PREFACE (TNM v2.5 UPDATE SHEET)

This Technical Manual is for the Federal Highway Administration's Traffic Noise Model (FHWA TNM®), Version 1.0 -- the Federal Highway Administration's computer program for highway traffic noise prediction and analysis. Subsequent Technical Manual insert sheets address the changes implemented in FHWA TNM®, Version 2.5. A companion User's Guide, and various version-specific addendums, describes how to use TNM [Anderson 1998]. In addition, a companion technical report documents the vehicle noise-emissions data base [Fleming 1995], and a companion, multi-phase validation report and associated addendums compare TNM performance against measured data [Rochat 2002].

Overview of TNM: TNM computes highway traffic noise at nearby receivers and aids in the design of highway noise barriers. As sources of noise, it includes 1994-1995 noise emission levels for the following cruise-throttle vehicle types:

- 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; and

- Motorcycles: all vehicles with two or three tires and an open-air driver/passenger compartment.

Noise emission levels consist of A-weighted sound levels, one-third octave-band spectra, and subsource-height strengths for the following pavement types:

- Dense-graded asphaltic concrete (DGAC);
- Portland cement concrete (PCC);
- Open-graded asphaltic concrete (OGAC); and
- A composite pavement type consisting of data for DGAC and PCC combined.

In addition, 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; and
- On-ramp start points.

TNM combines these full-throttle noise emission levels with its internal speed computations to account for the full effect (noise emissions plus speed) of roadway grades and traffic-control devices.

ACKNOWLEDGMENTS (TNM V2.5 UPDATE SHEET)

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Bowlby & Associates, Inc.: William Bowlby -- TNM Trainer CD-ROM and program testing; Geoffrey Pratt – program testing.
Serac Technology Group, Inc.: Theodore Patrick -- TNM Trainer CD-ROM
University of Central Florida: Roger Wayson -- emission-data design/measurement/analysis.
Florida Department of Transportation: Win Lindeman -- Funding and management of subsource-height study.
Florida Atlantic University: Stewart Glegg, Robert Coulson -- subsource height measurements [Coulson 1996].
Maryland State Highway Administration: Kenneth Polcak -- emission data.
Ohio University: Lloyd Herman -- emission data.
Environmental Acoustics, Inc.: Harvey Knauer – program testing.
Emission-data state agencies: California, Connecticut, Florida, Kentucky, Maryland, Massachusetts, Michigan, New Jersey, Tennessee.

Further details on vehicle noise emission levels are given in Section 2.1 and Appendix A of this manual.

1.2 Free Field Levels

Characteristics of the free-field noise level computations include:

- TNM computes three different sound-level descriptors, depending on user selection: the energy-equivalent sound level over a one-hour time period (1HEQ, represented by the symbol, L_{Aeq1h}), the average day-night sound level (DNL, represented by the symbol, L_{dn}), or the average day-evening-night sound level, designated as the Community Noise Equivalent Level (CNEL, represented by the symbol, L_{den}).[2]

- Traffic control devices can be inserted, and the TNM computes vehicle speeds and emission levels accordingly. Such devices include traffic signals, stop signs, toll booths, and on-ramp start points.

- Computations are performed in **a**-octave bands for increased accuracy; this aspect is not visible to users.

- The TNM computes noise contours if specified; the NMPLOT Version 3.05 contouring program is used for compatibility with the Federal Aviation Administration's Integrated Noise Model (INM) Version 5.0 and higher [Olmstead 1996], and the U.S. Air Force's NOISEMAP program [Moulton 1990].

More details on the computation of vehicle speeds are given in Section 2.2 and Appendix B of this manual; details on the computation of free field levels are given in Section 2.3 and Appendix C.

4.1 Shielding and Ground Effects

The TNM incorporates state-of-the-art sound propagation and shielding algorithms. These algorithms are based on fairly recent research on sound propagation over ground of different types, atmospheric absorption, and the shielding effects of barriers, berms, ground, buildings, and trees. The TNM does not account for atmospheric effects such as varying wind speed or direction or temperature gradients. The TNM propagation algorithms assume neutral atmospheric conditions. Characteristics of the propagation algorithms include:

- Ground location and type is incorporated in the TNM. Users input terrain lines to define ground location. Users input default ground type or define ground zones to specify ground type, which varies in acoustic “hardness” (effective flow resistivity).

- Berms can be defined, with user-selectable heights, and side slopes; they are computed as if they were terrain lines. Berms can also be defined with top-widths in versions of TNM 2.1 and earlier, but are limited to a top-width of 0 meters (or feet) for TNM 2.5, because of apparent diffraction algorithm anomalies associated with flat top berms in all versions of TNM. For documentation purposes, descriptions of the acoustics and functionality

[2] All noise descriptors in the TNM are consistent with the definitions in American National Standard, ANSI S1.1-1994, Acoustical Terminology [ANSI 1994].

associated with flat top berms remains in this manual, in case they are implemented in future versions of TNM.

- Rows-of-buildings attenuation is included, with user-definable height and percentage of area blocked relative to the source roadway(s).

- Tree zones can be defined; the ISO standard for attenuation by dense foliage is used [ISO 1996].

- Multiple reflections between parallel barriers that flank a roadway are computed in two dimensions, unlike other TNM acoustics, which are computed in three dimensions. This is discussed further in Section 1.5 and Appendix E. Reflections in TNM outside of the parrallel barrier module are disabled in all versions of TNM. Descriptions of the acoustics and functionality associated with reflections remains in this manual for documentation purposes, in case they are implemented in future versions of TNM.

- Double-barrier diffraction is included. The net effect of diffraction from the most effective *pair* of barriers, berms or ground points that interrupt the source-receiver line-of-sight is computed. The other objects that interrupt the path are ignored.

More details on the computation of shielding and ground effects are given in Sections 2.4, 2.5, 2.6, and Appendix D of this manual.

10.1 High-level Flow Chart

This section presents a flow chart to outline the overall flow of the TNM during sound level calculation. It is presented as Figure 1.

10.2 Parallel Barrier Analysis

A two-dimensional multiple-reflections module has been included within the TNM for computing the degradation of barrier performance due to the presence of a reflective barrier on the opposite side of the roadway. The results from this module are generalized by the user to modify the TNM's results where multiple reflections exist. The module is most effective in computing the effects of sound-absorbing material on the surfaces of barriers or retaining walls. More details on the parallel barrier module are given in Appendix E of this manual.

and 2000 Hz, the sound energy distribution transitions gradually between the two values. Further detail about the energy distribution is presented in Appendix A, including curves showing the sound energy split by frequency for each vehicle type.

Table 1. Sound Energy Distribution Between Sub-source Heights[3]

Vehicle Type	Operating Condition	Percentage of Total Sound Energy at Upper Sub-source Height: 1.5m (5 ft), except 3.66m (12 ft) for HT	
		At Low Frequencies (500 Hz and below)	At High Frequencies (2000 Hz and above)
Autos	Cruise or Full Throttle	27%	2%
Medium Trucks & Buses	Cruise	36	6
Medium Trucks & Buses	Full Throttle	37	11
Heavy Trucks	Cruise	57	46
Heavy Trucks	Full Throttle	57	48
Motorcycles	Cruise or Full Throttle	28	2

Further detail about the energy distribution is presented in Appendix A, Section A.4.

10.4 Vehicle Speed Computation

The TNM computes adjusted speeds based on the user input speeds, roadway grade, and traffic control devices. For level or down-grade roadways, TNM uses the speeds assigned to the roadway by the user (the "input speed"). For heavy trucks (only) on upgrades equal to 1.5 percent or more, TNM reduces the input speeds. The speeds are reduced depending on the steepness and length of the upgrade in accordance with speed-distance curves similar to those published for geometric design by the American Association of State Highway and Transportation Officials [AASHTO 1990 and TRB 1985]. The TNM speed-distance curves were calibrated to the speeds measured during the emission level noise measurement program. Appendix B describes the details of these computations and gives examples.

The TNM allows the user to enter the following traffic-control devices: traffic signals, stop signs, toll booths, and on-ramp start points. The reason for these devices is to allow a more precise modeling of vehicle speeds and emission levels under these interrupted-flow conditions. TNM will compute speeds all along any roadways with traffic control devices. These devices abruptly reduce speeds to the device's "speed constraint," for the device's

[3]Note: The values in this table for autos, medium trucks, buses and motorcycles have been corrected; they were previously the ratio of upper to lower subsource heights, rather than the precentage of total sound energy at the upper subsource height. For heavy trucks, 20% more energy has been shifted to the upper subsource height.

Table 6. Constants for subsource-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	DG AC	OG AC	PCC	Yes	No	L	M	N	P	Q
X					X	X	X	X	X	X	0.373239	0.976378	-13.195596	39.491299	-2.583128
	X				X	X	X	X	X		0.579261	0.871354	-177.249214	558.980283	-0.026532
	X				X	X	X	X		X	0.566933	0.93352	-25.497631	80.239979	-0.234435
		X			X	X	X	X	X		1.330000	0.08000	-204.84400	592.56800	-159.34400
		X			X	X	X	X		X	0.850000	-0.33000	163.021000	-492.45100	-58.00500
			X		X	X	X	X	X		0.579261	0.871354	-177.249214	558.980283	-0.026532
			X		X	X	X	X		X	0.563097	0.928086	-31.517739	99.099777	-0.263459
				X	X	X	X	X	X		0.391352	0.978407	-19.278172	60.404841	-0.614295
				X	X	X	X	X		X	0.391352	0.978407	-19.278172	60.404841	-0.614295

A.4.2 User-defined vehicles

For a user-defined vehicle, TNM substitutes the subsource heights for the built-in vehicle that the user designates as most similar. Table 6 mentions this substitution in the appropriate column heading.

A.5 Vertical Subsources, Free Field

Next TNM eliminates the ground effects within these measured vehicle emissions. To do this, it multiplies each measured vertical subsource emission by the values in Table 7.

Mathematically:

$$\begin{aligned} E_{\text{emis},\, i,\, \text{upper},\, \text{ff}}(s_i, f) &= m_{\text{upper}}\, E_{\text{emis},\, i,\, \text{upper}} \\ E_{\text{emis},\, i,\, \text{lower},\, \text{ff}}(s_i, f) &= m_{\text{lower}}\, E_{\text{emis},\, i,\, \text{lower}}\ . \end{aligned} \qquad (8)$$

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 7. Multiplier, *m* , for each built-in subsource height.

Freq (Hz)		50	63	80	100	125	160	200	250	315	400	500	630
Multiplier, *m*	Height: 3.66 m	0.30	0.32	0.36	0.44	0.52	0.69	0.95	1.78	1.00	0.32	0.40	0.25
	Height: 1.5 m	0.26	0.27	0.27	0.28	0.30	0.33	0.38	0.48	0.62	0.79	1.12	1.58
	Height: zero	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.20

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	0.20	0.25	0.27	0.34	0.42	0.47	0.52	0.59	0.67

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

A.6 Plots of All Noise Emissions

Figure 6 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):

D.4.4 Diffraction function. The complete diffraction term is defined by the following function:

$$D = \frac{R}{L}\frac{e^{-i\frac{\pi}{4}}}{\sqrt{\pi}} e^{ik(L-R)} e^{-i\chi^2} F(\chi) \qquad (30)$$

where L is defined as the propagation path length. (In Figure 61, which shows the diffraction geometry, $L = r + r$.)

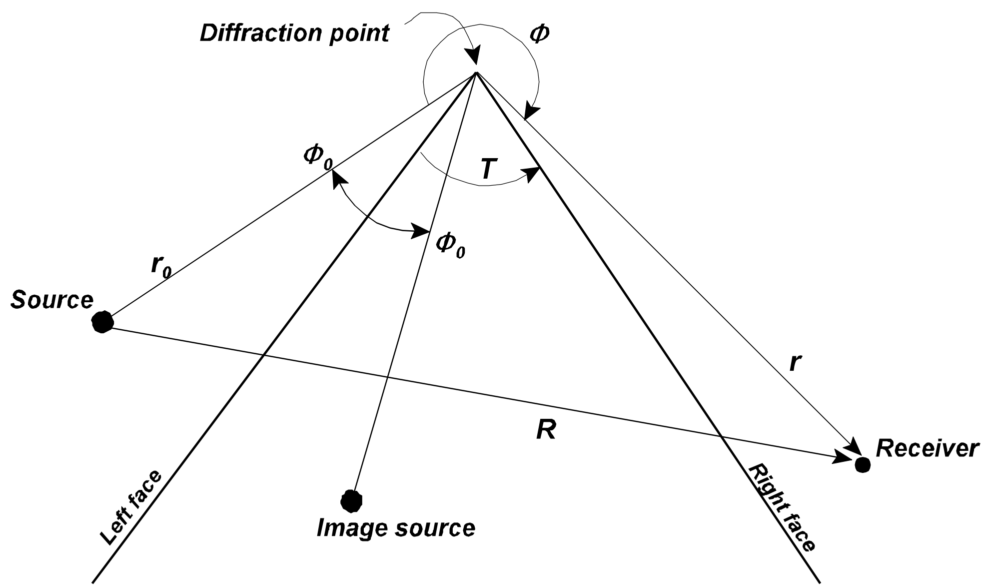

Figure 60. Diffraction geometry.

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 1.2. The factor $\boldsymbol{Q}$ is included to account for the surface impedances at the diffracting edge (see Section D.4.5). This results in the following equation:

$$D = (sgn)ADQ \qquad (31)$$

Chi function: The chi (P) 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,

APPENDIX G
MODEL VERIFICATION (TNM v2.5 UPDATE SHEET)

This appendix provides a comparison of TNM 1.0 results to measurements and to the model results of others. Comparisons are made to five different data sets, three of which involved point-source geometry, and the remaining two involved in-situ measurements of barrier performance along actual highways. The first comparison is with Embleton's model for reflection from ground of finite impedance [Embleton 1983]. The second is to measurements by Parkin and Scholes over grassland [Parkin 1965], the third is to measurements of a noise barrier by Scholes, also over grassland [Scholes 1971]. The fourth and fifth are to measurements of noise barrier performance at two different highway locations by Hendriks and Fleming, respectively [Hendriks 1991][Fleming 1992]. Overall, the agreement with measurements is found to be very satisfactory.

Comparisons of results from later versions of TNM to measurements are presented in the TNM validation report [Rochat 2002]. An addendum to this report reviewing the performance of TNM 2.5 will be published in 2004.

G.1 Ground Reflection Model

The TNM's model for reflection coefficients is based on the approach of Chessell [Chessell 1977], which incorporates the single-parameter ground-impedance model first proposed by Delany and Bazley [Delany 1970]. Embleton, Piercy and Daigle further developed the model and conducted measurements to determine empirically the relationship between ground type and effective flow resistivity (EFR) [Embleton 1983]. Figures 71 through 74 present a comparison of the TNM model with Embleton's model for Embleton's published geometry and four values of EFR. The geometry was: source height = 0.31 meters (1.0 feet); receiver height = 1.22 meters (4.0 feet); source-to-receiver distance = 15.2 meters (50 feet). The values of EFR span the range from very soft ground (powder snow, EFR = 10 cgs Rayls) to hard ground (10,000 cgs Rayls).

Plotted in the figures are values of the "ground effect" in dB, which represents the difference between the free-field (no-ground) condition and the condition with the ground. At low frequencies, the ground adds up to 6 dB, due to pressure doubling. In the middle frequencies and over soft ground (EFR = 100 to 500) the fairly broadband "ground-effect dip" exhibits significant reductions in sound level due to destructive interference.

G.2 Measurements Over Grassland

The TNM's reflection model is compared with very carefully-conducted measurements of sound propagation over grassland by Parkin and Scholes [Parkin 1965]. The atmospheric conditions for the measurements were a normal temperature gradient (no strong lapse or inversion) and zero vector wind (no components in the source-to-receiver direction). The ground surface at the site, called "Hatfield," was grass up to 5 centimeters (2 inches) high covering silty soil. The ground was especially flat, within ± 0.3 meters (1 foot) for more than

Menge 1991 — Menge, C. W., G. Anderson, T. Breen, C. Bajdek, A. Hass. *Noise Analysis Technical Report: Brooklyn-Queens Expressway, Queens Boulevard to Grand Central Parkway.* Report No. 290800. Lexington, MA: Harris Miller Miller & Hanson Inc., April 1991.

Moulton 1990 — Moulton, C.L. *Air Force Procedure for Predicting Aircraft Noise Around Airbases: Noise Exposure Model (NOISEMAP), User's Manual*. Report No. AAMRL-TR-90-011. Wright-Patterson Air Force Base, OH: U.S. Air Force, February 1990.

Olmstead 1996 — Olmstead, Jeffrey R., et. Al. Integrated Noise Model (INM) Version 5.1 User's Guide. Report No. FAA-AEE-96-02. Washington, DC: Federal Aviation Administration, December 1996.

Parkin 1965 — Parkin, P. H. and W. E. Scholes, "The Horizontal Propagation of Sound from a Jet Engine Close to the Ground, at Hatfield," *J. Sound Vib.*, vol. 2, no. 4, pp. 353-374, 1965.

Rochat 2002 — Rochat, J. L. and G. G. Fleming. *Validation of FHWA's Traffic Noise Model® (TNM): Phase 1.* Report No. FHWA-EP-02-031 and DOT-VNTSC-FHWA-02-01. Cambridge, MA: John A. Volpe National Transportation Systems Center, Acoustics Facility, August 2002.

Scholes 1971 — Scholes, W. E., A. C. Salvidge, and J. W. Sargent, "Field Performance of a Noise Barrier," *J. Sound Vib.*, vol. 16, pp. 627-642, 1971.

TRB 1985 — Transportation Research Board. *Highway Capacity Manual.* Special Report 209. Washington DC: National Research Council, 1985.