U.S. Department of Transportation
Federal Highway Administration

Technical Manual Update for

TNM 3.0 Acoustics

FHWA-HEP-17-035

Introduction

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 TGCAD is obsolete and no longer supported by the original developer.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. The discussion is divided into sections that deal with changes to aspects of the acoustics code originally covered by the TNM Technical Manual[1] and those that do not.

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[1] FHWA Traffic Noise Model (FHWA TNM®) Technical Manual, February 1998.
http://www.fhwa.dot.gov/environment/noise/traffic_noise_model/old_versions/tnm_version_10/tech_manual/index.cfm

Updates to Aspects not covered by the TNM Technical Manual

Core Language, Libraries, and Coding Tools

In order to provide a more manageable foundation for the acoustics, TNM 3.0 Acoustics was 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[2], GeoAPI[3], C5[4]. The additional libraries provided new object classes as well as mathematical functions. Microsoft's Visual Studio 2010 with .NET 4.0[5] was used as the primary development environment. TortoiseHg with Mercurial(Hg)[6] were used for tracking version and revision history as well as managing multiple code branches. NUnit[7] was used for unit testing.

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 has been 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. In 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.

In the future, it may be desired to allow pavements to have different acoustic impedances. 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. This constraint was considered unnecessary. Therefore, TNM 3.0 Acoustics has been designed to accept control devices at any point on a road.

Bug Fixes[8]

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 has been fixed in TNM 3.0. Because TNM 3.0 computes

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2 powercollections.codeplex.com
3 code.google.com/p/nettopologysuite
4 www.itu.dk/research/c5/
5 www.microsoft.com
6 tortoisehg.bitbucket.org
7 www.nunit.org
8 These bugs were fixed in an updated version of TNM to aid in the development of the TNM 3.0 acoustics. TNM 2.6 is the version of TNM that utilizes the TNM 2.5 acoustics and GUI but includes these bug fixes.

these bands, the bug fix is moot; however this indexing issue is mentioned here as it relates to computed differences between the two acoustic codes.

Impedance Averaging (SP1)

Boulanger developed a method for averaging acoustics impedances and published his findings in the Journal of the Acoustic Society of America[9]. 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 2.6[10] and 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 (SP4)

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.

[9] Boulanger, Patrice, T. Waters-Fuller, K. Attenborough, and K. M. Li. "Models and measurements of sound propagation from a point source over mixed impedance ground," J. Acoust. Soc. Am., vol. 102, no. 3, pp. 1432-1442, 1997.
[10] TNM 2.6 is a version of TNM based on TNM 2.5 that has several bug fixes implemented, essentially providing an improved version of TNM 2.5.

Metrics

The traffic input dialog in the TNM 3.0 GUI 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:

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

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:

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

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:

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

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:

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

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:

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

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:

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

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:

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

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:

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

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:

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

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 *%Night* distributes the total evening traffic *amongst* the vehicle types.

Similarly, the nighttime hourly traffic is defined as:

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

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 have been added in TNM 3.0 acoustics, L_{10} and L_{50}. The first attempt to implement this utilized code originally developed for STAMINA[11], however, conversion of the code was impractical and instead Anderson[12] developed the current implementation of these metrics by using statistical models developed Kurze[13,14]. Anderson's development included generalizations of Kurze's model as well as specific parameter values appropriate for TNM. The implementation utilizes the following equations:

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

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

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

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

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

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

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

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

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

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

[12] Anderson, Grant, "TNM 3.0: Conversion of Leq to L10 and L50, Revision 1," Unpublished Volpe Document, June 28th, 2012.

[13] Kurze, U.J., "Statistics of road traffic noise," Journal of Sound and Vibration (1971) 18 (2), 171-195.

[14] Kurze, U.J., "Noise from complex road traffic," Journal of Sound and Vibration (1971) 19 (2), 167-177.

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

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

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

Updates to Aspects covered by the TNM Technical Manual

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 in 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.

Changes in Section 2.3.3 – Free-field Divergence

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 corrects this, accounting for both the horizontal as well as the vertical component of the free-field divergence.

Changes in Section 2.4.3

Single barrier reflections have been implemented in TNM 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.

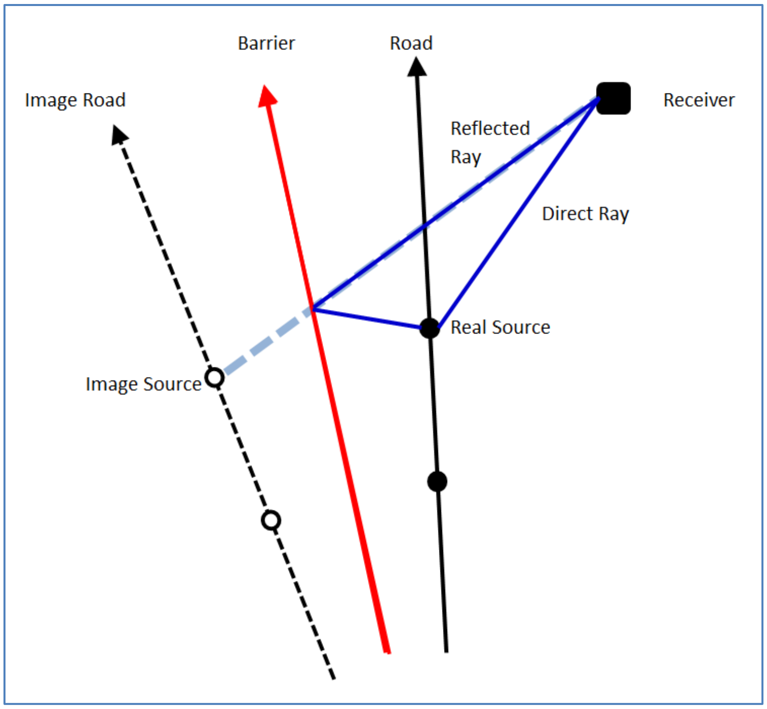

Figure 1: Illustration of single barrier reflection geometry

Conversion values in Table 1 of this document were updated to conform to the standard EFR values described in Table 2 of the TNM Technical Manual. 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 1. 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
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

Changes in Section 2.6

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 implements 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. This is described in Appendix F.3 of the technical manual. In order to create the gradient, TNM3.0 requires a uniform grid. Because the initial grid refinement can result in a grid with different spatial resolutions at various points, TNM 3.0 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.

Appendix A: Vehicle Noise Emissions

A few typographical errors were identified in the technical manual's regression coefficients found in Table 5 of the TNM Technical Manual. These are 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 TNM Technical Manual are highlighted in red in Table 2 of this document.

Table 2. Constants for A-weighted sound-level emissions and 1/3rd-octave-band spectra

Vehicle Type	Pavement Type	Full Throttle	Coefficient	Technical Manual	TNM 3.0
HT	DGAC	NO	H2	-54.9684***55***0	-54.9684***45***0
HT	PCC	NO	G1	-298.5689***55***	-298.5689***60***
BUS	ALL	ALL	J2	-0.282***5570***	-0.282***5557***
MC	ALL	NO	C	56.0***00000***0	56.0***86099***0

Appendix B: Vehicle Speeds

The coefficients presented in Table 9 of Appendix B, 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.

Table 9. Regression coefficients for decelerating heavy trucks (TNM 2.5).

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

	E = 0.180	G = 0.105	

Table 9. Regression coefficients for decelerating heavy trucks (TNM 3.0).

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 Equation 13 of Appendix B:

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

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 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.

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.

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 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.

Appendix E: Parallel Barrier Analysis

No changes were made to the parallel barrier analysis.

Appendix F: Contours

See discussion of changes in section 2.6.

Appendix G: Model Verification

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