as affected by traffic-control devices). Because of this regression based on field-measured speed data, the TNM curves are fully consistent with TNM’s full-throttle emission levels. Moreover, the heavy-truck curves for both acceleration and deceleration are consistent with performance curves for a truck with a weight-to-horsepower ratio of 97 kg/kW (160 lb/hp) and a weight-to-frontal area ratio of 1,760 kg/m2 (360 lb/ft2).

The curves in each of these figures show vehicle dynamics for an average vehicle, as a function of grade. In **Figure 22**, for example, a heavy truck starting from speed zero on a 4-percent upgrade would reach 43 kilometers per hour (27 miles per hour) after traveling 305 meters (1,000 feet), and 53 kilometers per hour (33 miles per hour) after traveling another 305 meters (1,000 feet), for a total of 610 meters (2,000 feet). Then after traveling another 3,050 meters (10,000 feet) — for a total of 3,660 meters (12,000 feet) — this truck would reach its maximum sustainable speed for this grade: 66 kilometers per hour (41 miles per hour). This speed is called the truck's “crawl speed.” If the truck started out at 43 kilometers per hour (27 miles per hour), instead, the distance/speed relationships would be the same: 53 kilometers per hour (33 miles per hour) after 305 meters (1,000 feet), 66 kilometers per hour (41 miles per hour) after another 3,050 meters (10,000 feet), for a total of 3,355 meters (11,000 feet). The starting speed, combined with distance, determine the ending speed.

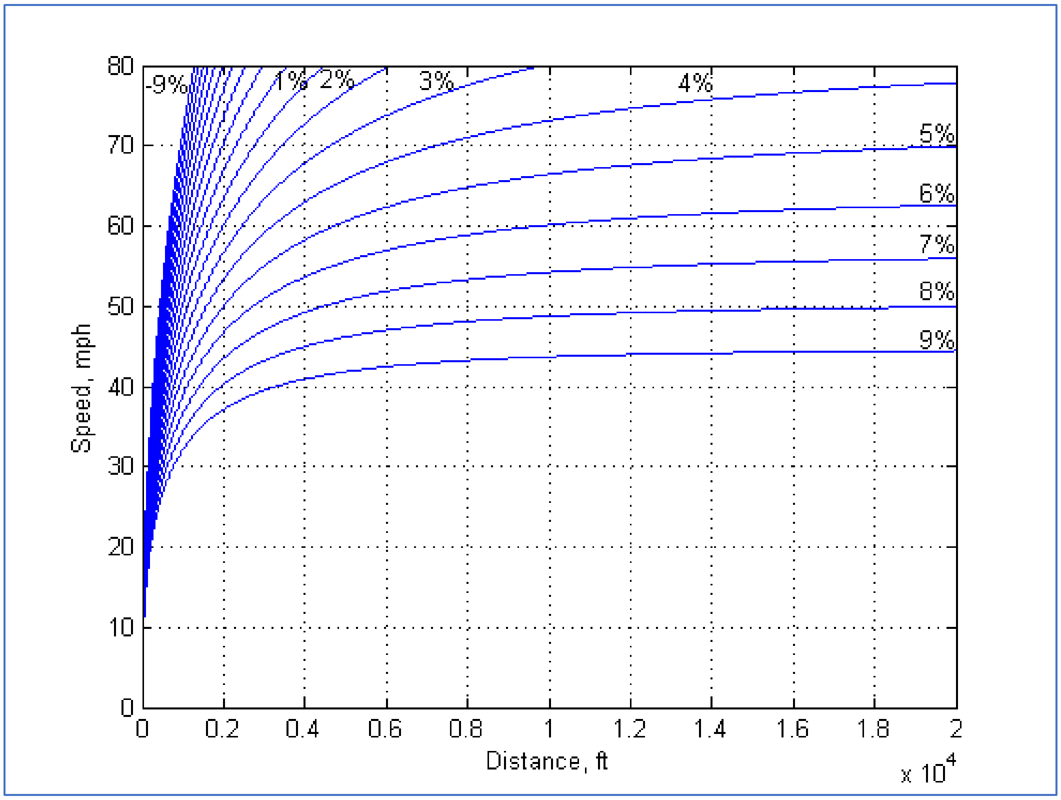

Figure 20 *Acceleration away from traffic-control devices: Automobiles and motorcycles*

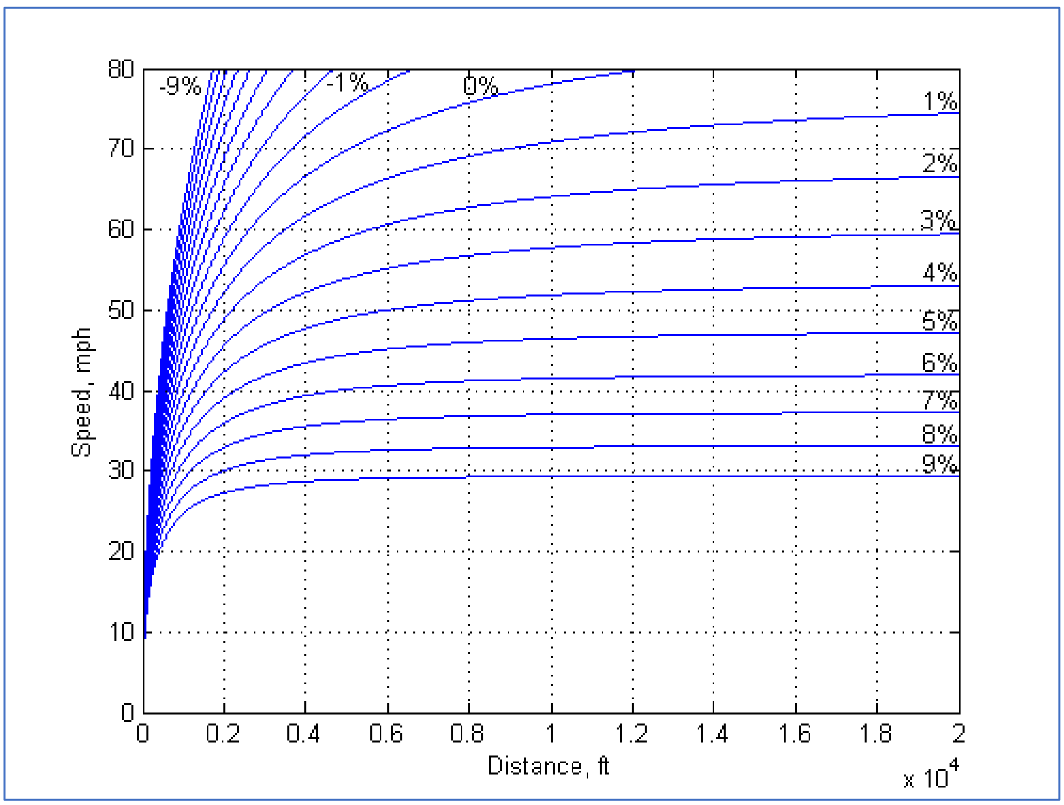

Figure 21 *Acceleration away from traffic-control devices: Medium trucks and buses*

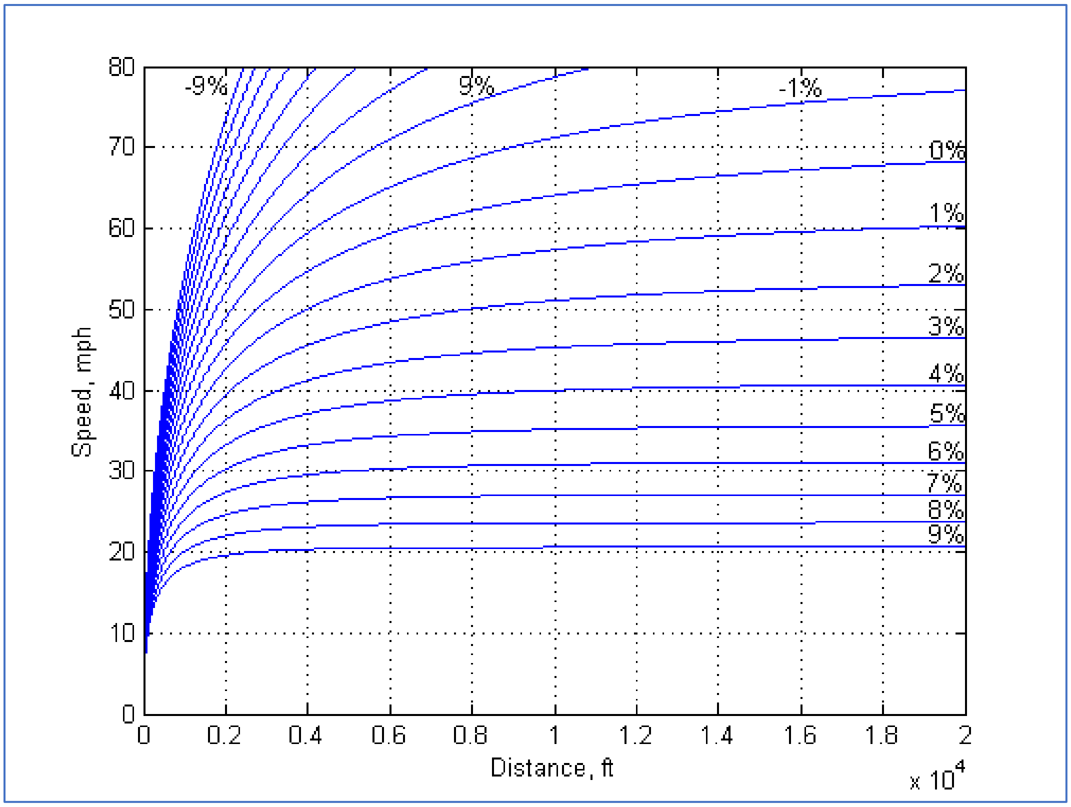

***Figure 22** Acceleration away from traffic-control devices: Heavy trucks*

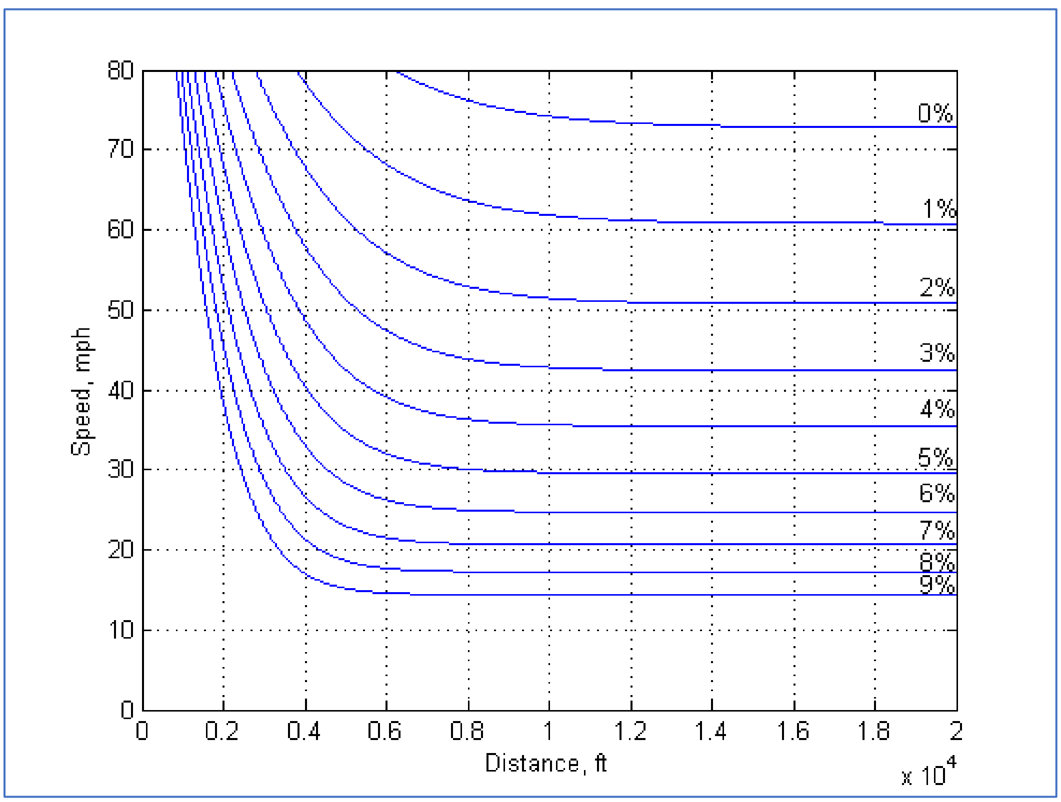

***Figure 23** Deceleration caused by upgrades 1.5 percent or more: Heavy trucks*

In summary, vehicle type tells which vehicle's curves to use. Roadway grade determines the crawl speed for that vehicle type. The entrance speed, $s_{entrance}$, determines whether heavy trucks accelerate or decelerate. Finally, the entrance speed and sub-segment length, x, determine the speed, s_x, at distance x along the sub-segment — including the sub-segment's exit speed, s_{exit}, when x is set to the full sub-segment length.

Example: Roadway 16 in **Figure 18**[7] contains upgrades, which affect only heavy trucks. The sketches in **Figure 24** show the resulting heavy-truck speeds as a function of distance along Roadway 16. No other vehicle speeds are affected by upgrades.

In the first segment (1.2 percent up), heavy-truck speeds are not yet affected. They therefore equal the user's heavy-truck input speed for this roadway segment. The second segment (1.7 percent up) causes TNM to start tracking heavy-truck speeds, because its grade equals 1.5 percent or more. Heavy trucks start on this segment at their input speed and then decelerate according to the deceleration curve for heavy trucks on a 1.7- percent upgrade. At the end of the segment, their speed is reduced to approximately one-third of input speed. Equally important, TNM is still tracking heavy-truck speeds because they have not accelerated back to the user's input speed. For this reason, speed is continuous from segment to segment (no abrupt changes). Heavy-truck speeds on the third segment (1.3 percent up) therefore start out at the exit speed of the prior segment and then start to increase as heavy trucks accelerate on this less-steep upgrade. Acceleration occurs here because the entrance speed is less than the heavy-truck crawl speed for a 1.3 percent upgrade.

When heavy trucks reach the fourth segment (0.0 percent), they begin to accelerate more rapidly because there is no grade on this segment. In fact, on this segment, heavy trucks happen to accelerate fully back up to input speed. At this point, TNM stops tracking heavy-truck speeds. It also stops enforcing speed continuity from segment to segment. Note that the user's heavy-truck input speed was reached on this segment partly due to the vehicle acceleration and partly because this segment has a lower input speed.

The fifth segment (1.8 percent up) again causes TNM to start tracking heavy-truck speeds, and therefore heavy trucks decelerate as shown. Note that they start out at the heavy-truck input speed for this segment, even though this means their speed abruptly increases from its value on the prior segment. TNM allows such abrupt speed changes, whether or not upgrades are involved, whenever the user decides to abruptly change input speeds from segment to segment. Normally TNM does not accelerate/decelerate vehicles from one input speed to the next. Only when TNM is tracking speeds does it provide speed continuity.

Finally, the heavy trucks then accelerate upon entering the sixth segment (1.3 percent down). At the end of this segment, the heavy trucks are still not quite up to input speed. Nevertheless, this is the end of the full roadway and therefore TNM stops tracking speeds.

[7] *This was previously Roadway 16 in Figure 41 of the TNM 1.0 Technical Manual.*

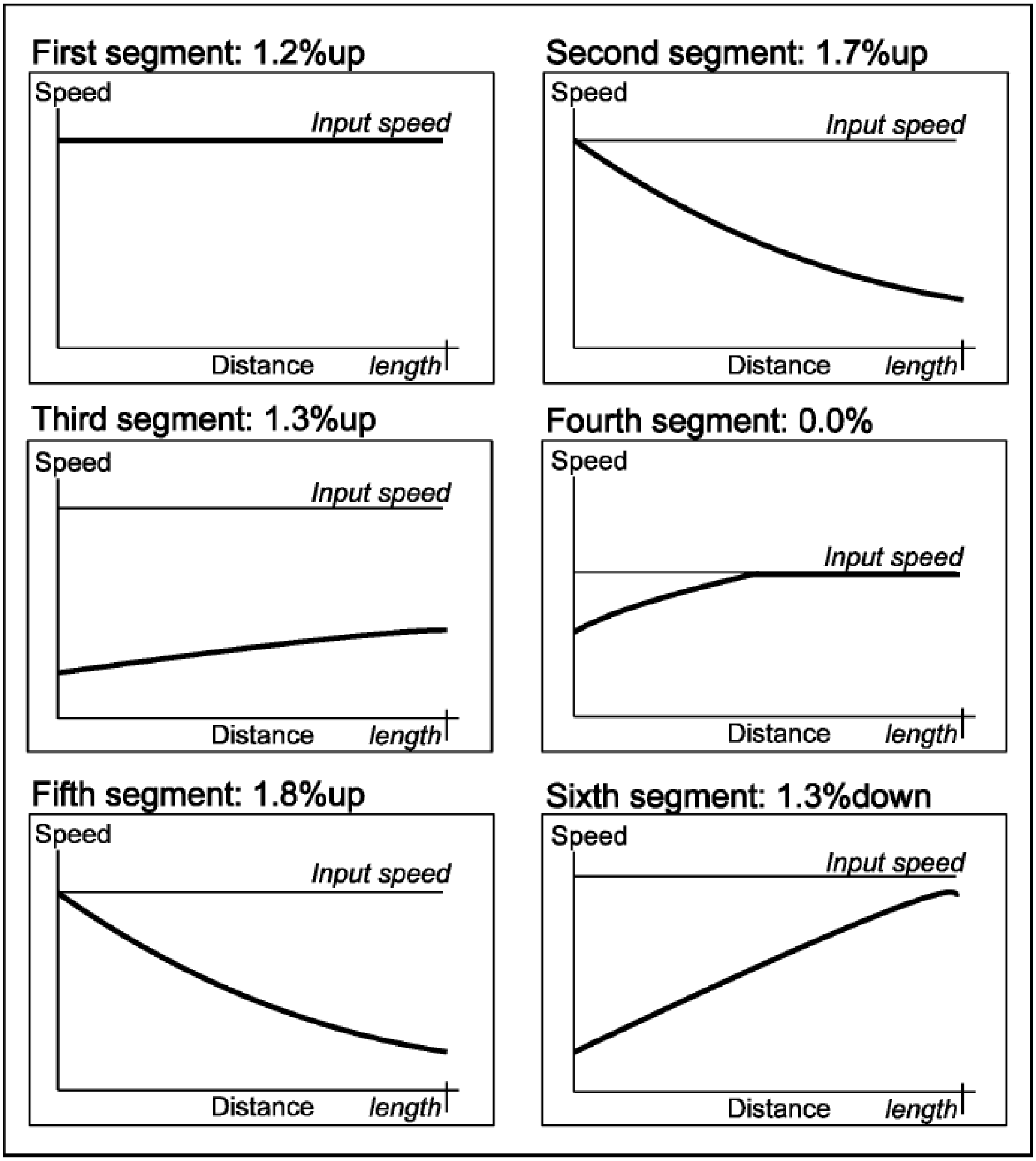

***Figure 24** Speeds for Roadway 16 – Upgrades*

Example: Roadway 22 in **Figure 18**[8] contains a traffic-control device (on-ramp entrance point), which affects the speeds of all vehicle types. The sketches in **Figure 25** show only the resulting heavy-truck speeds, as a function of distance along Roadway 22. Speeds for other vehicle types are tracked similarly, though they vary in their details.

[8] *This was previously Roadway 22 in Figure 41 of the TNM 1.0 Technical Manual.*

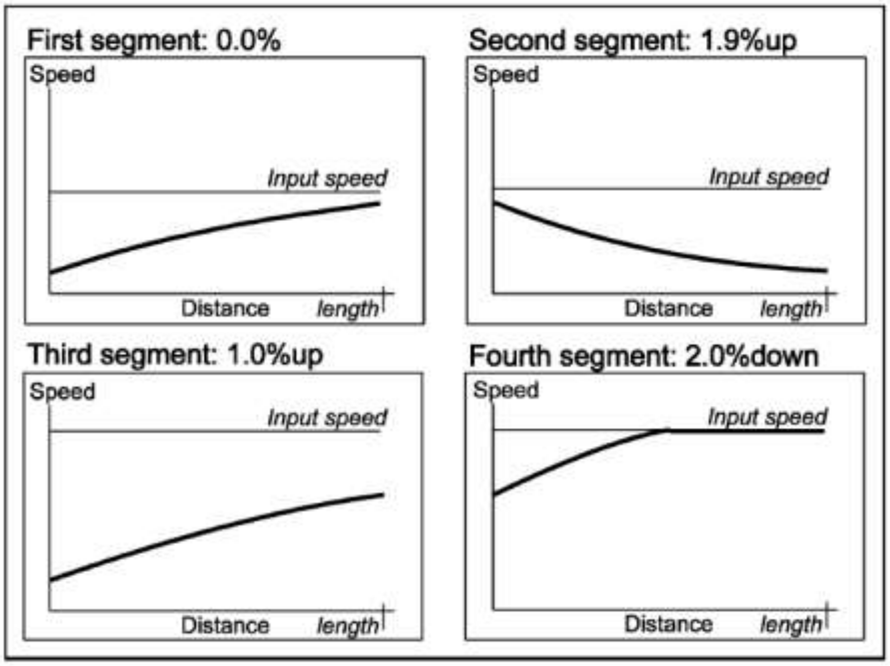

Figure 25 *Speeds for Roadway 22 – Traffic-control devices and subsequent grades*

The first segment (0.0 percent) starts with a traffic-control device: onramp entrance point. This type of traffic-control device allows a non-zero speed constraint. The one shown in the figure is relatively low, but not quite zero. TNM starts tracking speeds for all vehicles, with this as the initial start speed. Then heavy trucks accelerate according to the heavy-truck acceleration curve for level (zero percent) grade. At the end of the segment, they have not quite reached heavy-truck input speed for this roadway segment.

Speed is continuous from the first to the second segment (1.9 percent up) because TNM is still tracking heavy-truck speeds. (On the other hand, if heavy trucks had managed to accelerate up to input speed in the first segment, then TNM would stop tracking them. In turn, their speed would abruptly change upon entering the second segment, up to heavy-truck input speed for this segment.) On this second segment, heavy trucks then decelerate. Note that the upgrade of this segment, by itself, would have caused TNM to track heavy-truck speeds, even if it had stopped tracking them part way through the first segment.

On the third segment (1.0 percent up), heavy trucks accelerate up towards their crawl speed on this grade. In the fourth segment (2.0 percent down), they accelerate more rapidly because of the downgrade. On this segment they reach input speed, and TNM stops tracking heavy-truck speeds.

A.6.1: Some Additional Points

Each vehicle's speed is calculated independently of the others, because the user is free to enter different input speeds for different vehicles. Some commonality exists, however. TNM only contains vehicle dynamics (acceleration/deceleration curves) for three vehicle types: autos, medium trucks and heavy trucks. Other vehicles "mimic" these three. In particular, buses mimic medium trucks and motorcycles mimic autos. In addition, user-defined vehicles mimic whatever TNM vehicle the user designates as most similar.

APPENDIX B: VEHICLE NOISE EMISSION LEVELS

This appendix supplements discussions in Section 2.3 and is largely a reproduction of the portions of Appendix A of (Anderson, et al., 1998), modified only to reflect changes between TNM 1.0 and TNM 3.1 and to avoid repetition of some materials already presented in the main body. Note, for ease of reference, some information originally presented in the main body is still repeated here.

This appendix contains noise-emission equations and graphs for the five built-in vehicle types within FHWA TNM:

- Automobiles: all vehicles having two axles and four tires — designated primarily for transportation of nine or fewer passengers, i.e., automobiles, or for transportation of cargo, i.e., light trucks. Generally, the gross vehicle weight is less than 4500 kg (9900 lb).
- Medium trucks: all cargo vehicles with two axles and six tires. Generally, the gross vehicle weight is greater than 4,500 kg (9,900 lb), but less than 12,000 kg (26,400 lb).
- Heavy trucks: all cargo vehicles with three or more axle. Generally, the gross vehicle weight is greater than 12,000 kg (26,400 lb).
- Buses: all vehicles having two or three axles and designated for transportation of nine or more passengers
- Motorcycles: all vehicles with two or three tires with an open-air driver and/or passenger compartment

For each vehicle type, this appendix contains equations for the following components of sound-level emissions:

- A-weighted sound-level emissions
- One-third octave spectra, relative to A-weighted sound-level emissions
- Vertical sub-source strengths, relative to one-third octave band spectra

In addition, this appendix describes how user-defined vehicles merge with TNM's built-in noise-emission equations.

B.1 OVERVIEW

As a single vehicle passes by a microphone 15 meters (50 feet) to the side, its sound level rises, reaches a maximum, and then falls as the vehicle recedes down the roadway. The maximum A-weighted sound level during the pass-by is called that vehicle's noise-emission level.

Measurement of vehicle noise-emission levels for TNM are reported separately (Fleming, Rapoza, & Lee, Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model, 1995). These TNM emission-level measurements were confined to relatively flat ground, with the microphone at height 1.5 meters (5 feet) and horizontal distance 15 meters (50 feet). Generally, the ground between the roadway edge and the microphone was acoustically absorptive, although not always. At the moment of maximum A-weighted sound level, the vehicle's one-third octave band spectrum was also measured at the microphone. This spectrum, relative to the A-weighted sound level, is called the vehicle's noise- emission spectrum.

Measurement of vertical sub-sources for TNM are also reported separately (Coulson, 1996). These sub-source measurements were also confined to relatively flat ground, with an array of microphone heights at horizontal distance 7.5 meters (25 feet). For these measurements, the ground between the roadway edge and the microphone array was acoustically hard, although the data were analyzed to subtract out the effects of ground reflections.

This appendix describes the results of all TNM emission-level measurements and their statistical analysis.

B.2 Definition of Variables

To calculate sound levels for entire traffic streams, TNM must incorporate energy-average vehicle noise emissions for each vehicle type. These energy-average emission levels depend upon the following variables:

f is the nominal one-third octave band center frequency, in Hz

i is the index for vehicle type and iterates over built-in types and user-defined types

p is the index for pavement types:

- Average (of DGAC and PCC)
- DGAC (dense-graded asphaltic concrete), often called asphalt
- PCC (Portland cement concrete), often called concrete
- OGAC (open-graded asphaltic concrete).

s is the vehicle speed, in kilometers per hour. Speed varies with roadway segment. It may also vary by vehicle type, either because the user enters a different input speed or because TNM internally calculates speed due to upgrades or traffic-control devices (see Appendix A).

B.3 A-weighted Noise-Level Emissions and One-third Octave Band Spectra, as Measured

TNM needs three constants to compute A-weighted noise-level emissions: *A*, *B* and *C*. In addition, it needs fourteen additional constants to convert these A-weighted noise-level emissions to one-third octave band spectra: $D1$, $D2$, $E1$, $E2$, $F1$, $F2$, $G1$, $G2$, $H1$, $H2$, $I1$, $I2$, $J1$ and $J2$.

These seventeen constants depend upon two indexes, *i* and *p* (vehicle type and pavement type, respectively), plus whether the vehicle is full throttle or not. Vehicles are full throttle when they accelerate away from traffic-control devices, until they reach the user's input speed. In addition, heavy trucks are full throttle on upgrades equal to 1.5 percent or more, until later level grades and downgrades allow them to accelerate back up to the user's input speed.

B.3.1 Built-in vehicle types

Table 10 contains the required seventeen constants, for all combinations of vehicle type, pavement type, and throttle condition.

For any roadway/traffic situation, the pavement type and throttle condition will be known. The traffic will include several different vehicle types, *i*, each with its own speed, s_i. For these emission calculations, TNM substitutes the relevant constants from ***Table 10*** into the following set of equations, to determine each vehicle type's total measured noise emissions:

$$E_A(\ s_i\ ) = (\ 0.6214\ s_i\ )^{A/10} \cdot 10^{B/10} + 10^{C/10} \tag{35}$$

$$\begin{aligned} L_{emis,\ i}(\ s_i, f\ ) = {} \\ & L_A(s_i) + (\ D_1 + 0.6214\ D_2 s_i\ ) + (\ E_1 + 0.6214\ E_2 s_i\ )\ [\log_{10}(\ f\ )] + \\ & (\ F_1 + 0.6214\ F_2 s_i\ )\ [\log_{10}(\ f\ )]^2 + (\ G_1 + 0.6214\ G_2 s_i\ )\ [\log_{10}(\ f\ )]^3 + \\ & (\ H_1 + 0.6214\ H_2 s_i\ )\ [\log_{10}(\ f\ )]^4 + (\ I_1 + 0.6214\ I_2 s_i\ )\ [\log_{10}(\ f\ )]^5 + \\ & (\ J_1 + 0.6214\ J_2 s_i\ )\ [\log_{10}(\ f\ )]^6 \end{aligned} \tag{36}$$

$$E_{emis,i}(\ s_i, f\ ) = 10^{L_{emis,i}/10} \tag{37}$$

where speed, *s*, is in kilometers per hour.

The first of these equations yields the energy form, E_A, of the maximum pass-by A-weighted sound level for the vehicle type. The second equation converts this E_A to a one-third octave band spectrum. This spectrum is also A-weighted, because each of its measured one-third octave-band levels has been A- weighted. Therefore, when the energies are added for each frequency band, using the equation for $L_{emis,\ i}(\ s_i, f\ )$, the sum, converted to a level, is the A-weighted sound level, without need for further A- weighting. The third equation converts these one-third octave band levels to their energy form.

This set of equations determines each built-in vehicle type's energy-mean emission spectrum, as measured during individual vehicle pass-bys at 15 meters (50 feet) over flat, generally absorptive terrain.

B.3.2 User-defined vehicle types

Subject to FHWA policy guidelines, TNM allows user-defined vehicle types to supplement its built-in vehicle types. FHWA provides specific instructions in (Lee & Fleming, 1996) for the required field measurements and data analysis. In brief, each vehicle type’s A-weighted emission levels must be measured in the field, as a function of speed, and then energy-mean emissions must be regressed against vehicle speed. This regression yields the three vehicle-emission constants: *A*, *B* and *C*. Next the resulting constant *B* must be converted into the vehicle’s energy-mean emissions at 80 kilometers per hour (50 miles per hour), which the user enters along with *A* and *C* into TNM’s traffic dialog box for user-defined vehicles.

Through this process, TNM incorporates customized A-weighted sound-level emissions for user-defined vehicles. For the user-defined vehicle type, TNM substitutes the spectrum constants (*D* through *J*) for whichever built-in vehicle the user designates as most similar, again in the traffic dialog box.

B.4 Vertical Sub-sources, as Measured

TNM needs five additional constants to compute vertical sub-source vehicle emissions: *L*, *M*, *N*, *P* and *Q*. These constants also depend upon the two variables, *i* and *p*, plus throttle condition.

B.4.1 Built-in vehicle types

Table 2[9] contains the measured values of these five constants, for all combinations of vehicle type, pavement type, and throttle condition.

For any roadway/traffic situation, the pavement type and throttle condition will be known. The traffic will include several different vehicle types, *i*, each with its own speed, s_i. For this calculation, TNM then substitutes the relevant five constants from ***Table 2***[10] into the following equation, to determine the sub-source-split ratio, r_i:

$$r_i(\, f\,) = L + (\, 1 - L - M\,)\left[1 + e^{(N \log_{10}(f) + P)}\right]^{Q} \quad (38)$$

Note that the frequency, *f*, appears explicitly in this equation and also that the equation is independent of vehicle speed, s_i. In this equation, *r* is the ratio of upper-height to lower height energy spectra. Intuitively, one might expect the sub-source height split to be a function of vehicle speed, e.g., as speed increases, the split should be more heavily weighted towards the lower height because of the increased effect of tire/road noise. The current sub-source height database contains limited data at low speeds (less than 30 mph). If additional sub-source height data is obtained at low speeds, it is expected that the above equation would need to be modified to take into account vehicle speed.

TNM next combines these ratios, r_i, with each vehicle type's total measured emissions from the previous section, to split its total emissions into vertical sub-sources:

$$E_{emis,i,upper}(\, s_i, f\,) = \left(\frac{r_i}{r_i + 1}\right) E_{emis,i} \quad (39)$$

$$E_{emis,i,lower}(\, s_i, f\,) = \left(\frac{1}{r_i + 1}\right) E_{emis,i} \quad (40)$$

Physically, this last equation represents each vehicle type's energy-mean emission spectrum, split into its two vertical sub-sources, as measured during individual vehicle pass-bys at 15 meters (50 feet) over flat, generally absorptive terrain. Note that *L*, *M*, *N*, *P*, and *Q* were obtained by regression from data at 7.5 meters (25 feet) over flat hard terrain. However, these data were analyzed in a manner that subtracts out the effect of the hard terrain and makes their use here, in this manner, legitimate.

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[9] *This is repeated as Table 11 in this Technical Manual; and was previously Table 6 in the TNM 1.0 Technical Manual.*

[10] *This is repeated as Table 11 in this Technical Manual; and was previously Table 6 in the TNM 1.0 Technical Manual.*

Table 10: Constants for A-Weighted Sound Level Emissions and One-Third Octave Band Spectra

Vehicle type, *i*					Pavement type, *p*				Full throttle		Constants																
											For a user-defined vehicle, substitute its measured values for these three constants			For a user-defined vehicle, use the TNM-equivalent vehicle to choose the relevant table row for these fourteen constants													
Au	MT	HT	Bus	MC	Avg	DGAC	OGAC	PCC	Yes	No	A	B	C	D1	D2	E1	E2	F1	F2	G1	G2	H1	H2	I1	I2	J1	J2
X					X				X		41.740807	1.148546	67	-7516.580054	-9.7623	16460.1	11.65932	-14823.9	-1.233347	7009.474786	-4.327918	-1835.189815	2.579086	252.418543	-0.573822	-14.268316	0.045682
X					X					X	41.740807	1.148546	50.128316	-7516.580054	-9.7623	16460.1	11.65932	-14823.9	-1.233347	7009.474786	-4.327918	-1835.189815	2.579086	252.418543	-0.573822	-14.268316	0.045682
X						X			X		41.740807	0.494698	67	-7313.985627	-19.697019	16009.5	34.363901	-14414.4	-22.462943	6814.317463	6.093141	-1783.723974	-0.252834	245.299562	-0.170266	-13.86487	0.022131
X						X				X	41.740807	0.494698	50.128316	-7313.985627	-19.697019	16009.5	34.363901	-14414.4	-22.462943	6814.317463	6.093141	-1783.723974	-0.252834	245.299562	-0.170266	-13.86487	0.022131
X							X		X		41.740807	-1.065026	67	-9549.987851	-146.173482	21064	340.622686	-19060.8	-324.802942	9032.990872	161.886578	-2363.810485	-44.454426	324.077238	6.378783	-18.21167	-0.373971
X							X			X	41.740807	-1.065026	50.128316	-9549.987851	-146.173482	21064	340.622686	-19060.8	-324.802942	9032.990872	161.886578	-2363.810485	-44.454426	324.077238	6.378783	-18.21167	-0.373971
X								X	X		41.740807	3.520004	67	-2027.8376	-70.674562	3728.329033	155.109567	-2768.001364	-138.780925	1030.541403	64.525774	-195.32456	-16.430316	16.418899	2.17435	-0.339616	-0.117021
X								X		X	41.740807	3.520004	50.128316	-2027.8376	-70.674562	3728.329033	155.109567	-2768.001364	-138.780925	1030.541403	64.525774	-195.32456	-16.430316	16.418899	2.17435	-0.339616	-0.117021
	X				X				X		33.918713	20.591046	74	-8997.974274	96.301703	19015.4	-196.241744	-16587	162.56952	7627.874332	-70.394575	-1950.412341	16.876826	263.093464	-2.132793	-14.645109	0.111404
	X				X					X	33.918713	20.591046	68.002978	-1238.353632	-68.218944	2532.436947	151.781493	-2124.165806	-140.388413	919.784302	68.545463	-215.745405	-18.551234	25.909788	2.634001	-1.244253	-0.153272
	X					X			X		33.918713	19.903775	74	-8997.974274	96.301703	19015.4	-196.241744	-16587	162.56952	7627.874332	-70.394575	-1950.412341	16.876826	263.093464	-2.132793	-14.645109	0.111404
	X					X				X	33.918713	19.903775	68.002978	-230.440015	-82.783198	172.725033	186.80143	131.655819	-174.718246	-207.664798	86.12481	95.139145	-23.513441	-18.96669	3.366475	1.407549	-0.197472
	X						X		X		33.918713	19.345214	74	-8997.974274	96.301703	19015.4	-196.241744	-16587	162.56952	7627.874332	-70.394575	-1950.412341	16.876826	263.093464	-2.132793	-14.645109	0.111404
	X						X			X	33.918713	19.345214	68.002978	-234.711357	-103.147894	162.036132	244.033651	133.970948	-237.867685	-196.613672	121.527971	87.517298	-34.222359	-17.12562	5.031804	1.253128	-0.301914
	X							X	X		33.918713	22.141611	74	-8997.974274	96.301703	19015.4	-196.241744	-16587	162.56952	7627.874332	-70.394575	-1950.412341	16.876826	263.093464	-2.132793	-14.645109	0.111404
	X							X		X	33.918713	22.141611	68.002978	-139.27717	-132.207111	97.357937	296.574807	65.350117	-273.981431	-104.555273	132.85439	47.637332	-35.600554	-9.424641	4.997542	0.689877	-0.287335
		X			X				X		35.87985	21.019665	80	-6864.586846	-94.379848	14368.7	226.701375	-12459.2	-220.015419	5710.525999	110.518825	-1458.340416	-30.365892	196.811136	4.33716	-10.977676	-0.252197
		X			X					X	35.87985	21.019665	74.298135	1468.440649	-235.319117	-3852.393214	537.981518	3886.430673	-502.160068	-1986.858782	244.714955	549.002247	-65.686556	-78.239429	9.217734	4.509121	-0.529106
		X				X			X		35.87985	20.358498	80	-6864.586846	-94.379848	14368.7	226.701375	-12459.2	-220.015419	5710.525999	110.518825	-1458.340416	-30.365892	196.811136	4.337165	-10.977676	-0.252197
		X				X				X	35.87985	20.358498	74.298135	-290.277032	-196.828915	156.854882	450.144699	151.082001	-420.250062	-168.033708	204.806845	60.772941	-54.968445	-9.681901	7.711617	0.570105	-0.442469
		X					X		X		35.87985	19.107151	80	-6864.586846	-94.379848	14368.7	226.701375	-12459.2	-220.015419	5710.525999	110.518825	-1458.340416	-30.365892	196.811136	4.337165	-10.977676	-0.252197
		X					X			X	35.87985	19.107151	74.298135	-258.941348	-255.205946	135.514216	587.489921	132.973712	-552.824216	-151.366531	272.102657	57.66924	-73.912732	-9.928293	10.514055	0.649271	-0.612569
		X						X	X		35.87985	21.822818	80	-6864.586846	-94.379848	14368.7	226.701375	-12459.2	-220.015419	5710.525999	110.518825	-1458.340416	-30.365892	196.811136	4.337165	-10.977676	-0.252197
		X						X		X	35.87985	21.822818	74.298135	87.378338	-224.132311	-497.410428	509.705253	579.584033	-473.326603	-298.5689960	229.5809	78.021585	-61.374037	-10.058424	8.58403	0.498685	-0.49149
			X		X				X		23.47953	38.006238	74	4621.365424	-123.140566	-11601.5	284.796174	11535.3	-267.623062	-5896.461017	130.822488	1645.797051	-35.139019	-238.929963	4.927783	14.139828	-0.2825557
			X		X					X	23.47953	38.006238	68.002978	4621.365424	-123.140566	-11601.5	284.796174	11535.3	-267.623062	-5896.461017	130.822488	1645.797051	-35.139019	-238.929963	4.927783	14.139828	-0.2825557
			X			X			X		23.47953	37.318967	74	4621.365424	-123.140566	-11601.5	284.796174	11535.3	-267.623062	-5896.461017	130.822488	1645.797051	-35.139019	-238.929963	4.927783	14.139828	-0.2825557
			X			X				X	23.47953	37.318967	68.002978	4621.365424	-123.140566	-11601.5	284.796174	11535.3	-267.623062	-5896.461017	130.822488	1645.797051	-35.139019	-238.929963	4.927783	14.139828	-0.2825557
			X				X		X		23.47953	36.760406	74	4621.365424	-123.140566	-11601.5	284.796174	11535.3	-267.623062	-5896.461017	130.822488	1645.797051	-35.139019	-238.929963	4.927783	14.139828	-0.2825557
			X				X			X	23.47953	36.760406	68.002978	4621.365424	-123.140566	-11601.5	284.796174	11535.3	-267.623062	-5896.461017	130.822488	1645.797051	-35.139019	-238.929963	4.927783	14.139828	-0.2825557
			X					X	X		23.47953	39.556803	74	4621.365424	-123.140566	-11601.5	284.796174	11535.3	-267.623062	-5896.461017	130.822488	1645.797051	-35.139019	-238.929963	4.927783	14.139828	-0.2825557
			X					X		X	23.47953	39.556803	68.002978	4621.365424	-123.140566	-11601.5	284.796174	11535.3	-267.623062	-5896.461017	130.822488	1645.797051	-35.139019	-238.929963	4.927783	14.139828	-0.2825557
				X	X	X	X	X	X		41.022542	10.013879	67	7546.65902	-8.870177	-17396	7.899209	16181.8	2.526152	-7828.632535	-5.314462	2085.468458	2.344913	-290.816544	-0.435913	16.614043	0.03005
				X	X	X	X	X		X	41.022542	10.013879	56.086099	7546.65902	-8.870177	-17396	7.899209	16181.8	2.526152	-7828.632535	-5.314462	2085.468458	2.344913	-290.816544	-0.435913	16.614043	0.03005

TABLE 11: CONSTANTS FOR SUB-SOURCE HEIGHT SPLIT

Vehicle type, *i*					Pavement type, *p*				Full throttle		Constants For a user-defined vehicle, use the TNM-equivalent vehicle to choose the relevant table row for these five constants				
Au	MT	HT	Bus	MC	Avg	DGAC	OGAC	PCC	Yes	No	L	M	N	P	Q
X					X	X	X	X	X		0.37324	0.97638	-13.195596	39.491299	-2.583128
X					X	X	X	X		X	0.37324	0.97638	-13.195596	39.491299	-2.583128
	X				X	X	X	X	X		0.57926	0.87135	-177.24921	558.98028	-0.026532
	X				X	X	X	X		X	0.56693	0.93352	-25.497631	80.239979	-0.234435
		X			X	X	X	X	X		1.33	0.08	-204.844	592.568	-159.344
		X			X	X	X	X		X	0.85	-0.33	163.021	-492.451	-58.005
			X		X	X	X	X	X		0.57926	0.87135	-177.24921	558.98028	-0.026532
			X		X	X	X	X		X	0.5631	0.92809	-31.517739	99.099777	-0.263459
				X	X	X	X	X	X		0.39135	0.97841	-19.278172	60.404841	-0.614295
				X	X	X	X	X		X	0.39135	0.97841	-19.278172	60.404841	-0.614295

B.4.2 USER-DEFINED VEHICLES

For a user-defined vehicle, TNM substitutes the sub-source heights for the built-in vehicle that the user designates as most similar. ***TABLE 10*** mentions this substitution in the appropriate column heading.

B.5 VERTICAL SUB-SOURCES, FREE FIELD

Next TNM eliminates the ground effects within these measured vehicle emissions. To do this, it multiplies each measured vertical sub-source emission by the values in ***TABLE 12***.

Mathematically:

$$E_{emis,\ i,\ upper,\ ff}(\,s_i, f\,) = m_{upper} \cdot E_{emis,\ i,\ upper} \tag{41}$$

$$E_{emis,\ i,\ lower,\ ff}(\,s_i, f\,) = m_{lower} \cdot E_{emis,\ i,\ lower} \tag{42}$$

The subscripts, *ff*, stand for free field. Physically, this last equation represents each vehicle type's measured energy-mean emission spectrum, as if the vehicles passed by during measurements at 15 meters (50 feet) without any intervening ground (that is, free field).

TABLE 12: MULTIPLIER, M, FOR EACH BUILT-IN SUB-SOURCE HEIGHT

Freq (Hz)		50	63	80	100	125	160	200	250	315	400	500	630
Multiplier, *m*	Height 3.66 m (12 ft)	0.3	0.32	0.36	0.44	0.52	0.69	0.95	1.78	1.00	0.32	0.4	0.25
	Height 1.5 m (5 ft)	0.26	0.27	0.27	0.28	0.3	0.33	0.38	0.48	0.62	0.79	1.12	1.58
	Height 0 m (0 ft)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.2

Freq (Hz)		800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
Multiplier, *m*	Height 3.66m	0.25	0.25	0.25	0.25	0.32	0.56	1.00	1.00	1.00	1.00	1.00	1.00
	Height 1.5 m	0.40	0.50	0.32	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Height zero	0.25	0.25	0.22	0.2	0.25	0.27	0.34	0.42	0.47	0.52	0.59	0.67

These values were derived by using propagation algorithms of TNM to determine the effect of the (absorptive) ground present during the emission-level measurements.

B.6 PLOTS OF ALL NOISE EMISSIONS

Figure 26 shows A-weighted sound-level emissions for TNM's built-in vehicle types, for average pavement and cruise throttle. The following figures plot all noise emissions, separately by vehicle type and throttle condition (cruise or full):

- **Figure 26** to **Figure 36**: A-weighted sound-level emissions
- **Figure 37** to **Figure 52**: emission spectra, separately by pavement type
- **Figure 53** to **Figure 62**: high/low energy split

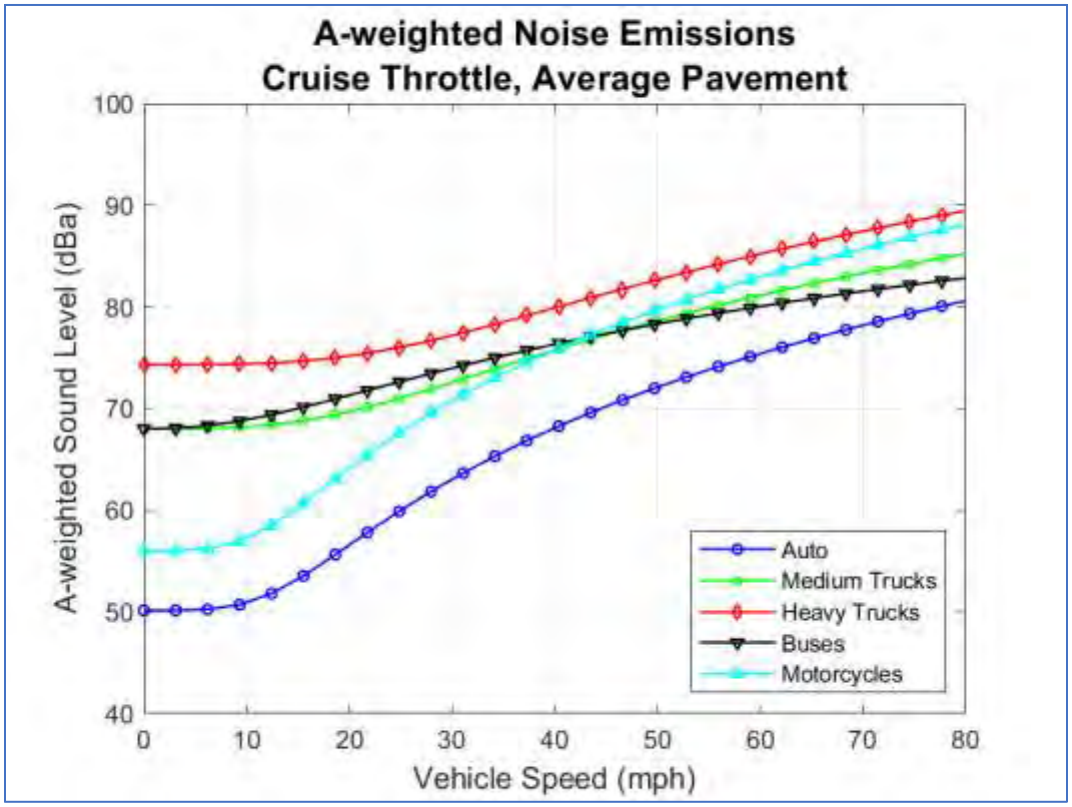

Figure 26 *A-weighted sound-level emissions: Average pavement, cruise throttle*

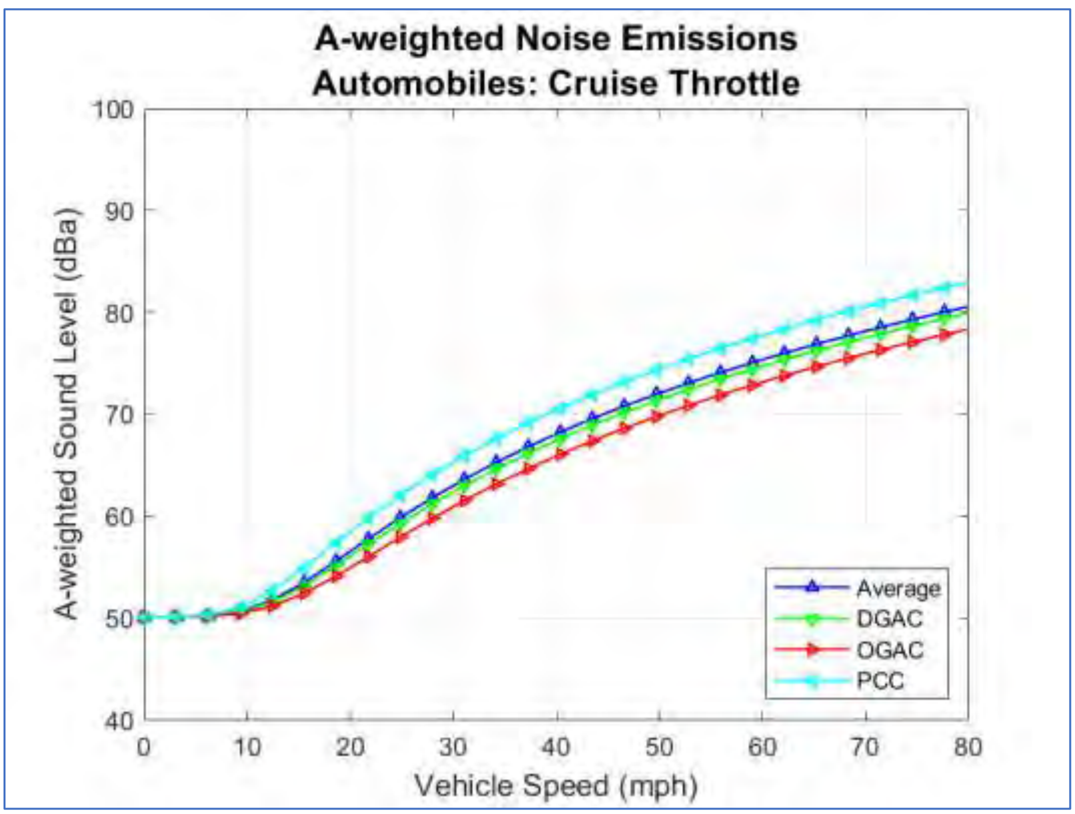

Figure 27 *A-weighted sound-level emissions: Automobiles, cruise throttle*

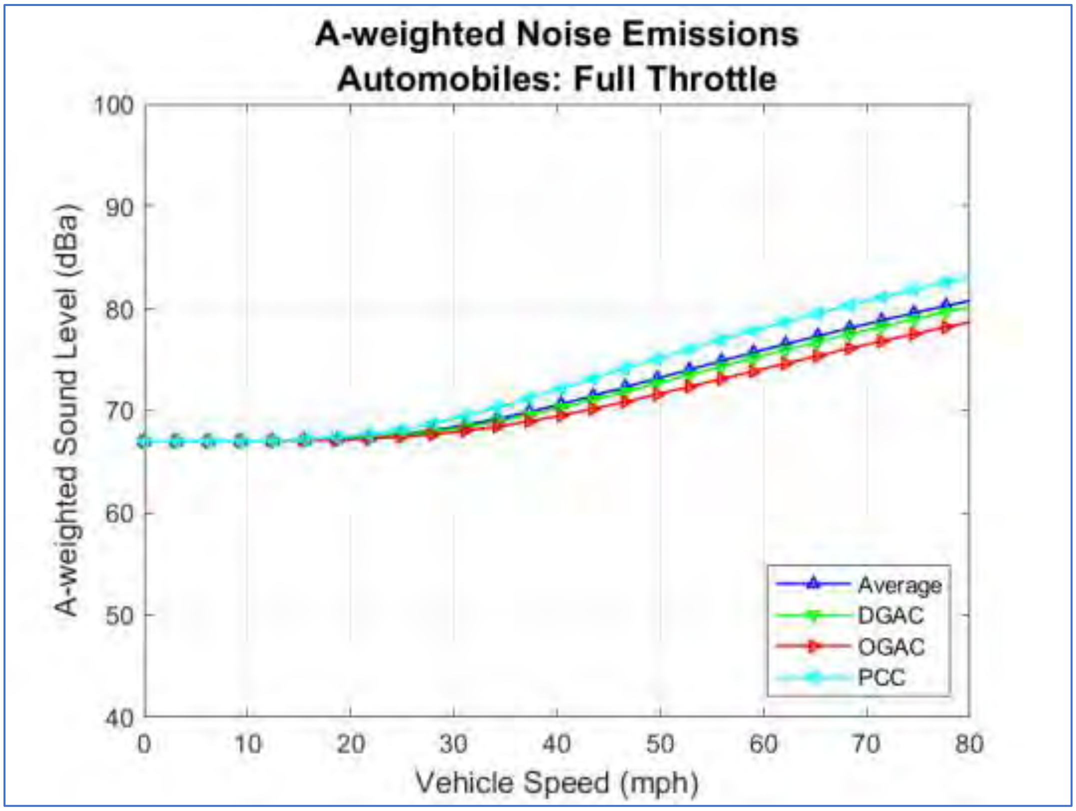

Figure 28 *A-weighted sound-level emissions: Automobiles, full throttle*

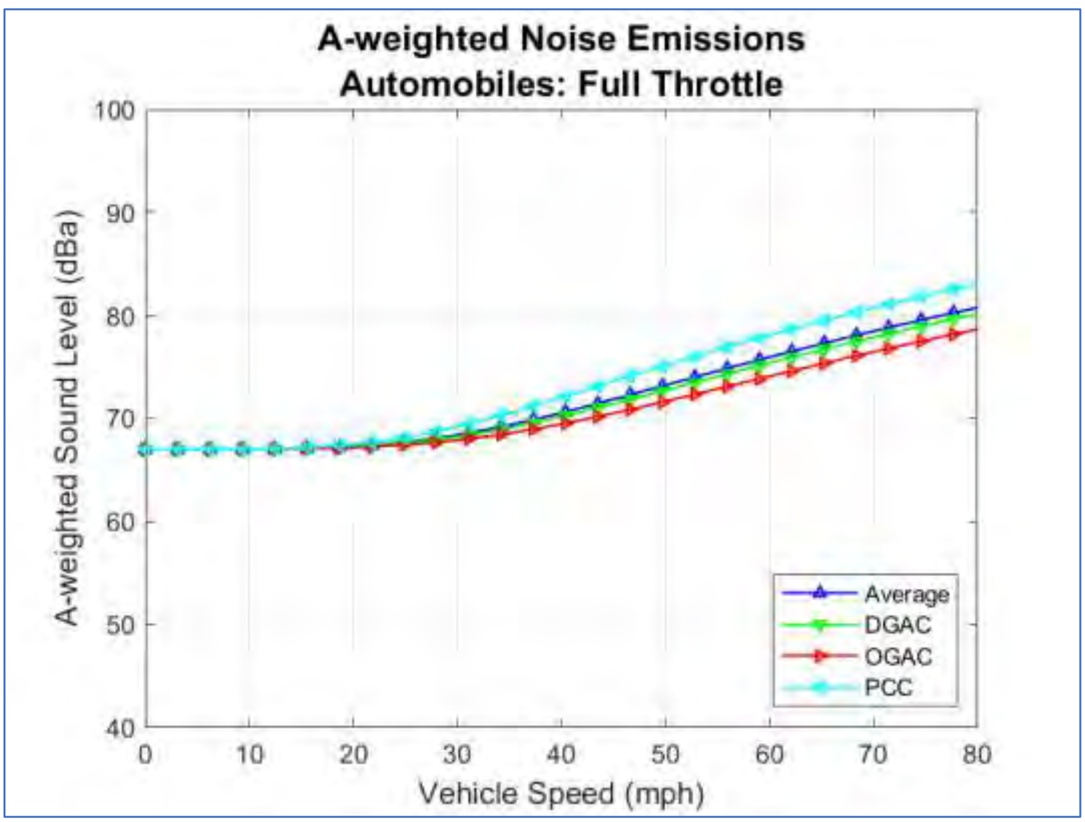

Figure 29 *A-weighted sound-level emissions: Medium trucks, cruise throttle*

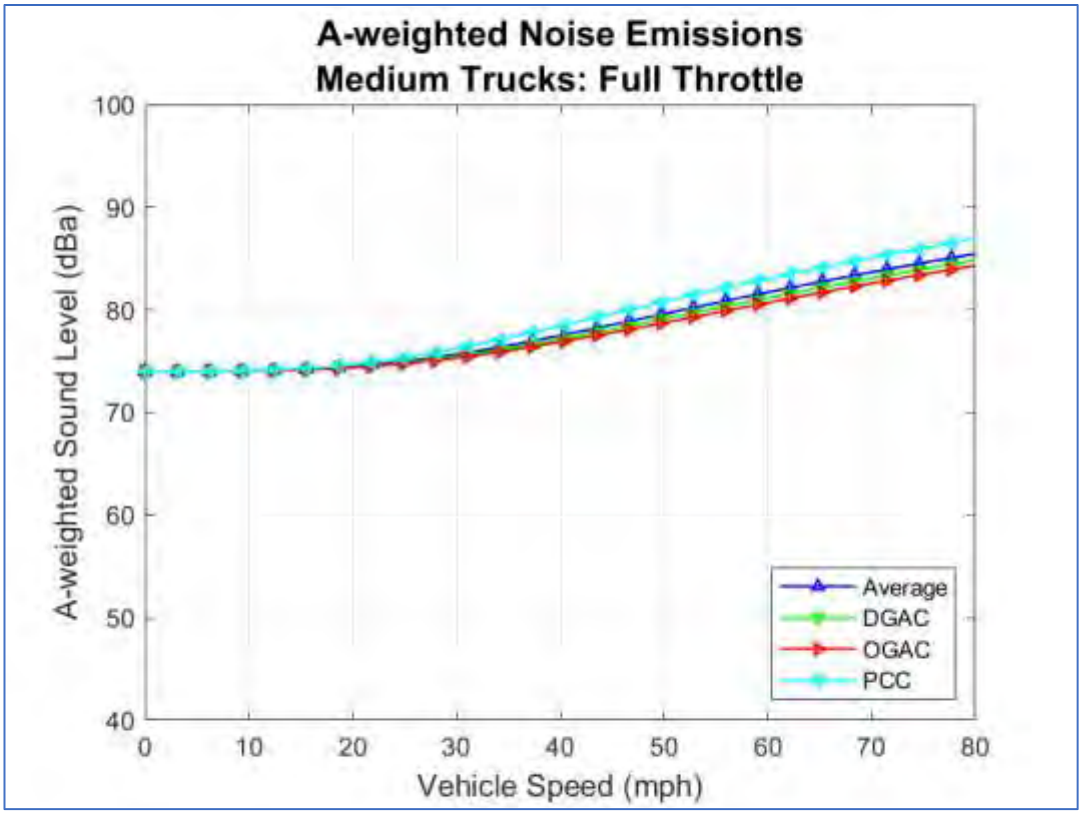

__Figure 30__ A-weighted sound-level emissions: Medium trucks, full throttle

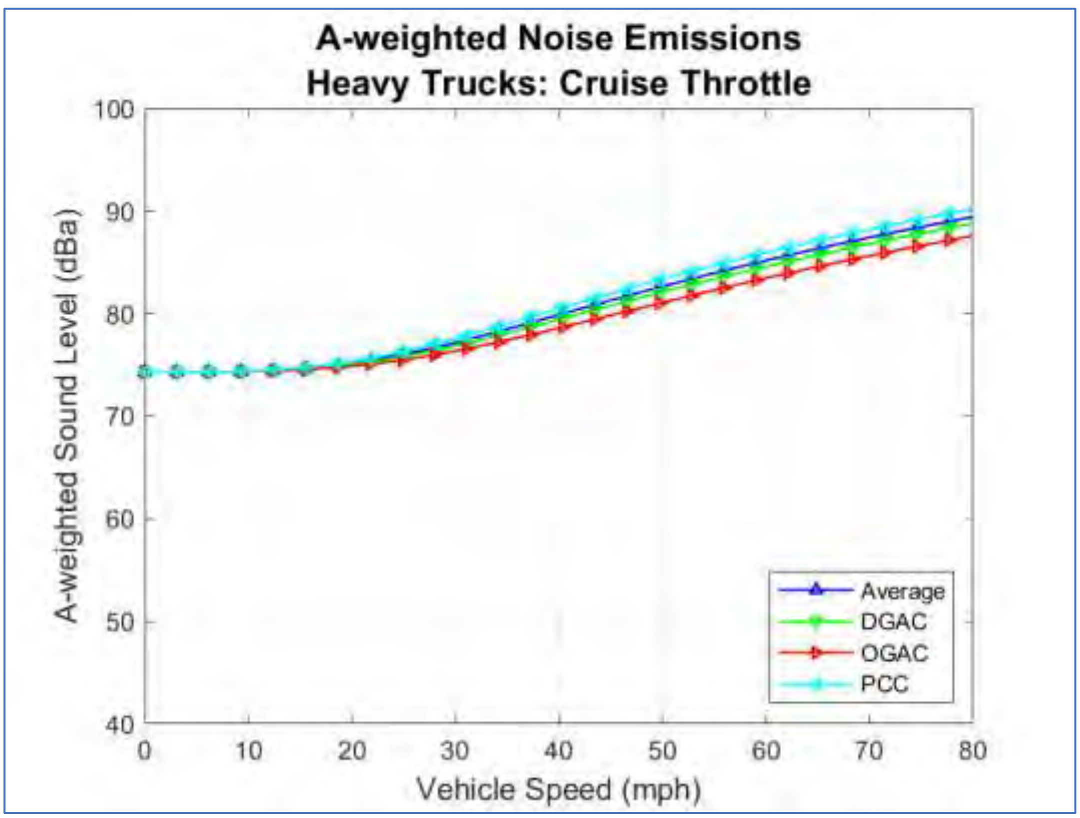

__Figure 31__ A-weighted sound-level emissions: Heavy trucks, cruise throttle

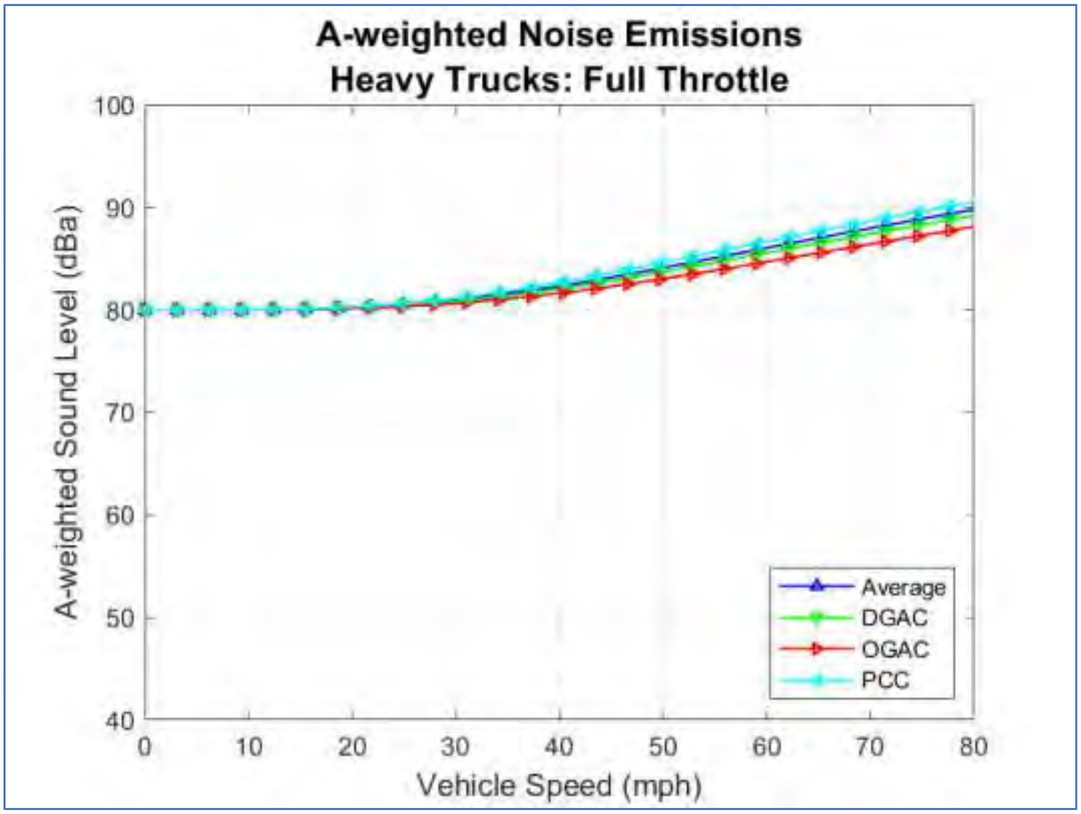

Figure 32 *A-weighted sound-level emissions: Heavy trucks, full throttle*

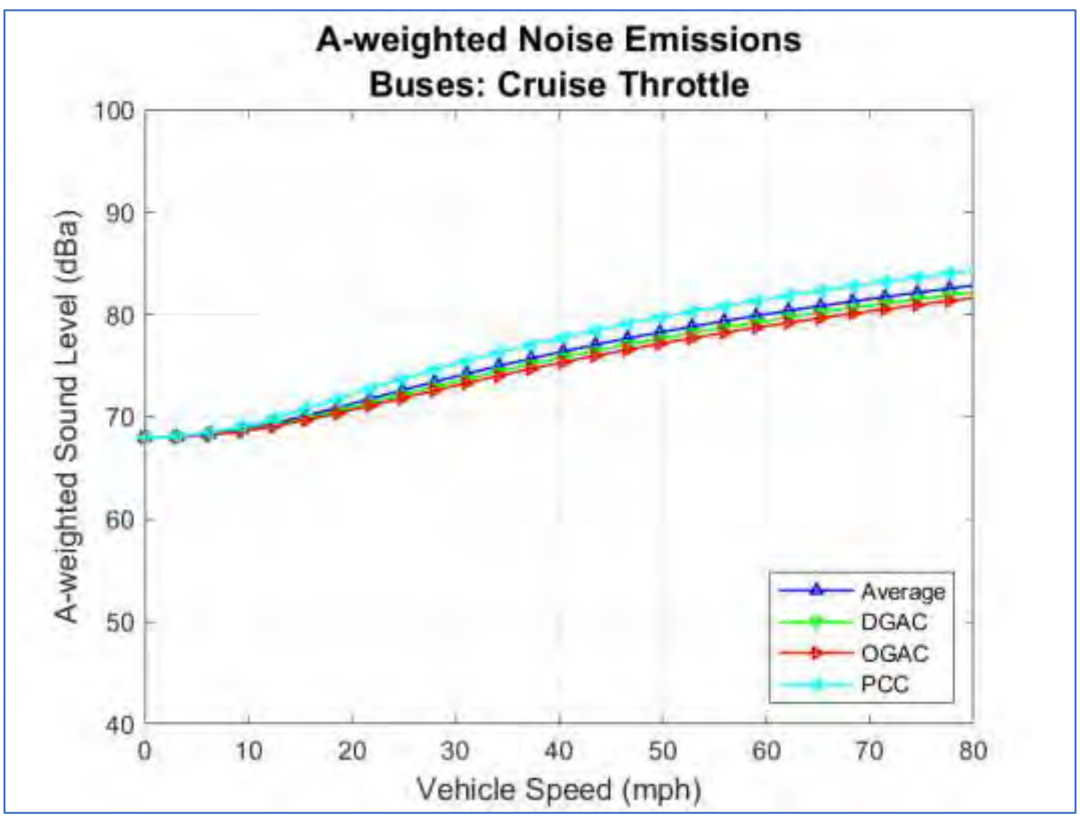

Figure 33 *A-weighted sound-level emissions: Buses, cruise throttle*

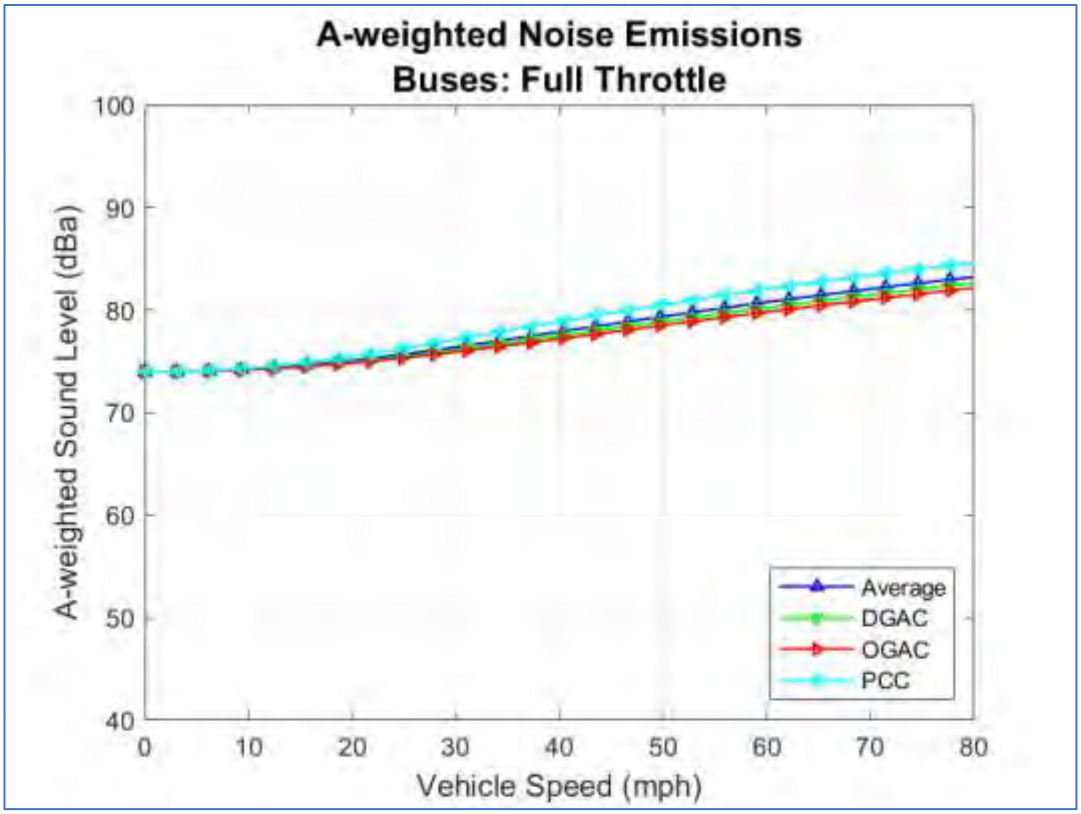

Figure 34 *A-weighted sound-level emissions: Buses, full throttle*

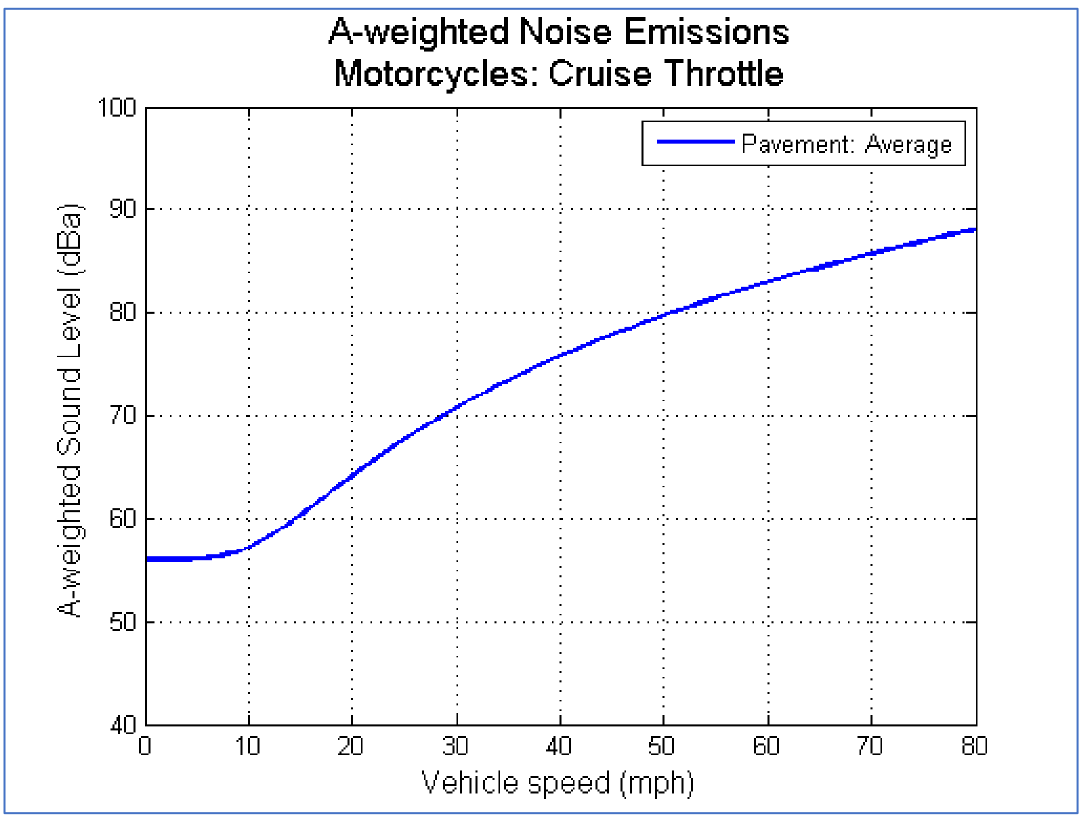

Figure 35 *A-weighted sound-level emissions: Motorcycles, cruise throttle*

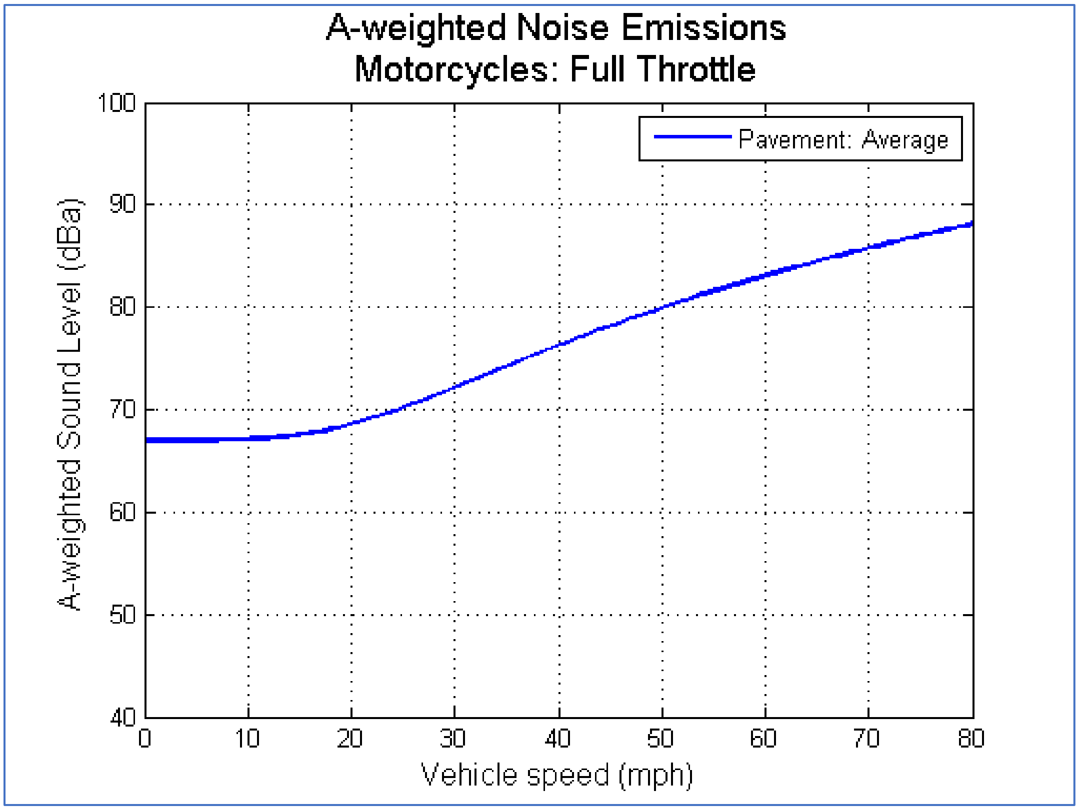

Figure 36 *A-weighted sound-level emissions: Motorcycles, full throttle*

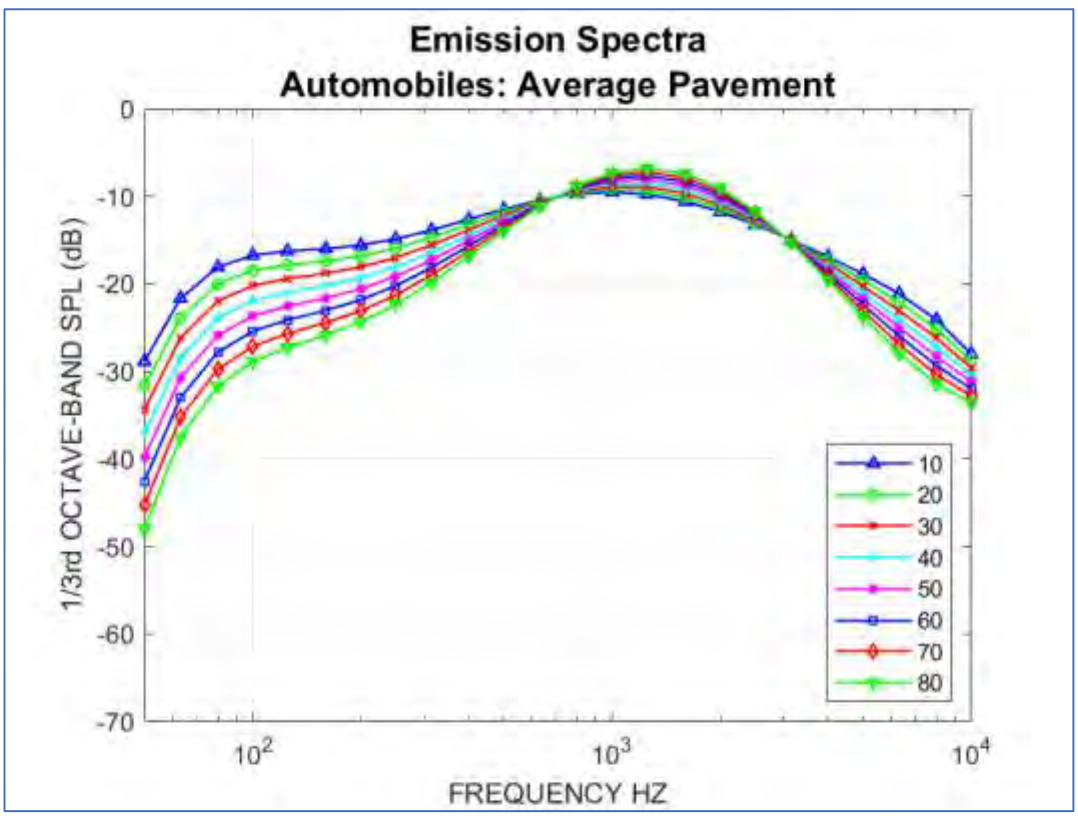

Figure 37 *A-weighted emission spectra: Automobiles, average pavement*

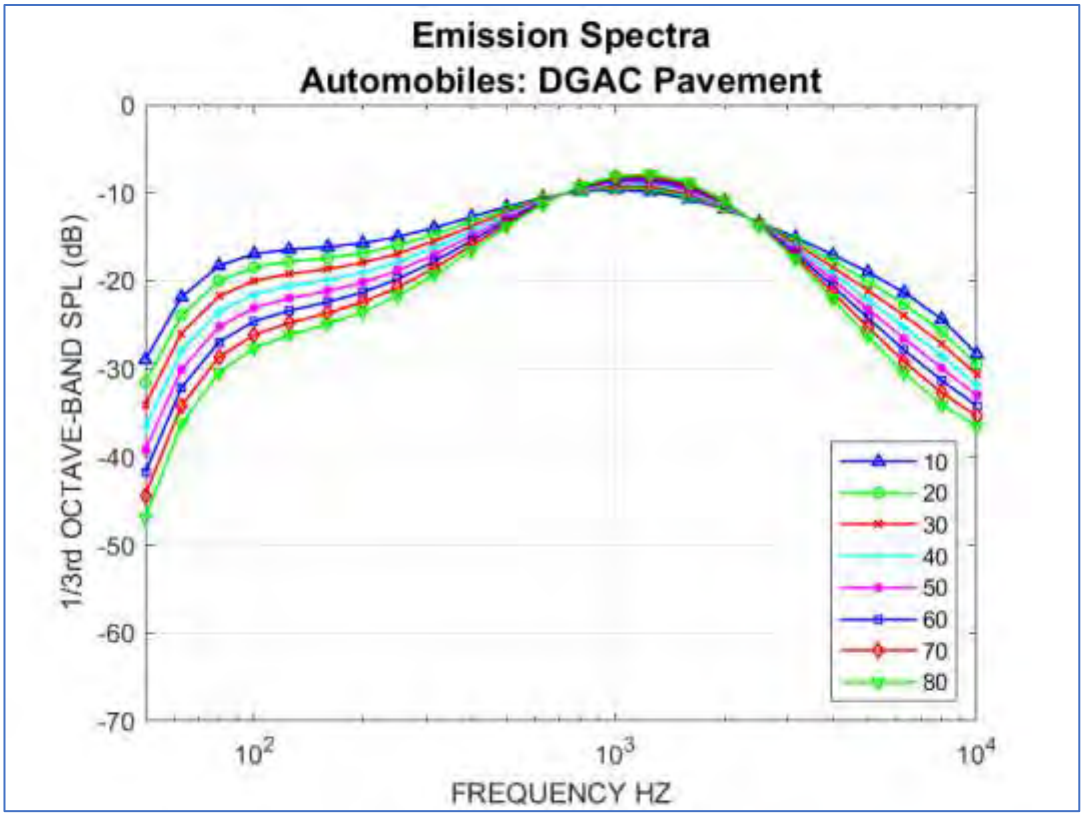

Figure 38 *A-weighted emission spectra: Automobiles, DGAC pavement*

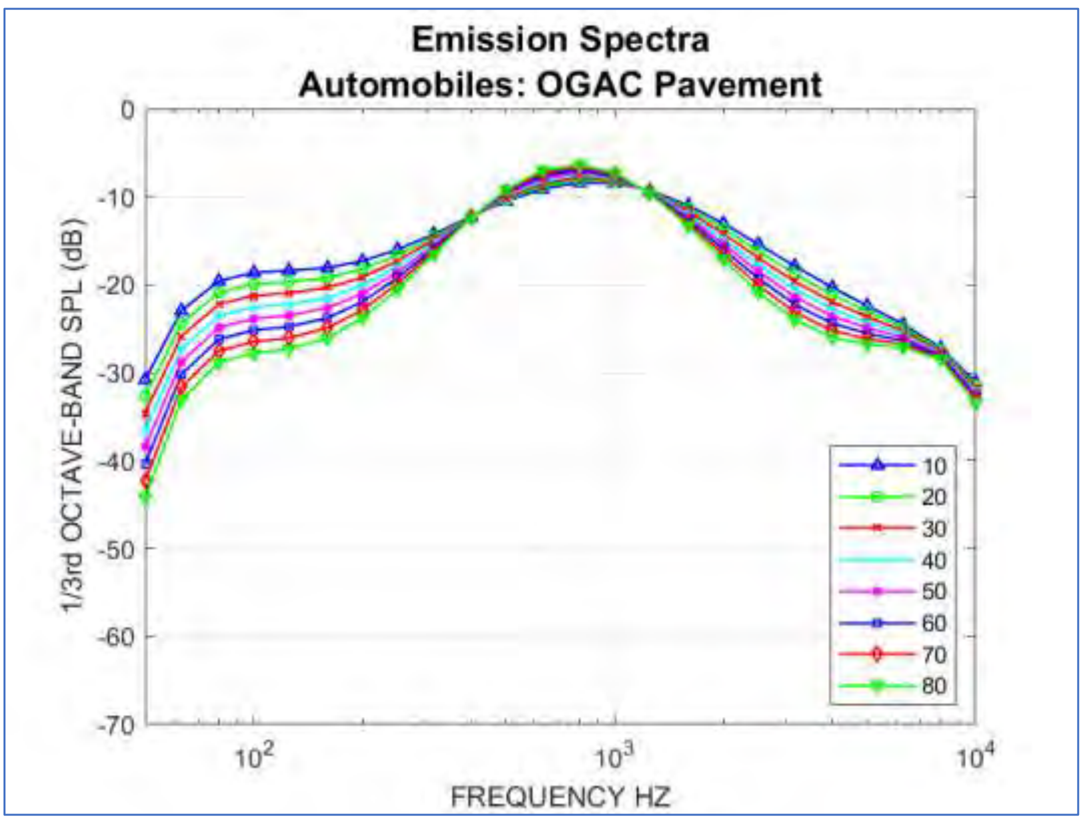

Figure 39 *A-weighted emission spectra: Automobiles, OGAC pavement*

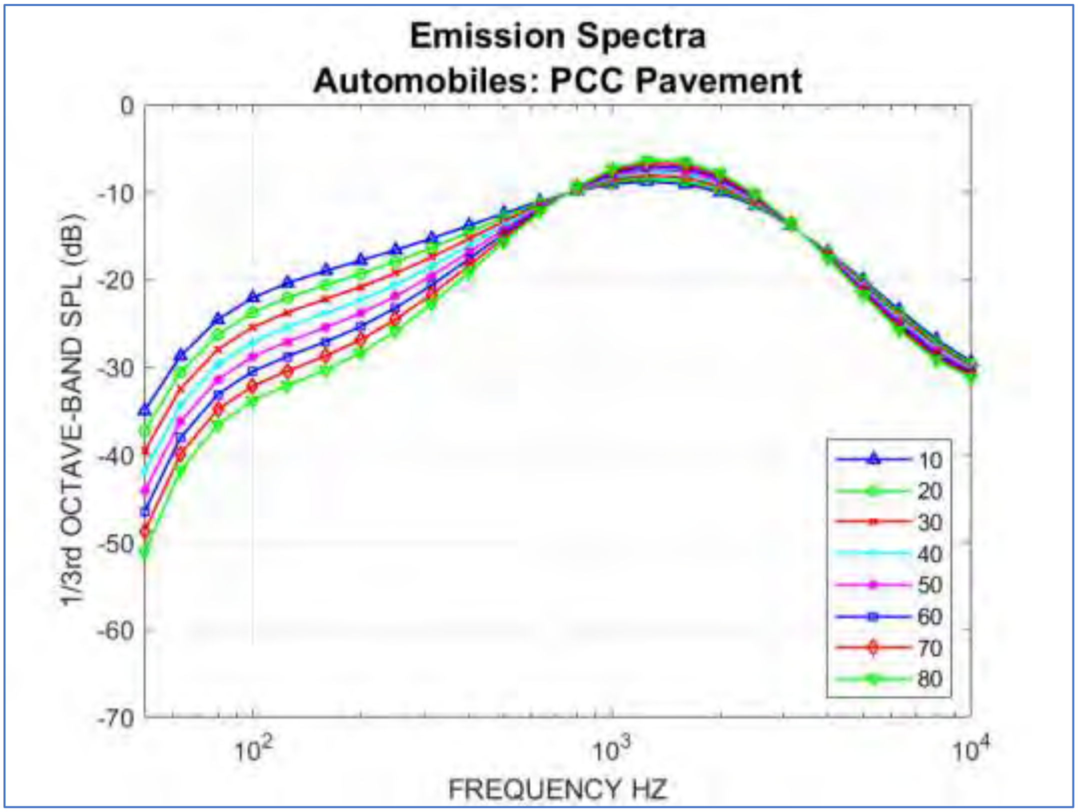

Figure 40 *A-weighted emission spectra: Automobiles, PCC pavement*

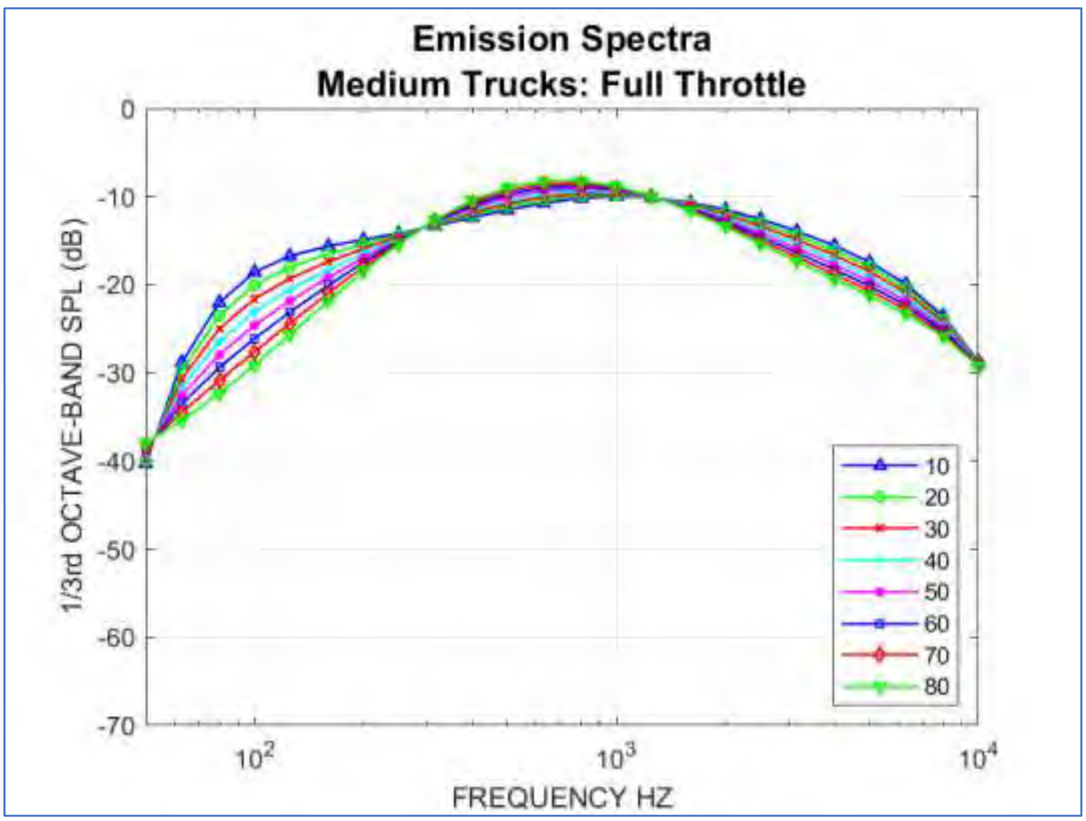

Figure 41 *A-weighted emission spectra: Medium trucks, full throttle*

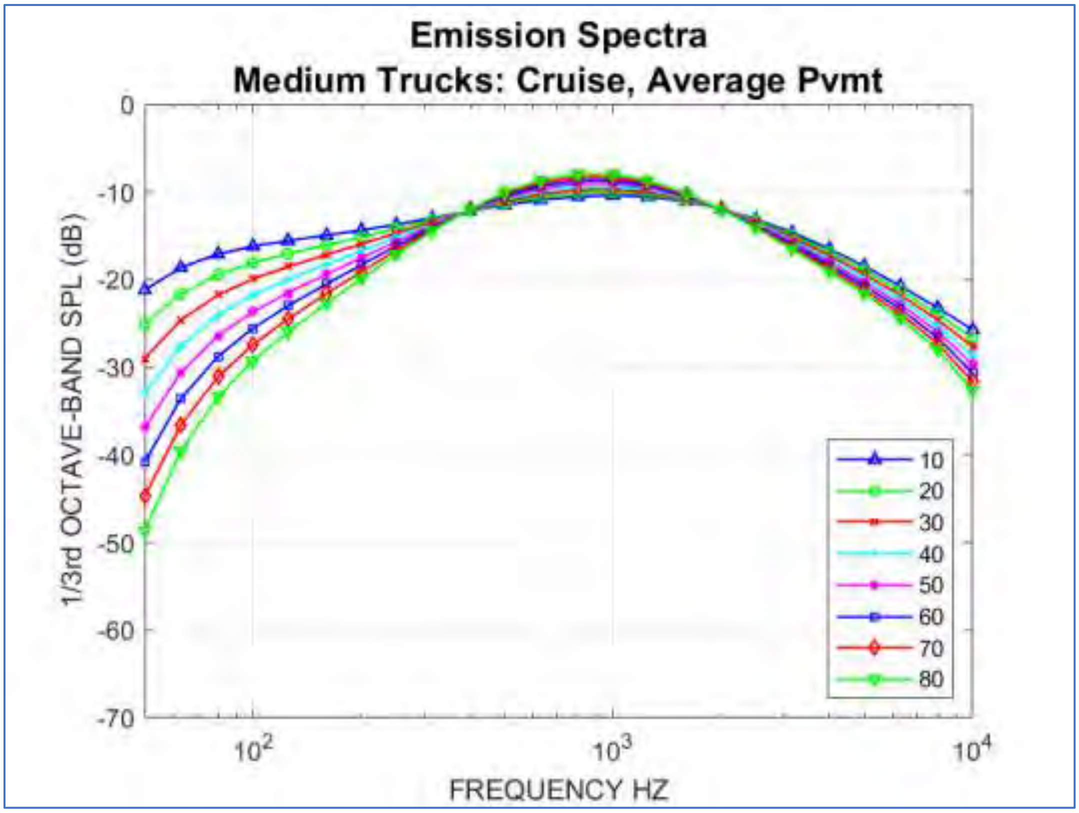

Figure 42 *A-weighted emission spectra: Medium trucks, cruise throttle, average pavement*

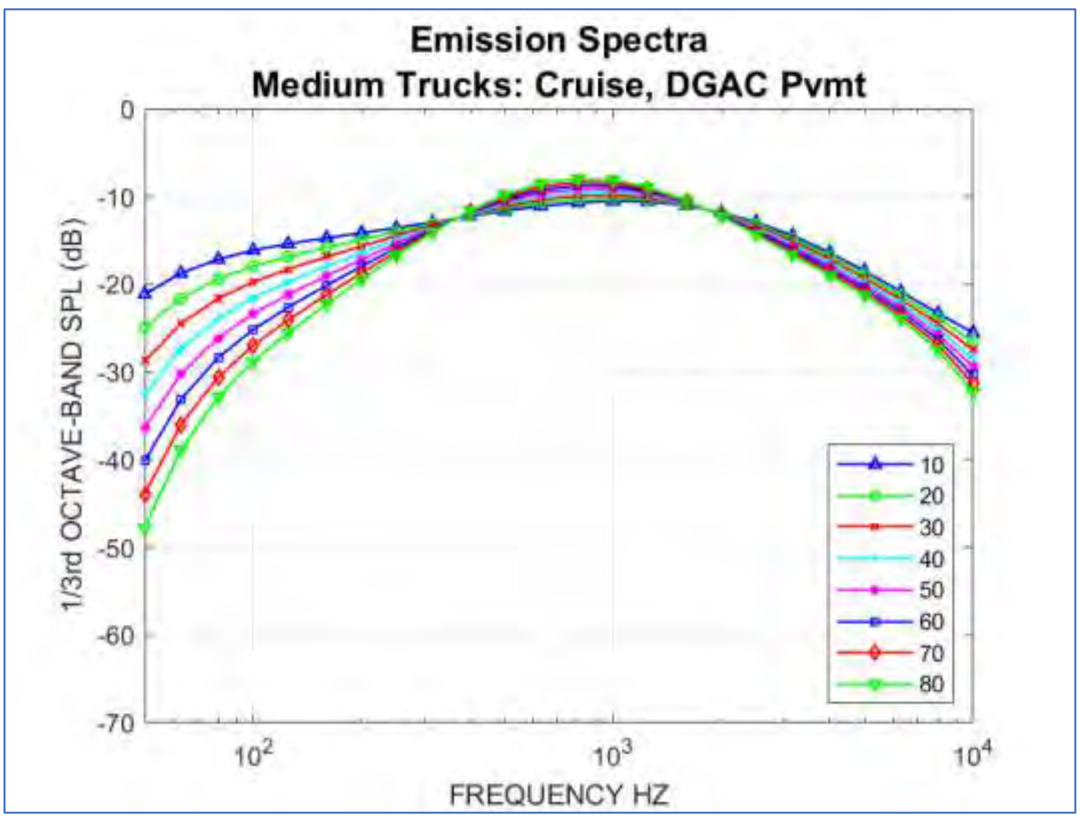

Figure 43 *A-weighted emission spectra: Medium trucks, cruise throttle, DGAC pavement*

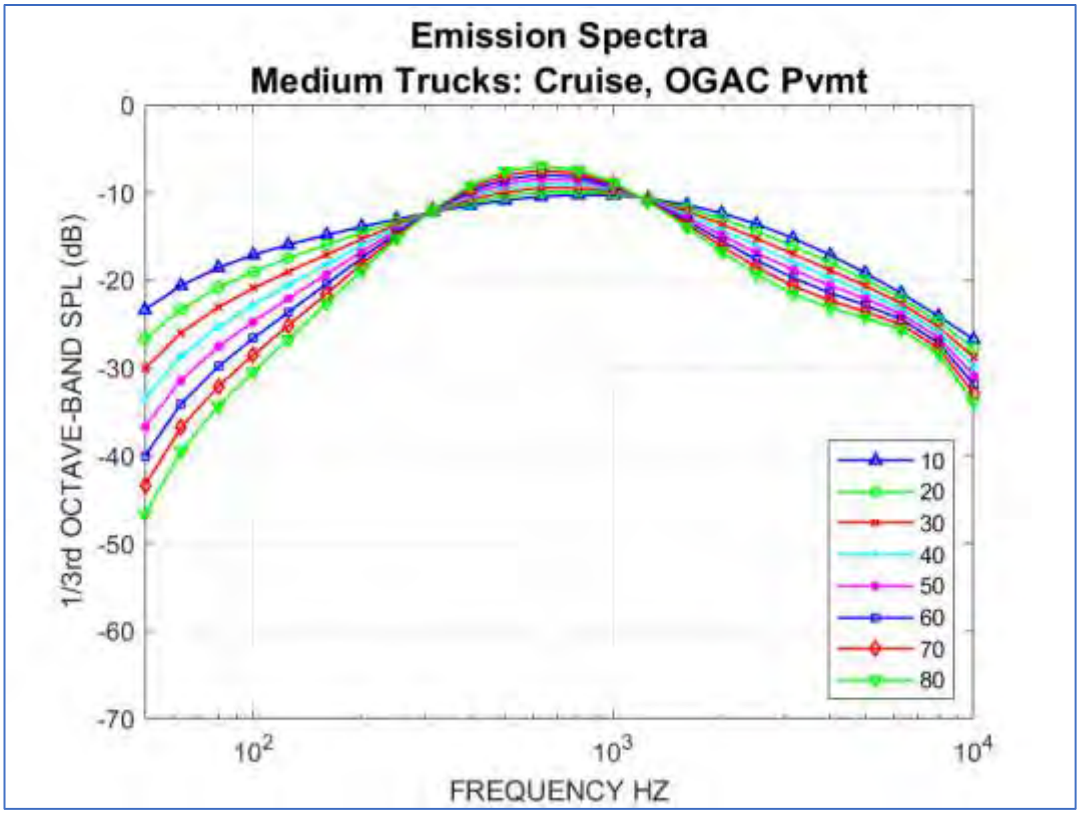

Figure 44 *A-weighted emission spectra: Medium trucks, cruise throttle, OGAC pavement*

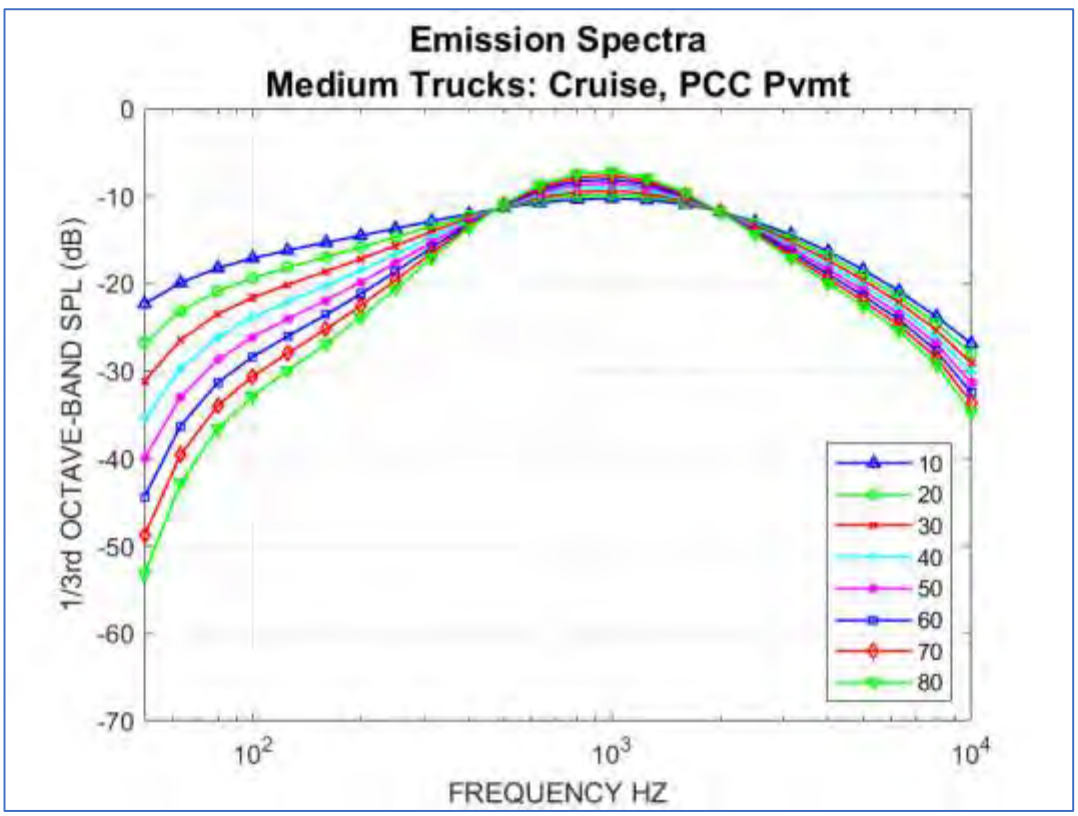

Figure 45 *A-weighted emission spectra: Medium trucks, cruise throttle, PCC pavement*

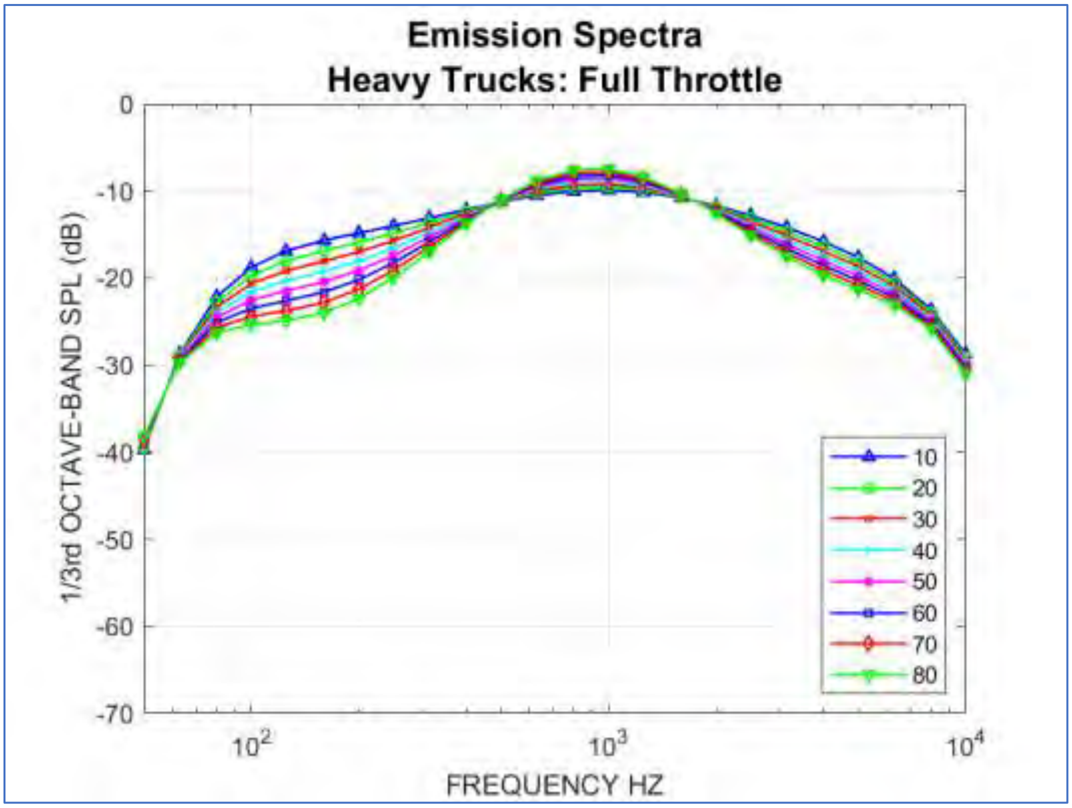

Figure 46 *A-weighted emission spectra: Heavy trucks, full throttle*

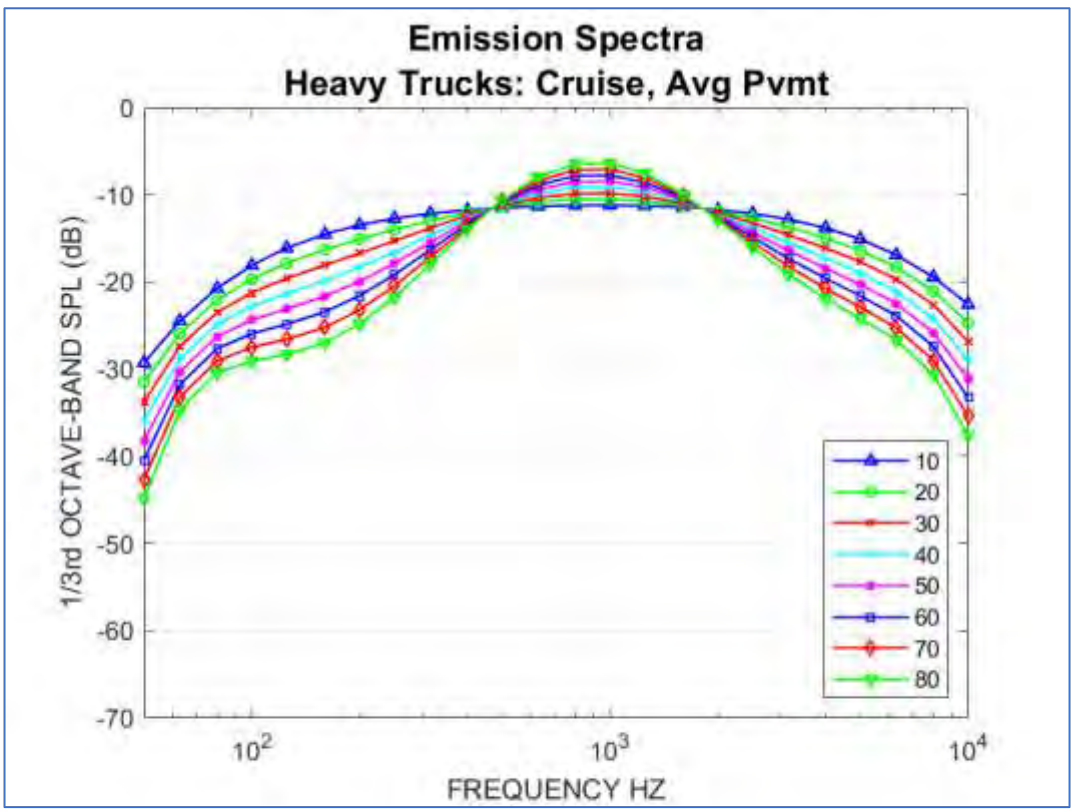

Figure 47 *A-weighted emission spectra: Heavy trucks, cruise throttle, average pavement*

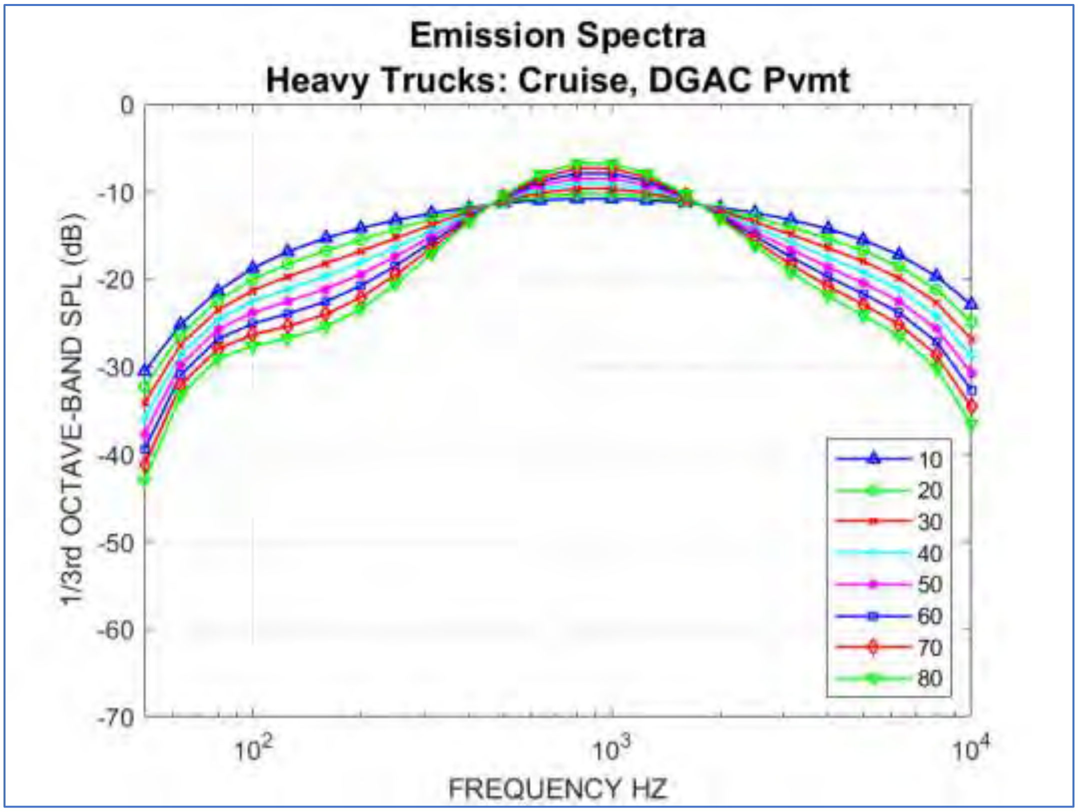

Figure 48 *A-weighted emission spectra: Heavy trucks, cruise throttle, DGAC pavement*

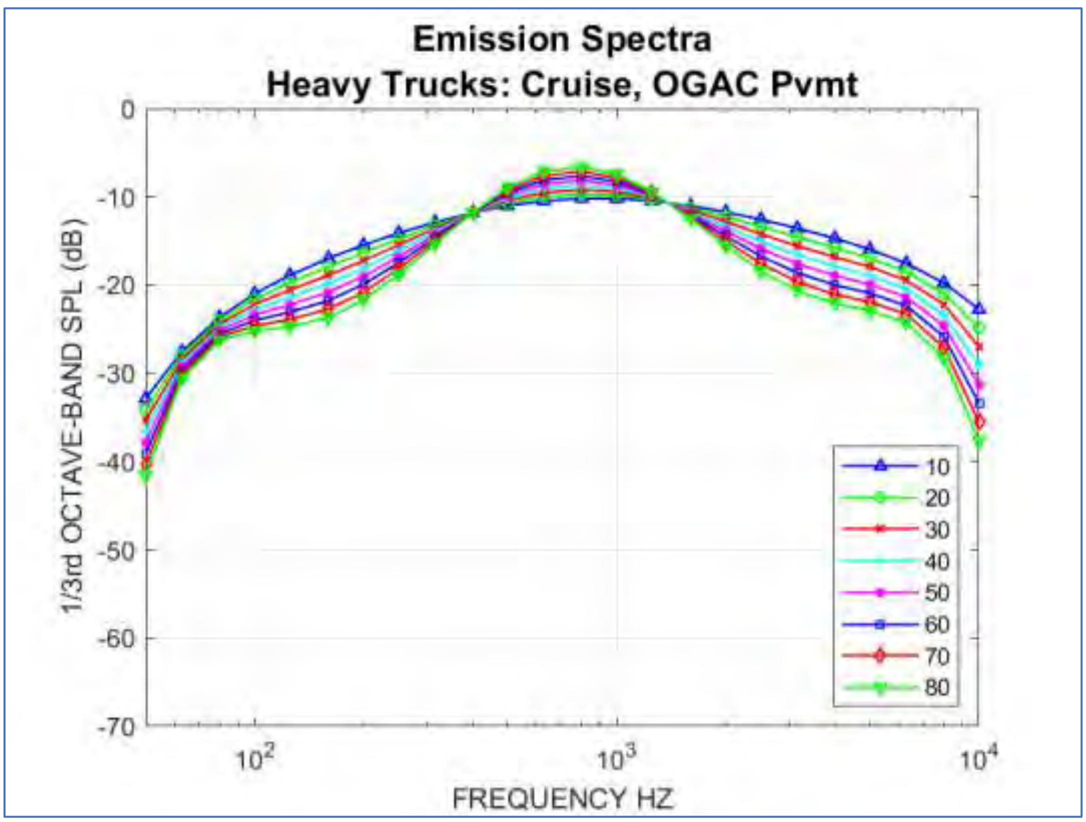

Figure 49 *A-weighted emission spectra: Heavy trucks, cruise throttle, OGAC pavement*

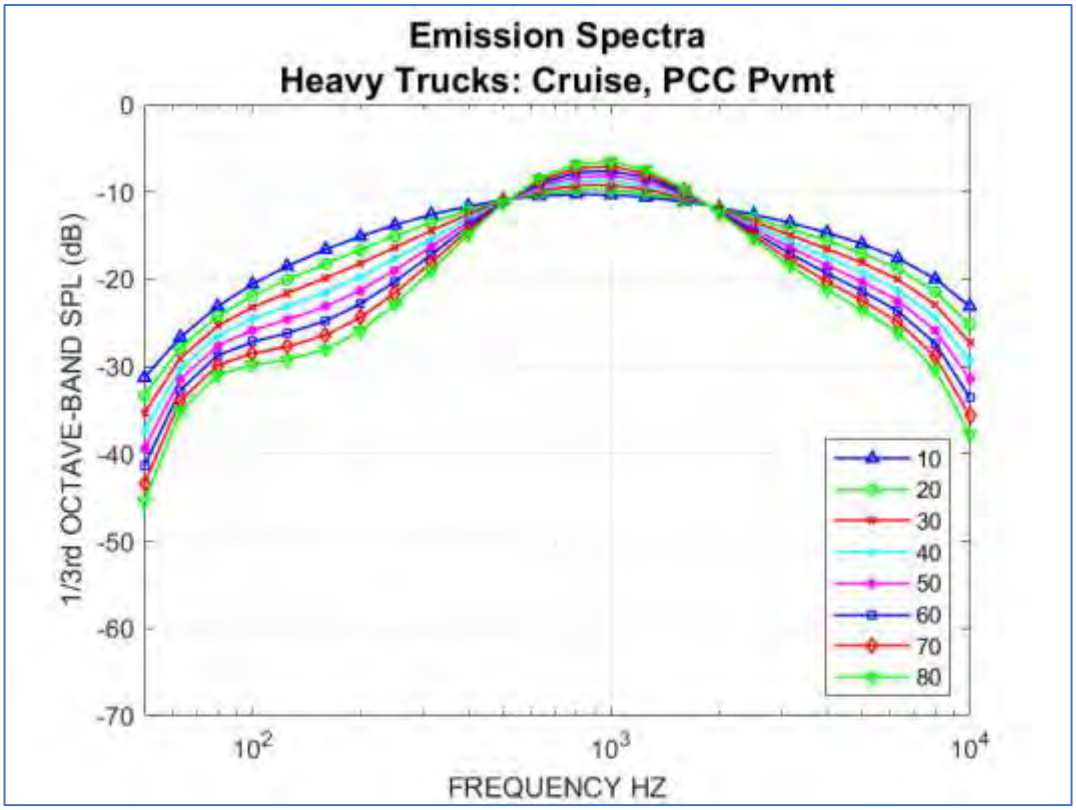

Figure 50 *A-weighted emission spectra: Heavy trucks, cruise throttle, PCC pavement*

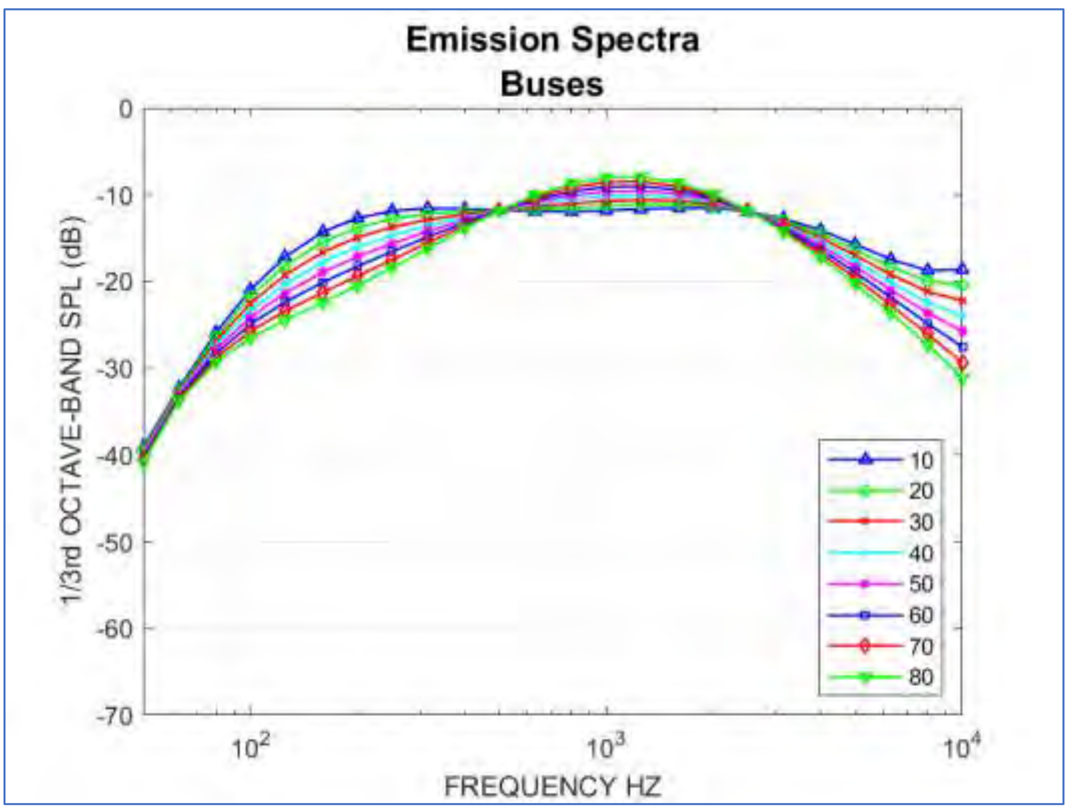

Figure 51 *A-weighted emission spectra: Buses*

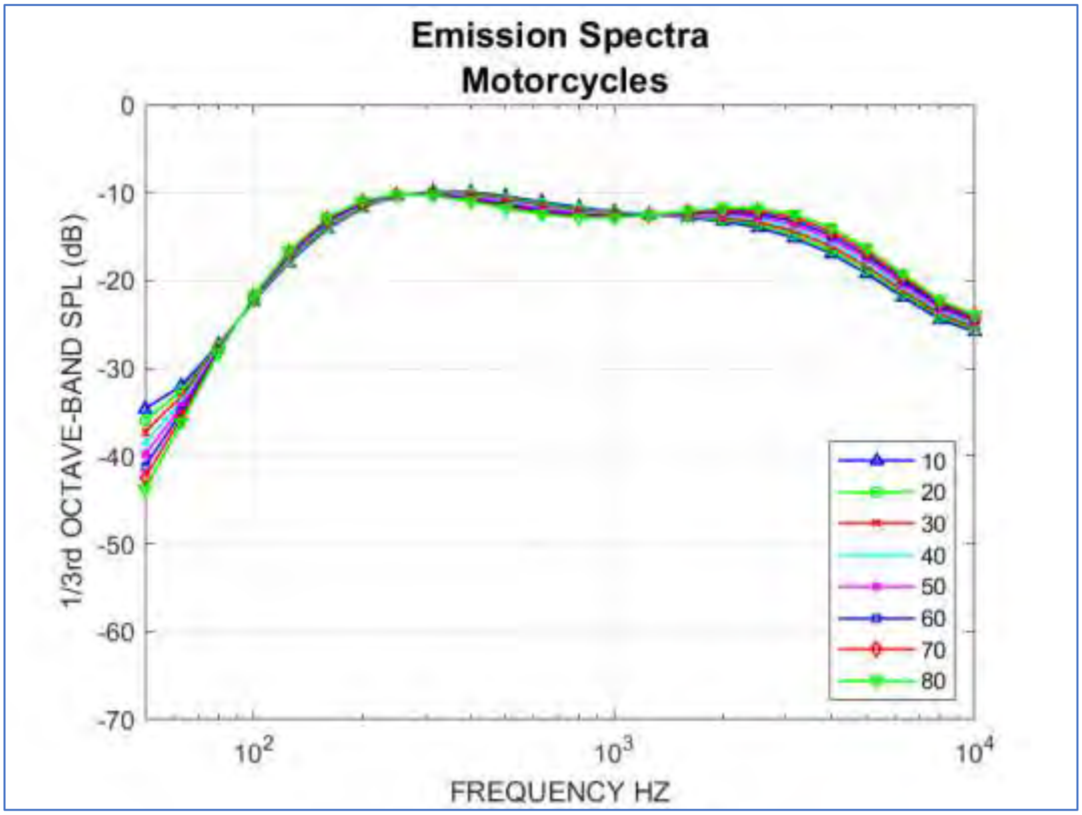

Figure 52 *A-weighted emission spectra: Motorcycles*

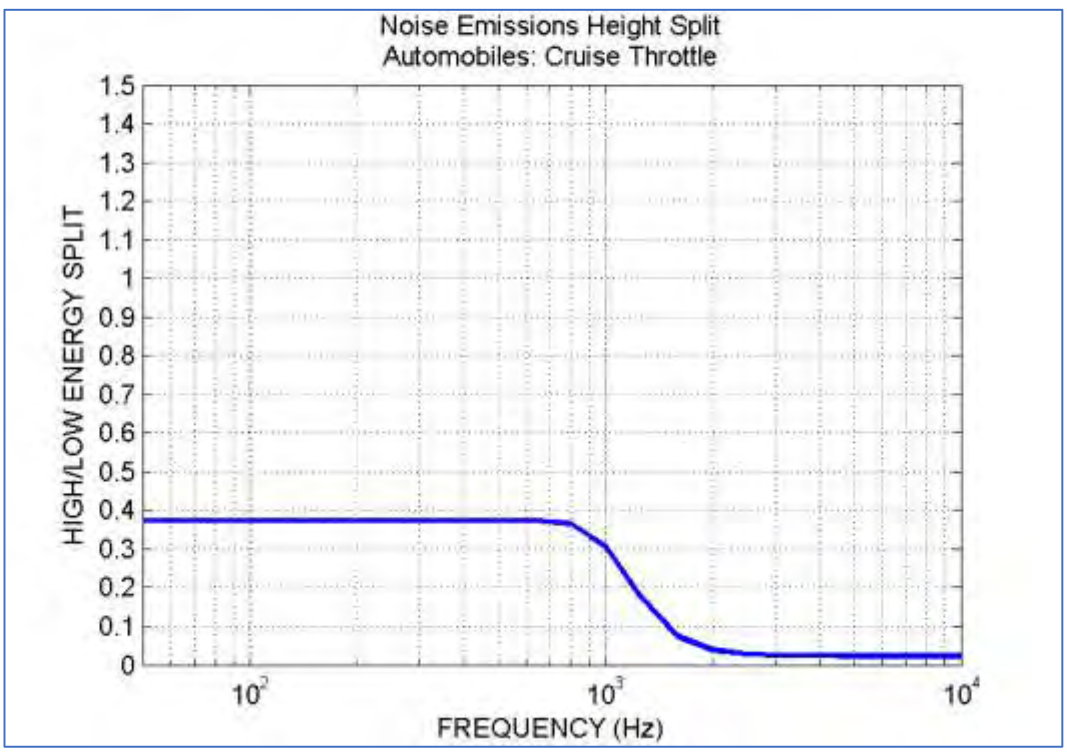

Figure 53 *Sound emissions, high/low energy split: Automobiles, cruise throttle*

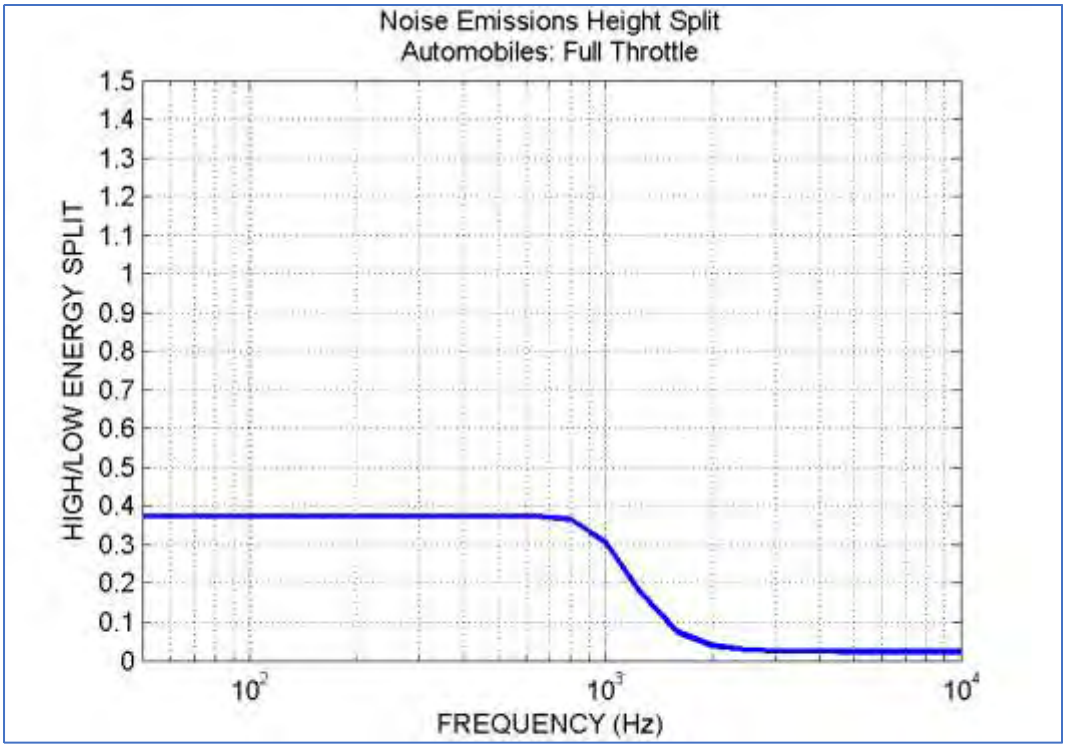

Figure 54 *Sound emissions, high/low energy split: Automobiles, full throttle*

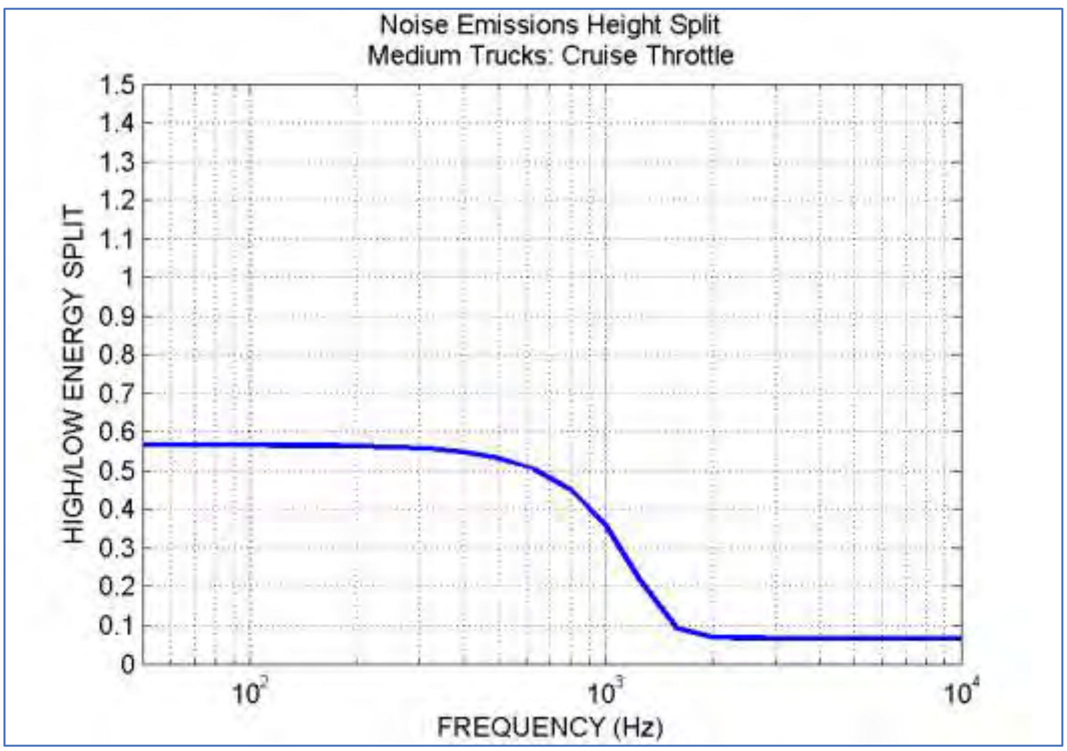

Figure 55 *Sound emissions, high/low energy split: Medium trucks, cruise throttle*

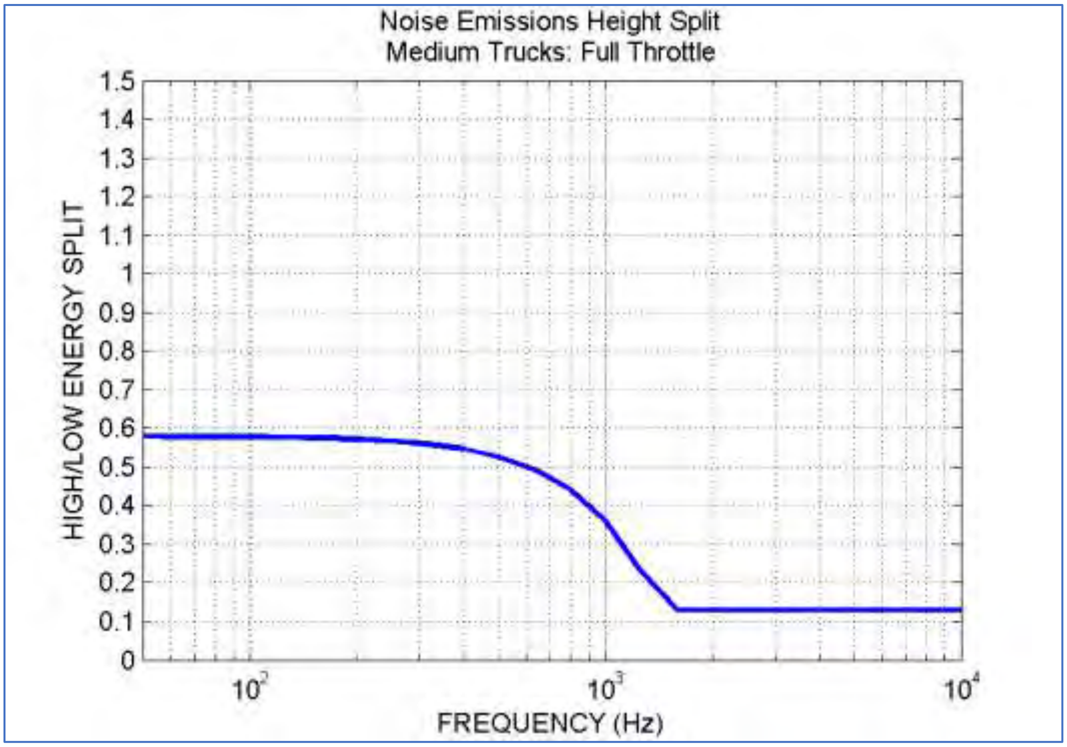

Figure 56 *Sound emissions, high/low energy split: Medium trucks, full throttle*

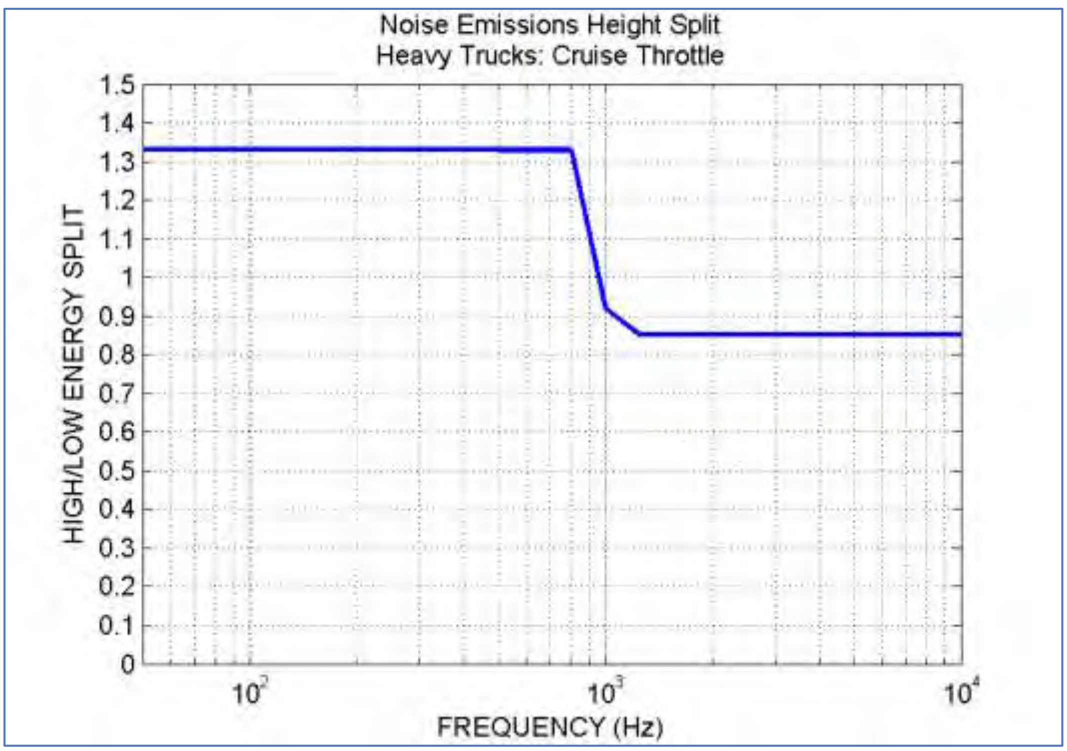

Figure 57 *Sound emissions, high/low energy split: Heavy trucks, cruise throttle*

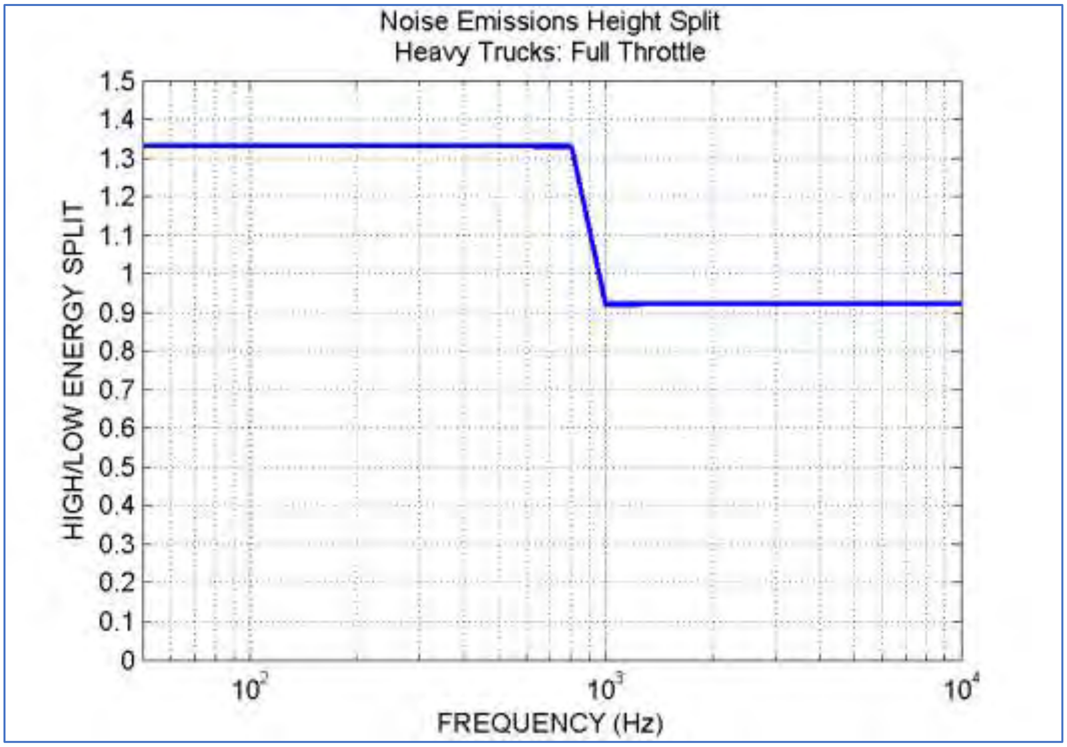

Figure 58 *Sound emissions, high/low energy split: Heavy trucks, full throttle*

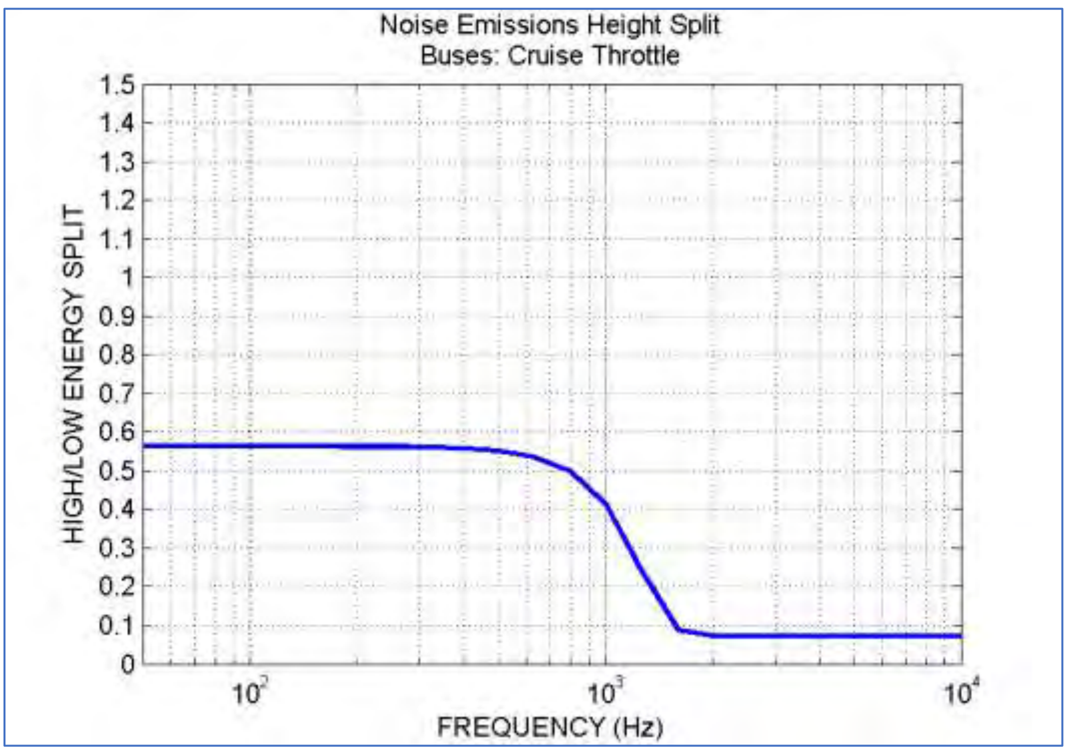

Figure 59 *Sound emissions, high/low energy split: Buses, cruise throttle*

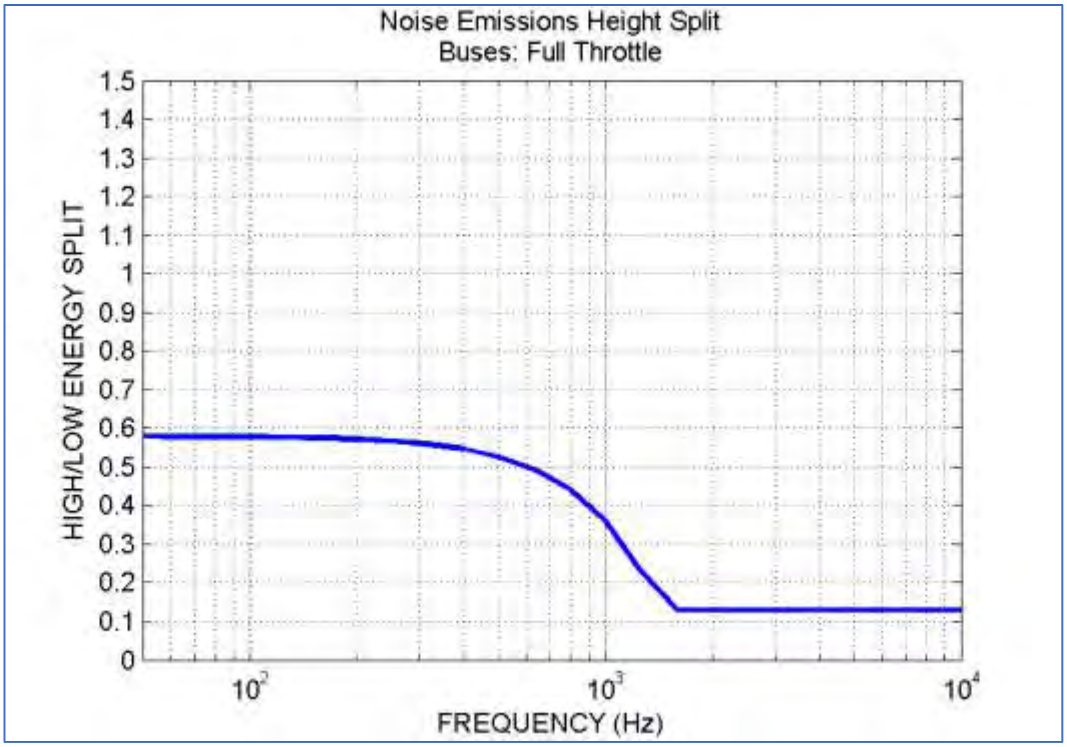

Figure 60 *Sound emissions, high/low energy split: Buses, full throttle*

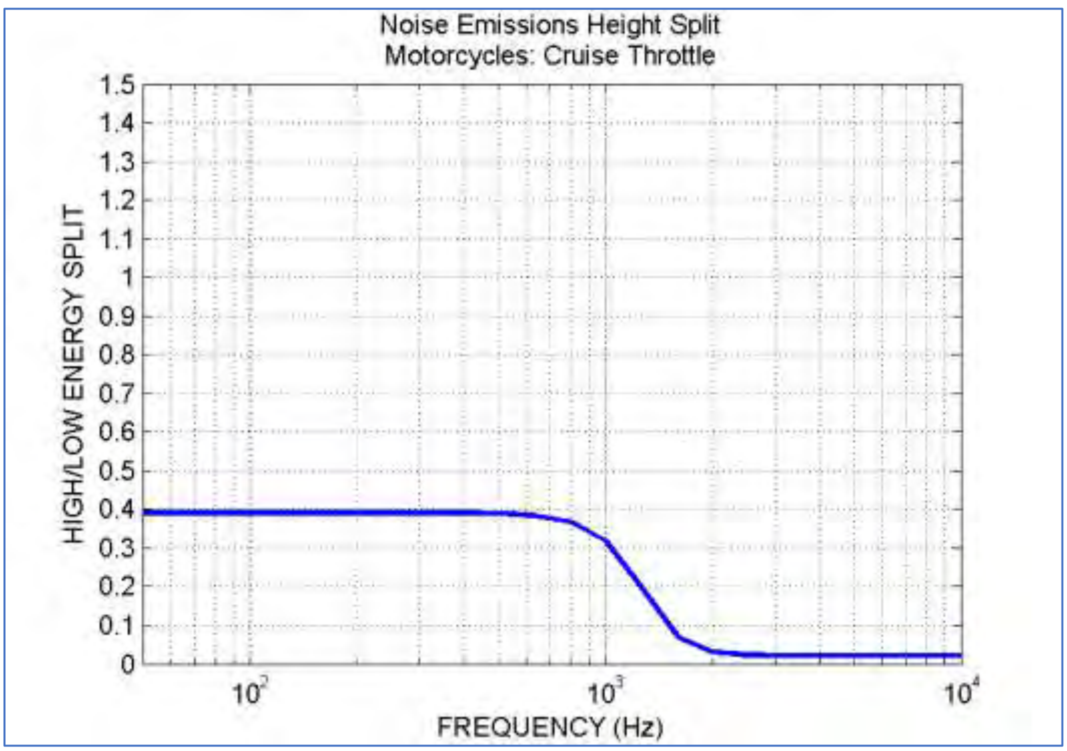

Figure 61 *Sound emissions, high/low energy split: Motorcycles*

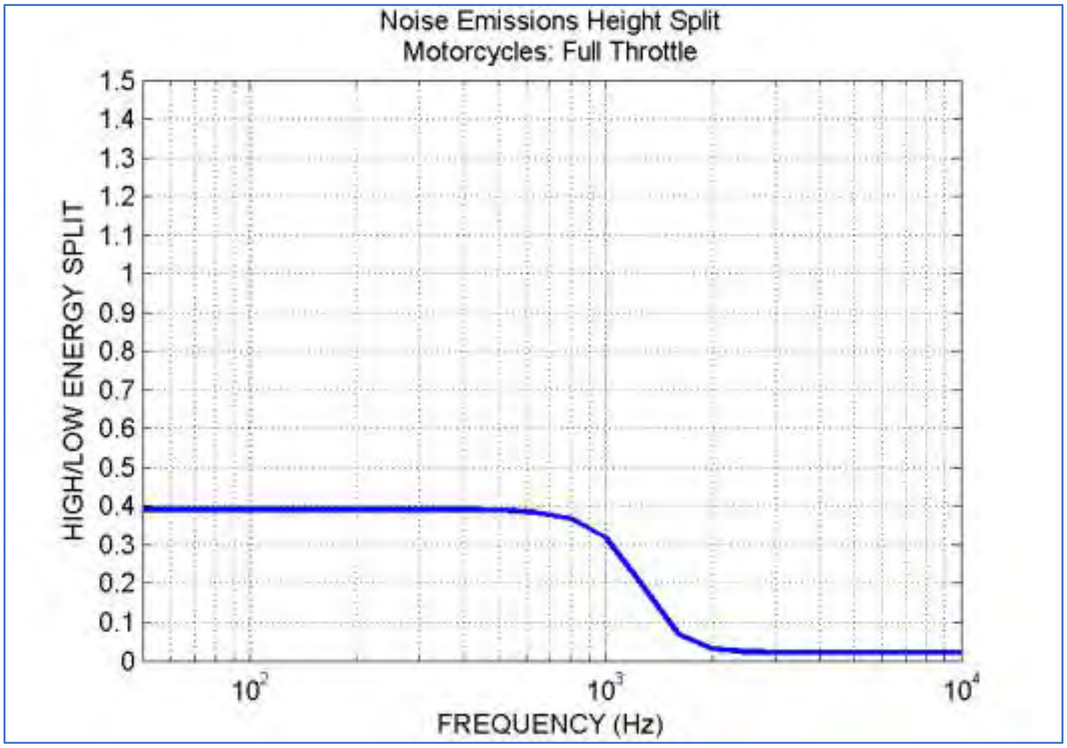

***Figure 62** Sound emissions, high/low energy split: Motorcycles, full throttle*

APPENDIX C: HORIZONTAL GEOMETRY ACOUSTICS

This appendix supplements discussions in Chapter 3 and is largely a reproduction of the portions of Appendix C of (Anderson, et al., 1998), modified only to reflect changes between TNM 1.0 and TNM 3.1 and to avoid repetition of some materials already presented in the main body. Note, for ease of reference, some information originally presented in the main body is still repeated here.

TNM computes free-field sound levels by ignoring all attenuating mechanisms except acoustical divergence. This appendix describes the acoustical algorithms associated with these horizontal-geometry, free-field computations and covers:

- The concept of an elemental triangle
- The equations for free-field sound energy and sound level

In addition, this appendix outlines TNM's free-field "sorting" calculations, which it uses to sort roadway segments from most to least important before vertical geometry and attenuation calculations.

C.1 ELEMENTAL TRIANGLES

Initially, TNM defines source-to-receiver elemental triangles by the closest angular spacing, at the receiver, of all object endpoints in the XY plane, as shown in **Figure 63**.

To ensure sufficient precision where object endpoints are not closely spaced (as in the figure), TNM divides elemental triangles so that the maximum subtended angle is no larger than a fixed size (10 degrees in TNM, Version 1.0). For example, **Figure 64** shows **Figure 63** after TNM imposes upon it a maximum angle of 10 degrees. Note that the last angle subdivision might well be less than 10 degrees. It is the "left-over" angle.

TNM does not further subdivide elemental triangles. Attenuation for the elemental triangles equals the (energy) average of the attenuation along the two sides (legs) of the triangle.

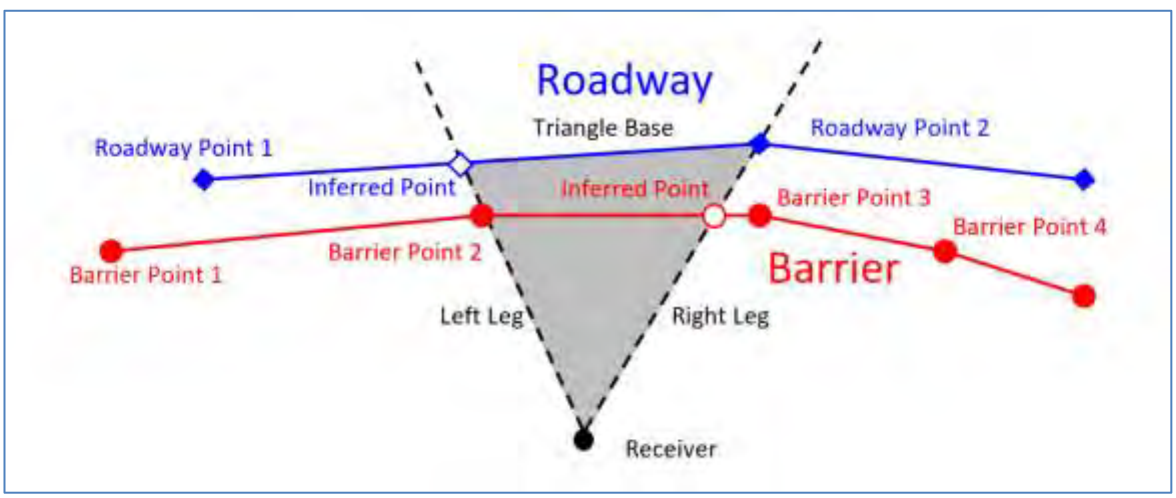

***Figure 63** Preliminary Triangle with no Points within the Geometry*

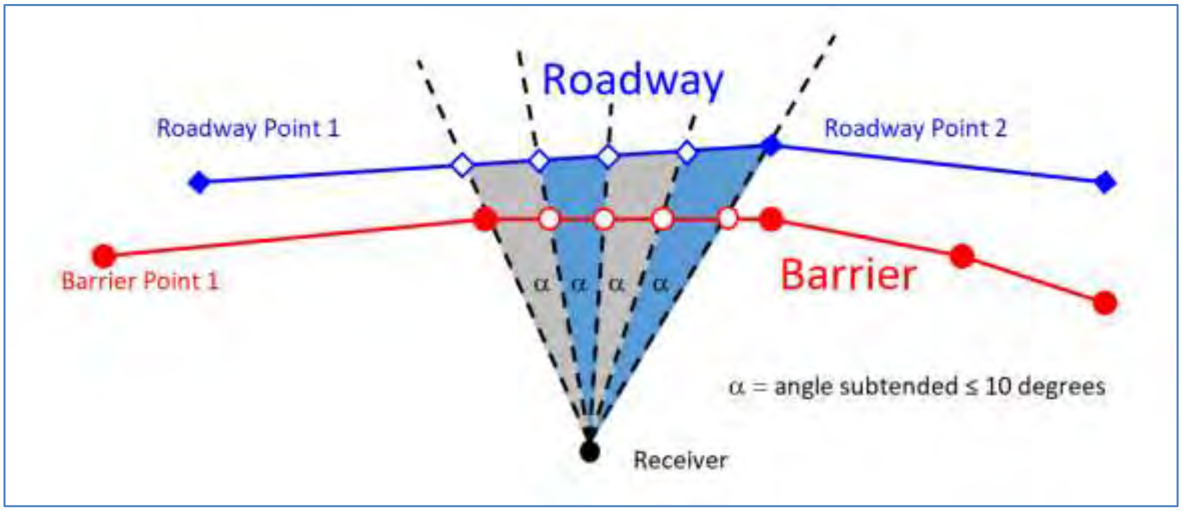

Figure 64 *Maximum Elemental Triangle Set to 10 Degrees*

C.2 Equations for Traffic Sound Energy and Sound Level

C.2.1 Definitions

TNM's acoustical calculations involve the following indices and variables:

i index over vehicle types: built-in types and user-defined types

h index over subsource heights: 0 and 3.66 meters (12 feet) for heavy trucks and user defined vehicles that mimic heavy trucks; 0 and 1.5 meters (5 feet) for all other vehicles

s "effective" vehicle speed, in kilometers per hour. Speed depends upon roadway segment. It may also differ by vehicle type — either because the user enters a different input speed or because TNM calculates a different speed due to upgrades and traffic-control devices

v vehicle volume, in vehicles per hour

v_{equiv} equivalent hourly vehicle volume, in vehicles per hour

a_h average hourly traffic, in vehicles per hour, which only applies to computation of $L_{Aeq,1h}$, and only when user inputs traffic percentages instead of volumes

ad average daily traffic, in vehicles per 24 hours, which only applies to computation of L_{dn} and L_{den}

ρ_i percentage of total hourly traffic: vehicle type i, which only applies to computation of $L_{Aeq,1h}$, and only when user inputs traffic percentages instead of volumes

$\rho_{i,day}$ percentage of average daily traffic: vehicle type i, daytime, which only applies to computation of L_{dn} (daytime equals 7 am to 10 pm) and L_{den} (daytime equals 7 am to 7 pm)

$\rho_{i,even}$ percentage of average daily traffic: vehicle type i, evening, which only applies to computation of L_{den} (evening equals 7 pm to 10 pm)

$\rho_{i,night}$ percentage of average daily traffic: vehicle type i, nighttime, which only applies to computation of $L_{dn}$and L_{den} (nighttime equals 10 pm to 7 am)

f 1/3rd-octave-band nominal center frequency, in Hz

d_1 distance from receiver to first point of roadway sub-segment, in meters (see Figure 65)

d_2 distance from receiver to second point of roadway sub-segment, in meters (see Figure 65)

d perpendicular distance from receiver to roadway sub-segment, in meters, where sub-segment is extended if needed to meet the perpendicular (see Figure 65)

α angle subtended at the receiver by the roadway sub-segment, in degrees (see Figure 65)

ΔL user-entered adjustment factor for a particular receiver/roadway-segment pair, in dB

TNM computes traffic sound levels - $L_{Aeq,1h}$, L_{dn} and L_{den} - only as its very last calculation step for each receiver. Prior to this last step, it calculates traffic sound energies instead. As discussed further below, sound levels (L) and sound energies (E) are related by:

$$L = 10 \cdot \log_{10}(E) \tag{43}$$

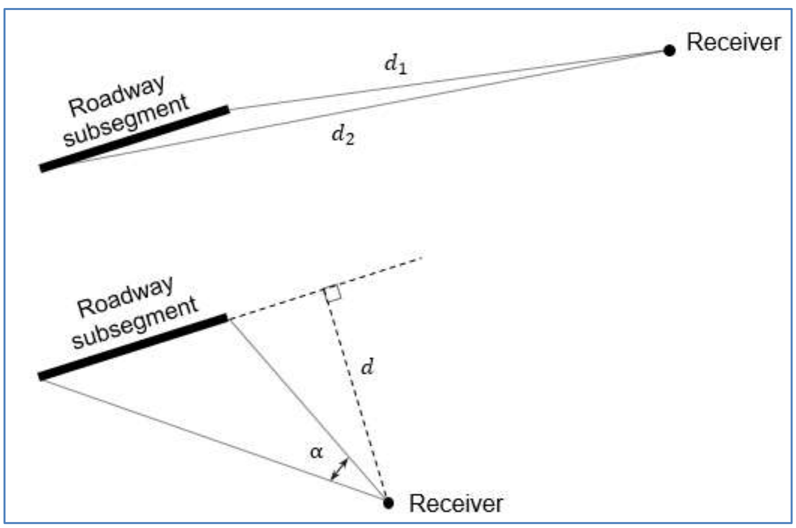

Figure 65 *Definition of Relevant Distances and Angles*

C.2.2 Traffic Sound Energy: "Reference" Conditions

As its first step in computing free-field sound energy, TNM converts vehicle emission spectra to traffic sound energy at specific "reference" conditions. As a result, subsequent computed values refer to full streams of traffic, rather than to individual vehicles.

The word "reference" indicates that the computed traffic sound energies are for a hypothetical reference position at 15 meters (50 feet) from an infinitely long, straight roadway. The 15-meter (50-foot) position substitutes temporarily for actual receiver positions. TNM converts from this reference position to actual receiver positions later. The infinite straight roadway substitutes for the actual roadway length and its curvature. TNM converts to this actual roadway geometry later, as well. Finally, the words "free field" indicates no attenuation from intervening objects (barriers, building rows, terrain lines, ground zones, and tree zones). TNM accounts for such attenuation later, as well.

To compute reference traffic sound energies, TNM first computes an equivalent hourly volume. Separately for each vehicle type, i:

$$v_{i,equiv} = v_i \qquad \text{for } L_{Aeqlh}, \text{volume input} \tag{44}$$

$$v_{i,equiv} = \frac{a_h \rho_i}{100} \qquad \text{for } L_{Aeqlh}, \text{percentage input} \tag{45}$$

$$v_{i,equiv} = \frac{a_d\left(\rho_{i,day} + 10\rho_{i,night}\right)}{2400} \qquad \text{for } L_{dn} \tag{46}$$

$$v_{i,equiv} = \frac{a_d\left(\rho_{i,day} + 3\rho_{i,even} + 10\rho_{i,night}\right)}{2400} \qquad \text{for } L_{den} \tag{47}$$

Use of this effective volume allows all subsequent calculations to be identical for the three optional metrics: $L_{Aeq,1h}$, L_{dn} and L_{den} . Such an effective traffic volume is possible for Ldn and Lden because TNM's input does not allow differing vehicle speeds for the different portions of the day.

In the L_{den} portion of this equation, evening percentages are multiplied by a factor of 3. The accepted international standard for this multiplier is 3.162, which corresponds to an evening sound-level increment of 5.0 decibels. Instead of 3.162, however, TNM uses a factor of 3 to conform to state law of California, the only state that uses L_{den} for traffic-noise assessment. This factor of 3 corresponds to an evening sound-level increment of 4.8 decibels. It is anticipated that this subtle difference will be of no practical consequence in the computations.

TNM then converts from vehicle emissions to "reference" traffic sound energy as follows:

$$E_{traf,\ ref,\ upper}\left(s_i, v_{i,equiv}, f \right) = 0.0476 \left(\frac{v_{i,\ equiv}}{s_i} \right) E_{emis,i,upper,ff} \tag{48}$$

$$E_{traf,\ ref,\ lower}\left(s_i, v_{i,equiv}, f \right) = 0.0476 \left(\frac{v_{i,\ equiv}}{s_i} \right) E_{emis,i,lower,ff} \tag{49}$$

for each vehicle type, i, where speed, s, is in kilometers per hour.

In these equations, the factor of 0.0476 results from the complex geometrical relationship between the maximum pass-by sound energy for a single vehicle, E_{emis} (on the right of the equation), and the time-average sound energy for a full stream of traffic, E_{traf} (on the left of the equation). This factor of 0.0476 corresponds to the term -13.2 dB in Equation 18 — that is,

$$10 \cdot \log_{10}(0.0476) = -13.2 \text{ dB.}$$

Speed enters the equation above, in the denominator, to account for sound-level "duration" during vehicle passbys. Larger vehicle speeds result in shorter durations and therefore lower energy-average sound levels.

Physically, this last equation represents each vehicle type's contribution to sound energy, separately for its two vertical sub-sources, for a hypothetical "reference" location 15 meters (50 feet) from an infinitely long straight roadway, without influence of intervening ground (that is, free field).

Conceptually, if the upper-height and lower-height sound energies were added, this would yield the total sound energy from that vehicle type. They cannot be added at this point in the calculation, however, because the attenuation from roadway to receiver differs for upper-height and lower-height energies. Also, conceptually, one might think of adding together the zero-height sound energies for all vehicle types, so that attenuation could be applied just once to this composite energy. TNM does not do this, however, because it must be able to diagnose sound levels by vehicle type, if desired by the user.

C.2.3 Traffic sound energy at true receiver: Free field

Next TNM takes into account the actual receiver and its subdivided source-receiver triangle, still assuming free field propagation. **Figure 65** shows the two possible geometric situations: (1) receiver nearly on the extended roadway segment; and (2) receiver relatively clear of the extended roadway segment.

TNM first performs a numerical test to distinguish between these two geometric situations and then computes, as follows:

- If the perpendicular distance, d, is less than 0.3 m (1 ft) then:

$$E_{traf,upper,ff}\left(s_i, v_{i,equiv}, f \right) = 15.9\left(\frac{|d_2 - d_1|}{d_2 d_1}\right)E_{traf,ref,upper} \tag{50}$$

$$E_{traf,lower,ff}\left(s_i, v_{i,equiv}, f \right) = 15.9\left(\frac{|d_2 - d_1|}{d_2 d_1}\right)E_{traf,ref,lower} \tag{51}$$

  for each vehicle type, i. The absolute-value signs are needed to ensure that the expression in parentheses is positive.

  In Equation (50) and (51), the factor of 15.9 results from the complex geometrical relationship between the receiver and the two ends of the traffic segment. This factor corresponds to the term 12 dB in Equation 21 – that is,

$$10 \cdot \log_{10}(15.9) = 12 \text{ dB.}$$

- Otherwise TNM computes the free-field traffic sound energy at the receiver by using Equations (52) and (53):

$$E_{traf,upper,ff}\left(s_i, v_{i,equiv}, f \right) = \left(\frac{\alpha}{180}\right)\left(\frac{15}{d}\right)E_{traf,ref,upper} \tag{52}$$

$$E_{traf,lower,ff}\left(s_i, v_{i,equiv}, f \right) = \left(\frac{\alpha}{180}\right)\left(\frac{15}{d}\right)E_{traf,ref,lower} \tag{53}$$

  for each vehicle type, i. In these equations, α is in degrees and d is in meters.

C.2.4 Traffic sound energy at true receiver: Attenuated

Next TNM attenuates the free-field traffic sound energy at each receiver to account for all intervening TNM objects, including the ground, plus the user-entered adjustment factor, ΔL, for this receiver/roadway-segment pair.

To determine the effect of intervening TNM objects, the model submits vertical geometries of the two legs of the source-receiver triangle to its vertical-geometry routines, which return attenuation fractions, $\phi_{h,f,barrs}$, for each of the three possible sub-source heights, h, for each frequency, f , and for each possible barrier-height perturbation. The vertical geometry routines compute attenuations for each leg of the elemental triangle and return (energy) average attenuations for the triangle as a whole. For the details on the vertical geometry algorithms, see Appendix D: Vertical Geometry Acoustics.

Then TNM combines its previous computations with these values of ϕ and ΔL, to compute the attenuated traffic sound energy at the receiver, as follows:

$$E_{traf,h,atten,barrs}\left(s_i, v_{i,equiv}, f \right) = \left(\phi_{h,f,barrs}\right)\left(10^{\Delta L/10} \right)E_{traf,h,ff} \quad (54)$$

for each vehicle type, i, and each relevant sub-source height, h. In this equation, the subscript "barrs" indicates that the result depends upon the heights of intervening, perturbable barriers.

C.2.5 Traffic sound levels (L_{AEQ1H}, L_{DN} and L_{DEN}) at the true receiver: Attenuated

TNM must calculate all of the prior values for all barrier perturbations, because they affect the attenuation between source and receiver. For these computations, TNM computes energies instead of levels. Once the user chooses a barrier design, however, TNM is ready to combine energies into the total energy at the receiver, and then to convert sound energies to sound levels.

For any given barrier design (combination of specific barriers heights, one per barrier segment), TNM finally computes the total traffic sound level at a receiver as follows:

$$L_{traf} = 10 \cdot \log_{10}\left(\sum_{\substack{\text{all freqs,}\\ \text{f}}} \left\{ \sum_{\substack{\text{all subdivided}\\ \text{triangles}}} \left[\sum_{\substack{\text{all vehicle}\\ \text{types,i}}} \left(\sum_{\substack{\text{three subsource}\\ \text{heights,h}}} \left[E_{\substack{traf,h,atten,\\ specific\ barr\ heights}} \right] \right) \right] \right\} \right) \quad (55)$$

The sound level computed by this equation depends upon the input traffic, such that L_{traf} equals

- L_{Aeq1h} if the user has entered L_{Aeq1h} traffic, either as volumes or percentages
- L_{dn} if the user has entered L_{dn} traffic
- L_{den} if the user has entered L_{den} traffic

C.3 Outline of Free-field Sorting Computations

The calculations above are needed within TNM's main calculation loop, in which it computes attenuated sound levels at all receivers, for all combinations of barrier heights. Prior to this main calculation loop, TNM computes free-field sound levels (no attenuation, no subdivision of roadway segments) to sort roadway segments from most to least important. This section outlines these free-field, sorting calculations.

To perform the sorting calculations:

- TNM first determines the entrance and exit speeds of each vehicle type on the roadway segment under computation, by using Appendix A. From these two speeds, TNM then computes the roadway segment's average speed, s_i , where i is an index over vehicle types.

- Then TNM computes $E_{emis,i}\ (s_i, 500\ Hz)$, by using Appendix B, for each vehicle type, i. Note that the model computes only at 500 Hz for these sorting calculations.
- Then TNM computes an equivalent hourly volume, $v_{i\ ,equiv}$, from Equations (44) to (47), for each vehicle type, i.
- Then TNM computes $E_{traf\ ,ref}\ (s_i, v_{i,equiv}, 500\ Hz)$ from the following modification of Equation (56):

$$E_{traf,ref}\left(s_i, v_{i,equiv}, 500\text{ Hz}\right) = 0.0476\left(\frac{v_{i,equiv}}{s_i}\right)E_{emis,i} \qquad (56)$$

for each vehicle type, i, where speed, s, is in kilometers per hour.

- Then TNM makes the relevant geometric test. Based upon the outcome of that test, the model then computes $E_{traf,ff}\ (s_i, v_{i,equiv}, 500\ Hz)$ from either Equation (57) or (58):

$$E_{traf,ff}\left(\ s_i, v_{i,equiv}, 500\text{ Hz}\ \right) = 15.9\left(\frac{|d_2 - d_1|}{d_2 d_1}\right)E_{traf,ref} \qquad (57)$$

$$E_{traf,ref}\left(s_i, v_{i,equiv}, 500\text{ Hz}\right) = \left(\frac{\alpha}{180}\right)\left(\frac{15}{d}\right)E_{traf,ref} \qquad (58)$$

- Then TNM computes $E_{traf,atten}\ (s_i, v_{i,equiv}, 500\ Hz)$ by using:

$$E_{traf,atten}\left(\ s_i, v_{i,equiv}, 500\text{ Hz}\ \right) = \left(\ 10^{\Delta L/10}\ \right)E_{traf,ff} \qquad (59)$$

for each vehicle type, i. This modification accounts for only the user-entered adjustment factor between the receiver and roadway segment under consideration. It ignores all other attenuations and is therefore computed very quickly.

- Then TNM sums traffic energies over all vehicle types, by using:

$$E_{traf} = \sum_{\substack{\text{all vehicle}\\ \text{types},i}} \left[E_{traf,atten}\right] \qquad (60)$$

- Finally, for this receiver TNM sorts all roadway segments according to the energies computed by Equation (60), from high to low. This is the order in which these roadway segments are then computed, for this receiver, in TNM’s main calculation loop.

Note that this sorting process proceeds quickly, because: (1) its computations are free field rather than attenuated; and (2) roadway segments are not subdivided during computation.

Once roadway segments are sorted in this manner, then TNM does its full set of attenuated/subdivided computations *in the sorted roadway order*. As a result, for these very time-consuming computations, TNM considers the most important roadway segments first and the least important last.

During these time-consuming computations, as TNM finishes with each individual roadway segment it computes a running total of the attenuated sound level up to that point in the computation. It then adds to this running total the *free field* sound level from all *remaining* roadway segments. If this remaining free-field sound level contributes less than 1 decibel to the running total, then TNM stops its computations. Certainly, the remaining *attenuated* sound level cannot be significant if the remaining *unattenuated* sound level is not.

Because of this sorting process, TNM avoids computing attenuated sound levels for roadway segments that are completely insignificant and thereby reduces computation time.

Appendix D: Vertical Geometry Acoustics

This appendix supplements discussions in Chapter 4 and is largely a reproduction of the portions of Appendix D of (Anderson, et al., 1998), modified only to reflect changes between TNM 1.0 and TNM 3.1 and to avoid repetition of some materials already presented in the main body. Note, for ease of reference, some information originally presented in the main body is still repeated here.

This appendix describes the details of the acoustical propagation algorithms and mathematics of the "vertical geometry." It also presents much of the logic that is used in creating and evaluating propagation paths. Much of the material in this appendix was prepared during the TNM's design, as a concept and design document; therefore, the style of writing is somewhat different from that of the other appendices.

D.1 Overview

The vertical geometry computations are performed for a single line or cross-section between a source and receiver. This portion of the model evaluates all of the elements or objects that are present between the source and receiver. It is called the "vertical geometry" because the geometry at this level is two dimensional - in the vertical plane of the source and receiver. It is at this level that all of the terrain and shielding computations are made.

The vertical geometry algorithms receive vertical geometry information between source and receiver pairs from the "horizontal geometry" routines. The vertical geometry section computes attenuation for each leg of the elemental triangle in one-third octave bands, then (energy) averages the attenuations. The average attenuation values are then applied to the entire elemental triangle.

Section D.2 discusses the various elements found in the vertical geometry and the approximations that are made to reduce computation time. Section D.3 discusses how the elements are combined to create propagation paths from the source to the receiver. Finally, Section D.4 presents the mathematics used to calculate the ground effect and shielding attenuation between the source and the receiver.

D.2 Vertical Geometry Elements and Approximation

The vertical geometry is defined by an X-Z cross section of the horizontal geometry. Z is the Z-axis, and X is a projection of the X-Y plane in the horizontal geometry onto the line from the source to the receiver. The geometry is defined such that it always starts with the source and ends with the receiver. For purposes of definition in this document, it is assumed that sound propagates from the source on the left to the receiver on the right. Surfaces in the geometry have a left face, a right face, or both depending on whether the surface(s) face the source or the receiver. A surface is said to face left if it faces toward the source. A surface is said to face right if it faces toward the receiver. If it faces neither left nor right, the surface is said to be flat. **Figure 66** shows the definitions of various surfaces in the vertical geometry.

An element of vertical geometry is defined as any object that can affect propagation between the source and the receiver. The set of elements includes sources, receivers, ground points, barriers, berms, ground zones, tree zones and buildings. Propagation is affected by the presence of a reflecting surface or a diffraction point. The following section lists and describes the elements affecting sound propagation that are modeled in TNM.

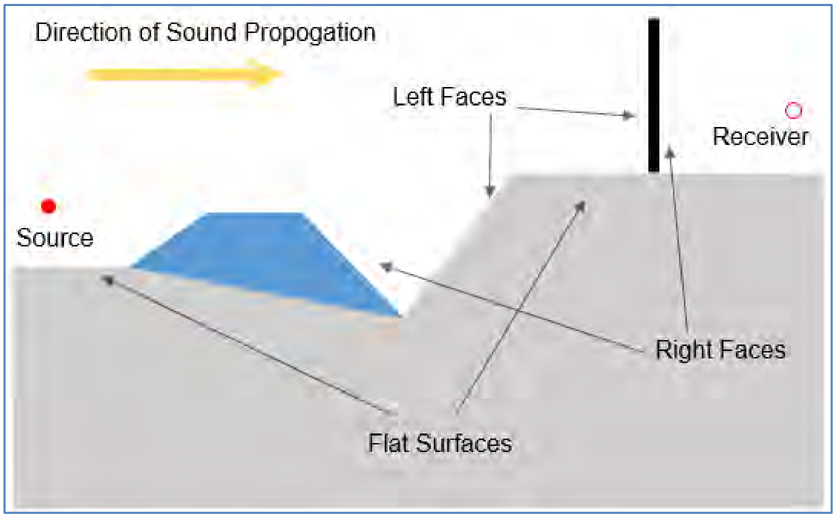

Figure 66 *Vertical Geometry Definitions*

D.2.1 Elements of Vertical Geometry

This section provides definitions of the elements of the vertical geometry and how they are used. Details on the implementation and governing equations are given in Section D.4.

Ground points: Other than the source and the receiver, ground points are the most commonly encountered component of the vertical geometry. Ground points are created at the source and receiver locations and from other objects such as terrain lines. Ground points are passed from the horizontal geometry routines and are stored as points of known elevation and distance from the source. The model assumes that the ground between any two points changes linearly. The line segment between ground points is called a ground segment. Each ground segment has a ground impedance assigned to it. (The user specifies ground type or a value of Effective Flow Resistivity to define the "acoustic hardness" of the ground. These values are converted to impedance.) The ground impedance is passed from the horizontal geometry routines. The ground location is critical in that it defines where reflections and diffractions may need to be modeled.

Diffraction ("diffraction points") can occur at ground points when two ground segments meet to form an angle other than 180 degrees. Diffraction points are also formed when any two ground segments with different impedances meet at any angle. In addition to diffraction, ground segments can also serve to reflect sources, receivers, diffraction points and other objects in the geometry that are positioned to the left of the segment. Reflections in the ground are calculated as normal propagation paths but with the reflected geometry and a (complex) multiplicative factor based on the ground impedance of the reflecting segment. For reflections in the segment, the direction of sound propagation for the image is toward the reflecting segment, until the path reaches the reflecting segment. At this point, sound propagation continues toward the receiver (see Section D.3.3 for more detail). A single ground impedance value is assigned to each segment.

Impedance discontinuities: Impedance discontinuities are points where two ground segments of different impedances meet, such as at the edge of a roadway, where acoustically hard ground meets soft ground. These points always form a diffraction point, but may or may not be modeled depending on the expected contribution to the total sound level at the receiver (see Fresnel Zones in Section D.4.4).

The diffraction is calculated based on the impedances and angles of the segments on either side of the common point.

Barriers: Barriers are structures that stand vertically in the Z-axis direction, and have a height and a base. They also have surface impedances associated with them on each side. Reflections in barrier surfaces are modeled like reflections in ground segments, and impedances are computed from user-entered Noise Reduction Coefficients. The default surface is acoustically hard, with a reflection coefficient of unity.

Barriers have diffracting points at the bottom of the left face, the top, and the bottom of the right face (see **Figure 67**). Barriers also have reflecting surfaces on both the left and the right face. The left face can reflect the geometry to the left of the barrier in the same way a ground segment does. As described above, one-third octave absorption coefficients are given for each face, therefore the associated attenuation is attributed to reflections in the barrier surface. The right face can reflect the receiver only. The barrier top and bottom are assumed to have zero width.

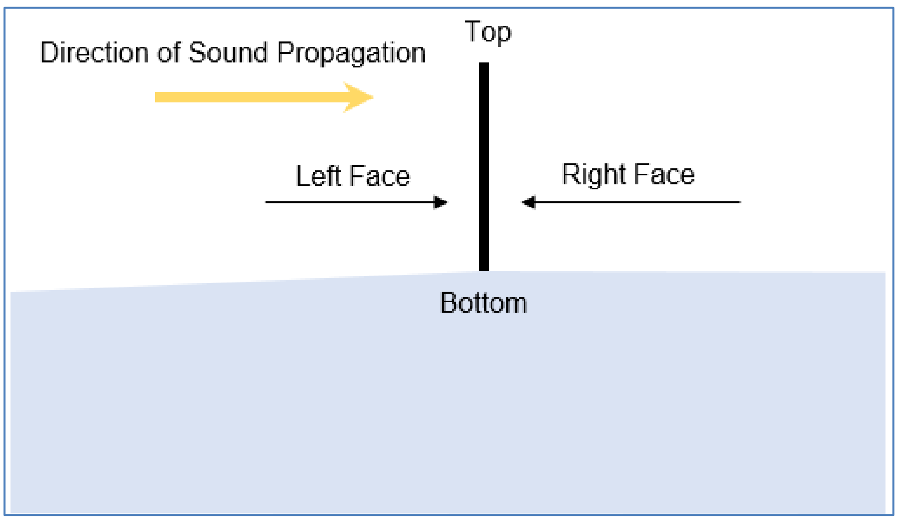

***Figure 67** Barrier Face Definitions*

As with impedance discontinuities, barrier diffraction is only modeled when the contribution of the diffracted components are significant, as determined by the Fresnel zone test (see Section D.4.4).

Berms: A berm is a special type of ground line formation that acts like a barrier. To the user, it is a shorthand method for entering a specific combination of ground lines. Berms are implicitly modeled with a ground point algorithm. A berm is modeled as two wedges that share a flat top surface. (Ground effects are calculated for the berm's flat top.) Although TNM maintains a default value of 0 for berm top width, the width can be changed. However, TNM has shown some apparent anomalies in the diffraction algorithms for berms with a top width.

A berm consists of (normally) soft ground segments with user-specified sloped sides and top width. The vertical geometry receives the center point (x,z) coordinate of the berm (this point is used as a ground point) the height, the angle made with the leg and the berm line, and a pointer to the berm element that contains the widths of the top and bottom of the berm. From this information, the model calculates the ground points that form the berm by finding its intersections with the ground present around the berm center using geometric routines. Like wall-type barriers, diffraction from the intersection of the side of the berm and the ground (base corners, D_{cor}) will be computed, along with the reflection (image) of the source in the sides of the berm and reflection along the top of the berm.

Like wall-type barriers, berms can be specified with multiple heights (perturbations), as shown in **Figure 68**. The multiple height indexing will be handled inside this algorithm and results for the perturbations will be returned. If the berm is perturbed, all possible base corners and top locations are computed. (Note that the Z_0 base height of the berm is a true ground point, or a point of known ground elevation.) The user is allowed to put barriers on berms. In this case the berm is not perturbable.

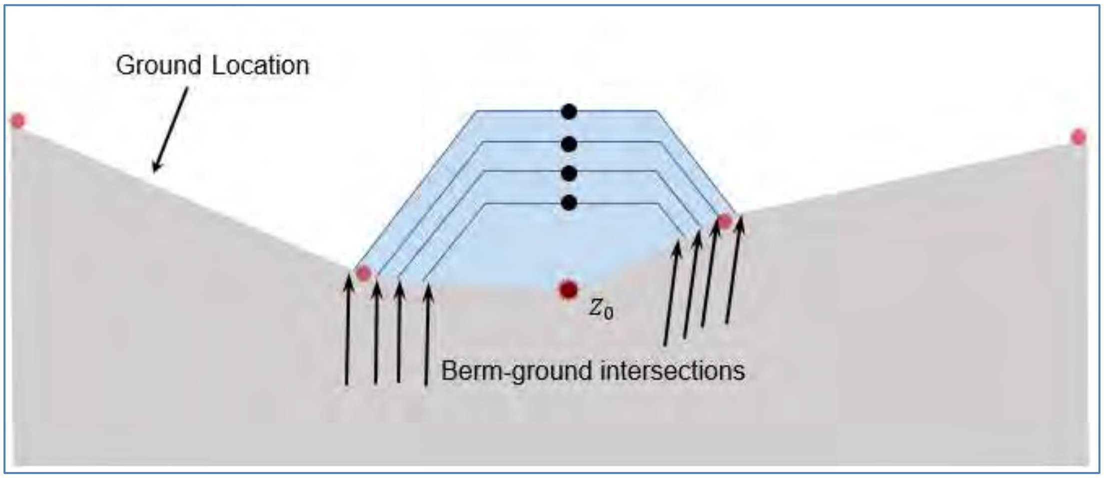

Figure 68 *Example Berm, Shown at Four Perturbation Heights*

Tree zones: Tree zones are areas of the vertical geometry through which propagation paths may pass. Tree zones begin at a vertical segment that is anchored to a specific ground point and extends from the ground upward in the Z direction to a user-defined height. Zones end at a segment anchored to another ground point and extending from the ground up to the same user-defined height. The model determines the distance the propagation path passes through this zone (see **Figure 69**). The ground type under the tree zone is determined by the ground type for the ground segments beneath the Tree Zone and is independent of the Tree Zone. Ground propagation through the Tree Zone is calculated ignoring the Tree Zone (i.e., in the normal way). The Tree Zone simply adds additional attenuation to the propagation paths. Details of tree attenuation are given in section D.4.6.

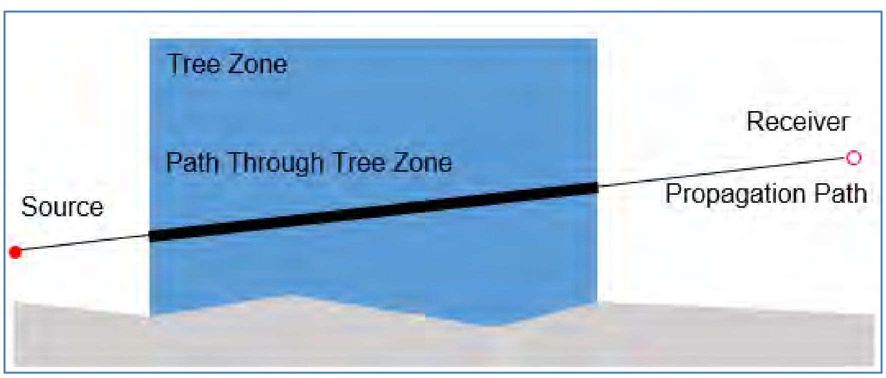

Figure 69 *Propagation Path through Tree Zone*

Rows of buildings: Rows of buildings are similar to tree zones in that they only affect propagation paths that pass through them. A building percentage is assigned to each row. The building percentage represents the amount of linear space, for each building row, that contains building structures. This percentage is used to determine the total shielding provided by the building row.

D.2.2 Approximations

This section describes several approaches taken within the TNM's vertical geometry routines to reduce computation time.

Perturbable barrier reduction: The TNM is designed to handle up to two perturbable barriers in the source-receiver path. If three or more perturbable barriers are encountered, TNM chooses the most effective pair of barriers based on their input heights. This test is performed at the beginning of the evaluation of a given vertical geometry, and TNM then discards all other perturbable barriers for the remainder of the analysis. The choice of the most effective pair of barriers is made with the “Foss selection algorithm” (Foss, 1976). This is a relatively simple and quick procedure that computes attenuation for two barriers in series from path length differences. The procedure follows directly from Foss' scale model measurements, which show good agreement with the algorithm. The equations and an illustration are given in Section D.4.10.

Ground smoothing: The purpose of ground smoothing is to “smooth” away multiple ground points that have small effects on the overall shape of the ground. Smoothing is performed to reduce computation time by minimizing the number of diffraction points and the number of reflecting segments in the vertical geometry to be modeled where the effect on the sound level would be small. The smoothing algorithm has been designed to make only small changes to the vertical geometry. Only inflection points in terrain of the same ground type are considered for smoothing (including small berms); ground-impedance discontinuities are never smoothed away.

The ground-smoothing algorithm looks at three or more points in series. It fixes a line between the outer two points and then checks the perpendicular distance from this line to all the points between. This distance is checked against “max_point_offset,” a variable that fixes the maximum allowable deviation from a line. If the distance for a point is less than max_point_offset, the point is thought to lie close enough to the line formed by the two outer points to be ignored in the propagation calculations. Therefore, the inner point can be removed from the geometry. Points that fail this test are flagged as necessary inflection points in the geometry. The TNM is structured to allow max_point_offset values to be set separately for upward and downward deviations.

Geometry simplification: The TNM works with up to two highest path points (HPPs) between the source and receiver. If more than two HPPs exist in the source-receiver path, the Foss selection algorithm is used to reduce the number of HPPs to the two most effective. The simplification is very similar to that used for the selection of the perturbable barriers, however it is applied to both barrier tops and ground points that are HPPs.

Regression ground and ground-impedance averaging: The TNM next evaluates the complexity of the geometry and if necessary, approximates it as discussed below. To enable TNM to handle complex geometry and to improve run time for those cases, straight-line approximations to the ground has been combined with a method of ground-impedance averaging (Boulanger, Waters-Fuller, Attenborough, & Li, 1997). This (combined) approach is used where more diffraction points are encountered than the De Jong model can properly handle, such as would be encountered with one or more intervening roadways or hilly terrain. Potential diffraction points occur at each impedance discontinuity and at each ground inflection point that has not been smoothed away by the initial smoothing algorithm.

The ground regression is performed differently for two different frequency regions. For the potentially most significant diffraction point in the geometry, a test is performed to determine if the point is in the source-to-receiver Fresnel zone for N > -0.3. If the point is inside that zone, a transition frequency, f_T, at which the point moves outside of the Fresnel zone is computed. Then, for frequencies above f_T, the ground regression algorithm approximates the ground between “source” and “receiver” (either of which can be a highest path point), and the sound propagation paths are generated (see below) based on that representation of the ground. For frequencies below f_T, the point is designated a “near-highest path point” (NHPP) and the ground regression algorithm is used separately to approximate the ground between the source and the NHPP and again between the NHPP and the receiver. A separate set of propagation paths are then generated for the revised geometry, including the NHPP as a diffraction point.

Any impedance discontinuities present in the original geometry are projected onto the regression ground line(s), and the ground-impedance averaging is performed.

The Boulanger approach to ground-impedance averaging is used for cases where more than one impedance discontinuity is present in the local geometry between source and receiver or highest path points. Instead of computing the multiple diffraction paths explicitly, this approach computes a Fresnel ellipse about the reflection point on the ground and computes the area inside the ellipse represented by each type of ground. Then, an average reflection coefficient is computed from the reflection coefficient for each ground type weighted by the ratio of its area to the total area. The average reflection coefficient is used, and no diffraction terms are computed at all. However, the size of the ellipse is a function of frequency, so the average impedance and therefore the reflection coefficient will often change for each one-third octave band. Section D.4.6 explains this approach further and includes an illustrative figure.

Path significance test: A Fresnel zone test is used for each propagation path generated, to determine if the path is significant enough to be included for computation. A path is considered significant and is computed if the receiving point falls into the region where the Fresnel number is greater than -0.3. This quick test was incorporated into the TNM to avoid the time-consuming computation of the many possible diffraction paths in the more complex geometries with barriers. This test is performed for bright-zone diffractions only; all diffraction paths where the receiving point is in the shadow zone are assumed to be significant.

D.3 Propagation Paths

A propagation path is defined as any path that starts at the source and ends at the receiver. The path can be reflected in surfaces, be diffracted around specific obstructions, or pass through tree zones or rows of buildings. For any given vertical geometry, there will usually be multiple propagation paths. All of the propagation paths associated with a single vertical geometry are summed at the receiver to yield a net sound pressure and resulting attenuation relative to free field.

A single propagation path is made up of propagation segments. Propagation segments start and end with path points. A path point can be a source, a diffracting point or a receiver. (See Section D.3.2 for more on diffractions.) Only sources can start a propagation path, and are found only at the beginning of the first segment. Only receivers can end a propagation path, and are found only at the end of the last segment. The complete set of propagation paths for a vertical geometry contains paths with all possible combinations of sources (real and image), diffraction points, and receivers (real and image) connected in the direction of sound propagation (ignore back propagation). For a diffraction point to be used in a path one of the following two conditions must exist: (1) the next point in the path must fall in the Fresnel Zone of the geometry formed by it, the diffraction point in question, and the path point just before the diffraction (see Section D.4.4); or (2) the next point must be in the shadow of the diffraction point in question and the path point just before the diffraction.

Propagation paths always start at the source or an image source. From there, all possible propagation segments are formed, by connecting the source to either a diffraction point or the receiver in the direction of sound propagation (this is to the right for all real sources and diffraction points, but may change when dealing with images). To make this connection, the source must have an unobstructed view of the point. If the connection is made to the receiver, the path ends. If the connection is made to a diffraction path a test must be made to see if the diffraction point is either in the Fresnel zone or in the shadow. If it passes this test, the diffraction point becomes the new effective source or "emitter," and the process continues with an attempt to connect to another diffraction point or a receiver. This process continues until all propagation paths end at a receiver.

The Fresnel zone calculation (see Section D.4.4) is frequency dependent. The test to determine if the path that includes the diffraction will significantly contribute to the total sound pressure at the receiver is done using a low frequency (250 Hz) as the cutoff. Any paths with diffractions that don't meet these criteria are ignored. For a path to be modeled, all the diffractions in the path must pass the Fresnel zone test. As a time saving measure, the transition frequency, based on the Fresnel zone, is saved for each path. This is the lowest frequency above which at least one of the diffractions in the path is insignificant (fails the Fresnel zone test).

Reflections in ground segments and barriers can add extra propagation paths. Reflected propagation paths start at the source image in the surface and propagate toward the image reflecting surface. The propagation progresses normally using the reflected geometry. The entire geometry to the left of a reflecting segment, including reflections in those segments being reflected, is reflected into the segment. At the reflecting surface, the path continues normal propagation to the receiver using the real geometry. This way the complete reflected field and all reflected paths are modeled.

The following sections discuss various elements that can describe propagation paths.

D.3.1 Free Field

This is the simplest propagation path to be calculated. It is simply the straight line (line of sight) path from the true source to the true receiver. The free field path ignores all obstructions and images in the vertical geometry.

D.3.2 Diffractions

"Diffractions" are used to model areas of propagation paths that pass around edges in the vertical geometry. An edge can be a point where two ground segments meet, the top of a barrier or the bottom of a barrier. Where the sound wave diffracts over an edge, energy from the original wave is redirected.

An “altered” wave now propagates from the diffraction point. The energy from the original wave decreases in magnitude based on the Chi (χ) function, which is dependent on the angles and distances to the source and the receiver from the diffraction point. The diffraction field has a maximum of half the sound pressure of the free field on the “grazing line.” The grazing line is the line formed by the source and the diffraction point. The Fresnel integral function is used to calculate the reduction in energy, and is based on the χ function. Since sound appears to emanate from the diffraction point, the diffraction point is, for the purposes of the model, mechanically treated as a "sound emitter" with similar properties to a real source (except that a propagation path cannot start with a diffraction point) when constructing propagation paths.

See Fresnel Zones in Section D.4.4, for details on when diffraction points are included in a propagation path.

Single diffractions: Single diffractions involve a source, a diffraction point, and a receiver. For example, diffraction points can be points where two ground segments meet, the top of a barrier, or the bottom of a barrier. An example of the diffraction geometry with a barrier top as the diffraction point is shown in **Figure 70**. To calculate the diffraction coefficients, the following effective distances must be known: the source to the diffraction point, the diffraction point to the receiver, and the source to the receiver. In addition, the angles that the source-diffraction point and diffraction point-receiver segments make with the left side of the diffracting surface must be determined. These values are used to calculate χ in the diffraction coefficient. This is explained in more detail in Section D.4.3.

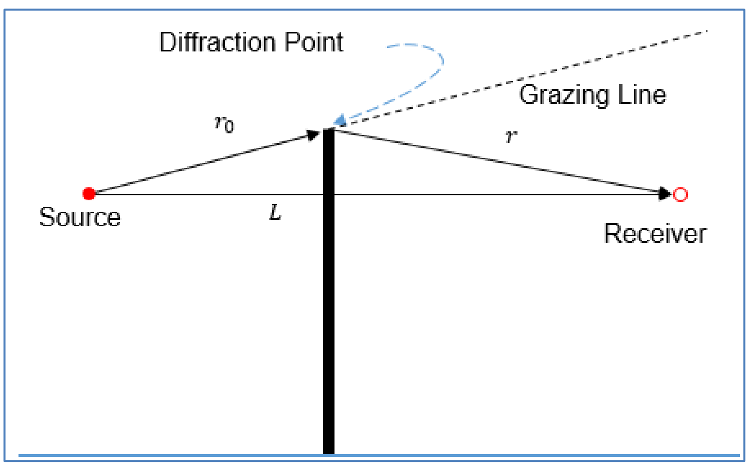

***Figure 70** Single Diffraction Geometry*

Multiple diffractions: Multiple diffractions are very similar to single diffractions. The paths consist of more than one diffraction point, a source, and a receiver, as shown in **Figure 71**. They are modeled with multiple single diffractions, multiplied together. Each diffraction point in the path is modeled with one single diffraction calculation. For each single diffraction in a multiple diffraction case, the angle about a diffraction point and the total path length are kept constant while the source and the receiver are moved to their effective locations, so that proper angles and path lengths are preserved. To determine the effective location of the source, the first propagation path segment on the source side of the diffraction is fixed. Segments following this one back, moving back toward the source, are rotated about any intermediate points so that they extend the left segment along the same line. The same is then done on the receiver side of the diffraction to position it in its effective location (see **Figure 72**). The new rotated geometry is used to calculate the diffraction resulting from this diffraction point using the single diffraction algorithm. This is repeated for each diffraction point in the path. The diffraction coefficients are then multiplied together to calculate the total diffraction for the path.

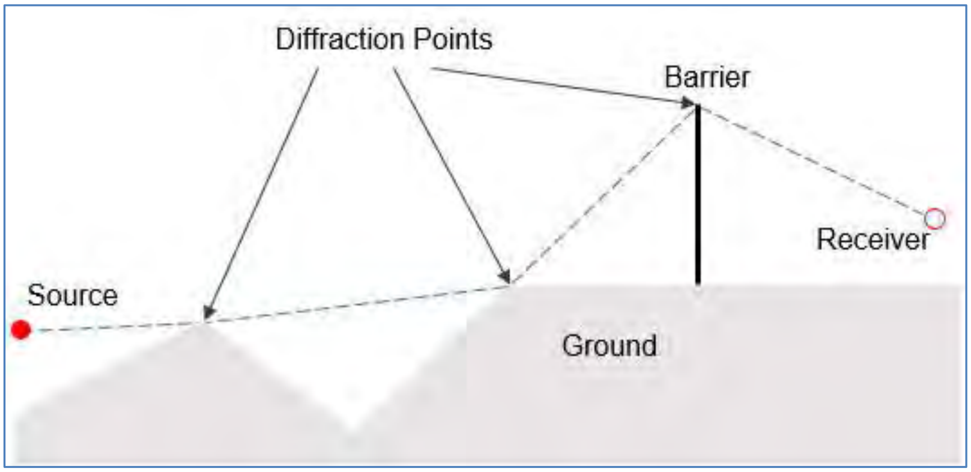

Figure 71 *Example of Multiple Diffractions*

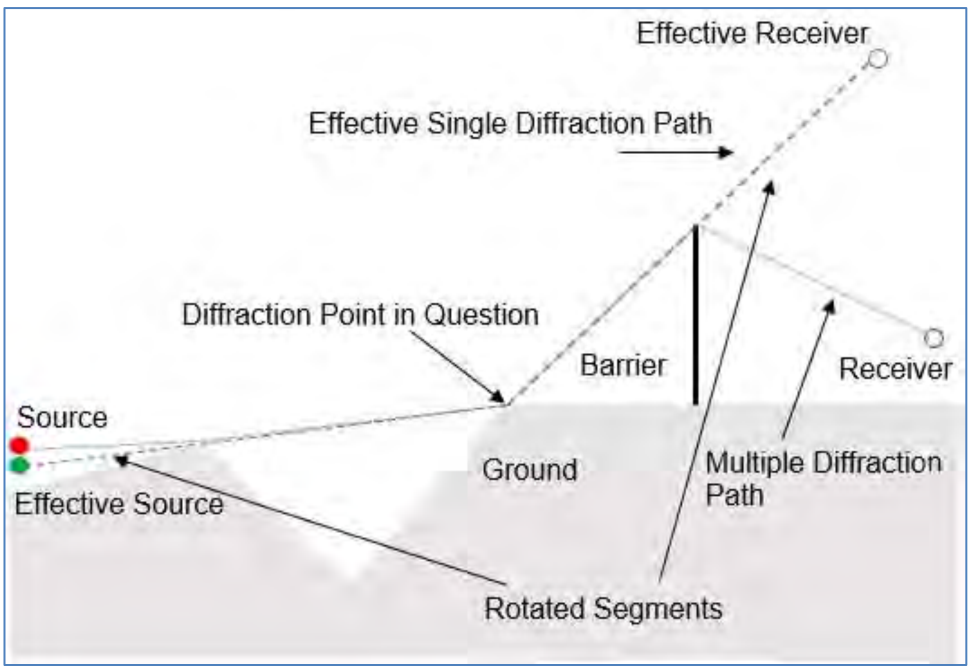

Figure 72 *Example of an Effective Single Diffraction from a Multiple Diffraction Path*

D.3.3 Reflections

Reflections create extra propagation paths that can result in increased sound pressure at the receiver. This section discusses how and where reflections are accounted for in the vertical geometry.

Reflections in ground segments: Every segment in the vertical geometry may reflect the geometry above or to the left of it. To check if a segment reflects, first extend the line defined by the segment endpoints in both directions. Take the right most point from the vertical geometry that lies to the left of the left end of the real segment, if one exists. Objects directly over the right most end point are excluded. Reflect this point and the entire vertical geometry to the left of that point, including all reflections that take place in the geometry being reflected, about the reflecting segment. The geometry of **Figure 73** shows some examples of reflections. (Note that left is defined as the side closest to the source and right is defined as the side closest to the receiver.)

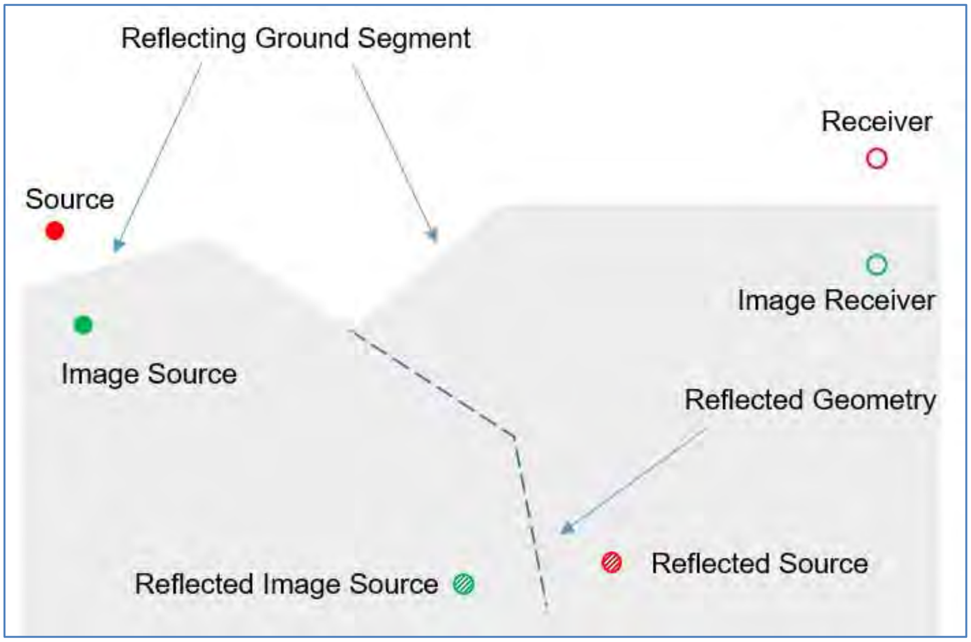

Figure 73 *Example of a Geometry with Reflections*

The direction of sound propagation is, for the real source and diffractions points, always to the right, toward the receiver. The direction of propagation from reflected (image) sources and diffractions point may not always be to the right, but it is in the direction of the receiver. For image propagation path points, the direction of propagation is always toward the segment that reflected the points. For compound reflections, this starts with the segment that last reflected the point to the segment that first reflected it. **Figure 74** shows a few examples of the direction of propagation. Propagation paths are also drawn to image receivers.

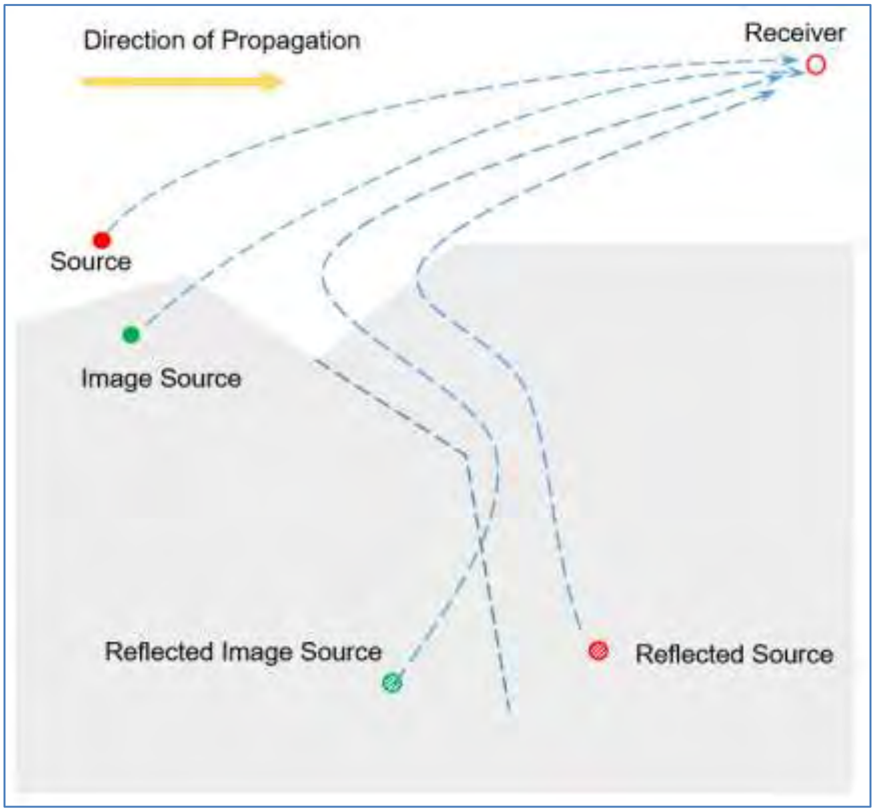

Figure 74 *Example Direction of Propagation Paths*

When starting at one point, only diffraction points closer to the receiver, along the direction of propagation, can be used when creating the propagation path from the source to the receiver. Points not in the direction of propagation are ignored. This prevents the propagation path from using any point in the geometry.

Each reflected path must be multiplied by the proper reflection coefficient for every segment that reflects the path. This requires the knowledge of each segment's ground or surface impedance. When an image ground segment reflects an image point, the real ground segment's impedance is used.

Reflections in berms: Since berms are special cases of ground segments, they are treated just like ground segments.

Reflections in barriers: Reflected images in barriers are handled in the same way as images in ground segments. Barriers have different impedances associated with them, however.

One value of impedance is assigned to each side of the barrier, depending on the NRC entered by the user.

D.3.4 Propagation Path Generation Algorithm

This section describes the path generation algorithm in a logical form called pseudocode. The Path Generation Algorithm is called by the calculation function in the TNM Acoustical Module. The calculate function calls the path generation algorithm with a sorted, smoothed and simplified version of the Vertical Geometry Object List (VGOL). The types of objects in the list are Source Points, Ground Points, Barrier Points, Building Points and Receiver Points. Each point in the list is sorted based on its location on the source-to-receiver axis. This list does not contain Tree Zone points. The algorithm generates propagation paths and applies the acoustical functions in TNM to them to calculate a-octave band sound pressure levels at the receiver.

Path generation algorithm:

Start with the Vertical Geometry Object List.

Set all one-third octave-band sound pressure totals to zero.

Set Highest Path Tree Zone Penetration Distance to zero.

Create a Propagation Point List (PPL) from the VGOL:

Starting at the source's ground point, and ending with the receiver's ground point. Include all points from the VGOL object list in the order in which they appear in the list.

Barriers have the following diffraction points:

First point: Base on the source side

2nd point: Top

3rd point: Base on the receiver side.

Source ground point is placed before the source.

Receiver ground point is placed after the receiver.

Rows of Buildings have no diffraction points, but their ground points are in the list (with a reference to the top).

Ground Points are a single point.

The PPL has the following structure: [source ground point] [source] [1st point] [2nd point] [ ] ... [ ] [receiver] [receiver ground point].

Create surface-vectors (normal to the segment) for each point in the PPL.

Assign each point in the PPL a reflection level of zero.

If there is a reflecting barrier in the PPL, then each point to the Left of it has a reflection level of one.

Create propagation paths with the PPL and VGOL and sum partial sound pressures.

Return one-third octave-band sound pressures for the receiver.

Propagation path creation algorithm:

With a PPL:

Create a Path List Structure.

Create Path Nodes with each source, receiver and diffraction point in the PPL.

Label the Path Nodes in increasing order, starting at the source and ending at the receiver, where the source is Node 1, and the receiver is Node N.

> (*Note: Rows of buildings, the ground under the source, and the ground under the receiver cannot be targets because they are not diffraction points.*)

Loop (i) over all Path Nodes from 1 to N-1:

- Set point i to be the emitter.
  - Loop (j) over all Path Nodes from i to N-1:
    - Set point j+1 to be the target.
    - Check to see if a Line-of-sight (LOS) exists between the emitter and the target.
      - If LOS exists:
        - Create a link with emitter and target and Assign to Path Node as exiting and entering respectively.

Add a Path to the Path List for each unique Path Node combination starting with the source and ending with the receiver.

- Loop (i) over all Path Nodes from 1 to N-1:
- Set M to the number of outward going Path Links.
  - If M = 0 then go to top of Loop.
  - Copy all Paths Ending in Node i M-1 times.
    - Loop (j) from 1 to M.
    - Add Path Node at the end of Path Link j to the end of jth Path ending in Path Node i.
    - Call Fresnel Zone Filter Algorithm with the Path j.
- Delete any Path not ending with the receiver.

For each Path in the Path List:

- If the Path has too many diffraction points (reference to the Highest Path), then delete it.
- If the Path wasn't deleted, calculate the path’s partial sound pressure.
- Sum a-octave band partial pressure results to VGOL a-octave band pressure totals.

Delete all Paths in the Path List, Nodes, and Node Links.

D.4 Propagation Path Calculations and Mathematical Description

The mathematical model used to calculate the attenuations due to the vertical geometry between the source and the receiver was in large part developed from work by De Jong, Chessell, Delany, Boulanger and Foss (De Jong, Moerkerken, & van der Toorn, 1983) (Chessell, 1977) (Delaney & Bazley, 1970) (Boulanger, Waters-Fuller, Attenborough, & Li, 1997) (Foss, 1976). De Jong's methodology was used as the basis for the diffraction field model. Work by Chessell, Delany and Boulanger was used to calculate reflections in surfaces, and Foss' double-barrier method was used to simplify the vertical geometry.

The following sections describe the mathematical and logical functionality used for calculating propagation path sound pressures.

D.4.1 Definitions

TNM's acoustical calculations in the vertical plane involve the following variables:

α	barrier-reflection parameter: single-frequency absorption coefficient, dimensionless
δ	path-length difference caused by diffraction, in meters
λ	wavelength of propagating acoustic wave, in meters
ν	diffraction parameter: normalized exterior wedge angle, dimensionless
σ	reflection parameter: effective flow resistivity of the reflecting surface, in mks Rayls
ϕ	reflection parameter: grazing angle of incidence, in radians
ϕ	diffraction parameter: angle clockwise from the left wedge face to the edge-receiver line, in radians
ϕ_0	diffraction parameter: angle clockwise from the left wedge face to the edge-source line, in radians
χ	parameter within the Fresnel integral, dimensionless
$Atten_{row}$	building-row parameter: attenuation due to a row of intervening buildings, in dB
c	speed of sound, in meters per second
D	multiplicative diffraction factor, dimensionless
f	frequency of a propagating acoustic wave, in Hertz
F	Foss parameter: higher of the two barrier attenuations, in dB
$F(\chi)$	Fresnel integral
$F(w)$	reflection parameter: ground-wave function, dimensionless
$F_{linear-Gap}$	building-row parameter: linear gap fraction of the intervening row of buildings, dimensionless

f_{rN}	Atmospheric parameter: nitrogen relaxation frequency, in Hertz
f_{r0}	Atmospheric parameter: oxygen relaxation frequency, in Hertz
h	Atmospheric parameter: molar concentration of water vapor, in percent
h_r	Atmospheric parameter: relative humidity, in percent
$IL_{Barrier}$	building-row parameter: insertion loss of the row of buildings, in dB, computed as if the row of buildings had no gaps
IL_{eff}	Foss parameter: effective insertion loss for two barriers in sequence, in dB
J	Foss parameter: attenuation for the modified geometry, in dB
k	wave number of a propagating acoustic wave, in inverse meters
L	diffraction parameter: propagation path length over the top of the intervening barrier or wedge, in meters
N	Fresnel number, dimensionless
N'	building-row parameter: Fresnel number (at 630 Hz) for the row of buildings, dimensionless
NRC	barrier-reflection parameter: Noise Reduction Coefficient, dimensionless
p_0	Atmospheric parameter: standard reference pressure, 101.325 kilo-Pascal
$p_{free-field}$	free-field pressure of a propagating acoustic wave, in kilo-Pascal
P_{path}	pressure at the receiver, in kilo-Pascal, after the propagating sound undergoes one or more diffractions or reflections
p_{sat}	Atmospheric parameter: saturation vapor pressure, in kilo-Pascal
P_{total}	Total pressure at the receiver due to all N propagation paths combined, in kilo-Pascal
Q	reflection parameter: reflection coefficient of a spherical acoustic wave from a surface, dimensionless
Q_1	reflection parameter: reflection coefficient from the left (first) surface of a diffracting corner
Q_2	reflection parameter: reflection coefficient from the right (second) surface of a diffracting corner
r	diffraction parameter: distance from the diffraction edge to the receiver, in meters
r	reflection parameter: total distance between source and receiver, in meters
R	barrier-reflection parameter: reflection factor, dimensionless
R	free-field, direct-line (passing through intervening obstructions) distance from source to

	receiver, in meters
r_0	diffraction parameter: distance from the diffraction edge to the source, in meters
R_p	reflection parameter: reflection coefficient of a plane acoustic wave from a surface, dimensionless
t	"dummy" variable within the Fresnel integral
T	Foss parameter: total distance between source and receiver, in meters
T	Atmospheric parameter: ambient air temperature, in K
T	diffraction parameter: interior (below-the-ground) wedge angle, in radians
T_0	Atmospheric parameter: reference air temperature, 293.15 K
T_{01}	Atmospheric parameter: triple-point isotherm temperature, 273.16 K
$T_{Celsius}$	Atmospheric parameter: temperature, in C
$T_{Fahrenheit}$	Atmospheric parameter: temperature, in F
T_{Kelvin}	Atmospheric parameter: temperature, in K
w	reflection parameter: numerical distance for a reflecting spherical wave, dimensionless
W	Foss parameter: distance between the two barriers, in meters
Z	reflection parameter: acoustic impedance of the reflecting surface, dimensionless
Z_0	reflection parameter: acoustic impedance of air, dimensionless

D.4.2 Free Field

The free-field sound pressure calculation is used as one of the factors for each propagation path; it is given by:

$$p_{free-field} = \frac{e^{ikR}}{kR} \tag{61}$$

where the wave number, k, is defined as

$$k = \frac{2\pi f}{c} \tag{62}$$

and where f is the frequency in Hertz; c is the speed of sound, 345 m/sec (772 miles/hour); and R is the free-field, direct-line distance from the source to the receiver.

D.4.3 Fresnel Integral

The Fresnel integral is one of the functions used in computing the diffraction coefficient (see next section). It is used to calculate the magnitude and phase shift incurred by a propagation path that diffracts from an inflection in the ground or an impedance discontinuity. The Fresnel integral is defined by the following equation:

$$F(\chi) = \int_{\chi}^{\infty} e^{it^2} dt \tag{63}$$

The complex exponential can be substituted with cosine and sine terms using Euler's equation:

$$F(\chi) = \int_{\chi}^{\infty} (\cos(\, t^2\,) + i\sin(\, t^2\,))\, dt \tag{64}$$

TNM computes this function with a "C" programming language algorithm from (Baker, 1992).

D.4.4 DIFFRACTION FUNCTION

The complete diffraction term is defined by the following function:

$$D = \frac{R}{L}\frac{e^{-\frac{i\pi}{4}}}{\sqrt{\pi}} e^{ik(L-R)} e^{-i\chi^2} F(\chi) \tag{65}$$

where L is defined as the propagation path length. In **Figure 75**, which shows the diffraction geometry, $L = r_0 + r$.

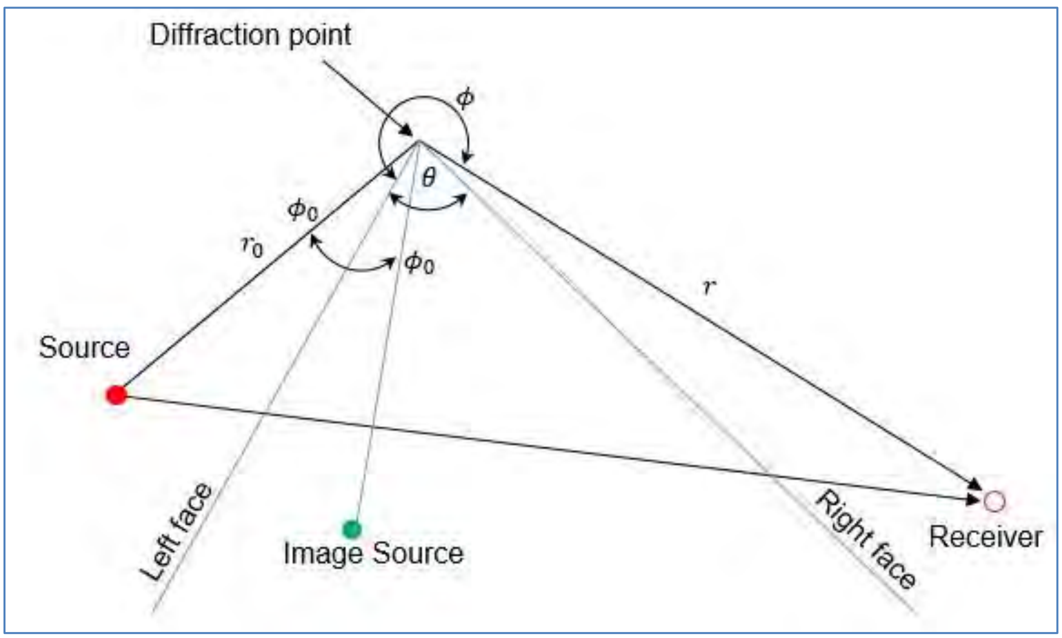

Figure 75 *Diffraction Geometry*

D is multiplied by a sign function that is positive when the receiver is in the dark zone and negative when the receiver is in the bright zone. To adjust the diffraction field to make it consistent with empirical results, D is also multiplied by an adjustment factor, A. A is currently set to 1.0. The factor Q is included to account for the surface impedances at the diffracting edge (see Section D.4.5). This results in the following equation:

$$D = (sgn)ADQ \tag{66}$$

Chi function: The chi (χ) function is used to pass information about the diffracting geometry to the Fresnel function. It takes into account the distances from the diffraction point for the effective source and the receiver, the angle formed about the diffraction point, and the top angle of the obstruction causing the diffraction. The χ function has the following formula

$$\chi = \left(\frac{krr_0}{2L}\right)^{1/2} \left| \frac{\cos\left(\frac{\pi}{v}\right) - \cos\left(\frac{\phi-\phi_0}{v}\right)}{\left(\frac{1}{v}\right)\sin\left(\frac{\pi}{v}\right)} \right| \tag{67}$$

where

$$v = \frac{2\pi - T}{\pi} \tag{68}$$

and T is the positive “top angle" of the wedge (T = 0 for a barrier, and $T = \pi$ for a flat surface). (The absolute value missing from De Jong’s publication is shown here; the sign of ϕ_0 is accounted for as defined below.)

The angles ϕ and ϕ_0 are measured in radians, referenced to the left side of the diffracting obstruction. Clockwise measured angles are positive. Angles for images of the source in the obstruction are measured in a counterclockwise direction and have negative angles. The geometry is defined in **Figure 75**.

For diffracting edges like barriers, where the interior wedge angle, T, is 0, ϕ can be simplified to the following equation:

$$\chi = \sqrt{\frac{k(L-R)(L+R)}{2L}} \tag{69}$$

(De Jong’s simplification allowed $L + R = 2L$, but the above formulation retains the distinction, since it is more precise.)

Single diffraction: A propagation path with a single diffraction is calculated by substituting the correct values in the diffraction function to calculate D. The total sound pressure for the path is then found by multiplying the free-field path sound pressure by the diffraction coefficient. The following equation is used to calculate the sound pressure for a propagation path with a single diffraction, assuming that material at the diffraction point is acoustically hard:

$$P_{path} = p_{free-field} D \tag{70}$$

If the material at the diffraction point is other than acoustically hard, D is multiplied by the reflection coefficient, Q, which is described below in Section D.4.5.

Multiple diffraction: Multiple diffractions are modeled by multiplying single diffractions. First, for each diffraction point, the effective geometry must be calculated for the source and the receiver. This information is then used to calculate the effective single diffraction for that point. This is repeated for each diffraction point in the propagation point. Once all diffractions have been calculated for the propagation path, they are all multiplied together. The product is used as the effective diffraction for the propagation path. The effective diffraction is then multiplied by the free-field sound pressure to calculate the pressure for the propagation path. The following equation represents the calculation for a propagation path with N diffractions, for the case where each diffraction point is acoustically hard:

$$P_{path} = p_{free-field} \prod_{i=1}^{N} D_{<effective>i} \tag{71}$$

If the material at the diffraction points is not acoustically hard, D_i is multiplied by the reflection coefficient, Q_i, for each material type. The reflection coefficient is defined below in Section D.4.5.

Corner discontinuities: Corner diffractions are those that occur when two segments in the vertical geometry meet in an acute angle, to form a corner. Diffractions at corner discontinuities are calculated with the same diffraction coefficient function as follows:

$$D_{cor} = \frac{R}{L} \cdot \frac{e^{-\frac{i\pi}{4}}}{\sqrt{\pi}} e^{ik(L-R)} e^{-i\chi^2} F(\chi) \tag{72}$$

Fresnel zone/path significance test: The Fresnel zone test is a quick test for significance of diffraction paths. It was incorporated into the TNM to avoid the time-consuming computation of all diffraction paths, whether they are important or not. The Fresnel zone test is performed only for points in the "bright" zone, where line of sight exists between source and receiver. Under this definition, the source can be a reflected source, a secondary emitting point such as a barrier top, or a reflected emitting point, and the receiver can be a secondary receiving point, real or reflected. All diffraction paths where the receiving point is in the shadow zone are assumed to be significant. If a path is not found to be significant, then the combination of points that created the diffraction are not included in the detailed calculation described above. The test is simply a check to see if the receiver lies within a hyperbola defined by the source and the diffraction point. The hyperbola is defined by the following equation:

$$N = \frac{2\delta}{\lambda} \tag{73}$$

N is the Fresnel Number. δ is called the path length difference and equals $(r_0 + r) - R$. (Note that the hyperbola is defined using $R - (r_0 + r)$. Conventions in acoustics multiply the expression $(r_0 + r) - R$ by -1, so that N is positive in the dark zone.) λ is the wavelength and equals c/f, where c is the speed of sound in m/sec and f is the frequency in Hz. A receiver is said to be inside the Fresnel zone (and the diffraction is significant) if $N > -0.3$, in the bright zone only.

D.4.5 Reflection Coefficients

Coefficients of reflection Q are calculated using the model defined in (Chessell, 1977). This model uses the user-specified effective flow resistivity of the reflecting segment and calculates the magnitude and phase change to the propagation path that reflected it. This model is dependent on frequency, effective flow resistivity of the reflecting segment, and the geometry defined by the propagation path. The value, Q is computed from the absorption coefficients according to the following equation:

$$Q = R_p + F(w)(1 - R_p) \tag{74}$$

where R_p is the term for the incident wave and is calculated with the following equation:

$$R_p = \frac{\sin(\phi) - \frac{Z_0}{Z}}{\sin(\phi) + \frac{Z_0}{Z}} \tag{75}$$

Here, Z_0 is defined as the impedance of air ($\rho_0 c_0$ =1.18 kg/m3 * 345 m/sec). ϕ is the angle of incidence of the propagation path on the reflecting segment. Z is the acoustic impedance of the reflecting surface. For ground segments, Z is defined by the following equation, which was derived from empirical measurements of many fibrous porous materials (Delaney & Bazley, 1970). This equation has been shown to be a good model for various ground surfaces ranging in impedance from snow to grass to asphalt (Embleton, Piercy, & Daigle, 1983).

$$Z = \left[1 + 0.051 \left(\frac{f}{\sigma} \right)^{-.75} + 0.077 \left(\frac{f}{\sigma} \right)^{-.73} i \right] Z_0 \tag{76}$$

Here, σ is the effective flow resistivity (EFR) for the reflecting segment in MKS Rayls. Values for σ are entered for ground segments based on the type of material selected for the ground.

$F(w)$ is the ground wave function. It is defined by the following equation:

$$F(w) = \begin{cases} 1 + ie^{-w}\sqrt{\pi w} - 2e^{-w} \sum_{n=1}^{\infty} \frac{w^n}{(n-1)!\,(2n-1)} & |\,w\,| < 10 \\ -\sum_{n=1}^{\infty} \frac{(2n)!}{2^n n!\,(2w)^n} & |\,w\,| \geq 10 \end{cases} \tag{77}$$

where w, known as the "numerical distance," is defined as follows:

$$w = \frac{1}{2} ikr \frac{(\sin(\phi) + Z_0/Z)^2}{(1 + \sin(\phi)\, Z_0/Z)} \tag{78}$$

where k is the wave number and r is the total distance between the source and the receiver, through the medium.

Reflections in barrier surfaces: For computing the effects of reflections in the barrier surfaces, a similar approach is taken as for ground segments, except that values of EFR (σ) had to be derived to correspond to the user-specified Noise Reduction Coefficient (NRC) on the barrier surfaces.

The single-frequency absorption coefficient is given in terms of the "reflection factor", R:

$$\alpha = 1 - |R^2| \tag{79}$$

where

$$R = \frac{Z - Z_0}{Z + Z_0} \tag{80}$$

and Z_0 is the impedance of air. The barrier surface impedance, Z, is derived from the EFR from Delany's empirical fit for fibrous materials, given in Eq. (41), above. NRC is defined as the arithmetic average of the absorption coefficients at 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz. In an iterative process, individual values of EFR were found that corresponded to values of NRC in steps of 0.05 between 0.0 and 1.0.

Table 13 lists the EFR values used for all user-selectable NRC values.

Table 13: Effective Flow Resistivity used for Values of Noise Reduction Coefficient (NRC)

NRC	EFR (cgs Rayls)
0.00	20000
0.05	4250
0.10	1570
0.15	865
0.20	555
0.25	385
0.30	282
0.35	214
0.40	165
0.45	129
0.50	102
0.55	81
0.60	64
0.65	50
0.70	39
0.75	30
0.80	22
0.85	16
0.90	10.4
0.95	5.5
1.00	0.1

TABLE 14 shows the effective one-third octave band absorption coefficients used within TNM when calculating reflections in barrier surfaces for selected values of NRC.

TABLE 14: ABSORPTION COEFFICIENTS AS A FUNCTION OF FREQUENCY FOR SELECTED VALUES OF NOISE REDUCTION COEFFICIENTS (NRC)

One-Third Octave Band Frequency, Hz	One-Third Octave Band Absorption Coefficients for Selected Values of NRC					
	0.05	0.30	0.50	0.70	0.80	0.90
50	0.01	0.05	0.09	0.18	0.26	0.41
63	0.01	0.05	0.11	0.21	0.30	0.46
80	0.01	0.06	0.13	0.24	0.35	0.52
100	0.01	0.07	0.15	0.28	0.39	0.57
125	0.01	0.09	0.17	0.32	0.44	0.63
160	0.01	0.10	0.21	0.37	0.50	0.68
200	0.02	0.12	0.24	0.42	0.56	0.73
250	0.02	0.14	0.27	0.47	0.61	0.78
315	0.02	0.16	0.31	0.53	0.67	0.82
400	0.03	0.19	0.36	0.59	0.72	0.86
500	0.03	0.22	0.41	0.64	0.77	0.89
630	0.04	0.26	0.46	0.70	0.81	0.91
800	0.05	0.30	0.52	0.75	0.85	0.94
1000	0.06	0.34	0.58	0.79	0.88	0.95
1250	0.06	0.39	0.63	0.83	0.91	0.96
1600	0.08	0.44	0.69	0.87	0.93	0.97
2000	0.09	0.50	0.74	0.90	0.95	0.98
2500	0.11	0.55	0.78	0.92	0.96	0.99
3150	0.12	0.61	0.83	0.94	0.97	0.99
4000	0.15	0.67	0.86	0.95	0.98	0.99
5000	0.17	0.72	0.89	0.97	0.98	0.99
6300	0.20	0.77	0.92	0.97	0.99	1.00
8000	0.23	0.81	0.94	0.98	0.99	1.00
10000	0.27	0.85	0.95	0.99	0.99	1.00

Reflected paths: Paths reflected by segments in the vertical geometry are multiplied by the reflection coefficient Q, defined in the previous section. The angle of incidence at the intersection of the propagation path, the effective flow resistivity of the reflecting segments material, and the frequency are used to determine Q for the reflection. This factor is multiplied with the propagation path to account for energy loss and phase shift due to the reflection. A propagation path is multiplied by one coefficient for each segment that reflects the path. **Figure 76** shows a simple propagation path that contains one reflection and one diffraction. The equation for that propagation path has the following form:

$$P_{path} = p_{free-field}\, Q \cdot D \tag{81}$$

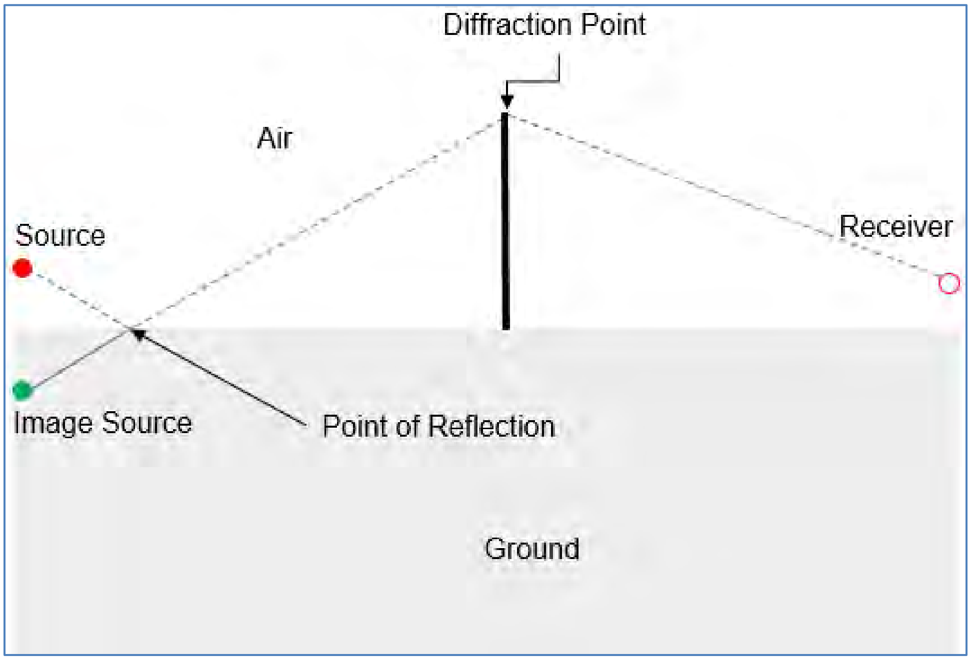

Figure 76 *Example Geometry Showing Reflection*

Impedance discontinuities: Propagation paths with diffractions at impedance discontinuities are multiplied by the difference between the segment impedance on the source's side and the receiver's side. **Figure 77** shows a sample geometry with a propagation path containing a diffraction at an impedance discontinuity. The following expression shows the form of the equation for the propagation path in **Figure 77**:

$$P_{path} = p_{free-field}\,(\,Q_1 - Q_2\,) \cdot D \tag{82}$$

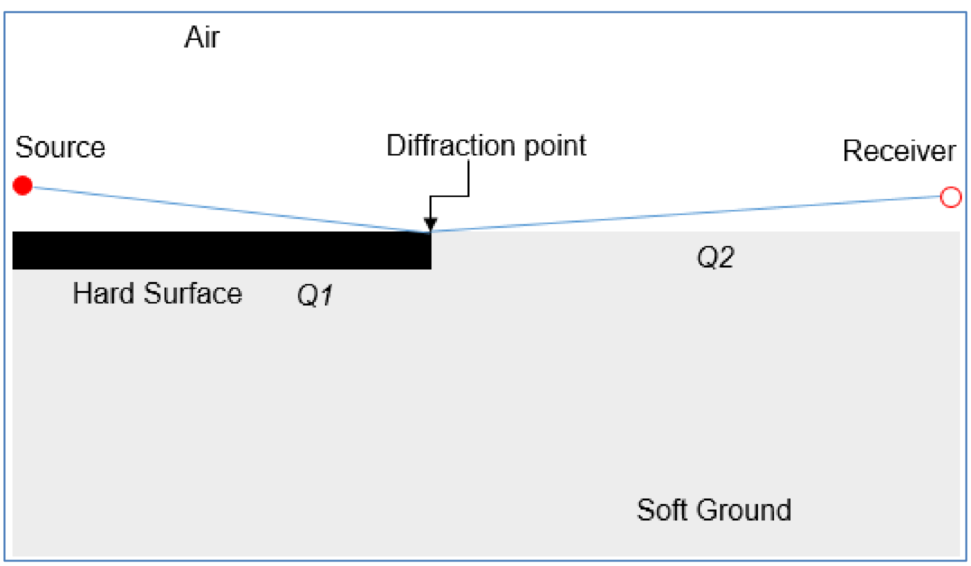

Figure 77 *Example Geometry Showing an Impedance Discontinuity*

Corner diffractions: A propagation path containing a diffraction formed by two ground segments meeting or a ground segment and a barrier meeting point is multiplied by the reflection coefficient to the left and to the right of the point in the following form:

$$P_{path} = p_{free-field}(\, Q_1 - Q_2 \,) \cdot D_{cor} \tag{83}$$

Figure 78 shows a sample geometry for a corner diffraction. The incidence angle for Q1 is measured from the Q1 surface and the incidence angle for Q2 is measure from the Q2 surface.

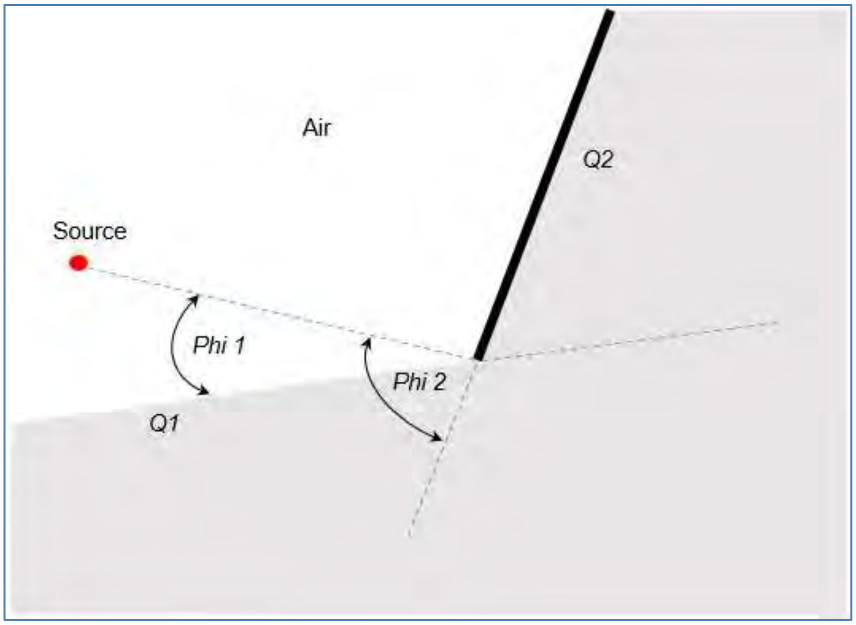

Figure 78 *Example Geometry for Corner Diffraction*

D.4.6 Ground Impedance Averaging

The Boulanger approach to ground-impedance averaging is then used for cases where: (1) more than one impedance discontinuity is present in the local geometry between source and receiver or highest path points; or (2) a single discontinuity has not been chosen to be computed explicitly (as it would if designated a near highest path point). Instead of computing the multiple diffraction paths explicitly, this approach computes a Fresnel ellipse about the reflection point on the ground and computes the area inside the ellipse represented by each type of ground. Then, an average reflection coefficient is computed from the reflection coefficient for each ground type weighted by the ratio of its area to the total area. The average reflection coefficient is used, and no diffraction terms are computed at all. However, the size of the ellipse is a function of frequency, so the average impedance and therefore the reflection coefficient will often change for each one-third octave band. **Figure 79** shows how the averaging applies at two different frequencies. At low frequencies, where the Fresnel ellipse is large, two discontinuities are encountered, and three different sections of ground are incorporated in the average; their areas are represented by A1 and A3, which are soft ground, and A2 in the center, which is hard ground. At such low frequencies, the reflection coefficient is based on an average of soft and hard ground. However, at high frequencies, where the ellipse is small, only hard ground is encompassed and the reflection coefficient is based on hard ground only.

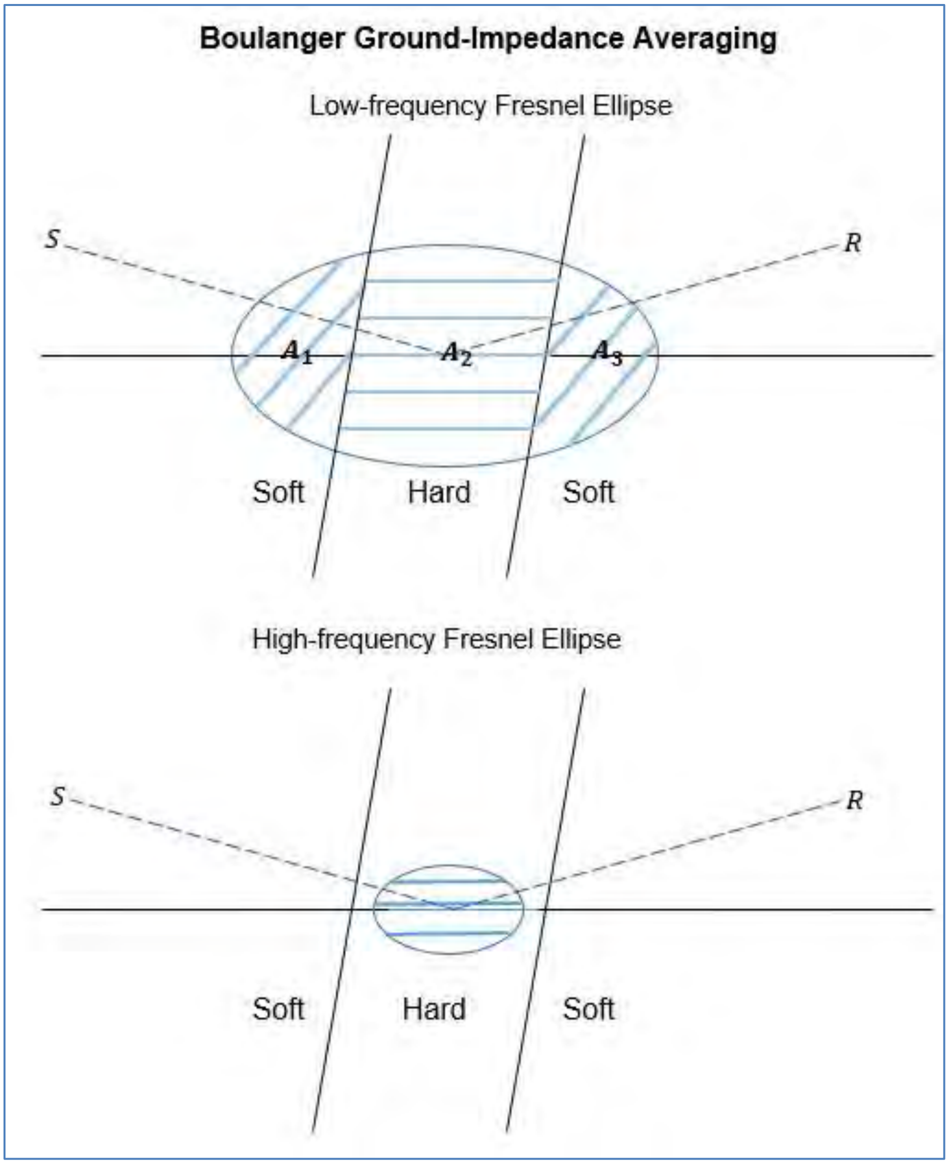

Figure 79 *Ground Impedance Evaluation at Two Frequencies*

D.4.7 TREE ZONES

TNM incorporates tree zones as an optional element in the propagation path. Tree zones have both ground height and top height, and, therefore, define ground points at their edges. The vertical geometry algorithms compute the distance the propagation paths travel through tree zones. For simplicity, the model calculates attenuation for the highest path only. This attenuation is then applied to all of the other paths, except a scale factor is applied based on the ratio of the lengths of the highest path to the other paths. TNM uses ISO 9613-2 standard attenuation for dense foliage (ISO, 1996), which is defined as "sufficiently dense to completely block the view along the propagation path; i.e., it is impossible to see a short distance through the foliage." The octave band attenuation as a function of distance through foliage is given in ***TABLE 15***. In TNM, the octave-band values shown in ***TABLE 15*** are applied to each of the one-third octave bands within the associated octave band.

TABLE 15: ATTENUATION THROUGH DENSE FOLIAGE

Octave Band Center Frequency (Hz)	63	125	250	500	1K	2K	4K	8K
Attenuation (dB, total) for d_f < 10 meters	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Attenuation (dB, total) for d_f between 10m and 20m	0.00	0.00	1.00	1.00	1.00	1.00	2.00	3.00
Attenuation (dB per meter) for d_f between 20m and 200m	0.02	0.03	0.04	0.05	0.06	0.08	0.09	0.12
Maximum attenuation (dB) for $d_f \geq$ 200m	4	6	8	10	12	16	18	24

D.4.8 ROWS OF BUILDINGS

In the initial identification of rows of buildings, the two highest-path points on either side of the group of building rows are identified. Often, these two points are source and receiver, but a barrier or ground line may interrupt the source-receiver path and will be substituted as “effective” source or receiver points. Next, all building rows that interrupt the effective source-receiver path are identified. Rows that do not interrupt the propagation path are ignored. For each row (independently) that interrupts the path, the row attenuation is computed based on the German rail industry equation:

$$Atten_{row} = MAX\left(0\ , -10 \cdot \log_{10}\left(F_{Linear-Gap} + 10^{\frac{-IL_{Barrier}}{10}}\right)\right) \tag{84}$$

where $F_{Linear-Gap}$ is the gap fraction associated with the building row and ILBarrier is the insertion loss of the building row, as if it were a solid barrier. Users define “building percentage,” which is: $100 \cdot (1 - F_{Linear-Gap})$. The building-as-barrier attenuation, $IL_{Barrier}$, is computed with the geometry of the effective source and receiver and the building under evaluation alone. The attenuation is computed from the path length difference and Fresnel number at 630 Hz, the ISO attenuation equation for N>0, and a smooth-fitting form for N<0 that goes to 0 where N is approximately -0.25:

$$Il_{Barrier} = \begin{bmatrix} 10 \cdot \log_{10}(3 + 20N') & N' > 0 \\ 4.77 - 9.54\sqrt{|N'|} & N' \leq 0 \end{bmatrix} \tag{85}$$

The rows of buildings with the highest $Atten_{row}$ is selected as the "best row," and $Atten_{row}$ is computed as the appropriate attenuation for that row in each one-third octave band. Attenuation attributed to each remaining row of buildings that interrupts the propagation path is 1.5 dB in each one-third octave band. Maximum attenuation for any number of rows of buildings is a function of frequency, and matches the frequency dependence of barrier attenuation. The maximum has been set to 10 dB(A) based on a typical traffic noise spectrum. The maximum building-row attenuation by frequency is given in ***TABLE 16***.

TABLE 16: MAXIMUM ATTENUATION FOR ROWS OF BUILDINGS BY FREQUENCY

One-Third Octave Band Center Freq., Hz	Max. Atten. (dB)
50	5.30
63	5.43
80	5.59
100	5.77
125	5.99
160	6.28
200	6.59
250	6.94
315	7.37
400	7.86
500	8.38
630	8.98

One-Third Octave Band Center Freq., Hz	Max. Atten. (dB)
800	9.65
1000	10.33
1250	11.05
1600	11.89
2000	12.69
2500	13.52
3150	14.40
4000	15.33
5000	16.23
6300	17.17
8000	18.15
10000	19.08

Interactions with the ground are not affected by the presence of rows of buildings.

D.4.9 ATMOSPHERIC ABSORPTION

The ISO 9613-1 standard (ISO, 1993) is used to compute atmospheric absorption for TNM. The user is allowed to specify temperature and relative humidity, but not atmospheric pressure. Standard atmospheric pressure of one atmosphere at sea level is used as the reference pressure (101.325 kPa, 760 mm or 29.92 in. of Hg). The following equations are taken from the ISO standard, with the atmospheric pressure variable set to the above constant value.

The atmospheric absorption coefficient, A_{atm}, in decibels per meter, is given by:

$$A_{atm} = 8.686f^2\left[\left(1.84\times10^{-11}\sqrt{\frac{T}{T_0}}\right)+\frac{\left(\frac{T}{T_0}\right)^{5/2}\left(0.01275e^{-2239.1/T}\right)}{\left(f_{ro}+\frac{f^2}{f_{ro}}\right)}+\frac{\left(0.1068e^{-3352.0/T}\right)}{\left(f_{rN}+\frac{f^2}{f_{rN}}\right)}\right] \quad (86)$$

where T_0 is defined as 293.15 Kelvin (20° C), the reference air temperature, T is the ambient air temperature in Kelvin, h is the molar concentration of water vapor, in percent, and f is the frequency of sound, in this case the nominal one-third octave band center frequency, in Hz.

The oxygen relaxation frequency, f_{r0}, in Hz, is defined as:

$$f_{rO} = 24 + 4.04 \cdot 10^4 h \left(\frac{0.02 + h}{0.391 + h} \right) \tag{87}$$

and the nitrogen relaxation frequency, f_{rN}, in Hz, is defined as:

$$f_{rN} = \sqrt{\frac{T_0}{T}} \left(9 + 280 h e^{-4.170\left(\left(\frac{T_0}{T}\right)^{\frac{1}{3}} - 1\right)} \right) \tag{88}$$

The following equations are used to convert the units of the input temperature and humidity values to those required for the above equations.

For temperature:

$$T_{Celcius} = \frac{5}{9} T_{Fahrenheit} - 32 \tag{89}$$

$$T_{Kelvin} = T_{Celcius} + 273.15 \tag{90}$$

For humidity:

$$h = h_r \frac{p_{sat}}{p_{so}} \tag{91}$$

where h_r is the relative humidity in percent (user input), p_{sat} is the saturation vapor pressure, and p_{so} is the standard reference pressure of 101.325 kPa.

Also,

$$\frac{p_{sat}}{p_{so}} = 10^C \tag{92}$$

where

$$C = -6.8346(T_{01}/T\,)^{1.261} + 4.6151 \tag{93}$$

In this last equation, T_{01} equals 273.16 K, the triple-point isotherm temperature.

While these equations are relatively complex, the attenuation per meter is only computed once for each one-third octave band, since the user can specify the temperature and humidity only once per study problem. The default temperature is 20° Celsius (68° Fahrenheit, 293.15 Kelvin) and the default humidity is 50-percent relative humidity (RH).

Atmospheric attenuation per meter at 20° C (68° F), 50- percent RH and one atmosphere (the default conditions), as a function of one-third octave band center frequency, are given in ***TABLE 17***.

TABLE 17: ATMOSPHERIC ABSORPTION BY FREQUENCY FOR DEFAULT ATMOSPHERIC CONDITIONS

One-Third Octave Band Center Freq., Hz	Atten. (dB/m)
50	7.81E-05
63	1.22E-04
80	1.94E-04
100	2.94E-04
125	4.40E-04
160	6.71E-04
200	9.54E-04
250	1.31E-03
315	1.74E-03
400	2.24E-03
500	2.73E-03
630	3.27E-03

One-Third Octave Band Center Freq., Hz	Atten. (dB/m)
800	3.91E-03
1000	4.66E-03
1250	5.71E-03
1600	7.45E-03
2000	9.89E-03
2500	1.36E-02
3150	1.97E-02
4000	2.97E-02
5000	4.42E-02
6300	6.76E-02
8000	1.05E-01
10000	1.59E-01

D.4.10 FOSS SELECTION ALGORITHM

As described above in various sections, the vertical geometry algorithms simplify geometries to contain at most two obstructions to reduce the amount of time required to calculate the attenuation. When the number of obstructions received by the vertical geometry is greater than two, all pairs of obstructions are evaluated for their approximate effective attenuation using the Foss double-barrier algorithm (Foss, 1976). The pair of obstructions with the highest computed attenuation are selected for use. These two obstructions are then used to calculate the attenuation for the vertical geometry based on using the full De Jong model. In the case of two or more pairs having the same attenuation, the first pair in the list is used. This algorithm assumes that any barriers beyond the first two would provide negligible additional attenuation.

Potentially, this algorithm is used twice in the calculation process. The first is to reduce the number of perturbable obstructions (barriers or berms) to two if more than two are present. The TNM can only handle attenuations from up to two perturbable obstructions in its tables for a given vertical geometry. In this pass, only the perturbable obstructions are considered, and the test is performed using the user's “input” heights. Perturbable obstructions not selected are completely removed from the calculation process for this vertical geometry only (subsequent vertical geometries may select a different obstruction pair given the same set of barriers to choose from). The second possible occasion the Foss algorithm is used, is to reduce the number of obstructions from the current vertical geometry before calculating the attenuation. This evaluation is performed for every perturbation combination for the perturbable obstructions that are retained. In this pass all obstructions are considered (except perturbable obstructions removed in the first pass described above). The Foss algorithm is used to select the best pair of obstructions, and all others are completely removed from the geometry. The De Jong model is then applied to this geometry. The results are stored in the results matrix in the location designated for this perturbation of the selected perturbable objects.

A brief description of the Foss double-barrier attenuation model follows. **Figure 80** shows the parameters of the double-barrier calculations.

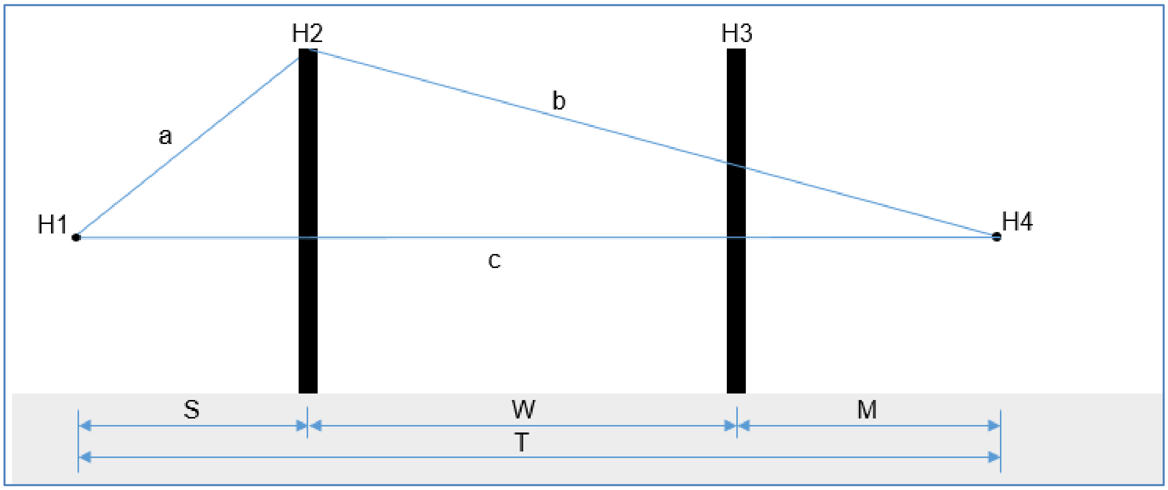

Figure 80 *Foss Double-Barrier Geometry*

The effective attenuation is calculated using the following equation:

$$IL_{eff} = F + J - \left[6e^{-\frac{2W}{T}} + 1.3\left(e^{-\frac{35W}{T}} - 1\right)\right]\left(1 - e^{-\frac{J}{2}}\right) \tag{94}$$

A detailed explanation of this equation can be found in (Foss, 1976); it is outlined here. W, the width between the barriers, and T, the total distance, are shown in **Figure 80**. The attenuation is calculated for each barrier alone, ignoring the other, using an approach similar to that used in STAMINA (Barry & Regan, 1978). The higher of the two attenuations equals F, and its associated barrier is designated as the “best” barrier. Then, depending on which is closer, either the source or the receiver is moved to the top of the best barrier. A modified barrier geometry is then drawn from the top of the best barrier over the other barrier to actual source or receiver. The attenuation for this modified geometry is J.

D.4.11 Total Sound Pressure

The total sound pressure for a given vertical geometry is calculated by summing over all the propagation paths for that geometry. The following equation shows the sound pressure calculation for a vertical geometry with N propagation paths:

$$P_{Total} = \sum_{i=1}^{N} P_{path_i} \tag{95}$$

D.4.12 Attenuation

The final attenuation for a vertical geometry, A_s, is calculated in reference to the free-field sound pressure as:

$$A_s = 20 \cdot \log_{10}\left|\frac{P_{Total}}{P_{free-field}}\right| \tag{96}$$

for each leg of the elemental triangle. The attenuation fraction, needed by the horizontal geometry, is defined as $\phi_S = 10^{A_s/10}$ - computed for both legs of the triangle: ϕ_{SL}, ϕ_{SR}. Then the average over the triangle is computed as $\phi_{SAvg} = \frac{1}{2}(\phi_{SL} + \phi_{SR})$. This is equivalent to $\phi_{h,f,barrs}$ in Equation 54 in Appendix C, Section C.2.4.

APPENDIX E: PARALLEL BARRIERS

This appendix supplements discussions in Section 5.2 and is largely a reproduction of the portions of Appendix E of (Anderson, et al., 1998), modified only to reflect changes between TNM 1.0 and TNM 3.0 and to avoid repetition of some materials already presented in the main body. Note, for ease of reference, some information originally presented in the main body is still repeated here.

When a roadway is flanked by parallel reflective barriers, retaining walls, or a combination of the two, sound reflects back and forth across the roadway many times before ultimately progressing outwards towards nearby receivers. These multiple reflections increase the sound level at nearby receivers, so that a receiver's intervening barrier or retaining wall provides less attenuation than otherwise. The increase in sound level due to multiple reflections from parallel barriers or retaining walls is called parallel-barrier degradation.

TNM 3.0 computes parallel-barrier degradation from cross-sectional (two-dimensional) geometries inferred[11] from user entered objects in the model. Once computed, the user must enter appropriate adjustment factors for receivers, to account for multiple reflections.

This appendix:

- Overviews the computation of parallel-barrier degradation
- Describes all required input for the computations
- Describes the parallel-barrier ray tracing procedure
- Provides equations for ray acoustic energies, both at the source and as the rays propagate
- Describes the computation of parallel-barrier degradation
- Mentions that the user must generalize these parallel-barrier degradations to TNM's regular sound-level receivers.

E.1 OVERVIEW

Sometimes highway projects contain cross sections where the highway is depressed below grade and thereby flanked by vertical retaining walls. **Figure 81** shows a typical depressed section in a highly urbanized area. In addition to the cross-sectional geometry, the figure also shows: (1) the center lines of each roadway, including a ramp that is descending into the depressed section; and (2) adjacent residential buildings.

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[11] TNM 3.1's GUI does not provide a mechanism for explicitly defining the cross-sectional geometry. Because of this, complicated cross-sectional geometries cannot be computed when using the parallel barrier analysis in TNM 3.1. If a user needs to enter a complex cross-sectional geometry, this can be done in TNM 2.5, which uses the same parallel acoustics algorithms. The adjustment determined by TNM 2.5 can then be applied in TNM 3.1. For completeness and future compatibility, algorithms described here address the case were a complex cross-sectional geometry may be encountered.

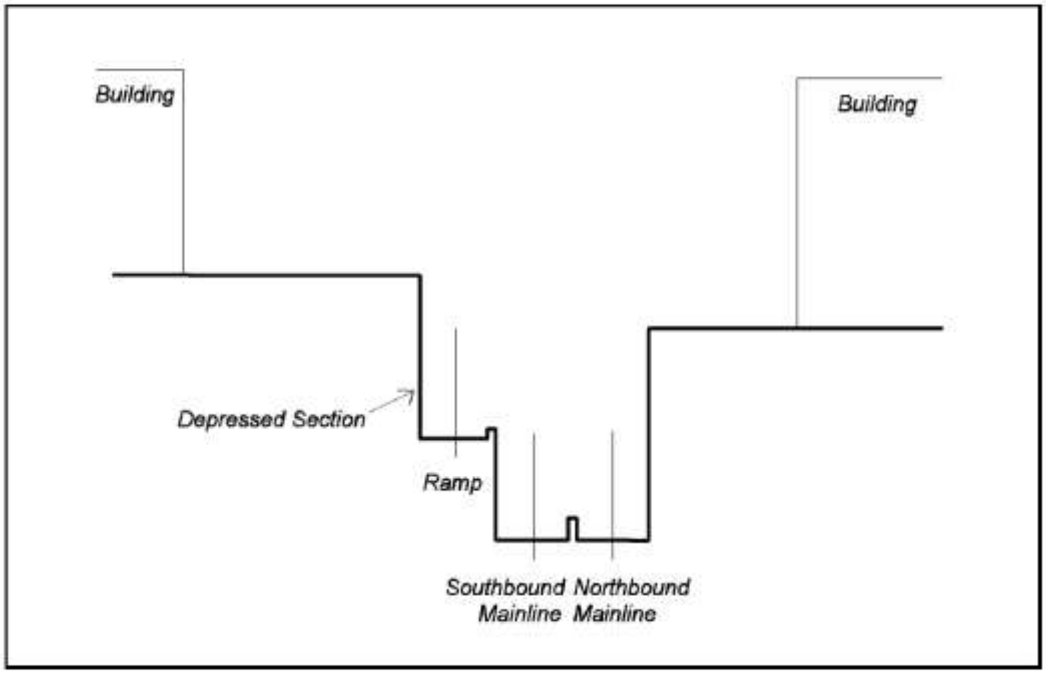

Figure 81 *Typical Depressed Section in a Highly Urbanized Area*

At other times, highway projects contain cross sections where the highway is flanked by vertical reflective noise barriers, one on each side. Other cross sections sometimes contain a combination of vertical reflective barriers and vertical reflective retaining walls.

Two things change acoustically when a roadway is flanked in these ways by parallel reflective barriers or retaining walls. First, direct lines-of-sight between receivers and traffic are interrupted by the intervening barrier or retaining wall — the one on the receiver's side of the roadway. When this happens, some receivers no longer have direct view of some traffic-noise sources. The intervening barrier or retaining wall reduces noise levels at receivers with reduced views of the traffic.

Second, the parallel barriers or retaining walls cause multiple reflections of the noise, from side to side across the roadway. The resulting reverberation tends to increase noise levels at nearby receivers. This noise increase due to reverberation may partially offset the noise reduction due to interruption in the lines-of-sight. As a result, the intervening barrier or retaining wall does not provide as much noise reduction as it would without the reverberation — that is, without the presence of the barrier or retaining wall on the opposite side of the roadway.

TNM's regular sound-level computations can predict the sound-level reduction due to an intervening barrier or retaining wall. However, TNM's regular sound-level computations cannot take multiple reflections into account. For this reason, they cannot predict the "reverberation" effect — that is, the parallel-barrier degradation — due to parallel barriers or retaining walls.

Separate from its regular sound-level computations, TNM can predict parallel-barrier degradation in two dimensions, as described in the remainder of this appendix (Menge C. W., 1991). Once computed, the user must then generalize these parallel-barrier degradations for all actual TNM receivers and then must enter appropriate adjustment factors for these receivers, to account for multiple reflections.

E.2 Overview of Parallel-barrier Computations

TNM begins its computation of parallel-barrier degradation by tracing individual acoustic rays outward from each traffic noise sub-source. Some rays come close enough to receivers or diffraction edges to contribute their portion of sound energy. Others do not come close enough and are lost to the sky. In TNM, “close enough” means within 0.3 meters (1 foot).

To compute parallel-barrier degradation, TNM first computes ray energies twice:

- **Multiple reflections:** Each ray is reflected according to NRCs input by the user.
- **No multiple reflections:** The same as for multiple reflections, except for the following. When a ray reflects from one of the flanking barriers or retaining walls, its energy is completely absorbed, as if the barrier or wall was not there. In this manner, rays that reach the diffracting edge after barrier reflections are reduced in strength to zero, and thereby eliminated. As a result, all reverberantly reflected rays are eliminated. Only those rays remain that reach the diffracting edge either directly from the source or after reflection from the pavement or other non-barrier surfaces.

TNM’s parallel-barrier computations[12] allow complete flexibility in: (1) cross-sectional geometry; (2) the location of roadways between the parallel barriers or retaining walls; and (3) the location of adjacent receivers. The resulting parallel-barrier degradation is a function of: (1) traffic on each roadway; (2) the location of the roadways; (3) the detailed location, orientation, and NRC of each reflecting surface; (4) the location of the diffracting edges at each side of the cross section; and (5) the location of each receiver.

E.3 Required Input

Figure 82 shows an example of input for TNM parallel-barrier computations, embedded in an HZ coordinate system, where H means “horizontal.” (The rays in this figure are discussed later.) Parallel-barrier input consists of three items: roadways, a cross-section (including NRC values), and receivers.

[12] *The TNM 3.1 GUI allows for the computation of cross-sectional geometries based on the roadway, barrier and receiver geometries that are include in the “cut” in the plan view of TNM 3.1. More complex geometries can be defined in TNM 2.5.*

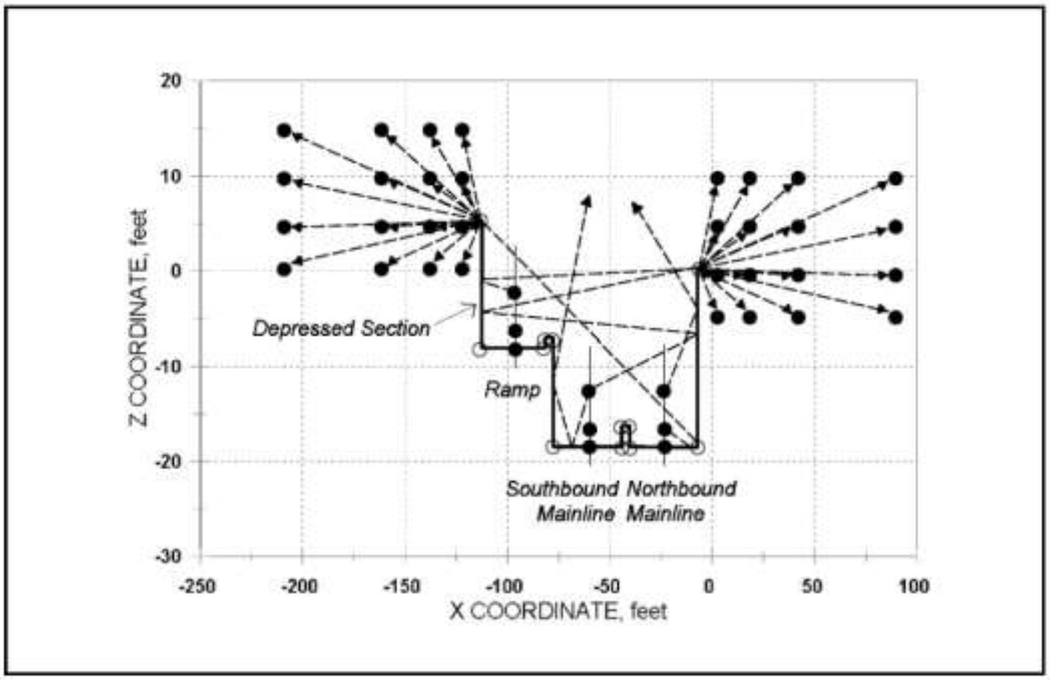

Figure 82 *Detailed Input and Representative Rays*

E.3.1 Roadway Input

Each traffic stream appears in the figure as a separate roadway, represented by three sub-source dots and a vertical line connecting them. These sub-source dots correspond to TNM's built-in sub-source heights: zero; 1.5 meters (5 feet); and 3.66 meters (12 feet). The user needs to enter only the H position of each roadway, which is done in the plan view in TNM 3.1. TNM computes all the Z coordinates, including the intersection with the roadway.

In addition to location, roadway input includes traffic speed and hourly traffic volume for each vehicle type. TNM needs this traffic input to predict the effect of reverberation, because reverberation depends upon the relative sound energy from each roadway and each roadway's three sub-sources. TNM also obtains these data from the roadway entered by the user in the plan view.

For example, if heavy trucks dominate the noise level at a certain receiver, reverberation may not affect that receiver's noise level significantly, because it may still have direct line-of-sight to the truck exhaust stacks. The same might be true if ramp traffic dominates the noise level at some receivers. On the other hand, if the dominant source of traffic noise for a receiver is significantly shielded by the intervening barrier or retaining wall, then the effect due to reverberation might be larger.

E.3.2 Cross-Section Input

Cross-section input appears in **Figure 82** as a single, thick connected line, from one diffracting edge to the opposite one. The cross-section is inferred by TNM from the objects in the plan view. The user also enters an NRC for each surface element. Typical NRCs might be 0.0 (or perhaps 0.05, which will have essentially the same result) for pavement, vertical retaining walls, and reflective noise barriers; 0.6 for sloped, grassed areas within the cross section; and 0.60 to 0.95 for absorptive noise barriers or for special absorptive material applied to retaining walls.

The computations assume that this cross-sectional geometry continues unchanged up and down the roadway, in both directions. For this reason, if the cross-section changes rapidly along the roadway, the user must: (1) use TNM's parallel-barrier analysis several times, with varying cross-sectional geometry; and then (2) combine the separate results for each receiver, weighting most heavily the results for the roadway geometry directly adjacent to the receiver location.

E.3.3 Receiver Input

Receiver input consists of each receiver's HZ coordinates. These too are inferred by TNM 3.1 from the objects in the plan view. Note that parallel-barrier receivers are called "analysis locations" within TNM, to distinguish them from TNM's receivers for sound-level computations. Within this appendix, however, they are called "receivers," for simplicity.

E.4 Ray Tracing

TNM generates 10,000 rays outward from each roadway sub-source (three per roadway). TNM spaces these 10,000 rays equally in direction around the sub-source, with a randomized initial direction. TNM then traces each ray outward from the source and reflects if from the surface segments it hits. Several rays appear in **Figure 82**.

Reflection is purely "specular" as from a mirror, without scattering. TNM remembers the surface segment for each reflection, so it can later reduce that ray's acoustic energy according to the surface's NRC. In addition, TNM remembers the total length of each ray as it progresses outward.

If a ray approaches within 0.3 meters (1 foot) of a receiver, the ray contributes to the receiver's sound level. In addition, if a ray approaches within 0.3 meters (1 foot) of a diffracting edge, the ray is diffracted to receivers on that side of the roadway. Rays that come within 0.3 meters (1 foot) of receivers or diffracting edges are called "successful" rays. Rays that "miss" receivers and diffracting edges escape to the sky and are forgotten by TNM.

E.5 Ray Acoustic Energies

Each ray starts out with acoustic energy proportional to the strength of its source. It then is reduced in energy as it either reflects from a surface or diffracts over a barrier top towards receivers.

E.5.1 Initial Ray Energy

Computations of initial ray energy first proceed separately for each vehicle type on the parallel-barrier roadway, and then are combined into the three required sources: bottom, middle and top. These computations use several of the same equations that are used for TNM's regular sound-level calculations.

From the user's parallel-barrier input, TNM determines the vehicle type, i, and the pavement type, p. Then from these values of i and p, TNM combines its emission-level regression coefficients (*A, B, C, L, M, N, P* and *Q*) with the vehicle speed, s_i , for that vehicle type, to compute

$$E_{Aemis,i}(s_i) = (0.6214 s_i)^{A/10} \cdot 10^{B/10} + 10^{C/10} \tag{97}$$

and

$$r_i(500\ Hz) = L + (\ 1 - L - M\ )\left[1 + e^{N\cdot\log_{10}(500)+P}\right]$$
$$= L + (1 - L - M)\left[1 + e^{(2.7N+P)}\right]^Q \tag{98}$$

where speed, s, is in kilometers per hour. Note that TNM assumes cruise throttle for all vehicles, because the difference in effective source height between cruise and full-throttle vehicles is not sufficiently large to affect these computations. Also note that parallel-barrier degradation is computed at a frequency of 500 Hz, as an approximation to the degradation for the full A-weighted sound level.

Next TNM computes

$$E_{Aemis,i,upper,ff}(\ s_i\ ) = \left(\frac{r_i}{r_i + 1}\right) E_{Aemis,i} \tag{99}$$

$$E_{Aemis,i,lower,ff}(\ s_i\ ) = \left(\frac{1}{r_i + 1}\right) E_{Aemis,i} \tag{100}$$

Then it computes

$$E_{eq,upper} = 0.0476\left(\frac{v_i}{s_i}\right) E_{Aemis,i,upper,ff}$$

$$E_{eq,lower} = 0.0476\left(\frac{v_i}{s_i}\right) E_{Aemis,i,lower,ff} \tag{101}$$

where v_i is the parallel-barrier traffic volume and s_i is the traffic speed, in kilometers per hour, for this vehicle type, i. Finally, TNM combines results for all vehicle types into the three required source reference noise levels (abbreviated here as $E_{eq,ref}$), as follows:

$$E_{eq,ref,0\ meters\ (0\ feet)} = \sum_{\substack{i=all\ vehicle\\ types}} \left(E_{eq,lower,i}\right) \tag{102}$$

$$E_{eq,ref,1.5\ meters\ (5\ feet)} = \sum_{\substack{i=all\ vehicle\\ types\ except\\ heavy\ trucks}} \left(\ E_{eq,upper,i}\ \right) \tag{103}$$

$$E_{eq,ref,3.6\ meters\ (12\ feet)} = E_{eq,upper,i=heavy\ trucks} \tag{104}$$

In this manner, each TNM parallel-barrier roadway becomes three sub-sources: the first at a Z coordinate of TNM's parallel-barrier roadway Z coordinate, the second 1.5 meters (5 feet) above this Z coordinate, and the third 3.66 meters (12 feet) above it. All three of these sub-sources have the same H coordinate.

Note that each ray carries this initial energy with it, rather than only 1/10,000th of the energy. The resulting parallel-barrier degradation is not affected, because it is a relative measure of sound level (with and without the reverberation).

E.5.2 Reduction in Ray Energy as the Ray Propagates Outward

As each ray progresses outward, its relative energy is affected by the following acoustical mechanisms:

- Divergence
- Ground attenuation
- Reflection
- Barrier attenuation

This section describes each of these effects upon ray energy. Note that TNM's parallel-barrier computations ignore any affects due to wind or temperature gradients, consistent with TNM's full sound-level computations.

Divergence: Sound level drops off from a line source by 3 decibels per distance doubling. Correspondingly, sound energy is reduced by half for each distance doubling. Because TNM's ray tracing is two dimensional, this divergence is completely accounted for by the diverging rays themselves. For example, if the source-receiver distance is doubled, then only half as many rays will "hit" the receiver. As a result, no additional computations are needed to account for divergence. Line-source divergence is automatic with two-dimensional ray tracing.

Ground attenuation: TNM accounts for ground by explicitly incorporating an additional divergence of 1.5 decibels per distance doubling into the parallel-barrier computations. To incorporate this additional divergence, TNM divides each ray's energy by 1.414 for every doubling of distance, starting at 8.84 meters (29 feet) from the roadway.

Reflection, NRC: Two parameters influence ray reflection: the surface's NRC and the proximity of the reflection point to a diffraction edge.

To account for the surface's NRC upon reflection, TNM multiplies the ray's energy by the NRC, which is always less than 1.0. In this manner, energy is absorbed out of the ray by the material of the reflecting surface. This occurs for all reflecting surfaces: roadway, grassed slopes, retaining walls, barriers, and so forth. Even though TNM's parallel barrier degradation is computed at 500 Hz, sound energy, as a result of surface reflections, is reduced according to the composite NRC of the surface, not the absorption coefficient at 500 Hz.

Reflection near a barrier top: When a sound wave reflects near the top of a barrier, the lower portion of the wave front strikes the barrier and is reflected, while the upper portion misses it and is therefore not reflected. Instead, this upper portion diffracts over the barrier top to its other side. TNM combines this partial reflection of wave fronts with ray tracing, as shown in **Figure 83**.

The top portion of the figure shows a traced ray that reflects near the barrier top. Shown to the left is the actual reflection. Shown to the right is TNM's method of computing the reduction in energy due to the barrier top's proximity. First the source is replaced by its image behind the barrier. Then the barrier is flipped on its head, thereby coming down from the sky to the same barrier-top position. The resulting geometry yields an image source in direct view of the receiver, plus a diffraction from the flipped barrier top. This diffraction combines with the direct path, to reduce its intensity according to TNM's regular sound-level algorithm for barriers. When the ray just grazes the barrier top, then the combined effect of the direct and diffracted rays is 6 decibels less than the direct ray alone. Half the (coherent) energy is lost upon reflection, because only half the wave front reflects.

The bottom portion of **Figure 83** shows the comparable situation, but where the reflection just misses the barrier top. To the left is the actual reflection. Even though the ray does not look as if it reflects, TNM must reflect it from a “phantom” upward extension of the barrier, for sound-level continuity. Shown to the right are the image source and the flipped barrier. In this case, the direct line-of-sight between image source and receiver is interrupted by the flipped barrier. As a result, only the diffracted ray reaches the receiver, reduced by the flipped barrier’s attenuation. When the ray just barely misses the barrier top, then the diffracted rays contributes 6 decibels less than the direct ray alone would have contributed, had it reached the receiver. Relative to the direct ray, half the (coherent) energy is lost upon this phantom reflection, because only half the wave front reflects.

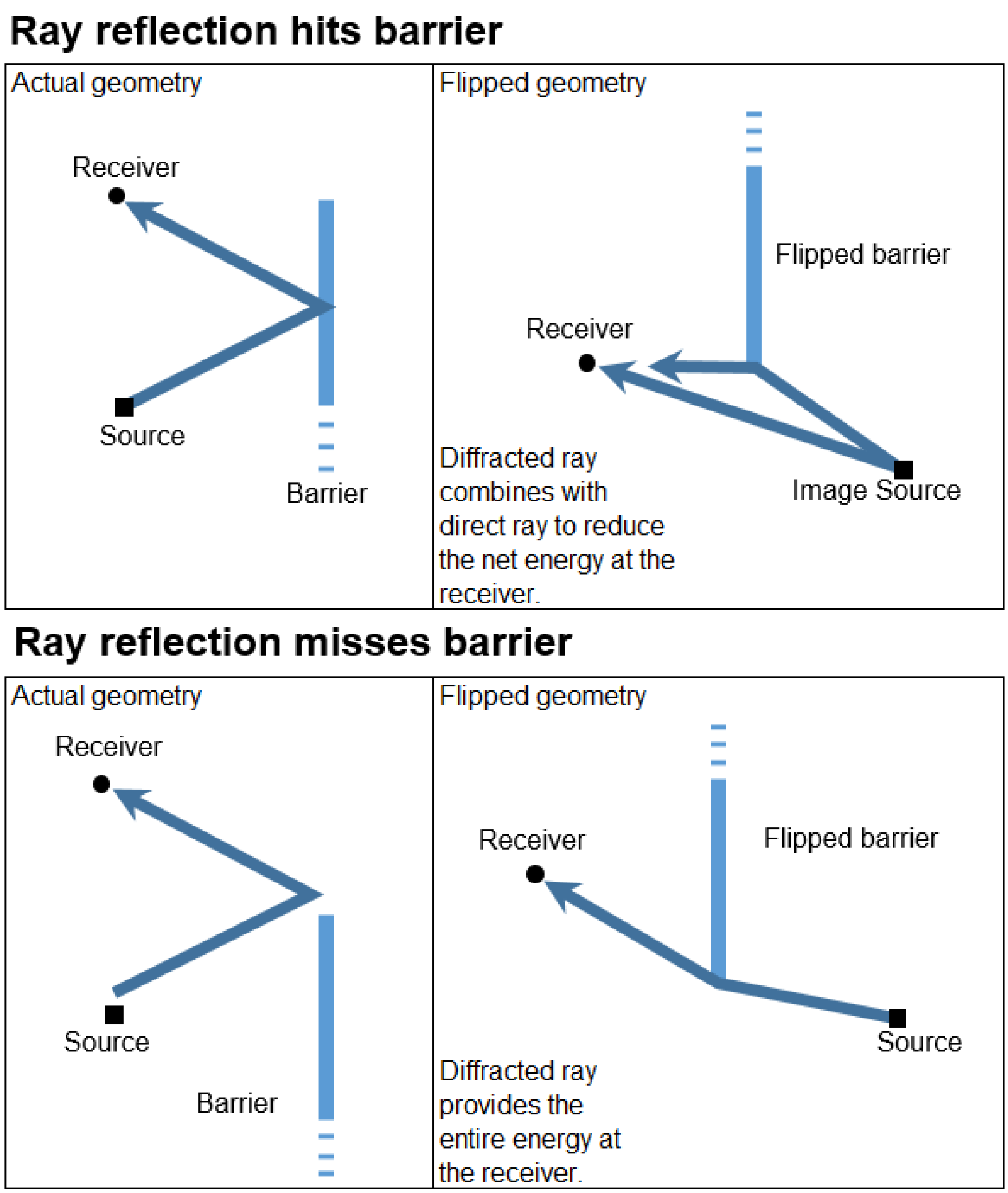

Figure 83 *Partial Reflection near tops of Parallel Barriers*

Barrier attenuation: Upon diffraction over the top edge of a barrier or retaining wall, TNM multiplies the ray's energy by $10^{(-A/10)}$, where the barrier attenuation, A, is computed with TNM's line-source barrier equation. In addition, TNM adds additional divergence to account for the increased distance between the ray target (diffraction edge) and the receiver.

Combination of barrier and ground attenuation: TNM retains the larger of these two attenuations and ignores the other.

E.6 Computation of Parallel-barrier Degradation

To compute parallel-barrier degradation, TNM first computes ray energies twice:

- Multiple reflections: Each ray is reflected according to NRCs input by the user.
- No multiple reflections: The same as for multiple reflections, except for the following. When a ray reflects from one of the flanking barriers or retaining walls, its energy is completely absorbed, as if the barrier or wall was not there. In this manner, rays that reach the diffracting edge after barrier reflections are reduced in strength to zero, and thereby eliminated. As a result, all reverberantly reflected rays are eliminated. Only those rays remain that reach the diffracting edge either directly from the source or after reflection from the pavement or other non-barrier surfaces.

  To compute for no multiple reflections, TNM must determine which of the user's surfaces are flanking barriers and retaining walls. Most obviously, the leftmost and the right-most surface segments must be these flanking ones. In addition, TNM assumes that additional surface segments contiguous with these two are also part of the flanking barriers/walls, as long as the contiguous ones are collinear with the left-most and right-most segments.

After these two computations, TNM converts the resulting energies to sound levels. For each receiver, the difference in noise level between these two computations (multiple reflections and no multiple reflections) is the direct effect of multiple reflections — that is, of reverberation between the parallel retaining walls and/or barriers. This effect is called parallel-barrier degradation. For example, if this parallel-barrier degradation is 4 decibels, then the reverberation from the opposite wall/barrier has increased the noise level by 4 decibels, relative to the situation without multiple reflections.

E.7 Generalization to TNM Sound-level Receivers

TNM computes parallel-barrier degradation for two-dimensional cross-sectional geometries. Once computed, the user must generalize these degradations for the actual TNM receivers and then enter appropriate adjustment factors for these receivers, to account for multiple reflections.

E.8 Calibration of Results with Field Measurements

The algorithm described above overestimates parallel-barrier degradation in some instances, compared to field measurements. For this reason, TNM results are calibrated to field measurements before reported to the user.

E.8.1 Initial comparisons of measured and predicted degradations

Three sets of measured field data were used to calibrate TNM's parallel-barrier degradation:

- Route 99 in California (Hendricks, 1991): w/h ratio = 15:1
- I-495 in Montgomery County, Maryland (Fleming & Rickley, 1992): w/h ratio = 9:1
- Dulles Airport experimental barrier (Fleming & Rickley, Parallel Barrier EffectivenessL Dulles Noise Barrier Project, 1990): w/h ratio = 6:1

These measurement sets are summarized in (Fleming & Rickley, 1994). In this list of measurement sets, w/h is the width-to-height ratio of the measurement site's cross section; width, w, is the total distance between the parallel barriers; and height, h, is the average of the two barrier heights relative to the roadway elevation. ***Table 18*** summarizes the initial comparison of field measurements and TNM computations, before calibration.

Table 18: Parallel Barrier Degradations: Initial Comparison of Measured and Computed Values

Data set	Width/ Height ratio (w/h)	Parallel-Barrier Degradations					
		Measured, dB		Computed, dB		Over Prediction (computed minus measured), dB	
		Range	Avg	Range	Avg	Range	Avg
Route 99, California	15:1	0.1 to 1.4	0.9	0.8 to 3.9	2.6	+0.1 to +3.0	+1.7
I-495, Montgomery County MD	9:1	0.6 to 2.8	2.0	1.0 to 4.7	3.0	+0.2 to +1.9	+1.0
Dulles Airport	6:1	-0.6 to 5.8	1.7	0.1 to 4.9	2.0	-4.8 to +2.7	+0.3

All comparisons in this table involve nine microphone positions: three distances, three heights each. Measurements on Route 99 and I-495 involve many hundreds of vehicles, as they passed by. Dulles measurements involve controlled passbys of four heavy trucks.

As the table shows, over prediction is significant for w/h ratios around 15:1, but not significant for smaller w/h ratios around 6:1. Although the table does not show it, over prediction also varied systematically with microphone height and distance from the roadway.

E.8.2 Sensitivity to assumed source height

Parallel-barrier degradation computed by TNM is very sensitive to TNM's built-in vertical sub-source heights and built-in vertical energy splits (see Appendix B). For example, degradation was initially computed for five different source heights, as shown in ***Table 19***, using Route-99 traffic and roadway geometry.

TABLE 19: SENSITIVITY OF COMPUTED DEGRADATIONS TO ASSUMED SOURCE HEIGHT

Assumed source height	Computed parallel barrier degradation, dB	
	Range	Average
0.03 meters (0.1 feet)	1.0 to 5.7	3.4
0.7 meters (2.3 feet)	0.7 to 4.7	2.7
2.44 meters (8 feet)	0.6 to 2.6	1.6
3.05 meters (10 feet)	0.6 to 2.4	1.1
3.66 meters (12 feet)	0.2 to 0.6	0.4
For comparison, vehicle emissions split per Stamina- 2.0 heights: 0 meters (0 feet) for automobiles 0.7 meters (2.3 feet) for medium trucks 2.44 meters (8 feet) for heavy trucks	0.8 to 4.0	2.6

These sensitivity results show clearly that computed TNM degradation depends critically upon the specific sub-source heights used for computation, and in turn upon the sub-source height energy split for any pair of sub-source heights.

E.8.3 CALIBRATION METHOD

For adequate accuracy, TNM parallel-barrier computations obviously need to be calibrated against measurements. Over prediction of degradation is too large without such calibration. The following method was used to determine a calibration method for TNM's parallel-barrier computations:

- Parallel-barrier computations: First, the three parallel-barrier measurement sites were entered as TNM parallel-barrier input. For this input, cross-sectional shape within the roadway section was carefully matched and field-measurement traffic volumes and speeds were used. Then for each of these three sites, parallel-barrier degradation was computed at each site's nine microphone locations.
- Comparison and regressions: For all three sites combined, each microphone's measured and computed degradation ($g_{meas,mic}$ and $g_{comp,mic}$, respectively) were tabulated along with their ratio, $R_{mic} = g_{meas,mic} / g_{comp,mic}$. Note that $R \cdot g_{comp} = g_{meas}$. For this reason, R_{mic} is a first cut at the required calibration multiplier.

Then R_{mic} was plotted and regressed against the following independent variables:

- The microphone cross-section's w/h ratio, $r_{w/h,mic}$, where

$$r_{w/h,mic} = \frac{\left(H_{diff,right} - H_{diff,left} \right)}{\left(\overline{Z_{diff}} - \overline{Z_{road}} \right)} \tag{105}$$

In this equation

$H_{diff,right}$ = the H coordinate of the right - end diffraction point

$H_{diff,left}$ = the H coordinate of the left - end diffraction point

Z_{diff} = the average Z coordinate of the two diffraction points

Z_{road} = the average Z coordinate of all the roadways (at the pavement).

- The microphone's horizontal distance from the near barrier, $d_{horiz,mic}$, where

$$d_{horiz,mic} = \left| H_{mic} - H_{diff,near} \right| \tag{106}$$

In this equation

H_{mic} = the H coordinate of the microphone (analysis location)

$H_{diff,near}$ = the H coordinate of the near diffracting edge.

- The microphone's height above the top barrier edges, $d_{vert,mic}$, where

$$d_{vert,mic} = Z_{mic} - \overline{Z_{barr\ tops}} \tag{107}$$

In this equation

Z_{mic} = the Z coordinate of the microphone (analysis location)

$Z_{barr\ tops}$ = the average Z coordinate of the tops of the two barriers.

E.8.4 Calibration Results

The regression produced the following adjustments to the computed output of TNM's parallel-barrier code:

$$\begin{aligned} g_{calibrated,mic} = (\ g_{computed,mic}\ )\left[1 + e^{(\ 4r_{w/h,mic} - 21.42\ )}\right]^{-0.019} + 0.072 \\ +0.04 d_{vert,mic} - 0.003 d_{horiz,mic} \end{aligned} \tag{108}$$

Subject to the constraint that

$$g_{calibrated,mic} \leq g_{computed,mic} \tag{109}$$

In these two equations, $g_{calibrated,mic}$ is the calibrated degradation at a given microphone and $g_{computed,mic}$ is the degradation computed directly by the parallel-barrier code. The three independent variables ($4r_{w/h,mic}$, $d_{horiz,mic}$, and $d_{vert,mic}$) are defined in Equations (105), (106) and (107), respectively.

Appendix F: Summary of Differences between TNM 2.5 and TNM 3.1

The Federal Highway Administration's (FHWA) Traffic Noise Model (TNM) is a software application for the modeling of noise related to highway traffic in areas adjacent to highways. TNM accounts for vehicle type and speed, road grade, terrain geometry and acoustic impedance, tree zones, building rows, barriers, and other factors affecting the propagation of sound. TNM 2.5 was the last major update, which was released in 2004. This version, provided bug fixes and optimizations to match measured data better but did not move the application towards modern standards of interface design or software maintenance. TNM 2.5 and all previous versions henceforth referred to collectively as legacy versions, no longer conform to norms of modern software maintenance and user interface design.

The legacy versions, were developed by using Borland C++ for the programming language, TGCAD for the graphics, and POET, an object-oriented database, for the data structure. At the time of the original development, this was the best approach to deal with limited hardware resources and utilized the then current state of the art in software development. Since this time, hardware capabilities and software development have improved dramatically. The use of Borland's development tools enforced an interface development approach that, although similar to modern interfaces, is antiquated and contains idiosyncrasies that can make the use difficult for the first-time user. The use of C++ as a software development language is becoming less common as managed code gains popularity. Managed code takes much of the burden off of the developer for dynamic memory allocation, creation, destruction, and cleaning of objects. This makes the software more robust and allows the developer to focus on functional improvements rather than basic housekeeping. TGCAD is obsolete and no longer supported by the original developer. Bugs found in TGCAD's libraries are difficult to repair and visualizations using TGCAD's wire frame format is antiquated compared to modern shaded/graded geometries. The POET database, which was used to optimize memory usage for case of unknown size, is no longer needed since modern computers can easily handle case memory requirements.

In addition to the obsolescence of these tools, the acoustics and GUI in legacy versions of TNM are intertwined. This adds complexity to maintaining the software. For example, replacing the GUI is not possible without also re-implementing the acoustics as well. It is even difficult to make small changes to the GUI without generating bugs in the acoustics and vice versa due to this lack of abstraction. If the acoustics and GUI were abstracted from one another, then one could more easily be modified or replaced without affecting the other. This would allow the GUI to be updated to be more consistent with the way modern interfaces work, to provide graphics that are easier to interpret, and to facilitate documentation of results. It would also make it easier to make improvements to the acoustic code, adding functionality, refining parameters, etc.

The development of TNM 3.0 was an effort to modernize the code development process, the GUI, and to provide new features and bug fixes to the acoustics. TNM 3.0 development thus included TNM 3.0 GUI development and TNM 3.0 Acoustics development. This document describes the updates made to TNM's acoustics, which are now present in TNM 3.1. The discussion is divided into sections that deal with changes to aspects of the acoustics code originally covered by the TNM Technical Manual for version 1.0 (Anderson, et al., 1998) and those that do not.

F.1 Updates to Aspects not covered by the TNM 1.0 Technical Manual

F.1.1 Core Language, Libraries, and Coding Tools

In order to provide a more manageable foundation for the acoustics, TNM 3.0 Acoustics were developed using C#. This provides a modern managed code platform. However, like C++, this language requires additional libraries to provide additional functionality. To meet these needs the following additional libraries were used: PowerCollections[13], GeoAPI[14], and C5[15]. The additional libraries provided new object classes as well as mathematical functions. Microsoft's Visual Studio 2010 with .NET 4.0[16] was used as the primary development environment.

F.1.2 Modeling

TNM 2.5 interpolates below 250 Hz and extrapolates above 5000 Hz. These are a legacy of the effort to speed computations on the slower computers that were available at the time of TNM's original development. This interpolation and extrapolation was removed in TNM 3.0 in favor of explicit computation of these regions.

In TNM 2.5, roadway widths are assigned to roadway segments. This limits the ability to generate tapered roadway segments, which may occur when two roads merge. Since TNM 3.0, roadway widths are assigned to both ends of a roadway segment independently, so the road segments can have a uniform or tapered width.

A Roadway hierarchy was developed for TNM 3.0 to remove the ambiguity of roadway acoustic impedance in situations where roadways overlap. The overlap precedence is as follows: mainline, ramp, shoulder. These are defined in the GUI but are supported and used by the acoustics.

Historically, control devices could only be applied to the beginning of a roadway. In order to have a roadway with, for example, a stop sign, the road needed to be broken into two roadways such that the stop sign was at the beginning of the second roadway. Since TNM 3.0, the acoustics accept control devices at any point on a road.

F.1.3 Bug Fixes

Indexing of interpolated/extrapolated bands

During the development of TNM 3.0 Acoustics, it was discovered that TNM 2.5 has a bug in its indexing of bands in the interpolation and extrapolation region. This bug was fixed in TNM 3.0. However, because TNM now computes these bands, the bug fix is moot. This indexing issue is mentioned here as it relates to computed differences between the two acoustic codes.

Impedance Averaging

Boulanger developed a method for averaging acoustics impedances and published his findings in the

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[13] *powercollections.codeplex.com*
[14] *code.google.com/p/nettopologysuite*
[15] *www.itu.dk/research/c5/*
[16] *www.microsoft.com*

Journal of the Acoustic Society of America (Boulanger, Waters-Fuller, Attenborough, & Li, 1997). An external source identified an issue with the equations in TNM 2.5's source code. Upon further review, it was determined that there were in fact two errors in Boulanger's equations as published. Both of these equations were implemented in TNM 2.5 as originally printed. There errors are as follows:

1. Equation 13 had a sign error in the third term of the square root. Equation 13 should read:

$$x_{1,2} = \pm b\sqrt{1 - \frac{(y_m \cos(\theta) - c)^2}{a^2} - \frac{y_m^2 \sin^2(\theta)}{b^2}}$$

2. Equation 15 had a sign error, the negative B/A should have been positive B/A. Equation 15 should read:

$$y_{1,2} = +\frac{B}{A} \pm \sqrt{\frac{1}{A} - \left(\frac{c\sin(\theta)}{Aab}\right)^2}$$

Both of these equations were updated in TNM 3.0 to include the correct signs. These differences can affect the elliptical region over which ground impedances are averaged. One situation where this could be significant is for regions where the source or receiver is on the boundary of two large areas with dissimilar acoustics impedances, for example a roadway with a field on one side and a parking lot on the other.

Highest Path Point Selection for Multiple Barriers

During the development of TNM 2.5 a bug was introduced when a variable was redefined in the code, but not correctly accounted for in the single barrier insertion loss evaluation. This is a bug that only occurs when TNM needs to determine which two barriers or barriers and building rows should be included in the HPPs (implying at least three HPPs). In TNM 2.5, some legitimate Fresnel numbers, which should cause a positive insertion loss to be returned, return essentially zero insertion loss. Thus a barrier in a barrier pair could be evaluated as ineffectual when in actuality it is effective. Thus, the bug can result in the selection of the "wrong" pair when the receiver is located along a line near the grazing angle. This can result in the selection of an unintended pair (although this could still be the best pair since the check is based only on the non- perturbed heights). The bug does not affect the actual computation for attenuation once the pair is selected. This bug was fixed in TNM 3.0.

F.1.4 Metrics

The traffic input dialog in the TNM 3 GUIs now allows for more information to be entered about traffic patterns for day/evening/night periods. Therefore, the L_{dn} and L_{den} computations have been updated in the acoustics to make use of the new data. The two different approaches, TNM 2.5 and TNM 3.0 are described below.

Day-Night Average Sound Level, L_{dn}

It should be noted that TNM 2.5's approach is itself a modification of TNM 1.0's approach. While TNM 1.0 divided traffic between day and night equally, TNM 2.5 divides traffic between hours equally.

TNM 2.5 Approach

Daytime hourly traffic is defined as:

$$VPH_{day} = ADT \times R_{day} \frac{\%Day}{100} \tag{110}$$

where VPH_{day} is the vehicles per hour during the daytime, *ADT* is the average daily traffic, R_{day} is the number of daytime hours (15) divided by the total number of hours (24), and *%Day* is the value input by the user in the Roadway input dialog for the given vehicle type.

Similarly, the nighttime hourly traffic is defined as:

$$VPH_{night} = ADT \times R_{night} \frac{\%Night}{100} \tag{111}$$

where VPH_{night} is the vehicles per hour during the nighttime, *ADT* is the average daily traffic, R_{night} is the number of nighttime hours (9) divided by the total number of hours (24), and *%Night* is the value input by the user in the Roadway input dialog for the given vehicle type.

TNM 3.0 Approach

Daytime hourly traffic is defined as:

$$VPH_{day} = ADT \times R_{day} \frac{\%ADT}{100} \cdot \frac{\%Day}{100} \tag{112}$$

where VPH_{day} is the vehicles per hour during the daytime, *ADT* is the average daily traffic, R_{day} is the number of daytime hours (15) divided by the total number of hours (24), %ADT apportions the fraction of ADT for the total daytime traffic, and *%Day* distributes the total daytime traffic *amongst* the vehicle types.

Similarly, the nighttime hourly traffic is defined as:

$$VPH_{night} = ADT \times R_{night} \frac{\%ADT}{100} \cdot \frac{\%Night}{100} \tag{113}$$

where VPH_{night} is the vehicles per hour during the daytime, *ADT* is the average daily traffic, R_{night} is the number of nighttime hours (9) divided by the total number of hours (24), %ADT apportions the fraction of ADT for the total nighttime traffic, and *%Night* distributes the total nighttime traffic *amongst* the vehicle types.

Day-Evening-Night Average Sound Level, L_{den}

TNM 2.5 Approach

Daytime hourly traffic is defined as:

$$VPH_{day} = ADT \times R_{day} \frac{\%Day}{100} \tag{114}$$

where VPH_{day} is the vehicles per hour during the daytime, *ADT* is the average daily traffic, R_{day} is the number of daytime hours (12) divided by the total number of hours (24), and *%Day* is the value input by the user in the Roadway input dialog for the given vehicle type.

Similarly, the evening hourly traffic is defined as:

$$VPH_{evening} = ADT \times R_{evening} \frac{\%Evening}{100} \tag{115}$$

where $VPH_{evening}$ is the vehicles per hour during the evening, *ADT* is the average daily traffic, $R_{evening}$ is the number of evening hours (3) divided by the total number of hours (24), and *%Evening* is the value input by the user in the Roadway input dialog for the given vehicle type.

Similarly, the nighttime hourly traffic is defined as:

$$VPH_{night} = ADT \times R_{night} \frac{\%Night}{100} \tag{116}$$

where VPH_{night} is the vehicles per hour during the nighttime, *ADT* is the average daily traffic, R_{night} is the number of nighttime hours (9) divided by the total number of hours (24), and *%Night* is the value input by the user in the Roadway input dialog for the given vehicle type.

TNM 3.0 Approach

Daytime hourly traffic is defined as:

$$VPH_{day} = ADT \times R_{day} \frac{\%ADT}{100} \cdot \frac{\%Day}{100} \tag{117}$$

where VPH_{day} is the vehicles per hour during the daytime, *ADT* is the average daily traffic, R_{day} is the number of daytime hours (12) divided by the total number of hours (24), %ADT apportions the fraction of ADT for the total daytime traffic, and *%Day* distributes the total daytime traffic *amongst* the vehicle types.

Similarly, the evening hourly traffic is defined as:

$$VPH_{evening} = ADT \times R_{evening} \frac{\%ADT}{100} \cdot \frac{\%Evening}{100} \tag{118}$$

where $VPH_{evening}$ is the vehicles per hour during the evening, *ADT* is the average daily traffic, $R_{evening}$ is the number of evening hours (9) divided by the total number of hours (24), %ADT apportions the fraction of ADT for the total nighttime traffic, and *%Evening* distributes the total evening traffic *amongst* the vehicle types.

Similarly, the nighttime hourly traffic is defined as:

$$VPH_{night} = ADT \times R_{night} \frac{\%ADT}{100} \cdot \frac{\%Night}{100} \tag{119}$$

where VPH_{night} is the vehicles per hour during the nighttime, *ADT* is the average daily traffic, R_{night} is the number of nighttime hours (9) divided by the total number of hours (24), %ADT apportions the fraction of ADT for the total nighttime traffic, and *%Night* distributes the total nighttime traffic *amongst* the vehicle types.

Statistical Metrics, L_{10} and L_{50}

In addition to the refinement of L_{dn} and L_{den}, two new metrics were added in TNM 3.0 acoustics, L_{10} and

L_{50}. The first attempt to implement this utilized code originally developed for STAMINA[17], however, conversion of the code was impractical and instead Anderson (2012) developed the current implementation of these metrics by using statistical models developed Kurze (Statistics of road traffic noise, 1971) and (Noise from complex road traffic, 1971). Anderson's development included generalizations of Kurze's model as well as specific parameter values appropriate for TNM. The implementation utilizes the following equations:

$$L_{10} = L_{eq} - \frac{\sigma_L^2}{8.7} + 1.28\sigma_L \tag{120}$$

$$L_{50} = L_{eq} - \frac{\sigma_L^2}{8.7} \tag{121}$$

$$\sigma_L = 4.34\sqrt{\ln{(1 + k_2)}} \tag{122}$$

$$k_2 = \frac{\sum_{e=1}^{E}\sum_{t=1}^{T}\left(\frac{\lambda_{t,e}}{d_e^3}\right)\left\{\frac{\left|2\left(\alpha_{2,e}-\alpha_{1,e}\right)+\sin\left(2\alpha_{2,e}\right)-\sin\left(2\alpha_{1,e}\right)\right|}{4}\right\}E_{t,s}^2F_t^4}{\left[\sum_{e=1}^{E}\sum_{t=1}^{T}\left(\frac{\lambda_{t,e}}{d_e}\right)\left|\left(\alpha_{2,e}-\alpha_{1,e}\right)\right|E_{t,s}F_t\right]^2} \tag{123}$$

$$\lambda_{t,e} = \frac{v_{t,e}}{1000s_{t,e}} \tag{124}$$

$$E_{t,s} = 10^{\left(\left(L_{ref}\right)_{t,s}-A_{t,e}\right)/10} \tag{125}$$

$$F_t = e^{0.0265\left(\sigma_{ref}\right)_t^2} \tag{126}$$

$$\left(\sigma_{ref}\right)_{Autos} = 2.70 \tag{127}$$

$$\left(\sigma_{ref}\right)_{MTs} = 2.90 \tag{128}$$

[17] Rudder, F. F., "User's manual, FHWA level 2 highway traffic noise prediction model, stamina 1.0", FHWA-RD-78-138, January 1, 1979.

$$\left(\sigma_{ref}\right)_{HTs} = 2.45 \tag{129}$$

$$\left(\sigma_{ref}\right)_{Buses} = 2.35 \tag{130}$$

$$\left(\sigma_{ref}\right)_{MCs} = 5.08 \tag{131}$$

F.2 Updates to Aspects covered by the TNM 1.0 Technical Manual

In this section, all section references refer to sections in the original TNM Technical Manual.

F.2.1 Changes in Section 2.3.1 - Elemental Triangles

TNM 2.5 guarantees that subtended angles for all elemental triangles are 10 degrees or less. This is done in TNM 2.5 by creating contiguous 10-degree subtending angles until the remaining angle of the section is 10 degrees or less. This means that often, the last triangle is much less than 10 degrees. It could be, for example 9, 1, or even ½ degree. See also Appendix C.1.

Elemental triangles since TNM 3.0 are also guaranteed to be 10 degrees or less, however, the angles are the same for an acoustically homogenous section. This is done by determining the minimum number of triangles with equal subtending angles less than or equal to 10 degrees.

F.2.2 Changes in Section 2.3.3 – Distance and Roadway Length Adjustment

TNM 2.5 accounted for free field divergence only in the horizontal plane. It did not account for source or receiver heights. This means that source / receiver distances that include a large vertical difference will have their free-field divergence under represented. See also Appendix C 2.3.

TNM 3.0 acoustics corrected this, accounting for both the horizontal as well as the vertical component of the free-field divergence.

F.2.3 Changes in Section 2.4.3 – Elements in the Propagation Path

Single barrier reflections have been implemented in TNM since version 3.0. These are implemented by creating an image source reflected about the barrier in question. Because the source is on the opposite side of the barrier, diffraction computations are evaluated for a barrier dropping down to the barrier height. That is, reflections only occur for the portion of the sound path that would normally be considered to be shielded from the receiver. This includes reflections as well as diffractions. The direct and reflected sources are added incoherently because of the expected de-correlation that would result from passing through the turbulent region within the roadway corridor.

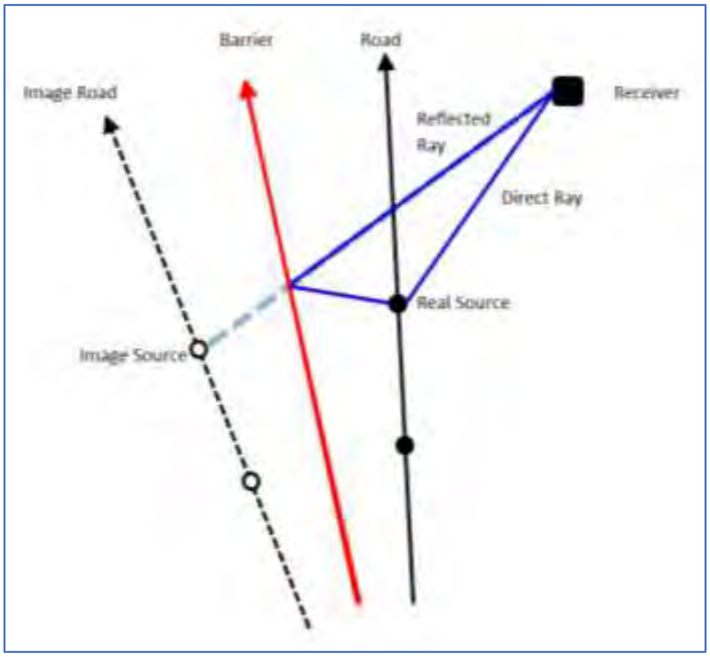

Figure 84 *Illustration of Single Barrier Reflection Geometry*

Conversion values in Table 3 (of the original technical manual) were updated to conform to the standard EFR values described in ***TABLE 6*** (of this updated technical manual). The two versions are compared in ***TABLE 20***. Note that this functions as a look-up table. In order to use this, the user should select the NRC/EFR pair that best matches the barrier material.

TABLE 20: EFFECTIVE FLOW RESISTIVITY USED FOR VALUES OF NOISE REDUCTION COEFFICIENT (NRC)

	EFR cgs Rayls	
NRC	TNM 3.0	TNM 2.5
0.00	20000	20000
0.05	***5000***	***4250***
0.10	1570	1570
0.15	865	865
0.20	***500***	***555***
0.25	385	385
0.30	300	300
0.35	214	214
0.40	***150***	***165***
0.45	129	129
0.50	102	102

	EFR cgs Rayls	
NRC	TNM 3.0	TNM 2.5
0.55	81	81
0.60	64	64
0.65	50	50
0.70	***40***	***39***
0.75	30	30
0.80	22	22
0.85	16	16
0.90	***10***	***10.4***
0.95	5.5	5.5
1.00	0.1	0.1

F.2.4 CHANGES IN SECTION 2.6 - CONTOURS

TNM 2.5 relied on an external DOS program to compute the contour curves from the TNM computed grid. See also Appendix F.1. TNM 3.0 implemented the entire contour process natively, generating shaded gradients instead of contours. The initial grid selection and refinement is the same for both TNM 2.5 and TNM 3.0 (and thus TNM 3.1). This is described in Appendix F.3 of the original technical manual.

In order to create the gradient, TNM requires a uniform grid. Because the initial grid refinement can result in a grid with different spatial resolutions at various points, TNM now creates a uniform grid by using a bi-linear interpolation (i.e. interpolation in the x- and y-directions) to refine regions that have a coarse resolution. Because these coarse regions have already met the required tolerances, the interpolated grid will also meet the required tolerances. The uniform grid is then represented using a color map.

F.2.5 Changes in Appendix A: Vehicle Noise Emissions

A few typographical errors were identified in the technical manual's regression coefficients found in Table 5 of the original technical manual (corrected in ***Table 10*** of this technical manual). These were not present in TNM 2.5's code, nor are they present in TNM 3.0's code. The differences between the code and the original technical manual are shown in ***Table 21***.

Table 21: Constants for A-weighted sound-level emissions and one-third octave band spectra

Vehicle Type	Pavement Type	Full Throttle	Coefficient	Original Technical Manual	TNM 3.0
HT	DGAC	NO	H2	-54.9684550	-54.9684450
HT	PCC	NO	G1	-298.5689955	-298.5689960
BUS	ALL	ALL	J2	-0.2825570	-0.2825557
MC	ALL	NO	C	56.0000000	56.0860990

Although not a change between TNM 2.5 and 3.0, the multiplier, m, for each built-in sub-source height (Table 7 of the original technical manual) was updated between TNM 1.0 and 2.5. For reference the original table and the updated table are given below.

Table 22: Multiplier, m, for each Built-In Sub-Source Height (TNM Version 1.0, Table 7)

Freq (Hz)		50	63	80	100	125	160	200	250	315	400	500	630
Multiplier, *m*	Height: 3.66 m (12 ft)	0.32	0.35	0.41	0.51	0.76	1.66	6.46	4.79	0.95	0.41	0.41	1.00
	Height: 1.5 m (5 ft)	0.30	0.30	0.32	0.34	0.37	0.44	0.55	0.81	5.37	5.37	4.47	1.02
	Height: 0 m (0 ft)	0.30	0.31	0.32	0.34	0.35	0.38	0.41	0.44	0.50	0.50	0.54	0.56

Freq (Hz)		800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
Multiplier, *m*	Height: 3.66 m	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Height: 1.5 m	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Height: zero	0.56	0.54	0.49	0.42	0.35	0.3	0.25	0.22	0.21	0.21	0.3	0.36

TABLE 23: MULTIPLIER, M, FOR EACH BUILT-IN SUB-SOURCE HEIGHT (AS OF TNM VERSION 2.5)

Freq (Hz)		50	63	80	100	125	160	200	250	315	400	500	630
Multiplier, *m*	Height: 3.66 m (12 ft)	0.3	0.32	0.36	0.44	0.52	0.69	0.95	1.78	1.00	0.32	0.4	0.25
	Height: 1.5 m (5 ft)	0.26	0.27	0.27	0.28	0.3	0.33	0.38	0.48	0.62	0.79	1.12	1.58
	Height: 0 m (0 ft)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.2

Freq (Hz)		800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
Multiplier, *m*	Height: 3.66 m	0.25	0.25	0.25	0.25	0.32	0.56	1.00	1.00	1.00	1.00	1.00	1.00
	Height: 1.5 m	0.40	0.50	0.32	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Height: zero	0.25	0.25	0.22	0.2	0.25	0.27	0.34	0.42	0.47	0.52	0.59	0.67

F.2.6 CHANGES IN APPENDIX B: VEHICLE SPEEDS

The coefficients presented in Table 9 of Appendix B of the original technical manual, were modified to improve heavy truck deceleration computations. This was done, by using the same data as used in the original curve-fit, but then increasing the acceptable speed range. Therefore, it does not represent the results of new data, but rather represents the results of a new, more robust curve fit. The original technical manual Table 9 is shown below for comparison with ***TABLE 9*** of this technical manual, repeated as ***TABLE 24*** and
TABLE 25 respectively for convenience.

TABLE 24: REGRESSION COEFFICIENTS FOR DECELERATING HEAVY TRUCKS (ORIGINAL TECHNICAL MANUAL)

Vehicle Type	A	B	C
Heavy Trucks	D exp(-E g), where D = 72.803 E = 0.180	F exp(-G g), where F = 3792.117 G = 0.105	1.303

TABLE 25: REGRESSION COEFFICIENTS FOR DECELERATING HEAVY TRUCKS (REPEATED FROM APPENDIX A OF THIS TECHNICAL MANUAL)

Vehicle Type	A	B	C
Heavy Trucks	D exp(-E g), where D = 64.606 E = 0.196	F exp(-G g), where F = 3996.848 G = 0.121	1.268

These coefficients are used in Equations (33) and (34) of Appendix A:

Note that in addition to these changes, elemental speed calculations should not be expected to match exactly since, as mentioned before, elemental triangles in TNM 3.0, and thus TNM 3.1, have uniform subtending angles for a given acoustically homogeneous region, while TNM 2.5 has constant 10-degree subtending angles up to, but not including, the last element.

F.2.7 Changes in Appendix C: Horizontal Geometry and Acoustics

C.2.2 Traffic Sound Energy: "Reference" Conditions

While the penalties for evening and nighttime traffic in Equation 15 are correct, the true traffic is computed in a manner consistent with the description of VPH in the first section of this document.

F.2.8 Changes in Appendix D: Vertical Geometry and Acoustics

Other than as described previously, no changes were made to the fundamentals of the vertical geometry and acoustics. It should be noted however, that equations used in the vertical acoustics can be sensitive to the smallest changes in numerical precision. Because these equations were implemented using C# in TNM 3.0, and by extension in TNM 3.1, compared to C++ in TNM 2.5, small changes in final results are expected. Current testing has found differences of approximately 0.1 dB for some of the sensitive cases.

F.2.9 Changes in Appendix E: Parallel Barrier Analysis

No changes were made to the parallel barrier analysis.

F.2.10 Changes in Appendix F: Contours

See discussion of changes in section 2.6.

F.2.11 Changes in Appendix G: Model Verification

Neither TNM 2.5 nor TNM 3.0, and thus TNM 3.1, acoustics have been validated for single barrier reflections. This function should be considered experimental.

APPENDIX G: ENGLISH EQUIVALENT EQUATIONS (EEE)

Because TNM's acoustics utilizes equations scaled for metric inputs, the equations in the body of this report are presented for metric inputs as well. However, it is often more convenient to work with English units. For this reason, the equations for computing noise level and energy are repeated here using the English form.

$$L_{emis,\ i}(s_i, f) =$$

$$10 \cdot \log_{10}(E_a) + (D_1 + D_2 s_i) + (E_1 + E_2 s_i)[\log_{10}(f)] +$$
$$(F_1 + F_2 s_i)[\log_{10}(f)]^2 + (G_1 + G_2 s_i)[\log_{10}(f)]^3 +$$
$$(H_1 + H_2 s_i)[\log_{10}(f)]^4 + (I_1 + I_2 s_i)[\log_{10}(f)]^5 +$$
$$(J_1 + J_2 s_i)[\log_{10}(f)]^6 \tag{132}$$

where s_i is now given in miles per hour.

$$E_a(s_i) = (s_i)^{A/10} \cdot 10^{B/10} + 10^{C/10} \tag{133}$$

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