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Federal Highway Administration

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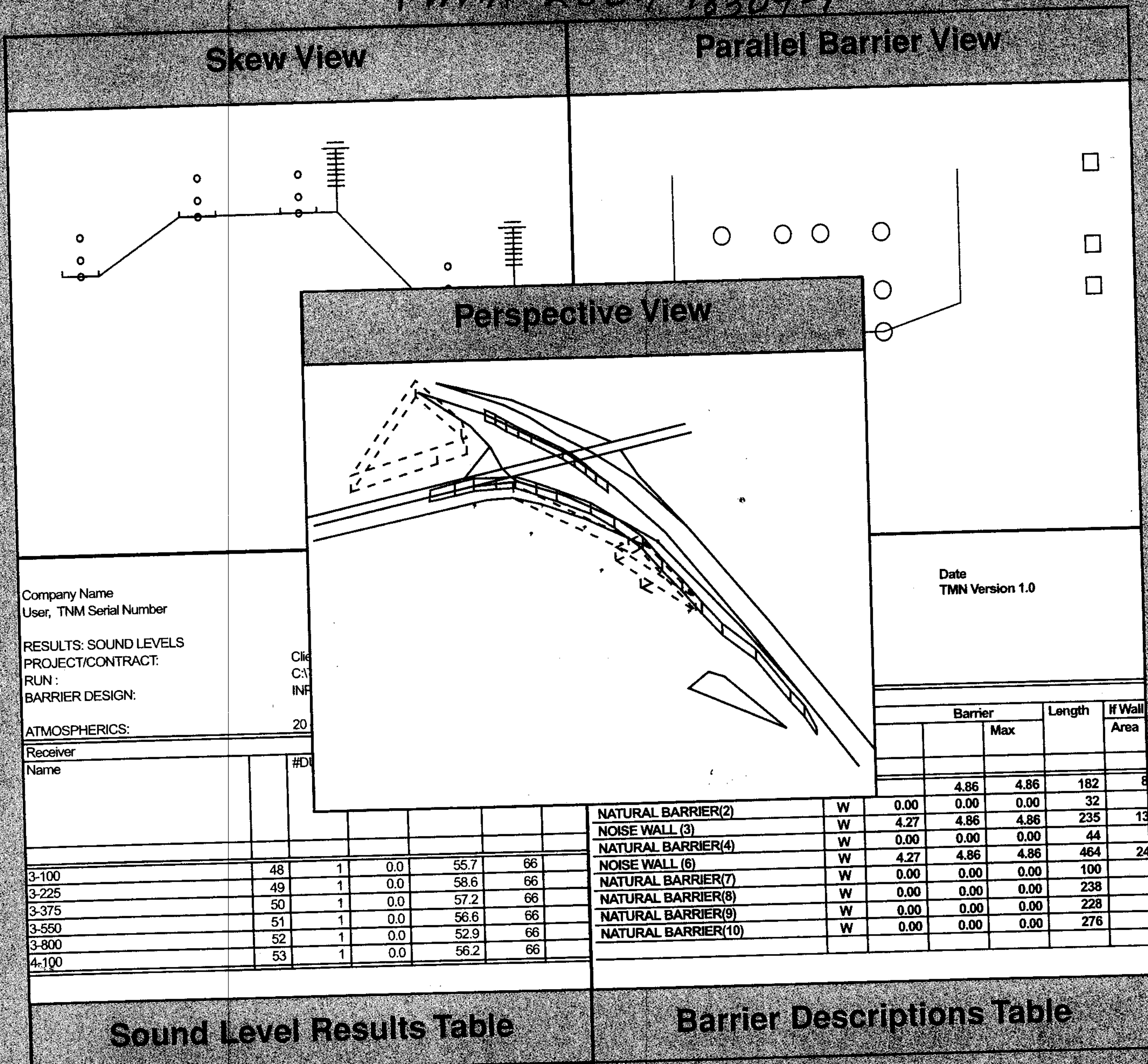

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This Technical Manual is for the *Federal Highway Administration's* Traffic Noise Model (FHWA TNM®), Version 1.0 -- the FHWA's computer program for highway traffic noise prediction and analysis. Two companion reports, a User's Guide and a data report, respectively, describe the use of TNM and its vehicle noise-emissions data base. The Technical Manual documents the fundamental equations, the acoustical algorithms, and the interactive logic for all computations within TNM.

Section 1 overviews the basic elements of TNM's prediction model. It describes the basic concepts of the model, from vehicle noise emissions to predicted sound levels. Section 2 describes TNM's prediction model in more detail, with references to the manual appendixes for detail on algorithms and mathematics. In particular, this section describes the following: (1) vehicle noise emissions for TNM's built-in vehicle types, (2) computation of vehicle speeds, when they are affected by upgrades and traffic-control devices, (3) geometrical complexity in the XY plane, plus computation of free-field sound levels from a roadway segment, (4) geometrical complexity in the vertical plane, along any line between roadway and receiver, plus the computation of attenuation relative to free field along any such line, (5) computation of parallel-barrier degradation for barriers or retaining walls that flank the roadway, and (6) computation of sound-level contours, insertion-loss contours, and level-difference contours. In addition, this manual contains detailed appendixes for each of these subjects.

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ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (ha) = 4,000 square meters (m^2)

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1 ounce (oz) = 28 grams (gm)
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1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

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°C=5/9(°F - 32)

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LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

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°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

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PREFACE

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. A companion User's Guide describes how to use TNM [Anderson 1998]. In addition, a companion technical report documents the vehicle noise-emissions data base [Fleming 1995].

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.

TNM propagates sound energy, in one-third-octave bands, between highway systems and nearby receivers. Sound propagation takes the following factors into account:

- Atmospheric absorption;
- Divergence;

- Intervening ground: its acoustical characteristics and its topography;
- Intervening barriers: walls, berms and their combination;
- Intervening rows of buildings; and
- Intervening areas of heavy vegetation.

TNM computes the effect of intervening ground (defined by its type, or optionally by its flow resistivity) with theory-based acoustics that have been calibrated against field measurements. In addition, TNM allows sound to propagate underneath selected intervening roadways and barriers, rather than being shielded by them.

During calculation, TNM perturbs (increases/decreases) intervening barrier heights up and down from their input height, to calculate for multiple heights. Then during acoustical design of selected barriers, combined with selected receivers, TNM displays sound-level results for any combination of height perturbations, where a perturbation is defined as the height increment that a noise barrier's input height is increased (perturbed up) or decreased (perturbed down) during barrier design. It also contains an input-height check, to determine if noise barriers break the lines-of-sight between sources and receivers. In addition, it provides summary cost and benefit information for each barrier design, from user-supplied unit barrier costs and land-use information.

For selected cross sections, TNM also computes the effect of multiple reflections between parallel barriers or retaining walls that flank a roadway. The TNM user can then enter the computed parallel-barrier degradations as adjustment factors for individual receivers in TNM's calculation of receiver sound levels.

TNM computes three measures of highway traffic noise:

- L_{Aeq1h}: hourly A-weighted equivalent sound level (1HEQ);
- L_{dn}: day-night average sound level (DNL); and
- L_{den}: Community Noise Equivalent Level (CNEL), where "den" stands for day/evening/night.

TNM computes these three noise measures at user-defined receiver locations, where it also computes several diagnostics to aid in noise-barrier design. In addition, it computes three types of contours:

- Sound-level contours;
- Noise Reduction, i.e., insertion-loss, contours for noise barriers; and
- Level-difference contours between any two noise-barrier designs.

TNM runs under Microsoft® Windows Version 3.1 (or later). Within Windows, it allows digitized input using a generic Windows digitizer driver, plus the import of DXF files from CAD programs and input files from STAMINA 2.0/OPTIMA. Note: TNM will run under Microsoft® Windows 95 or Windows NT, however, TNM is a 16-bit program and will not take full advantage of the 32-bit architecture associated with Windows 95 or NT.

To aid during input and to document the resulting input and barrier designs, TNM shows the following graphical views:

- Plan views;
- Skew sections;

- Perspective views, including a specialized perspective view for noise-barrier design; and
- Roadway profiles.

TNM Version 1.0 replaces FHWA's prior pair of computer programs, STAMINA 2.0/OPTIMA. In addition, this Technical Manual replaces FHWA's prior prediction model: *FHWA Highway Traffic Noise Prediction Model,* FHWA-RD-77-108 [Barry 1978].

This manual documents the fundamental equations, the acoustical algorithms, and the interactive logic for all computations within the TNM. The manual is organized as follows:

Section 1. **Overview of TNM:** This section overviews the basic elements of the TNM's prediction model. It describes the basic concepts of the model, from vehicle noise emissions to predicted sound levels.

Section 2. **Model Description:** This section describes the TNM's prediction model in more detail, with references to the manual's appendixes for detail on algorithms and mathematics. In particular, this section describes:

- Vehicle noise emissions for the TNM's built-in vehicle types.
- Computation of vehicle speeds, where they are affected by upgrades and traffic-control devices.
- Geometrical complexity in the horizontal plane, plus computation of free-field sound levels from a roadway segment.
- Geometrical complexity in the vertical plane, along any line between roadway and receiver, plus the computation of attenuation due to shielding and ground effects along any such line.
- Computation of degradation of barrier insertion loss due to multiple reflections between barriers that flank the roadway.
- Computation of sound-level contours.

In addition, this manual contains the following detailed appendixes:

Appendix A. **Vehicle noise emissions;**

Appendix B. **Vehicle speeds;**

Appendix C. **Horizontal geometry and acoustics;**

Appendix D. **Vertical geometry and acoustics;**

Appendix E. **Parallel barriers;**

Appendix F. **Contours;**

Appendix G. **Model verification;**

References;

Index;

FHWA TNM Announcement and Order Form; and

FHWA TNM Registration Card.

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1. OVERVIEW

The Federal Highway Administration Traffic Noise Model (FHWA TNM®), like many other noise prediction models, computes a predicted noise level through a series of adjustments to a reference sound level. In the TNM, the reference level 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 meters (50 feet). Adjustments are then made to the emission level to account for traffic flow, distance, and shielding. These factors are related by the following equation:

$$L_{Aeq1h} = EL_i + A_{traff(i)} + A_d + A_s \,, \tag{1}$$

where EL_i represents the vehicle noise emission level for the i^{th} vehicle type (Sections 1.1 & 2.1),

$A_{traff(i)}$ represents the adjustment for traffic flow, the vehicle volume and speed for the i^{th} vehicle type (Sections 1.2 & 2.3.2),

A_d represents the adjustment for distance between the roadway and receiver and for the length of the roadway (Sections 1.2 & 2.3.3), and

A_s represents the adjustment for all shielding and ground effects between the roadway and the receiver (Sections 1.3 & 2.4).

The TNM is based on a three-dimensional coordinate system and is designed to run on a personal computer (PC).[1] This manual documents the equations and algorithms that form the TNM.

1.1 Vehicle Emission Levels

The TNM incorporates an entirely new data base of vehicle noise emission levels, based on measurements conducted throughout the U.S. in 1994 and 1995 [Fleming 1995]. Components of those data include:

- Slow-speed and accelerating vehicles
- Bus and motorcycle data
- Vehicles on grade
- Vehicles on different pavement types, including dense-graded asphaltic concrete (DGAC), open-graded asphaltic concrete (OGAC), and Portland cement concrete (PCC).

Other aspects of the noise emission data are:

- Energy apportioned to two source heights: one at the pavement level and one at 1.5 meters (5 feet) above the pavement, except for heavy trucks, where the upper height is 3.66 meters (12 feet) above the pavement.
- Data stored in ⅓-octave bands.

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1 See the User's Guide for details on the recommended PC platform.

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 ⅓-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.

1.3 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, top widths and side slopes; they are computed as if they were terrain lines.
- 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].

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

- 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.
- 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.

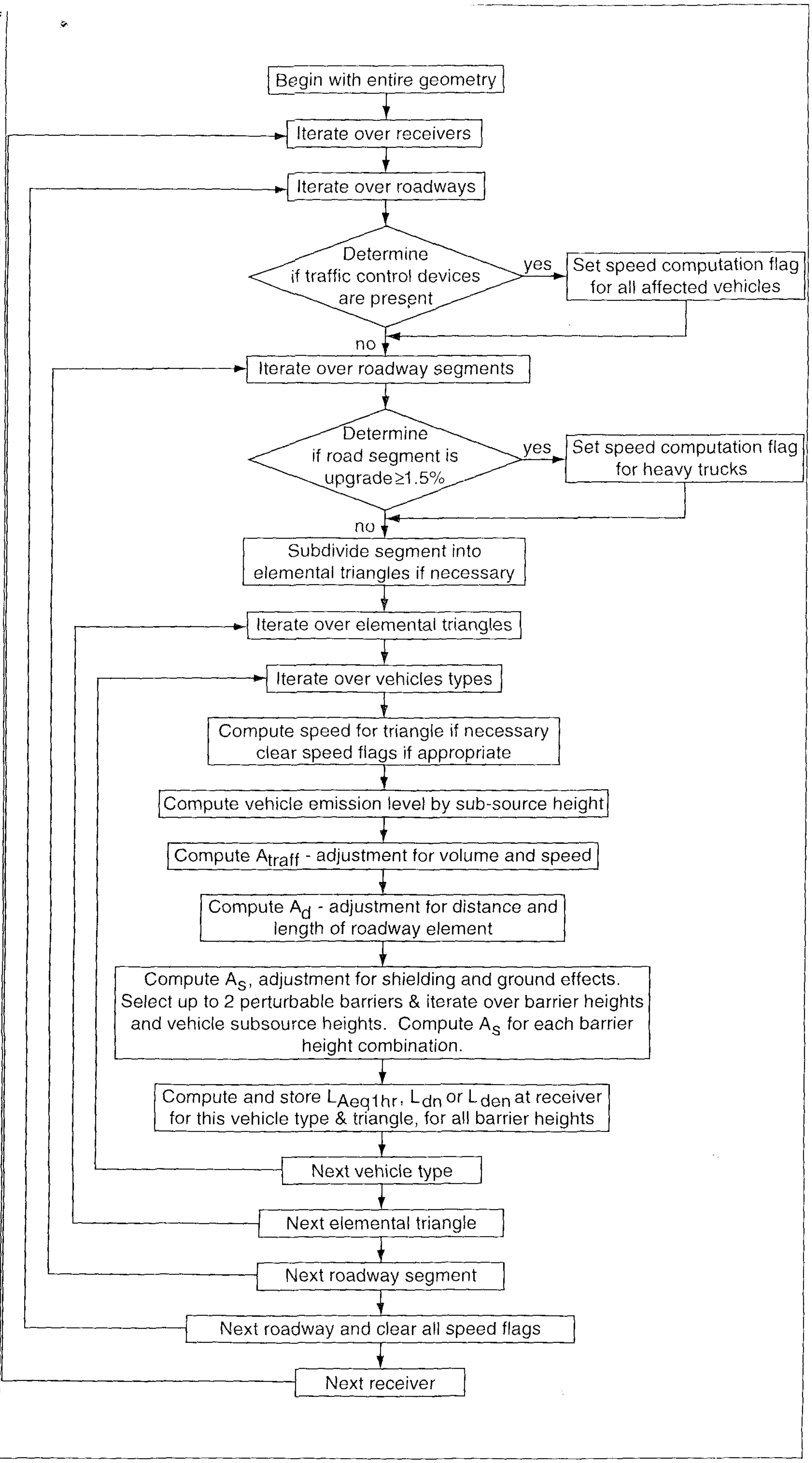
More details on the computation of shielding and ground effects are given in Sections 2.4, 2.5, 2.6, and Appendix D of this manual.

1.4 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.

1.5 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.



'igure 1. High-level flow chart of TNM calculations.

2. MODEL DESCRIPTION

The following section of the manual describes the basic formulation, capabilities and logic flow of the FHWA TNM®. As appropriate, references are given to the literature and the detailed appendices. This section limits mathematical description to a minimum; some equations are used where necessary for clarity. The detailed mathematical description is given in the appendixes.

The organization of this section roughly parallels that of the preceding Section 1. First, vehicle noise emission levels are discussed (Section 2.1), followed by discussions of vehicle speed computation (Section 2.2), and free-field noise levels (Section 2.3). A large section is then devoted to the "vertical geometry" and acoustics (Section 2.4), including the basis of the acoustical model, the combining of two cross sections to represent an "elemental triangle," elements in the propagation path, and the logic flow and the geometry modeling of path elements. A section is devoted to the two-dimensional parallel-barrier calculation module (Section 2.5), and lastly, a section on noise contours is included (Section 2.6).

2.1 Vehicle Noise Emission Levels

In 1994 and 1995, the Volpe National Transportation Systems Center Acoustics Facility organized and collected vehicle pass-by noise emission data as the basis for a new emissions data base for the TNM [Fleming 1995]. Approximately 6000 vehicles were measured in 9 states. As described in Section 1, data were collected for many vehicles under various operating conditions. The data base includes automobiles (2 axles and 4 tires), medium trucks (2 axles and 6 tires), heavy trucks (3 or more axles and 6 or more tires), buses (2 or 3 axles and 6 or more tires) and motorcycles (2 or 3 tires). Data were collected for vehicles cruising, accelerating, idling, and for vehicles on grades. In addition, data were obtained for vehicles traveling different pavement types, including DGAC, OGAC, and PCC. Both ⅓-octave band data and A-weighted sound level data were collected.

Figure 2 shows the 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). The complete set of emission level curves for all vehicle types under all conditions is given in Appendix A. The appendix also shows the generalized vehicle spectra at various speeds. The ⅓-octave band emission level spectra are used by the TNM for all sound level calculations.

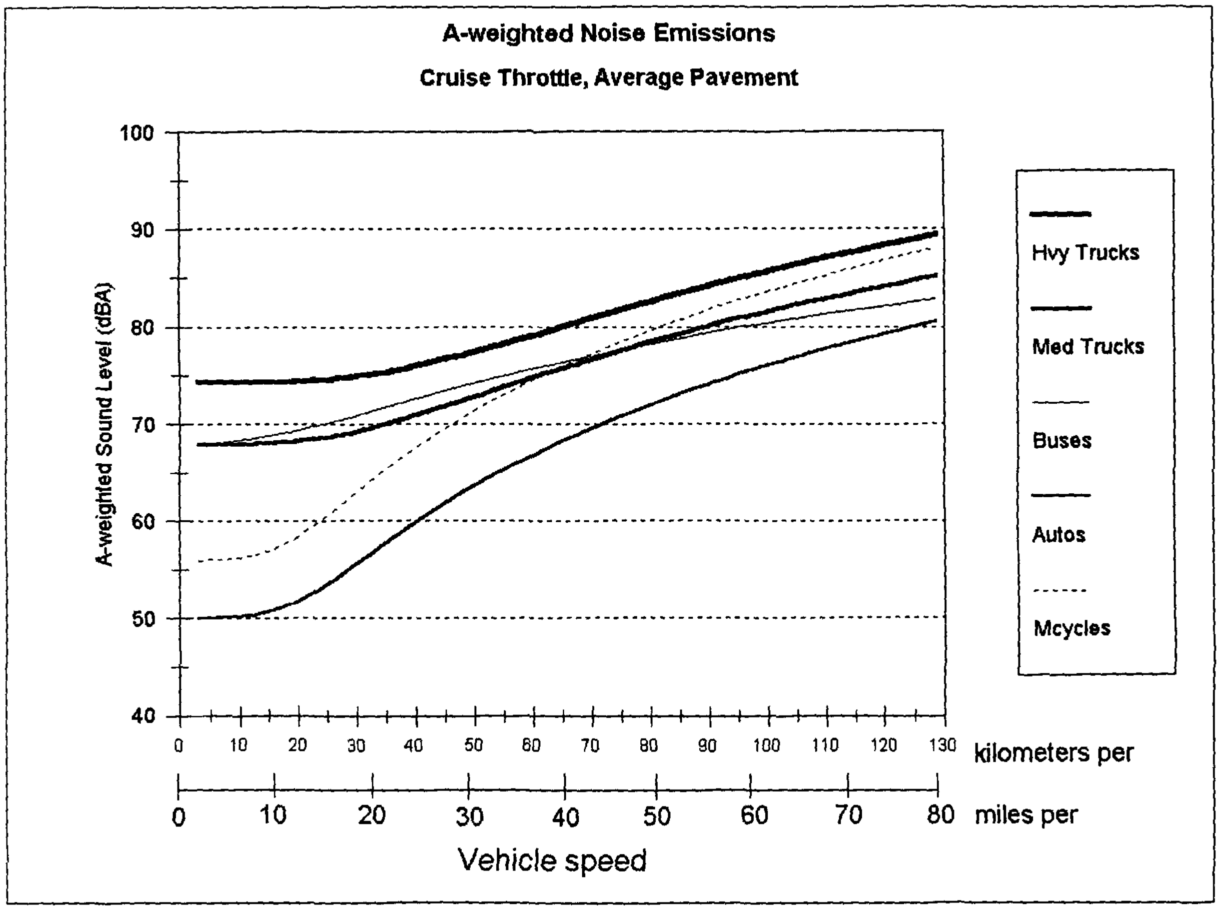


Figure 2. A-Weighted Vehicle Noise Emission Levels under Cruise Conditions

Noise data acquisition methods, data analysis procedures, and the complete set of emission levels for vehicles under all conditions are documented in *Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model* [Fleming 1995]. Additional detail pertaining to accelerating vehicles are documented by Bowlby [Bowlby 1997].

TNM uses the full-throttle emission levels where there is an upgrade roadway (heavy trucks only on grades equal to 1.5 percent or more) or where user-entered traffic control devices indicate an acceleration condition. (The next section discusses speed computations associated with these conditions.)

An additional 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 are 0 meters (0 feet) and 1.5 meters (5 feet) above the pavement for all vehicles except heavy trucks, where the upper source is 3.66 meters (12 feet) 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 (cruising or full throttle). Table 1 shows the percentage of total emission sound energy distributed to the upper source height at the low frequencies and at the high frequencies. In the middle frequency range, between 500 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

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	37%	2%
Medium Trucks & Buses	Cruise	57	7
Medium Trucks & Buses	Full Throttle	58	13
Heavy Trucks	Cruise	37	26
Heavy Trucks	Full Throttle	37	28
Motorcycles	Cruise or Full Throttle	58	13

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

2.2 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 "percentage of vehicles affected." Stop signs, toll booths, and on-ramp start points affect 100 percent of the vehicles. However, traffic signals affect only the portion of the traffic stopped at the red signal phase, so the TNM allows the user to define the percentage of vehicles affected by traffic signals. Speed computations are stopped at whichever comes first: the vehicles accelerate back up to the user's input speed, or the end of the current roadway. TNM *never* tracks vehicles from one roadway to the next when computing speeds. Appendix B provides more detailed descriptions of the way speeds are computed and the conditions under which they are computed.

2.3 Free Field Levels and Horizontal Geometry

The following section describes the way the TNM computes free-field sound levels. In this section, we define two of the three adjustment terms in the equation for L_{Aeq1h} presented in Section 1, $A_{traff(I)}$ for traffic flow and A_d for distance and roadway length. First, the way in which TNM divides up the "horizontal geometry" into "elemental triangles" is described.

2.3.1 Elemental triangles.

The term "horizontal geometry" represents the *x-y* plane (the geometry in plan view). Before any details in the vertical plane (*z* direction) are evaluated, TNM must break down the overall geometry into small "elemental triangles," each defined by a receiver and two points on a roadway segment. An elemental triangle is the smallest unit of a roadway line segment that TNM evaluates; there can be no points inside an elemental triangle, only at its edge. Various input objects may cross inside the triangle, such as barriers, terrain lines, buildings, and tree zone lines. The acoustical effects of these elements are considered separately, and are discussed below in Section 2.4.2. Figure 3 shows how first-level roadway-to-receiver elemental triangles are defined by the closest spacing of the object endpoints in the x-y plane.

To ensure sufficient precision where object endpoints are not closely spaced (as in Figure 3), TNM divides elemental triangles so that the maximum subtended angle is no larger than a fixed size. For example, Figure 4 shows Figure 3 after TNM imposes upon it a maximum angle of 10 degrees. Further subdivision of elemental triangles is not performed.

The primary factors of concern in the horizontal geometry are roadway geometry relative to the receiver, and traffic flow. These combine with the vehicle noise emission levels to produce an overall free-field sound level at the receiver associated with each elemental triangle.

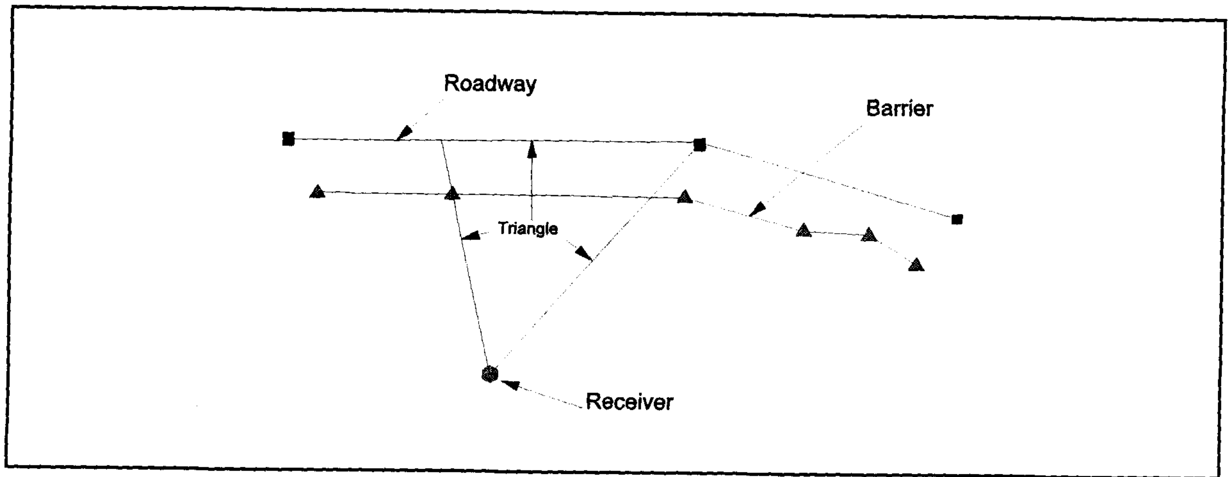


Figure 3. First-level elemental triangle.

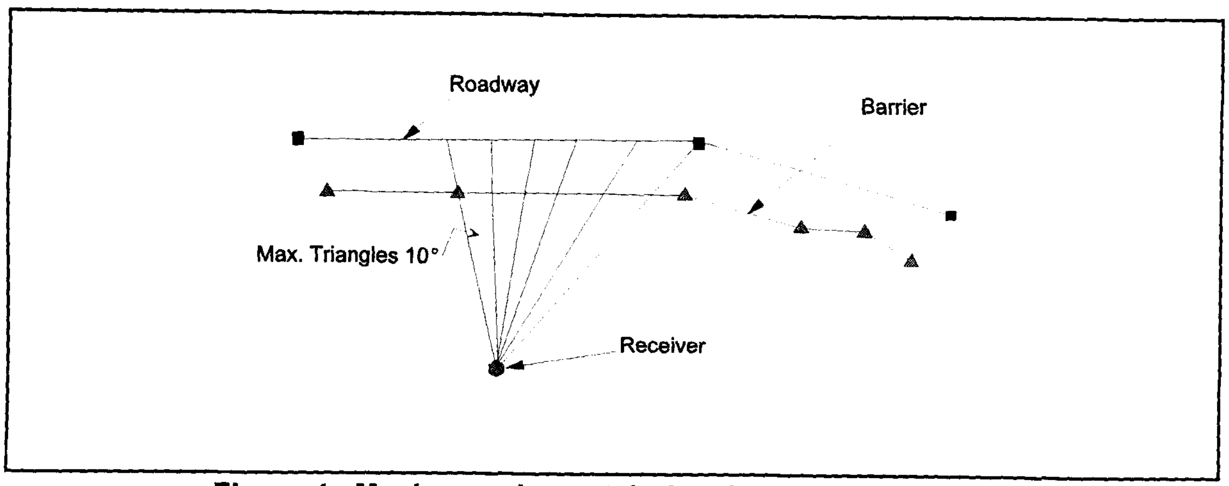


Figure 4. Maximum elemental triangle set to 10 degrees.

2.3.2 Traffic flow adjustment.

The adjustment for traffic flow is simply a function of vehicle volume (number of vehicles per hour) and speed. Of course, the adjustment is computed separately for each vehicle type:

$$A_{traff(i)} = 10 \times Log_{10}\left(\frac{V_i}{S_i}\right) - 13.2 \quad dB, \tag{2}$$

where V_i is the vehicle volume in vehicles per hour,
and S_i is the vehicle speed in kilometers per hour.

Although not shown here, the computation of $A_{traff(i)}$ is performed in ⅓-octave bands for each sub-source height. Those details are shown in Appendix C.

interference (cancellation) 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 relatively near the ground. The TNM allows users to enter various ground types, which are based on the effective flow resistivity measured by Embleton [Embleton 1983]. The ground types and associated EFR are given in Table 2.

Table 2. Ground Type and Effective Flow Resistivity

Ground Type Name	Effective Flow Resistivity (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 represents a generic acoustically hard ground surface. TNM's Field Grass ground type represents a generic acoustically soft ground surface.

Impedance discontinuities: Impedance discontinuities occur where one ground type changes to another. An impedance discontinuity can occur without the user specifying one explicitly, as at the edge of the roadway when the default ground type is "lawn." They also occur where a user has entered a "ground zone" with a different ground type from the default.

Diffraction components are often computed at impedance discontinuities. Where a reflection occurs near an impedance discontinuity, a diffracted path from the impedance discontinuity must be computed to modify the magnitude and phase of the reflected path. The diffracted component is needed for the sound field to remain continuous across the discontinuity.

Barriers: 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 (height "perturbations"). The TNM can compute diffraction from the barrier top and its base points on both sides.

The De Jong [De Jong 1983] model requires computation of reflections in the barrier surfaces to compute single-barrier diffraction properly. This is the way the model 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.

The users specify an NRC for a barrier surface, which is then used to compute a reflection coefficient. The approach taken to determine a reflection coefficient based on barrier surface NRC follows the approach used for ground surfaces, to maintain consistency within the model. As with ground, the barrier's surface impedance is computed from a value of effective flow resistivity (EFR). The approach is described in detail in Appendix D; it is described here briefly. 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 from Delany's empirical fit for fibrous materials [Delany1970]. Individual values of EFR were found that corresponded to values of NRC (see Table 3). This approach allowed a single parameter to be used for each value of NRC chosen by the user. Figure 5 shows the absorption coefficients as a function of frequency that are used within TNM for selected values of NRC.

Table 3. Effective Flow Resistivity used for values of Noise Reduction Coefficient (NRC).

NRC	EFR(cgs rayls)
0.00	20000.0
0.05	4250.0
0.10	1570.0
0.15	865.0
0.20	555.0
0.25	385.0
0.30	282.0
0.35	214.0
0.40	165.0
0.45	129.0
0.50	102.0
0.55	81.0
0.60	64.0
0.65	50.0
0.70	39.0
0.75	30.0
0.80	22.0
0.85	16.0
0.90	10.4
0.95	5.5
1.00	0.1

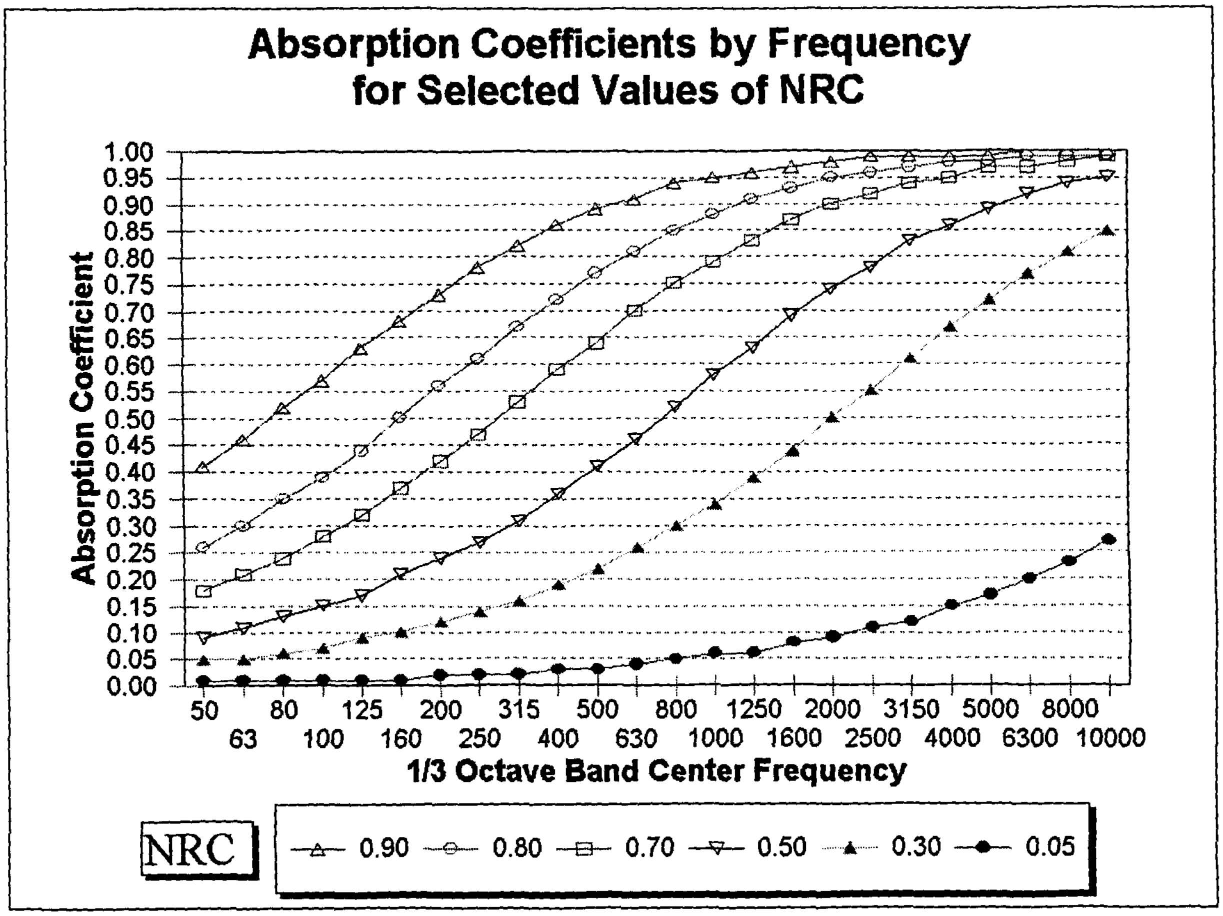


Figure 5. Absorption coefficient as a function of frequency for selected values of NRC

Berms: To the TNM's acoustical calculations, berms are simply a series of ground points. Users have the option of entering berms as a type of barrier, with heights, top widths, and side slopes. In that case, the TNM's vertical geometry routines must compute the location of the intersections between the bases of berms and the ground. Those intersections then become ground points in the vertical geometry. Berms that break the source-to-receiver line of sight and that are defined with a finite top width have two diffracting edges. This will lead to somewhat greater insertion loss than for "wedges" (berms with no top width). 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.

Berms assume 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.

Tree zones: The 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. TNM uses the 1996 ISO standard attenuation for dense foliage [ISO 9613-2], 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 4. In TNM, the octave-band values shown in Table 4 are applied to each of the ⅓-octave bands within the associated octave band.

Table 4. 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

Building rows: The TNM incorporates rows of buildings as optional elements in the propagation path. Like tree zones, they have both ground height and top height, but building rows have no width. Rows of buildings 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 of the German rail industry standard [Kurze 1988] (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 a mixed-traffic spectrum; the limits are 8.4 dB at 500 Hz and 10.4 dB at 1000 Hz). Rows of buildings are not treated like barriers within TNM, in that propagation paths are allowed to go through building rows. 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.

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

2.4.4 Logic flow and 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 are covered in greater detail in Appendix D, often with illustrations and examples.

Perturbable barriers: The 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.

Highest path points, including barriers and ground points: The 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 from all of them, and only the most effective pair is retained. 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 diffraction was available for the purpose of validation.

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.

Regression ground and near-highest path points: 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 1997], which is described below as it occurs in the logic flow. 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 (described above).

Ground regression is performed at this stage in the process. 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. 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.

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.

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 the 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.

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 ⅓ octave band. Appendix D explains this approach further and includes an illustrative example.

Sum over propagation paths: Finally, for each ⅓-octave frequency band, TNM computes contributions to the acoustic pressure from each propagation path at the receiver. The complex sum (magnitude and phase) of each 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.

2.5 Parallel Barrier Analysis

The TNM incorporates a two-dimensional ray-tracing module for computing multiple sound reflections [Menge 1991]. The module is designed to assist users in calculating the acoustical effects of parallel barriers or retaining walls on both sides of a highway.
Two things change acoustically when a roadway is flanked by parallel barriers or retaining walls. First, direct lines-of-sight between vehicles and receivers are interrupted by the intervening barrier or retaining wall. 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 receivers; this increase is called "degradation" of barrier insertion loss.

The TNM's regular sound-level computations cannot take multiple reflections into account, and therefore cannot predict the degradation of barrier performance due to parallel barriers or retaining walls. However, TNM contains a special module that can be used to compute values of degradation due to multiple reflections in two dimensions.

Users enter the vertical-plane cross-section geometry and assign values of NRC to each surface. (Appropriate values of NRC are 0.05 for hard surfaces like pavement and concrete walls, and 0.30 for grass.) The module can handle very general cross sections, including tilted barriers and walls.

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 TNM's multiple-reflections module allows complete flexibility in cross-sectional geometry, the location of roadways between the parallel barriers or retaining walls, and 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.

Appendix E contains details of TNM's parallel-barrier computations.

2.6 Contours

The TNM computes sound levels and analyzes barrier designs at receivers that are individually entered by the user. In addition, the TNM allows the user to compute contours within specified contour zones. Three types of contours are available:

- Sound-level contours for a specified barrier design, in the user's chosen set of sound-level units: L_{Aeq1h} , L_{dn} , or L_{den}
- Insertion-loss 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 above the ground. If needed, it subdivide each grid cell and adds additional receivers to obtain the user's requested contour tolerance.

Once the 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 submits this grid file to the computer program NMPLOT Version 3.05, which computes the corresponding contours and returns them to the TNM for display.

Appendix F provides more detail on contours.

2.7 Model Verification

Comparisons of TNM results to measurements and to the model results of others were made. Specifically, five different data sets were used for the comparisons, three of which involved point-source geometry, and the remaining two involved in-situ measurements of barrier performance along actual highways.

Appendix G provides more detail on the data sets used and presents the results of TNM model verification.

APPENDIX A
VEHICLE NOISE EMISSIONS

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
- 1/3rd-octave-band spectra, relative to A-weighted sound-level emissions
- Vertical subsource strengths, relative to 1/3rd-octave-band spectra.

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

A.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 passby is called that vehicle's noise-emission level.

Measurement of vehicle noise-emission levels for TNM are reported separately [Fleming 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 1/3rd-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 subsources for TNM are also reported separately [Coulson 1996]. These subsource 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.

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

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

p index over 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 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 B).

A.3 A-weighted Noise-Level Emissions and 1/3rd-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 1/3rd-octave-band spectra: D_1, D_2, E_1, E_2, F_1, F_2, G_1, G_2, H_1, H_2, I_1, I_2, J_1 and J_2.

These seventeen constants depend upon two variables, *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.

A.3.1 Built-in vehicle types Table 5 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 5 into the following set of equations, to determine each vehicle type's total measured noise emissions:

$$
\begin{aligned}
E_A(s_i) &= (0.6214 s_i)^{A/10} 10^{B/10} + 10^{C/10} \\
L_{emis,i}(s_i, f) &= 10 \times \mathrm{Log}_{10}(E_A) + (D_1 + 0.6214 D_2 s_i) + (E_1 + 0.6214 E_2 s_i)[\mathrm{Log}_{10} f] \\
&\quad + (F_1 + 0.6214 F_2 s_i)[\mathrm{Log}_{10} f]^2 + (G_1 + 0.6214 G_2 s_i)[\mathrm{Log}_{10} f]^3 \\
&\quad + (H_1 + 0.6214 H_2 s_i)[\mathrm{Log}_{10} f]^4 + (I_1 + 0.6214 I_2 s_i)[\mathrm{Log}_{10} f]^5 \\
&\quad + (J_1 + 0.6214 J_2 s_i)[\mathrm{Log}_{10} f]^6 \\
E_{emis,i}(s_i, f) &= 10^{(L_{emis,i}/10)},
\end{aligned}
\tag{5}
$$

where speed, s, is in kilometers per hour and "Log_{10}" denotes the common logarithm (base 10).

The first of these equations yields the energy form, E_A, of the maximum passby A-weighted sound level for the vehicle type. The second equation converts this E_A to a 1/3rd-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 1/3rd-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 passbys at 15 meters (50 feet) over flat, generally absorptive terrain.

A.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 1997] 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.

Table 5. Constants for A-weighted sound-level emissions and 1/3rd-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	DG AC	OG AC	PCC	Yes	No	A	B	C	D_1	D_2	E_1	E_2	F_1	F_2	G_1	G_2	H_1	H_2	I_1	I_2	J_1	J_2
X					X				X		41.740807	1.148546	67.00	-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	67.00	-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	67.00	-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	67.00	-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	74.00	-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	74.00	-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	74.00	-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	74.00	-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		35.879850	21.019665	80.00	-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	35.879850	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		35.879850	20.358498	80.00	-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	35.879850	20.358498	74.298135	-290.277032	-196.828915	156.854882	450.144699	151.082001	-420.250062	-168.033708	204.806845	60.772941	-54.968455	-9.681901	7.711617	0.570105	-0.442469
		X					X		X		35.879850	19.107151	80.00	-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	35.879850	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		35.879850	21.822818	80.00	-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	35.879850	21.822818	74.298135	87.378338	-224.132311	-497.410428	509.705253	579.584033	-473.326603	-298.5689955	229.5809	78.021585	-61.374037	-10.058424	8.58403	0.498685	-0.49149
			X		X				X		23.479530	38.006238	74.00	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	-0.282557
			X		X					X	23.479530	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	-0.282557
			X			X			X		23.479530	37.318967	74.00	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	-0.282557
			X			X				X	23.479530	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	-0.282557
			X				X		X		23.479530	36.760406	74.00	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	-0.282557
			X				X			X	23.479530	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	-0.282557
			X					X	X		23.479530	39.556803	74.00	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	-0.282557
			X					X		X	23.479530	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	-0.282557
				X	X	X	X	X	X		41.022542	10.013879	67.00	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	56.00	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

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.

A.4 Vertical Subsources, as Measured

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

A.4.1 Built-in vehicle types Table 6 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 6 into the following equation, to determine the subsource-split ratio, r_i:

$$r_i(f) = \mathrm{L} + (1 - \mathrm{L} - \mathrm{M})\left[1 + e^{(\mathrm{N}\,\mathrm{Log}_{10} f + \mathrm{P})}\right]^{\mathrm{Q}} . \qquad (6)$$

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 subsource 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 subsource height data base contains limited data at low speeds (less than 30 mph). If additional subsource 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 subsources:

$$\begin{aligned} \mathrm{E}_{\mathrm{emis},\,i,\,\mathrm{upper}}(s_i, f) &= \left(\frac{r_i}{r_i + 1}\right) \mathrm{E}_{\mathrm{emis},\,i} \\ \mathrm{E}_{\mathrm{emis},\,i,\,\mathrm{lower}}(s_i, f) &= \left(\frac{1}{r_i + 1}\right) \mathrm{E}_{\mathrm{emis},\,i} . \end{aligned} \qquad (7)$$

Physically, this last equation represents each vehicle type's energy-mean emission spectrum, split into its two vertical subsources, as measured during individual vehicle passbys 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.

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		0.577394	0.609787	-309.046731	890.880597	-8519.429646
		X			X	X	X	X		X	0.594848	0.643317	-36.503587	102.627995	-132.679357
			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	0.32	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	0.30	0.30	0.32	0.34	0.37	0.44	0.55	0.81	1.55	5.37	4.47	1.02
	Height: zero	0.30	0.31	0.32	0.34	0.35	0.38	0.41	0.44	0.47	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	0.30	0.25	0.22	0.21	0.21	0.3	0.36

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):

- Figures 7 through 16: A-weighted sound-level emissions
- Figures 17 through 32: emission spectra, separately by pavement type
- Figures 33 through 40: high/low energy split.

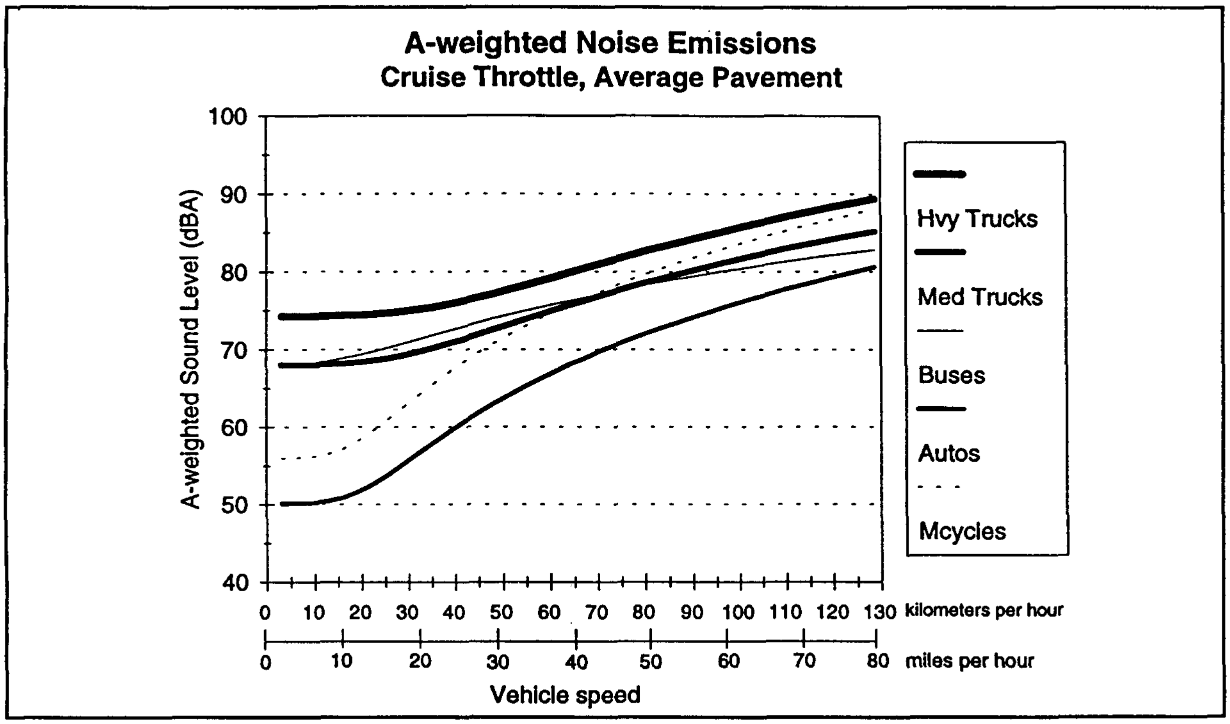


Figure 6. A-weighted sound-level emissions: Average pavement, cruise throttle.

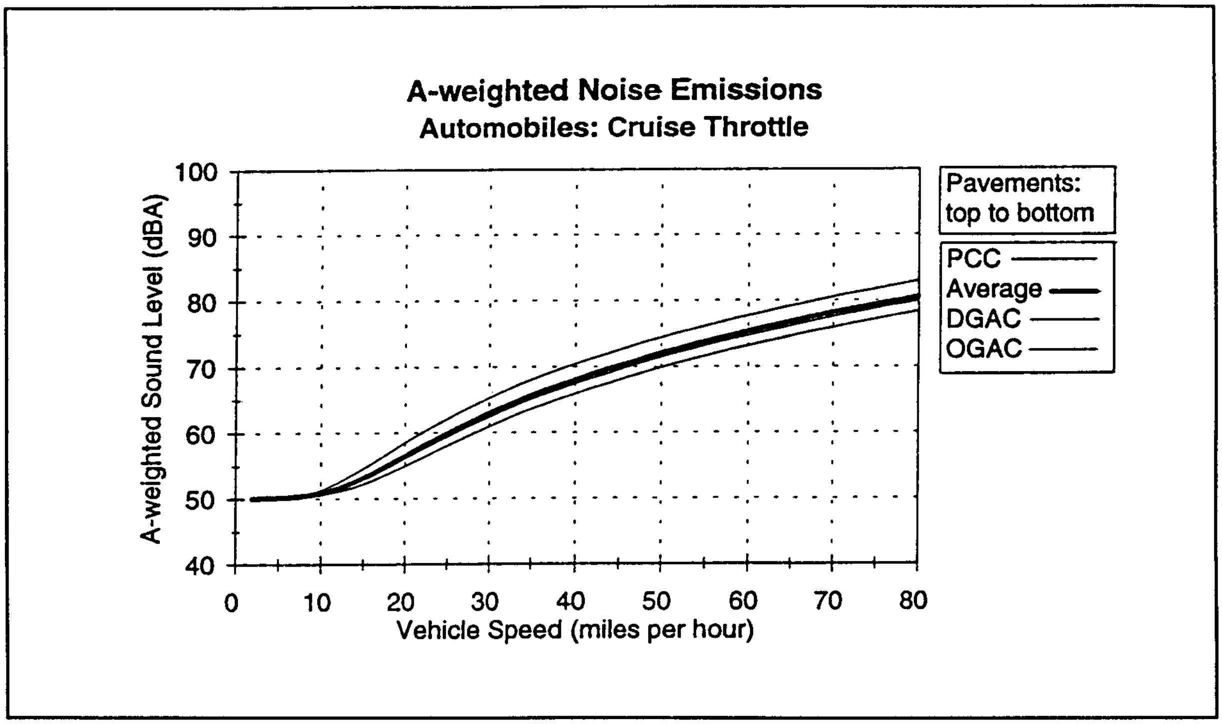


Figure 7. A-weighted sound-level emissions: Automobiles, cruise throttle.

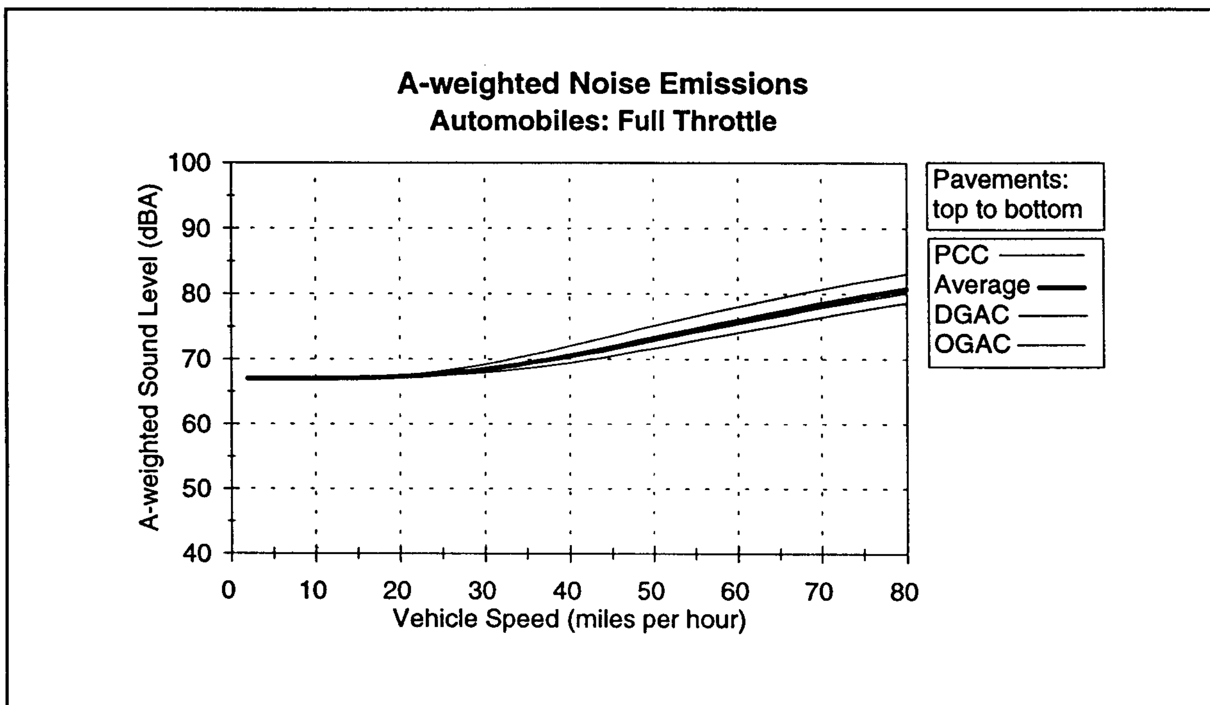


Figure 8. A-weighted sound-level emissions: Automobiles, full throttle.

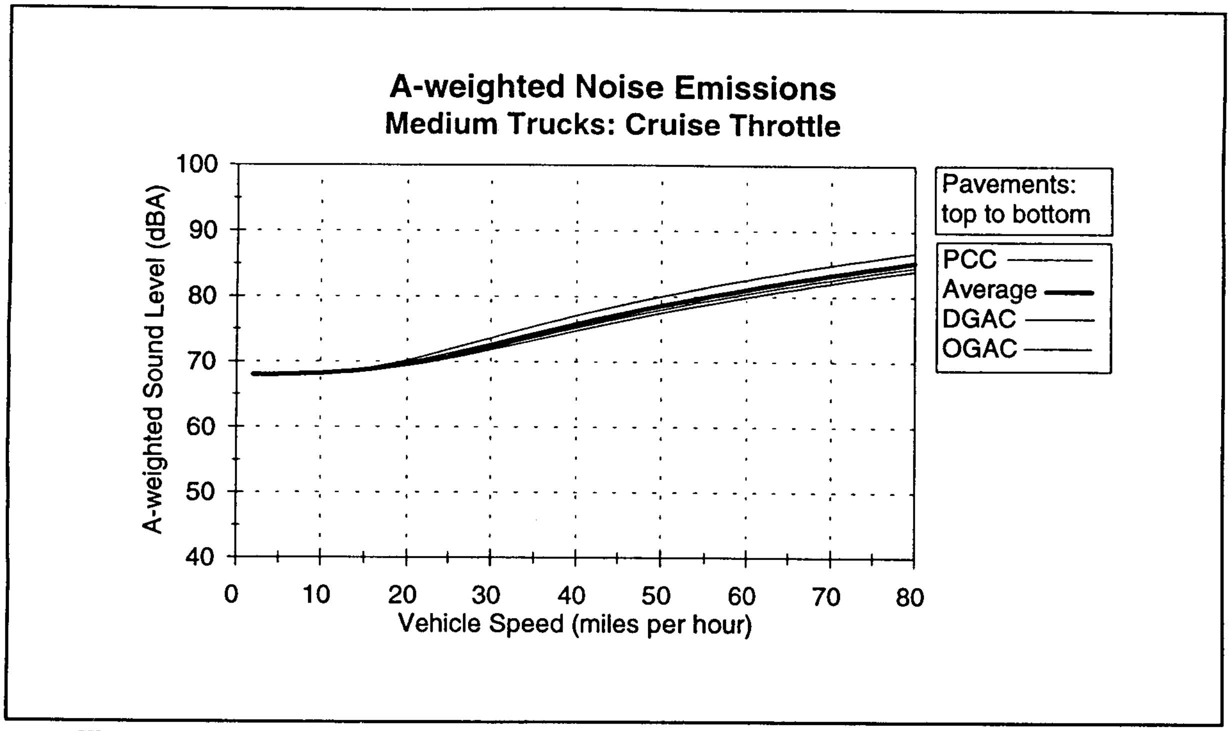


Figure 9. A-weighted sound-level emissions: Medium trucks, cruise throttle.

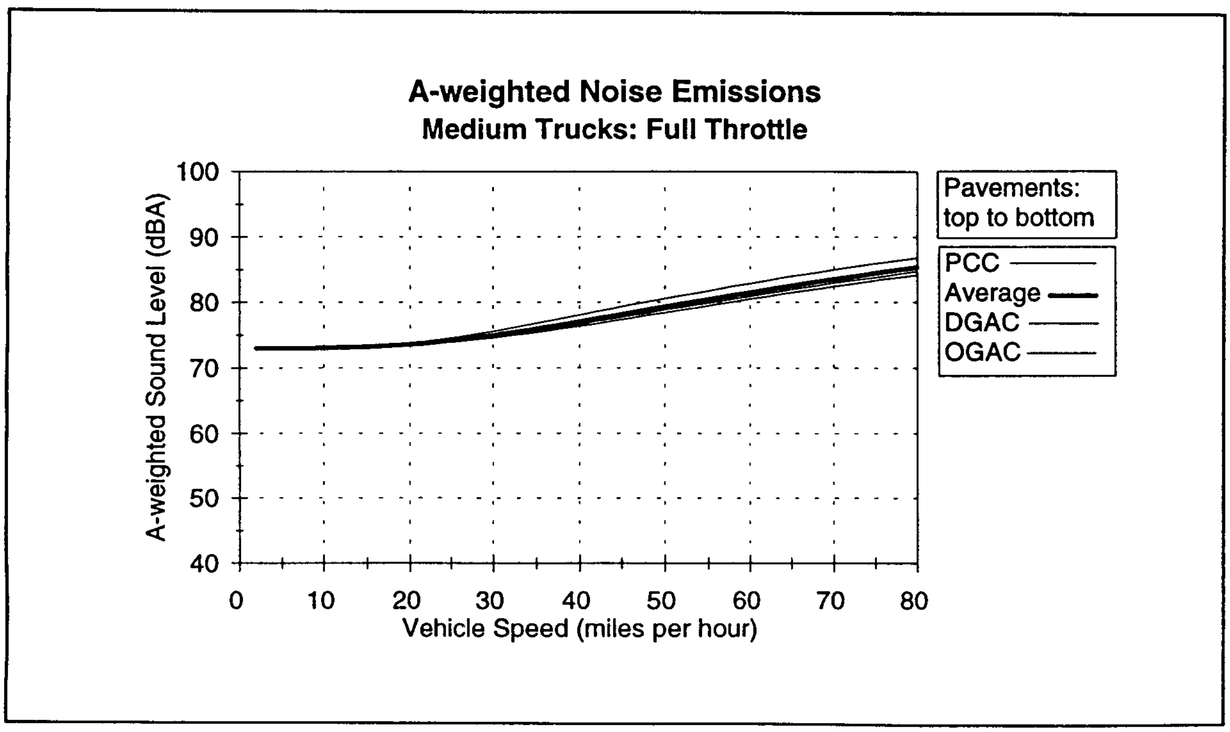


Figure 10. A-weighted sound-level emissions: Medium trucks, full throttle.

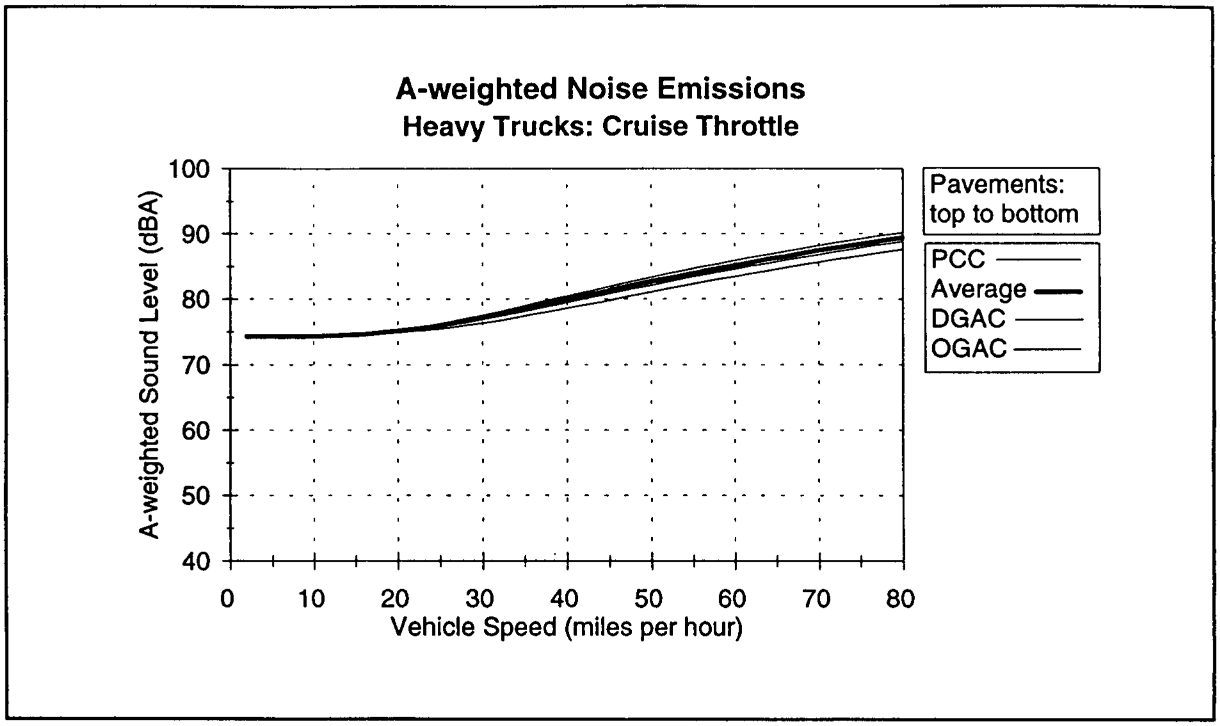


Figure 11. A-weighted sound-level emissions: Heavy trucks, cruise throttle.

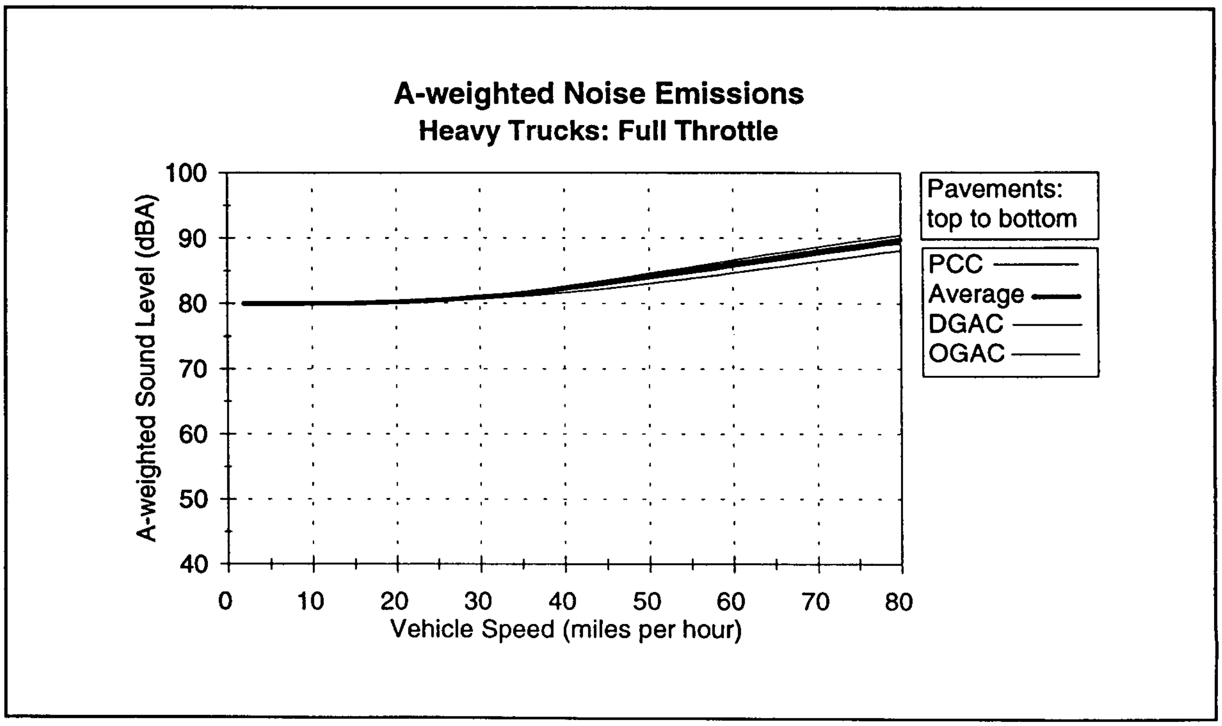


Figure 12. A-weighted sound-level emissions: Heavy trucks, full throttle.

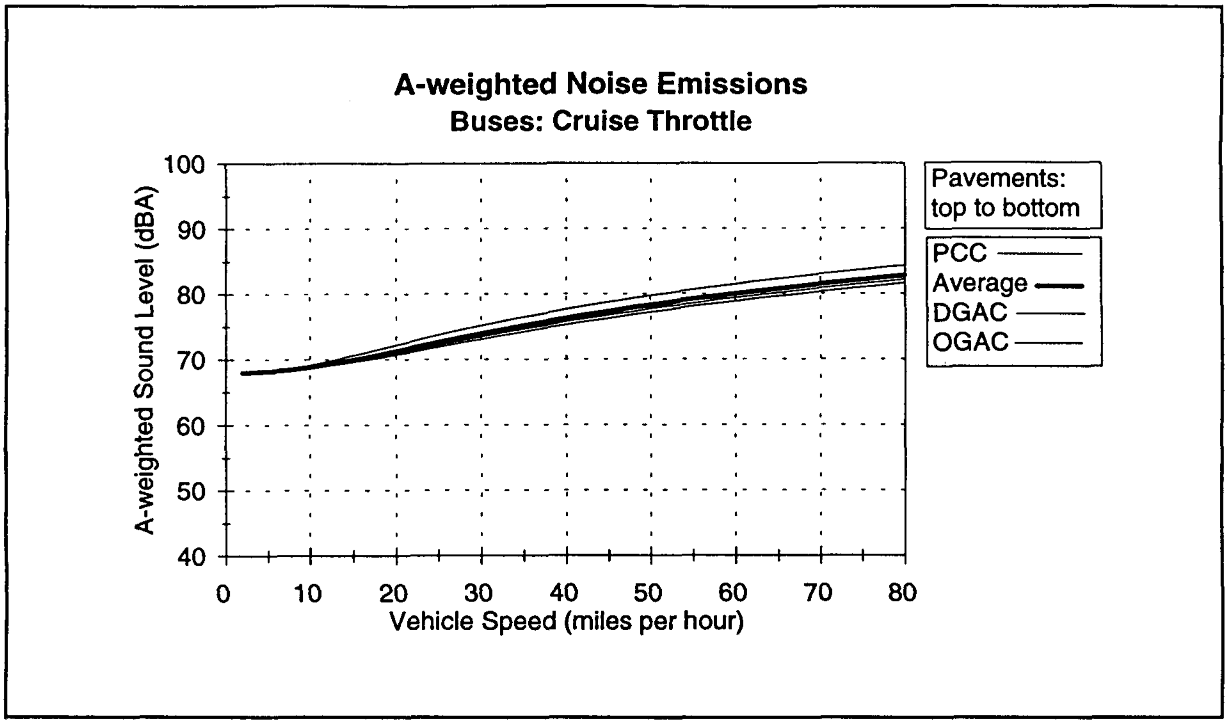


Figure 13. A-weighted sound-level emissions: Buses, cruise throttle.

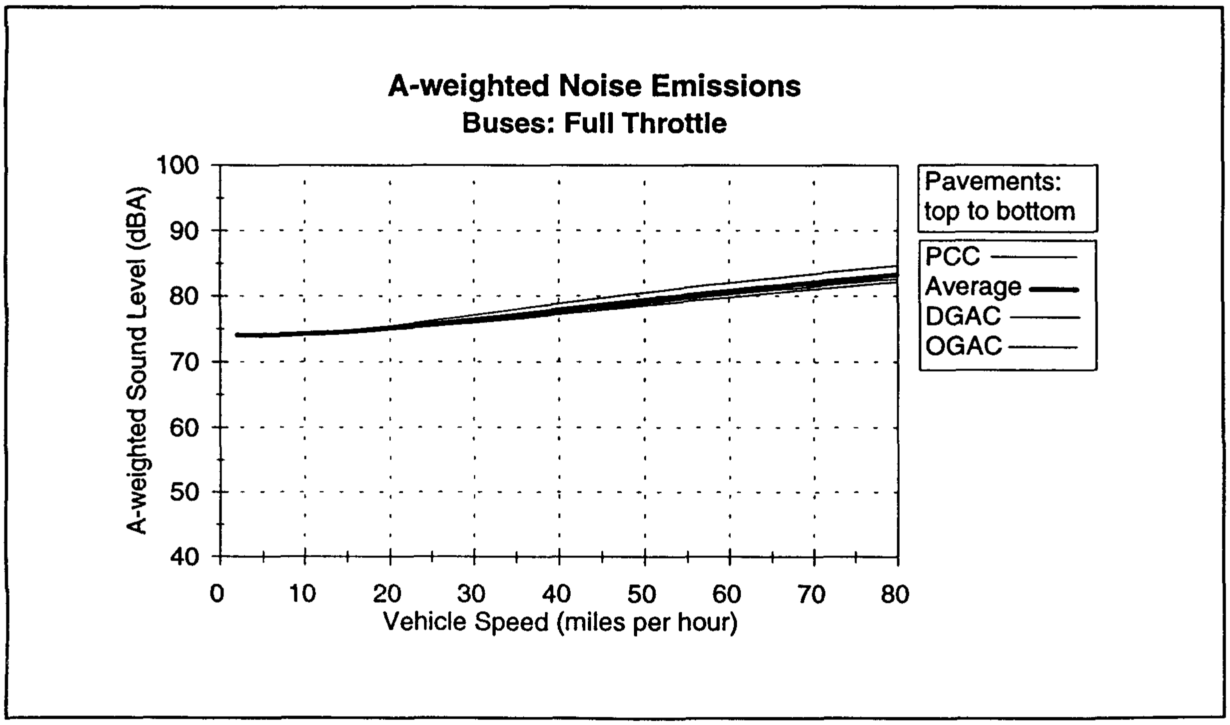


Figure 14. A-weighted sound-level emissions: Buses, full throttle.

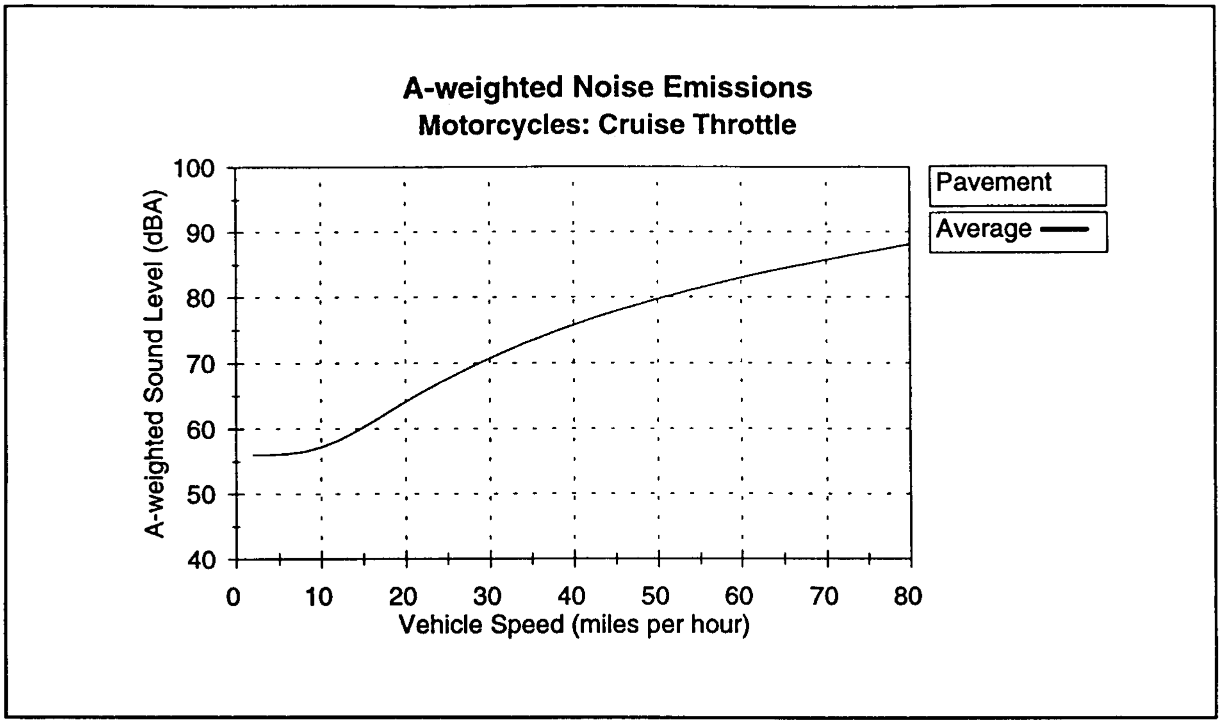


Figure 15. A-weighted sound-level emissions: Motorcycles, cruise throttle.

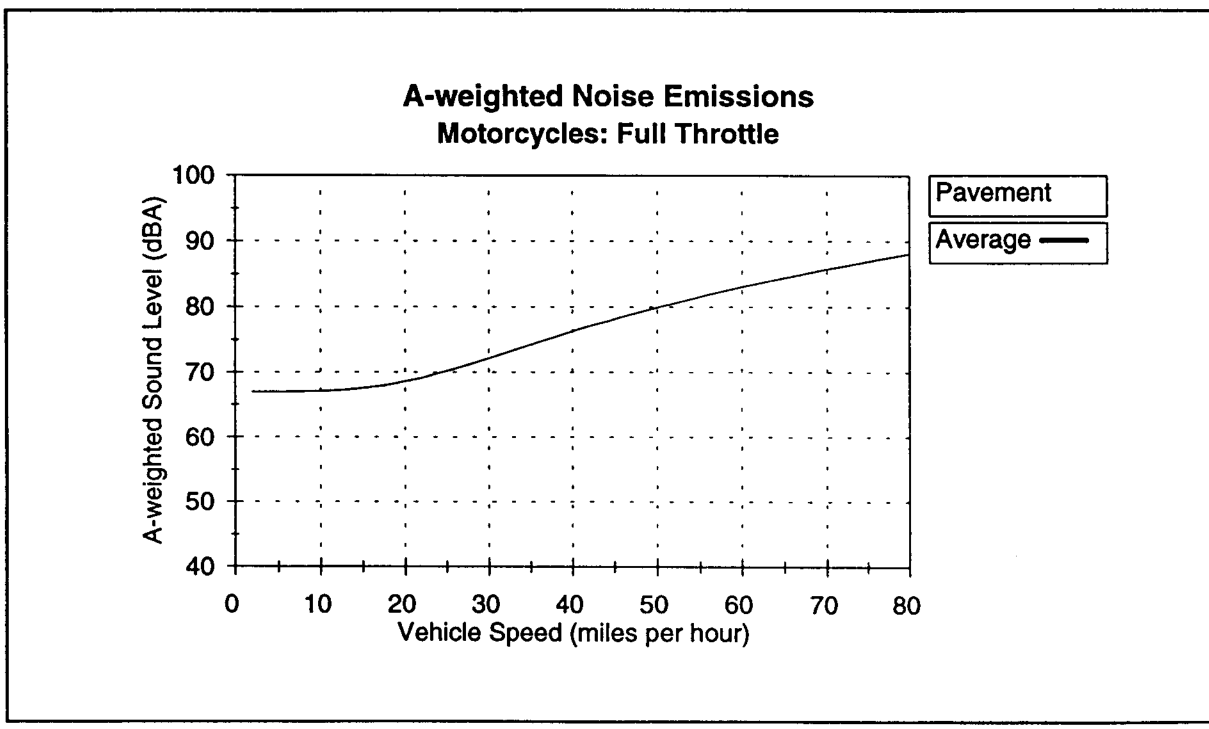


Figure 16. A-weighted sound-level emissions: Motorcycles, full throttle.

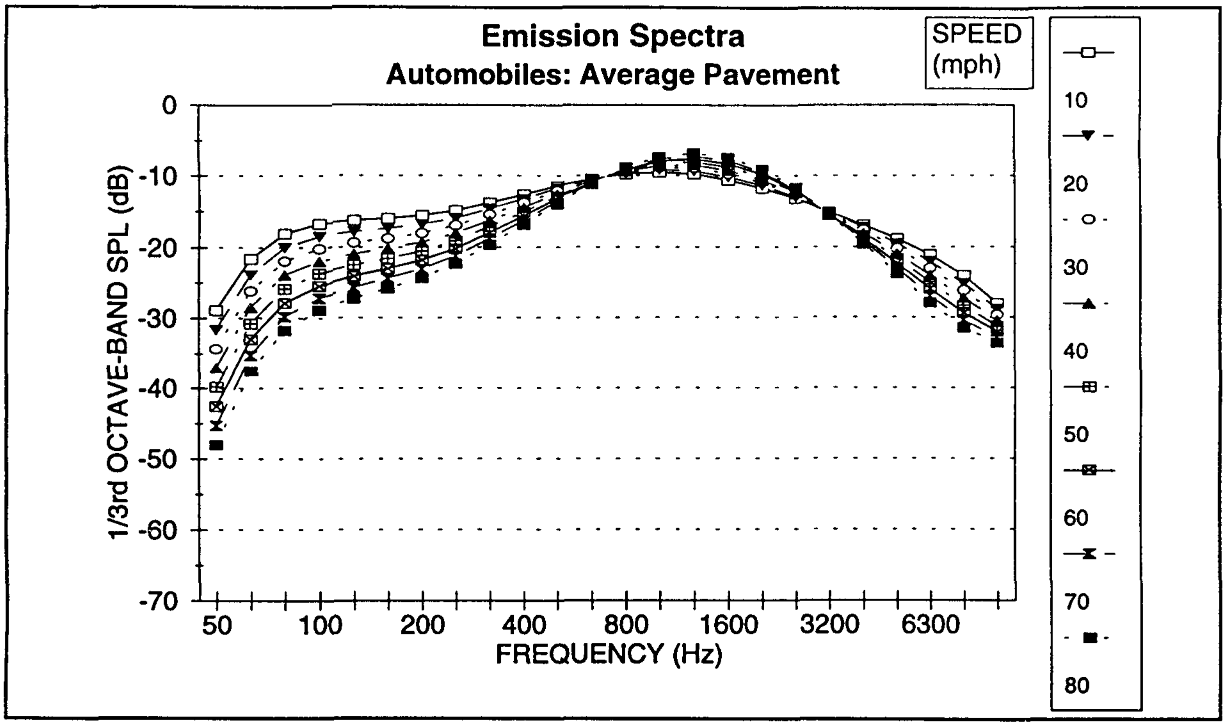


Figure 17. Emission spectra: Automobiles, average pavement.

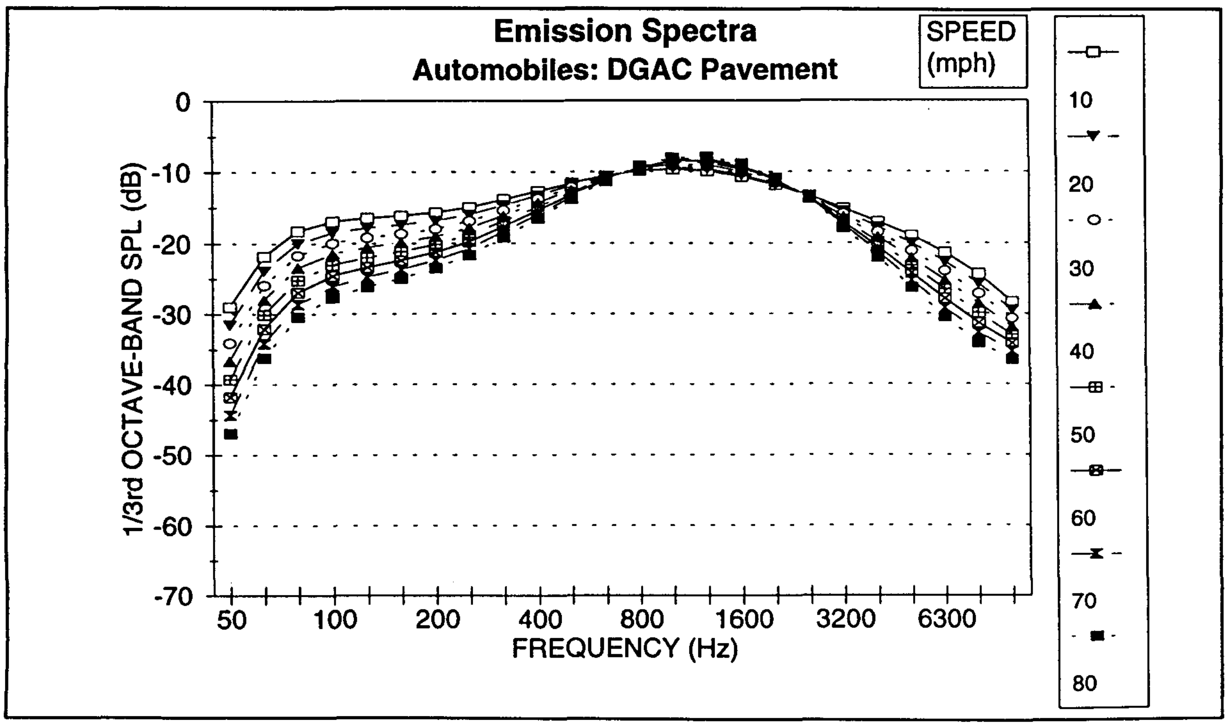


Figure 18. Emission spectra: Automobiles, DGAC pavement.

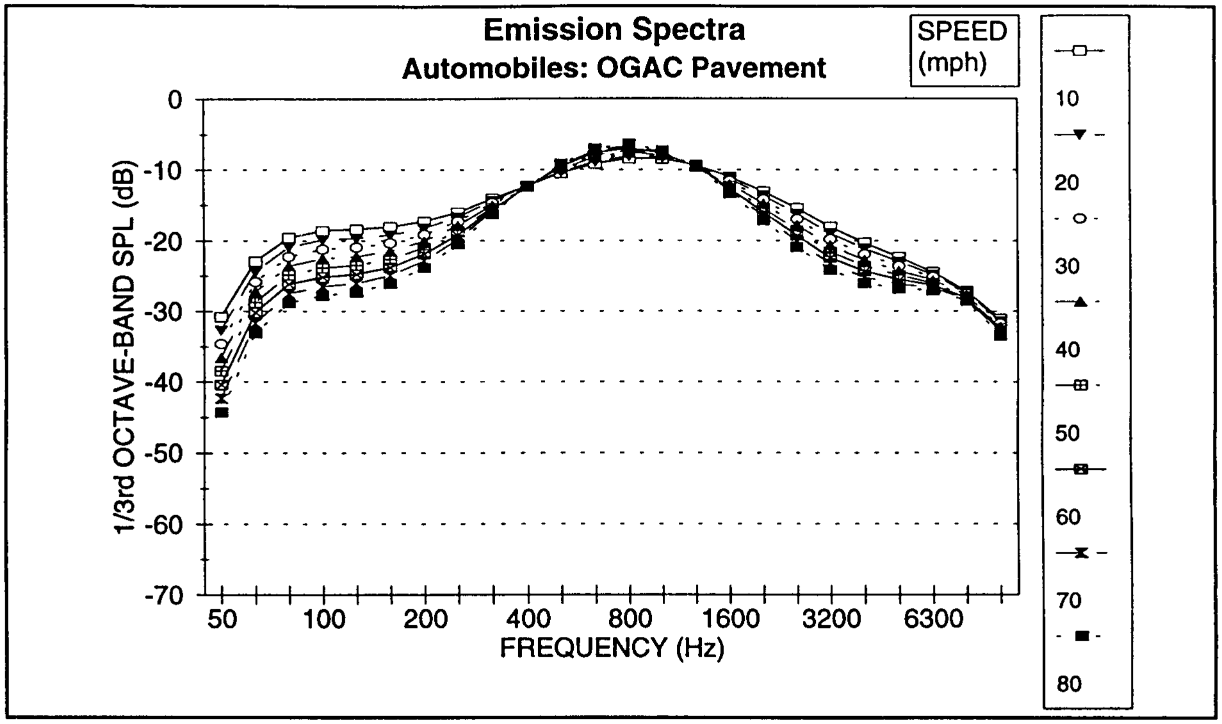


Figure 19. Emission spectra: Automobiles, OGAC pavement.

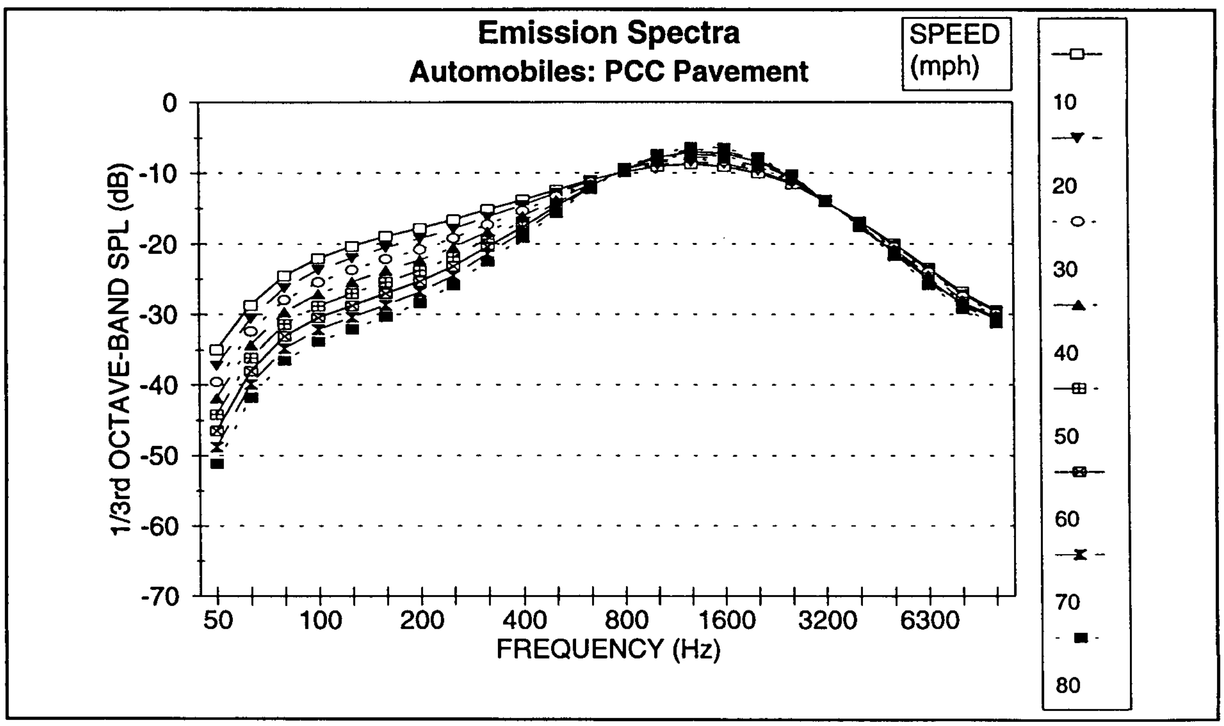


Figure 20. Emission spectra: Automobiles, PCC pavement.

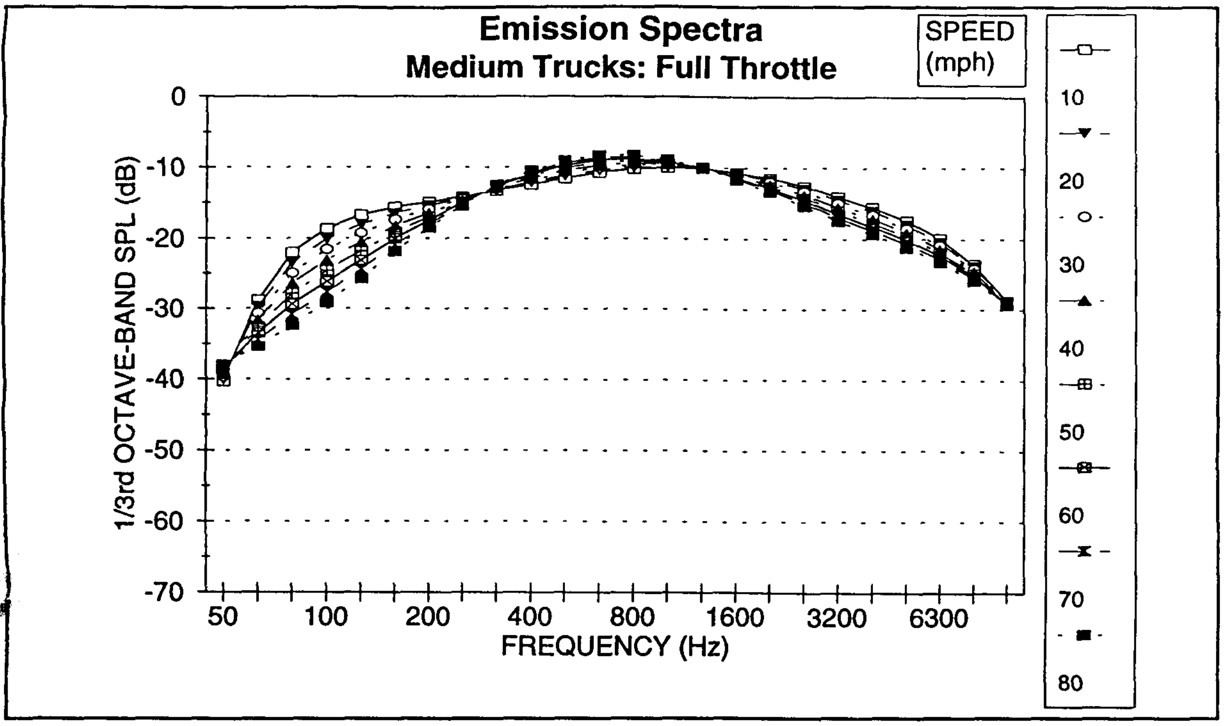


Figure 21. Emission spectra: Medium trucks, full throttle.

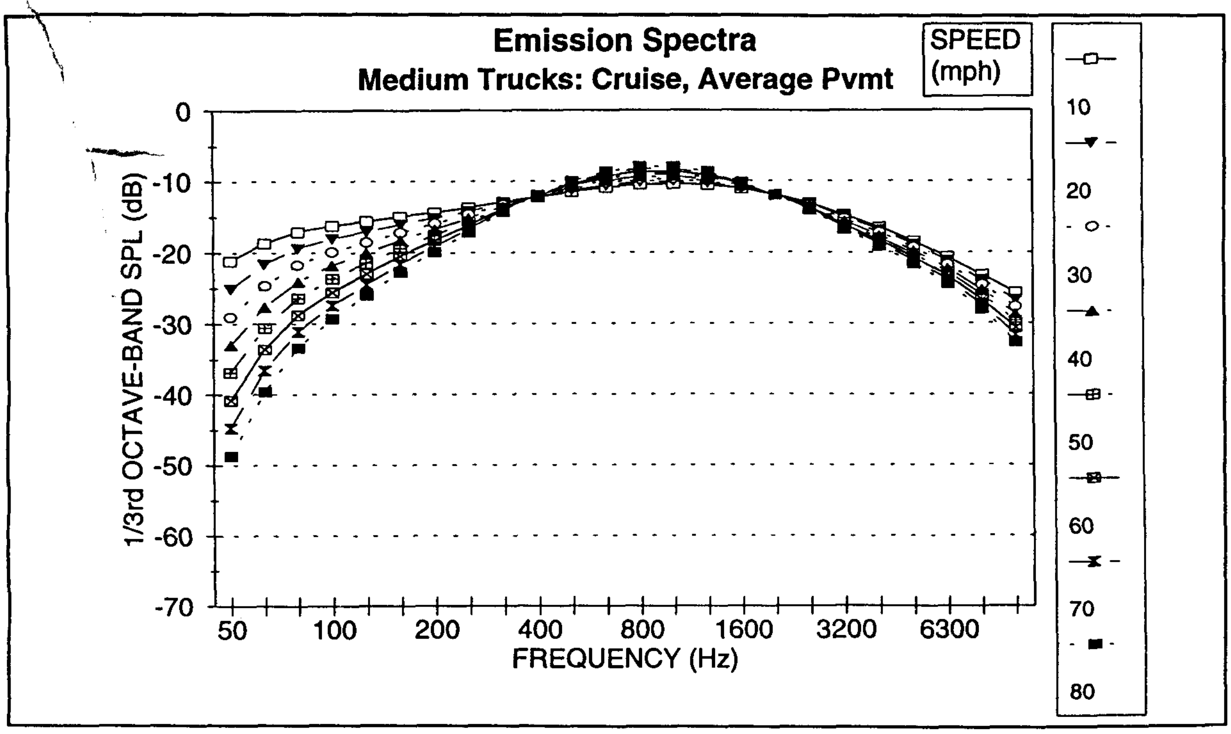


Figure 22. Emission spectra: Medium trucks, cruise throttle, average pavement.

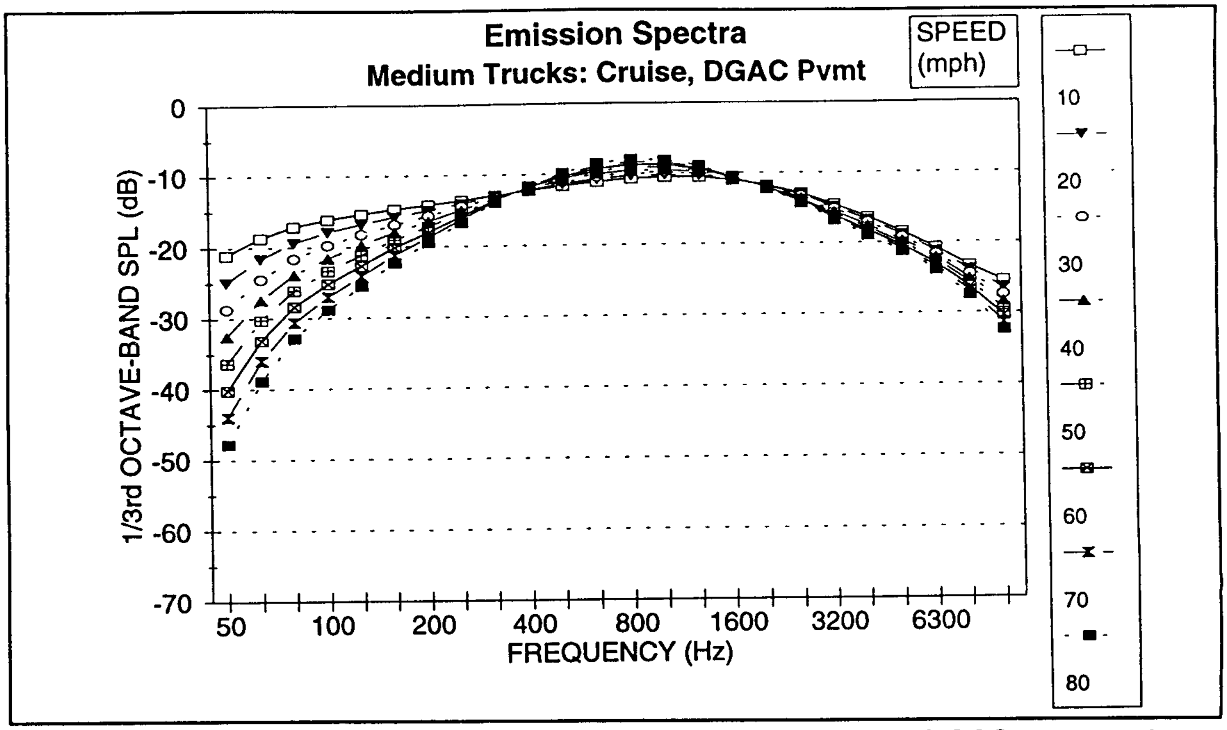


Figure 23. Emission spectra: Medium trucks, cruise throttle, DGAC pavement.

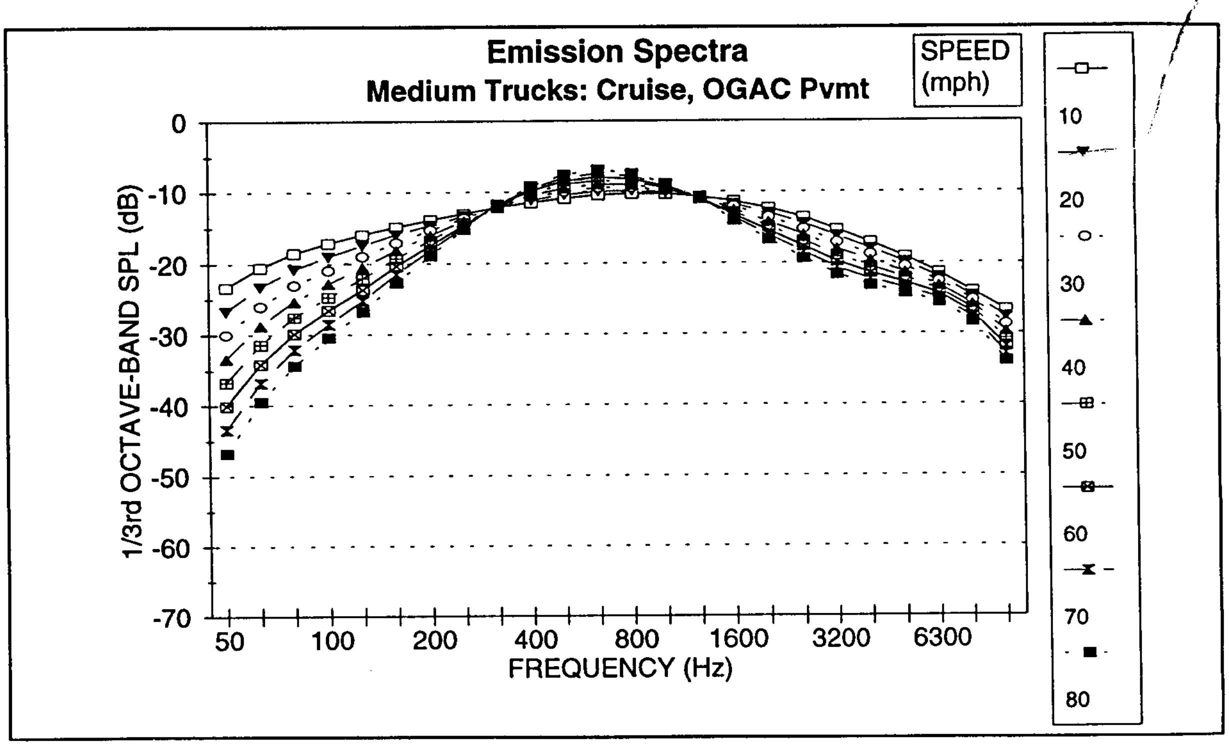


Figure 24. Emission spectra: Medium trucks, cruise throttle, OGAC pavement.

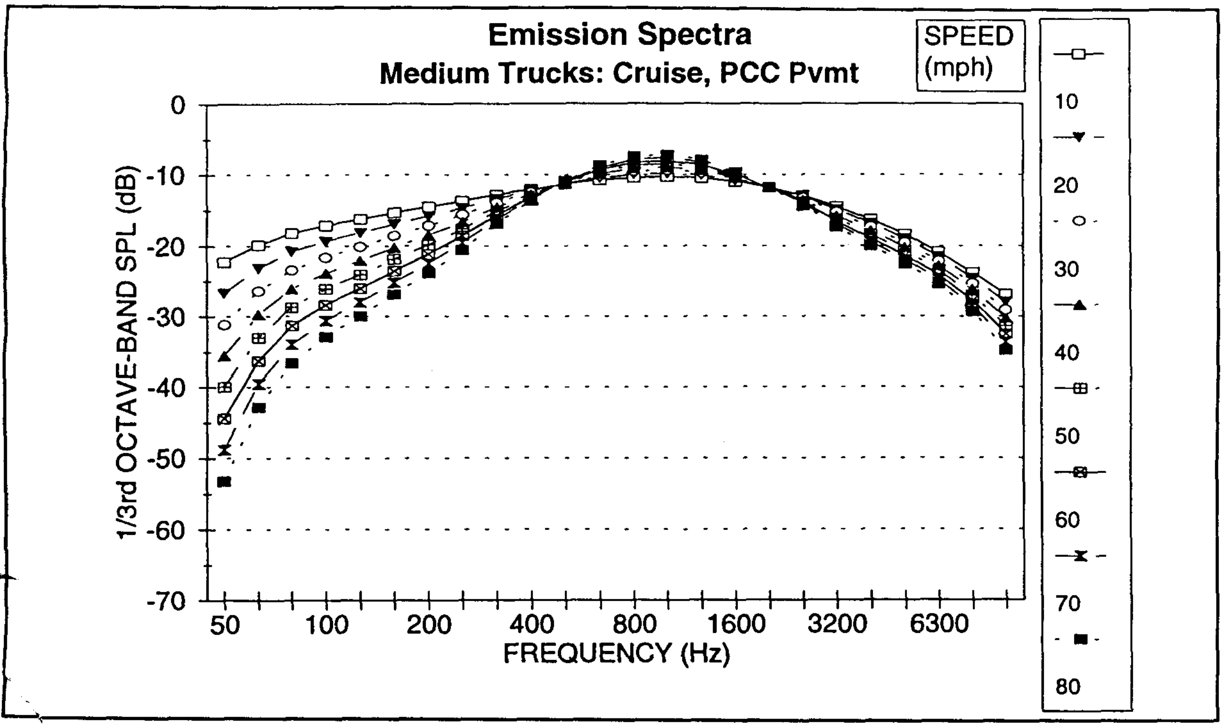


Figure 25. Emission spectra: Medium trucks, cruise throttle, PCC pavement.

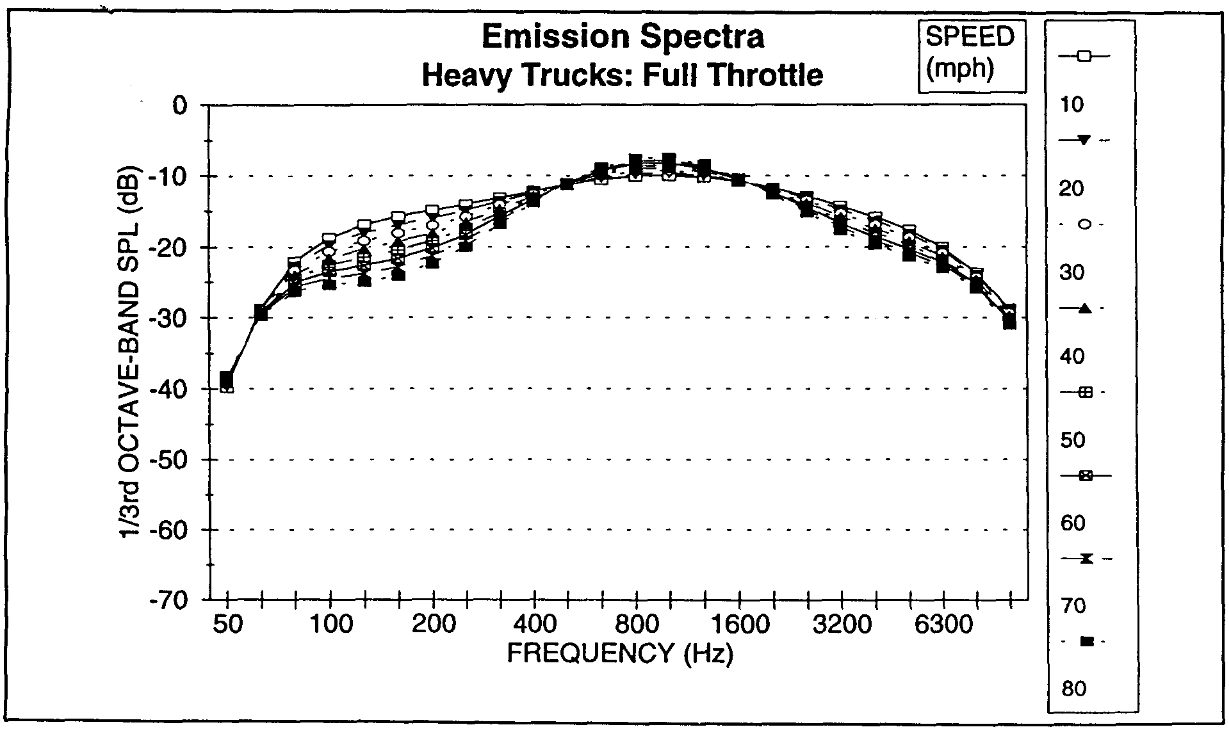


Figure 26. Emission spectra: Heavy trucks, full throttle.

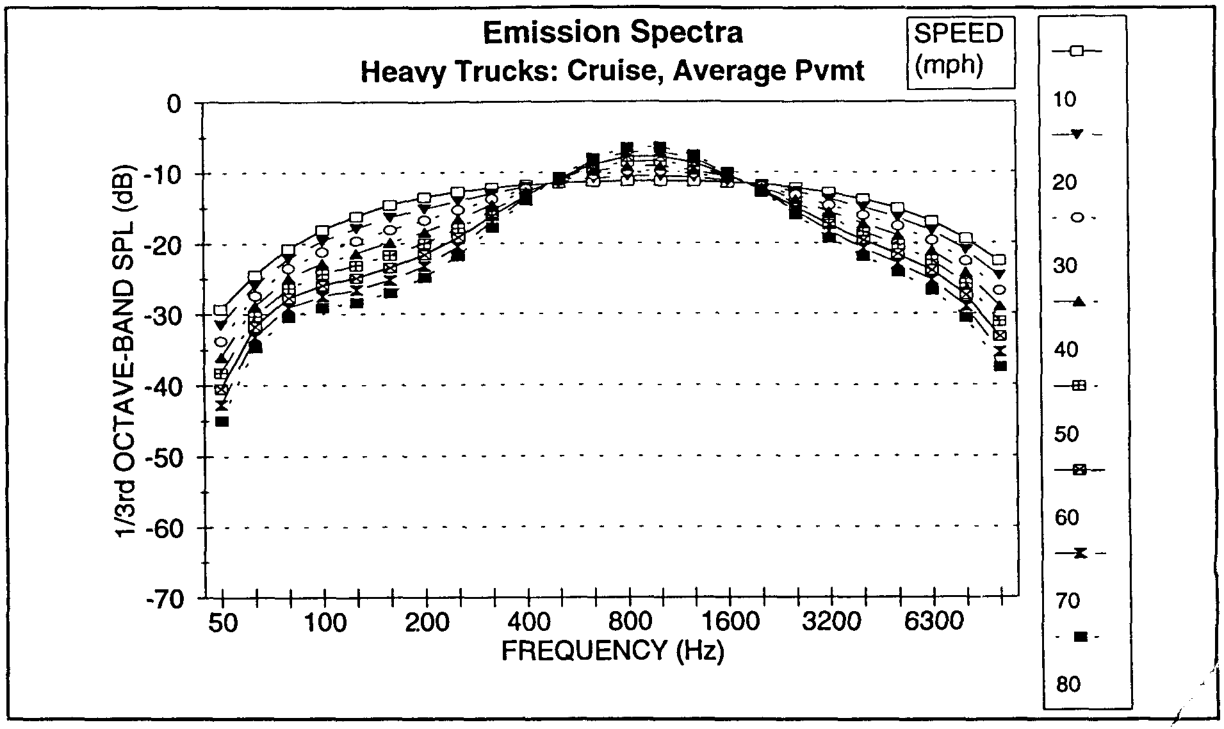


Figure 27. Emission spectra: Heavy trucks, cruise throttle, average pavement.

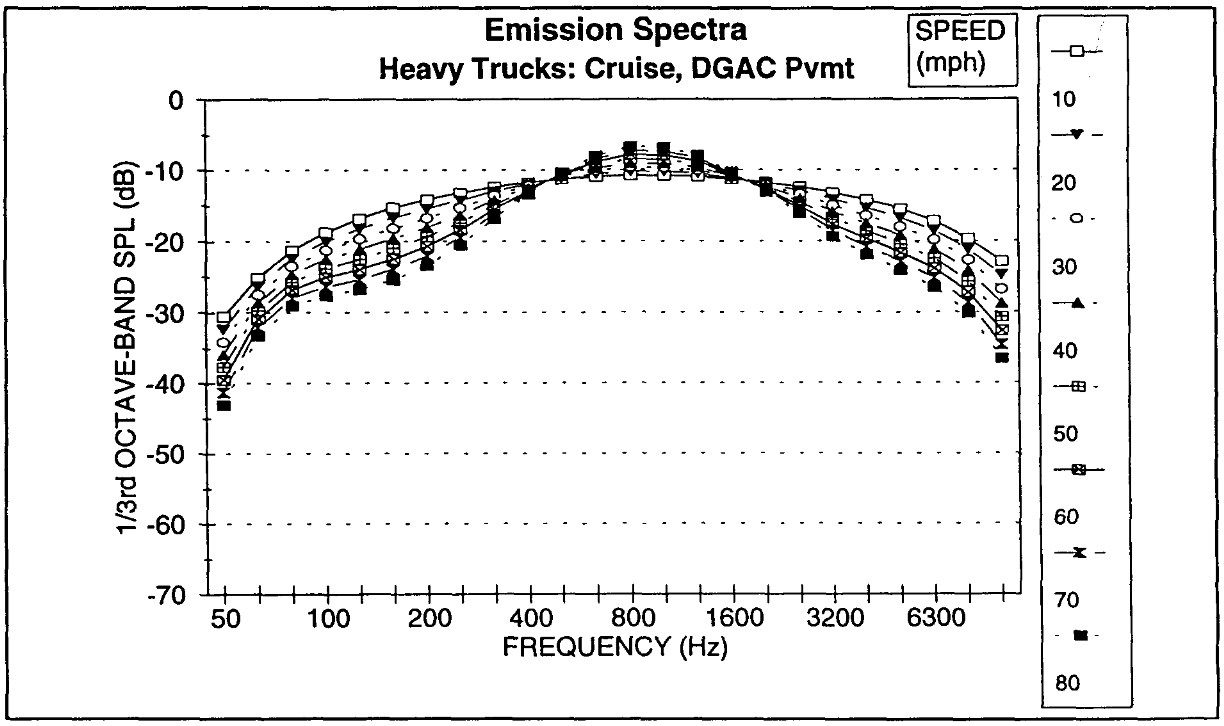


Figure 28. Emission spectra: Heavy trucks, cruise throttle, DGAC pavement.

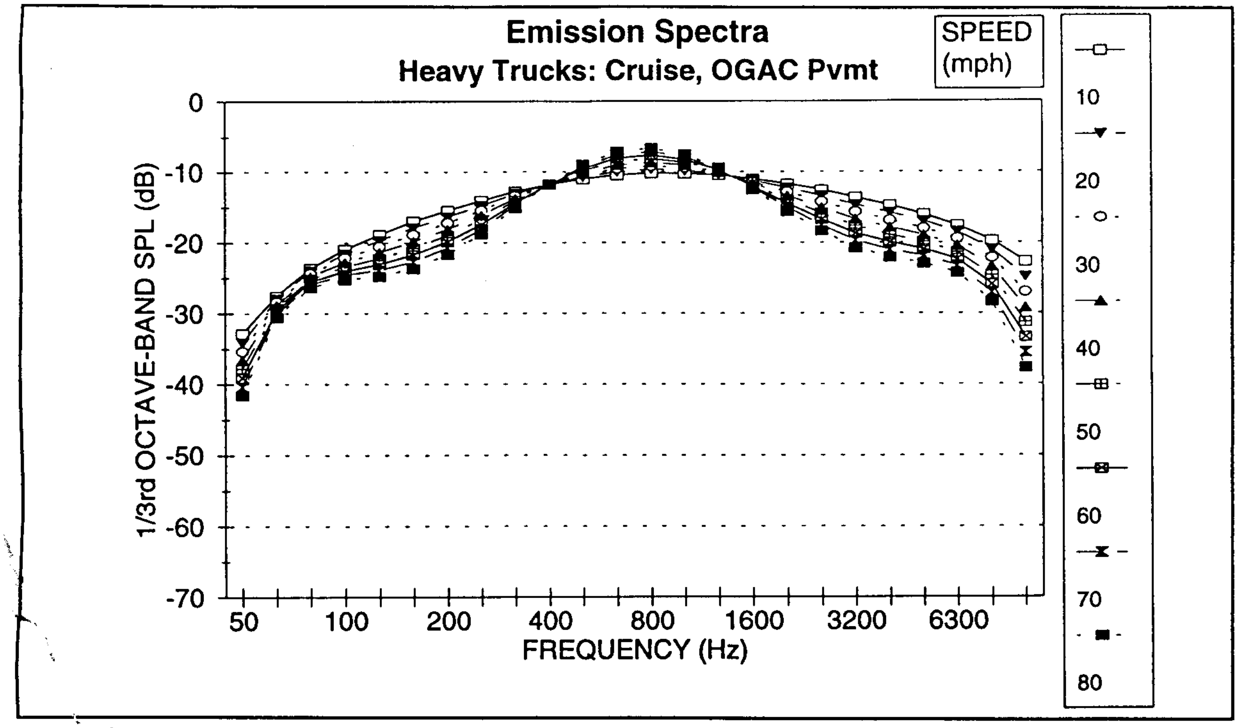


Figure 29. Emission spectra: Heavy trucks, cruise throttle, OGAC pavement.

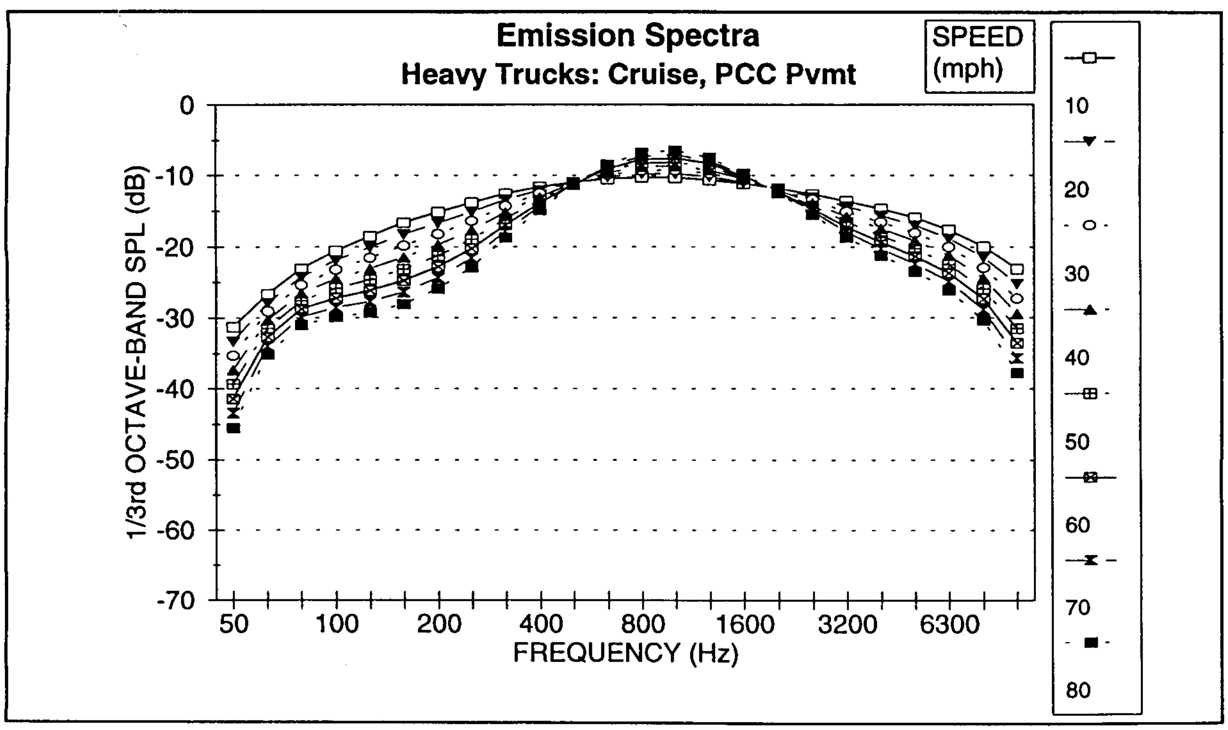


Figure 30. Emission spectra: Heavy trucks, cruise throttle, PCC pavement.

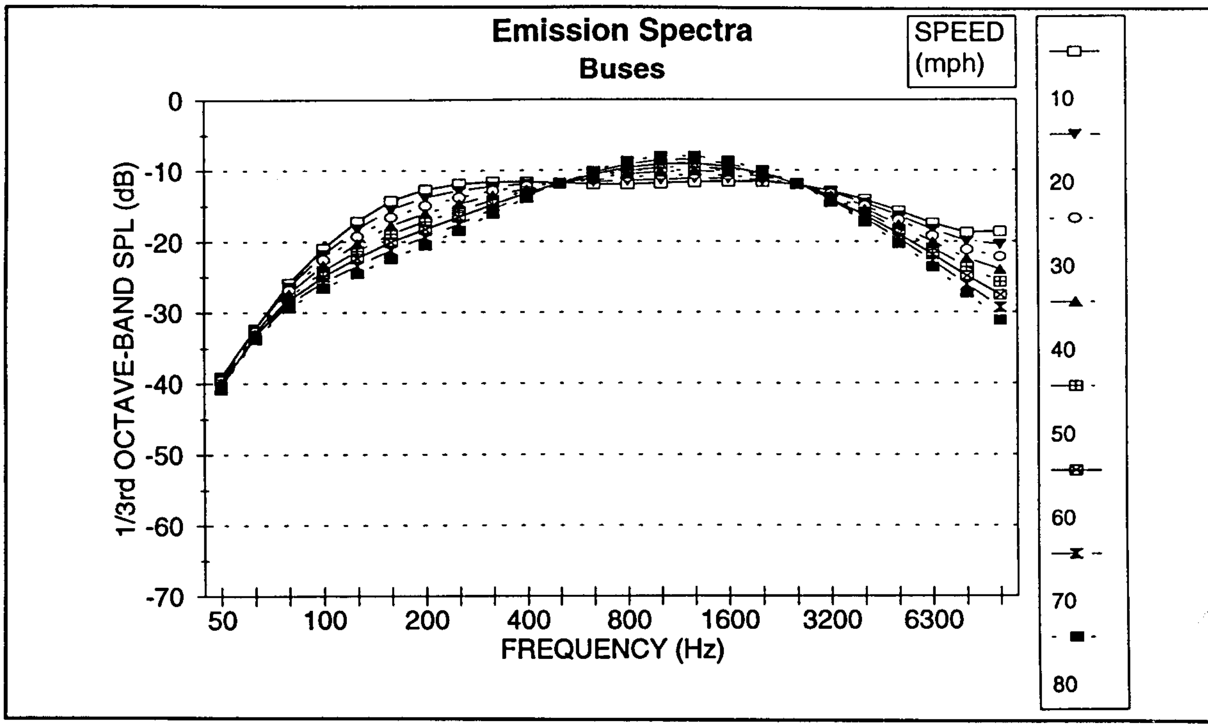


Figure 31. Emission spectra: Buses.

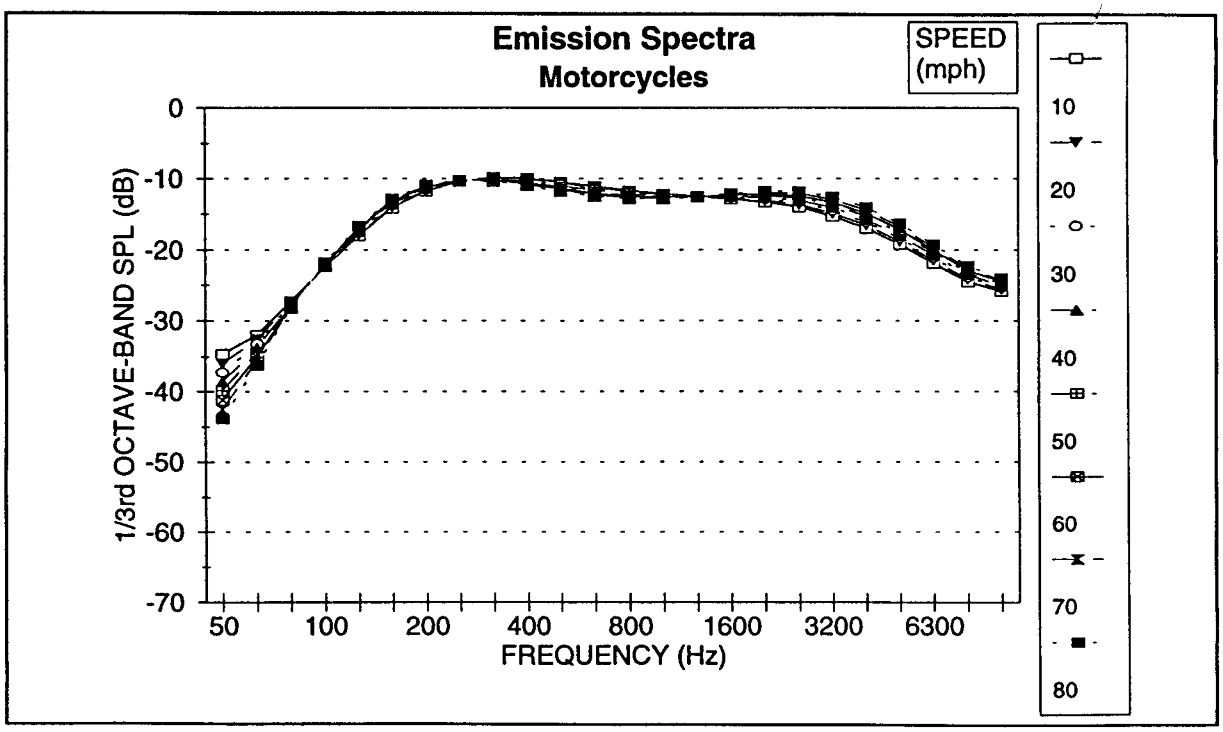


Figure 32. Emission spectra: Motorcycles.

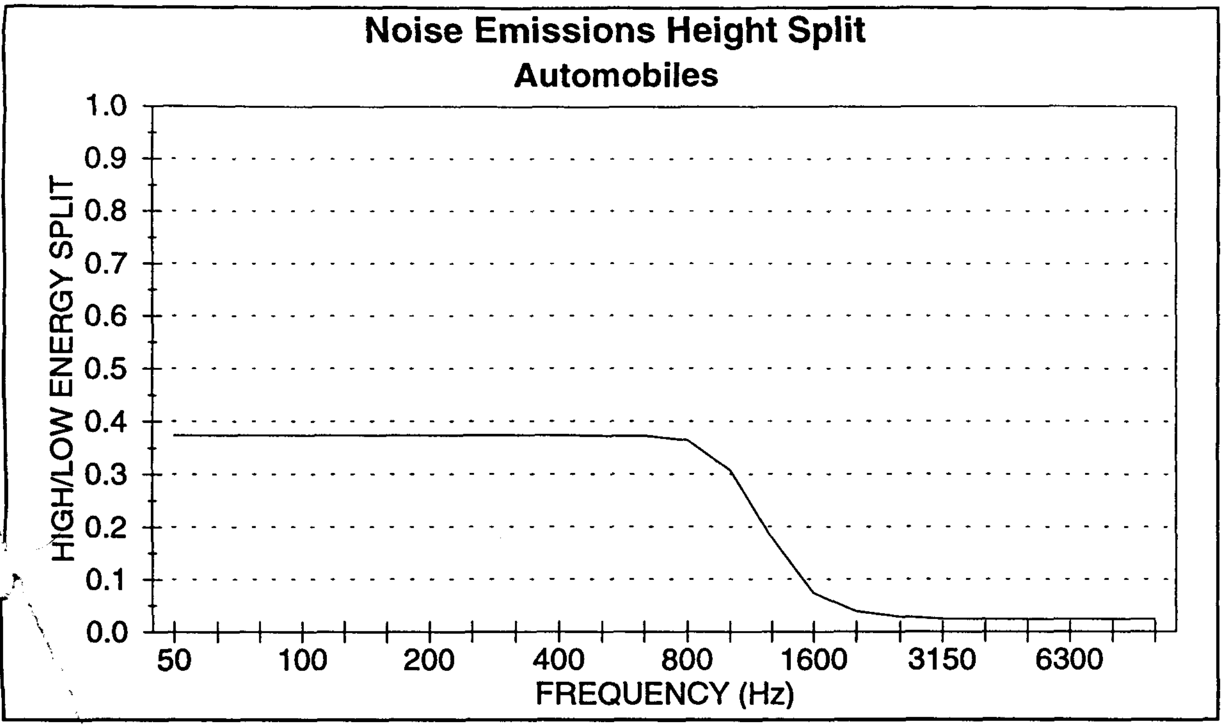


Figure 33. Sound emissions, high/low energy split: Automobiles.

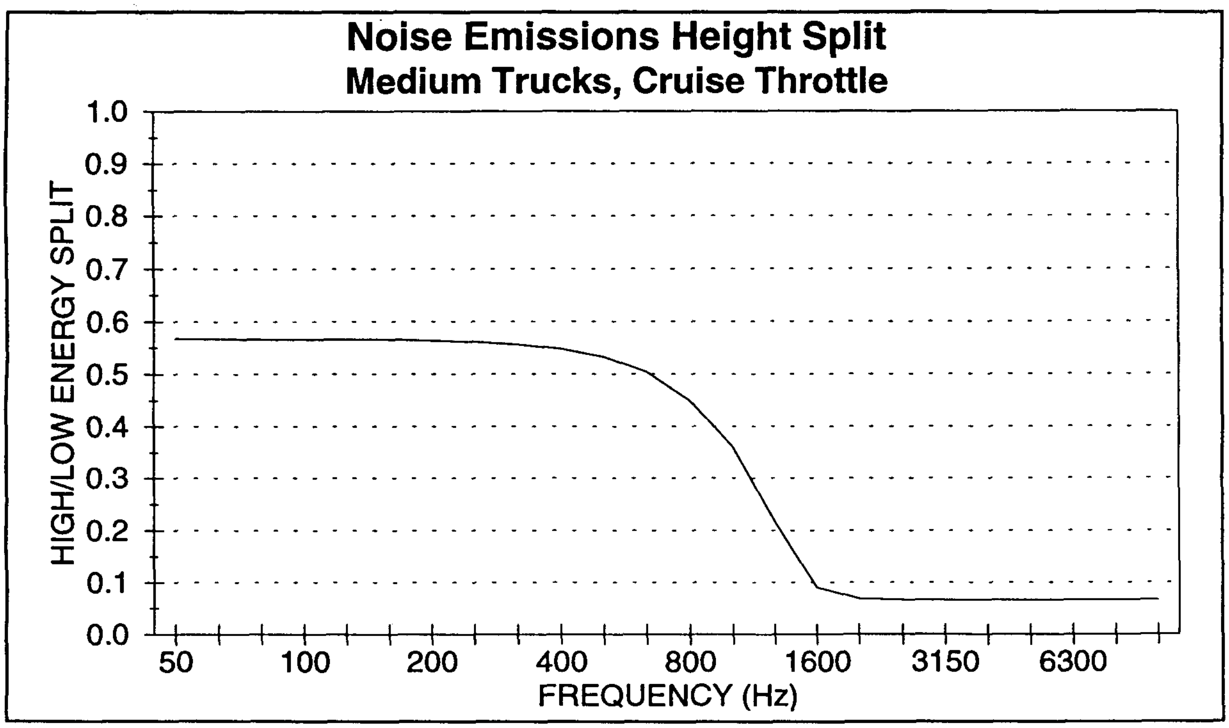


Figure 34. Sound emissions, high/low energy split: Medium trucks, cruise throttle.

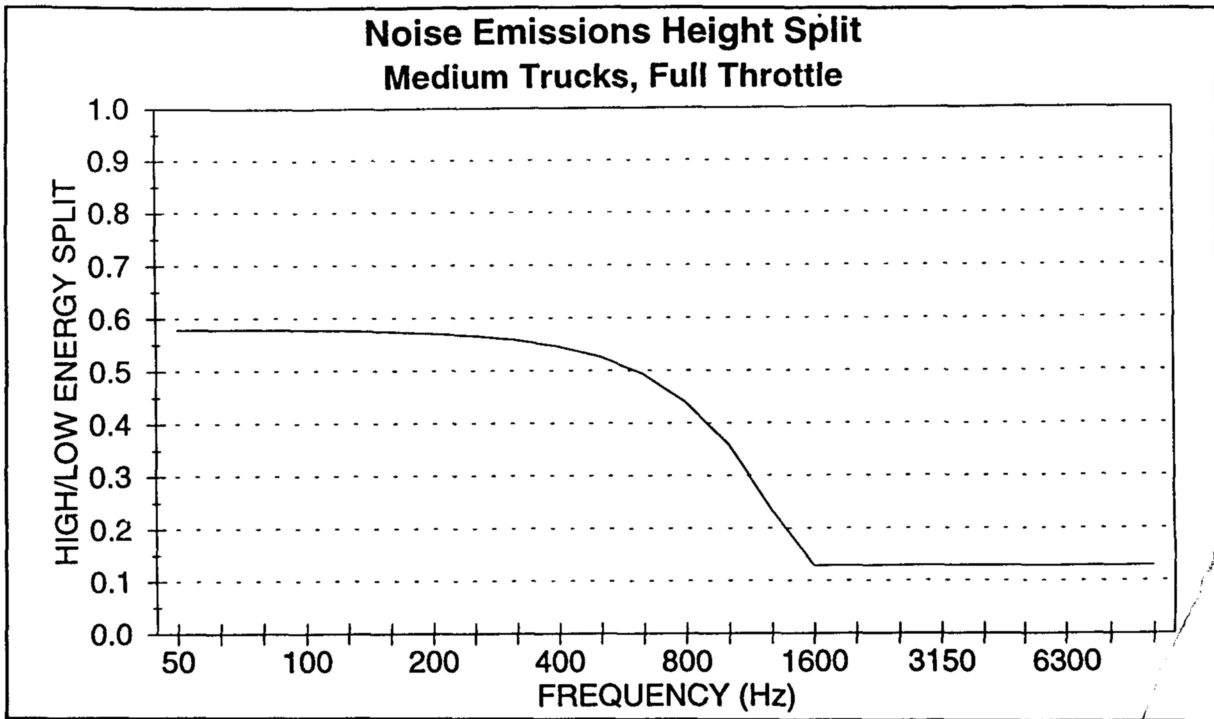


Figure 35. Sound emissions, high/low energy split: Medium trucks, full throttle.

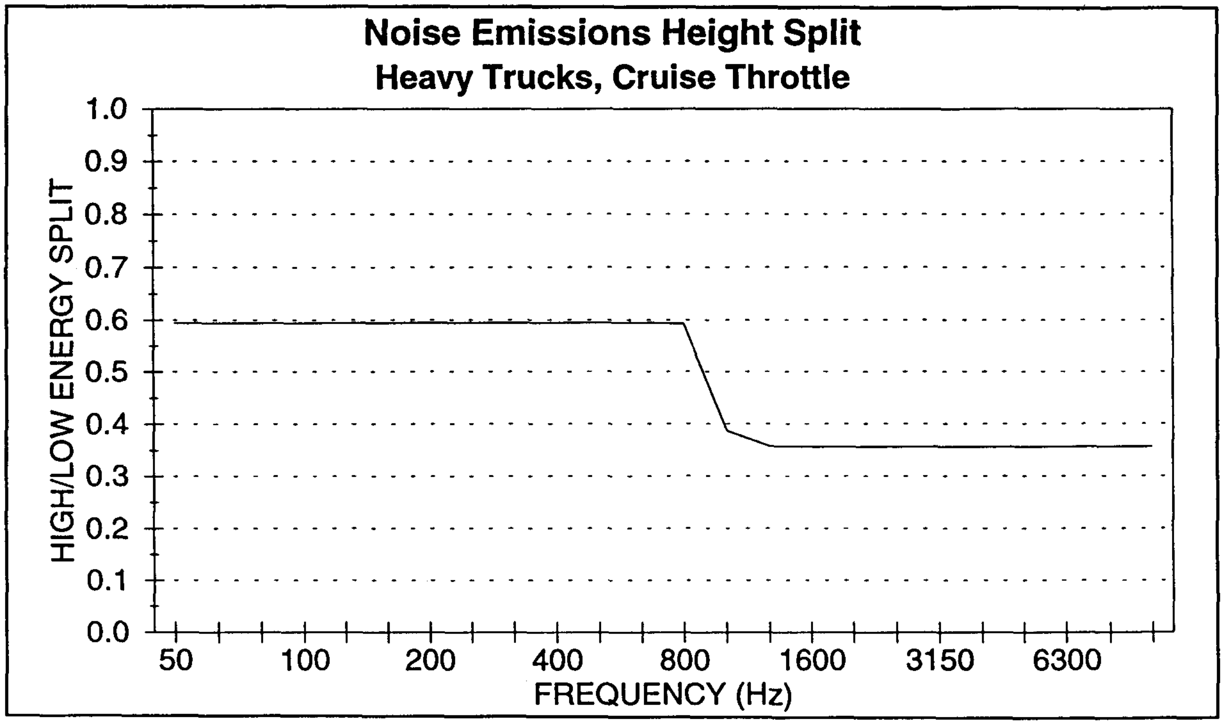


Figure 36. Sound emissions, high/low energy split: Heavy trucks, cruise throttle.

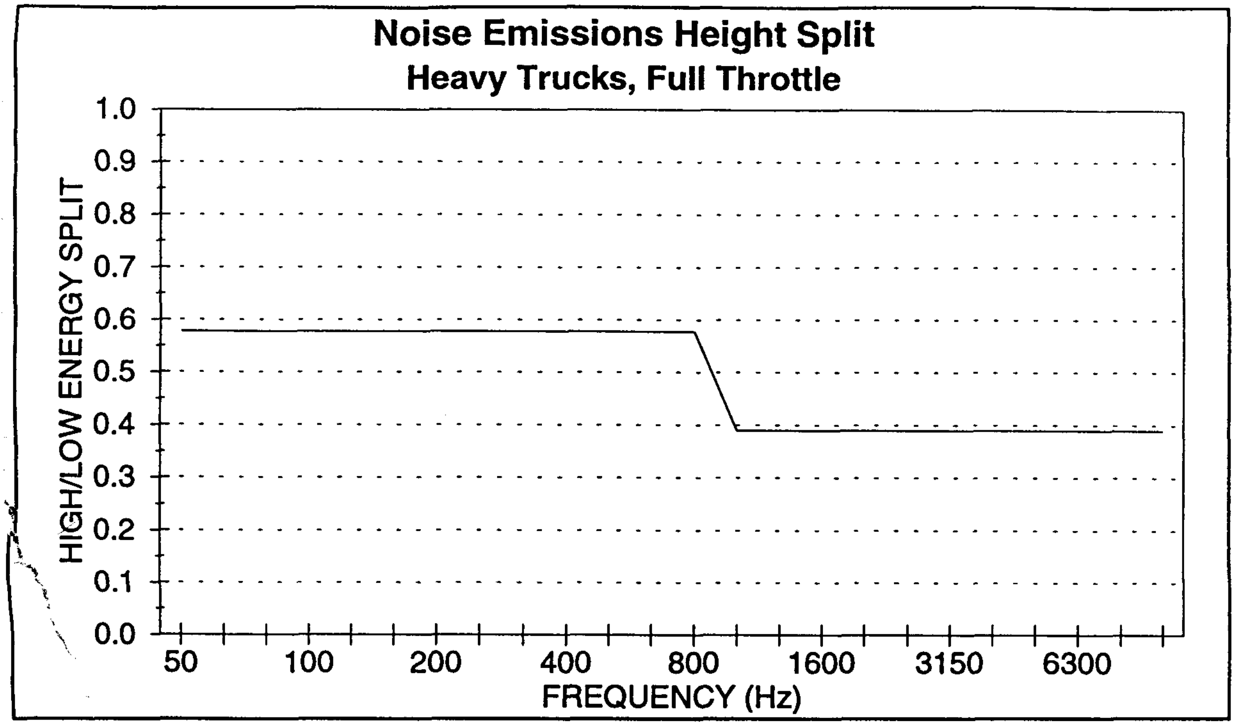


Figure 37. Sound emissions, high/low energy split: Heavy trucks, full throttle.

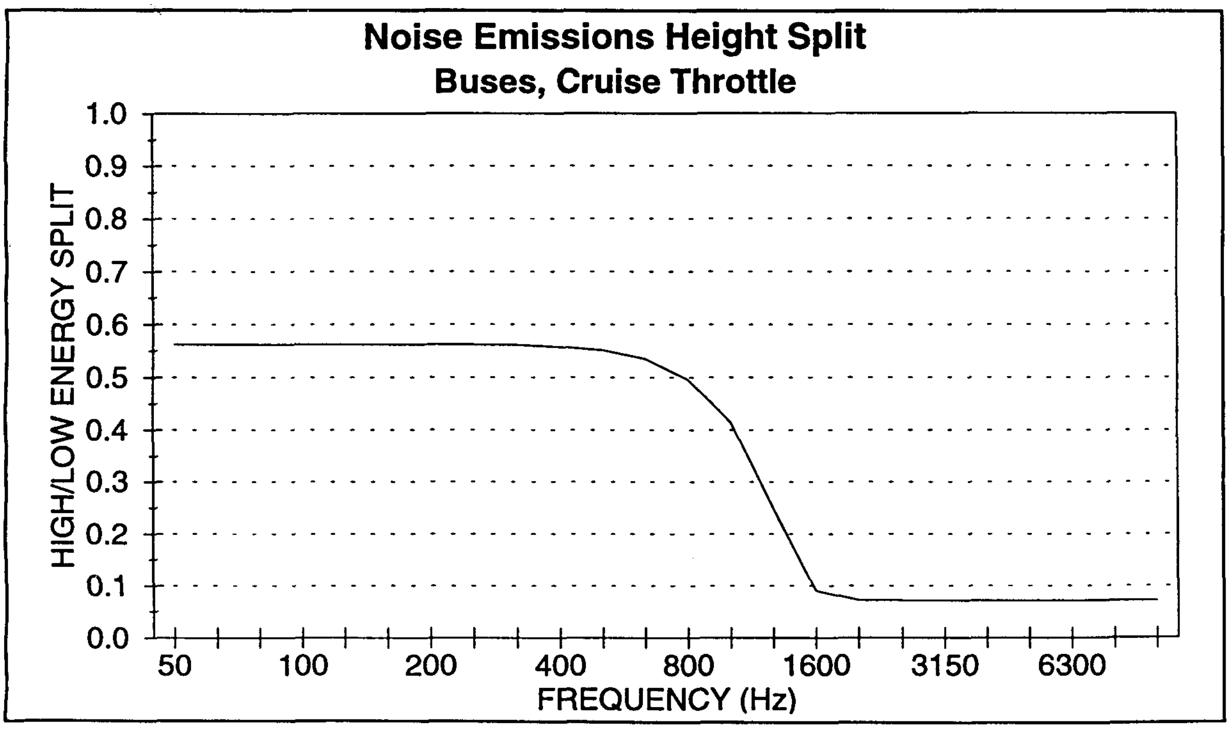


Figure 38. Sound emissions, high/low energy split: Buses, cruise throttle.

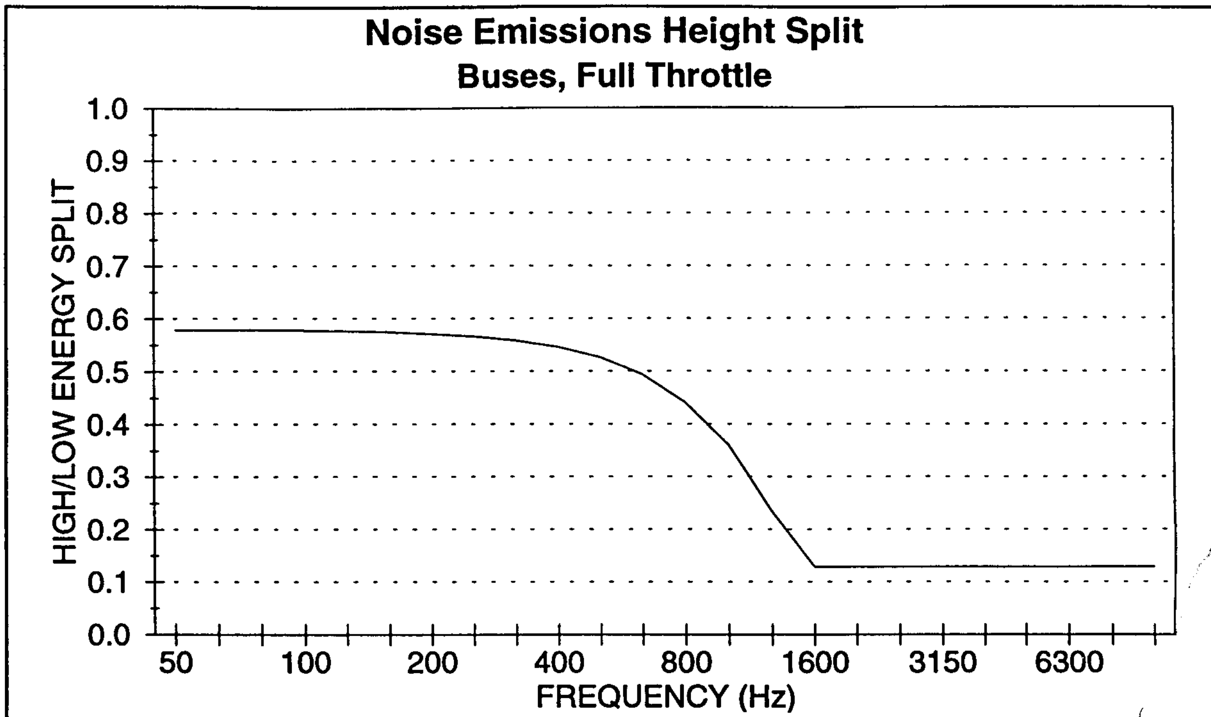


Figure 39. Sound emissions, high/low energy split: Buses, full throttle.

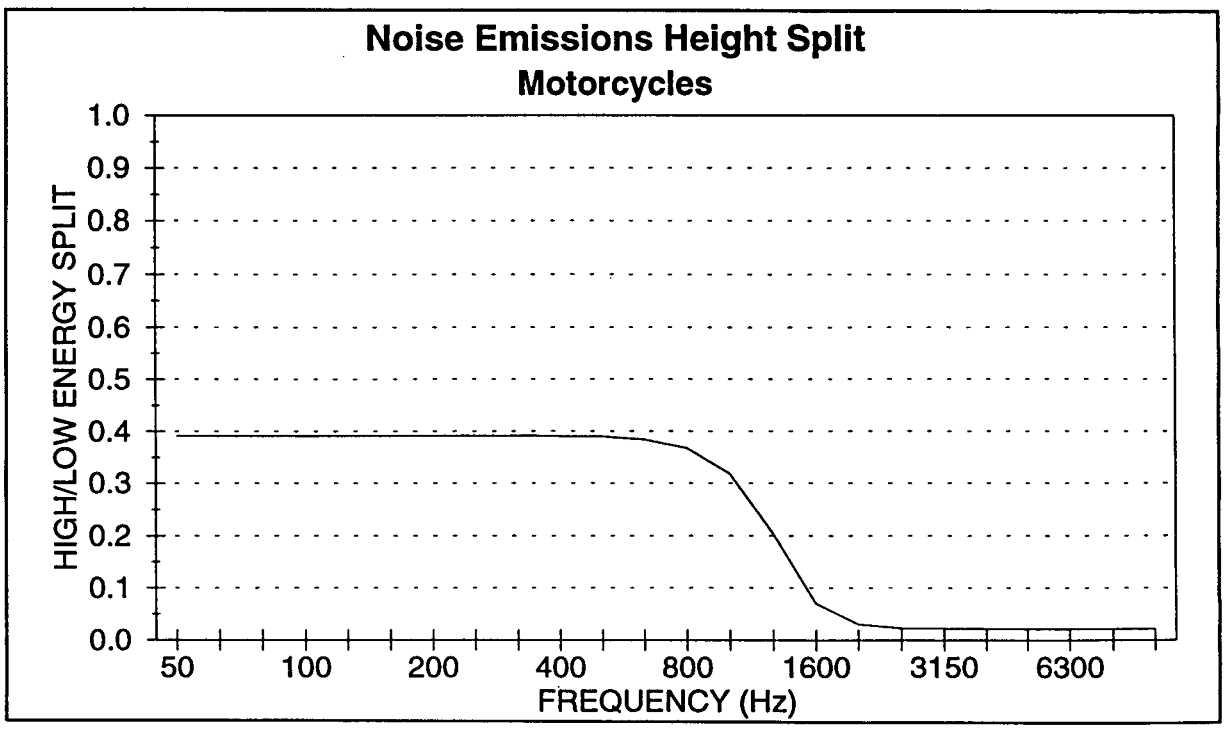


Figure 40. Sound emissions, high/low energy split: Motorcycles.

APPENDIX B
VEHICLE SPEEDS

Under most situations, FHWA TNM® uses vehicle speeds that are input by the user. However, in two situations TNM computes vehicle speeds on its own, instead: (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.

B.1 Overview

Figure 41 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.

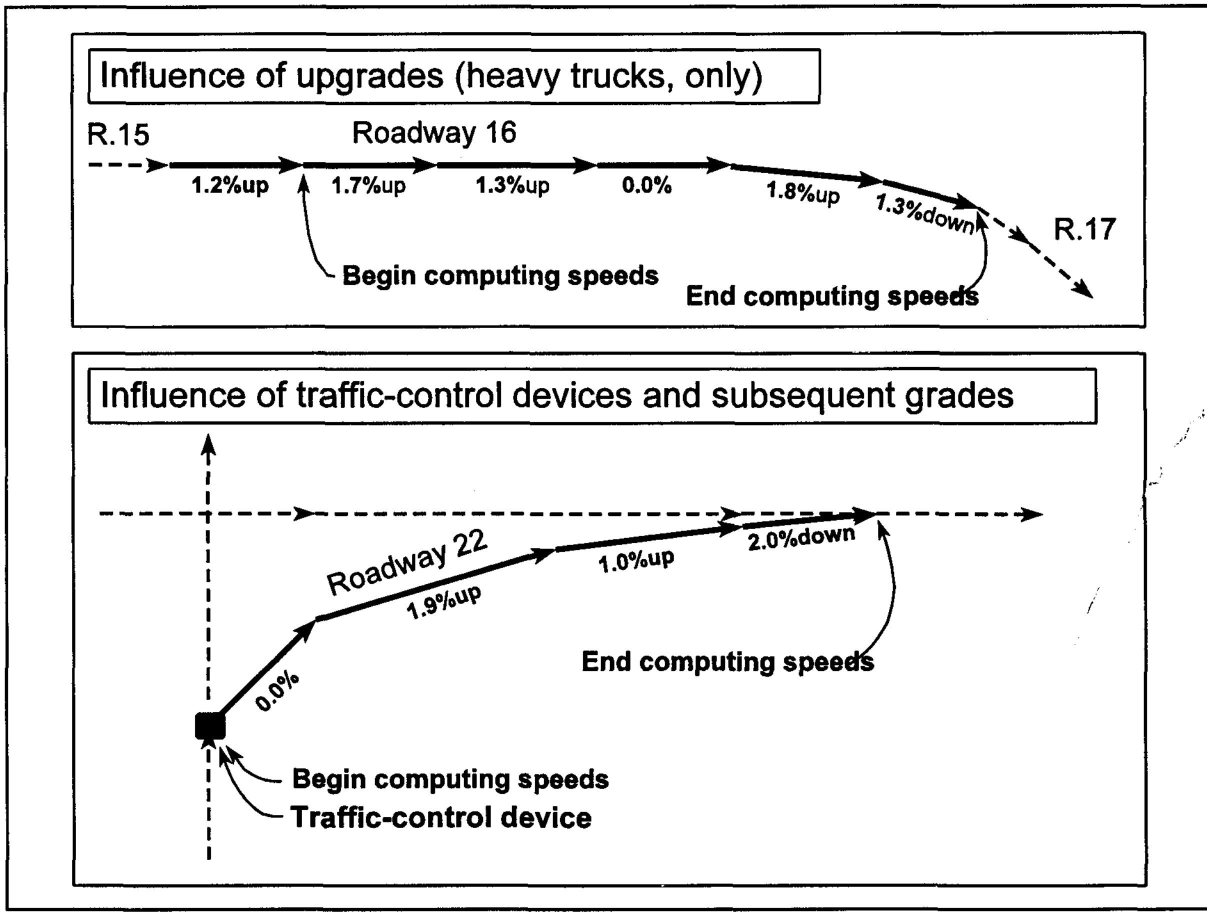


Figure 41. Geometrics for speed effects of upgrades and traffic-control devices.

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

B.2 Entrance and Exit Speeds: Overview

Figure 42 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 (subsegments) needed for computation.

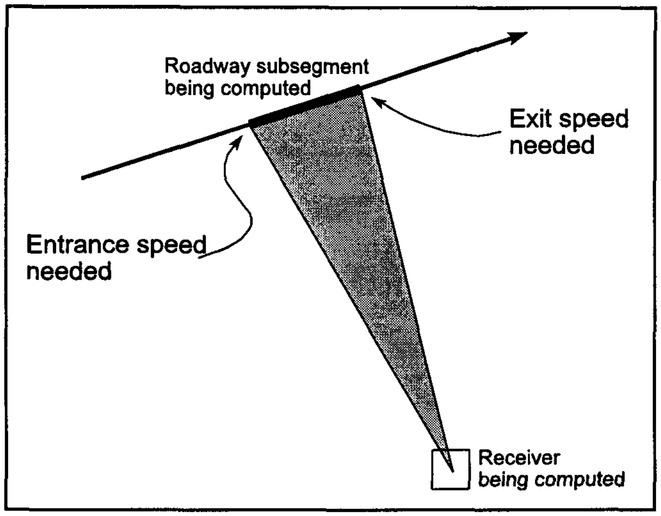


Figure 42. Entrance and exit speeds.

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

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

$$s_{average} = \frac{(s_{entrance} + s_{exit})}{2} \ . \qquad (9)$$

Because of this averaging equation, TNM only needs to know speeds at entrances and exits, not continuously along the roadway subsegment.

B.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 subsegment. 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 subsegment, 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 subsegment, 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 subsegment to subsegment, TNM preserves speed continuity. Specifically, it first computes each vehicle type's exit speed for the current subsegment, i, as described in the next section. Then it assigns these speeds as entrance speeds for the next subsegment, 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.

B.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 subsegment.

Whenever TNM is tracking speed for a particular vehicle type, it must compute subsegment 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.

B.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.

B.5.1 Regression equation for accelerating vehicles For vehicles accelerating from an entrance speed of zero,

$$s_x = 1.609\,\mathrm{A}\left\{1-\exp\left[-\left(\frac{0.3048\,x}{\mathrm{B}}\right)^{\mathrm{C}}\right]\right\}, \quad (10)$$

where s_x is vehicle speed, in kilometers per hour, at distance x along the roadway subsegment, in meters. For this equation, A, B and C appear in Table 8. The function "exp(...)" means the constant "e" raised to the (...) power.

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:

$$s_x = 1.609\,\mathrm{A} \times \left\{1-\exp\left[-\left(\frac{\left\{0.3048\,x+\mathrm{B}\left[\ln(\mathrm{A})-\ln\left(\mathrm{A}-0.6214\,s_{entrance}\right)\right]^{1/\mathrm{C}}\right\}}{\mathrm{B}}\right)^{\mathrm{C}}\right]\right\}, \quad (11)$$

where $s_{entrance}$ is vehicle speed, in kilometers per hour, at the entrance to the roadway subsegment, and s_x is vehicle speed, in kilometers per hour, at distance x along the subsegment, in meters.

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	0.510

B.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),

$$s_x = 1.609\mathrm{A} + (121 - 1.609\mathrm{A})\exp\left[-\left(\frac{0.3048\,x}{\mathrm{B}}\right)^{\mathrm{C}}\right], \qquad (12)$$

where s_x is vehicle speed, in kilometers per hour, at distance x along the roadway subsegment, in meters. 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 = 72.803 E = 0.180	F exp(-G *g*), where F = 3792.117 G = 0.105	1.303

When the entrance speed is not 121 kilometers per hour (75 miles per hour), TNM uses the following equation, which is derived from the previous one:

$$s_x = 1.609\,\mathrm{A} + (121 - 1.609\mathrm{A}) \times \exp\left[-\left(\frac{\left\{0.3048\,x + \mathrm{B}\left[\ln(121 - 1.609\mathrm{A}) - \ln(s_{\mathrm{entrance}} - 1.609\mathrm{A})\right]^{1/\mathrm{C}}\right\}}{\mathrm{B}}\right)^{\mathrm{C}}\right], \qquad (13)$$

where $s_{entrance}$ is vehicle speed, in kilometers per hour, at the entrance to the subsegment, and s_x is the speed at distance x along the subsegment, in meters.

B.6 Graphs of Acceleration and Deceleration

Figures 43 through 46 plot Eqs. (10) and (12) from above. They show TNM's functional relationships between vehicle speed and distance along a roadway subsegment, 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 currently in use for highway geometric design [AASHTO 1990] [TRB 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/m^2 (360 lb/ft^2).

The curves in each of these figures show vehicle dynamics for an average vehicle, as a function of grade. In Figure 45, 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.

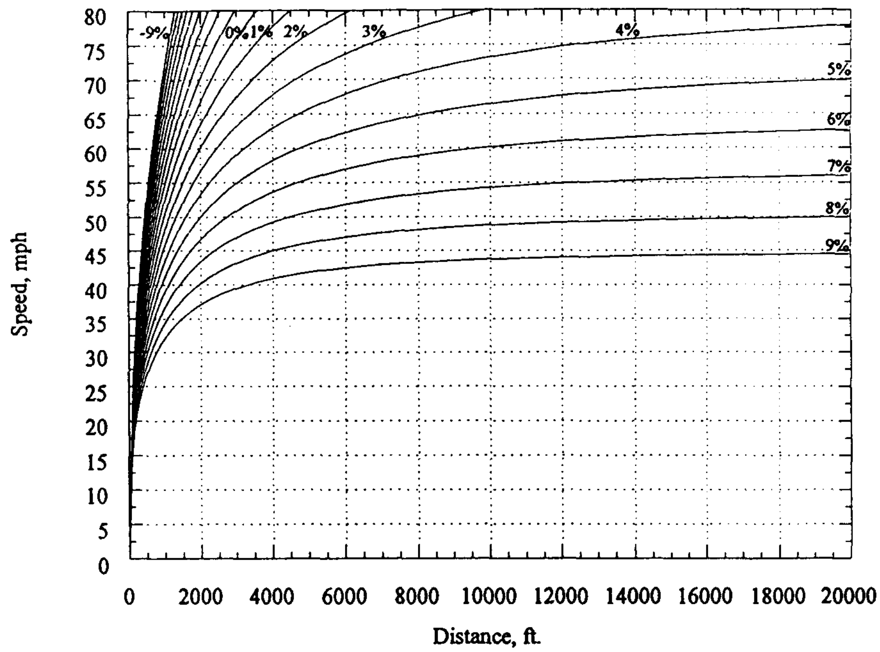


Figure 43. Acceleration away from traffic-control devices: Automobiles and motorcycles.

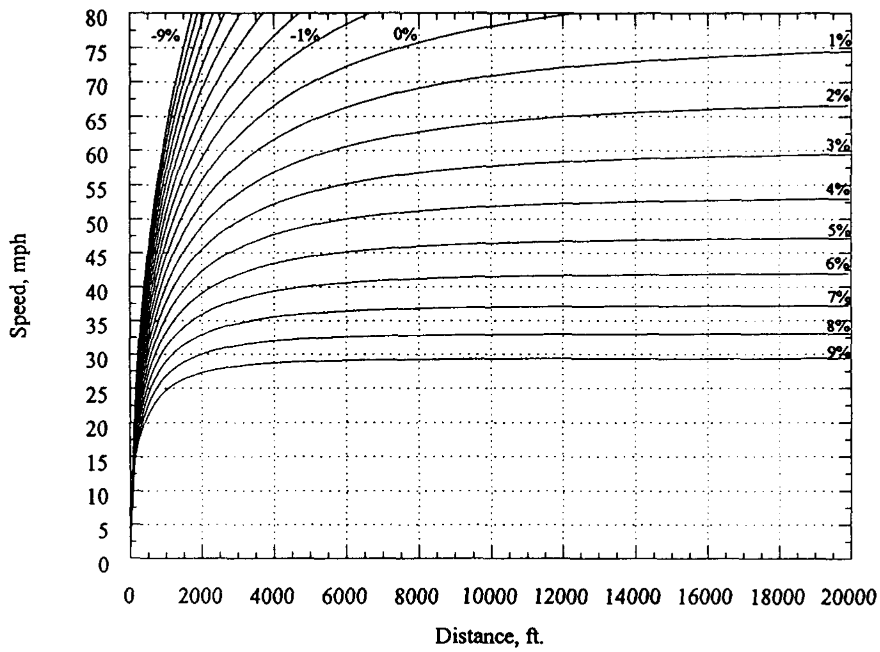


Figure 44. Acceleration away from traffic-control devices: Medium trucks and buses.

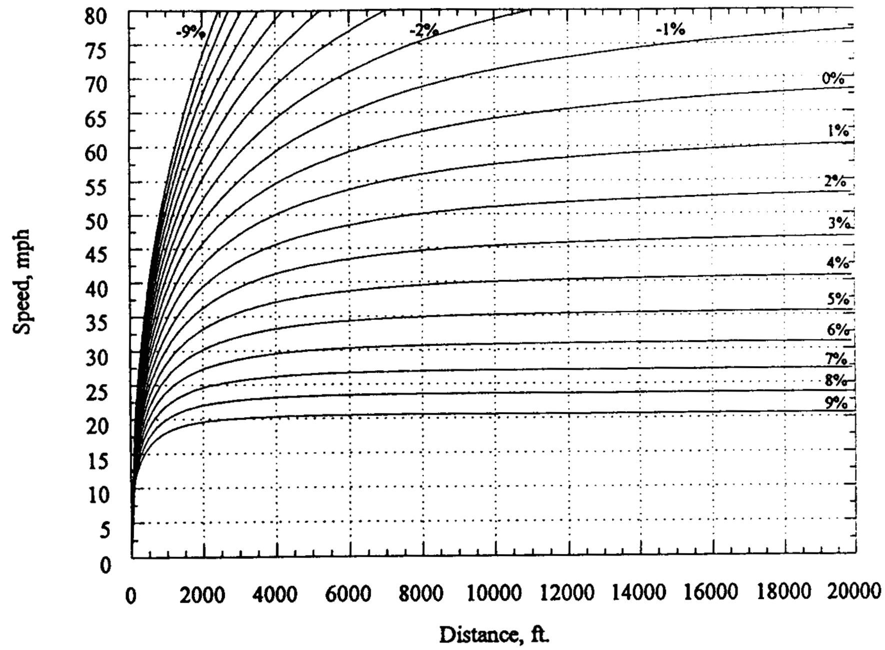


Figure 45. Acceleration away from traffic-control devices: Heavy trucks.

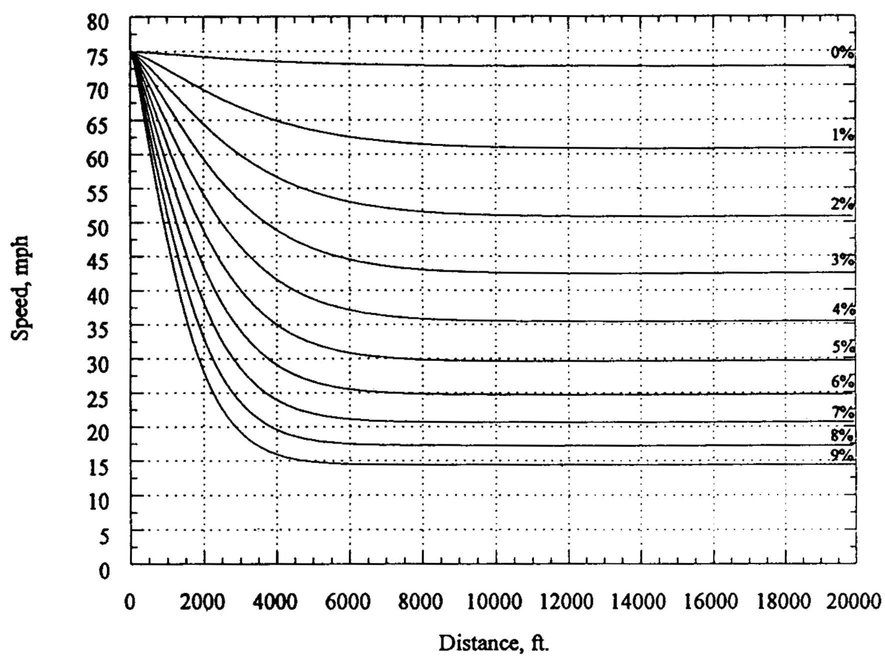


Figure 46. Deceleration caused by upgrades greater than 1.5 percent: Heavy trucks.

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 subsegment length, *x*, determine the speed, s_x, at distance *x* along the subsegment — including the subsegment's exit speed, s_{exit}, when *x* is set to the full subsegment length.

Example: Roadway 16 in Figure 41: Roadway 16 in Figure 41 contains upgrades, which affect only heavy trucks. The sketches in Figure 47 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.

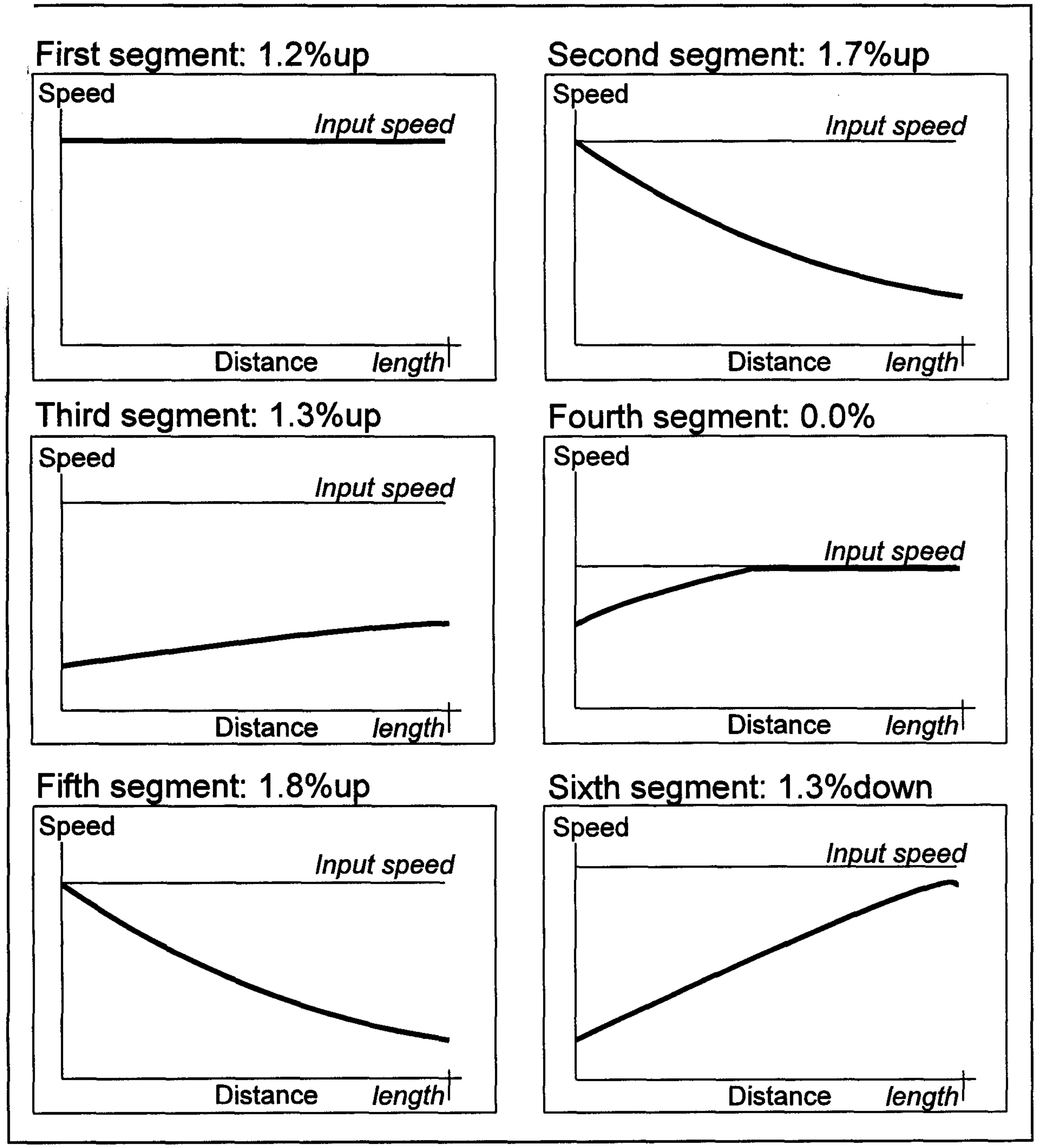


Figure 47. Speeds for Roadway 16: Upgrades.

Example: Roadway 22 in Figure 41: Roadway 22 in Figure 41 contains a traffic-control device (onramp entrance point), which affects the speeds of all vehicle types. The sketches in Figure 48 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.

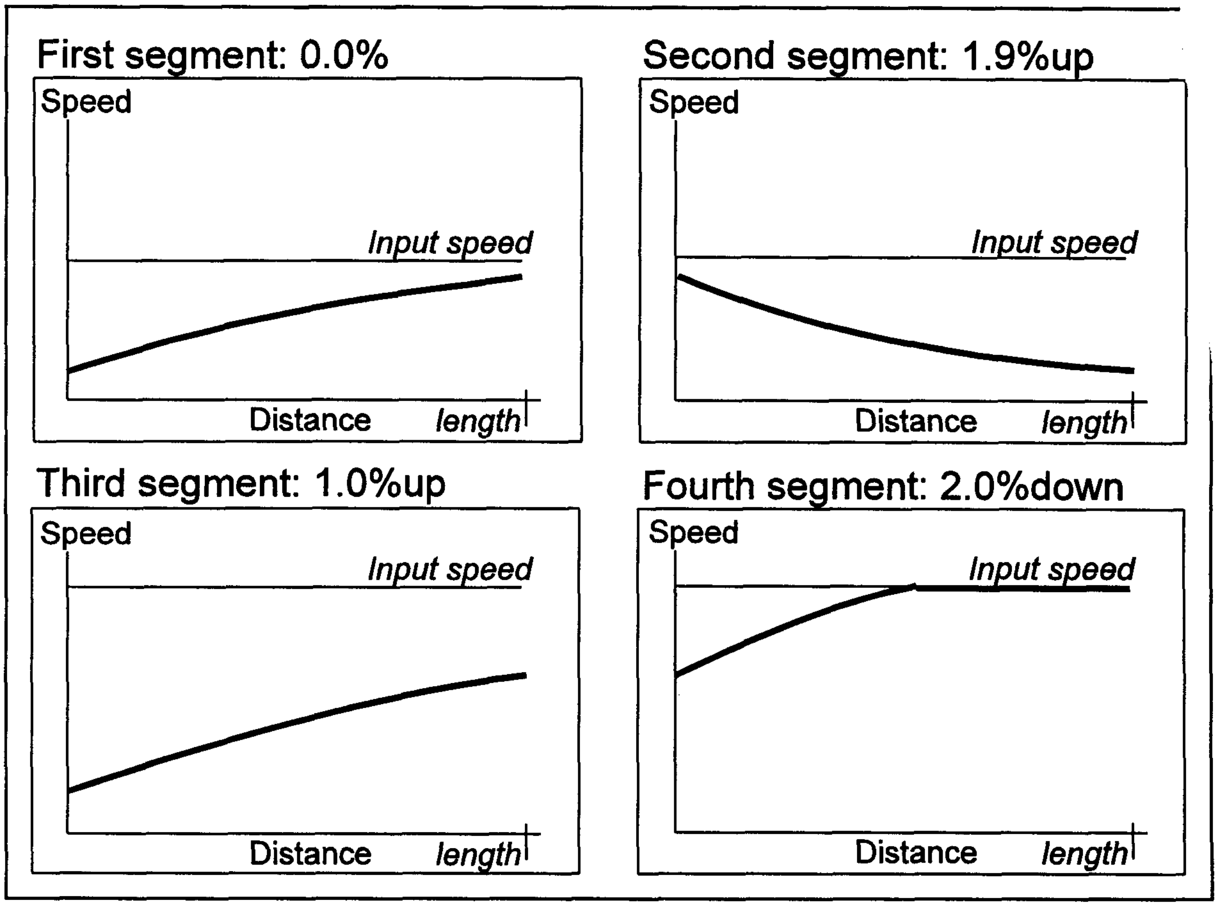


Figure 48. Speeds for Roadway 22: Traffic-control devices and subsequent grades.

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 then accelerate upwards towards their crawl speed on this grade. After entering the fourth segment (2.0 percent down), they accelerate more rapidly because of the downgrade. On this segment they happen to reach input speed, and therefore TNM stops tracking heavy-truck speeds.

.6.1 Some additional points Each vehicle's speed is calculated independently of the .hers, because the user is free to enter different input speeds for different vehicles. Some ɔmmonality exists, however. TNM only contains vehicle dynamics (acceleration/deceleration ɹrves) 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. n addition, user-defined vehicles mimic whatever TNM vehicle the user designates as most ;imilar.

APPENDIX C
HORIZONTAL GEOMETRY AND ACOUSTICS

)nce speeds and emission levels are known, FHWA TNM® next computes free-field sound ɘvels, ignoring all attenuating mechanisms except acoustical divergence. This appendix lescribes the acoustical algorithms associated with these horizontal-geometry, free-field ɔomputations:

- 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 49.

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 50 shows Figure 49 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.

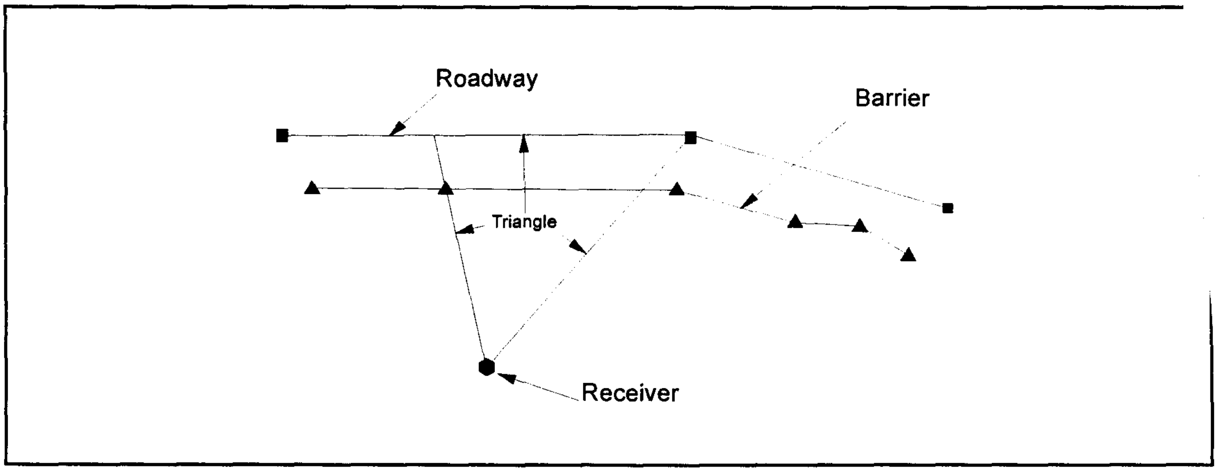


Figure 49. Initial elemental triangle.

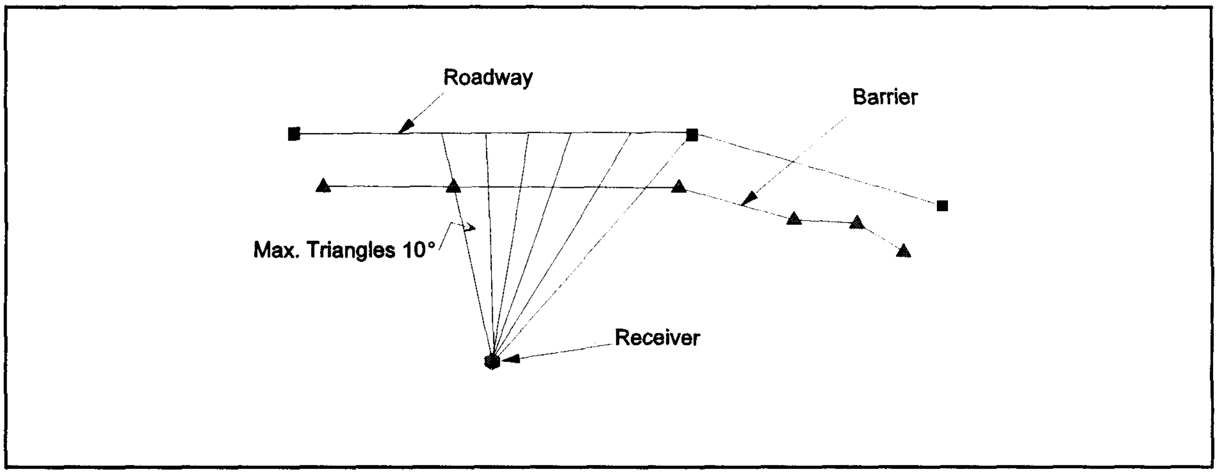


Figure 50. Maximum elemental triangle set to 10 degrees.

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.

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_{Aeq1h}, and only when user inputs traffic percentages instead of volumes.

a_d average daily traffic, in vehicles per 24 hour, 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_{Aeq1h}, and only when user inputs traffic percentages instead of volumes.

$\varrho_{i,\,day}$ 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).

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

$\varrho_{i,\,night}$ 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 subsegment, in meters (see Figure 51).

d_2 distance from receiver to second point of roadway subsegment, in meters (see Figure 51).

d perpendicular distance from receiver to roadway subsegment, in meters, where subsegment is extended if needed to meet the perpendicular (see Figure 51).

α angle subtended at the receiver by the roadway subsegment, in degrees (see Figure 51).

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

TNM computes traffic *sound levels* — L_{Aeq1h}, 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:

$$L = 10 \times \text{Log}_{10}(E), \tag{14}$$

where "Log_{10}" denotes the common logarithm (base 10).

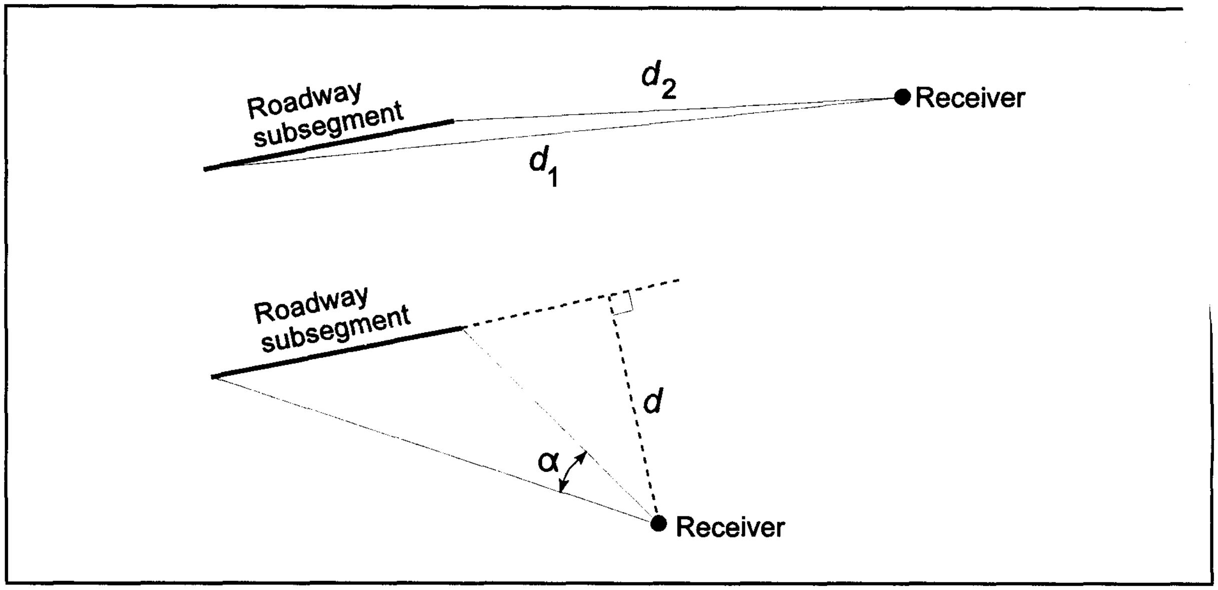


Figure 51. Definition of relevant distances and angles.

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 :

$$
\begin{aligned}
v_{i,\text{equiv}} &= v_i \text{ for } \mathrm{L}_{\mathrm{Aeq1h}}, \text{ volume input} \\
&= \frac{a_h \rho_i}{100} \text{ for } \mathrm{L}_{\mathrm{Aeq1h}}, \text{ percentage input} \\
&= \frac{a_d\left(\rho_{i,\text{day}} + 10\rho_{i,\text{night}}\right)}{2400} \text{ for } \mathrm{L}_{\mathrm{dn}} \\
&= \frac{a_d\left(\rho_{i,\text{day}} + 3\rho_{i,\text{even}} + 10\rho_{i,\text{night}}\right)}{2400} \text{ for } \mathrm{L}_{\mathrm{den}} .
\end{aligned}
\tag{15}
$$

Jse of this effective volume allows all subsequent calculations to be identical for the three ›ptional metrics: L_{Aeq1h}, L_{dn} and L_{den}. Such an effective traffic volume is possible for L_{dn} and L_{den} because TNM's input does not allow differing vehicle speeds for the different portions of :he 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:

$$
\begin{aligned}
E_{\text{traf, ref, upper}}(s_i, v_{i,\text{ equiv}}, f) &= 0.0476\left(\frac{v_{i,\text{ equiv}}}{s_i}\right) E_{\text{emis, }i\text{, upper, ff}} \\
E_{\text{traf, ref, lower}}(s_i, v_{i,\text{ equiv}}, f) &= 0.0476\left(\frac{v_{i,\text{ equiv}}}{s_i}\right) E_{\text{emis, }i\text{, lower, ff}},
\end{aligned}
\qquad (16)
$$

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

In this equation, the factor of 0.0476 results from the complex geometrical relationship between the maximum passby 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 Eq. (2) of Section 2 — that is, $10\text{x}\text{Log}_{10}(0.0476) = -13.2$ 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 subsources, 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 49, above, 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: (1) the perpendicular distance, d, is less than 0.3 meters (1 foot); and also (2) the angle subtended, α, is less than 20 degrees, then TNM computes the free-field traffic sound energy at the receiver as follows:

$$\begin{aligned} E_{\text{traf, upper, ff}}(s_i, v_{i,\text{ equiv}}, f) &= 15.9\left(\frac{|d_2 - d_1|}{d_2 d_1}\right) E_{\text{traf, ref, upper}} \\ E_{\text{traf, lower, ff}}(s_i, v_{i,\text{ equiv}}, f) &= 15.9\left(\frac{|d_2 - d_1|}{d_2 d_1}\right) E_{\text{traf, ref, lower}}, \end{aligned} \qquad (17)$$

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

In this equation, 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 Eq. (4) of Section 2 — that is, $10\text{x}\text{Log}_{10}(15.9) \approx 12$ dB.

- Otherwise, TNM computes the free-field traffic sound energy at the receiver as follows:

$$\begin{aligned} E_{\text{traf, upper, ff}}(s_i, v_{i,\text{ equiv}}, f) &= \left(\frac{\alpha}{180}\right)\left(\frac{15}{d}\right) E_{\text{traf, ref, upper}} \\ E_{\text{traf, lower, ff}}(s_i, v_{i,\text{ equiv}}, f) &= \left(\frac{\alpha}{180}\right)\left(\frac{15}{d}\right) E_{\text{traf, ref, lower}}, \end{aligned} \qquad (18)$$

for each vehicle type, i. In this equation, 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, $\varphi_{h,f,\text{barrs}}$, for each of the three possible subsource 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.

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:

$$E_{\text{traf, }h\text{, atten, barrs}}(s_i, v_{i,\text{ equiv}}, f) = \left(\phi_{h,f,\text{ barrs}}\right)\left(10^{\Delta L/10}\right) E_{\text{traf, }h\text{, ff}}\,, \tag{19}$$

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

This equation relates to others in this technical manual as follows. The term A_s of Eq.(1) in Section 1 equals $10\text{xLog}_{10}\,(\varphi_{h,f,\text{ barrs}})$. In addition, the term $|P_{Total} / P_{Freefield}|$ in the last equation of Appendix D equals the square root of $\varphi_{h,f,\text{ barrs}}$. In energy terms, attenuating mechanisms such as sound barriers multiply energy by a value less than unity, thus decreasing the sound energy. In sound-level terms, attenuating mechanisms reduce sound levels equivalently, through subtraction. Note that when $\varphi_{h,f,\text{ barrs}}$ is less than unity, then $10\text{xLog}_{10}\,(\varphi_{h,f,\text{ barrs}})$ is negative — that is, A_s is negative.

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:

$$L_{\text{traf}} = 10 \times \text{Log}_{10}\left(\sum_{\substack{\text{all freqs,}\\ f}} \left\{ \sum_{\substack{\text{all subdivided}\\ \text{triangles}}} \left[\sum_{\substack{\text{all vehicle}\\ \text{types, } i}} \left(\sum_{\substack{\text{three subsource}\\ \text{heights, } h}} \left[E_{\substack{\text{traf, } h\text{, atten, specific}\\ \text{barr heights}}} \right] \right) \right] \right\} \right). \tag{20}$$

The sound level computed by this equation depends upon the input traffic, as follows:

L_{traf}	$= L_{\text{Aeq1h}}$	if the user has entered L_{Aeq1h} traffic, either as volumes or percentages
	$= L_{\text{dn}}$	if the user has entered L_{dn} traffic
	$= L_{\text{den}}$	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, using Appendix B. 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), using Appendix A, 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 Eq. (15) above, for each vehicle type, i.

- Then TNM computes $E_{traf,\,ref}(s_i, v_{i,\,equiv}$, 500 Hz) from the following modification of Eq. (16):

$$E_{traf,\,ref}(s_i, v_{i,\,equiv},\ 500\ Hz) = 0.0476\left(\frac{v_{i,\,equiv}}{s_i}\right)E_{emis,\,i}\ , \tag{21}$$

  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 a modified Eq. (17) or a modified Eq. (18).

  Modified Eq (17):

$$E_{traf,\,ff}(s_i, v_{i,\,equiv},\ 500\ Hz) = 15.9\left(\frac{|d_2 - d_1|}{d_2 d_1}\right)E_{traf,\,ref}\ , \tag{22}$$

  for each vehicle type, i.

  Modified Eq. (18):

$$E_{traf,\,ff}(s_i, v_{i,\,equiv},\ 500\ Hz) = \left(\frac{\alpha}{180}\right)\left(\frac{15}{d}\right)E_{traf,\,ref}\ , \tag{23}$$

  for each vehicle type, i, where perpendicular distance, d, is in meters.

Then TNM computes $E_{traf, atten}$ (s_i, $v_{i, equiv}$, 500 Hz) from the following modification of Eq. (19) above:

$$E_{traf,\ atten}(s_i, v_{i,\ equiv},\ 500\ Hz) = \left(10^{\Delta L/10}\right) E_{traf,\ ff}\ , \tag{24}$$

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, using the following modification of Eq. (20) above:

$$E_{traf} = \sum_{\substack{\text{all vehicle} \\ \text{types, } i}} \left[E_{traf,\ atten}\right]. \tag{25}$$

- Finally, for this receiver TNM sorts all roadway segments according to the energies computed by Eq. (25), 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 AND ACOUSTICS

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 ⅓-octave bands, then (energy) averages the attenuations. The average attenuation values are then applied to the entire elemental triangle.

Below, Section D.2 discusses the various elements that can be 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 52 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.

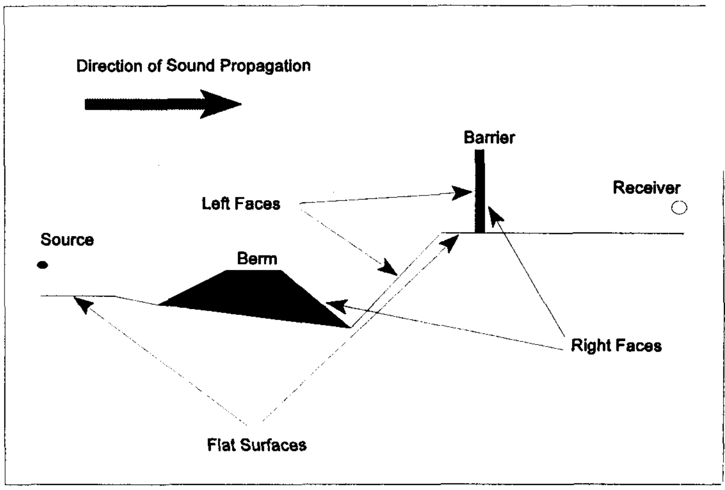


Figure 52. Vertical geometry definitions.

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 53). 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, ⅓-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.

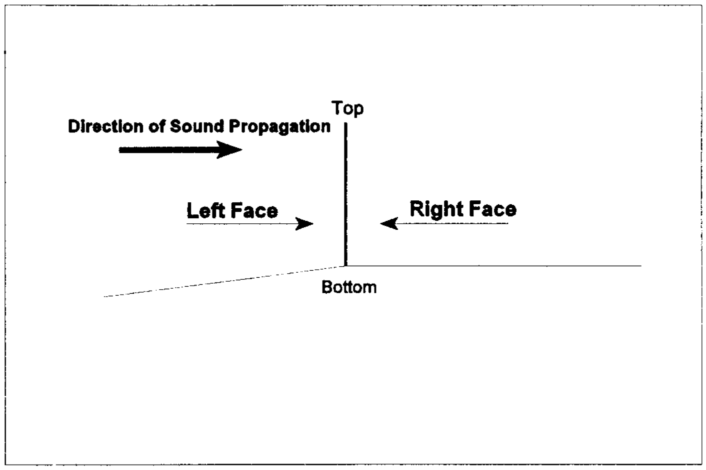


Figure 53. Barrier face definitions.

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 54. 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.

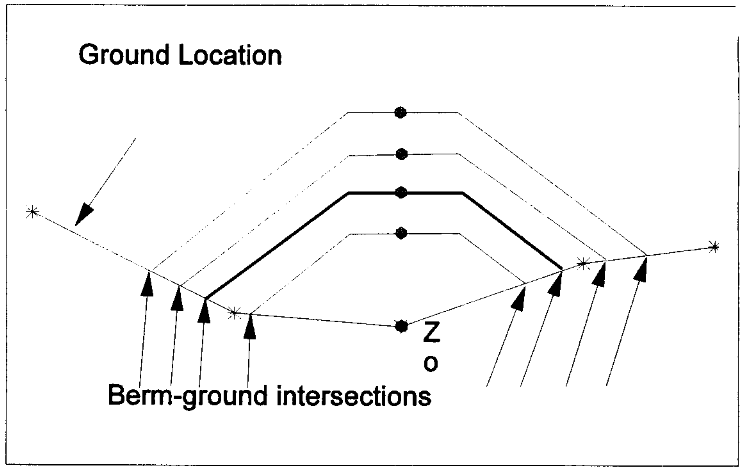


Figure 54. Example berm, shown at four perturbation heights.

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 55). 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.

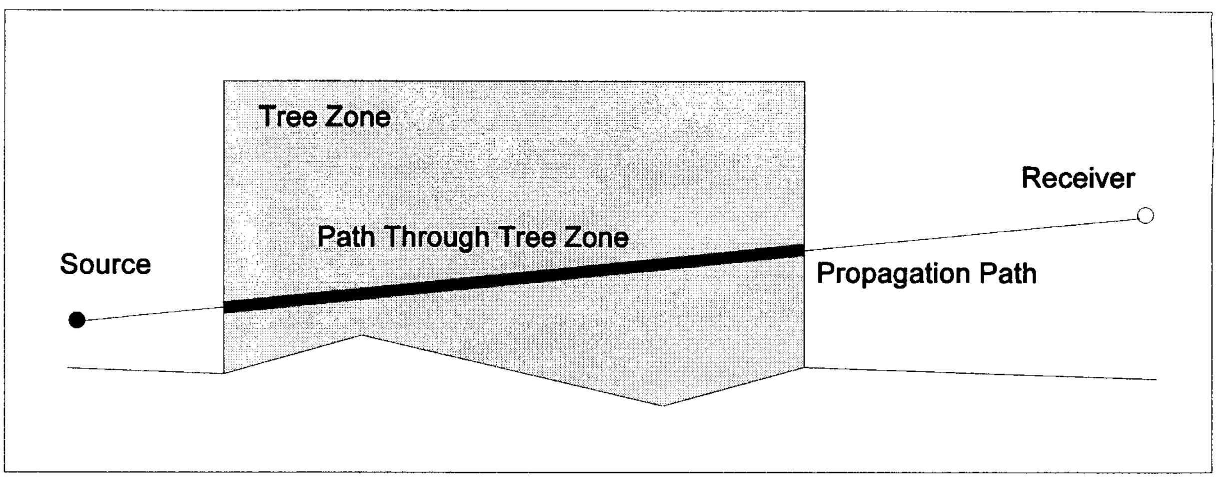


Figure 55. Propagation path through tree zone.

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 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 ⅓ 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 this 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 56. 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.

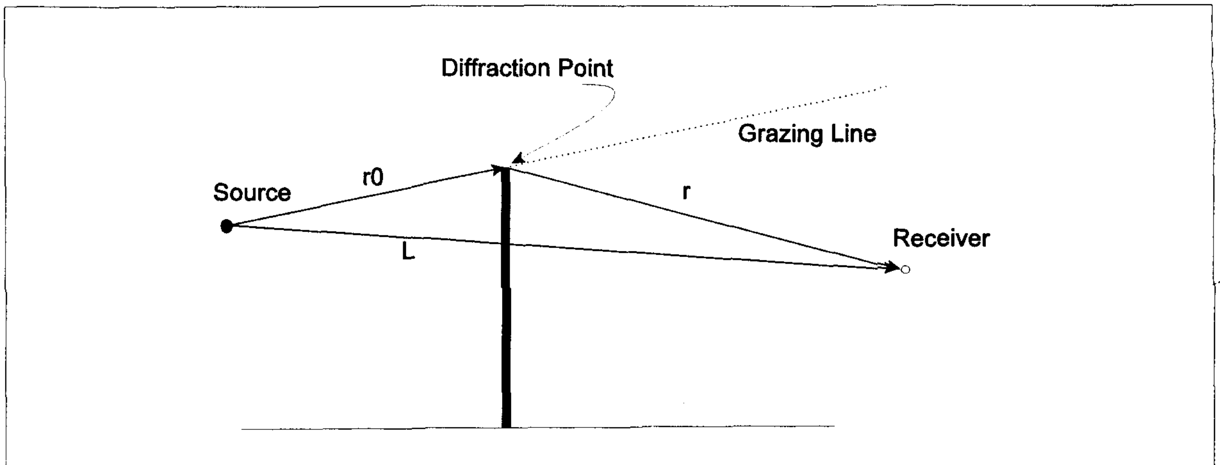


Figure 56. Single diffraction geometry.

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 57. 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

58). 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.

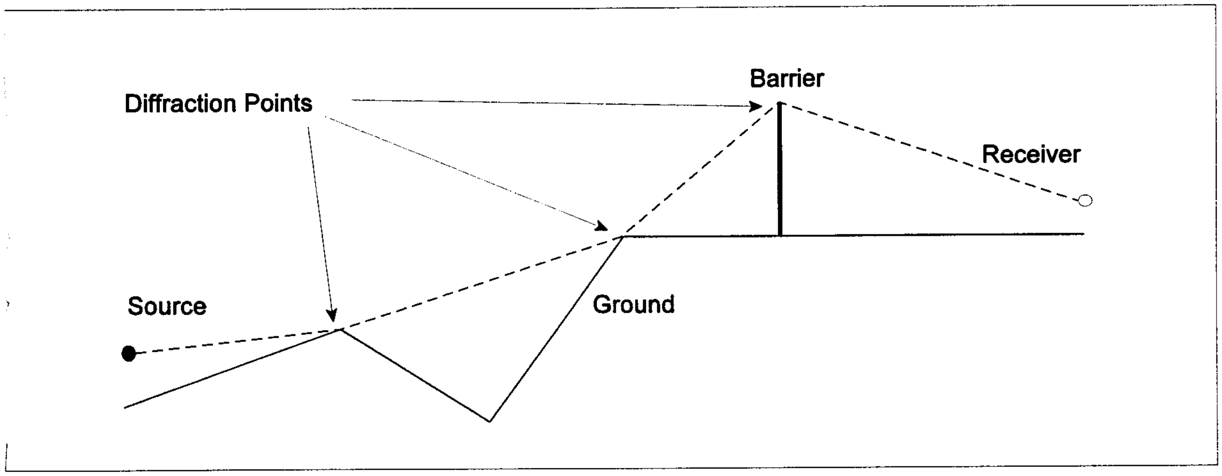


Figure 57. Example of multiple diffraction.

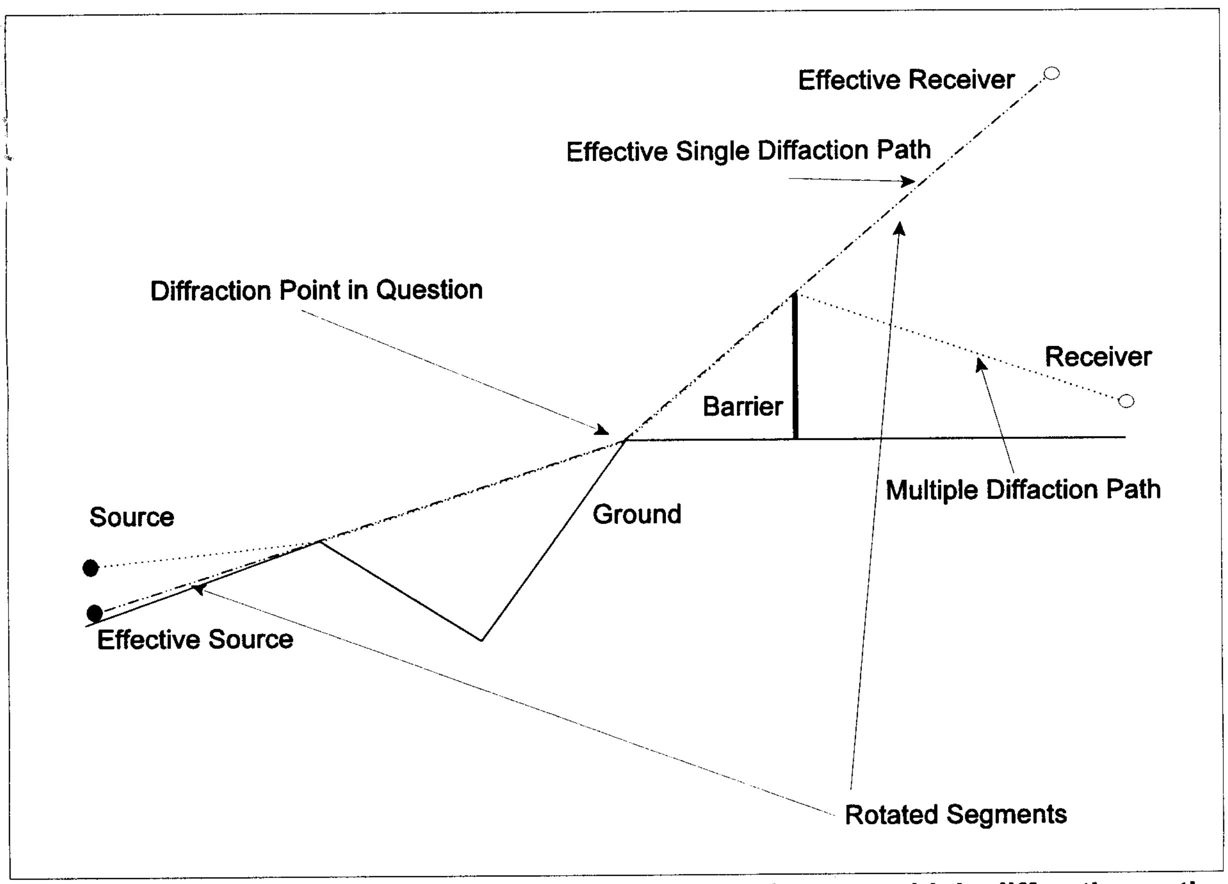


Figure 58. Example of an effective single diffraction from a multiple diffraction path.

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 59 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.)

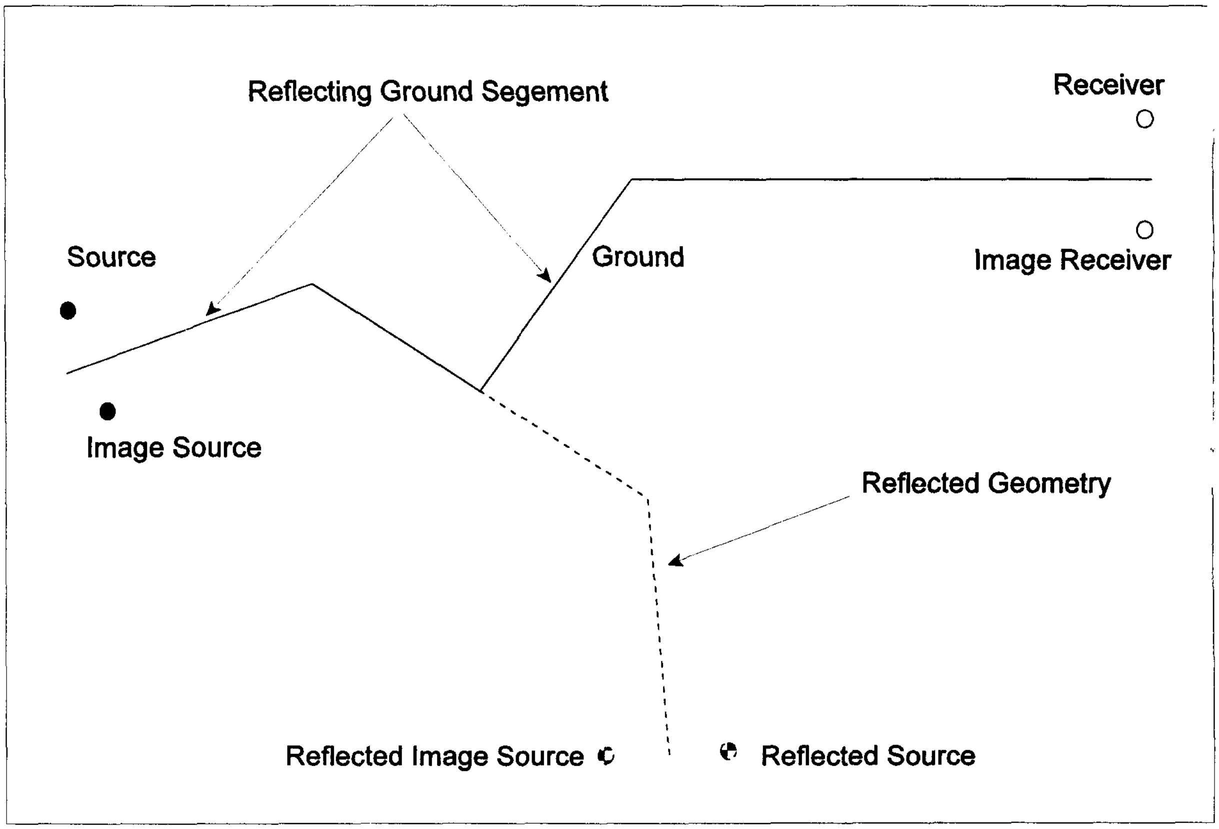


Figure 59. Example of a geometry with reflections.

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 60 shows a few examples of the direction of propagation. Propagation paths are also drawn to image receivers.

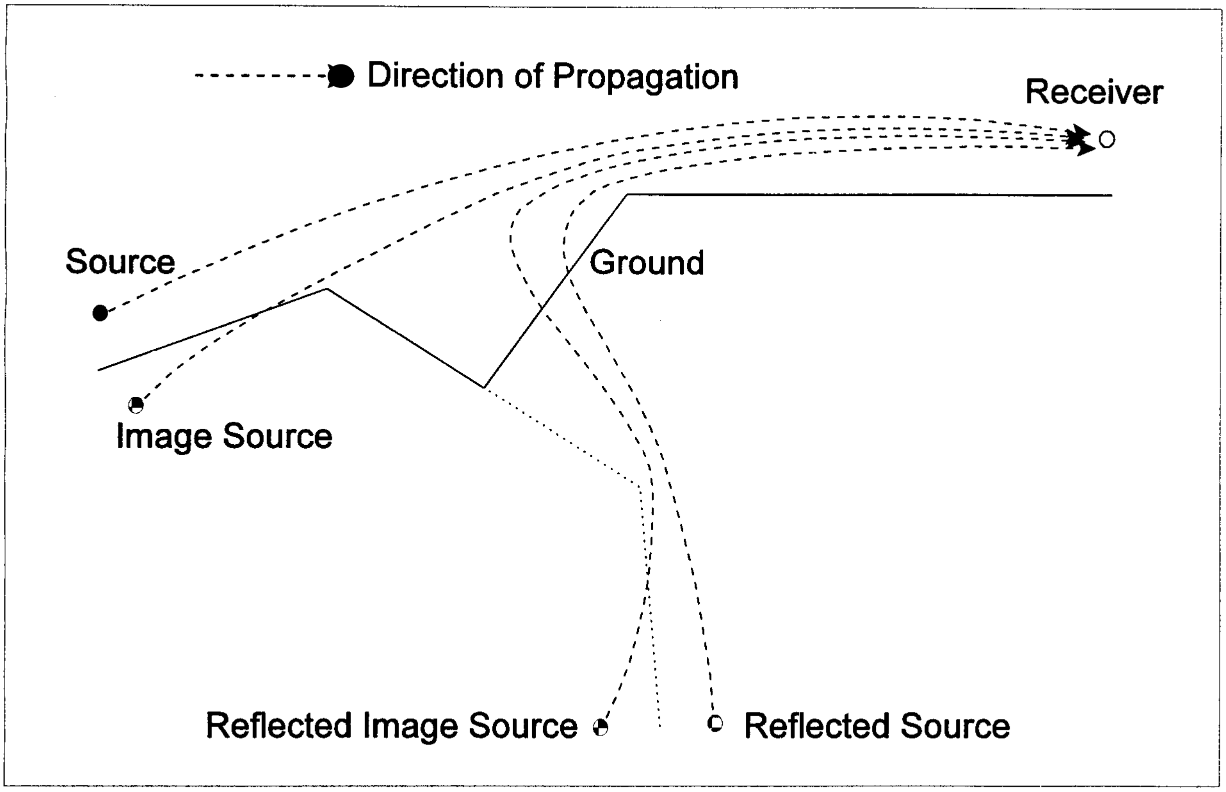


Figure 60. Example directions of propagation paths.

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 ⅓-octave band sound pressure levels at the receiver.

Path generation algorithm:

Start with the Vertical Geometry Object List.
  Set all ⅓-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 ⅓-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 ⅓-octave band partial pressure results to VGOL ⅓-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 1983] [Chessell 1977] [Delany 1970][Boulanger 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
$F_{linear\text{-}Gap}$	building-row parameter: linear gap fraction of the intervening row of buildings, dimensionless
f_{rN}	Atmospheric parameter: nitrogen relaxation frequency, in Hertz
f_{rO}	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 kiloPascal
$p_{free\text{-}field}$	free-field pressure of a propagating acoustic wave, in kiloPascal
P_{path}	pressure at the receiver, in kiloPascal, after the propagating sound undergoes one or more diffractions or reflections
p_{sat}	Atmospheric parameter: saturation vapor pressure, in kiloPascal
P_{total}	Total pressure at the receiver due to all N propagation paths combined, in kiloPascal
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:

$$p_{free\text{-}field} = \frac{e^{ikR}}{kR} \tag{26}$$

where the wave number, k, is defined as

$$k = \frac{2\pi f}{c} \tag{27}$$

and where f is the frequency in Hertz; c is the speed of sound, 345 m/sec (772 miles per 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:

$$F(\chi) = \int_{\chi}^{\infty} e^{it^2} dt \tag{28}$$

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

$$F(\chi) = \int_{\chi}^{\infty} \left(\cos(t^2) + i\sin(t^2)\right) dt \tag{29}$$

TNM computes this function with a "C" programming language algorithm from Baker [Baker 1992]

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

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

where L is defined as the propagation path length. (In Figure 61, which shows the diffraction geometry, $L = r_0 + r$.)

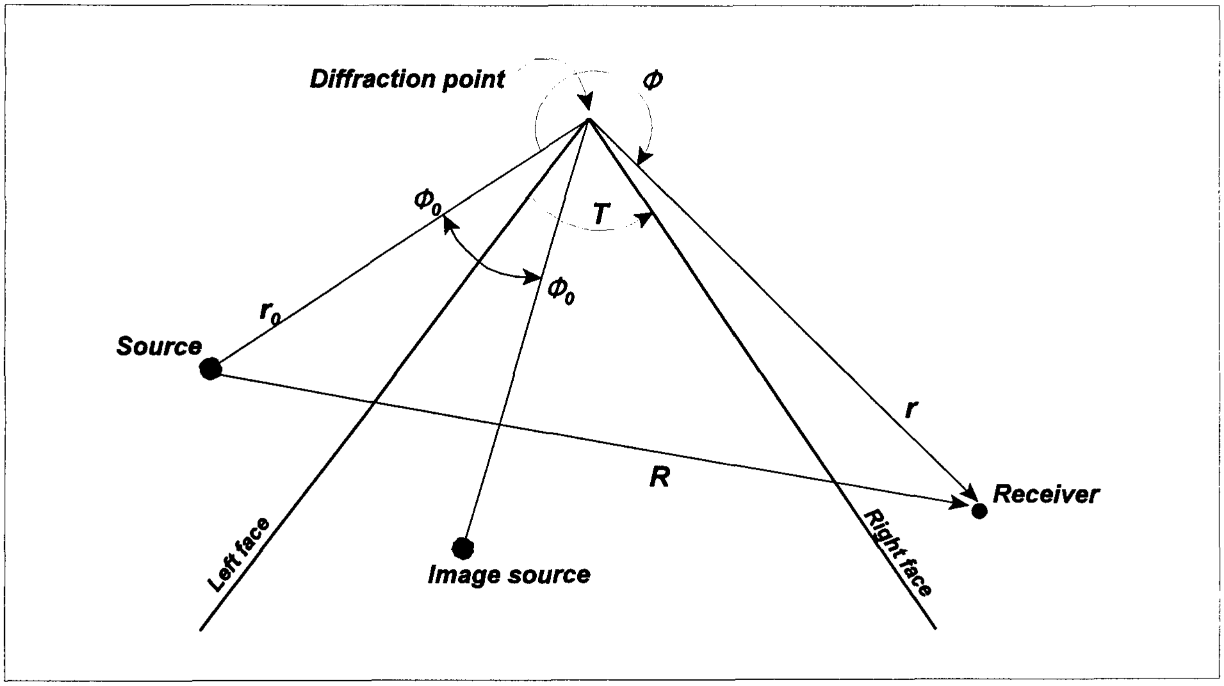


Figure 61. Diffraction geometry.

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:

$$D = (sgn)ADQ \tag{31}$$

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 forma

$$\chi = \left(\frac{krr_0}{2L}\right)^{1/2} \left|\frac{\cos(\pi/\nu) - \cos((\phi - \phi_0)/\nu)}{(1/\nu)\sin(\pi/\nu)}\right| \tag{32}$$

where

$$\nu = \frac{(2\pi - T)}{\pi} \tag{33}$$

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 (phi) and φ_0 (phi0) 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 61.

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

$$\chi = \sqrt{\frac{k(L - R)(L + R)}{2L}} \tag{34}$$

(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:

$$P_{path} = p_{free\text{-}field}\ D \tag{35}$$

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:

$$P_{path} = p_{free\text{-}field} \prod_{i=1}^{N} D_{<effective>i} \tag{36}$$

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:

$$D_{cor} = \frac{R}{L} \frac{e^{-i\frac{\pi}{4}}}{\sqrt{\pi}} e^{i\,k(L-R)} e^{-i\chi^2} F(\chi) \tag{37}$$

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:

$$N = \frac{2\delta}{\lambda} \tag{38}$$

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 [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:

$$Q = R_p + F(w)\,(1 - R_p) \tag{39}$$

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

$$R_p = \frac{\sin\phi - \dfrac{Z_0}{Z}}{\sin\phi + \dfrac{Z_0}{Z}} \tag{40}$$

Here, Z_0 is defined as the impedance of air ($\varrho_0 c_0$ = 1.18 kg/m^3 * 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 [Delany 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 1983].

$$Z = \left[1 + .051\left(\frac{f}{\sigma}\right)^{-.75} + .077\left(\frac{f}{\sigma}\right)^{-.73} i\right] Z_0 \tag{41}$$

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:

$$F(w) = \begin{bmatrix} 1 + ie^{-w}\sqrt{\pi w} - 2e^{-w}\displaystyle\sum_{n=1}^{\infty}\frac{w^n}{(n-1)!\,(2n-1)} & |w| < 10 \\ -\displaystyle\sum_{n=1}^{\infty}\frac{(2n)!}{2^n\,n!\,(2w)^n} & |w| \geq 10 \end{bmatrix} \tag{42}$$

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

$$w = \frac{1}{2} ikr \frac{(\sin\phi + Z_0/Z)^2}{1 + \sin\phi\, Z_0/Z} \tag{43}$$

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:

$$\alpha = 1 - |R^2| \tag{44}$$

where

$$R = \frac{Z - Z_0}{Z + Z_0} \tag{45}$$

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, α, 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 10 lists the EFR values used for all user-selectable NRC values.

Table 10. Effective Flow Resistivity used for values of Noise Reduction Coefficient (NRC).

NRC	EFR(cgs rayls)
0.00	20000.0
0.05	4250.0
0.10	1570.0
0.15	865.0
0.20	555.0
0.25	385.0
0.30	282.0
0.35	214.0
0.40	165.0
0.45	129.0
0.50	102.0
0.55	81.0
0.60	64.0
0.65	50.0
0.70	39.0
0.75	30.0
0.80	22.0
0.85	16.0
0.90	10.4
0.95	5.5
1.00	0.1

Table 11 shows the effective ⅓-octave band absorption coefficients used within TNM when calculating reflections in barrier surfaces for selected values of NRC.

Table 11. Absorption coefficients as a function of frequency, for selected values of Noise Reduction Coefficient (NRC).

⅓-O.B. Freq.	⅓-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 62 shows a simple propagation path that contains one reflection and one diffraction. The equation for that propagation path has the following form:

$$P_{path} = p_{free\text{-}field} \; Q \; D \tag{46}$$

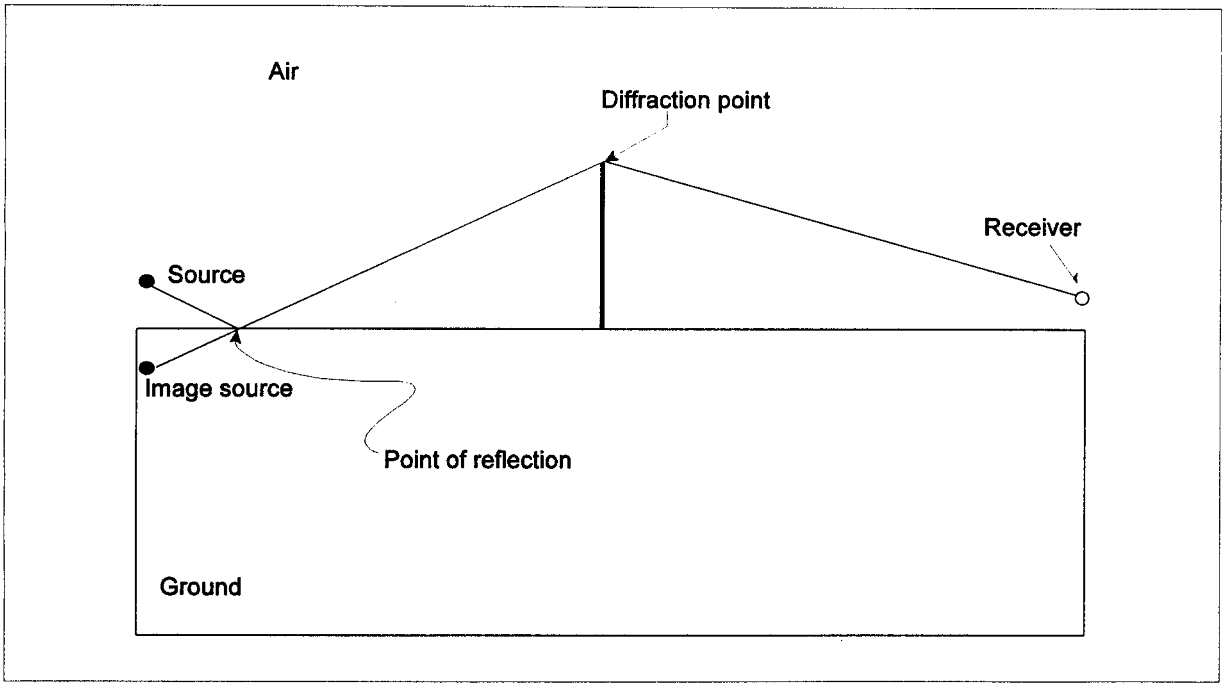


Figure 62. Example geometry showing reflection.

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 63 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 63:

$$P_{path} = p_{free\text{-}field} \; (Q_1 - Q_2) \; D \tag{47}$$

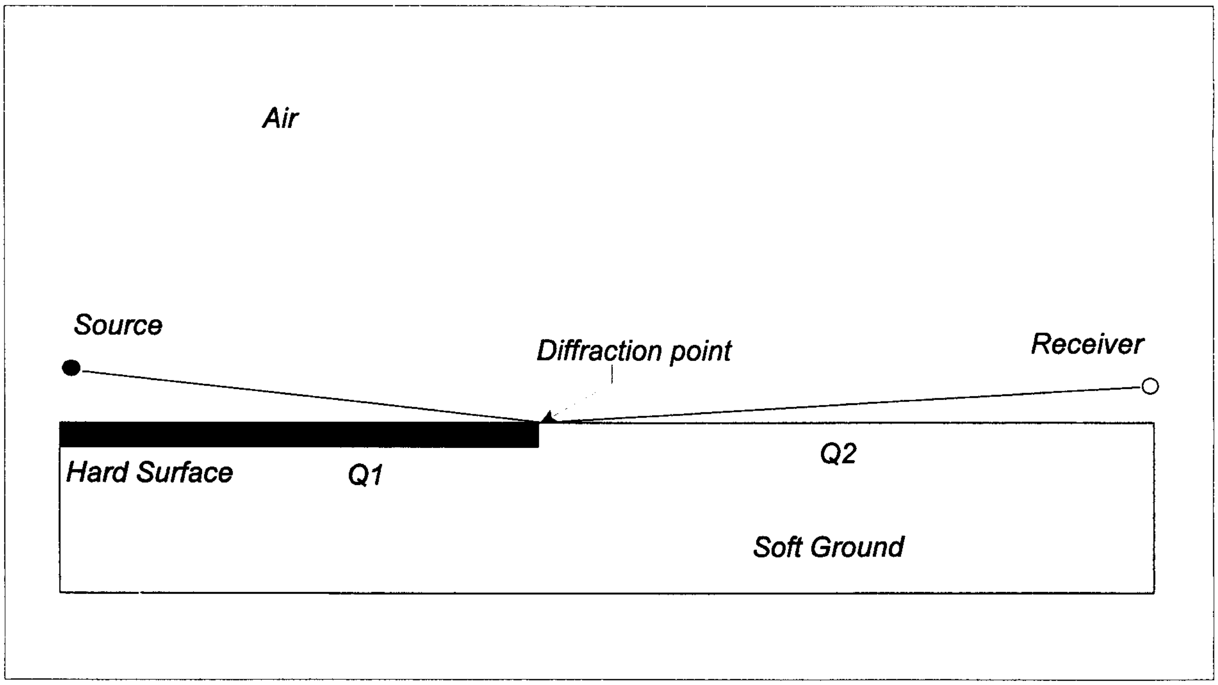


Figure 63. Example geometry showing an impedance discontinuity.

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:

$$P_{path} = p_{free\text{-}field}\ (Q_1 - Q_2)\ D_{Cor} \tag{48}$$

Figure 64 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.

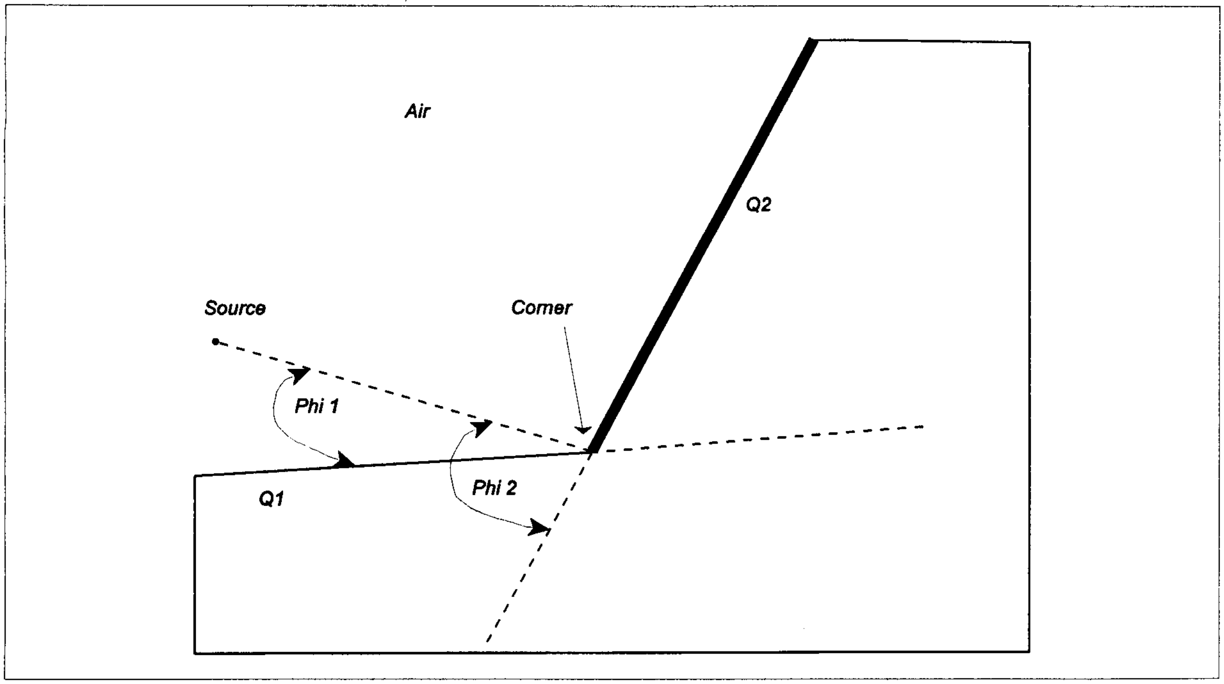


Figure 64. Example geometry for corner diffraction.

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 ⅓ octave band. Figure 65 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 A_1 and A_3, which are soft ground, and A_2 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.

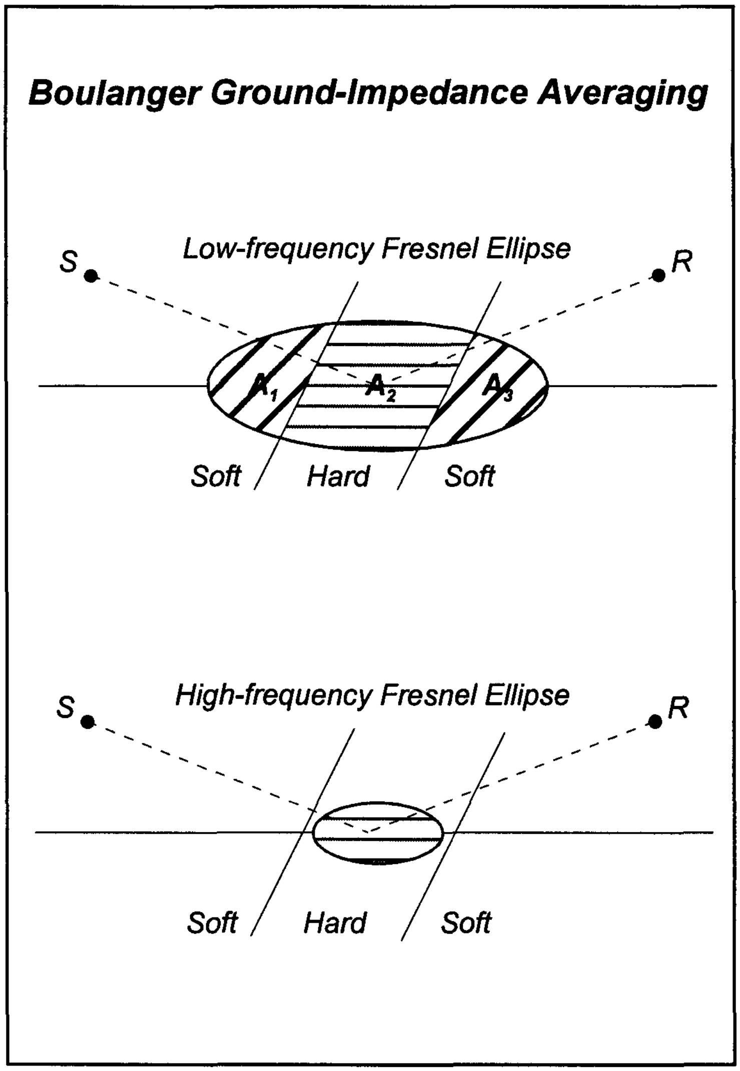


Figure 65. Ground impedance evaluation at two frequencies.

D.4.7 Tree zones. The 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 the 1996 ISO standard attenuation for dense foliage [ISO 9613-2], 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 12. In TNM, the octave-band values shown in Table 12 are applied to each of the ⅓-octave bands within the associated octave band.

Table 12. Attenuation through dense foliage.

Octave-band center frequency (Hz)	63	125	250	500	1K	2K	4K	8K
Attenuation (dB, total) for d_f less than 10 meters	0	0	0	0	0	0	0	0
Attenuation (dB, total) for d_f between 10m and 20m	0	0	1	1	1	1	2	3
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:

$$Atten_{row} = MAX\left(0 \ , \ -10 \times Log_{10}\left(F_{Linear-Gap} + 10^{-\frac{IL_{Barrier}}{10}}\right)\right) \tag{49}$$

where $F_{\text{linear gap}}$ is the gap fraction associated with the building row and IL_{Barrier} is the insertion loss of the building row, as if it were a solid barrier. Users define "building percentage," which is 100 (1-$F_{\text{linear gap}}$). 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 (so that N=δ), 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:

$$Il_{Barrier} = \begin{bmatrix} 10 \times Log_{10}(3 + 20N') & N' > 0 \\ 4.77 - 9.54\sqrt{|N'|} & N' \leq 0 \end{bmatrix} (dB) \tag{50}$$

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 ⅓-octave band. Attenuation attributed to each remaining row of buildings that interrupts the propagation path is 1.5 dB in each ⅓-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 13.

Table 13. Maximum attenuation for rows of buildings by frequency.

⅓-Octave Band Center Freq., Hz	Max. Atten. (dB)	⅓-Octave Band Center Freq., Hz	Max. Atten. (dB)
50	5.30	800	9.65
63	5.43	1000	10.33
80	5.59	1250	11.05
100	5.77	1600	11.89
125	5.99	2000	12.69
160	6.28	2500	13.52
200	6.59	3150	14.40
250	6.94	4000	15.33
315	7.37	5000	16.23
400	7.86	6300	17.17
500	8.38	8000	18.15
630	8.98	10000	19.08

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

D.4.9 Atmospheric absorption. The 1993 ISO standard [ISO 9613-1] 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:

$$A_{atm} = 8.686 f^2 \left[\left(1.84x10^{-11} \sqrt{\frac{T}{T_0}} \right) + \left(\frac{T_0}{T} \right)^{5/2} \frac{\left(0.01275 e^{-2239.1/T} \right)}{\left(f_{rO} + \frac{f^2}{f_{rO}} \right)} + \frac{\left(0.1068 e^{-3352.0/T} \right)}{\left(f_{rN} + \frac{f^2}{f_{rN}} \right)} \right] \qquad (51)$$

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 1/3 octave-band center frequency, in Hz.

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

$$f_{rO} = 24 + 4.04x10^4 h\left(\frac{0.02 + h}{0.391 + h}\right) \tag{52}$$

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

$$f_{rN} = \sqrt{\frac{T_0}{T}}\left(9 + 280he^{-4.170\left(\left(\frac{T_0}{T}\right)^{1/3} - 1\right)}\right) \tag{53}$$

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:

$$T_{Celsius} = \frac{5}{9}T_{Fahrenheit} - 32 \tag{54}$$

$$T_{Kelvin} = T_{Celsius} + 273.15 \tag{55}$$

For humidity:

$$h = h_r\frac{p_{sat}}{p_{so}} \tag{56}$$

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,

$$\frac{p_{sat}}{p_{so}} = 10^C \tag{57}$$

where

$$C = -6.8346\left(\frac{T_{01}}{T}\right)^{1.261} + 4.6151 \tag{58}$$

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 ⅓-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° Celsius (68° F), 50- percent RH and one atmosphere (the default conditions), as a function of 1/3-octave band center frequency, are given in Table 14.

Table 14. Atmospheric absorption by frequency for default atmospheric conditions.

1/3-Octave Band Center Freq., Hz	Atten. (dB/m)
50	7.8081e-05
63	1.2245e-04
80	1.9355e-04
100	2.9387e-04
125	4.3979e-04
160	6.7073e-04
200	9.5388e-04
250	1.3097e-03
315	1.7436e-03
400	2.2389e-03
500	2.7281e-03
630	3.2678e-03

1/3-Octave Band Center Freq., Hz	Atten. (dB/m)
800	3.9070e-03
1000	4.6647e-03
1250	5.7114e-03
1600	7.4506e-03
2000	9.8870e-03
2500	1.3640e-02
3150	1.9711e-02
4000	2.9666e-02
5000	4.4239e-02
6300	6.7625e-02
8000	1.0529e-01
10000	1.5884e-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 66 shows the parameters of the double-barrier calculations.

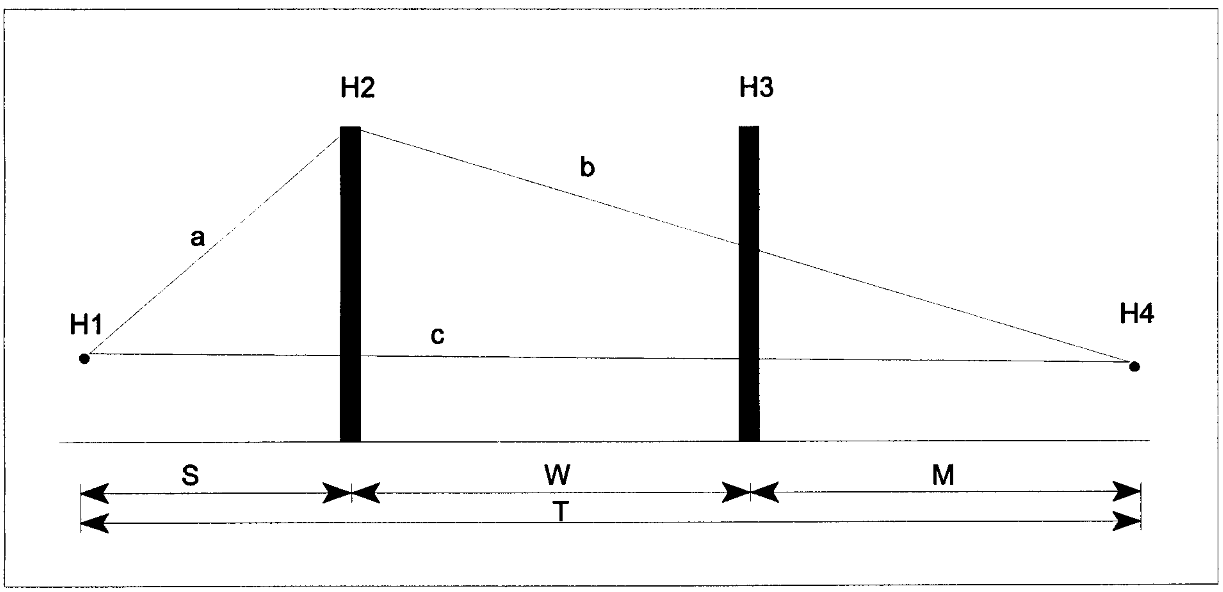


Figure 66. Foss double-barrier geometry.

The effective attenuation is calculated using the following equation:

$$IL_{eff} = F + J - \left[6e^{-\frac{2W}{T}} + 1.3\left(e^{-\frac{35W}{T}} - 1\right) \right] \left(1 - e^{-\frac{J}{2}}\right) \qquad (59)$$

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 66. The attenuation is calculated for each barrier alone, ignoring the other, using an approach similar to that used in STAMINA [Barry 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:

$$P_{Total} = \sum_{i=1}^{N} P_{path_i} \tag{60}$$

D.4.12 Attenuation. The final attenuation for a vertical geometry, A_s, is calculated in reference to the free-field sound pressure as:

$$A_s = 20 \times Log_{10} \left| \frac{P_{Total}}{P_{free\text{-}field}} \right| \tag{61}$$

for each leg of the elemental triangle. The attenuation fraction, needed by the horizontal geometry, is defined as $\varphi_S = 10^{(A_S/10)}$ — computed for both legs of the triangle: φ_{SL}, φ_{SR} . Then the average over the triangle is computed as $\varphi_{SAvg} = ½ (\varphi_{SL} + \varphi_{SR})$. This is equivalent to $\varphi_{n,f,barrs}$ in Eq. 19 in Appendix C, Section C.2.4.

APPENDIX E
PARALLEL BARRIER ANALYSIS

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 computes parallel-barrier degradation for explicitly entered cross-sectional (two-dimensional) geometries. Once computed, the user must generalize these degradations for the full set of TNM receivers and then must enter appropriate adjustment factors for these 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 67 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.

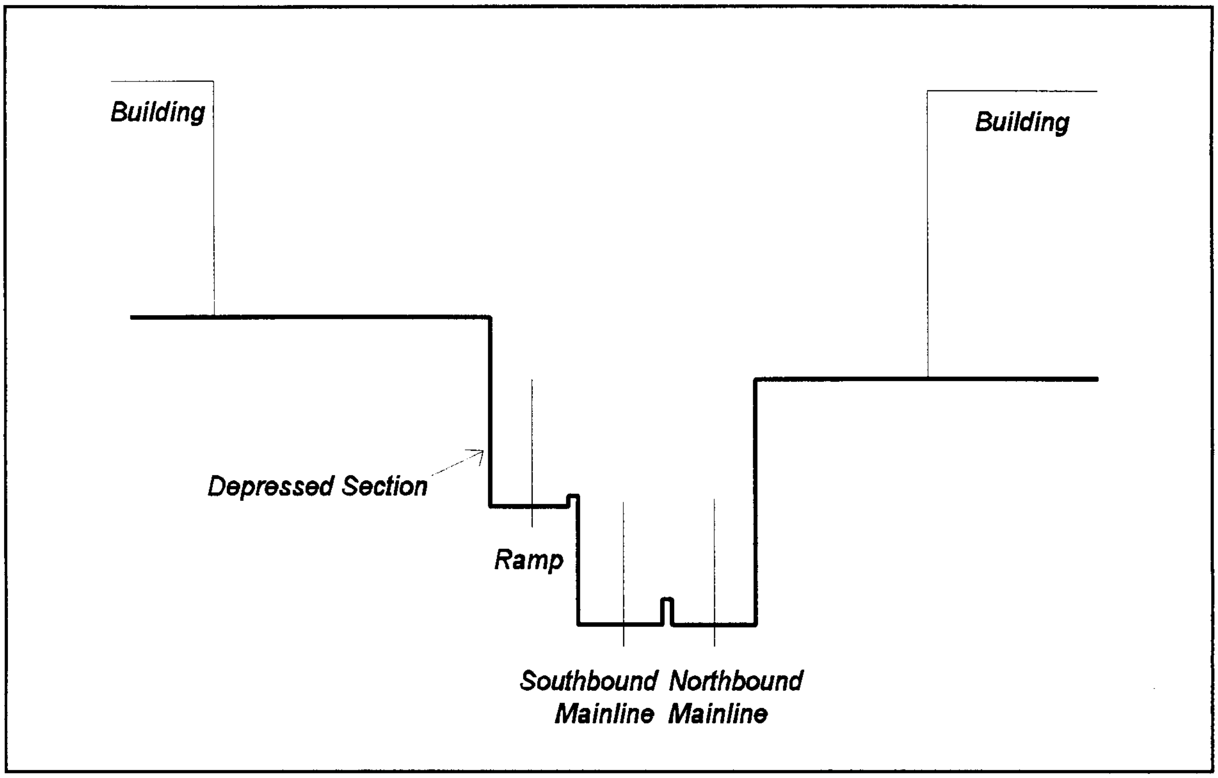


Figure 67. Typical depressed section in a highly urbanized area.

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.

Separately from its regular sound-level computations, TNM does predict parallel-barrier degradation in two dimensions, as described in the remainder of this appendix [Menge 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 subsource. 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 Version 1.0, "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 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 68 shows the required 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 types: roadway input, cross-section input, and analysis-location (or receiver) input.

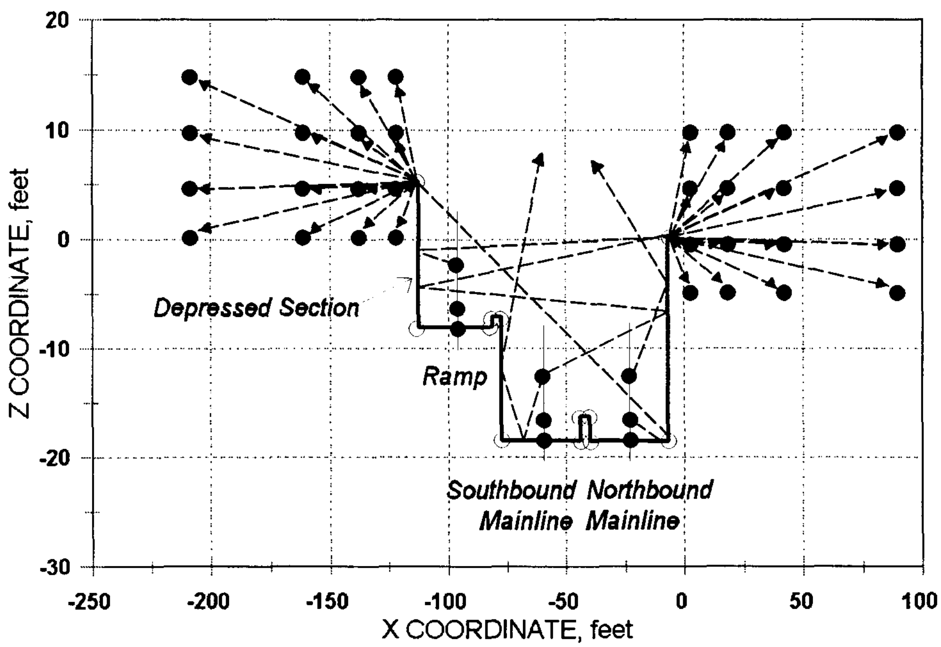


Figure 68. Detailed input and representative rays.

E.3.1 Roadway input. Each traffic stream appears in the figure as a separate roadway, represented by three subsource dots and a vertical line connecting them. These subsource dots correspond to TNM's built-in subsource 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. 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 subsources.

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 68 as a single, thick connected line, from one diffracting edge to the opposite one. The user enters the HZ coordinates for each point along this cross-section line. The user also enters a NRC for each surface element. Unfortunately, when performing a parallel barrier analysis, NRCs are not inherited from the main TNM run. 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. 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 subsource (three per roadway). TNM spaces these 10,000 rays equally in direction around the subsource, 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 68, above.

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

$$E_{\text{Aemis},\, i}(s_i) = \left(0.6214\, s_i\right)^{A/10} 10^{B/10} + 10^{C/10} \tag{62}$$

and

$$\begin{aligned} r_i(500\text{ Hz}) &= L + (1 - L - M)\left[1 + e^{(N\text{Log}_{10}500 + P)}\right]^Q \\ &= L + (1 - L - M)\left[1 + e^{(2.7N + P)}\right]^Q , \end{aligned} \tag{63}$$

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 effect 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

$$\begin{aligned} E_{\text{Aemis},\, i,\, \text{upper},\, \text{ff}}(s_i) &= \left(\frac{r_i}{r_i + 1}\right) E_{\text{Aemis},\, i} \\ E_{\text{Aemis},\, i,\, \text{lower},\, \text{ff}}(s_i) &= \left(\frac{1}{r_i + 1}\right) E_{\text{Aemis},\, i} \,. \end{aligned} \tag{64}$$

Then it computes

$$E_{\text{eq, upper}} = 0.0476\left(\frac{v_i}{s_i}\right) E_{\text{Aemis}, i, \text{upper, ff}}$$
$$E_{\text{eq, lower}} = 0.0476\left(\frac{v_i}{s_i}\right) E_{\text{Aemis}, i, \text{lower, ff}}, \qquad (65)$$

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 $E_{\text{eq, ref}}$), as follows:

$$E_{\text{eq, ref, 0 meters (0 feet)}} = \sum_{i = \text{all vehicle types}} \left(E_{\text{eq, lower}, i}\right)$$
$$E_{\text{eq, ref, 1.5 meters (1.5 feet)}} = \sum_{i = \text{all vehicle types except heavy trucks}} \left(E_{\text{eq, upper}, i}\right) \qquad (66)$$
$$E_{\text{eq, ref, 3.6 meters (12 feet)}} = E_{\text{eq, upper}, i = \text{heavy trucks}}.$$

In this manner, each TNM parallel-barrier roadway becomes three subsources: 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 subsources 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 69.

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 69 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.

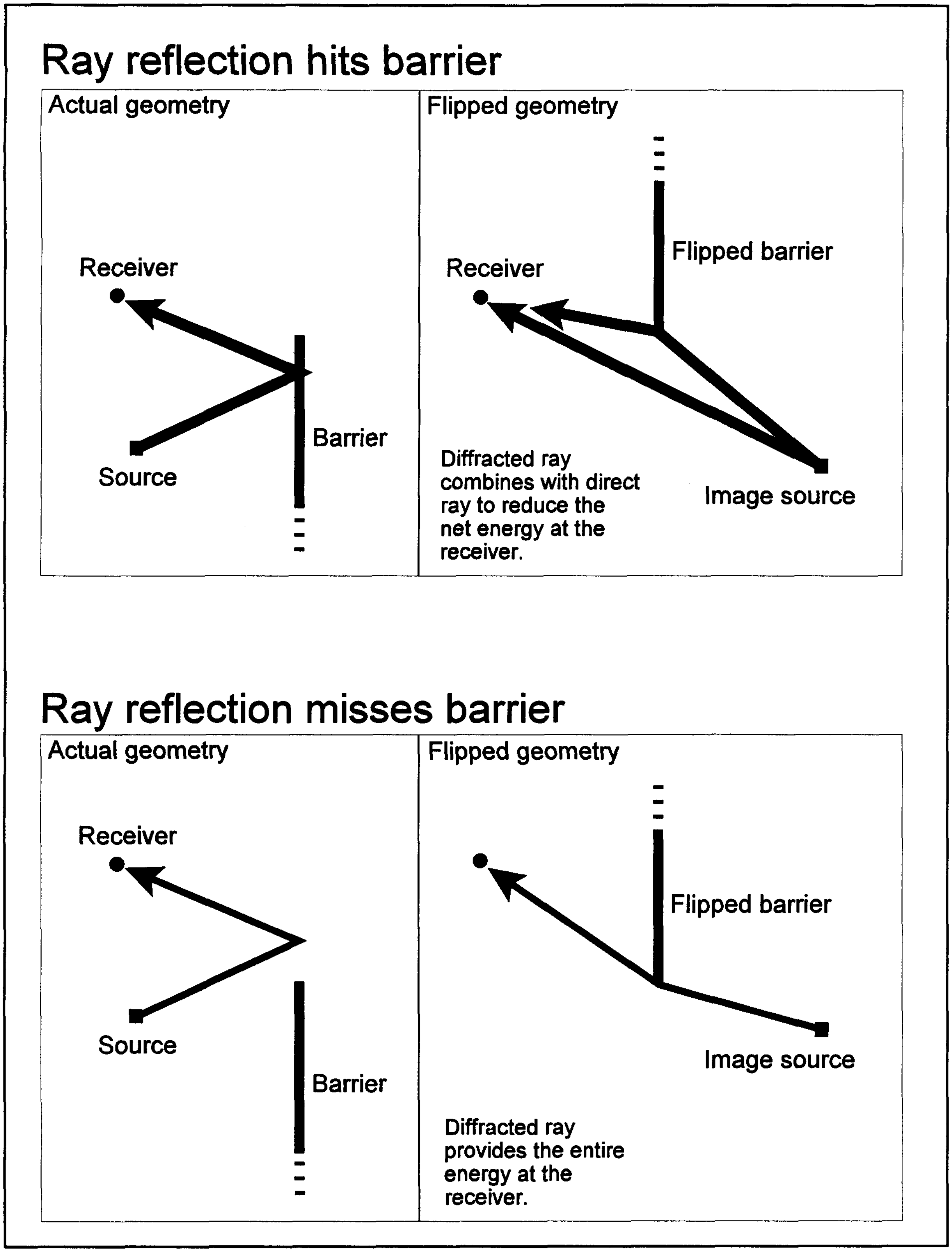


Figure 69. Partial reflection near tops of parallel barriers.

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 left-most 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 computation (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 explicitly entered 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 [Hendriks 1991]: w/h ratio = 15:1
- I-495 in Montgomery County, Maryland [Fleming 1992]: w/h ratio = 9:1
- Dulles Airport experimental barrier [Fleming 1990]: w/h ratio = 6:1

These measurement sets are summarized in [Fleming 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 15 summarizes the initial comparison of field measurements and TNM computations, before calibration.

Table 15. Parallel-barrier degradations: Initial comparison of measured and computed values.

Data set	Width/Height ratio (w/h)	Parallel-barrier degradations					
		Measured, dB		Computed, dB		Overprediction (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, overprediction 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, overprediction 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 subsource heights and built-in vertical energy splits (see Appendix A). For example, degradation was initially computed for five different source heights, as shown in Table 16, using Route-99 traffic and roadway geometry.

Table 16. 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 subsource heights used for computation, and in turn upon the subsource-height energy split for any pair of subsource heights.

E.8.3 Calibration method For adequate accuracy, TNM parallel-barrier computations obviously need to be calibrated against measurements. Overprediction 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 times g_{comp} yields 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

$$r_{w/h,mic} = \frac{\left(H_{diff,right} - H_{diff,left}\right)}{\left(\overline{Z_{diff}} - \overline{Z_{road}}\right)} . \tag{67}$$

In this equation,

$$\begin{aligned} H_{diff,right} &= \text{the H coordinate of the right - end diffraction point} \\ H_{diff,left} &= \text{the H coordinate of the left - end diffraction point} \\ \overline{Z_{diff}} &= \text{the average Z coordinate of the two diffraction points} \\ \overline{Z_{road}} &= \text{the average Z coordinate of all the roadways (at the pavement).} \end{aligned} \tag{68}$$

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

$$d_{horiz,mic} = \left|H_{mic} - H_{diff,near}\right| . \tag{69}$$

In this equation,

$$\begin{aligned} H_{mic} &= \text{the H coordinate of the microphone (analysis location)} \\ H_{diff,near} &= \text{the H coordinate of the near diffracting edge.} \end{aligned} \tag{70}$$

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

$$d_{vert,mic} = Z_{mic} - \overline{Z_{barr\ tops}} . \tag{71}$$

In this equation,

$$\begin{aligned} Z_{mic} &= \textit{the Z coordinate of the microphone (analysis location)} \\ \overline{Z_{barr\ tops}} &= \text{the average Z coordinate of the tops of the two barriers.} \end{aligned} \tag{72}$$

E.8.4 Calibration results. The regression produced the following adjustments to the computed output of TNM's parallel-barrier code:

$$g_{\text{calibrated, mic}} = \left(g_{\text{computed, mic}}\right)\left[1+e^{\left(4r_{\text{w/h,mic}}-21.42\right)}\right]^{-0.019} + 0.072 + 0.04d_{\text{vert,mic}} - 0.003d_{\text{horiz,mic}}\ , \tag{73}$$

subject to the constraint that

$$g_{\text{calibrated, mic}} \le g_{\text{computed, mic}}\ . \tag{74}$$

In these two equations, $g_{\text{calibrated, mic}}$ is the calibrated degradation at a given microphone and $g_{\text{computed, mic}}$ is the degradation computed directly by the parallel-barrier code. The three independent variables ($r_{\text{w/h,mic}}$, $d_{\text{horiz,mic}}$, and $d_{\text{vert,mic}}$) are defined in Eqs. (65), (67) and (69), respectively.

APPENDIX F
CONTOURS

FHWA TNM® computes sound levels and analyzes barrier designs primarily at receivers individually entered by the user. In addition to this primary intent, TNM also allows the user to compute contours within specified contour zones. Three types of contours are available:

- Sound-level contours for a specified barrier design, in the user's chosen set of sound-level units: L_{Aeq1h}, L_{dn}, or L_{den}
- Insertion-loss contours for a specified barrier design
- Level-difference contours between two specified barrier designs.

This appendix discusses TNM's computation of these three types of sound-level contours.

F.1 Contour computations

To compute contours, TNM:

- Generates an initial, regular grid within the user's contour zone
- Interpolates the ground elevation at all grid points
- Computes the sound level at each grid point, at 1.5 meters (5 feet) above the interpolated ground
- Subdivides each grid cell, as needed, to obtain the user's requested contour precision.

Contour computations are linked to "remembered" barrier designs. 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 "remembered" barrier design, with its particular barrier heights. Then TNM uses these heights to compute sound levels at all grid points.
- For insertion-loss contours, the user first chooses a "remembered" 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* "remembered" 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.

Sometimes barriers that are not in the chosen barrier design may affect sound levels within the contour zone. Generally this is not the case, however. Generally the user includes all influential barriers in the chosen barrier design. To compute, however, TNM must know *all* barrier heights, even those not in the chosen barrier design.

To be conservative, TNM assigns zero height to all barriers not in the chosen barrier design. For a perturbable barrier to have a non-zero height for contour computations, the user *must* include it in the barrier design and thereby set its height as desired.

Once TNM obtains computed values at all grid and necessary subgrid points, it generates a so-called "grid" file with these computed values, the XY coordinates of the grid points, and other miscellaneous data. It then submits this grid file to the computer program NMPLOT, which computes the corresponding contours and returns them to TNM.

This exchange between TNM and NMPLOT is essentially transparent to the user. The user may, however, name the grid file and thereby recall it for later use — or even run it independently under NMPLOT Version 3.05.

F.2 Details about Barrier Perturbations

Barrier input contains three values associated with perturbations:

- Perturbation increment
- Number of perturbations up
- Number of perturbations down.

Fixed, barrier-like features: If a user wishes to model an existing wall, or a Jersey barrier along the highway, or even a large building, then the user sets all three of the above parameters to zero. TNM then knows that such barriers are never perturbed down to their zero height. They are fixed features within the input, always there and always full height.

Perturbable barriers: If a user wishes to model a perturbable noise barrier along the highway, the user enters values for the above three parameters to indicate the height perturbations desired. TNM then computes the acoustics for all height perturbations, including zero height. In addition, TNM perturbs this barrier down to zero height as the baseline condition for insertion loss calculations.

Non-perturbable barriers: A third possibility exists, as well: the user wishes to model a non-perturbable noise barrier along the highway and to later learn its insertion loss. To do this, the user must enter *at least one non-zero perturbation value*: either: (1) non-zero number of perturbations up; or (2) non-zero number down; or (3) non-zero perturbation increment. This non-zero value tells TNM to perturb the barrier down to zero height for insertion loss calculations, even though the barrier top does not perturb.

F.3 Details about Grid Spacing

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:

$$\begin{aligned} \text{X-width} &= x_{\max} - x_{\min} \\ \text{Y-width} &= y_{\max} - y_{\min} \,. \end{aligned} \tag{75}$$

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 70 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 and 2.
- TNM subtracts the computed level at point B from the algebraic average at points 1 and 3.
- TNM subtracts the computed level at point C from the algebraic average at points 1 and 4.
- If *all* of these differences are within the user's requested precision, then TNM does not subdivide this cell. On the other hand, if *any one of them* 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.

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 subgrid size." For example, if the user is interested in geographic resolution down to only 10 meters (33 feet), then a minimum subgrid size of 10 meters (33 feet) would prevent TNM from subdividing any finer.

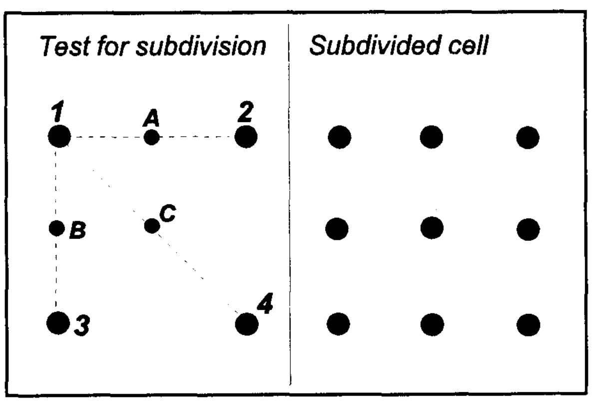


Figure 70. Subdivision of grid cells during contouring.

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.

F.4 Details about Computation Heights

To compute sound levels, TNM must know the Z coordinate of the ground at each grid/subgrid point. TNM computes at ear-height above this ground Z coordinate, using the user-entered receiver height above the ground. To determine the ground's Z coordinate at each grid/subgrid point:

- TNM augments the user's input by replacing every line segment (roadway, barrier, building row, terrain line, edge of tree zone) with a series of closely spaced points. These points define the Z coordinate of the ground continually along the line segment, from the input Z coordinates of its endpoints. Without such augmentation of Z coordinates, a line segment would define the ground only at its two endpoints.
- TNM drops a regularly spaced "net" down over the augmented input, with a net spacing equal to the initial grid spacing. Then TNM interpolates the ground Z coordinates at each grid point from all the Z coordinates for the augmented input.
- Then TNM adds 1.5 meters (5 feet) to all ground Z coordinates, to approximate ear height. Note that receiver heights above the ground may differ from receiver to receiver and so TNM cannot make this contour-receiver height specific to any single input-receiver's height.
- During subdivision, TNM determines the Z coordinate of each new subgrid point by interpolating between previously determined Z coordinates.

APPENDIX G
MODEL VERIFICATION

This appendix provides a comparison of TNM 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.

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 500 meters (1500 feet). The source was a jet engine at a height of 1.8 meters (6.0 feet) and the microphone heights were all 1.5 meters (5.0 feet) above the ground. One-third octave band sound level measurements were made at the following distances: 35 m (114 ft), 62 m (202 ft), 110 m (360 ft), 195 m (640 ft) and 348 m (1140 ft).

The TNM was exercised at the same geometric locations, and an EFR of 325 cgs Rayls was chosen as most likely to represent the characteristics of the ground at Hatfield. Figures 75 through 79 present the comparison of measured and modeled ground effect in ⅓-octave bands.

G.3 Measurements of Barrier Insertion Loss

The complete TNM reflection and diffraction model was compared with the careful barrier insertion loss measurements of Scholes [Scholes 1971]. Like the Parkin propagation measurements, the barrier measurements were also conducted at the Hatfield site. Numerous measurements were conducted at different distances, with different barrier and receiver heights, and under different atmospheric conditions. The comparisons with the TNM were made with a limited set of the measured data. The atmospheric conditions were neutral with zero vector wind. Comparisons are made for the following geometry: source height of 0.7 m (2.3 ft); barrier heights of 1.8 m (6 ft) and 4.9 m (16 ft); microphone heights of 1.5 m (5 ft), 3 m (10 ft), 6 m (20 ft), and 12 m (40 ft); source-to-barrier distance of 10 m (33 ft); and barrier-to-receiver distance of 30 m (100 ft). Measurements were made with and without the barrier and the resulting insertion loss reported in octave bands. For a direct comparison, the TNM's ⅓-octave band values were combined (energy sum prior to subtraction) to obtain octave-band values. As with the Parkin comparisons, an EFR of 325 cgs Rayls was assumed for the grass-covered Hatfield site. Figures 80 through 87 present the barrier insertion loss comparisons.

G.4 Measurements of In-Situ Barrier Performance

Comparisons between STAMINA and TNM for two recent studies show unprecedented predictive accuracy in the case of TNM. It should be pointed out that these two studies exercise the majority of the most-commonly used components within TNM, including barriers, propagation over acoustically soft ground, and moderately-changing terrain elevation. The comparisons are summarized below:

G.4.1 Rt. 99 in Sacramento, California. The study [Hendriks 1991] included sound-level measurements performed BEFORE and AFTER barrier construction, and the resultant INSERTION LOSS associated with the barrier. It consisted of 4 roadways, 1 barrier of interest in the AFTER case, 3 terrain lines, and 10 receivers. The receivers were located as follows: 1 reference microphone at 5 ft directly above the position of the barrier, 3 receivers placed at a 15-ft offset position behind the position of the barrier at 5-ft, 15-ft, 23-ft elevations, 3 receivers placed at a 75-ft offset position at the same elevations, and 3 receivers placed at a 200-ft offset position, also at the same elevations. The three microphone elevations will be referred to as low, middle, and high hereafter. The results shown in Tables 17 through 19 reflect sound levels adjusted for the reference microphone in accordance with ANSI S12.8-1987 [ANSI 1987].

Table 17. Rt. 99 CA: BEFORE (no barrier) levels.

Receiver	Measured Levels	Predicted Levels			
		STAMINA	Delta (Measured-STAMINA)	TNM	Delta (Measured-TNM)
200'-high	70.9	74.5	-3.6	70.2	0.7
200'-middle	71.0	74.5	-3.5	69.3	1.7
200'-low	64.7	74.5	-9.8	67.7	-3.0
75'-high	75.2	77.7	-2.5	75.5	-0.3
75'-middle	75.4	77.8	-2.4	74.2	1.2
75'-low	71.9	74.7	-2.8	72.4	-0.5
15'-high	79.5	80.5	-1.0	79.2	0.3
15'-middle	79.3	80.6	-1.3	78.6	0.7
15'-low	75.8	79.0	-3.2	76.8	-1.0
Average Delta			-3.34		-0.02

Table 18. Rt. 99 CA: AFTER (barrier) levels.

Receiver	Measured Levels	Predicted Levels			
		STAMINA	Delta (Measured-STAMINA)	TNM	Delta (Measured-TNM)
200'-high	65.0	70.2	-5.2	66.3	-1.3
200'-middle	63.4	69.4	-6.0	64.7	-1.3
200'-low	60.6	68.5	-7.9	62.5	-1.9
75'-high	72.0	75.8	-3.8	73.3	-1.3
75'-middle	66.9	72.6	-5.7	68.1	-1.2
75'-low	63.4	69.8	-6.4	63.9	-0.5
15'-high	80.4	80.9	-0.5	79.3	0.7
15'-middle	71.8	75.9	-4.1	71.6	0.2
15'-low	63.0	67.6	-4.6	63.2	-0.2
Average Delta			-4.91		-0.76

Table 19. Rt. 99 CA: Barrier insertion loss.

Receiver	Measured Levels	Predicted Levels			
		STAMINA	Delta (Measured-STAMINA)	TNM	Delta (Measured-TNM)
200'-high	6.4	4.8	1.6	4.4	2.0
200'-middle	8.1	5.6	2.5	5.1	3.0
200'-low	4.6	6.5	-1.9	5.7	-1.1
75'-high	3.7	2.4	1.3	2.7	1.0
75'-middle	9.0	5.7	3.3	6.6	2.4
75'-low	9.0	5.4	3.6	9.0	0.0
15'-high	-0.4	0.1	-0.5	0.0	-0.4
15'-middle	8.0	5.2	2.4	7.5	0.5
15'-low	13.3	11.9	1.4	14.1	-0.8
Average Delta			1.57		0.73

G.4.2 I-495 in Montgomery County, Maryland The study [Fleming 1992] only included sound-level measurements performed AFTER barrier construction. It consisted of 2 roadways, 1 barrier, and 10 receivers. The receivers were located as follows: 1 reference microphone at 5 ft directly above the position of the barrier, 3 receivers placed at a 16-ft offset position behind the position of the barrier at 7.9-ft, 18.3-ft, 28.9-ft elevations, 3 receivers placed at a 65.5-ft offset position at the same elevations, and 3 receivers placed at a 131-ft offset position, also at the same elevations. The three elevations will be referred to as low, middle, and high hereafter. The results shown in Table 20 reflect sound levels adjusted for the reference microphone in accordance with ANSI S12.8-1987.

Table 20. I-495 MD: AFTER (barrier) levels.

Receiver	Measured Levels	Predicted Levels			
		STAMINA	Delta (Measured-STAMINA)	TNM	Delta (Measured-TNM)
131'-high	67.9	71.2	-3.3	67.3	0.6
131'-middle	65.25	70.1	-4.85	65.2	0.05
131'-low	62.8	69.3	-6.5	63.9	-1.1
65.5'-high	72.15	73.95	-0.2	72.75	-0.6
65.5'-middle	67.9	71.25	-1.85	66.45	1.45
65.5'-low	64.75	68.75	-4.3	63.45	1.3
16'-high	80.3	80.4	-0.1	80.6	-0.3
16'-middle	73.15	75.6	-2.45	72.8	0.35
16'-low	66.45	67.7	-1.25	62.8	3.65
Average Delta			-3.07		0.60

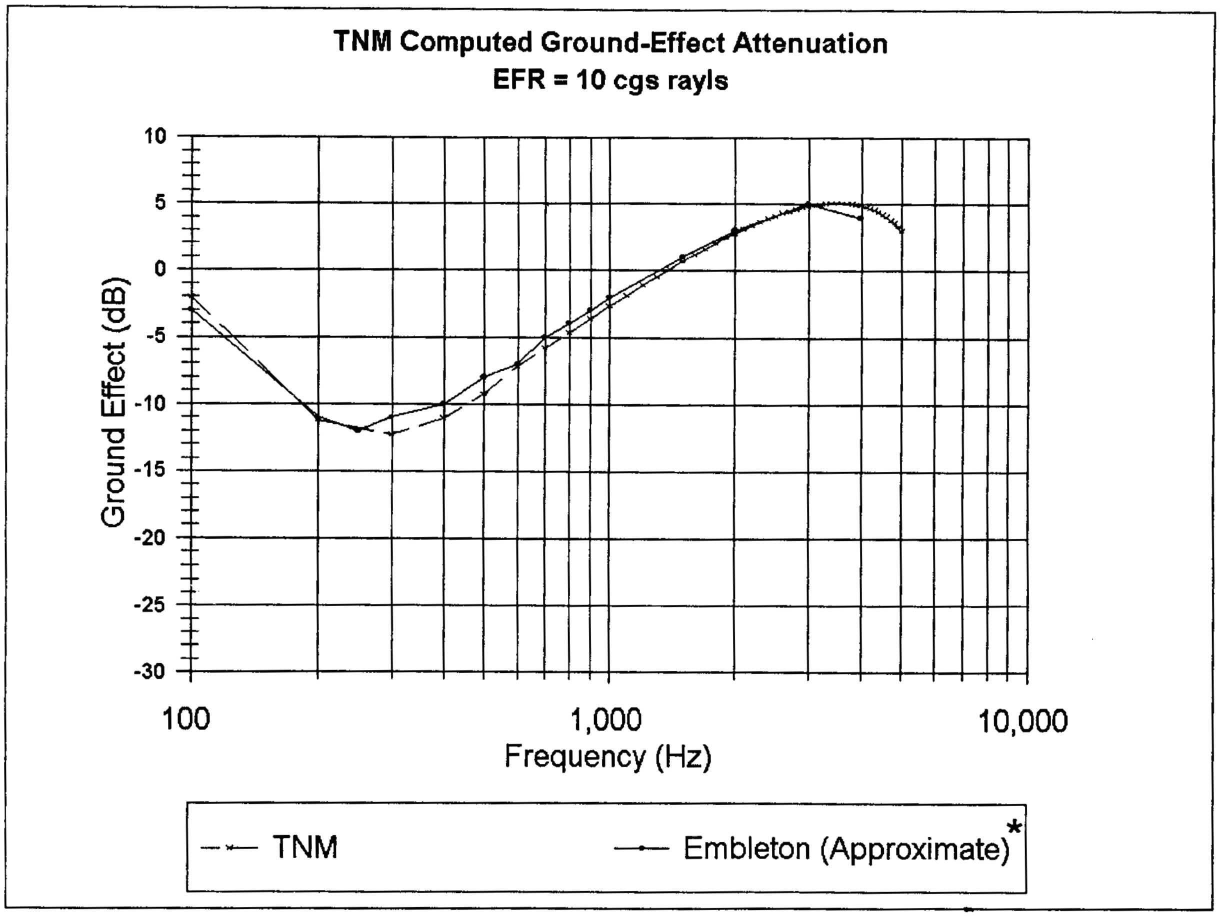


Figure 71. Ground-effect model comparison, EFR = 10 cgs Rayls.

* This comparison was based on published graphs of the Embleton model.

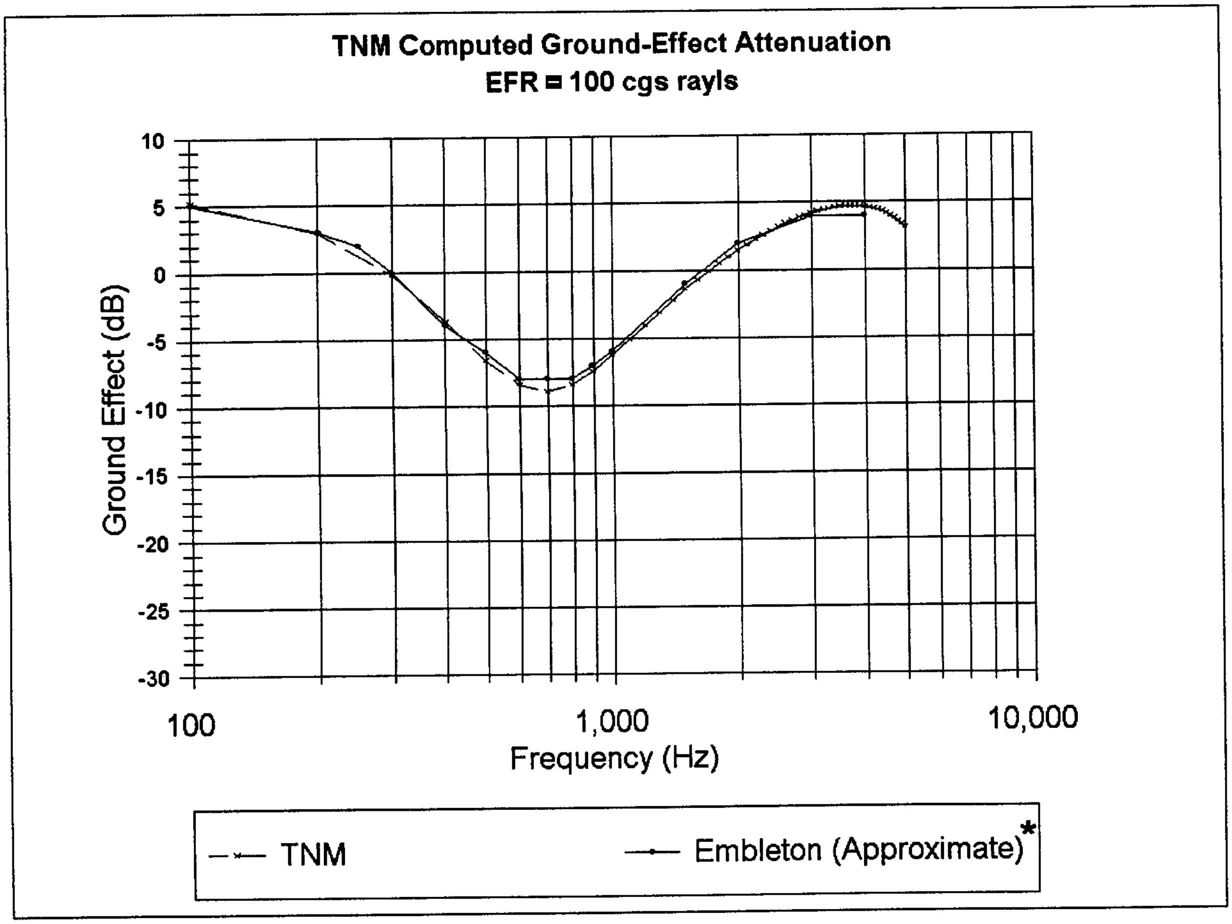


Figure 72. Ground-effect model comparison, EFR = 100 cgs Rayls.

* This comparison was based on published graphs of the Embleton model.

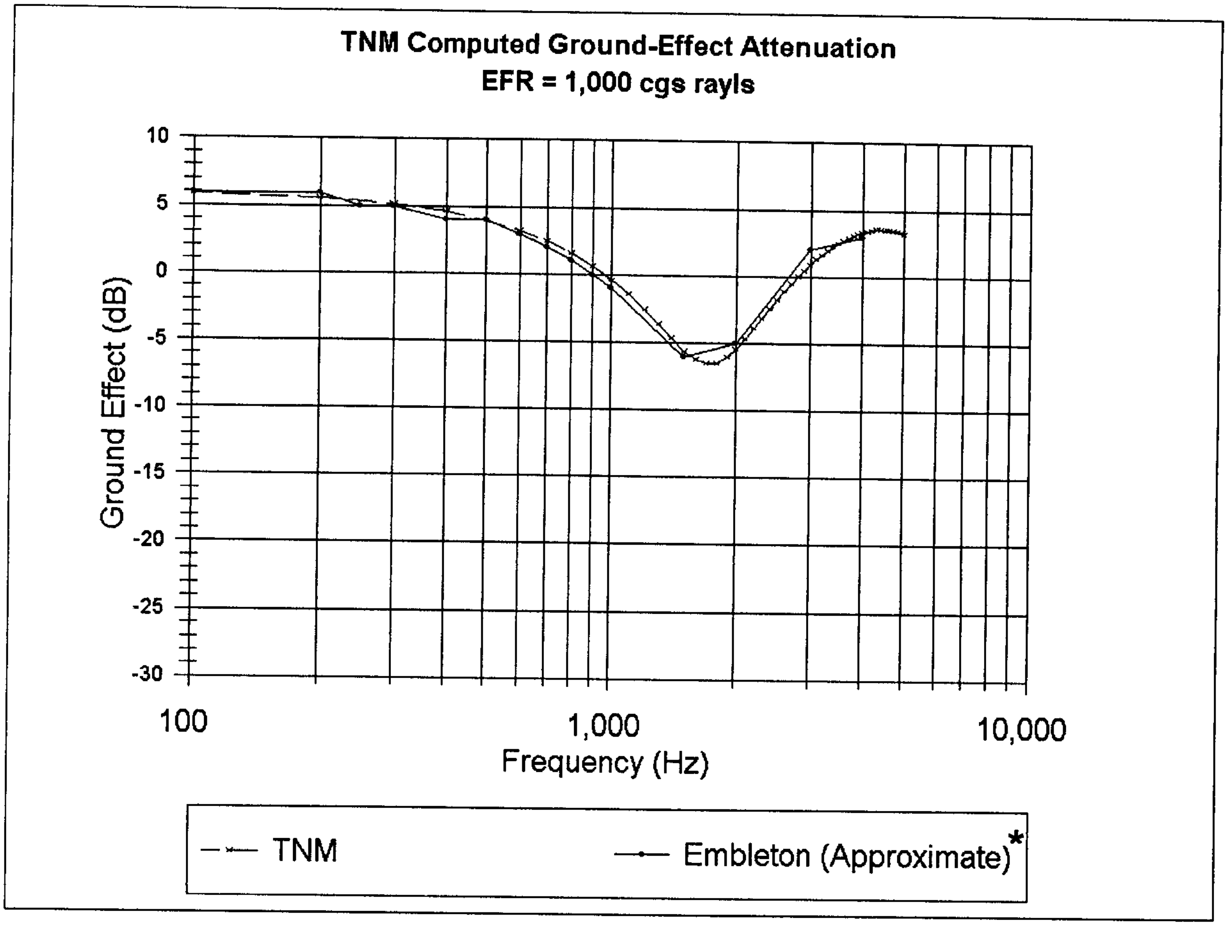


Figure 73. Ground-effect model comparison, EFR = 1000 cgs Rayls.

* This comparison was based on published graphs of the Embleton model.

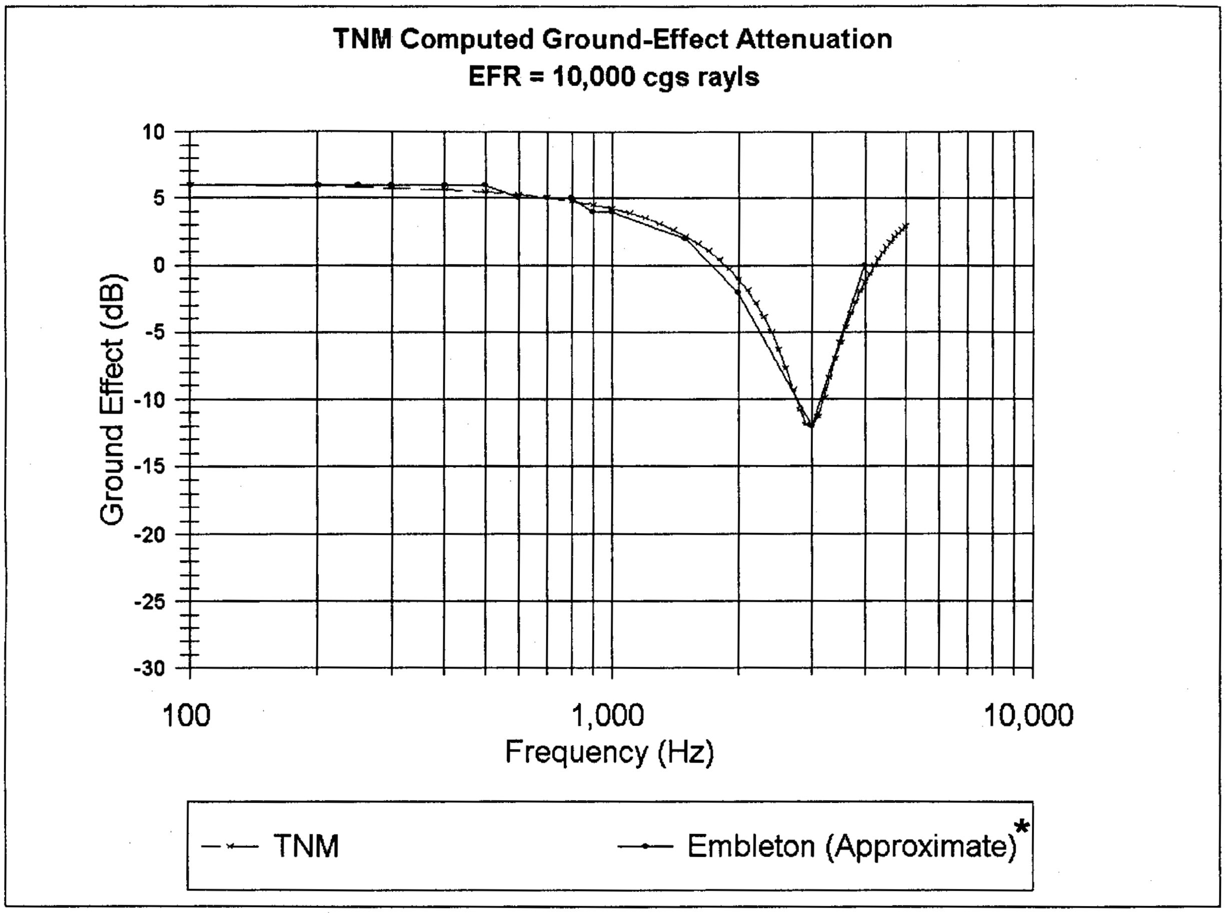


Figure 74. Ground-effect model comparison, EFR = 10,000 cgs Rayls.

* This comparison was based on published graphs of the Embleton model.

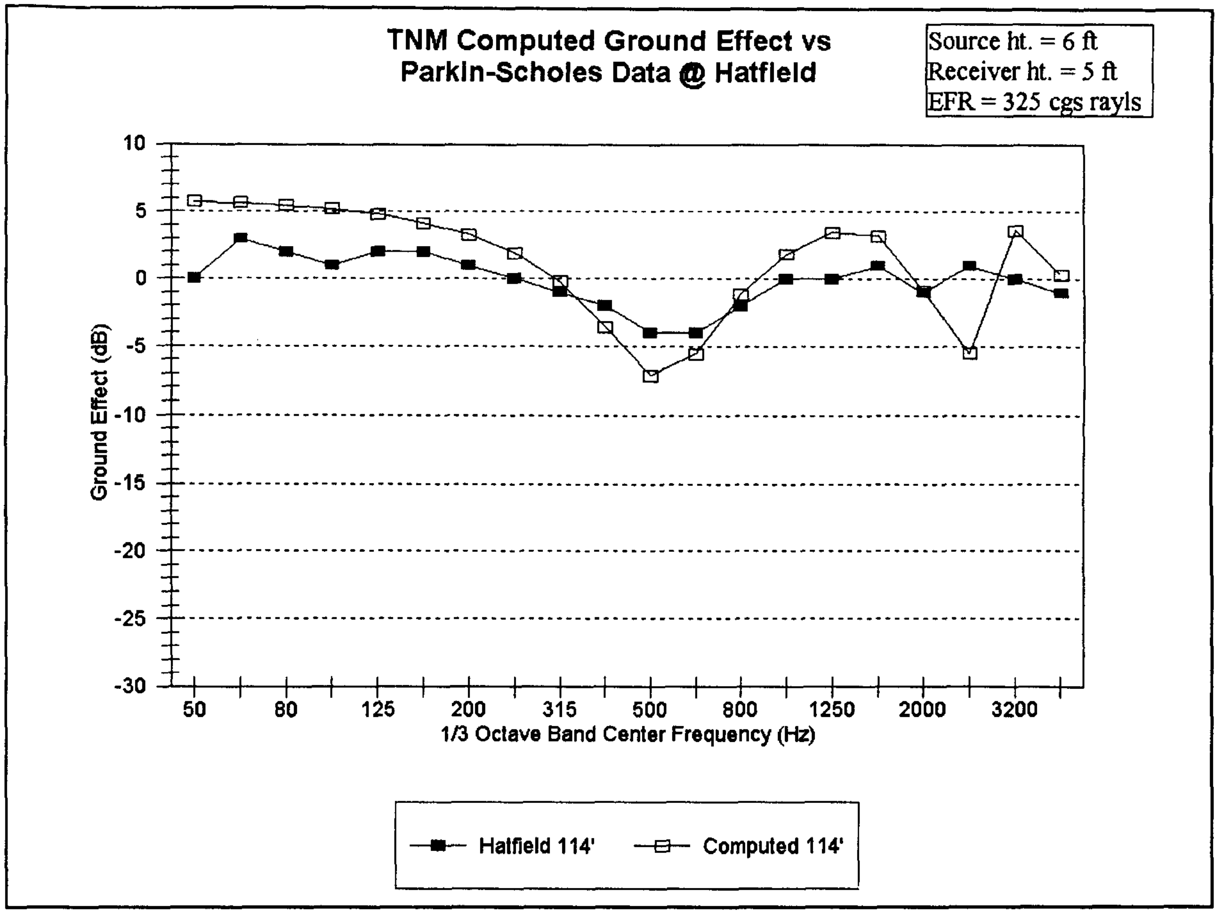


Figure 75. Comparison with measurements over grassland, distance = 35 meters (114 feet).

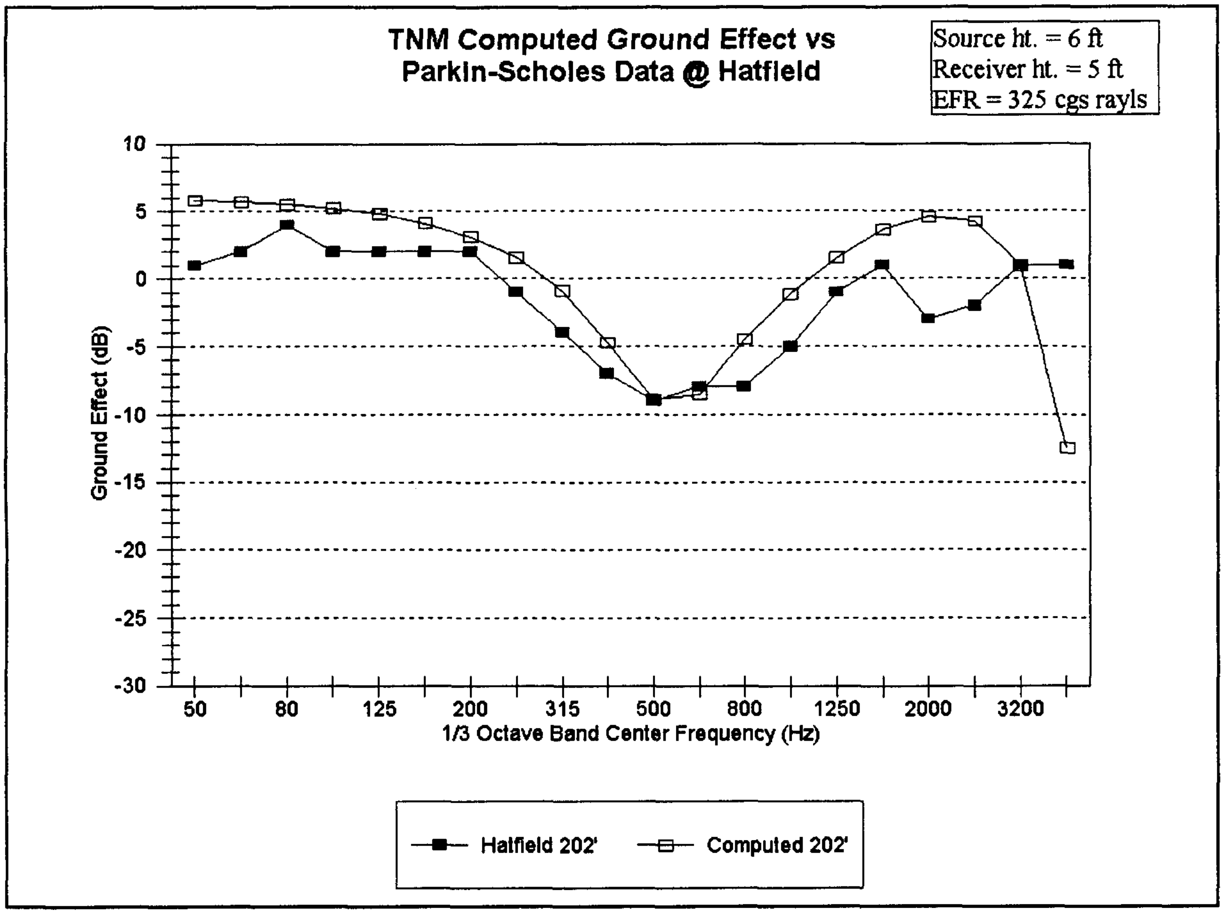


Figure 76. Comparison with measurements over grassland, distance = 62 meters (202 feet).

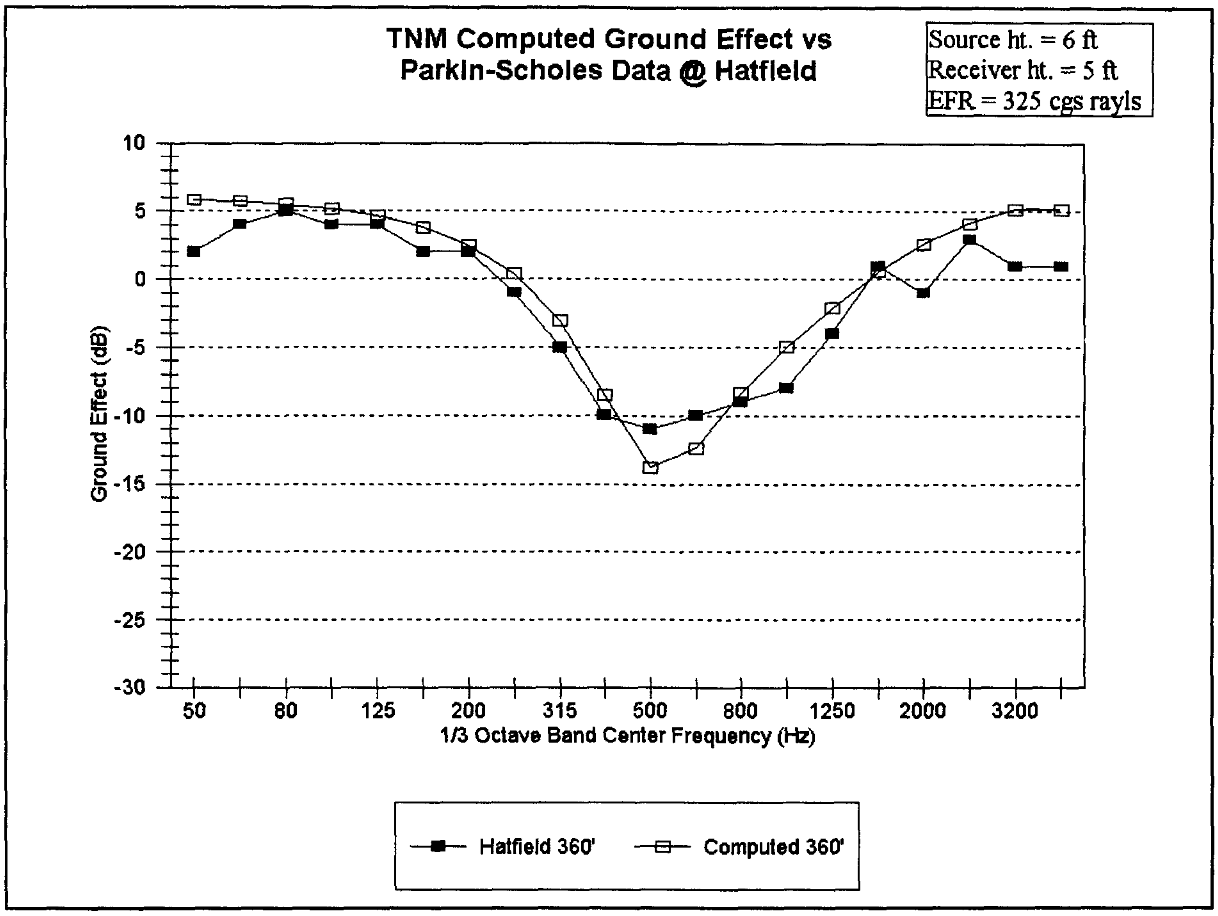


Figure 77. Comparison with measurements over grassland, distance = 110 meters (360 feet).

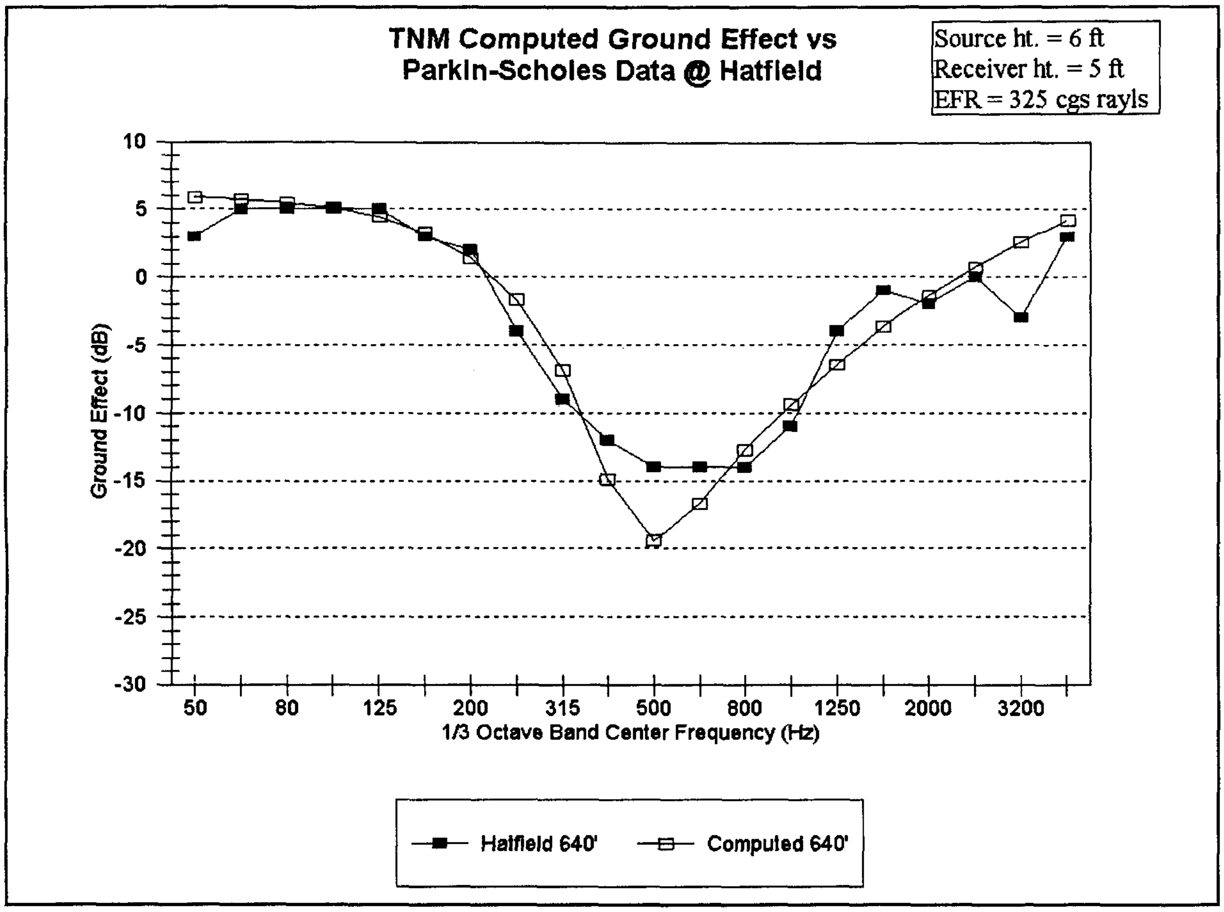


Figure 78. Comparison with measurements over grassland, distance = 195 meters (640 feet).

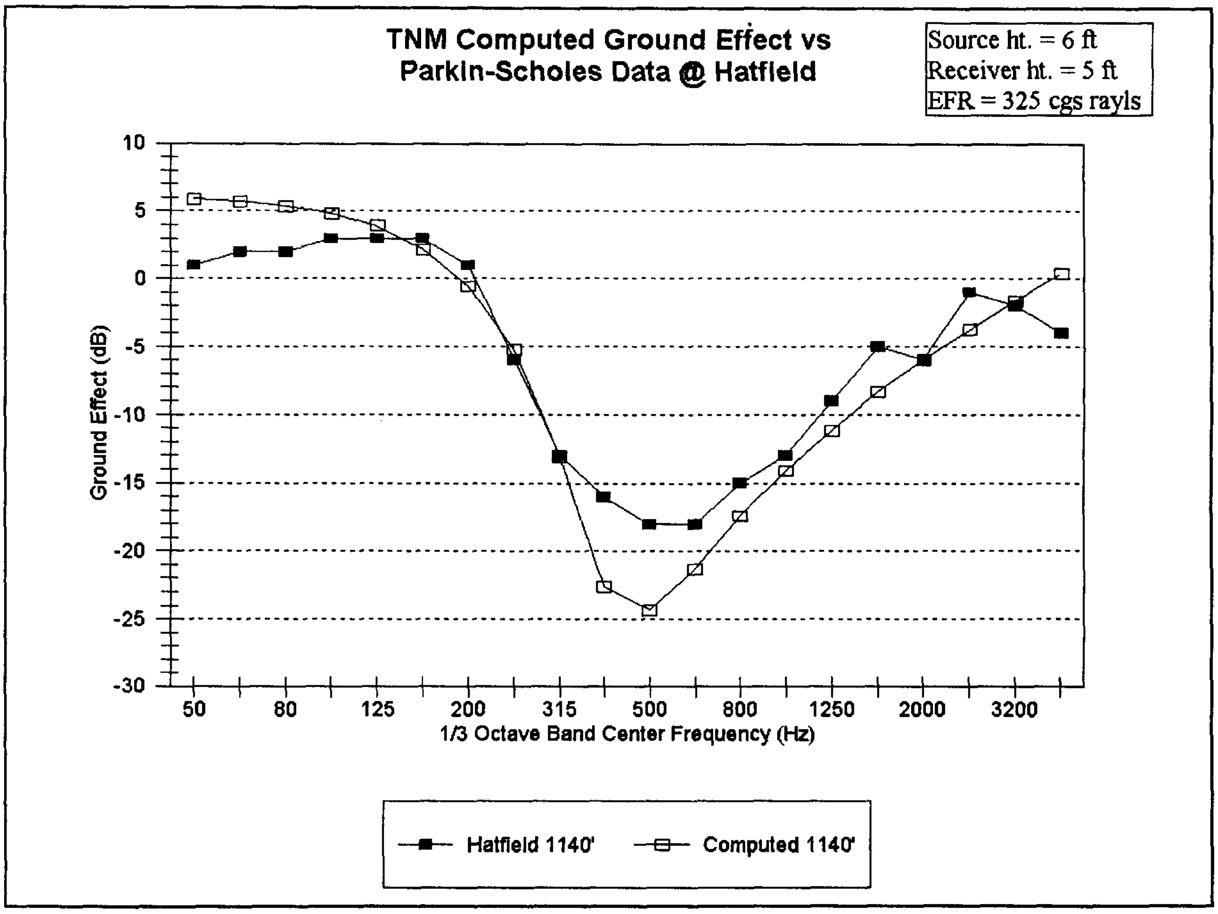


Figure 79. Comparison with measurements over grassland, distance = 348 meters (1140 feet).

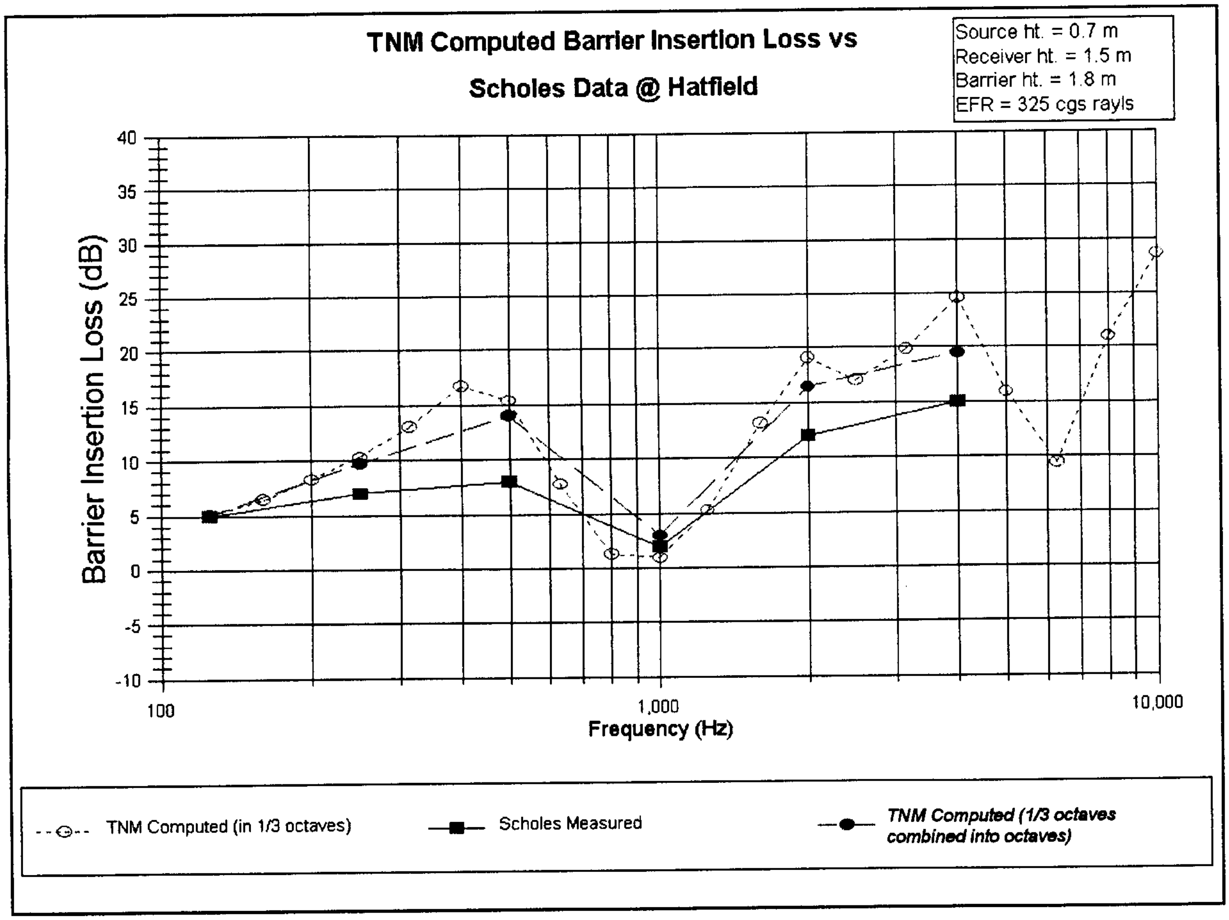


Figure 80. Comparison of barrier insertion loss in octave bands, receiver ht. = 1.5 m (5 ft), barrier ht. = 1.8 m (6 ft).

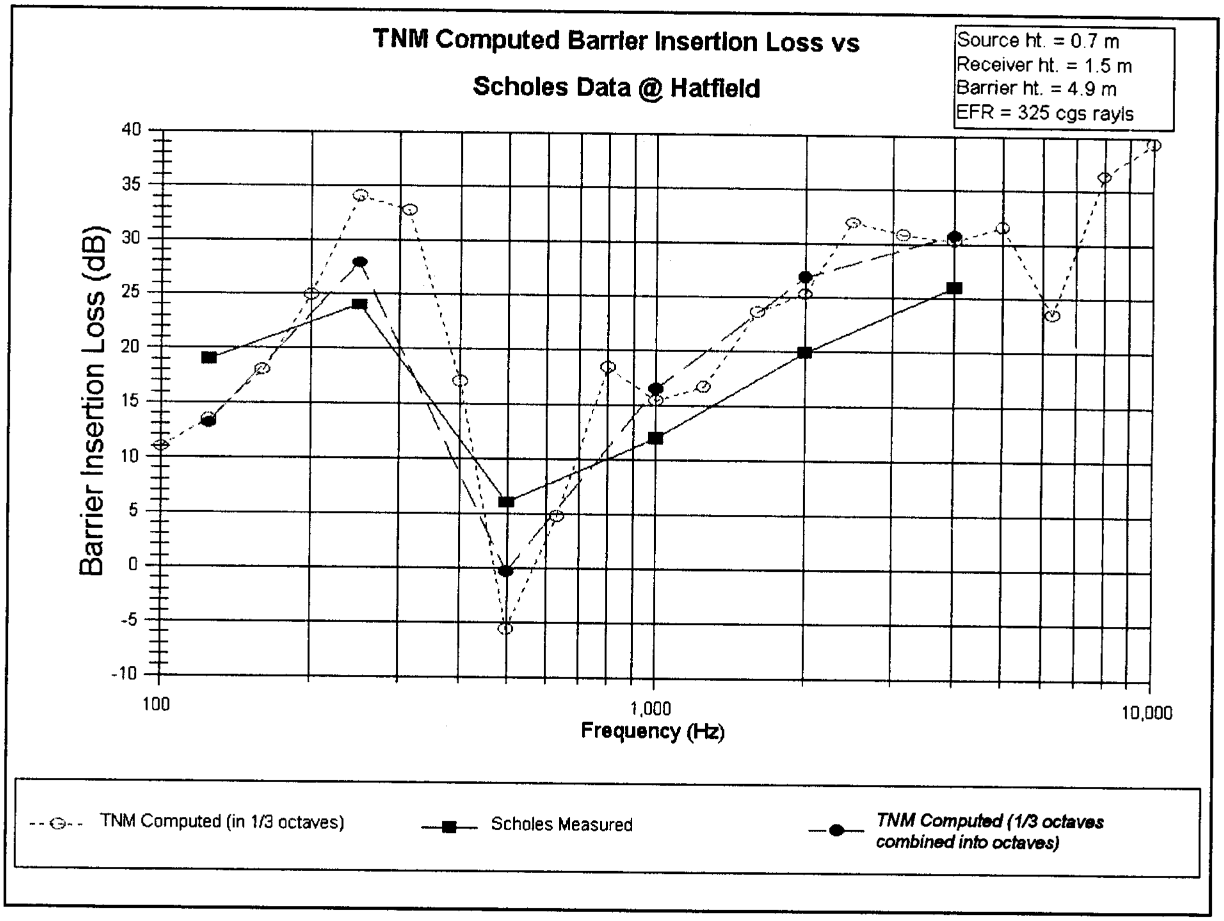


Figure 81. Comparison of barrier insertion loss in octave bands, receiver ht. = 1.5 m (5 ft), barrier ht. = 4.9 m (16 ft).

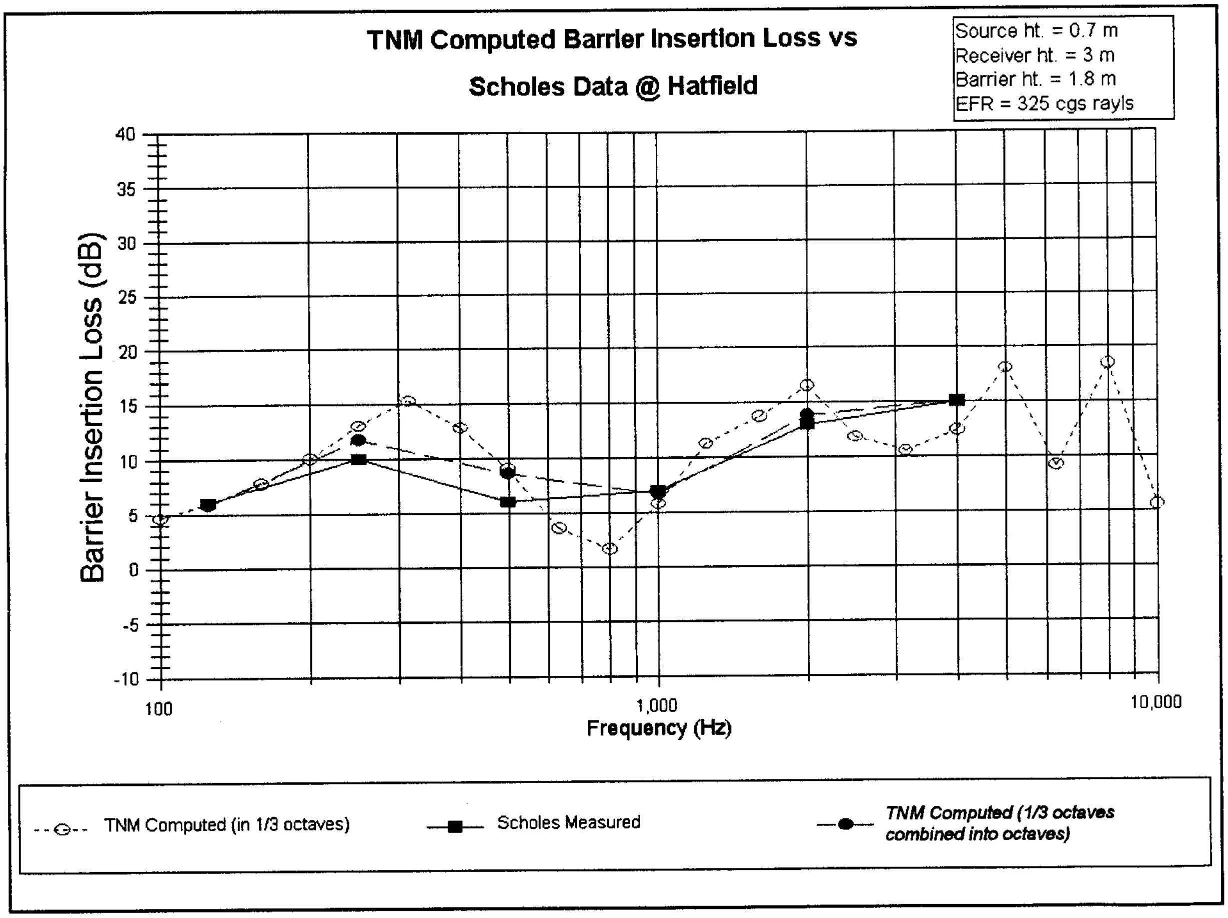


Figure 82. Comparison of barrier insertion loss in octave bands, receiver ht. = 3 m (10 ft), barrier ht. = 1.8 m (6 ft).

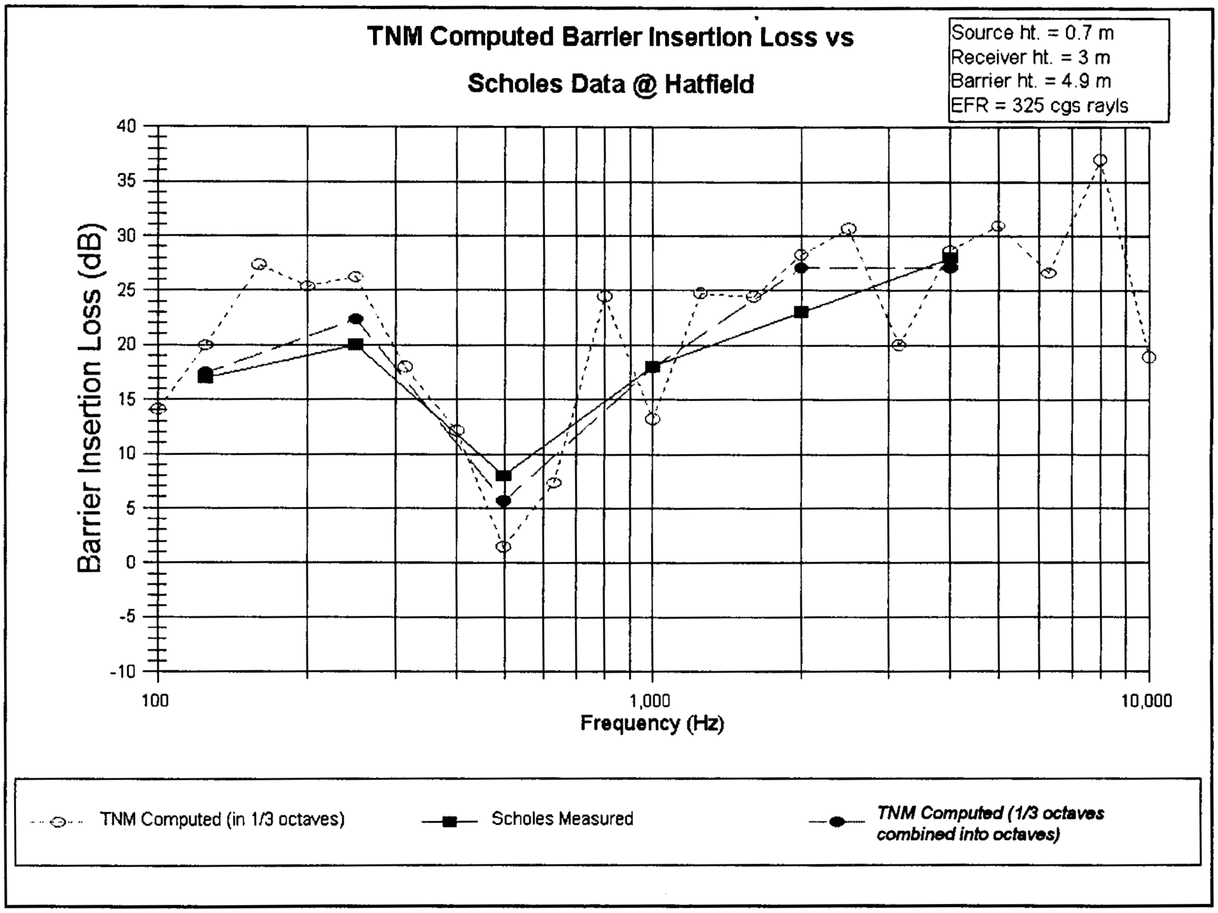


Figure 83. Comparison of barrier insertion loss in octave bands, receiver ht. = 3 m (10 ft), barrier ht. = 4.9 m (16 ft).

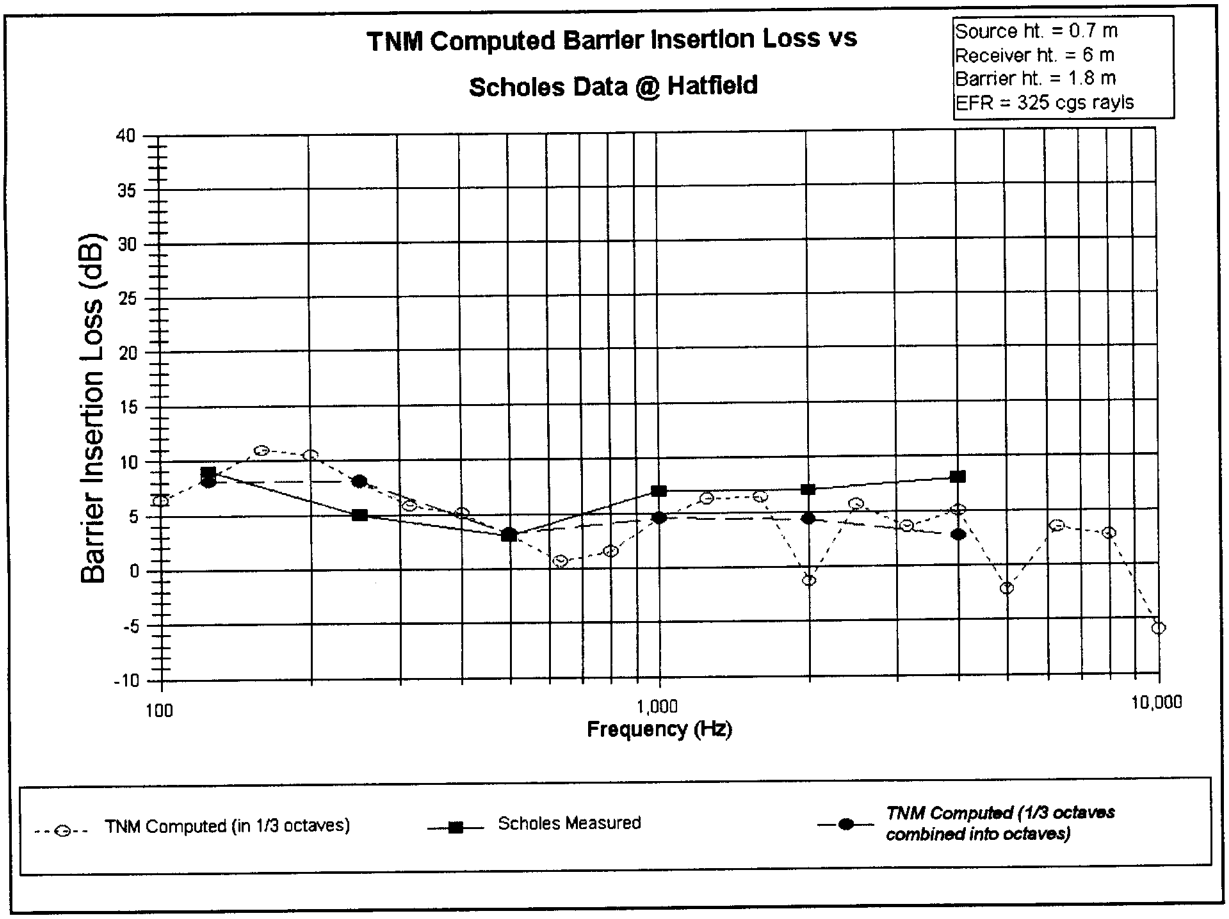


Figure 84. Comparison of barrier insertion loss in octave bands, receiver ht. = 6 m (20 ft), barrier ht. = 1.8 m (6 ft).

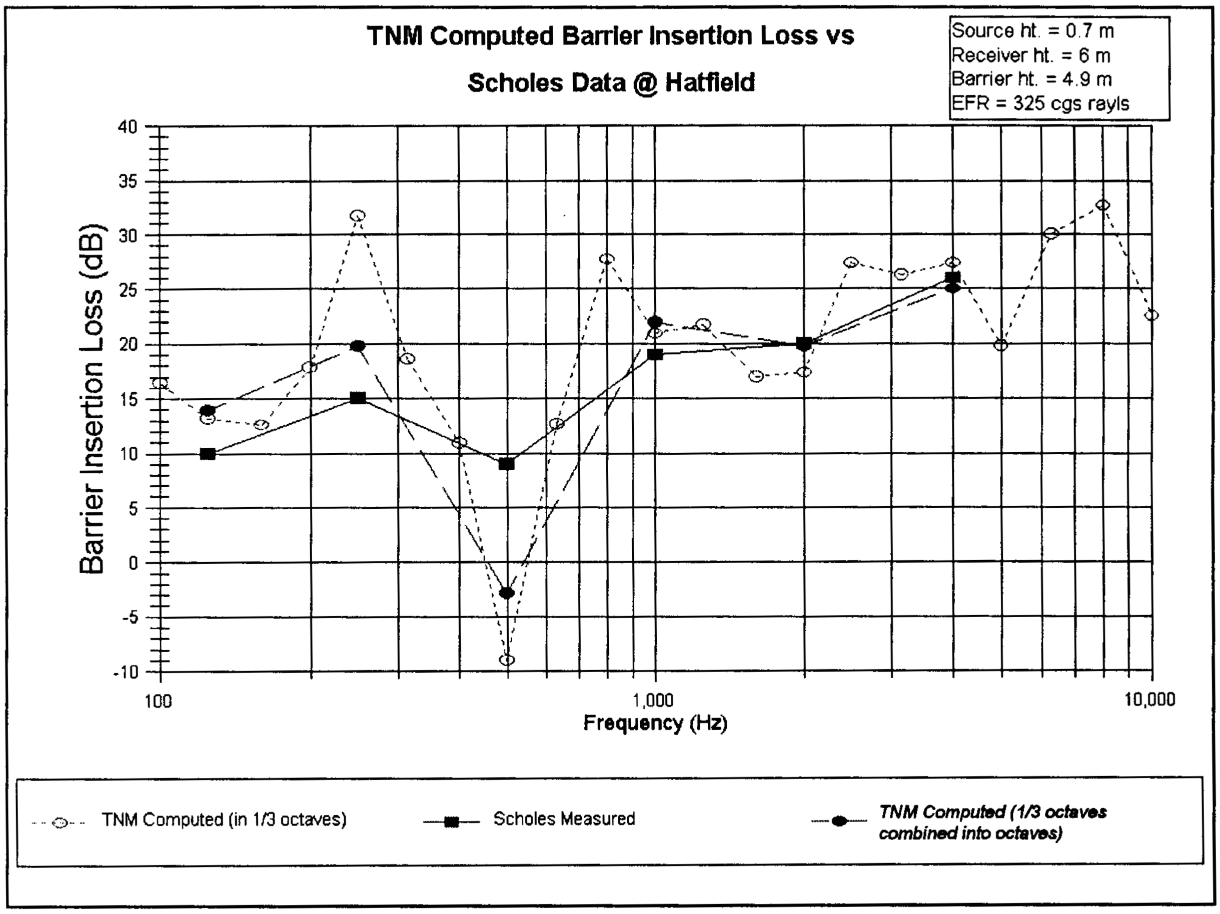


Figure 85. Comparison of barrier insertion loss in octave bands, receiver ht. = 6 m (20 ft), barrier ht. = 4.9 m (16 ft).

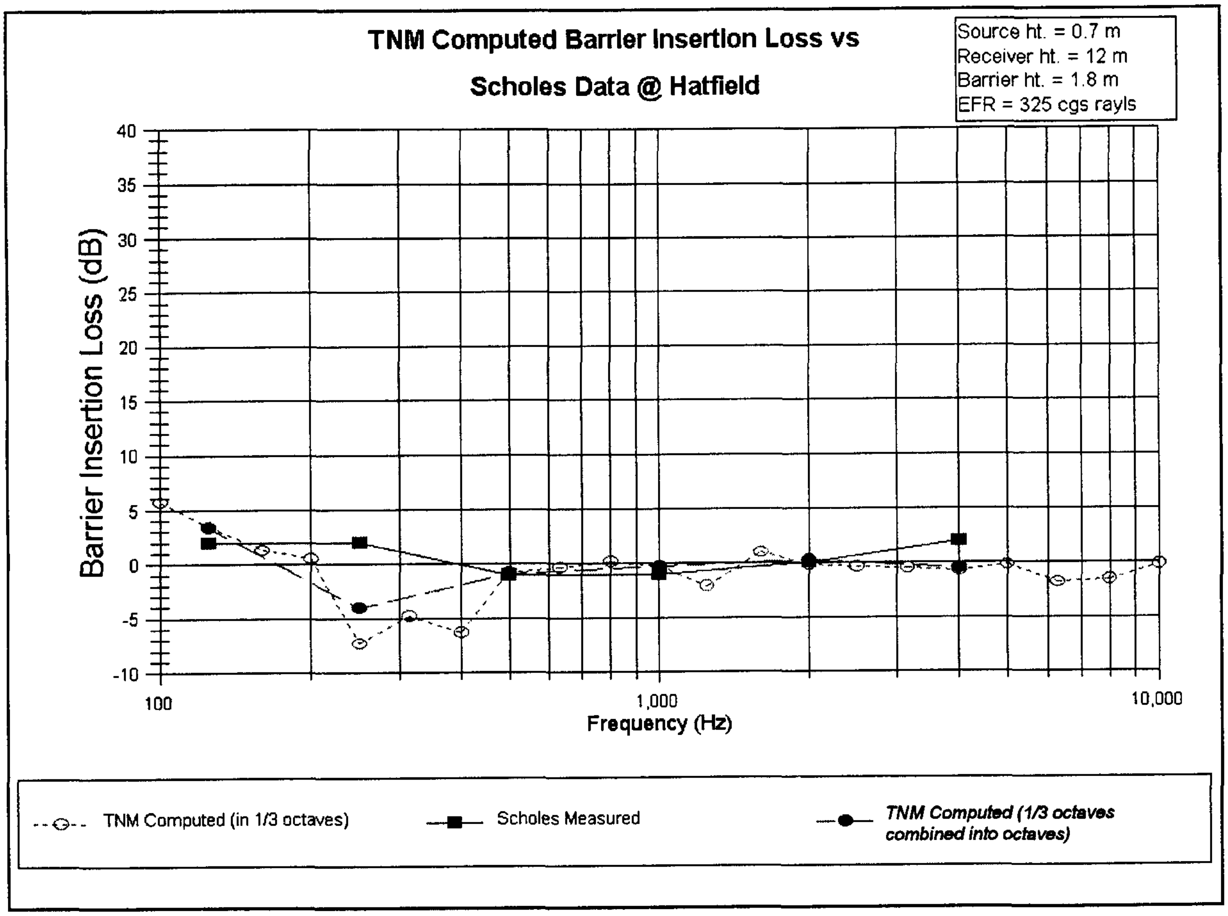


Figure 86. Comparison of barrier insertion loss in octave bands, receiver ht. = 12 m (40 ft), barrier ht. = 1.8 m (6 ft).

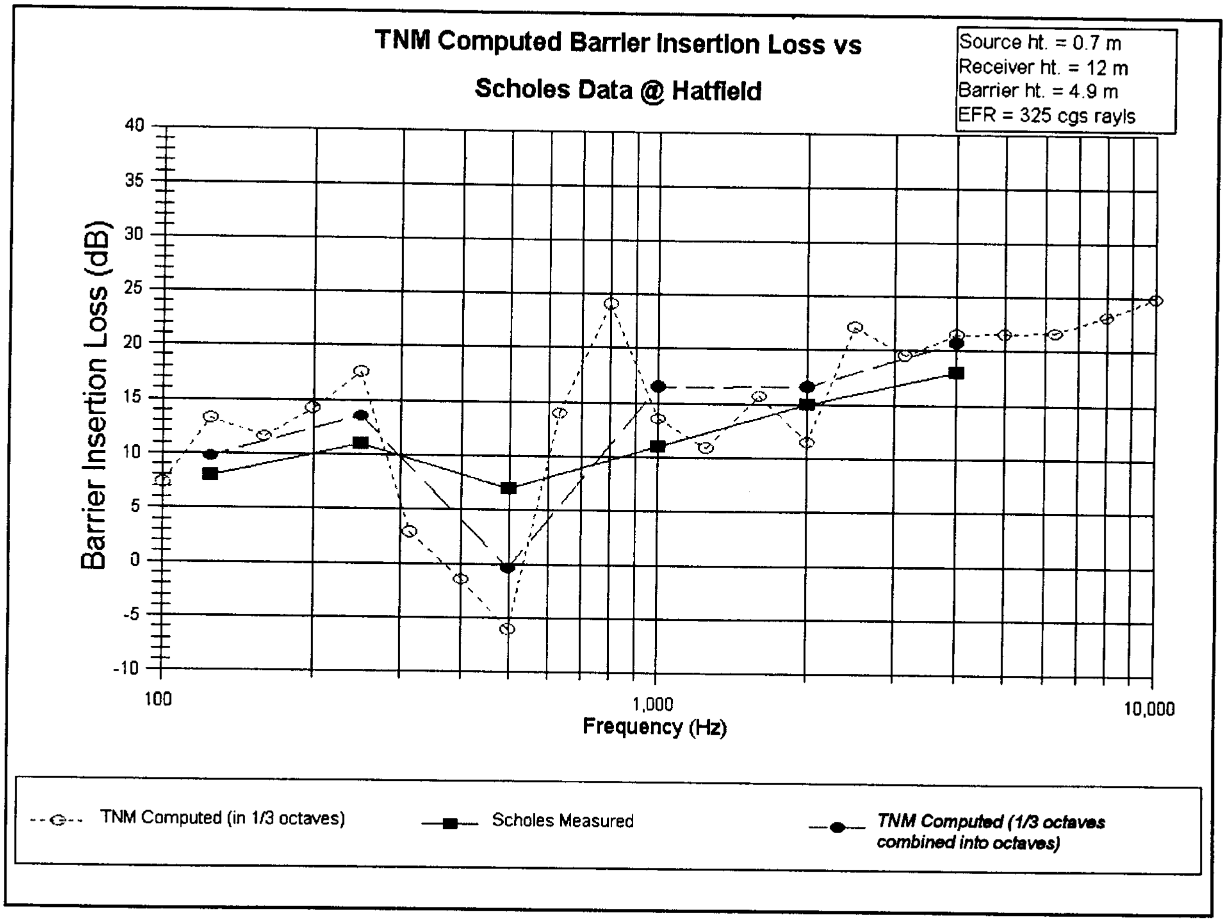


Figure 87. Comparison of barrier insertion loss in octave bands, receiver ht. = 12 m (40 ft), barrier ht. = 4.9 m (16 ft).

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**Federal Highway
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400 Seventh Ave., S.W.
Washington, D.C. 20590

FEDERAL HIGHWAY ADMINISTRATION TRAFFIC NOISE MODEL (FHWA TNM®)

VERSION 1.0
January 1998

The Federal Highway Administration (FHWA) is pleased to announce the release of the Traffic Noise Model, Version 1.0 (FHWA TNM). The FHWA TNM is an entirely new, state-of-the-art computer program used for predicting noise impacts in the vicinity of highways. It uses advances in personal computer hardware and software to improve upon the accuracy and ease of modeling highway noise, including the design of effective, cost-efficient highway noise barriers.

The FHWA TNM contains the following components:

- Modeling of five standard vehicle types, including automobiles, medium trucks, heavy trucks, buses, and motorcycles, as well as user-defined vehicles.
- Modeling of both constant-flow and interrupted-flow traffic using a 1994/1995 field-measured data base.
- Modeling of the effects of different pavement types, as well as the effects of graded roadways.
- Sound level computations based on a one-third octave-band data base and algorithms.
- Graphically-interactive noise barrier design and optimization.
- Attenuation over/through rows of buildings and dense vegetation.
- Multiple diffraction analysis.
- Parallel barrier analysis.
- Contour analysis, including sound level contours, barrier insertion loss contours, and sound-level difference contours.

These components are supported by a scientifically-founded and experimentally-calibrated acoustic computation methodology, as well as an entirely new, and more flexible data base, as compared with that of its predecessor, STAMINA 2.0/OPTIMA. The Data Base is made up of over 6000 individual pass-by events measured at forty sites across the country. It is the primary building block around which the acoustic algorithms are structured.

The most visible difference between the FHWA TNM and STAMINA 2.0/OPTIMA, is TNM's Microsoft® Windows interface. Data input is menu-driven using a digitizer, mouse, and/or keyboard. Users also have the ability to import STAMINA 2.0/OPTIMA files, as well as roadway design files saved in CAD, DXF format. Color graphics will play a central role in both case construction and visual analysis of results.

<u>Computer Requirements</u>

The recommended computer system requirements for TNM Version 1.0 are:

- Computer: IBM-compatible PC;
- Processor: 120 MHz Pentium (or faster);
- Memory: 32 MB (or more);
- Disk Drive: 3.5 inch, 1.44 MB;
- Mouse input device;
- Monitor: Accelerated Super VGA (1024 x 768), 16 colors, configured with "small" fonts;
- Software: Microsoft® Windows 3.1 (or later): Note: TNM will run under Microsoft® Windows 95 or Windows NT, however, TNM is a 16-bit program and will not take full advantage of the 32-bit architecture associated with Windows 95 or NT.
- 10 MB of hard-disk space for the TNM system (including sample runs); and
- Up to 1 MB of hard-disk space for each TNM run.

To digitize coordinates from plan sheets and roadway profiles, the following is required:

- Digitizer: Any manufacturer/model that meets the LCS/Telegraphics Wintab Interface Specification, preferably with a 16-button puck. The digitizer manufacturer should provide the file WINTAB.DLL, which must be resident on the hard disk for digitizer use.

<u>The FHWA TNM Package</u>: The FHWA TNM package includes the following:

- Two TNM manuals: This User's Guide and the TNM Technical Manual (Note: The User's Guide and Technical Manual may be photocopied. See below for information on how to order additional copies of either document.);
- The FHWA TNM software on three 3½" diskettes;
- One CD-ROM with the "TNM Trainer" tutorial; and
- The TNM registration card located on the last page of this User's Guide. Please fill out and return this card. Registered owners are entitled to receive technical support (see Section 1.8) and information on upgrades and supplementary guides.

<u>Copyright</u>: FHWA TNM is a registered copyright.

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<u>Availability</u>: The FHWA will distribute TNM Version 1.0 free of cost to every State Department of Transportation (DOT). All State DOTs may make sufficient copies of the TNM package for internal use only. For all other users, TNM will be distributed by the McTrans Center at the University of Florida. Non-State DOT users have three McTrans licensing options for the FHWA TNM: (1) they may purchase a single license, which is valid for a distinct address (or site); (2) they may purchase an unlimited agency license, which is valid for multiple addresses (or sites) within the same organization; or (3) they may purchase a license for training or educational purposes. A McTrans order form is attached. Purchase the FHWA TNM by selecting from the following McTrans product ordering numbers:

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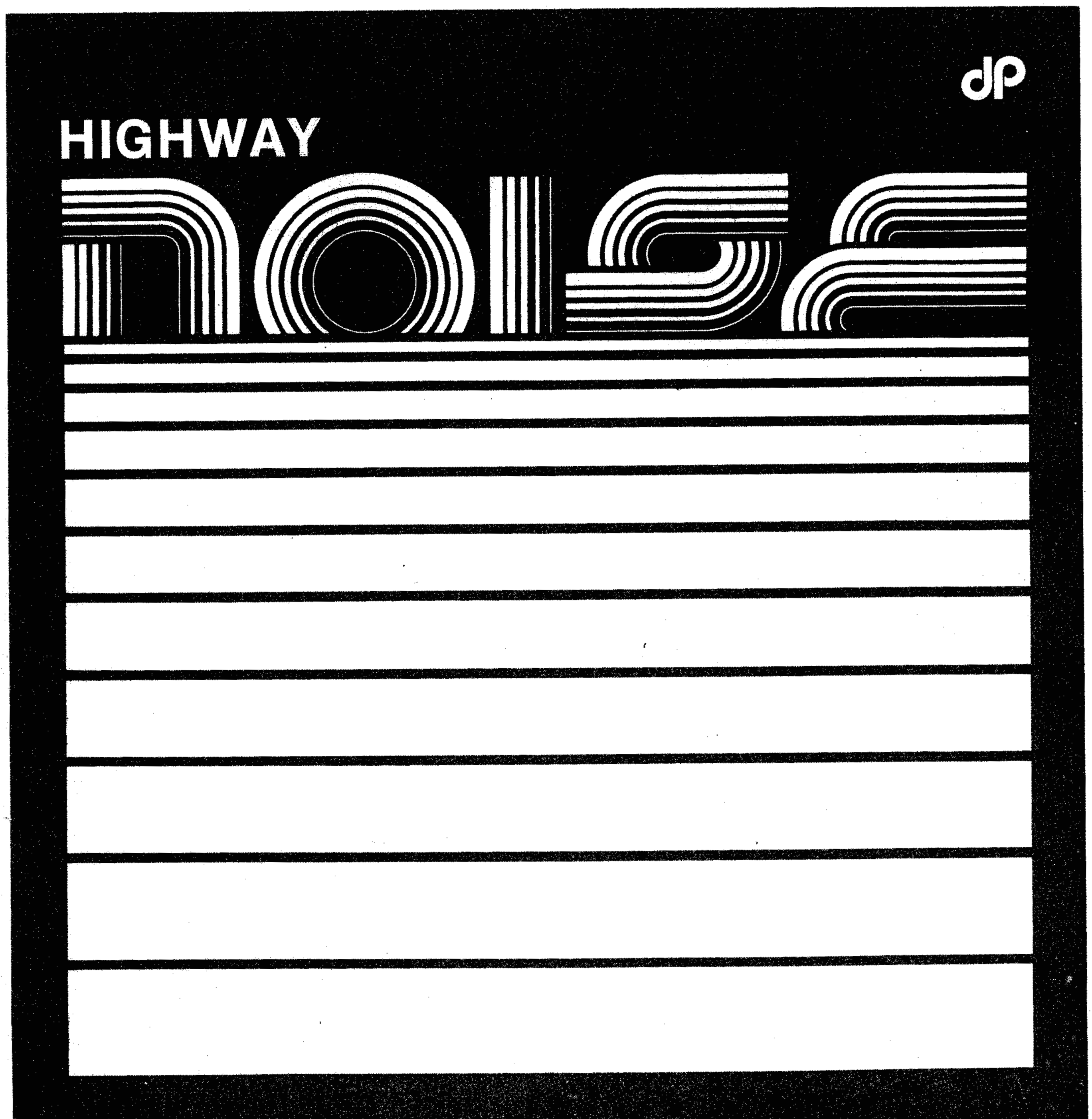
Sound Procedures for Measuring Highway Noise: Final Report

FHWA-DP-45-1R
Demonstration Projects Program
August 1981



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15. Supplementary Notes

The interim report was prepared by F.M. Kessler and M. Alexander of Dames & Moore, Inc. under contract with the Federal Highway Administration.

16. Abstract

This revised manual presents noise measurement procedures for use by Federal, State, or local transportation departments. Methods are included for the measurement of traffic/existing sound levels, vehicle sound levels, barrier field insertion loss, non-traffic noise source sound levels, construction equipment noise, building noise reduction, and worker noise exposure. The required instrumentation, test site restrictions, step by step measurement procedures, and computational methods are included.

This revision incorporates two measurement procedures issued after the interim report was published: Determination of Reference Energy Mean Emission Levels, Federal Highway Administration (FHWA) Report No. FHWA-OEP/HEV-78-1, which replaces chapter 4, and Determination of Noise Barrier Effectiveness, FHWA Report No. FHWA-OEP/HEV-80-1, which replaces chapter 5.

17. Key Words	18. Distribution Statement
Sound level measurements, traffic sound levels, vehicle sound levels, barrier field insertion loss, construction equipment noise, building noise reduction.	Available from National Technical Information Service, Springfield, Virginia

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1.0 INTRODUCTION

1.1 BACKGROUND

Numerous studies indicate that the most pervasive sources of noise in our environment today are those associated with transportation(Ref. 1-10). Transportation agencies have routinely measured noise levels for proposed highway projects since the issuance of Federal Highway Administration (FHWA) Policy and Procedure Memorandum (PPM) 90-2, "Noise Standards and Procedures" in 1973. The only formal training for these measurements was given as part of FHWA's "Fundamentals and Abatement of Highway Traffic Noise" training course. The course taught a hand-sampling method using a sound level meter to determine the statistical descriptor L10 (noise level exceeded 10 percent of measurement period.) PPM 90-2 was revised in 1976 as Volume 7, Chapter 7, Section 3 of the Federal-aid Highway Program Manual (FHPM 7-7-3). A new sound level descriptor, the energy-equivalent sound level, Leq(h) was introduced. In addition to these general existing noise level measurements, needs developed for more specialized procedures, such as determination of noise barrier effectiveness, reduction of outdoor sound inside a building, and levels of individual vehicles.

In the past, the methods used for these and other measurements varied widely. The lack of uniformity often resulted in data being collected incorrectly or in a manner that made comparison difficult from study to study.

This document represents a revision of an interim report of the same title prepared by Dames & Moore, Inc. (Report No. FHWA-DP-45-1) and published in May 1978. The major changes are the incorporation of two subsequently issued FHWA reports that expanded upon chapters 4 and 5 of the interim report.* In addition, newer data sheets have been added where appropriate.

This revised report provides uniform noise measurement procedures for use by Federal, State, or local transportation agencies. While it is not a standard, regulation, or requirement, its use is encouraged and recommended.

Chapter 8 has also been revised to allow alternative positions for the exterior microphone, and a note on data loggers for personal noise exposure was added to chapter 9.

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*Reagan, J.A. Determination of Reference Energy Mean Emission Levels. FHWA, Report No. FHWA-OEP/HEV-78-1, Washington, D.C., 1978.

Reagan, J.A. and Hatzi, P.J. Determination of Noise Barrier Effectiveness. FHWA, Report No. FHWA-OEP/HEV 80-1, Washington, D.C., 1980.

1.2 PURPOSE AND SCOPE

The purpose of this document is to provide functional, rational and cost-effective noise measurement procedures. The data acquired by different individuals using these procedures should be comparable. These procedures establish a desired level of accuracy and precision.

These techniques may also be used to provide input data for "calibration" of various traffic noise prediction models. The vehicle noise emission measurement procedure can provide emissions levels for vehicles specific to the region in which the measurements are being made. The traffic noise measurement procedure can be used at various distances from a roadway to establish a propagation constant specific to a site's terrain. Thus, the ability to accurately predict future highway noise emissions can be improved.

Noise measurement methods are provided for the following areas:

- Traffic/Existing Sound Levels
- Vehicle Sound Levels
- Barrier Field Insertion Loss
- Non-Traffic Noise Sources
- Construction Equipment Noise
- Building Noise Reduction
- Worker Noise Exposure

1.3 ORGANIZATION

The manual is divided into two major segments plus an Appendix. Chapter 2.0 presents information regarding personnel requirements, instrumentation and equipment and other items common to the measurement procedures presented in this manual.

Chapters 3.0 through 9.0 contain the noise measurement methods listed in Section 1.2.

Methods to measure existing sound levels, or sound levels created by highway traffic, are presented in Chapter 3.0. The principal technique has been previously presented in NCHRP Report 174, "Highway Noise: A Design Guide for Prediction and Control,"[11] and should therefore be familiar to highway personnel. This method presents the procedure for measuring the A-weighted sound level exceeded 10% of the time, L_{10}, and the equivalent sound level, L_{eq}. An alternate procedure, based upon the proposed SAE Procedure XJ1075 is also presented. The alternative procedure is simpler to accomplish but provides only an estimate of the equivalent sound level. Both techniques have been field tested over the past few years, and show good agreement with sophisticated analyses of the environmental noise using tape recording equipment and statistical analyzers.

Chapter 4.0 includes methods for the measurement of noise emissions of individual vehicles operating on thoroughfares. The technique is similar to the one presented in the Department of Transportation Bureau of Motor Carrier Safety Regulations for Enforcement of Motor Carrier Noise Emission Standards.[12] Measurements of individual vehicle sound emissions can be used to calibrate highway noise prediction models. Statistical requirements for determining the number of samples in each vehicle class are included.

A technique for determining highway noise barrier insertion loss is described in Chapter 5.0. Three alternatives for obtaining sound levels at an area without a barrier for comparison with the sound levels at the area with a barrier are discussed.

Techniques for measuring the noise emissions of sources other than highway traffic are presented in Chapter 6.0. The technique for the measurement of the equivalent A-weighted sound level of stationary sources is similar to the proposed SAE Procedure XJ1075. Techniques for measuring the sound level contributions from non-highway mobile noise sources such as boats, freight trains, or airplanes are also presented. These techniques assume specific time-history patterns for the source sound levels. Nomograms are provided for evaluating the equivalent sound levels for the passby. Although sophisticated equipment can provide more accurate results, the technique presented is of importance since it only requires the use of an inexpensive sound level meter.

Sound levels emitted from a construction site should be measured using the stationary source technique described in Chapter 6.0. For individual construction machines, a noise measurement procedure is provided in Chapter 7.0. The method is based on the SAE Recommended Practice J88a and Compressed Air and Gas Institute (CAGI) Consensus Standards. SAE and CAGI techniques require a test site with numerous acoustical environmental constraints. For example, the surface between the noise source and microphone must be sealed asphalt with no large reflecting surfaces within 30 metres (98.4 feet) of the microphone or equipment. Many construction sites do not satisfy these constraints. In addition, sound levels at these sites, due to equipment other than the unit under study, are often quite high. The measurement method presented in this manual is a pragmatic, cost-effective means for successfully making these measurements. It is not intended to be a procedure which provides measurements for new product noise level verificiation and enforcement.

Chapter 8.0 describes a technique for estimating the A-weighted outdoor to indoor noise reduction for a building. Techniques which use the existing noise of a highway or an artificial sound source (loudspeaker and amplifier) are included.

A review of techniques for measuring highway personnel noise exposure is presented in Chapter 9.0. The recommended procedure uses noise dosimeters. Guidelines for the use of dosimeters are included. An alternative technique using a sound level meter and time-motion studies is discussed.

Appendix A presents a bibliography of useful references, grouped by measurement procedure. Appendix B reproduces Part II of Report No. FHWA-OEP/HEV-80-1. Part I of that report is a revision of chapter 5 of the interim version of this report, and is presented as the new chapter 5 here. Part II deals with determining people's perception of barrier effectiveness through surveying techniques. Appendix C presents a blank two-sided data sheet for manual sampling as described in chapter 3.

1.4 REFERENCES

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2. Goodfriend, L.S., "Noise in the Community", Noise Control 4, 22-28, 68 (March 1958).

3. Ostergaard, P.B. and R. Donley, "Background Noise Levels in Suburban Communities," J. Acoust. Soc. Am. 36, 435-439 (1964).

4. "Noise in Urban and Suburban Areas: Results of Field Studies," Technical Study FT/TS-26, prepared by Bolt, Beranek and Newman, Inc., Van Neys, CA for the U.S. Department of Housing and Urban Development, Federal Housing Administration, March 1968.

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8. Young, R.W., "Measurement of Noise Level and Exposure," presented at Symposium on Acceptability Criteria for Transportation Noise, Seattle, WA. 26-28 March 1969. Published in Transportation Noises: A Symposium on Acceptability Criteria, edited by J. D. Chalupnik, pp. 102-110, University of Washington Press, 1970.

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10. Robinson, D.W., "Towards a Unified System of Noise Assessment," J. Sound Vib. 14(3), 279-298 (1971).

11. Transportation Research Board. National Research Council. Highway Noise: A Design Guide for Prediction and Control, (N.C.H.R.P. Report 174), 1976.

12. Dept. of Transportation, Bureau of Motor Carrier Safety, Regulation for Enforcement of Motor Carrier Noise Emission Standards, Title 49. Code of Federal Regulations Chapter II, Part 325, 40 FR 42437 September 12, 1975.

2.0 GENERAL RECOMMENDATIONS

2.1 INSTRUMENTATION

The procedures outlined in this manual require a minimum of acoustical instrumentation. A Type 1 or Type 2 sound level meter is required, depending on the procedure and the desired accuracy.* A "Precision" Type 1 sound level meter is more accurate and more expensive than a "General Purpose" Type 2 sound level meter. Specifications for sound level meters have been established by the American National Standards Institute and are included in ANSI S1.4-1971, Specifications for Sound Level Meters.

Type 1 sound level meters should be used with the microphone separated from the meter by an extension cable, according to the Field Methods section of ANSI S.13-1971 (R1976), Methods for the Measurement of Sound Pressure Levels.

Manufacturers' instructions for microphone orientation (either grazing or normal incidence) should be carefully followed. This will ensure maximum microphone output linearity.

Care should be taken that all auxiliary equipment are correctly used with the sound level meter. For example, filters, graphic level recorders, and headsets or earphones should have an input impedance appropriate for the sound level meter output impedance. Often these auxiliary equipment have a high input impedance. For maximum power transfer and minimum distortion, cables used with these equipment should have a matching impedance.

An acoustic calibrator provides a means for conducting an overall system check and calibration of the sound level meter. Calibrators are specifically designed for individual microphone systems so it is important that the proper calibrators be used. Otherwise, errors may result or microphones may be permanently damaged.

The sound level meter reading is adjusted to match the calibrator sound pressure level. For calibrators which emit sound at 1000 Hz, the calibration can be accomplished using any weighting network. Otherwise, sound level meters must be calibrated using the flat or C-weighting network.

Calibrator output is affected by changes in atmospheric (barometric) pressure. Care must be taken when using the calibrator at atmospheric pressures other than standard conditions. Calibrator manufacturers provide correction curves for calibrator use at atmospheric conditions other than standard.

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*A Type 1 meter may be used where Type 2 is specified, but not vice-versa.

Calibration should be accomplished with the system as it will be in actual use (for example, with the microphone and cables installed). Calibrate as often as possible, preferably before and after the measurement. If calibrations before and after a measurement differ by more than 0.5 decibel, the results should be suspect. Usually it is good practice to repeat the measurements. The equipment should be checked annually by its manufacturer or other certified laboratory to verify its accuracy.

In measurement procedures where vehicle speed is required, the "radar" instruments should be calibrated according to manufacturer's instructions at the same time the sound level measurement system is calibrated.

The movement of air around a microphone causes turbulence which in turn generates undesired noise at the diaphragm of the microphone. This noise can effectively mask the sound signal under study even though it may be inaudible to the human ear. In cases where measurements must be made in the presence of wind or where wind gusts are suspect during the course of measurement, a microphone windscreen should always be employed.

Windscreens are generally either spherical or cylindrical in shape, made of foamed polyvinyl, open-celled polyurethane, or a silk-covered grid. The windscreen is attached directly over the microphone. They are limited in their effectiveness; therefore, measurements should not be made when the wind speed exceeds 19 km/hr (12 mph).

Other equipment which are needed to make the measurements presented in this manual include a wind speed indicator (accurate to ±10% at 12 mph) and a sling psychrometer for measuring humidity and temperature.

2.2 METEOROLOGICAL RESTRICTIONS

Proper meteorological conditions are necessary for accurate measurements. Measurements should not be made when it is raining or snowing, or when wind speeds exceed 19 km/hr (12 mph). Measurements should not be made when road surfaces are wet. Manufacturers' recommendations for acceptable temperature and humidity ranges for equipment operation should be followed. Typically, these ranges are from -10°C to 50°C and from 5% to 90% relative humidity.

2.3 ALTERNATIVE EQUIPMENT

Sound level distribution analyzers measure and analyze ambient sound for long periods of time. They provide a statistical description, in the form of a histogram or cumulative distribution, of the time-varying signal. Some of these analyzers also provide the equivalent sound level, L_{eq}. The manual sampling techniques discussed in many of the measurement procedures are unnecessary if statistical distribution analyzers are used. But, at present, there are no domestic or international standards to ensure their accuracy. Those units which provide cumulative distribution values and equivalent sound levels are quite expensive ($2000 and up). New hand held L_{eq} meters have recently been introduced at a price below $1000.

For simultaneous measurements ("Building Noise Reduction" and "Barrier Field Insertion Loss"), a two-channel tape recorder will be helpful. Both sound signals are recorded simultaneously and can later be analyzed in the laboratory using a number of different procedures. When using recording devices, the entire sound level measurement system should be qualified per SAE specifications:

> SAE Draft Procedure XJ184a "Qualifying a Sound Data Acquisition System"

Graphic level recorders or sound level analyzers are very helpful, if not essential, for mobile non-traffic source L_{eq} contribution measurements.

2.4 PERSONNEL

Persons responsible for conducting sound level measurement tests should be trained in the operation of sound level meters and should be familiar with the specific test procedure being used and any corrections that may have to be applied. Recommendations for the number of persons required for carrying out each procedure are provided in each procedure.

3.0 EXISTING/TRAFFIC SOUND LEVEL MEASUREMENT PROCEDURES

3.1 PURPOSE

The measurement procedures presented in this section can be used to establish existing sound levels at proposed highway sites and to establish sound levels from traffic on existing highways. Major noise sources (other than traffic) are measured using techniques described in Chapter 6.0.

3.2 INSTRUMENTATION

The following instruments are required:

- Sound Level Meter (Type 2)
- Sound Level Calibrator
- Earphones or Headphones (optional)
- Wind Speed Indicator
- Sling Psychrometer (optional)
- Windscreen
- Watch with "seconds" Display or Flashing Timer
- Data Sheet
- Microphone Cable (optional)
- Tripod
- Spare Batteries (optional)

3.3 PERSONNEL

Although it is possible for one person to carry out these measurements, a second person may be helpful, particularly when traffic counts are necessary.

3.4 SITE SELECTION

Land use maps may be used to identify existing noise sources and noise sensitive land uses. Schools, hospitals, and places of worship are especially sensitive to noise impact since these areas require quiet for communication and minimum disturbance of sleep. Residential areas should be included in a sound level survey. Sometimes one measurement site in the residential zone near the existing or proposed highway route can be used to represent the sound climate at residences along the route. If traffic conditions or topography vary significantly, noise measurements at many locations may be required. A number of sites should be specifically located near existing highways or other noise sources in the study area, while a number of measurement locations far from the highway will provide data representative of the background sound levels in the community.

Field reconnaissance is also extremely valuable for identifying and/or verifying the location of sensitive sites and noise sources.

3.5 SELECTION OF SAMPLING PERIODS

Design noise levels in FHPM 7-7-3 are based in part on the design hour traffic volume. Some measurements should therefore be made at or near the design hour. The period with the highest sound levels, however, may not be at the peak traffic hour, but instead during some period when traffic volumes are lower, but the truck mix is higher. Also, the greatest change in existing sound levels, and with it potentially high impact, may occur during other times during the day (e.g., early morning hours when sleep may be interrupted). It may also be desirable to examine the Day-Night Sound Level [L_{dn}] and 24-hour Equivalent Sound Level [$L_{eq(24)}$]. The selection of the number of sampling periods should be based on economic and potential impact considerations.

3.6 MEASUREMENT PROCEDURE FOR CHECK-OFF METHOD

The sampling program described below provides the sound level exceeded 10% of the time during the measurement period, L_{10}, and the equivalent sound level, L_{eq}. For highway noise measurements, traffic data should be collected concurrent with noise measurements. A description of the vehicle classes used for the traffic counts is described in Section 4.8 ("Vehicle Noise Emissions Measurement Procedure").

1. A sketch of the measurement site should be prepared and appropriate distances and site features noted (see Figure 1). All information required on the data sheet should be entered.

2. Mount the microphone (or sound level meter/ microphone combination if the microphone cannot be remotely mounted) on a tripod of about 1.5 metres (5 feet) above the ground and not less than 3 metres (10 feet) from any reflecting surfaces. There may be instances where measurements must be made at different heights (e.g., upper story of residences) or closer to reflecting surfaces (e.g., urban areas). If this is necessary, note these facts on the data sheet.

3. Set the meter to "slow" response and A-weighting. "Slow" response allows the meter display to be read easily. If impulsve noise is dominant (e.g., dog barking), "fast" response may be preferable. Judgment should be made by the individual as to which response should be used.

4. Calibrate the sound level meter per manufacturer's instructions.

5. Record the time the measurement is to begin.

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
REGION 15

NOISE MEASUREMENT DATA SHEET

NAME: W.A. HENWAY — DATE 8/21/81

PROJECT: NOISEVILLE BYPASS

TIME:

SITE: 120' E OF NB I-999 (1012 HICKORY HOLLOW ROAD) — START 9 AM — END 9:09

RESULTS: L10 76 + 2 − 3 L50 66 LEQ 70.5

HOW TO USE: 2 X 80 = 160000

FILL IN OTHER SIDE

DBA	TOTAL	X	=
89		X 80	
88		X 63	
87		X 50	
86		X 40	
85		X 32	
84		X 25	
83		X 20	
82		X 16	
81		X 13	
80		X 10	
79		X 80	
78	1	X 63	63000
77	1	X 50	50000
76	3	X 40	120000
75	2	X 32	64000
74	2	X 25	50000
73	2	X 20	40000
72		X 16	
71	3	X 13	39000
70	1	X 10	10000
69	2	X 80	16000
68	5	X 63	31500
67	2	X 50	10000
66	4	X 40	16000
65	7	X 32	22400
64	5	X 25	12500
63	3	X 20	6000
62	3	X 16	4800
61	1	X 13	1300
60	2	X 10	2000
59		X 80	
58	1	X 63	630
57		X 50	
56		X 40	
55		X 32	
54		X 25	
53		X 20	
52		X 16	
51		X 13	
50		X 10	
49		X 80	
48		X 63	
47		X 50	
46		X 40	
45		X 32	
44		X 25	
43		X 20	
42		X 16	
41		X 13	
40		X 10	

EQUALS 100,000 — EQUALS 10,000 — EQUALS 1,000 — EQUALS 100

NUMBER OF SAMPLES: 10 20 30 40 50

TOTAL 50 DIVIDED INTO TOTAL 559130 EQUALS 11183

FIGURE 1. SAMPLE SOUND LEVEL MEASUREMENT DATA SHEET

FIGURE 1 (CONTINUED).

EQUIPMENT: METER AdB 2209 CALIBRATOR AdB 4230

CALIBRATION: START 94.0 DB END 94.2 DB

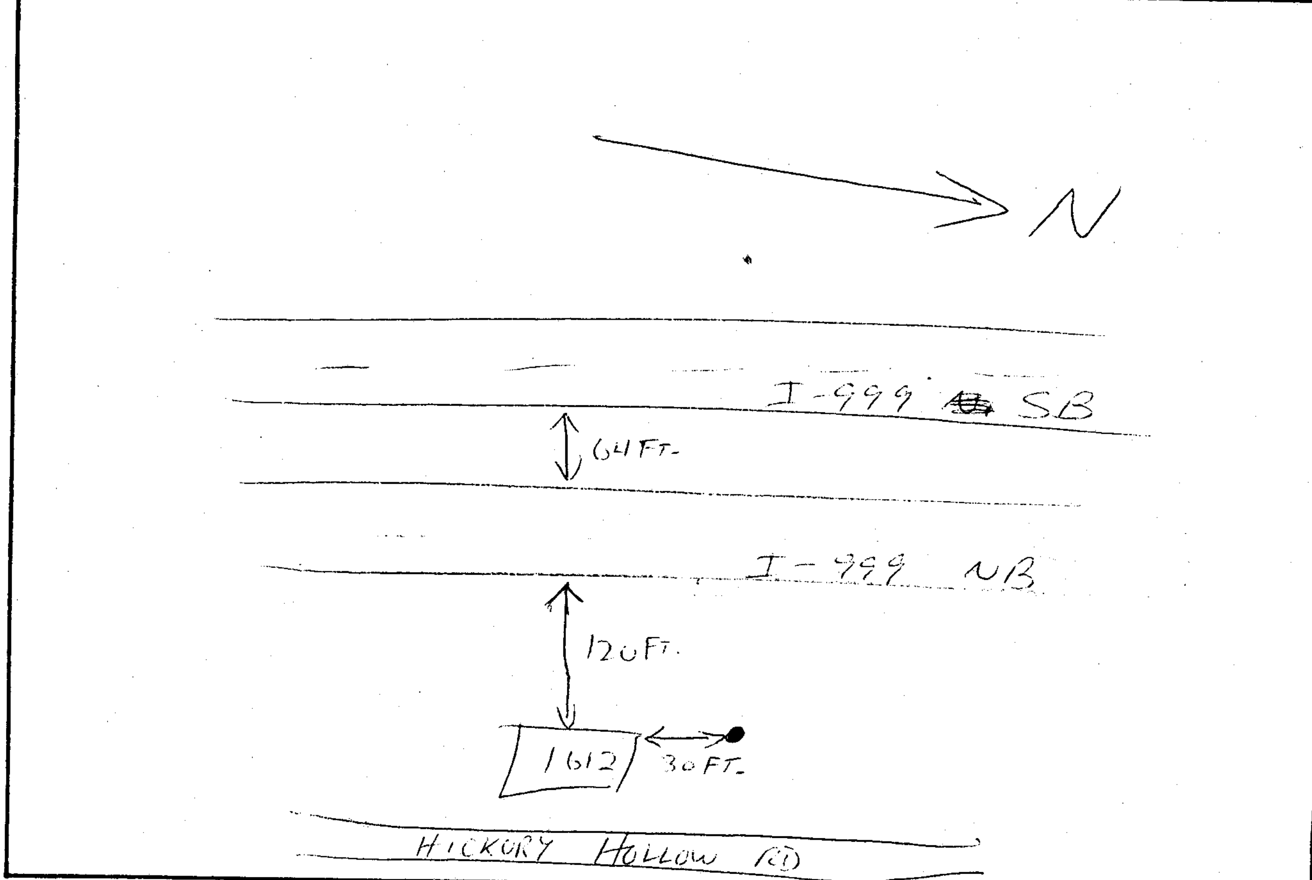
RESPONSE: ✓ FAST __ SLOW ✓ A-WEIGHTING ✓ BATTERY CHECK

WEATHER DATA CLEAR CALM 75°

TRAFFIC DATA			
ROAD	I-999 NB	I-999 SB	
AUTOS	150	200	
MED. TRKS.	12	6	
HVY. TRKS.	16	21	
DURATION	10 MIN	10 MIN	

CRITERION: ± 3DB			
NUMBER OF SAMPLES	UPPER LIMIT	L10	LOWER LIMIT
50	1ST	5TH	10TH
100	5TH	10TH	17TH
150	8TH	15TH	23RD
200	12TH	20TH	29TH

SITE SKETCH



BACKGROUND NOISE BIRDS, KIDS AT 200'

MAJOR SOURCES I-999

UNUSUAL EVENTS FIRE TRUCK (NOT SAMPLED)

OTHER NOTES CHANGED BATTERY BEFORE CALIB.

6. Read the A-weighted sound level every ten seconds, and place a check mark in the appropriate box on the data sheet (Figure 1). Work from left to right. Note if any unrepresentative sound sources influence the measurements. One method is to use a letter code for different sources. Instead of a check mark being entered on the data sheet, a letter corresponding to a particular source causing that sound level, is used (e.g., P - plane, J - jet, D - dog. Keep a running total of the number of samples on the sheet.

7. After 50 samples, test the samples using the method discussed below. If the samples meet the described criterion, the measurement program is complete. If the criterion is not met, obtain another 50 samples and repeat the test discussed below. This will yield the L_{10} sound level.

The following accuracy test is based upon a 95 percent confidence interval for ± 3dB error limits. As an option, 99 percent confidence limits may be used.

Count down from the top of the data sheet (and from left to right) and circle the data samples given in Tables 1 or 2, depending on the accuracy chosen. For example, after 50 samples have been recorded, the 1st, 5th,and 10th samples are circled. These samples constitute the L_{10} flanked by the upper and lower error limits. If the 1st and 10th samples are each within 3 dB of the 5th sample, the measurement program is complete.* Otherwise, an additional 50 samples must be observed and the accuracy test is repeated for a total of 100 samples. The process is repeated for up to 200 samples.

The L_{50} is determined in much the same way, the 25th sample representing the L_{50}.

8. The Equivalent Sound Level, L_{eq} is defined as:

$$L_{eq} = 10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^{n} 10^{(L_i/10)}\right]$$

where L_i is the A-weighted sound level measured in decibels.

The L_{eq} can be evaluated after the L_{10} criterion is met from the data collected on Figure 1 by using the computational worksheet shown in Figure 2 or the right-hand portion of the front side of Figure 1:

a. Enter the number of counts per sound level in Column B. Add them to get Sum B.

TABLE 1

95 PERCENT CONFIDENCE TEST SAMPLE TABLE FOR L_{10}

Total No. of Samples	Upper Error Limit	L_{10}	Lower Error Limit
50	1st Sample	5th Sample	10th Sample
100	4th Sample	10th Sample	16th Sample
150	7th Sample	15th Sample	23rd Sample
200	11th Sample	20th Sample	29th Sample

TABLE 2

99 PERCENT CONFIDENCE TEST SAMPLE TABLE FOR L_{10}

Total No. of Samples	Upper Error Limit	L_{10}	Lower Error Limit
50	1st Sample	5th Sample	11th Sample
100	2nd Sample	10th Sample	18th Sample
150	5th Sample	15th Sample	25th Sample
200	9th Sample	20th Sample	31th Sample

FIGURE 2. SAMPLE L_{eq} COMPUTATION WORKSHEET

A SOUND LEVEL dB	B COUNT		C RELATIVE SOUND ENERGY		D RELATIVE TOTAL SOUND ENERGY
100		x	100,000	=	
99		x	79,400	=	
98		x	63,100	=	
97		x	50,100	=	
96		x	39,800	=	
95		x	31,600	=	
94		x	25,100	=	
93		x	20,000	=	
92		x	15,900	=	
91		x	12,600	=	
90		x	10,000	=	
89		x	7,940	=	
88		x	6,310	=	
87		x	5,010	=	
86		x	3,980	=	
85		x	3,160	=	
84		x	2,510	=	
83		x	2,000	=	
82		x	1,590	=	
81		x	1,260	=	
80		x	1,000	=	
79		x	794	=	
78		x	631	=	
77		x	501	=	
76		x	398	=	
75		x	316	=	
74		x	251	=	
73		x	200	=	
72		x	159	=	
71		x	126	=	
70		x	100	=	
69		x	79.4	=	
68		x	63.1	=	
67		x	50.1	=	
66		x	39.8	=	
65		x	31.6	=	
64		x	25.1	=	
63		x	20.0	=	
62		x	15.9	=	
61		x	12.6	=	
60		x	10.0	=	
59		x	7.94	=	
58		x	6.31	=	
57		x	5.01	=	
56		x	3.98	=	
55		x	3.16	=	
54		x	2.51	=	
53		x	2.00	=	
52		x	1.59	=	
51		x	1.26	=	
50		x	1.00	=	
49		x	.794	=	
48		x	.631	=	
47		x	.501	=	
46		x	.398	=	
45		x	.316	=	
44		x	.251	=	
43		x	.200	=	
42		x	.159	=	
41		x	.126	=	
40		x	.100	=	
39		x	.079	=	
38		x	.063	=	
37		x	.050	=	
36		x	.040	=	
35		x	.032	=	

1. Sum B __________

2. Sum D __________

3. Sum D/Sum B __________

4. L_{eq} __________

FIGURE 2 (CONTINUED). EXAMPLE

DATA REQUIREMENTS:

Each sound reading must be taken at a standard time interval between measurements

Each sound level recorded is the instantaneous level

STEP	PROCEDURE
1	Enter number of counts per sound level in Column B.
2	Multiply the counts in Column B by the number in Column C and enter the result in Column D.
3	Add all values in Column B to determine Sum B, add all values in Column D to determine Sum D, and divide Sum D by Sum B.
4	Locate the value in Column C that is approximately equal to Sum D/Sum B. The corresponding value in Column A is equal to L_{eq}.

EXAMPLE

Given the data in Figure 1, compute L_{eq} using Figure 2 (below, left) and using the right-hand side of Figure 1 (below right).

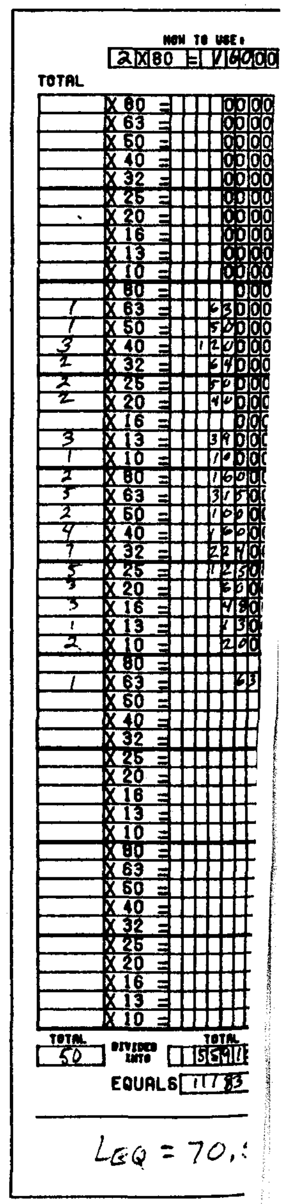
A SOUND LEVEL dB	B COUNT		C RELATIVE SOUND ENERGY		D RELATIVE TOTAL SOUND ENERGY
81		x	[illegible]	=	
80		x	1,000	=	
79		x	794	=	
78	1	x	631	=	631
77	1	x	501	=	501
76	3	x	398	=	1194
75	2	x	316	=	632
74	2	x	251	=	502
73	2	x	200	=	400
72		x	159	=	
71	3	x	126	=	378
70	1	x	100	=	100
69	2	x	79.4	=	168.8
68	5	x	63.1	=	315.5
67	2	x	50.1	=	100.2
66	4	x	39.8	=	159.2
65	7	x	31.6	=	221.2
64	5	x	25.1	=	125.5
63	3	x	20.0	=	60
62	3	x	15.9	=	47.7
61	1	x	12.6	=	12.6
60	2	x	10.0	=	20.0
59		x	7.94	=	
58	1	x	6.31	=	6.31
57		x	5.01	=	
56		x	3.98	=	

1. Sum B 50

2. Sum D 5575.01

3. Sum D/Sum B 111.5

4. L_{eq} 70.5



b. Multiply the counts in Column B by the number in Column C and enter the results in Column D.

c. Add all values in Column D to determine Sum D.

d. Divide Sum D by Sum B.

e. Locate the value in Column C that is approximately equal to Sum D/Sum B. The corresponding value in Column A approximates L_{eq}.

9. Recheck calibration.

3.7 MEASUREMENT PROCEDURE FOR REPRESENTATIVE SOUND LEVEL

An alternative, less complex procedure which only provides equivalent sound level, L_{eq}, is described below:

1. A sketch of the measurement site sould be pre-prepared and appropriate distances and site features noted. All information required on the data sheet should be entered (see Figure 3).

2. Mount the microphone (or sound level meter/microphone combination if the microphone cannot be remotely mounted) on a tripod at a height of about 1.5 metres (5 feet) above the ground and not less than 3 metres (10 feet) from any reflecting surfaces. There may be instances where measurements must be made at different heights (e.g., upper story of residences) or closer to reflecting surfaces (e.g. urban areas). If this is necessary, note these facts on the data sheet. Calibrate the sound level measurement system.

a. Set the sound level meter to the A-weighting network and "slow" response.

b. Observe the sound level meter during a 10 ±2 second sampling period at the start of each minute and half minute and note the maximum value each period, L_A, on data sheet (see Figure 3). Take 60 readings.

3. Determine the arithmetic average sound level L_A as:

$$L_A = \frac{1}{n} (L_1+L_2+L_3+L_4+....L_n)$$

where L_1, L_2, ...L_n are those sound levels that fall within a range of from 6 decibels less than the maximum level to the maximum level (e.g., if maximum is 70 dB, all levels from 64 dB to and including 70 dB are used).

n is the number of L_A values used for computing the arithmetic average.

FIGURE 3. SAMPLE SOUND LEVEL EXPOSURE DATA SHEET

Instructions:

1. Calibrate sound level meter using acoustic calibrator.
2. Install windscreen, select A-weighting network, select "slow" response.
3. Observe for 10 ±2 seconds at the start of each minute and 1/2 minute for 30 minutes.
4. Record maximum reading L_A during each 10 ±2 second period.

Determine Arithmetic Average $\overline{L}_A$

	L_A	Remarks		L_A	Remarks
1.			31.		
2.			32.		
3.			33.		
4.			34.		
5.			35.		
6.			36.		
7.			37.		
8.			38.		
9.			39.		
10.			40.		
11.			41.		
12.			42.		
13.			43.		
14.			44.		
15.			45.		
16.			46.		
17.			47.		
18.			48.		
19.			49.		
20.			50.		
21.			51.		
22.			52.		
23.			53.		
24.			54.		
25.			55.		
26.			56.		
27.			57.		
28.			58.		
29.			59.		
30.			60.		

SUM:*____________________

*Consider for the sum only those values within 6 dB of the maximum value obser

$\overline{L}_A$ = Sum/n: __________ n/60 __________ Correction (Table 3) __________ L_{eq} ______

Location____________________ Date____________________ Time_______________

Wind Velocity_______________mph. Temperature__________°F Engineer__________

Remarks ____

Sketch site on reverse side of Data Sheet.

FIGURE 3. SAMPLE SOUND LEVEL EXPOSURE DATA SHEET (cont.)

Instructions:

1. Calibrate sound level meter using acoustic calibrator.
2. Install windscreen, select A-weighting network, select "slow" response.
3. Observe for 10 ±2 seconds at the start of each minute and 1/2 minute for 30 minutes.
4. Record maximum reading L_A during each 10 ±2 second period.

Determine Arithmetic Average $\overline{L}_A$

	L_A	Remarks		L_A	Remarks
1.	70		31.	71	
2.	68		32.	74	✓
3.	66		33.	68	
4.	75	✓	34.	62	
5.	56		35.	64	
6.	71		36.	70	
7.	78	✓	37.	72	
8.	69		38.	75	✓
9.	62		39.	61	
10.	51		40.	64	
11.	64		41.	59	
12.	72		42.	70	
13.	76	✓	43.	59	
14.	71		44.	60	
15.	64		45.	62	
16.	62		46.	69	
17.	69		47.	74	✓
18.	73	✓	48.	66	
19.	71		49.	63	
20.	79	HIGHEST ✓	50.	58	
21.	74	✓	51.	63	
22.	61		52.	71	
23.	60		53.	69	
24.	70		54.	72	
25.	75	✓	55.	70	
26.	63		56.	70	
27.	72		57.	70	
28.	64		58.	66	
29.	60		59.	64	
30.	66		60.	71	

SUM:* 753 n=10

*Consider for the sum only those values within 6 dB of the maximum value observed.

$\overline{L}_A$ = Sum/n: 75.3 n/60 0.17 Correction (Table 3) -10 L_{eq} 65.3

Location 240' E. I-999 Date 8/21/81 Time 9:20AM

Wind Velocity 0 mph. Temperature 75 °F Engineer HENWAY

Remarks

Sketch site on reverse side of Data Sheet.

TABLE 3

Corrections to $\overline{L}_A$ to Obtain L_{eq}

n/60	Correction - dB
.8 to 1	0
.7 to .8	1
.6 to .7	2
.5 to .6	3
.4 to .5	4
.3 to .4	5
.2 to .3	7
<.2	10

where n is the number of samples used in the calculation of $\overline{L}_A$

$$L_{eq} = \overline{L}_A \rightarrow \text{correction}$$

4. Apply the corrections shown in Table 3 to obtain the equivalent sound level, L_{eq}.

3.8 DAY-NIGHT SOUND LEVEL CALCULATIONS

Day-night sound levels can be obtained using one of two sampling procedures. One procedure requires that equivalent sound levels, L_{eq}, be obtained for each hour of the 24 hours and then energy-averaged. The other procedure is a minimum sampling scheme which uses energy average values of sound level for representative periods.

3.8.1 Hourly Sound Level Measurements

To determine L_{dn} from hourly measurements,

1. Add 10 dBA to each hourly L_{eq} from 2200 hours to 0700 hours (nighttime).

2. Determine the number of hours represented by each L_{eq} value (for the nighttime hours, use the adjusted values from step 1), and enter these values in Column B of Figure 2.

3. For each sound level band, Column A, multiply the number of hours in Column B by the corresponding value in Column C. Enter the result in Column D.

4. Add all the values in Column D to obtain the Sum D. Divide Sum D by 24. Locate the value of Sum D/24 in Column C and note the corresponding sound level in Column A. This is the day-night sound level L_{dn}.

3.8.2 Representative Period Measurements

This minimum sound level measurement scheme requires that one measurement be made during each of the periods shown below:

Period	Time	Numbers of Hours Represented
Day	0700-1900	12
Evening	1900-2200	3
Nighttime	2200-0700	9

Figure 4 is again used to obtain an estimate of the day-night sound level, L_{dn}.

FIGURE 4. EXAMPLE OF L_{dn} COMPUTATION USING FIGURE 2

EXAMPLE: 24-HOUR SURVEY

Time of Day	Hourly L_{eq}
0700-0800	62
0800-0900	64
0900-1000	62
1000-1100	62
1100-1200	58
1200-1300	56
1300-1400	54
1400-1500	54
1500-1600	58
1600-1700	66
1700-1800	66
1800-1900	62
1900-2000	60
2000-2100	58
2100-2200	56
2200-2300	54*
2300-2400	52*
2400-0100	52*
0100-0200	50*
0200-0300	48*
0300-0400	48*
0400-0500	48*
0500-0600	48*
0600-0700	48*

*10-decibel penalties are added to these nighttime values.

A	B	C	D
66	2	39.8	79.6
65	0	31.6	
64	2	25.1	50.2
63	0	20.0	
62	6	15.9	95.4
61	0	12.6	
60	2	10.0	20.0
59	0	7.94	
58	8	6.31	50.48
57	0	5.01	
56	2	3.98	7.96
55	0	3.16	
54	2	2.51	5.02

Sum B = 24
Sum D = 308.66
Sum B/Sum D = 12.86
L_{dn} = 61 dBA

1. Enter the 11 hours for the daytime period in Column B corresponding to the equivalent sound level for this period. Similarly, enter the 4 hours for evening in Column B corresponding to this period L_{eq} values.

2. Enter the 9 hours for nighttime in Column B corresponding to the nighttime sound level plus 10 (L_{eq}+10).

3. Repeat the procedure discussed in Section 3.8.1 to obtain L_{dn}.

4.0 VEHICLE NOISE MEASUREMENT PROCEDURE

4.1 PURPOSE

This procedure describes how vehicle noise emission levels are measured (paragraphs 4.2 - 4.7) and how the reference energy mean emission levels are calculated (paragraph 4.8).

4.2 INSTRUMENTATION

The following equipment is required:

- Sound Level Meter (Type 1 or 2)
- Sound Level Calibrator
- Wind Speed Indicator
- Sling Psychrometer (Optional)
- Vehicle Speed Detection Unit (Radar)
- Windscreen
- Tripod
- Microphone Cable (Optional)
- Data Sheets
- Watch (w/seconds display - optional)
- Spare Batteries

4.3 PERSONNEL

At least two people are required to carry out the procedure. One person should make sound level measurements, and one person should identify vehicles and measure vehicle speed. A third person to record data may be helpful.

4.4 TEST SITE REQUIREMENTS

To achieve uniformity between States and reduce the need for adjustments to measure emission levels, the following test site guidelines must be met (see figure 5):

1. The test site shall consist of a level open space free of large reflecting surfaces, such as parked vehicles, signboards, buildings, or hillsides located within 30 metres (100 feet) of either the vehicle path or the microphone.

2. The microphone shall be located 15 metres (50 feet) from the centerline of the near traffic lane (see figure 6).

3. A clear line of sight to the roadway is required within an unobscured arc of 150 degrees from the 15-metre (50-feet) microphone position.

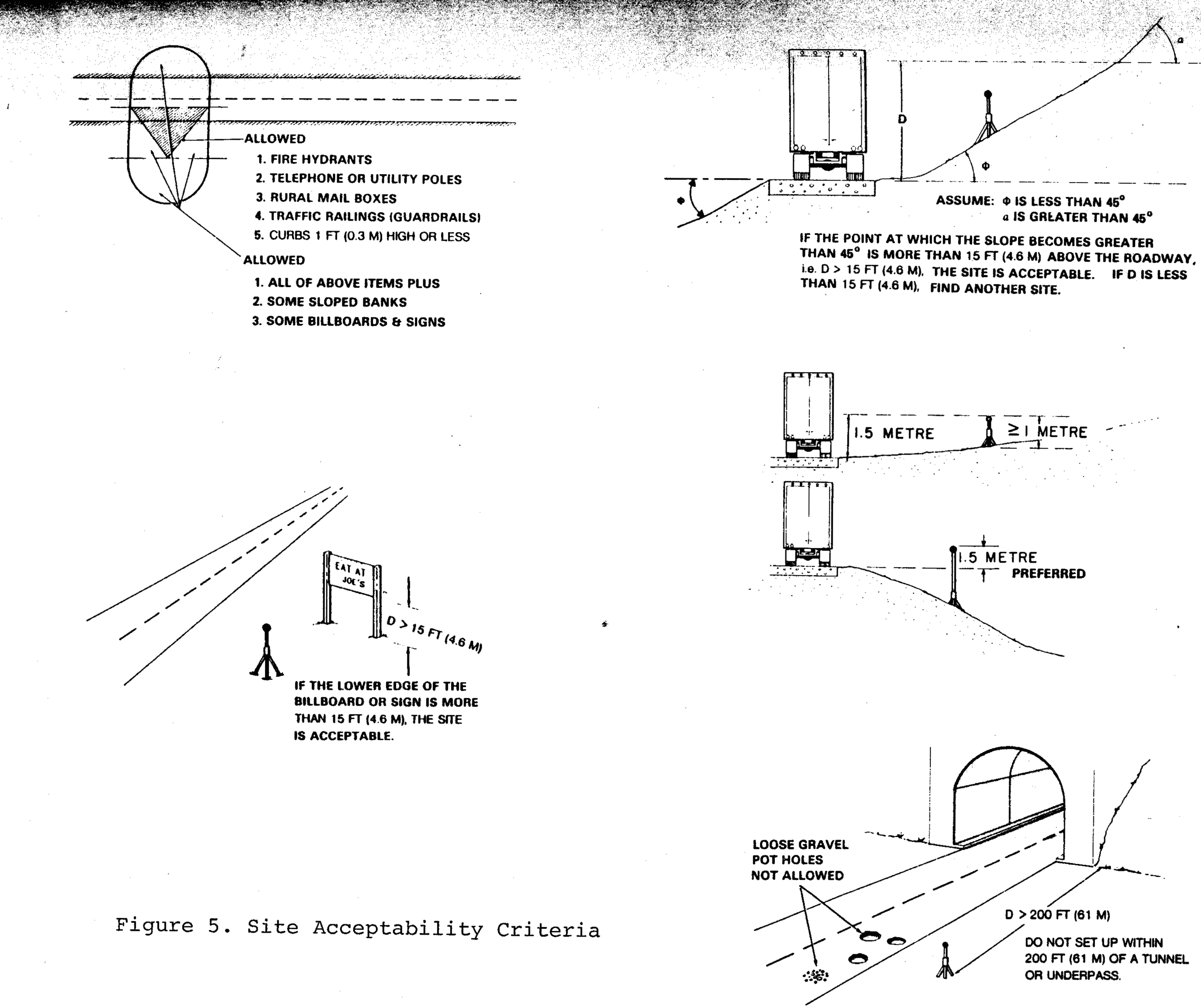


Figure 5. Site Acceptability Criteria

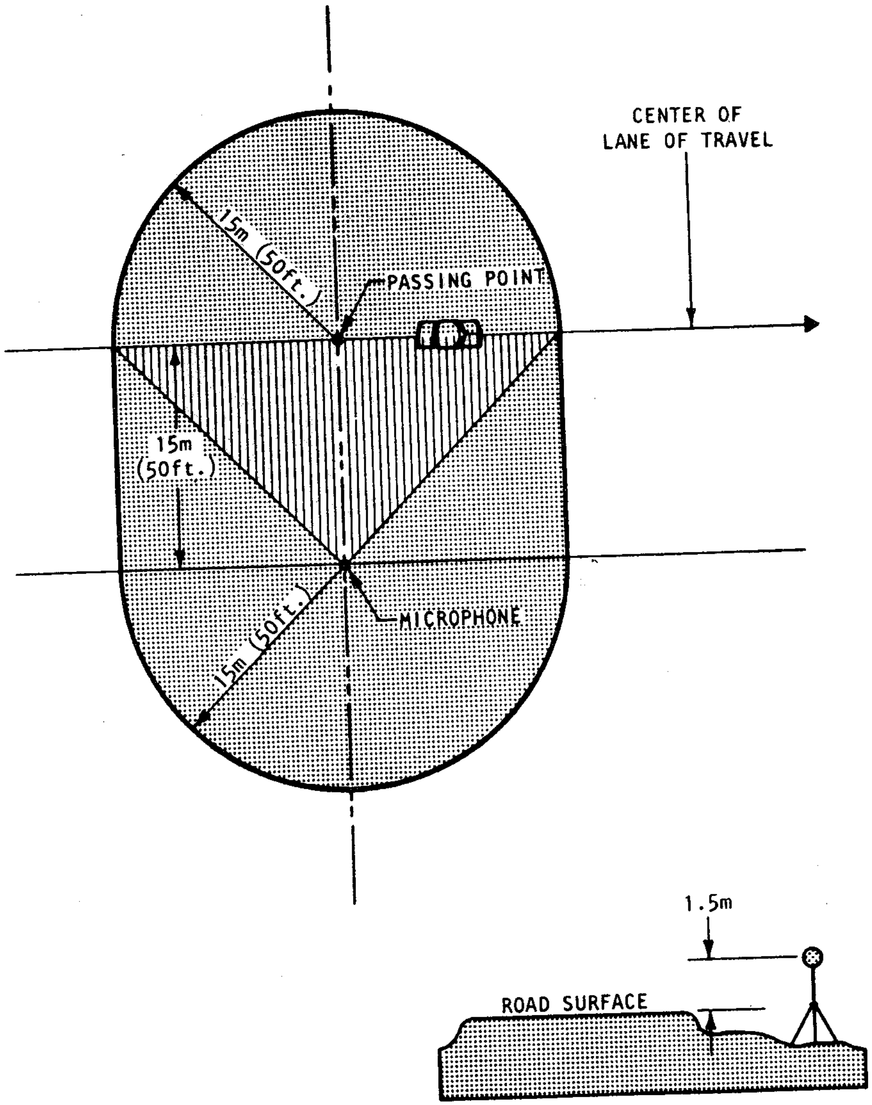


Figure 6. Preferred Roadside Test Site

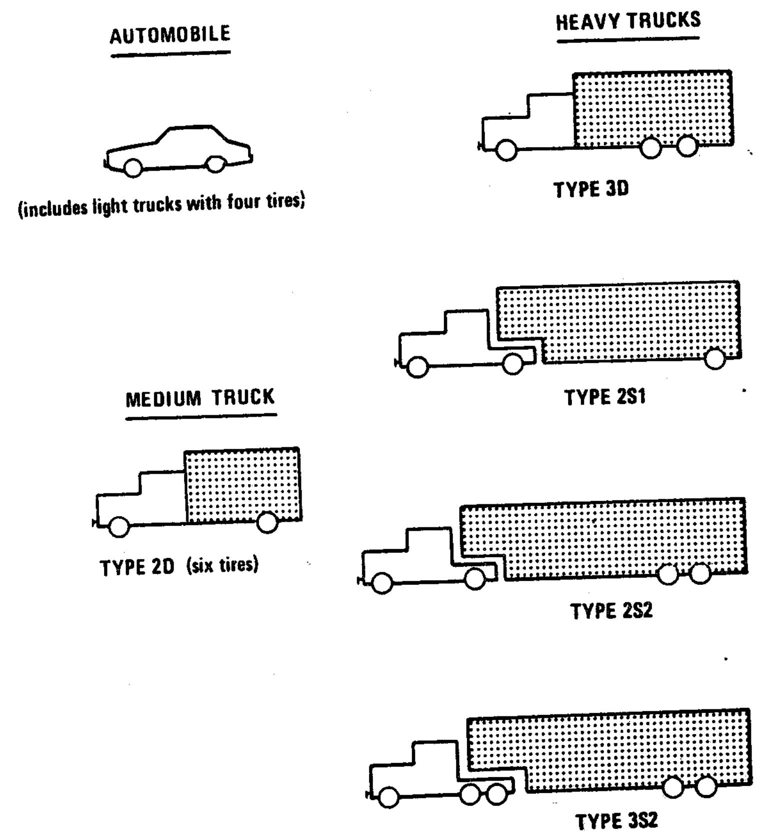


Figure 7. Vehicle Type Identification

4. The surface of the ground within the measurement area shall be free of snow and may be hard ($\alpha=0$) or soft ($\alpha=\frac{1}{2}$).

5. The vehicle path shall be relatively level (less than 2% grade), smooth, dry concrete or asphalt, and free of extraneous material such as gravel.

6. The existing sound level (including wind effects) coming from sources other than the individual vehicle being measured (this includes other vehicles) shall be at least 10 dBA lower than the level of the test vehicle.

4.5 VEHICLE OPERATION

Constant speed traffic operating under cruise conditions (i.e., the vehicles are not accelerating or decelerating).

4.6 MEASUREMENT PROCEDURE

1. Mount the microphone (or sound level meter/ microphone combination) on a tripod at a height of 1.5 metres ± 16 cm (5 feet ± 6 inches) above the surface on which the microphone stands (see Figure 6).

2. Locate the microphone at a distance of 15 metres (50 feet) from the centerline of the near lane of traffic.

3. Orient the microphone per the instrument manufacturer's specifications.

4. Place the vehicle speed measurement system so that the vehicle's speed can be measured as it passes the microphone.

5. Set the sound level meter (SLM) to "fast" response and the A-weighting network.

6. Observe the SLM as the vehicle passes the microphone.

7. Note the highest observed sound level measured by the SLM, i.e., the maximum pass-by sound level. This is the vehicle emission level, L_o.

VEHICLE NOISE EMISSION LEVELS

Page ____ Of ___

Time ______________ Equipment ______________________________

Name ______________________ Date ____________________ Site ______________________________

	Autos		Med Trk 2D		Heavy Trucks 3D		2S1		2S2		3S2		Vehicle Description
Sample	S*	Lo**	S	Lo	S	Lo	S	Lo	S	Lo	S	Lo	
1													
2													
3													
4													
5													
6													
7													
8													
9													
10													
11													
12													
13													
14													
15													
16													
17													
18													
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27													
28													
29													
30													
31													
32													
33													
34													
35													
36													
37													
38													
39													
40													
Total # of Sample													
Mean Sound Level													
Std. Dev.													
Energy Mean Level													

*Speed - Indicate if MPH or KPH **Peak Sound Level, dBA, Fast Response

Figure 8. Sample Data Sheet for Vehicle Noise Levels

8. Identify the vehicle by type. (See paragraph 4.7.1 and Figure 7 for discussion of vehicle types.)

9. Measure the vehicle's speed as it passes the microphone.

10. Record the vehicle type, emission level, and speed on the data sheet (Figure 8). Continue measurements until sufficient samples are obtained to describe the sound level for the representative vehicle class within the accuracy desired. (See paragraph 4.7.2 for discussion on the number of vehicle measurements that are needed.)

4.7 COMPUTING THE NUMBER OF SAMPLES REQUIRED

1. Past vehicle noise emission measurements have indicated that vehicles may be grouped into three acoustically similar classes.* These classes are:

   a. Automobiles (A) - All vehicles with two axles and four wheels designed primarily for transportation of nine or fewer passengers (automobiles), or transportation of cargo (light trucks). Generally, the gross vehicle weight is less than 4,500 kilograms (10,000 pounds).

   b. Medium Trucks (MT) - All vehicles having two axles and six wheels designed for the transportation of cargo or generally more than nine passengers. Generally, the gross vehicle weight is greater than 4,500 kilograms (10,000 pounds) but less than 12,000 kilograms (26,000 pounds). This category corresponds to American Association of State Highway and Transportation Officials (AASHTO) Classification 2D (see Figure 8).

   c. Heavy Trucks (HT) - All vehicles having three or more axles and designed for the transportation of cargo. Generally, the gross weight is greater than 12,000 kilograms (26,000 pounds). This category

*Highway Noise-Generation and Control, NCHRP Report 173, Transportation Research Board, Washington, D. C., 1976.

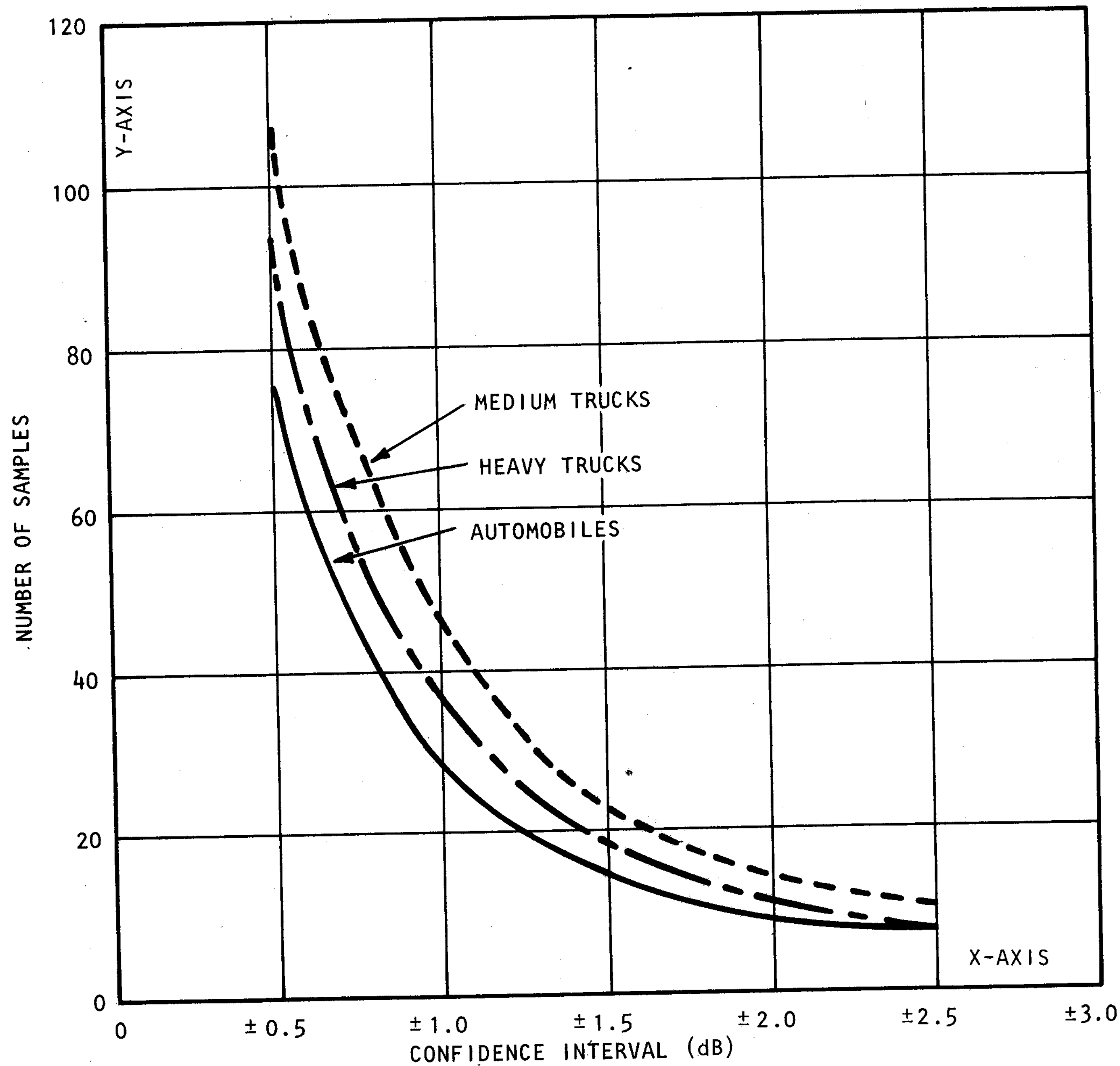


Figure 9. Sample Population Size For Vehicle Emission Sampling

95% CONFIDENCE

Note: Based on data from "Statistical Analysis of FHWA Traffic Noise Data," FHWA-RD-78-64 (Draft Final Report) July 1978.

includes AASHTO Classifications 3D, 2S1, 2S2, and 3S2 (see Figure 7), three-axle buses, and tractors without trailers.

2. Measurements should be made by vehicle type at a selected vehicle speed and recorded on Figure 8. Vehicles traveling at speeds within ±5 km/h (±3 mph) of the selected vehicle speed can be included as part of the sample in computing the sample size for a given speed. (Grouping vehicle speeds into a 10 km/h (5 mph) wide range may produce sound level measurement uncertainty of ±1.5 dBA at low speeds and ±1.0 dBA at high speeds for any given vehicle class.) The different vehicle types in the heavy truck classification may be grouped into one class for analysis. For accurate representation of the vehicle class, the number of measurements for each vehicle class at a selected speed is determined using Figure 9 as follows:

    a. Select a confidence interval (typically ±1 dBA).*

    b. Enter Figure 9 with this value.

    c. Move up from the X-axis to where this value intersects the curve corresponding to the vehicle class under consideration.

    d. Read the corresponding number of samples for this point from the Y-axis.

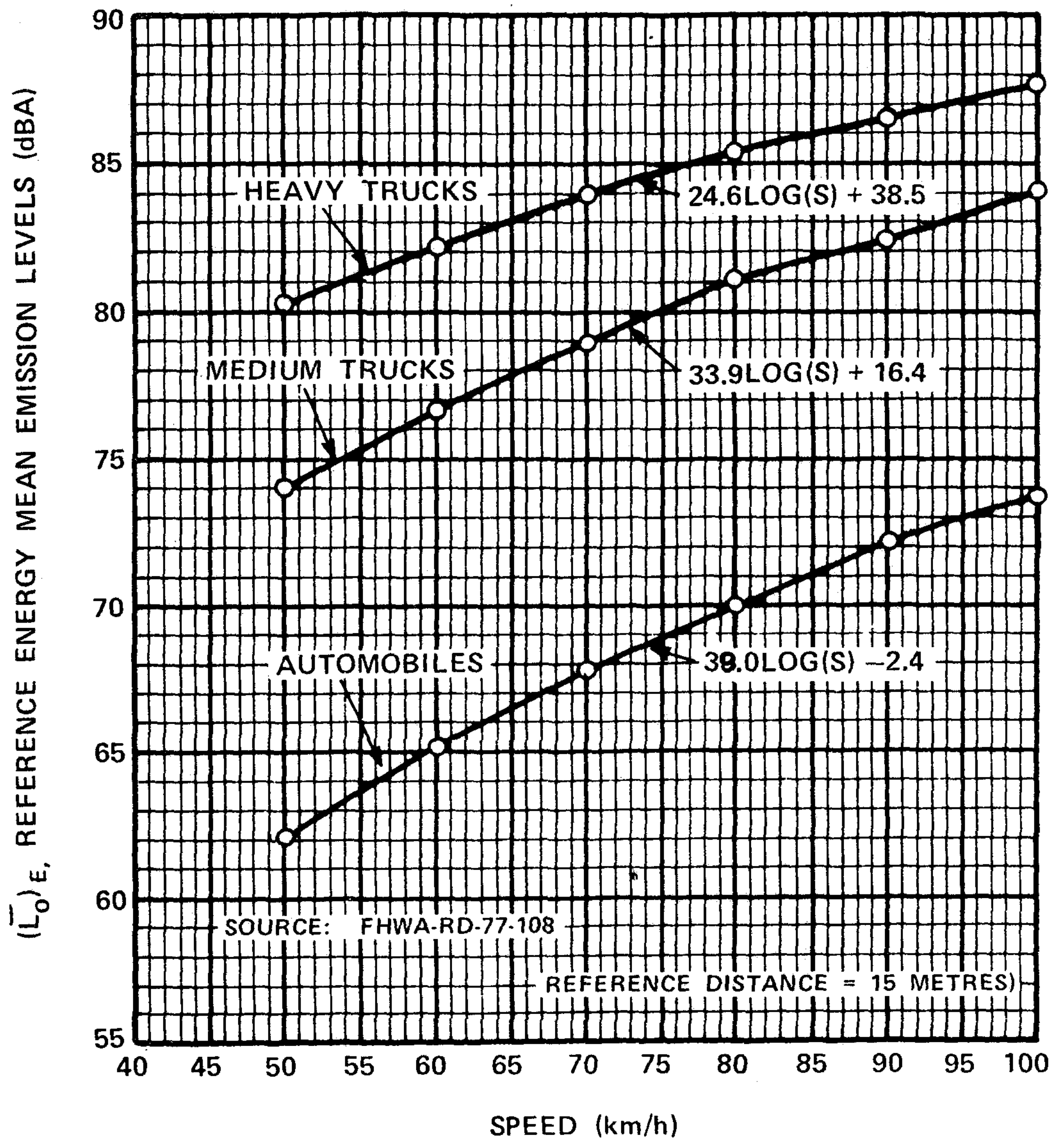
3. If fewer than the required samples are obtained during the measurement program, Figure 9 can be used to determine the accuracy with which those samples obtained describe the vehicle/speed population.

    a. Enter the Y-axis of Figure 9 with the number of samples for a given vehicle class at a selected speed.

    b. Move across the graph to where this value intersects the curve corresponding to the vehicle class under consideration.

    c. Read the corresponding confidence interval for these samples from the x-axis.

*A 95% confidence interval of ±1 dBA means that there is a 95-out-of-100 chance that the mean emission level of the data is within ±1 dBA of the mean value of the population of vehicles of that type.



LEGEND:

1. AUTOMOBILES: ALL VEHICLES WITH TWO AXLES AND FOUR WHEELS.
2. MEDIUM TRUCKS: ALL VEHICLES WITH TWO AXLES AND SIX WHEELS.
3. HEAVY TRUCKS: ALL VEHICLES WITH THREE OR MORE AXLES.

Figure 10. Reference Vehicle Sound Emission Levels

4.8 CALCULATION OF THE REFERENCE ENERGY MEAN EMISSION LEVELS

There are several ways in which the emission level/speed data obtained from the field measurements can be used to compute the reference energy mean emission levels. Any procedure which is statistically valid is acceptable. Two of the procedures are discussed here.

1. Calculation of the reference energy mean emission levels on data collected at a single speed (±5 km/h). Computation of the reference energy mean emission level for this situation uses the formula:

$$(\overline{L_o})_{Ei} = (\overline{L_o})_i + 0.115(\sigma_o)_i^2 \qquad (1)$$

where $(\overline{L_o})_{Ei}$ is the reference energy mean emission level for the i^{th} vehicle class for a single speed;

$(\overline{L_o})_i$ is the arithmetic average sound level, L_o, of the i^{th} class;

$(\sigma_o)_i$ is the standard deviation of the emission levels of the i^{th} vehicle class for a single speed.

a. Compute the arithmetic average emission level, $(\overline{L_o})_i$, for the i^{th} vehicle class.

$$(\overline{L_o})_i = \frac{1}{n}\sum_{k=1}^{n}(L_o)_{ki} \qquad (2)$$

where $(L_o)_{ki}$ is the k^{th} measured emission level of the i^{th} class of vehicles;

n is the number of measured emission levels in the sample.

VEHICLE NOISE EMISSION LEVELS

Time 2-3 PM Equipment GENRAD 1981B

Name W. HENWAY Date 8/21/81. Site I-99; 1.5 M. EAST of NOISEVILLE

	Autos		Med Trk 2D		Heavy Trucks 3D		2S1		2S2		3S2		Vehicle Description (ALL CARS)
Sample	S*	Lo**	S	Lo	S	Lo	S	Lo	S	Lo	S	Lo	
1 ✓	52	71											
2 ✓	54	70											
3 ✓	58	61											
4	46	65											
5 ✓	52	70											
6 ✓	55	70											
7	59	73											VAN
8 ✓	55	68											
9 ✓	56	71											
10	49	70											
11 ✓	52	70											
12 ✓	56	69											
13 ✓	58	74											
14	66	78											PICK-UP
15	50	70											
16 ✓	52	71											
17 ✓	55	71											
18 ✓	57	72											
19 ✓	57	73											
20 ✓	57	70											
21	49	68											
22 ✓	52	71											
23 ✓	55	69											PICK-UP
24 ✓	54	71											
25 ✓	55	72											
26	51	70											
27	59	73											
28	51	75											VW
29 ✓	56	72											
30 ✓	57	70											
31 ✓	54	70											
32 ✓	58	73											
33 ✓	55	71											
34 ✓	56	70											
35 ✓	56	74											PICK-UP
36 ✓	52	68											
37 ✓	54	70											
38	59	73											
39 ✓	57	71											
40 ✓	56	68											
Total # of Sample	29/40		(WITHIN 52-58 MPH)										
Mean Sound Level	70.7		(OF THOSE 29)										
Std. Dev.	1.58		(OF THOSE 29)										
Energy Mean Level	71.0		(FOR A SPEED OF 55 mph)										

*Speed - Indicate if (MPH) or KPH **Peak Sound Level, dBA, Fast Response

Notes: 1. All data between 52-58 mph used as if at 55 mph.

2. Energy Mean Level = Mean Sound Level + 0.115(Std. Dev.)^2

$$= 70.7 + 0.115(1.58)^2$$

$$= 71.0 \text{ dBA}$$

3. 95% confidence interval for 29 samples is ± 1.0 dBA.

Figure 11. Example of Emission Level Determination

(b) Compute the standard deviation, $(\sigma_o)_i$, of the i^{th} class of vehicles.

$$(\sigma_o)^2_i = \frac{1}{n-1}\left[\sum_{k=1}^{n}\left\{(L_o)_{ki} - (\overline{L_o})_i\right\}^2\right] \qquad (3)$$

where $(L_o)_{ki}$ is the k^{th} measured emission level of the i^{th} class.

2. Calculation of the reference energy mean emission levels on data collected over a wide range of speeds. This type of analysis involves curve fitting and is normally carried out using a computer with a statistical analysis program (i.e., the Social Sciences (SPSS) Version 7.2 program for an IBM 370 computer was used to develop the reference energy mean emission levels for the medium and heavy trucks shown in Figure 10). Computation of the reference energy mean emission levels still uses the form:

$$(\overline{L_o})_{Ei} = (\overline{L_o})_i + .115(\sigma_o)_i^2 \qquad (4)$$

where $(\sigma_o)_i$ is the standard deviation of the i^{th} class from the regression analysis; and

where $(\overline{L_o})_i$, the mean sound level, now takes the form of the following equation:

$$(\overline{L_o})_i = A_i + (B_i)\log(\text{speed})$$

where A_i and B_i are constants computed in the regression analysis.

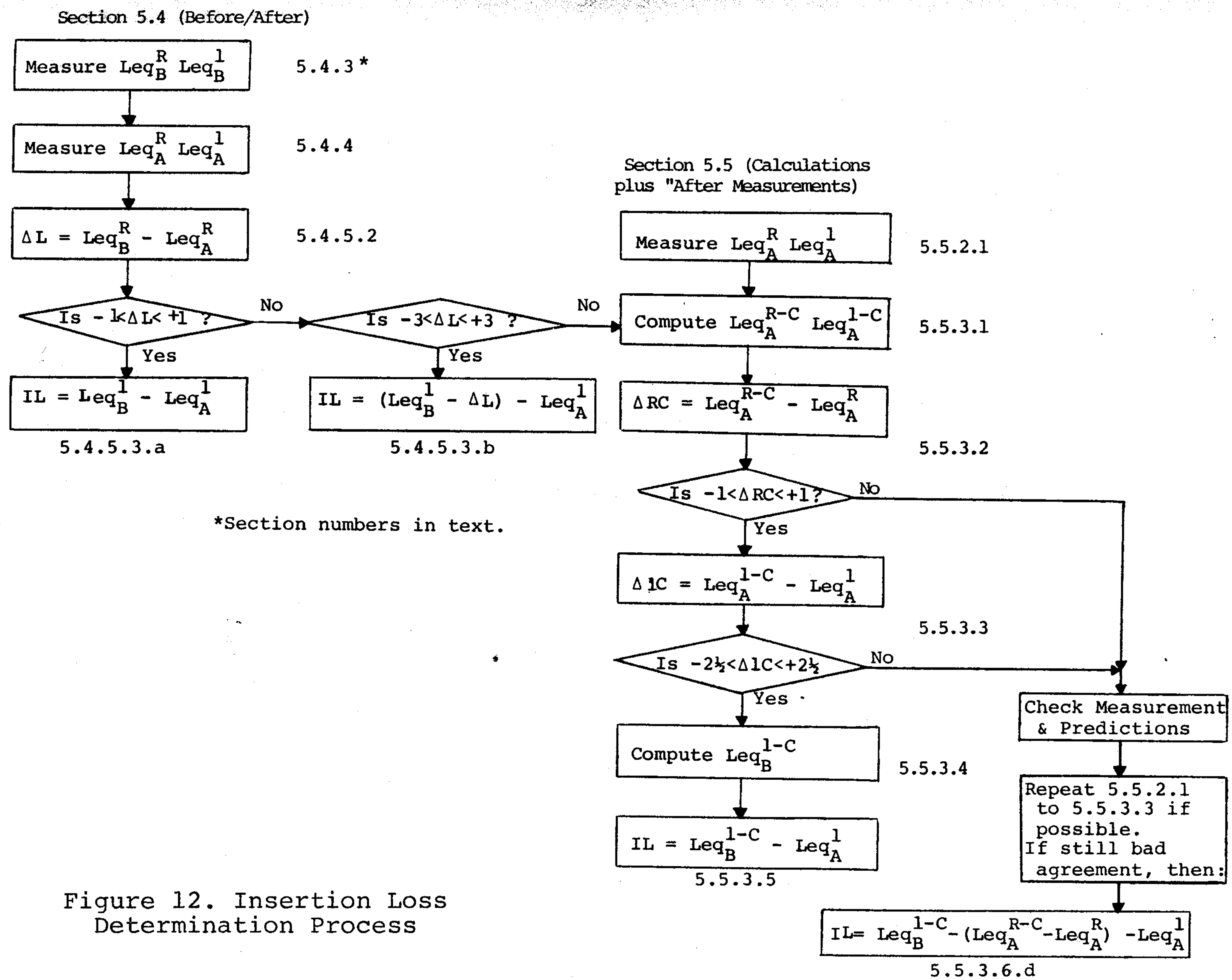
5.0 BARRIER FIELD INSERTION LOSS DETERMINATION PROCEDURE

5.1 PURPOSE

This chapter provides procedures that can be used to determine the field insertion loss (IL) provided by a noise barrier. The field insertion loss is the difference in sound levels at a particular microphone location caused by the construction of a noise barrier. If the sound barrier could be constructed "instantaneously," determination of IL would be simple. In this situation, a "before construction" sound level measurement would be made, the barrier would be "instantaneously" constructed, and an "after construction" sound level measurement would be made. The difference between the two levels would be the IL. Because of the time involved in building a barrier, a number of factors are introduced for which corrections must be made. These factors include changes in traffic volumes, mix and speed, changes in emission levels, and changes in terrain. The procedures presented here for determining IL are based upon measurements to the maximum extent possible.

In addition to determining the IL, people are also concerned about the accuracy of the prediction models used in the barrier design. Too often the predicted IL used during the barrier design is compared with a measured IL obtained shortly after barrier construction. This comparison may be invalid if the predicted IL and the measured IL are based on different traffic conditions. For a meaningful comparison, the conditions under which the measurements were made must be used in the prediction model. Thus, a valid comparison may be made between a measured IL and a calculated IL. Users of these procedures are urged to use the FHWA Model (see FHWA Report FHWA-RD-77-108, "The FHWA Highway Traffic Noise Prediction Model") for these calculations.

Procedures are provided in this chapter for determining field insertion loss of noise barriers for two cases. Case 1 (section 5.4) is for existing highways where "before construction" measurements can be obtained. Case 2 (section 5.5 through 5.6) is for new highways or for existing noise barriers where "before" measurements cannot be obtained. Figure 12 illustrates the decision process for determining insertion loss as explained in sections 5.4 through 5.6.



*Section numbers in text.

Figure 12. Insertion Loss Determination Process

5.2 INSTRUMENTATION

The following equipment is required:

- Sound Level Meters (Type 1 or 2) - 2
- Sound Level Calibrator
- Earphones or Headphones (Optional)
- Speed Detection Device (Radar)
- Stopwatches or Timers - 2
- Wind Speed Indicator
- Sling Psychrometer (Optional)
- Tripod - 2 (Optional)
- Data Sheets
- Microphone Cables - 2 (Optional)
- Windscreens - 2
- Spare Batteries

5.3 PERSONNEL

Two persons are needed to make sound level measurements. If the technique in section 5.4 is used, two other individuals will be needed to operate the speed detection equipment and to count the traffic. For the other two techniques, one person may be sufficient to count traffic. Familiarity with the FHWA Model is desirable.

5.4 TECHNIQUE FOR DETERMINING IL FOR EXISTING HIGHWAYS WHERE THE BARRIER HAS NOT BEEN BUILT

This procedure involves simultaneous measurements at "reference" and "study site" microphone locations. Two sets of measurements are made: one set before the barrier is built, and one set after the barrier is built. An adjustment is then made (if necessary) to the reference measurements, and the IL is calculated by subtracting the "after" measurement from the adjusted "before" measurement.

5.4.1 "Study Site" Microphone Location (Microphone #1)

1. Use maps and/or field reconnaissance to determine the desired "study site" location for the IL determination.

2. Once the location is selected, establish a baseline. The baseline is a line perpendicular to the centerline of the near traffic lane and passes through

microphone #1. The reference microphone will also be located along this baseline. Record the exact location of the baseline and microphone #1 (distance and elevation). Another set of measurements will be made at the same location after the barrier is built.

3. Microphone locations should not be selected within 3 metres of any vertical reflective surface. Measurements should not be taken at locations or times where extraneous sounds such as aircraft, animals, children, or traffic on side streets could influence the measurements.

4. If a comparison will be made between the measured insertion loss and a calculated insertion loss, the geometry and terrain between microphone #1 and the roadway should be as simple and uniform as possible. This will simplify the input data needed for the prediction model.

5.4.2. Reference Microphone

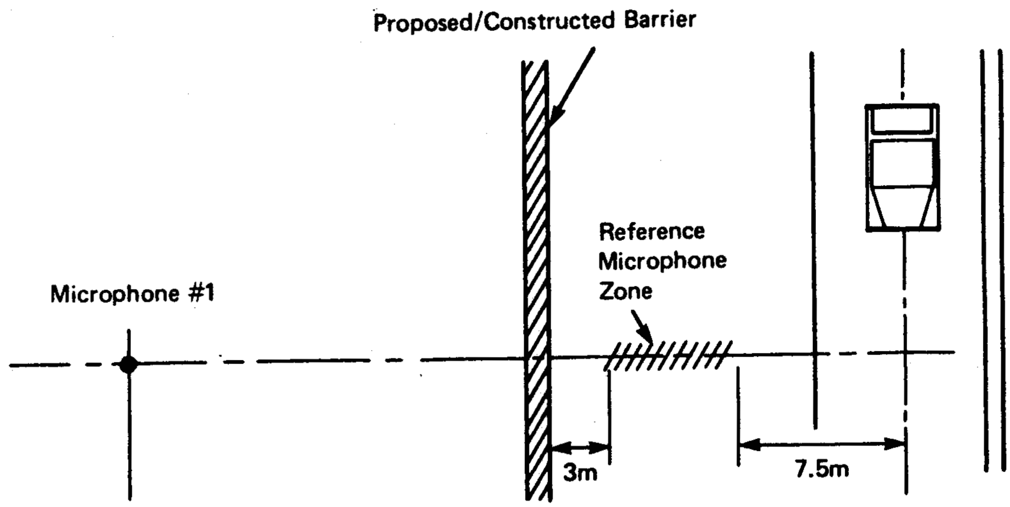
1. The reference microphone is located on the baseline determined by section 5.4.1.2.

2. The location, length, and elevation of the proposed barrier must be known before the reference microphone may be located.

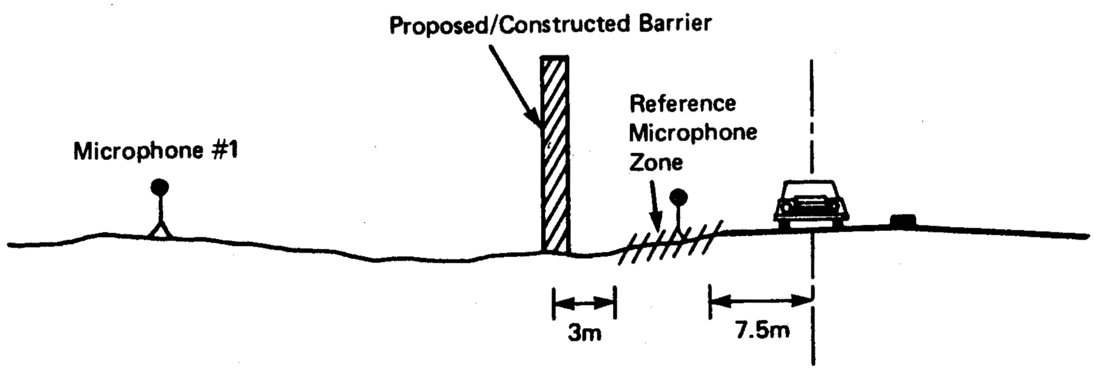
3. The reference microphone must have an unobstructed view of the roadway through a subtended arc of at least 160 degrees. Once this requirement is satisfied, any of three positions may be used.

   a. Position A (refer to Figure 13)--Between the roadway and the barrier provided that the microphone is at least 7.5 metres from the centerline of the near traffic lane, and at least 3.0 metres from any reflective surface (including the barrier).

   b. Position B (refer to Figure 14)--Directly over and 1.5 metres above the top of the barrier (still be at least 7.5 metres away from the centerline of the near traffic lane).



(a) Plan



(b) Profile

Figure 13. Reference Position A

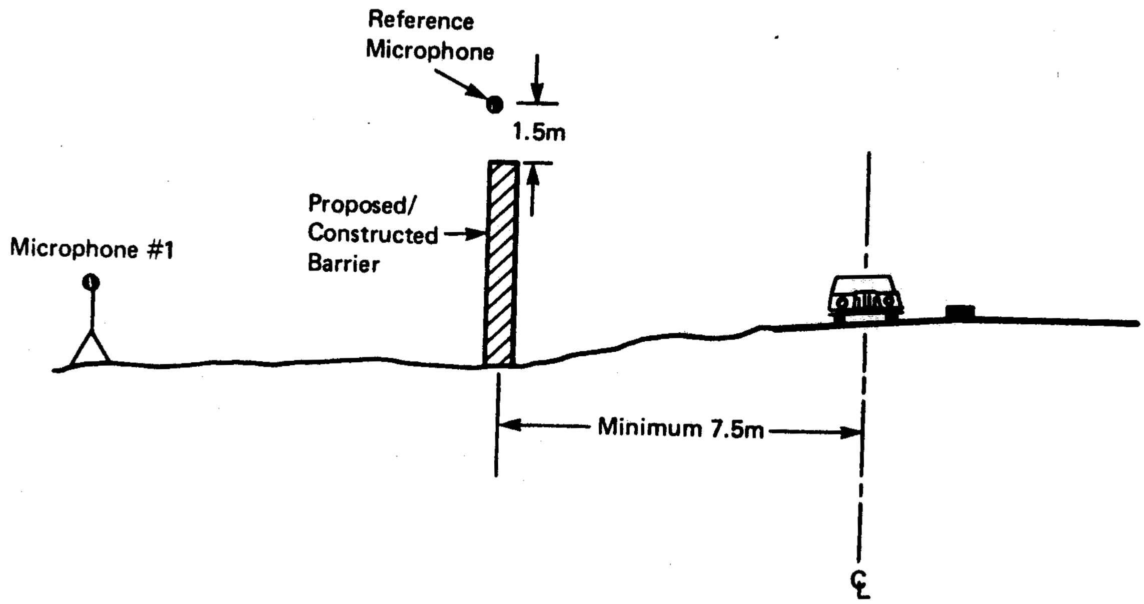


Figure 14. Reference Position B

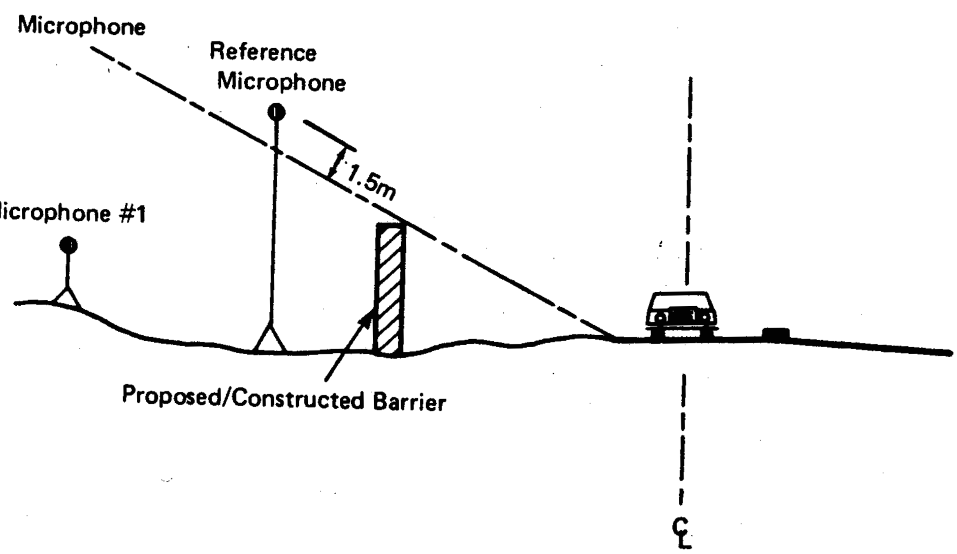


Figure 15. Reference Position C

c. Position C (refer to Figure 15)--Between the barrier and microphone #1. The reference microphone must be 1.5 metres higher (measured perpendicular) than a line drawn from the near edge of the pavement through the top front edge of the barrier.

4. If the measured IL is to be compared with a calculated IL, subsequent calculations will be simplified if the reference microphone location is exactly 15.0 metres from the centerline of the near lane.

5. Record the precise location of the reference microphone on the baseline. This location will be used for the "after" set of measurements.

5.4.3 Measurement and Calculations for the "Before Construction" Condition

1. Sound Level Measurement
   Through simultaneous measurements, obtain sound level data at the reference microphone and at microphone #1. Minimum measurement period is 8 minutes and 20 seconds. Chapter 3 discusses a typical manual measurement procedure. Determine the "before" Leq(h) at the reference microphone, $Leq(h)_B^R$, and at microphone #1, $Leq(h)_B^1$. Record these values. After the barrier is built, these values will be used to determine the measured IL.

2. Traffic and Environmental Data
   Concurrently with the sound level measurements, the traffic data must be measured. Vehicles must be separated into the three classes shown in Figure 16. Two-axle buses go into the medium category and three-axle buses go into the heavy category. Traffic counts volumes must be obtained for both directions of flow. Obtain representative speeds for each vehicle class (in both directions, if possible). Also, obtain information on the ground conditions, wind speed and direction, and other climatic conditions.

5.4.4 Measurements and Calculations for the "After Construction" Condition

It is important that this second set of measurements be made as soon as practical after the barrier has been completed and normal traffic flow has been restored. This will help minimize changes in traffic characteristics that could significantly alter the sound levels.

1. Microphone Location
   After the barrier has been built, use the information in sections 5.4.1 and 5.4.2 to establish both microphone locations in the field. Monitor the environmental conditions and, when these conditions are similar to those observed in section 5.4.3.2, make the second set of measurements.

2. Sound Level Measurements
   Through simultaneous measurements, obtain sound level data at the reference microphone and at microphone #1. The minimum measurement period is 8 minutes and 20 seconds. Chapter 3 discusses a typical manual measurement procedure. Determine the "after" Leq(h) at the reference microphone, $Leq(h)^{R}_{A}$, and microphone #1, $Leq(h)^{1}_{A}$. Record these values.

3. Traffic and Environmental Data
   Concurrently with the sound level measurements, the traffic data must be measured. Vehicles must be separated into the three classes shown in Figure 16. Two-axle buses go into the medium category and three-axle buses go into the heavy category. The traffic count must be according to the direction of flow. Obtain representative speeds for each vehicle class (in both directions, if possible). Carefully study the ground and vegetation conditions at the site. Record these conditions along with data on wind speed and direction and other climatic conditions.

5.4.5 Computation of the Field Insertion Loss

1. Traffic Data Compare the traffic data measured before and after barrier construction. If the traffic conditions change substantially, the procedures in section 5.5 may be needed to determine the IL.

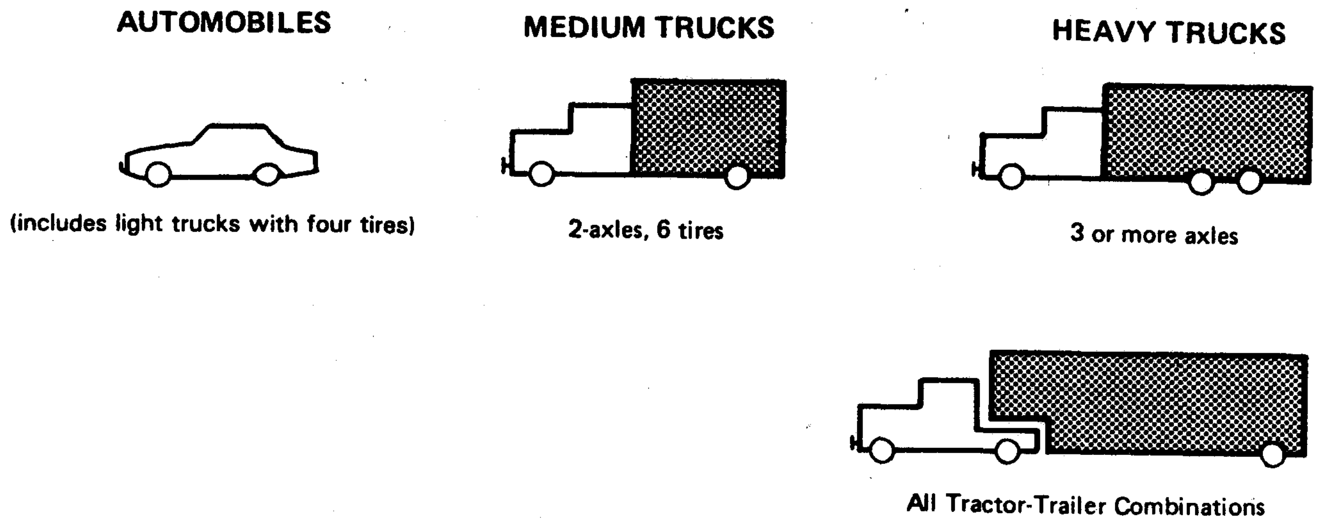


Figure 16. Vehicle Type Identification

Table 4. Criteria for Selection of Site Parameter

Situation	Drop-Off Rate
1. All situations in which the source or the receiver are located 3 metres above the ground or whenever the line-of-sight* averages more than 3 metres above the ground.	3 dBA ($\alpha = 0$)
2. All situations involving propagation over the top of a barrier 3 metres or more in height.	3 dBA ($\alpha = 0$)
3. Where the height of the line-of-sight is less than 3 metres and	
(a) There is a clear (unobstructed) view of the highway, the ground is hard and there are no intervening structures.	3 dBA ($\alpha = 0$)
(b) The view of the roadway is interrupted by isolated buildings, clumps of bushes, scattered trees, or the intervening ground is soft or covered with vegetation.	4.5 dBA ($\alpha = 1/2$)

*The line-of-sight (L/S) is a direct line between the noise source and the observer.

2. Reference Microphone Subtract the Leq(h) measured after the barrier was built from the Leq(h) measured before the barrier was built.

$$\Delta L = Leq(h)_B^R - Leq(h)_A^R \qquad (1)$$

where

ΔL is the difference in the Leq(h)'s

3. Microphone #1

   a. If ΔL is $\pm$ 1 dBA or less, compute the IL according to equation 2.

   $$IL = Leq(h)_B^1 - Leq(h)_A^1 \qquad (2)$$

   where

   IL is the field insertion loss.

   b. If ΔL is ± 3 dBA or less, compute the IL according to equation 3.

   $$IL = [Leq(h)_B^1 - \Delta L] - Leq(h)_A^1 \qquad (3)$$

   c. If ΔL is greater than 3 dBA, compute the IL according to the procedures in section 5.5.

5.5 TECHNIQUE #1 FOR DETERMINING IL FOR NEW HIGHWAYS OR EXISTING BARRIERS (CALCULATIONS PLUS "AFTER" MEASUREMENTS)

This procedure uses a combination of "after" sound level measurements and the FHWA model. Basically, a set of sound level measurements is made at two carefully selected locations. These measurements are used to calibrate the FHWA model. Once the calibration is completed, a "before" sound level is calculated. The IL is then determined by taking the difference between the calculated "before" and the measured "after" sound levels.

5.5.1. Microphone Location

See sections 5.4.1. and 5.4.2.

5.5.2. Measurement and Calculations Based on Existing Barrier

1. Sound Level Measurement
   See section 5.4.4.2.

2. Traffic and Environmental Data
   See section 5.4.4.3.

5.5.3. Computation of the Field Insertion Loss

1. Using the FHWA model, compute the calculated noise level at the reference microphone, $Leq(h)_A^{R-C}$, and at microphone #1, $Leq(h)_A^{1-C}$. Divide the roadway into at least two equivalent lanes, one for each direction of flow using the traffic data obtained in section 5.5.2.2. Use Table 4 and/or experience to determine the site parameter for the reference microphone and for microphone #1.

2. Compare the calculated traffic noise level at the reference microphone, $Leq(h)_A^{R-C}$, with the measured traffic noise level, $Leq(h)_A^{R}$. If the two values agree within ± 1 dBA, it can be assumed that the emission data in FHWA model correctly represents the traffic for this site and that the site around the reference microphone has been correctly modeled. If the two values do not agree within ± 1 dBA, refer to section 5.5.3.6.

3. Compare the calculated traffic noise level at microphone #1, $Leq(h)_A^{1-C}$, with the measured traffic noise level, $Leq(h)_A^{1}$. If the two values agree within ± 2 1/2 dBA, it can be assumed that the site has been correctly modeled. If the two values do not agree within ± 2 1/2 dBA, refer to section 5.5.3.6.

4. Using the FHWA model and traffic from section 5.5.2.2, calculate the noise level at microphone #1, $Leq(h)_B^{1-C}$, as if the barrier has not been built. Base the site parameter upon the conditions that would exist <u>if there were no barrier</u>.

It is important to note that this calculation will be complicated for houses beyond the first row because they will receive some degree of shielding from the first row houses.

5. Compute the IL according to equation 4.

$$IL = Leq(h)_B^{1-C} - Leq(h)_A^{1} \qquad (4)$$

6. If the measured and calculated values do not meet the tolerance requirements ($\pm$ 1 dBA at the reference microphone and $\pm$2 1/2 dBA at microphone #1), locate the source of the discrepancies as follows:

   a. Check the computation of the measured Leq(h).

   b. Check the input data used in the FHWA model.

   c. If the tolerance requirement in section 5.5.3.6 still cannot be met, repeat the measurements in section 5.5.2.

   d. Repeat the steps in sections 5.5.3.1 through 5.5.3.3. If the error persists, compute the IL according to equation 5.

$$IL = \{Leq(h)_B^{1-C} - [Leq(h)_A^{R-C} - Leq(h)_A^{R}]\} - Leq(h)_A^{1} \qquad (5)$$

5.6 TECHNIQUE #2 FOR DETERMINING FIELD INSERTION LOSS FOR NEW HIGHWAYS OR EXISTING BARRIERS (UNSHIELDED LOCATION ALONG THE HIGHWAY)

One measurement is made at a noise sensitive site shielded by the barrier. A second measurement is made at a similar site along the highway where there is no barrier.

Figure 17 presents a sketch of appropriate measurement locations and specifies the geometry involved. If available, extra microphones could be used at each site at reference locations as a check on reference level similarities.

5.6.1. Microphone Locations

1. The microphone-to-roadway distance for each location must be identical $\pm$0.5 metres).

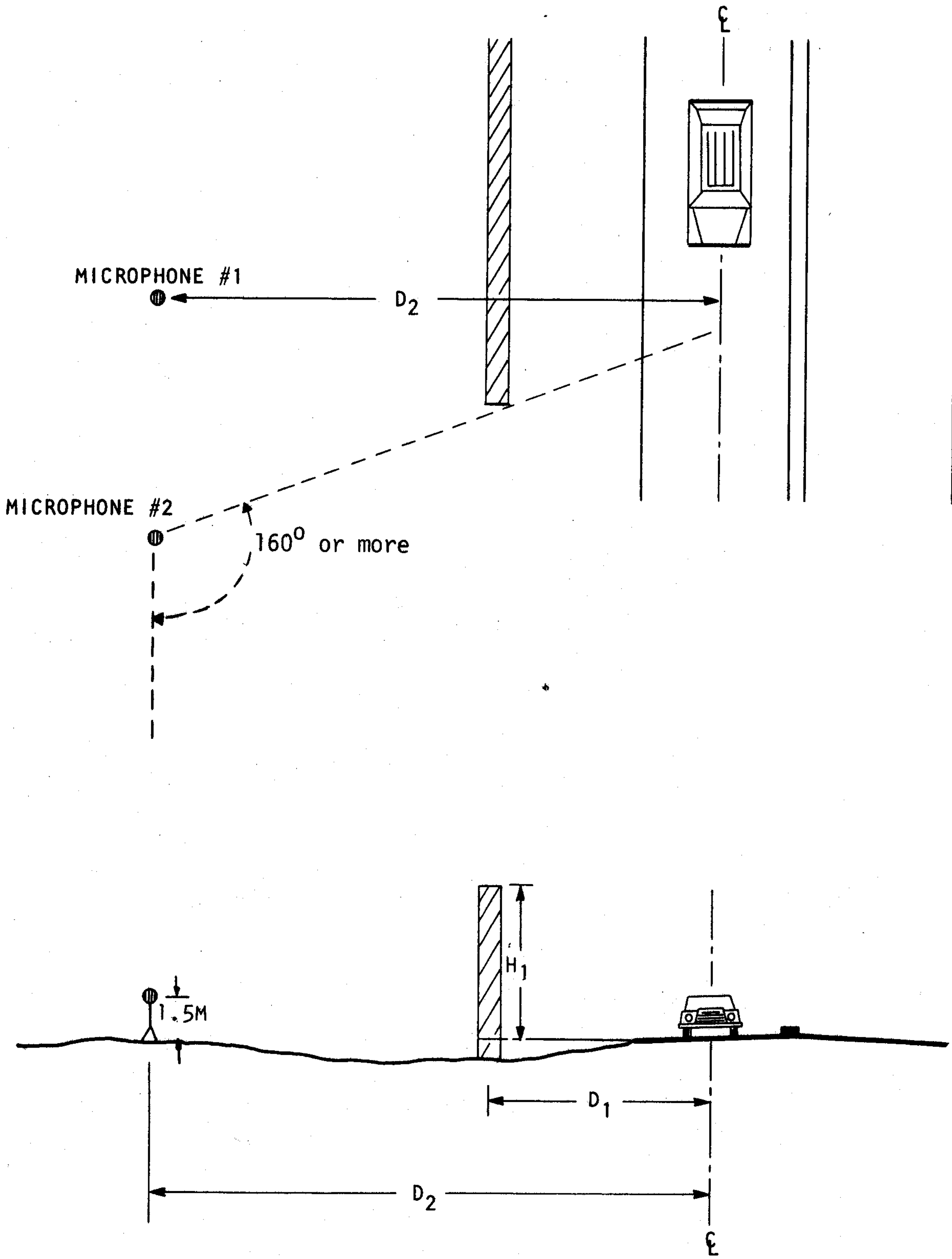


Figure 17. Microphone Locations for Simulated "Before" Site Method

2. The ground cover between the road and the microphone at each site must be similar.

3. The topography at each site should be similar.

4. The number of lanes and geometry of the roadway at each site should be identical. Road features such as median strips and guard barriers should be the same at each site.

5. Traffic flow conditions (vehicle/hour, mean vehicle speed) should be equivalent at each site.

6. The unshielded measurement location should have as great an angle of view of the highway as possible. An angle of at least 160 degrees is recommended. Both microphones are mounted on tripods at a height of 1.5 metres ±16 cm (5 feet ±6 inches) above the ground at the measurement point, or at the height of the receptor under study.

5.6.2. Measurements

1. Sound Level Measurement
Use the technique previously described in Chapter 3 to determine Leq at each microphone. Call the level at the unshielded site $Leq(h)_B^1$, and the level at the shielded site, $Leq(h)_A^1$

2. Traffic and Environmental Data
See section 5.4.3.2.

5.6.3. Computation of the IL

Use the procedure described in section 5.4.5, letting the unshielded site represent the "before" condition and the shielded site be the "after" condition. If the reference microphones were not used, the FHWA model should be used to compute the reference levels, $Leq(h)_B^R$ and $Leq(h)_A^R$. The IL will be the difference in levels at the two microphones, adjusted by differences in the reference levels.

6.0 NON-TRAFFIC NOISE SOURCE MEASUREMENT PROCEDURE

6.1 PURPOSE

This procedure is used to measure the contribution of noise sources (other than traffic) to ambient sound levels at noise sensitive land use areas. Typical of these noise sources are railroad activity, aircraft overflights, industrial plant operations, construction activity, etc. The A-weighted equivalent sound level (L_{eq}) due to the noise source is measured at the noise sensitive land use area. Two techniques are presented, one for stationary sources of sound and the other for mobile sources.

6.2 INSTRUMENTATION

The following equipment is required:

- Sound Level Meter (Type 2)
- Sound Level Calibrator
- Earphone/Headphone
- Stopwatch
- Wind Speed Indicator
- Psychrometer
- Tripod
- Microphone Cable
- Data Sheets
- Windscreen
- Spare Batteries

6.3 MEASUREMENT LOCATIONS

Measurements are made at noise sensitive land uses in the vicinity of a proposed highway, or at noise sensitive land uses along an existing route. The location should be chosen so that, if possible, noise sources other than the one being measured, have minimum influence on measurements.

6.4 PERSONNEL

The procedure can be accomplished by one person.

6.5 MEASUREMENT PROCEDURE

1. Mount the microphone (or sound level meter/microphone combination if the microphone cannot be remotely mounted on a tripod at a height of 1.5 metres ±16cm (5 feet ±6 inches) above the ground, and if practical, at least 3 metres (10 feet) from any substantial reflecting surface (e.g., buildings, vehicles, billboards).

2. Sketch the measurement locations, with site features and dimensions, on the back of the data sheet (Figure 18 or 19) to provide a record which can be used if future measurements are required. The sketch should be of sufficient detail to permit future measurements at the same location.

6.5.1 Stationary Sources

For stationary sources of noise (e.g., construction activity, industrial activity), the following procedure is used:

1. Set the sound level meter to the A-weighting network and "slow" response.

2. Observe the sound level meter during a 10 ±2 second sampling period at the start of each minute and half minute and note maximum value $\bar{L}_A$ in each period on data sheet.

   If the source is intermittent (e.g. operates for 15 minutes and then is off for 10 minutes) disregard periods when the source is not operating but continue to sample until 60 samples are acquired.

3. Disregard measurements affected by intrusive noise sources other than the identified noise source. Extend the number of half minute observations for more than 30 minutes until 60 valid measurements are obtained.

4. Determine the arithmetic average sound level $\bar{L}_A$ as:

$$\bar{L}_A = \frac{1}{n} (L_1+L_2+L_3+L_4+.......L_n)$$

   where L_1, L_2, ...L_n are those sound levels that fall within a range of from 6 decibels less than the maximum level to the maximum level (e.g., if maximum is 70 dB, all levels from 64 dB to and including 70 dB are used).

   n is the number of L_A values used for computing the arithmetic average.

5. Apply the corrections shown in Table 5 to obtain the equivalent sound level, L_{eq}.

6. Measurements should be made without the sound source operating to determine background ambient sound levels using the procedure presented in Steps 1-5.

FIGURE 18. SAMPLE SOUND LEVEL EXPOSURE DATA SHEET - STATIONARY SOURCES (ALTERNATIVE #1)

Instructions:

1. Calibrate sound level meter using acoustic calibrator.
2. Install windscreen, select A-weighting network, select "slow" response.
3. Observe for 10 ± 2 seconds at the start of each minute and 1/2 minute for 30 minutes.
4. Record maximum reading L_A during each 10 ± 2 second period.

Determine Arithmetic Average $\overline{L}_A$

	L_A	Remarks		L_A	Remarks
1.	______	______	31.	______	______
2.	______	______	32.	______	______
3.	______	______	33.	______	______
4.	______	______	34.	______	______
5.	______	______	35.	______	______
6.	______	______	36.	______	______
7.	______	______	37.	______	______
8.	______	______	38.	______	______
9.	______	______	39.	______	______
10.	______	______	40.	______	______
11.	______	______	41.	______	______
12.	______	______	42.	______	______
13.	______	______	43.	______	______
14.	______	______	44.	______	______
15.	______	______	45.	______	______
16.	______	______	46.	______	______
17.	______	______	47.	______	______
18.	______	______	48.	______	______
19.	______	______	49.	______	______
20.	______	______	50.	______	______
21.	______	______	51.	______	______
22.	______	______	52.	______	______
23.	______	______	53.	______	______
24.	______	______	54.	______	______
25.	______	______	55.	______	______
26.	______	______	56.	______	______
27.	______	______	57.	______	______
28.	______	______	58.	______	______
29.	______	______	59.	______	______
30.	______	______	60.	______	______

SUM:* ______________________

*Consider for the sum only those values within 6 dB of the maximum value observed.

$\overline{L}_A$ = Sum/n: ________ n/60 ________ Correction ________ L_{eq} ________

Location________________ Date________________ Time________________

Wind Velocity____________mph. Temperature________°F. Engineer________________

Remarks ____

____

Sketch site on reverse side

TABLE 5

Corrections to $\bar{L}_A$ to Obtain L_{eq}

n/60	Correction - dB
.8 to 1	0
.7 to .8	1
.6 to .7	2
.5 to .6	3
.4 to .5	4
.3 to .4	5
.2 to .3	7
< .2	10

where n is the number of samples used in the calculation of $\bar{L}_A$

$$L_{eq} = \bar{L}_A - \text{correction}$$

If the background ambient equivalent sound level is at least 10 decibels below the source equivalent sound level, the source equivalent sound level measurement requires no adjustment.

If the background ambient equivalent sound level is 3 to 10 decibels below the source equivalent sound level, apply corrections to the source sound levels in accordance with Table 6.

If the difference between the source L_{eq} and the background ambient is 0 to 3 decibels, no determination of the source equivalent sound level can be made.

6.5.2 Mobile Sources

The procedure, described below, can be used to measure the sound level of mobile sources which emit sounds of short duration (e.g., aircraft overflights, train passbys, etc.). Short duration sounds from mobile sources exhibit many different sound level-time patterns. As a simplification, they can be described as one of three major types shown in Figure 19 and described below. This simplification does introduce a degree of error on the order of 1-2 dB for sources where the time pattern is neither triangular or rectangular, but something in between.

Rectangular time pattern - The sound level rises rapidly, maintains a maximum level for some time and then decreases rapidly. Experience has shown that sources which cycle on and off intermittently, and passbys of freight trains measured at distant locations exhibit this type of noise-time pattern.

Triangular time pattern - The sound level rises at a constant rate from a background ambient sound level to a maximum sound level, and decreases to the background ambient sound level. The times for the sound to increase and decrease are approximately equal. Short trains, off road vehicles, and aircraft overflights typically exhibit this type of time-sound level pattern.

Combination time pattern - As the name implies, this sound level-time pattern is a combination of a short duration of higher sound followed by a steady sound. The sound level rises rapidly from the background ambient sound level to a maximum and decreases to an intermediate level. The intermediate sound level is maintained for some time until it drops to the background ambient sound level. Measurements of freight train noise at locations close to the track often exhibit this sound level-time pattern. The triangular portion is caused by the

TABLE 6

CORRECTION FACTORS FOR BACKGROUND AMBIENT SOUND LEVELS

$$L_s = 10 \log_{10} [10^{L_p/10} - 10^{L_o/10}]$$

L_s is stationary source sound level contribution

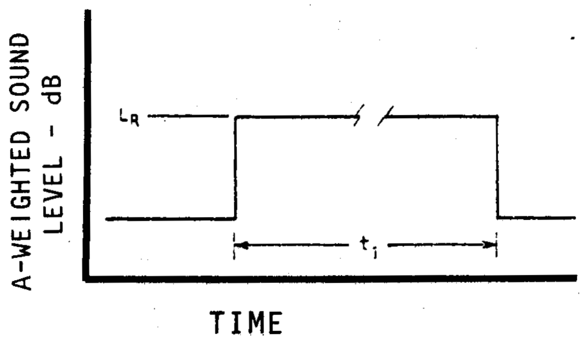
L_p is measured sound level with source operating

L_o is background sound level with source not operating

Difference between L_p and L_o	Subtract values from L_p to get L_s
0	*
1	*
2	*
3	3.0
4	2.5
5	2.0
6	1.5
7	1.0
8	1.0
9	0.5
10	0.5

*Cannot be determined. Background levels must be lower.

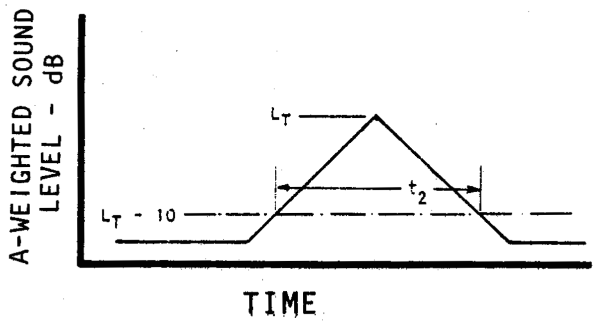
CATEGORY A RECTANGULAR



L_R = ______ dB

t_1 = ______ sec

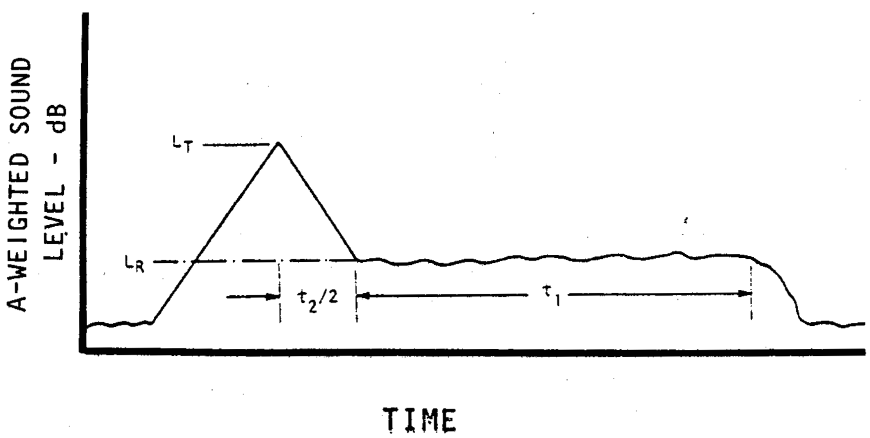
CATEGORY B TRIANGULAR



L_T = ______ dB

t_2 = ______ sec

CATEGORY C COMBINATION



L_T = ______ dB

L_R = ______ dB

t_2 = ______ sec

t_1 = ______ sec

Sketch site on reverse side

Figure 19. Mobile Sources Sound Level Time Patterns/Data Sheet

passing of the locomotive. The rectangular portion is due to the passage of freight cars.

Rectangular Time Pattern

1. Set the sound level meter for "fast" response and the A-weighting network.

2. Note the maximum sound level emitted by the source (noted as L_R) and the time period (t_1) that the source produces this level on a data sheet. (Figure 19).

3. Repeat these measurements for a number of sources (at least five).

4. Calculate the mean value for L_R and for t_1 from these samples.

Triangular Time Pattern

1. Set the sound level meter for "fast" response and the A-weighting network.

2. Note the maximum sound level produced by the source (noted as L_T) and the time required for the sound level to decrease 10 decibels below this maximum level ($t_2/2$). If the sound level does not drop 10 decibels, this technique is not valid. Multiply the latter value by 2 and enter these values (L_T and t_2) on a data sheet (Figure 19).

3. Repeat the measurements for a number of sources (at least five).

4. Calculate a mean value for L_T and for t_2 from these samples.

Combination Time Pattern

1. Note the following sound levels and time periods on a data sheet (Figure 19).

   L_T - Maximum sound level of triangular portion of time history, dB

   L_R - Maximum sound level of rectangular portion of time history, dB

   t_1 - Time that sound is at L_R, seconds

   t_2 - Twice the time for sound to decrease from the L_T to L_R, seconds

2. Repeat the measurements for a number of sources (at least five).

3. Calculate mean values for each of the variables.

6.6 ANALYSIS OF DATA

The equivalent sound level contribution of the source to the ambient sound level is evaluated from the data obtained from measurements described in Section 6.5 and data describing the operational characteristics of the source.

6.6.1 Stationary Sources

The following procedure is used to determine the equivalent sound level:

1. Calculate the fraction of time over the period being studied that the source operates. Observation of the sources over an extended period yields this information. The operator (plant superintendent, contractor, etc.) of the source may be able to supply pertinent data.

2. Enter the fraction of time in Column B of Figure 20 in the row corresponding to the equivalent sound level for the source.

3. Multiply the value in Column B by the value in Column C. Enter in Column D.

4. Locate the result in Column C. The corresponding value in Column A is the equivalent sound level contribution of the source.

   Note: An example of the use of this figure is presented in the section describing "Existing/Traffic Sound Level Measurement Procedures".

6.6.2 Mobile Sources

6.6.2.1 Rectangular Time Pattern

1. Multiply the number of occurrences per hour, n, by the mean duration $\bar{t}_1$(sec), (see Section 6.5.2).

2. Locate the value on the nt_1 axis on the nomograph in Figure 21.

3. Locate the mean maximum sound level on the L_R axis.

4. Connect these two points with a straight line.

A	B	C		D
SOUND LEVEL dB	FRACTION	RELATIVE SOUND ENERGY		RELATIVE TOTAL SOUND ENERGY
100	x	100,000	=	
99	x	79,400	=	
98	x	63,100	=	
97	x	50,100	=	
96	x	39,800	=	
95	x	31,600	=	
94	x	25,100	=	
93	x	20,000	=	
92	x	15,900	=	
91	x	12,600	=	
90	x	10,000	=	
89	x	7,940	=	
88	x	6,310	=	
87	x	5,010	=	
86	x	3,980	=	
85	x	3,160	=	
84	x	2,510	=	
83	x	2,000	=	
82	x	1,590	=	
81	x	1,260	=	
80	x	1,000	=	
79	x	794	=	
78	x	631	=	
77	x	501	=	
76	x	398	=	
75	x	316	=	
74	x	251	=	
73	x	200	=	
72	x	159	=	
71	x	126	=	
70	x	100	=	
69	x	79.4	=	
68	x	63.1	=	
67	x	50.1	=	
66	x	39.8	=	
65	x	31.6	=	
64	x	25.1	=	
63	x	20.0	=	
62	x	15.9	=	
61	x	12.6	=	
60	x	10.0	=	
59	x	7.94	=	
58	x	6.31	=	
57	x	5.01	=	
56	x	3.98	=	
55	x	3.16	=	
54	x	2.51	=	
53	x	2.00	=	
52	x	1.59	=	
51	x	1.26	=	
50	x	1.00	=	
49	x	.794	=	
48	x	.631	=	
47	x	.501	=	
46	x	.398	=	
45	x	.316	=	
44	x	.251	=	
43	x	.200	=	
42	x	.159	=	
41	x	.126	=	
40	x	.100	=	
39	x	.079	=	
38	x	.063	=	
37	x	.050	=	
36	x	.040	=	
35	x	.032	=	

FIGURE 20. SAMPLE EQUIVALENT SOUND LEVEL CONTRIBUTION WORKSHEET

5. Read the value at which the line intersects the central axis (L_{eq}). This is the hourly equivalent sound level contribution of the source.

6.6.2.2 Triangular Time Pattern

1. Multiply the number of occurrences per hour by the mean duration, $\bar{t}_2$(sec), (see Section 6.5.2).

2. Locate this value on the nt_2 axis on the nomograph in Figure 22.

3. Locate the mean maximum sound level on the L_T axis.

4. Connect these two points with a straight line.

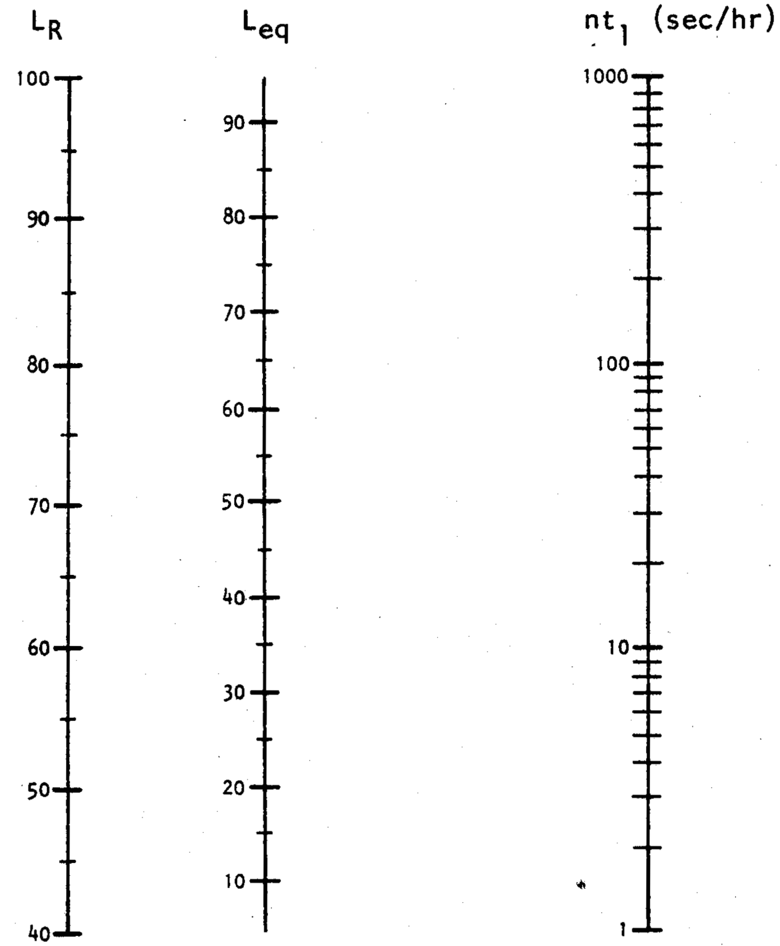
5. Read the value at which the line intersects the central axis (L_{eq}). This is the hourly equivalent sound level contribution of the source.

6.6.2.3 Combination Time Pattern

1. Calculate the hourly equivalent sound level contributions of the rectangular and triangular portions of the sound source time patterns using the techniques described in Sections 6.6.2.1 and 6.6.2.2. For the technique described in Section 6.6.2.2 to be valid, L_T-L_R must be greater than 7 decibels. If L_T-L_R is less than 7 decibels, the case reduces to a rectangular time pattern with a maximum value of L_R.

2. Combine the two hourly equivalent sound level contributions on an energy basis using Figure 23 to provide an hourly equivalent sound level contribution for the source.

$$Leq(h) = \overline{L_R} + 10\log(\overline{nt_1}) - 35.6 \text{ dBA}$$



L_R = Maximum sound level of source with rectangular time history, dB

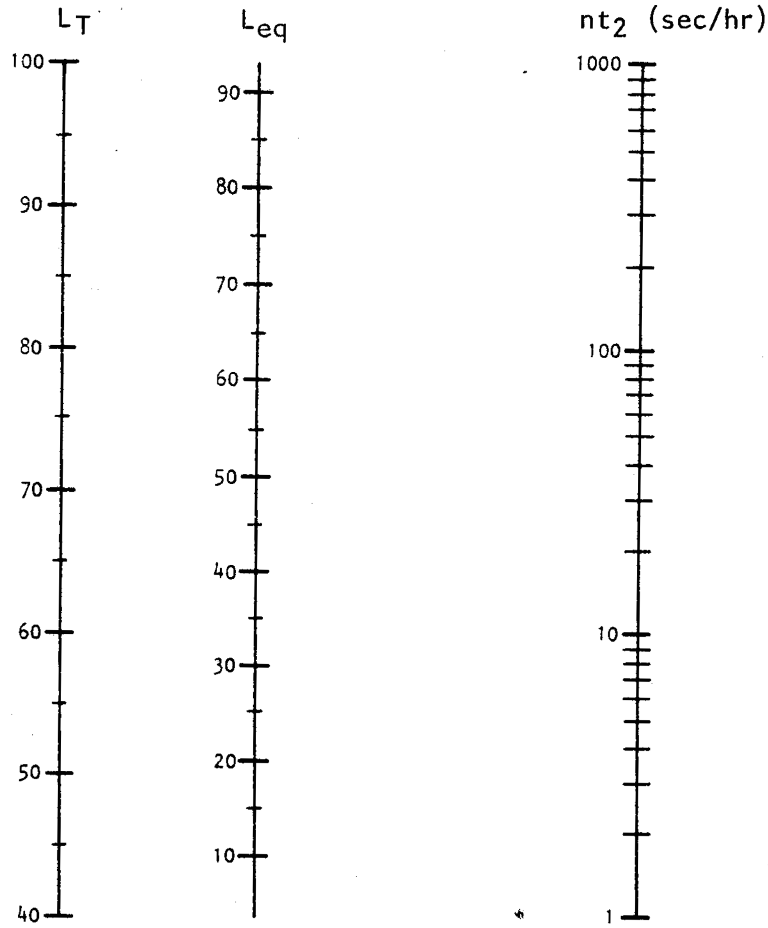
L_{eq} = Hourly equivalent sound level contribution of source, dB

n = Number of occurrences per hour

t_1 = Duration in seconds per occurrence

FIGURE 21. NOMOGRAPH FOR THE EQUIVALENT SOUND LEVEL OF A SOURCE WITH A RECTANGULAR TIME PATTERN

$$Leq(h) = \overline{L_T} + 10\log(\overline{nt_2}/2) - 35.6 \text{ dBA}$$



L_T = Maximum sound level of source with triangular history, dB
L_{eq} = Hourly equivalent sound level contribution of source, dB
n = Number of occurrences per hour
t_2 = Duration in seconds per occurrence

FIGURE 22. NOMOGRAPH FOR THE EQUIVALENT SOUND LEVEL OF A SOURCE WITH A TRIANGULAR TIME PATTERN

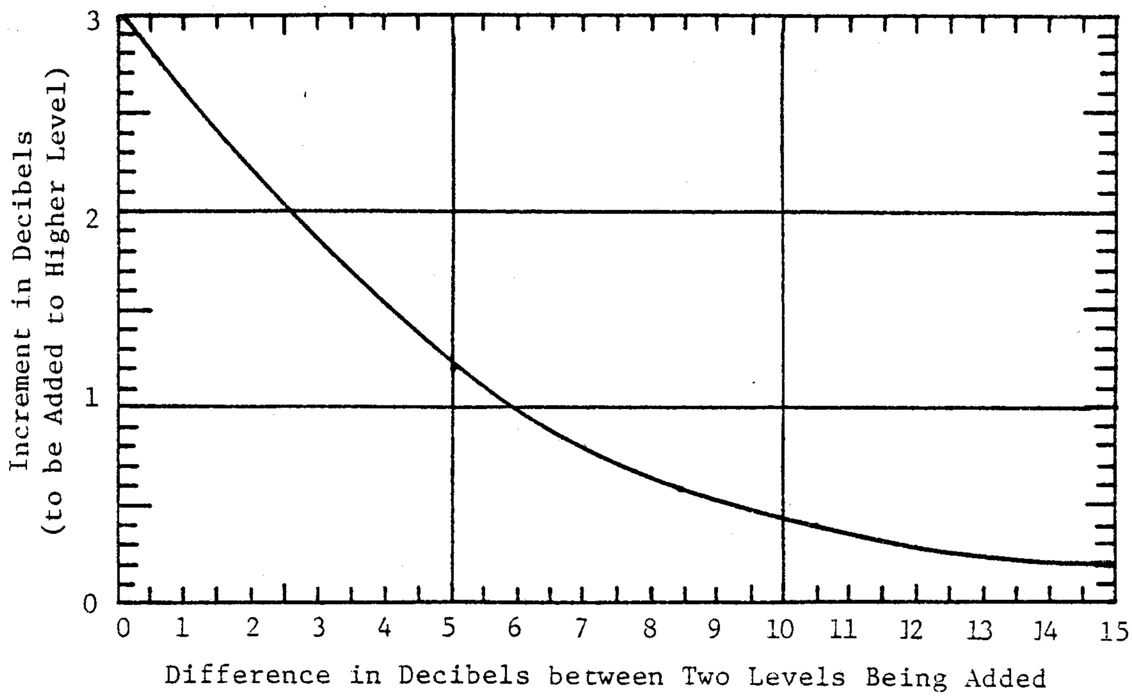


Figure 23. Chart for Combining Hourly Average Sound Levels

7.0 CONSTRUCTION EQUIPMENT NOISE MEASUREMENT PROCEDURE

7.1 PURPOSE

A procedure that can be used to measure the noise of individual construction equipment at a construction site is described. The procedure is designed to enable these measurements to be made while other equipment is operating on the site. The noise of individual equipment and its time of operation can be used to determine which equipment is the major contributor to the construction noise at the site.

The basis of the method is the Society of Automotive Engineers (SAE) Recommended Practice J88a, "Exterior Sound Level Measurement Procedure of Powered Mobile Construction Equipment", and the CAGI/PNEUROP Test Code.

7.2 INSTRUMENTATION

The following equipment is required to carry out the procedure:

- Sound Level Meter (Type 2)
- Sound Level Calibrator
- Wind Speed Indicator
- Sling Psychrometer
- Tachometer*
- Stopwatch
- Windscreen
- Data Sheet
- Tripod
- Microphone Cable
- Spare Batteries

7.3 PERSONNEL

The procedure described below can be accomplished by one person.

7.4 TEST SITE

Whenever possible, the construction equipment being tested should be moved to an area at the construction site which is as flat, open, and free from large reflecting surfaces and other noise sources as possible. Since ground surface conditions will vary from site to site (i.e., it may be "hard", concrete or asphalt; or "soft", grass or loose soil), ground conditions should be assessed and carefully noted on the data sheet.

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*Tachometers shall be compatible with both two- and four-stroke engines. An electromechanical tachometer may be required for ungoverned diesel engines.

7.5 EQUIPMENT OPERATION

Stationary equipment (e.g., pavement breakers, air compressors, cranes, concrete trucks) are operated at load and performance (i.e., rated engine speed, feed or work rate) which are typical of their normal operation.

Mobile equipment (e.g., graders, scrapers, bulldozers) should be operated in a stationary mode.

1. Operate the equipment with all component drive systems in neutral through the following cycle "low idle to maximum governed speed (high idle at no load) to low idle" as rapidly as possible. The engine must stabilize for at least 10 seconds at maximum governed speed before returning to low idle.

2. Operate the equipment at the maximum governed speed in a stabilized condition with all auxiliary equipment operating.

Haul trucks and other vehicles whose normal operation is on the road should be tested using the vehicle noise emission measurement procedure (Chapter 4.0).

7.6 MEASUREMENT PROCEDURE

1. Set the sound level meter/microphone on a tripod at a height of 1.5 metres ±16 cm (5 feet ±6 inches) above the ground.

2. Measurements are made at a preferred distance of 15 metres ±16 cm (50 feet ± 6 inches) from an imaginary reference surface forming the smallest rectangular box which completely encloses the equipment under test (see Figure 24).

3. Set the sound level meter for "slow" response and A-weighting.

4. Operate the construction equipment as outlined in Section 7.5.

5. Measurements are made at four orthogonal locations around the equipment.

6. The final reported sound level is the highest of the measured sound levels.

7. If the background ambient sound levels are within 10 decibels of the measured sound levels, either adjust the measured sound levels for other noise (section 7.7) or repeat the measurements at a distance less than 15 metres (50 feet) from the equipment (Section 7.7).

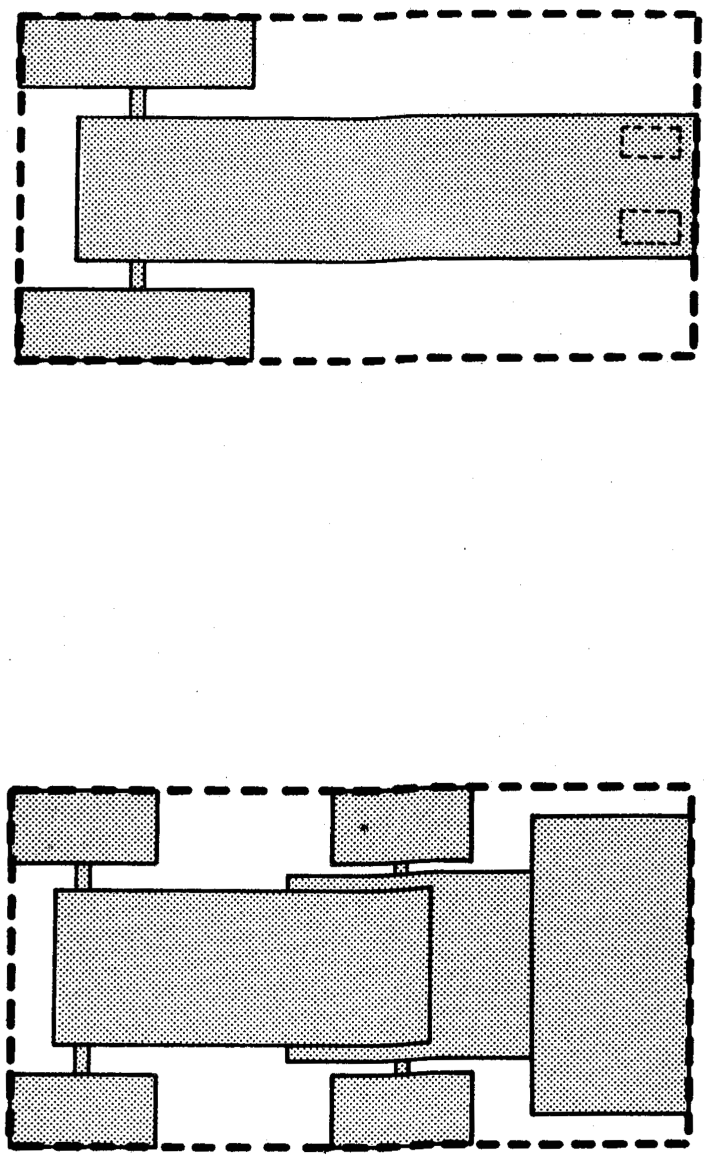

Figure 24. Reference Surface for Construction Equipment

Note: Equipment shaded.
Reference surface indicated by broken lines.

7.7 ADJUSTMENTS FOR HIGH AMBIENT NOISE CONDITIONS

Measurements are valid when the background ambient A-weighted sound levels, which include wind noise and all sources other than the equipment under test, are more than 10 decibels lower than the measured sound levels. Observe the background ambient sound level before and after each test. If these conditions are not met, two options exist:

1. Measurements can be made at locations less than 15 metres (50 feet) from the equipment being studied. The distance should be selected so that background ambient sound levels are at least 10 decibels lower than the measured sound levels. Carefully note the distance used for the measurements. Table 7 can be used to adjust the measured sound levels to a standard 15-metre (50 feet) distance. If measurements are made at distances from the equipment less than twice the equipment major dimension, near field effects can result in questionable results. Therefore, this situation should be avoided. The following alternative can be used.

2. Measurements of the source and of the background ambient sound levels are made at the 15-metre (50 feet) distance. Corrections are applied to the measured sound levels in accordance with Table 8 if the background ambient sound level is from 3 to 10 decibels below the measured sound level. If the background ambient sound level is 0 to 3 decibels below the measured sound levels, measurements closer to the source should be made, being aware of the near field effects described in Option 1 above.

7.8 USE OF THE MEASURED EQUIPMENT SOUND LEVELS

Equipment sound level measurements can be used to predict construction site sound levels. This requires knowledge of each equipment's

- sound level
- work cycle
- distance from receptor

FHWA Document, "Special Report - Highway Construction Noise - Measurement, Prediction, and Mitigation", presents techniques for calculating construction site noise levels.

TABLE 7

ADJUSTMENTS FOR MEASUREMENTS MADE AT DISTANCES OTHER THAN 15 METRES

Distance		Correction to be Added, dB	
Metres	Feet	Hard Site	Soft Site
10		-3.5	-3.5
11		-2.5	-2.5
12	40	-2	-2
13		-1	-1
14		- .5	- .5
15	50	0	0
16		.5	.5
17		1	1
18	60	1.5	1.5
19		2	2
20		2.5	3.0
21	70	3	3.5
22		3.5	4.0
23		4	4.5
24	80	4	5.0
25		4.5	6.0

TABLE 8

CORRECTION FACTORS FOR BACKGROUND AMBIENT SOUND LEVELS

$$L_s = 10 \log_{10} [10^{L_p/10} - 10^{L_o/10}]$$

L_s is stationary source sound level contribution

L_p is measured sound level with source operating

L_o is background sound level with source not operating

Difference between L_p and L_o	Subtract values from L_p to get L_s
0	*
1	*
2	*
3	3.0
4	2.5
5	2.0
6	1.5
7	1.0
8	1.0
9	0.5
10	0.5

*Cannot be determined. Background levels must be lower.

8.0 BUILDING NOISE REDUCTION MEASUREMENT PROCEDURES

8.1 PURPOSE

This section presents two techniques for measuring the noise reduction performance of building construction. In one technique, road traffic is used as a noise source. An alternate procedure utilizes a loudspeaker as a source when traffic noise levels are not sufficiently high (e.g., inside and outside of the structure, highway noise must be at least 10 dB above sound levels due to other sources). The values of noise reduction derived by the two methods may not always correspond to each other, due to different angular distributions in the incident sound fields.

These techniques reflect the latest thinking of the ISO and ASTM committees studying the subject regarding exterior microphone placement. In this, and other ways, these techniques will differ from previously recommended practices.[1]

8.2 INSTRUMENTATION

The procedures require:

- Sound Level Meter (Type 1) - 2
- Sound Level Calibrator
- Wind Speed Indicator
- Sling Psychrometer (optional)
- Tripods-2
- Microphone Cables-2 (optional)
- Data Sheets
- Windscreens-2

If an artificial sound source is used, the following additional equipement are required:

- A power amplifier with sufficient power to produce A-weighted sound levels at least 10 decibels above background ambient sound levels at exterior and interior locations without clipping the wave forms.

- A sound source. Acceptable choices are a tape recording or an electronically generated noise spectrum which is similar to typical traffic noise. This spectrum should be flat, from 31.5 Hz to 500 Hz, and decrease at six decibels per octave from 500 Hz to 4000 Hz (see Figure 25).

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[1] "Insulation of Buildings Against Highway Noise", FHWA TS-77-202.

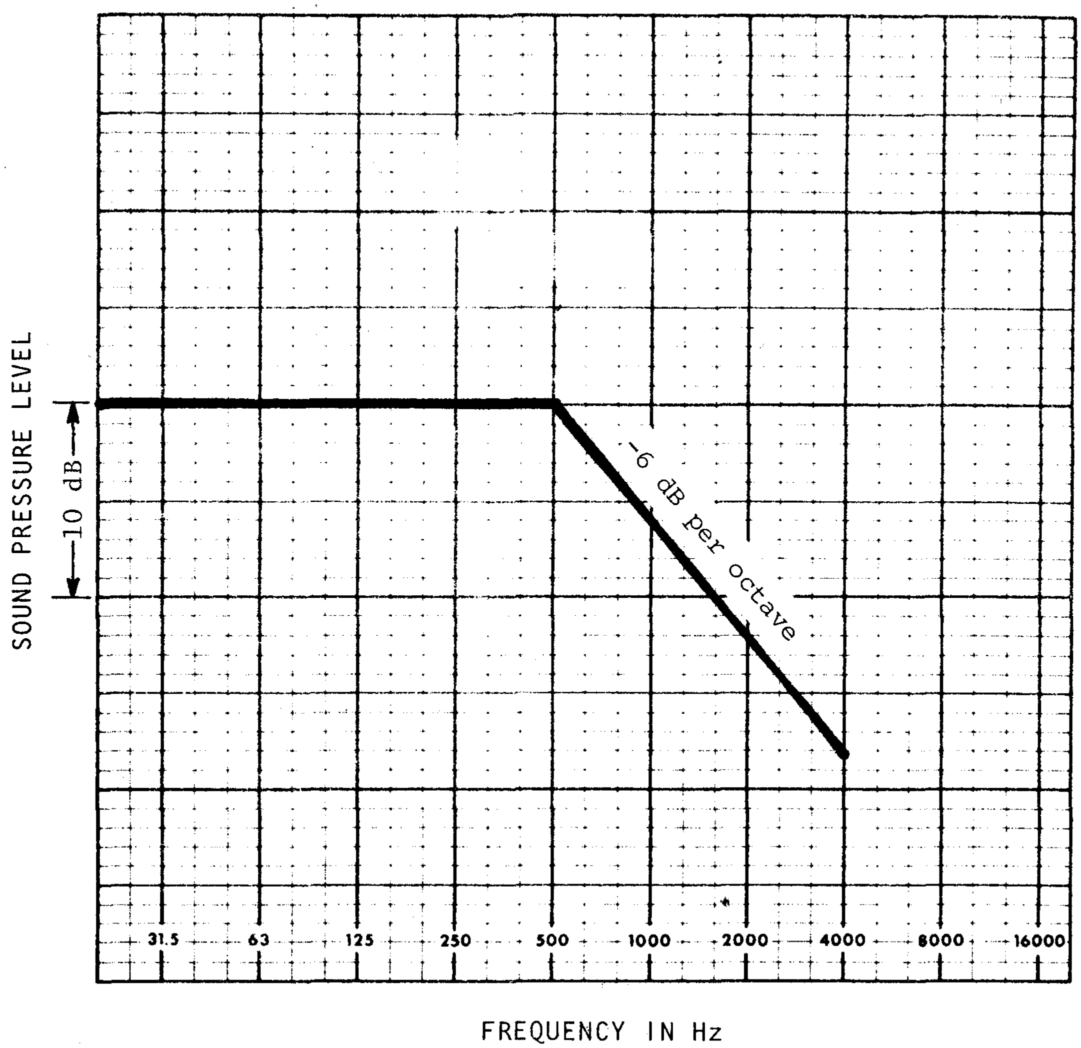

Figure 25. Artificial Sound Source Sound Pressure Level Spectrum

- One loudspeaker, enclosed except for its radiating surface. The loudspeaker's directional characteristics should be such that a 2000 Hz signal measured at 45 degrees from a perpendicular to the face of the speaker is no more than six decibels below the level measured at the same distance on the perpendicular axis. The loudspeaker should produce sound levels at least 10 decibels above the background ambient sound levels inside and outside of the structure being studied. Commercial quality loudspeakers meeting these specifications are readily available. Equipment specifications should be carefully examined to make certain that the equipment is properly chosen.

- A 120 volt A.C. power supply may also be required.

8.3 PERSONNEL

The techniques require two persons. With traffic as a noise source, two simultaneous measurements are required (inside and outside of the building). With an artificial constant noise source, one person makes the measurements while the other operates the amplification equipment.

8.4 MEASUREMENT LOCATIONS

8.4.1 Traffic Noise Source

Measurements are made simultaneously inside and outside the structure.

8.4.1.1 Interior Measurements

Locate the microphone at a point in the room where people would be impacted by the noise (above the chair, desk, or bed, for example). Do not place the microphone within 1 metre (3.5 feet) of a wall. It is very important to make measurements in the room in its typically furnished condition. Even still, levels can vary from point to point in the room. It may be necessary to make measurements at several different "sensitive" points in the room and average the resulting noise reduction. If windows will

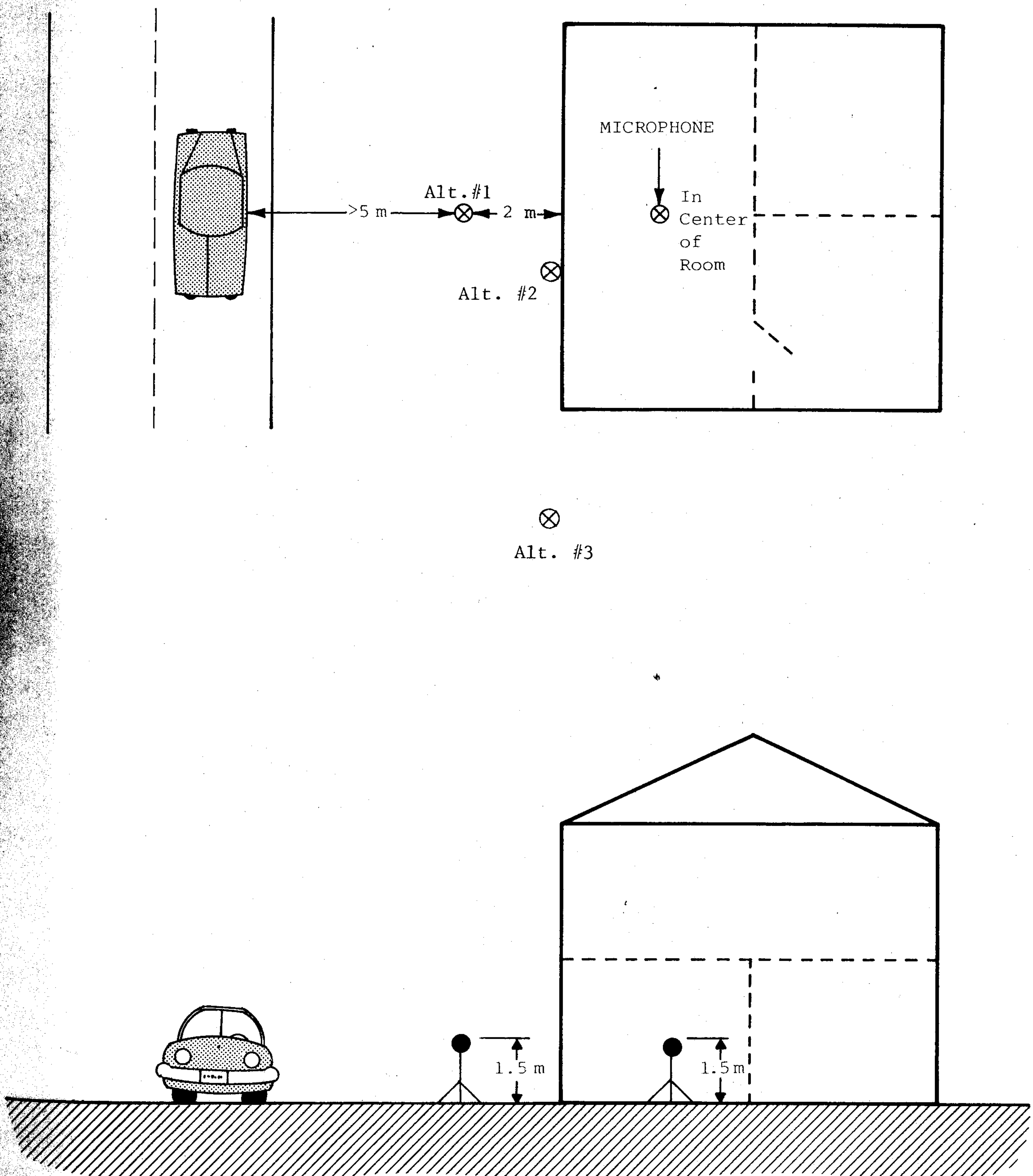

FIGURE 26. LOCATION OF INTERIOR AND EXTERIOR MICROPHONES FOR MEASUREMENTS USING TRAFFIC NOISE

be open during the portions of the year, they should be left open for the test (closed window levels may also be of interest, however, for comparison purposes).

8.4.1.2. Exterior Measurements

There are three possible positions for the exterior microphone as shown in Figure 26. Each position has its advantages and disadvantages, with its level being affected differently by sound reflections. The final noise reductions, however, are generally comparable. Pick the positions best suited to the site.

Point 1: Two metres (6.6 feet) from the outermost portion of the wall, at a point opposite the middle of the wall, at a height of 1.5 metres. This set-up is easily done, but may experience sound wave interference patterns and is not recommended if the building is within 7.5 metres (25 feet) of the road.

Point 2: Directly touching the wall, without a windscreen, pointing up, at a height of 1.5 metres. This setup is somewhat tricky to do and would not be good on windy days. It is, however, the most repeatable regarding sound pressure buildup due to reflections.

Point 3: Three metres (10 feet) from the side of the building, at the same distance from the road as the front wall, at a height of 1.5 metres. This set-up must be carefully done so that the microphone is not shielded from the road by the building or influenced by noise sources behind the building.

8.4.2 Artificial Sound Source

Measurements are made inside the structure and at an outdoor location where reflections cannot affect measurements. The microphone should be located outdoors at an equivalent distance to the artificial source as the indoor microphone position (see Figure 27).

8.4.2.1 Interior Measurements

Locate the microphone at the same position or positions that were used for the traffic noise source (see Section 8.4.1.1).

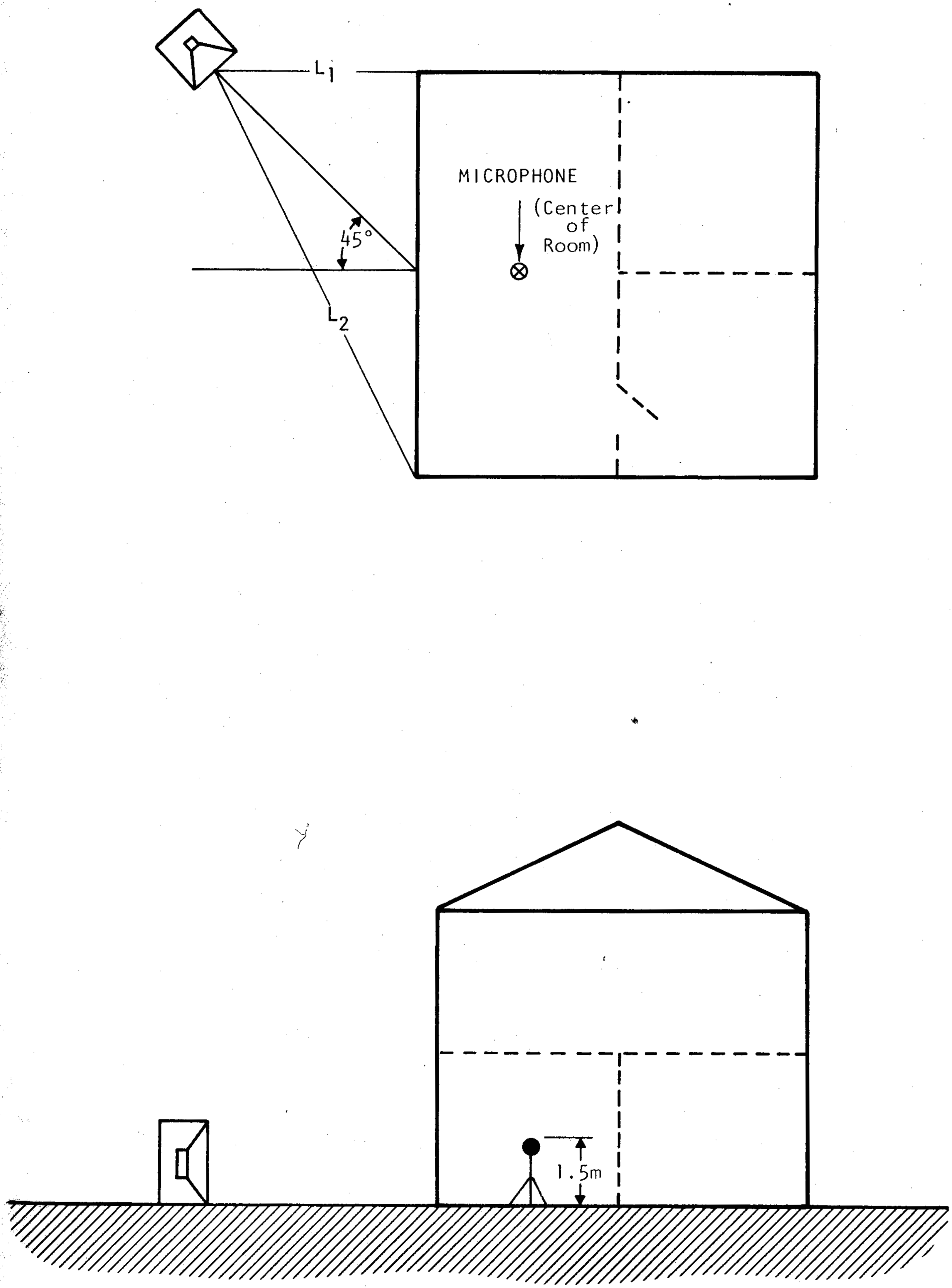

FIGURE 27. LOCATION OF INTERIOR MICROPHONE AND LOUDSPEAKER FOR MEASUREMENTS USING ARTIFICIAL SOUND SOURCE

PROJECT ____________________ DATE ____________________

LOCATION ____________________ ENGINEER ____________________

SKETCH OF MEASUREMENT LOCATION

□ TRAFFIC NOISE SOURCE □ ARTIFICIAL NOISE SOURCE

Exterior Microphone to Road Distance (D_1) ____________ metres

Interior Microphone to Road Distance (D_2) ____________ metres

SLM #1 __________ S/N __________ SLM #2 __________ S/N __________

CALIBRATOR #1 __________ S/N __________ CALIBRATOR #2 __________ S/N __________

MICROPHONE #1 __________ S/N __________ MICROPHONE #2 __________ S/N __________

CALIBRATION __________ dB(pretest) CALIBRATION __________ dB(pretest)

__________ dB(post test) __________ dB(post test)

LOUDSPEAKER, S/N __________ AMPLIFIER, S/N __________

SOUND SOURCE, S/N __________ ORIENTATION __________

L_{eq} or L_{10} (exterior) __________ dB - __________ = __________ dB

Uncorrected Reflection Adj. Corrected

L_{eq} or L_{10} (interior) - __________ dB

Noise Reduction __________ dB

FIGURE 28. SAMPLE DATA SHEET FOR BUILDING CONSTRUCTION NOISE REDUCTION

8.4.2.2 Exterior Measurements

To avoid outdoor measurements being affected by reflecting surfaces, select a measurement location where the loudspeaker and the microphone can be arranged in the same relative positions as interior measurements but away from the building being studied and other reflective surfaces. Other outdoor environmental features should be similar.

The microphone should be located at the distance and angle from the loudspeaker corresponding to the distance and angle from the loudspeaker at which the interior measurement position was located. (See Section 8.5.2 for the proper orientation of the loudspeaker.)

8.5 MEASUREMENT PROCEDURE

8.5.1 Traffic Noise Source

1. Prepare a sketch of the site on an appropriate data sheet (an example is given in Figure 28).

2. Set the sound level meter to "slow" response and A-weighting.

3. Begin interior and exterior measurements simultaneously.

4. Sample the sound level at both locations at the same time using one of the techniques described in "Existing/ Traffic Sound Level Measurement Procedures" (Chapter 3.0).

5. Record the interior or exterior L_{eq} or L_{10}* on the data sheet.

8.5.2 Artificial Noise Source

1. Prepare a sketch of the site on an appropriate data sheet.

2. Locate the loudspeaker so that the following requirements are fulfilled. The source should be far enough from the wall so that the ratio of the distances to nearest and farthest parts of the test surfaces is no more than two-to-one (see Figure 27). The loudspeaker is located so that the angle of incidence between the normal from the facade mid-point and the line joining the source to the mid-point is 45 degrees (see Figure 28). If conditions permit additional measurements should be made at 15 degrees, 30 degrees, and 60 degrees, and the results averaged. If one angle is used, it should be 45 degrees.

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*Either L_{eq} or L_{10} can be used, although L_{eq} is preferred.

3. At the indoor location, set the sound level meter to "slow" response and A-weighting.

4. Measure the interior sound level.

5. Move the loudspeaker and microphone to the outdoor free field positions as described in Section 8.4.2.2.

6. Measure the exterior sound level with the meter set to "slow" response and A-weighting.

8.6 COMPUTATION PROCEDURE

8.6.1 Traffic Noise Source

1. For an exterior microphone at point 1 (2 metres from wall), compute the building noise reduction (NR) as follows:

NR = Exterior Level - Interior Level - 3 dBA

The 3 dBA adjustment is for the approximate doubling of sound intensity (I) occuring at point 1 from reflections off the wall (10 log (2I/I)).

2. For an exterior microphone at point 2 (against the wall):

NR = Exterior Level - Interior Level - 5 dBA

Theoretically, the pressure of a sound wave doubles when it impacts against a hard surface. Doubling the sound pressure (p) increases the sound pressure level by 6dBA (20 log (2p/p)). Practically, the increase is only about 5dBA, which is the adjustment used here.

3. For an exterior microphone at point 3 (alongside the building):

NR = Exterior Level - Interior Level (dBA)

8.6.2 Artificial Noise Source

The difference in decibels between the indoor and outdoor data acquired as described in Section 8.5.2 is the building noise reduction.

9.0 WORKER NOISE EXPOSURE MEASUREMENT PROCEDURES*

9.1 PURPOSE

The procedure presented below may be used to measure worker noise exposure. Toll plaza and tunnel employees, highway maintenance and repair crews, highway inspectors, and laboratory personnel may be exposed to significantly high sound levels. Under Occupational Safety and Health Administration (OSHA) regulations, a worker's noise exposure is limited to A-weighted sound levels of 90 dB for an eight-hour workday. A sound level-time tradeoff of five decibels for each halving of exposure time is incorporated in the law. The upper limit for allowable exposure is 115 decibels. In addition, exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure level. Table 1 presents the exposure-sound level relationship.

When an individual is exposed to a variable sound level, the total noise exposure is computed as:

$$(C_1/T_1) + (C_2/T_2) + \ldots(C_n/T_n) = \sum_{i=1}^{n} (C_i/T_i) \qquad (1)$$

where C_i is the time exposed to a sound level, and

T_i is the total exposure time allowed for that sound level.

If this sum, called the noise dose, exceeds one, the combined sound level exceeds the regulation limits.

Two methods are presented for determining worker noise exposure. The recommended method is the use of personal noise dosimeters. A second method, using a sound level meter and time and motion studies, is also acceptable.

9.2 NOISE DOSIMETERS

A noise dosimeter is a small instrument which can be placed in a worker's shirt pocket. It has a microphone which can clip onto a shirt or fit on a helmet. There are no existing standards or regulations specifically for noise dosimeters.** The A-weighting netwook used in the dosimeter should meet the American National Standards Institute standards for sound level meters. Dosimeters compute the noise dose electronically. Most models also indicate whether the worker has been exposed to an A-weighted sound level in excess of 115 dB.

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*Solely intended for in-house use. Not intended for contractor personnel.

**A proposed dosimeter specification (ANSI S1.25-197X) has not yet been adopted.

9.3 PROPER DOSIMETER USAGE

The basic steps for conducting an audio dosimeter survey are reviewed below. Before the survey begins, the individual conducting the survey should read and understand, thoroughly the manufacturer's instruction manual.

1. Check batteries and replace if necessary.

2. Check dosimeter and microphone for damage, and replace if necessary.

3. Calibrate the dosimeter before (and after) the survey. The instrument's instruction manual will normally specify the calibrator and procedure to use. If no calibration procedure is specified, the dosimeter manufacturer should be requested to supply an accurate calibration procedure.

4. Caution the wearer against conditions which may invalidate dosimeter readings:

   a. The dosimeter must be worn for the full eight-hour shift.

   b. The wearer should not talk into the microphone.

   c. The microphone should not be moved from its original position.

5. Locate the microphone where it most accurately measures the sound levels experienced by the individual. In the case of work in an open area (free field situation), the optimum microphone placement is on the subject's shoulder, parallel to the body axis. In a closed "acoustically hard" work area (reverberant field), the optimum location is the left breast pocket 90 degrees to the body axis. For typical indoor locations (semi-reverberant field), the optimum location is at the top of the shoulder oriented 90 degrees to the body axis.

6. Place a windscreen on the microphone if measurements are made in an outdoor environment.

7. Turn the instrument on.

8. Periodically visit the persons wearing dosimeters to ensure that they are being used properly.

9. Remove the dosimeter at the end of the 8-hour shift.

10. Read the dosimeter output to determine the exposure index. Note the results plus other pertinent information (e.g., name of employee, task, instrumentation, model and serial number).

11. Recalibrate the dosimeter to determine measurement validity.

If a worker remains in the same position during a workday, the dosimeter may be placed in the vicinity of the worker, instead of on his person. Care must be taken to prevent shielding of the microphone from noise sources by people, walls, or any other obstructions.

9.4 TIME AND MOTION STUDIES

An alternative to the use of dosimeters is worker time-motion studies* (log of worker activities during the day) and sound level measurements at worker stations used during the work shift. The employee is followed throughout the workday and the sound level and time spent is measured at each location. The noise exposure is calculated using this information and Equation (1) for noise dose.

A Type 1 sound level meter should be used for these measurements. It should be calibrated at intervals not to exceed two hours. Manufacturers' instructions should be followed for the proper use of the equipment.

9.5 DATA LOGGERS

Dosimeter-size measurement devices are now on the market that accumulate and store noise level exposure data in one-minute increments for an entire workday. At the end of the day, the data is read by a second device that then prints a record of the 1-minute L_{eq}'s as well as cumulative values for L_{eq} and OSHA noise doses.

*A Bibliography for time-motion studies is included in Appendix A.

APPENDIX A

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APPENDIX B

TECHNIQUES FOR DETERMINING PEOPLE'S PERCEPTION OF NOISE BARRIER EFFECTIVENESS*

1. Introduction

While the physical effectiveness of a noise barrier in reducing traffic noise is important, a more meaningful measure of noise barrier performance is people's perception of how well it works. While it is obvious that perceptions will be influenced by the insertion loss provided by the barrier, other factors appear to be equally important. Preliminary work has shown that perception of barrier effectiveness is influenced by such factors as:

a. perception of the seriousness of the traffic noise problem before the barrier is built;

b. the skill with which the State Highway Agency (SHA) dealt with the people in resolving the traffic noise problem;

c. the appearance of the barrier; and

d. the view of the highway and its surroundings after the barrier is built.

In some instances, barriers with excellent insertion losses have been rated as ineffective by the people protected by them. In other instances, barriers which provide little acoustic protection have been rated as very effective.

Determination of perception of noise barrier effectiveness requires that people be surveyed. While routinely used procedures have not yet been developed for surveying people's perception, some useful preliminary work has been done. This appendix provides general information on who and when to survey, two techniques for conducting surveys, and example questionnaires.

2. Who to Survey Probably the only meaningful way of evaluating people's perception of noise barrier effectiveness is to establish their perception of the noise impact before the barrier is built and to establish their perception of the noise impact again after the barrier is built.

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*This is reproduced, with minor editing, from Part II of Determination of Noise Barrier Effectiveness, FHWA Report No. FHWA-OEP/HEV-80-1, published in June 1980.

Consequently, the survey site must be located on an existing highway and both "before" and "after" surveys are required.

If the individual responding to the "after" survey questionnaire is different from the individual responding to the "before" survey questionnaire, there is likelihood for considerable error in the results. For this reason, every possible effort should be made to assure that the same person who answered the "before" questionnaire answers the "after" questionnaire.

People who live inside a zone that will receive an insertion loss of 3 dBA or less should not be included in the survey. This is because most people will have considerable difficulty in perceiving noise reduction of less than 3 dBA. Even people who can perceive such a small change will probably forget it. A person's sound level memory is very short. Regardless of the boundaries selected for the survey, every effort should be made to reach 100 percent of the households in the survey area. This is because the population protected by a noise barrier is usually quite small. This type of situation is not well suited to statistical sampling techniques.

3. When to Survey

It has already been indicated that demonstration of people's perception of noise barrier effectiveness will require "before" and "after" surveys. If the survey is to be meaningful, the perception of the noise barrier effectiveness must be correlated with the measured physical insertion loss of the barrier. This means that "before" and "after" noise levels must be available for each set of interviews.

In addition, the "after" questionnaire must obtain information sufficiently similar to the "before" questionnaire so that rational conclusions can be drawn. This will probably require that the "after" survey be conducted at the same time of year as the "before" survey to account for any seasonal activities such as recreational use of backyards.

Finally, the "after" survey should be conducted as soon as possible after the barrier is built. This will minimize the reduction in sample size due to people moving. More importantly, it will help avoid distortions due to a change with time in people's perception of the mitigation of traffic noise by the noise barrier.

4. Survey Techniques

The FHWA has reviewed several questionnaires and the experiences of several SHA's and others in determining people's perception of noise barrier effectiveness. Based upon this review, two survey techniques have been identified that appear to adequately address the issues--home/telephone interviews and mail interviews. Both techniques require the use of "before" and "after" questionnaires.

a. Home/Telephone Interviews. Home/telephone interviews are more expensive to conduct than mail interviews. Further, home interviews require trained interviewers. With home/telephone interviews, it is usually possible to correct misunderstood questions, an opportunity which is not available on mail-back questionnaires. In addition, home/telephone interviews have the capability of overcoming language and illiteracy barriers. The major advantage of home/telephone interviews is that they have a very high response rate.

b. Mail Interviews. Since the person surveyed is not contacted directly, the choice of wording in the mail-back questionnaire is of extreme importance. The California Department of Transportation (CALTRANS) uses a mail-back questionnaire and has experienced a response rate of about 50 percent for the "before" barrier questionnaire. There is no response rate information from it on the "after" barrier questionnaire since it has not yet been used on a highway project. The major advantage of mail-back interviews is low cost.

5. Questionnaires

To give reliable results of people's perception, the "before" and "after" evaluations must be based upon structured questionnaires. The use of structured questionnaires guarantees that each household will be asked the same questions. The following questionnaires were developed by CALTRANS and by Dr. F. L. Hall of McMaster University.* Although neither of the questionnaires has yet been tested, it appears that they contain the essential information. The questionnaires can be modified to meet the specific needs and conditions of one's own survey. The CALTRANS questionnaire was developed for use in mail interviews. Dr. Hall's questionnaire is to be used only for home/telephone interviews.

*McMaster University, Department of Civil Engineering
1280 Main Street West, Hamilton, Ontario, Canada L8S 4L7.

3. How often do you or members of your family use your yard for relaxing or playing during warm weather?

_____ every day
_____ several times a week
_____ once or twice a week
_____ less than once a week

4. a. Have you regularly been forced to close your windows because of traffic noise?

_____ Yes   _____No

b. [If yes:] How often would you say this happens?

_____ once or twice a month
_____ once a week
_____ several times a week
_____ most of the time

5. What effect do you think the noise barrier has had on the traffic noise you hear while you are at home?

considerable reduction in noise	moderate reduction in noise	slight reduction in noise	no effect	slight increase in noise	moderate increase in noise
_____	_____	_____	_____	_____	_____

considerable increase in noise

_____

6. What effect do you feel the barrier and its associated landscaping have had on the general appearance of this residential area?

considerable improvement	moderate improvement	slight improvement	no effect	slight deter-ioration
___	___	___	___	___

moderate deter-ioration	considerable deterioration
___	___

7. Are there any suggestions you have regarding noise barriers we may build in the future in other areas to improve their appearance or effectiveness?

Thank you for your assistance.

Suggested Questionnaire for Post-Construction Survey for Barrier Effectiveness*

Hello. I am from the (State) Department of Transportation. Last year, we spoke to a person in your household about problems that may be affecting people who live near highways. The person we spoke to was [describe, from Q. 10 data]. Is he/she available? [If the appropriate person is not available, try to find the best time to call back when he/she will be available.]

Now that we have completed our work on the project in this area, we would like to know how the highway is affecting people here.

1. Here is a list of problems which were mentioned in last year's survey. Please rate each of them with regard to how great a problem it is now for you and your family while you are at home.

   [Read question stem at left, and each response as written.]

	not a problem at all	a minor problem	a moderate problem	a major problem or	an extremely bad problem
Is highway dust and dirt	______	______	______	______	______
Is headlight glare	______	______	______	______	______
Is litter from vehicles	______	______	______	______	______

*Reprinted with permission from Dr. F. L. Hall, McMaster University, Ontario, Canada

	not a problem at all	a minor problem	a moderate problem	a major problem	an extremely bad problem?
Is highway noise	_____	_____	_____	_____	_____
Is vibration from the road	_____	_____	_____	_____	_____
Are fumes from the road	_____	_____	_____	_____	_____
Are there any other road-related problems?	_____	_____	_____	_____	_____
Name? Severity	_____	_____	_____	_____	_____

2. How often does the noise from the road interrupt you during any of the following activities?

	never	only occasionally	several times per week	several times per day	almost all the time
conversation indoors	_____	_____	_____	_____	_____
conversation outdoors	_____	_____	_____	_____	_____
use of telephone	_____	_____	_____	_____	_____
watching television	_____	_____	_____	_____	_____
relaxing indoors	_____	_____	_____	_____	_____
relaxing outdoors	_____	_____	_____	_____	_____
sleeping	_____	_____	_____	_____	_____

	never	only occasion-ally	several times per week	several times per day	almost all the time
relaxing outdoors	_____	_____	_______	_______	_______
sleeping	_____	_____	_______	_______	_______

4. How often do you or members of your family use your yard for relaxing or playing during warm weather?

_____ every day
_____ several times a week
_____ once or twice a week
_____ less than once a week

5. a. Have you regularly been forced to close your windows because of traffic noise?

_____Yes No_____

b. [If yes:] How often would you say this happens?

_____ once or twice a month
_____ once a week
_____ several times a week
_____ most of the time

6. Have you made any modifications to your house or yard because of the traffic noise? Yes_____ No_____ [If yes:] What?

7. Are there any other problems associated with living near the highway which you would like to mention? Yes _____ No _____

[List responses]

8. How long have you lived at this address? ________________

9. Would you or other members of your household be interested in attending a public meeting about possible solutions to some of the problems mentioned earlier? Yes _____ No ______

10. And now, a few questions about yourself to assist us in contacting you, personally, for a possible follow-up survey.

    [If name is offered by respondent at this point, write it down, and do not ask remaining items.]

    a. Sex [do not ask] male _____ female _____
    b. How old are you? _____years
    c. What is your main occupation (that is, what sort of work do you do)?

    ____

Thank you for your assistance.

Suggested Questionnaire for Pre-Construction Survey for Barrier Effectiveness*

Hello. I am from the (State) Department of Transportation, which is concerned about problems that may be affecting people such as yourself who live near to major highways. We are actively considering solutions to some of the problems in your neighborhood. We would very much appreciate a few minutes of your time to answer the following questions.

1. What are the most important things you dislike about living in this area?

   [Notes to interviewer: write down the exact thing(s) said, for later coding. Probe slightly: "Is there anything else which you dislike?" Focus on the residential environment of a few surrounding blocks.] [Whether or not road-related problems are mentioned, use the following transition phrase to move to the next question:]

   The Department of Transportation is particularly interested in things you dislike which may be related to living near a highway.

2. Here is a list of problems which other people have mentioned. Please rate each of them with regard to how great a problem it is for you and your family while you are at home. [Read question stem at left, and each response as written.]

*Reprinted with permission from Dr. F. L. Hall, McMaster University, Ontario, Canada

	not a problem at all	a minor problem	a moderate problem	a major problem	an extremely bad problem
Is highway dust and dirt	____	____	____	____	____
Is headlight glare	____	____	____	____	____
Is litter from vehicles	____	____	____	____	____
Is highway noise	____	____	____	____	____
Is vibration from the road	____	____	____	____	____
Are fumes from the road	____	____	____	____	____
Are there any other road-related problems?	____	____	____	____	____

Name? Severity?

3. How often does the noise from the road interrupt you during any of the following activities?

	never	only occasionally	several times per week	several times per day	almost all the time
conversation indoors	____	____	____	____	____
conversation outdoors	____	____	____	____	____
use of telephone	____	____	____	____	____
watching TV	____	____	____	____	____
relaxing indoors	____	____	____	____	____

California Department of Transportation
Transportation Laboratory

QUESTIONNAIRE *

1. Has the noise in your neighborhood environment changed since the freeway noise barrier was built?

☐ much less noise ☐ less noise ☐ same ☐ noisier

2. Has your awareness or notice of the freeway noise changed since the noise barrier was built?

☐ same ☐ somewhat less aware ☐ much less aware

3. Check those items which may have improved since the building of the barrier.

☐ sleep ☐ ease of conversation ☐ use of TV/stereo/radio

☐ use of telephone ☐ reading ☐ use of yard ☐ relaxation

☐ general peacefulness other ______________________

4. Now that a noise barrier has been erected, how do you rank the annoyance of the following freeway features? (Put in numerical order with 1 being most annoying.)

____ air pollution ____ total traffic noise ____ congestion ____ truck noise

____ accidents ____ dust/dirt other ______________________

5. How do you rank the annoyance of the following environmental noises now that there is a barrier? (Put in numerical order with 1 being most annoying.)

____ neighborhood noises (children, stereos, dogs, lawnmowers, etc.)

____ airplanes ____ freeway noise ____ sirens ____ city street noise

____ industrial other ______________________

6. Which best describes your neighborhood now?

☐ very quiet ☐ quiet ☐ a little noisy ☐ noisy ☐ very noisy

*After Noise Barrier Construction Questionnaire

7. Do you find the barrier acceptable in appearance?

☐ very acceptable ☐ O.K. ☐ no

If not, why? ____________________

8. Has the barrier met your expectations in improving the neighborhood?

☐ yes ☐ no ☐ undecided

If not, in what way? ____________________

9. Do the advantages of the barrier outweigh the disadvantages?

☐ yes ☐ no

10. How do you feel about the barrier overall?

☐ like ☐ dislike ☐ neither (neutral)

11. Did you respond to the questionnaire sent before the barrier was constructed?

☐ yes ☐ no

12. Other comments ____________________

____

____

____

____

____

NOTE: If you need more information or clarification of questions, please call (916) 739-2400 collect, and ask for Mr. Mas Hatano or leave a message for him.

CALIFORNIA DEPARTMENT OF TRANSPORTATION
Transportation Laboratory
QUESTIONNAIRE *

1. How many persons live in your home? ____________

2. Was the freeway here when you moved into your present home?
   Yes ☐ No ☐

3. What is the family gross income? less than $10,000/yr.
   $10,000-15,000 ☐ $15,000-20,000 ☐ $20,000-30,000 ☐ over $30,000 ☐

4. If there are annoying features in your neighborhood environment, list them using "1" for most annoying, "2" for the next most annoying, etc.

   1.________ 2.________ 3.________ 4.________ 5.________

5. How do you rank the following freeway features in annoyance? (Use "1" for the most annoying, "2" for the next most annoying, etc.)

   ___air pollution ___total traffic noise ___congestion
   ___truck noise ___accidents ___dust/dirt ___sirens

6. How do you consider the present noise environment in your neighborhood?

   quiet ☐ a little noisy ☐ noisy ☐ very noisy ☐

7. Number the following noises in your neighborhood in order of their annoyance,(use "1" for the most annoying, "2" for the next most annoying, etc.)

   ___non-traffic noise (stereos, TV, radio, children, power equipment, animals, etc.)
   ___sirens ___airplanes ___city street noise
   ___neighbors ___freeway noise ___industrial noise

8. Does the freeway noise interfere with your day-to-day activities?
   No ☐ Yes ☐

   If yes, what activities? (You may check more than one.)
   TV/radio/stereo ☐ telephone ☐ reading ☐ sleeping ☐
   conversation indoors ☐ conversation outdoors ☐
   others(list)____________

9. Does noise keep you awake at night?
   often ☐ occasionally ☐ rarely ☐
   If often, what noises?____________

10. Are you ever awakened from your sleep by outside noises?
    never ☐ rarely ☐ once a week ☐ more than once a week ☐

11. Has the neighborhood noise environment influenced the outdoor use of your property?
    No ☐ Yes ☐
    If yes, is it used more ☐ less ☐ much less ☐

12. Has your awareness or notice of the freeway noise changed since you first moved in (or when the freeway was first built)?
    much more aware ☐ somewhat more ☐ same ☐ somewhat less ☐
    much less ☐

13. Can you see the freeway traffic from your home? clear view ☐
    partially obstructed view ☐ view obstructed ☐
    If obstructed, by what? trees or shrubs ☐ ground features ☐
    buildings or houses ☐

14. Do you believe trees or shrubs would effectively quiet the noise?
    yes ☐ no ☐ don't know ☐

15. What is your present attitude toward a noise barrier planned for construction on the freeway right-of-way adjoining your neighborhood?
    favor ☐ object ☐ undecided ☐

16. After a noise barrier is built, what change in the noise do you think will it make?
    increase ☐ no change ☐ decrease a little ☐ decrease a lot ☐

17. After a noise barrier is built what do you believe would be:
    advantages(list)____________
    disadvantages(list)____________

18. Do you believe the advantages outweigh the disadvantages?
    yes ☐ no ☐

19. What material for a noise barrier would you prefer from a visual point of view?
    (Number in order of preference, using "1" to indicate highest preference, "2" next highest preference, etc.)
    no preference ___ concrete ___ earth ___ brick ___ wood ___
    concrete block ___ metal ___ stucco ___

20. Did you attend the informal public meeting held ____________ on the construction of noise barriers in your neighborhood?
    yes ☐ no ☐

21. Would you like to receive a summary of the questionnaire information submitted from your community?
    yes ☐ no ☐

    If yes, address
    Name(optional) ____________
    Street ____________
    City, zip code ____________
    Telephone No. ____________

739-2400

Note: If you need more information or clarification of questions, please call (916) ~~444-4800~~ collect, and ask for Mr. Mas Hatano or leave a message for him.

Rev. 8/79

*Before Noise Barrier Construction Questionnaire

STATE OF CALIFORNIA—BUSINESS AND TRANSPORTATION AGENCY EDMUND G. BROWN JR., Governor

DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES AND ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY
5900 FOLSOM BLVD., P.O. BOX 19128
SACRAMENTO, CA 95819

Dear Resident:*

Prior to the erection of the Caltrans noise barrier along Highway 17, you and other residents in the first four rows of homes adjacent to the freeway were asked to respond to a questionnaire regarding neighborhood noise conditions. Now that the noise barrier is constructed, we would like to evaluate its effectiveness. That is why we also need your response to the attached follow-up questionnaire.

This questionnaire should be filled out by the same person who filled out the first questionnaire.

Your cooperation is greatly appreciated.

Very truly yours,

NEAL ANDERSEN, P.E.
Chief, Office of Transportation Laboratory

By Earl Shirley

Earl Shirley, P.E.
Chief, Enviro-Chemical Branch

Attachment

*Letter to Resident After Noise Barrier Construction

STATE OF CALIFORNIA—BUSINESS AND TRANSPORTATION AGENCY · EDMUND G. BROWN JR., Governor

DEPARTMENT OF TRANSPORTATION
DIVISION OF STRUCTURES AND ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY
P.O. BOX 19128
SACRAMENTO, CA 95819

Dear Resident:*

The California Department of Transportation (Caltrans) is responsible for providing effective transportation facilities in the State. Our goal is to do so in harmony with the environmental and social outlooks of the people. To accomplish this, we have to know how these outlooks vary with each community. That's the purpose of this letter to you and the enclosed questionnaire.

To achieve our goal, we need to receive information from you as well as others. It is important to us to have your personal response because the more information we receive, the better guide it is for planning and carrying out transportation projects in your community in a way that will satisfy you and your neighbors.

We realize that one hundred per cent satisfaction for all citizens is unlikely because people do have different outlooks. This is another reason it is so important to receive your personal response. We would like to provide a result that fits as well as possible with everyone's expressions of fact, judgment and opinion. Your cooperation is respectfully solicited and urged.

We would like the questionnaire to be filled out by the head or heads of your household. Items included relate to family history, environment, activities and normal living habits. We found in other studies that having some information on people's backgrounds makes the analysis and understanding of the preferences and expectations they express more reliable. Reliability is important because all the information we receive will be analyzed and reflected in our future projects.

Some questions ask for your judgment or opinion, while others simply call for recording of facts. Most questions require only a check in the box which fits your answer best; a few questions may be checked in more than one box; and a few others require a short answer. It's better if responses can represent the whole

*Letter to Resident Before Noise Barrier Construction family's views, if possible.

We emphasize that your response to this questionnaire will not have any bearing on the noise barrier to be constructed in your area. As a result of unanimous community support, design of the barrier project is nearing completion and construction should begin by late Summer of 1979.

We will hold your responses anonymous and treat them confidentially in every respect.

In case you feel the need for more information or clarification, please call Mas Hatano (916-444-4800), collect.

We will deeply appreciate your early response.

Very truly yours,

NEAL ANDERSEN, P.E.
Chief, Office of Transportation Laboratory

By Earl Shirley

Earl Shirley, P.E.
Chief, Enviro-Chemical Branch

P.S. If you would like to have a summary of the findings from your community's responses, please indicate this at the end of the questionnaire.

APPENDIX C - BLANK DATA SHEET FOR EXISTING NOISE LEVEL MEASUREMENTS

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
REGION 15

NOISE MEASUREMENT DATA SHEET

NAME: ______________________________ DATE ________

PROJECT: ______________________________ TIME:

SITE: ______________________________ START ________

______________________________ END ________

RESULTS: L10 ____ + ___ - ___ L50 ______ LEQ ______

HOW TO USE: 2 X 80 = 160000

FILL IN OTHER SIDE

DBA	TOTAL		=
9		X 80	= 00 00
8		X 63	= 00 00
7		X 50	= 00 00
6		X 40	= 00 00
5		X 32	= 00 00
4		X 25	= 00 00
3		X 20	= 00 00
2		X 16	= 00 00
1		X 13	= 00 00
0		X 10	= 00 00
9		X 80	= 000
8		X 63	= 000
7		X 50	= 000
6		X 40	= 000
5		X 32	= 000
4		X 25	= 000
3		X 20	= 000
2		X 16	= 000
1		X 13	= 000
0		X 10	= 000
9		X 80	= 00
8		X 63	= 00
7		X 50	= 00
6		X 40	= 00
5		X 32	= 00
4		X 25	= 00
3		X 20	= 00
2		X 16	= 00
1		X 13	= 00
0		X 10	= 00
9		X 80	= 0
8		X 63	= 0
7		X 50	= 0
6		X 40	= 0
5		X 32	= 0
4		X 25	= 0
3		X 20	= 0
2		X 16	= 0
1		X 13	= 0
0		X 10	= 0
9		X 80	=
8		X 63	=
7		X 50	=
6		X 40	=
5		X 32	=
4		X 25	=
3		X 20	=
2		X 16	=
1		X 13	=
0		X 10	=

EQUALS 100,000

EQUALS 10,000

EQUALS 1,000

EQUALS 100

DBA 10 20 30 40 50

NUMBER OF SAMPLES

TOTAL ______ DIVIDED INTO TOTAL ______

EQUALS ______

EQUIPMENT: METER ____________ CALIBRATOR ____________

CALIBRATION: START ____________ DB END ____________ DB

RESPONSE: ___FAST ___ SLOW ___A-WEIGHTING ___BATTERY CHECK

WEATHER DATA____

TRAFFIC DATA			
ROAD			
AUTOS			
MED. TRKS.			
HVY. TRKS.			
DURATION			

CRITERION: ± 3DB			
NUMBER OF SAMPLES	UPPER LIMIT	L10	LOWER LIMIT
50	1ST	5TH	10TH
100	5TH	10TH	17TH
150	8TH	15TH	23RD
200	12TH	20TH	29TH

SITE SKETCH

BACKGROUND NOISE ____

MAJOR SOURCES ____

UNUSUAL EVENTS ____

OTHER NOTES ____

*U.S. GOVERNMENT PRINTING OFFICE: 341-428/1327

FHWA-RD-77-108
FHWA HIGHWAY TRAFFIC NOISE PREDICTION MODEL

HIGHWAY NOISE

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

FOREWORD

This report presents the FHWA method for predicting equivalent sound levels generated by constant speed highway traffic and will be of interest to highway traffic noise specialists involved in the prediction and assessment of noise impacts due to traffic.

Research in highway noise and vibrations is included in the Federally Coordinated Program of Highway Research and Development as Task 5 of Project 3F, "Pollution Reduction and Environmental Enhancement." Dr. Howard Jongedyk is Project Manager and Dr. Timothy M. Barry is the Task Manager.

This report is the result of a joint effort between the Federal Highway Administration's Offices of Research and Environmental Policy. The prediction model presented in this report is developed in a straightforward manner with numerous example problems designed to emphasize the model's important features. The model was calibrated using data collected in 1975 by the Transportation Systems Center, U.S.D.O.T.

Sufficient copies of the report are being distributed to provide a minimum of one copy to each FHWA regional office, division office, and State highway agency. Direct distribution is being made to the division offices.

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

TECHNICAL REPORT STANDARD TITLE PAGE

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16. Abstract

This report presents the FHWA method for predicting noise generated by constant speed highway traffic. The report is intended to be a users' manual as well as a reference document detailing the development, use, and limitations of the prediction method. In the main body of the report, the prediction procedure is presented in a step-by-step fashion and includes numerous example problems designed to highlight important concepts and features. For those interested in the theoretical development of the model, an extremely detailed derivation is presented in the appendices. The basis of the model is the equivalent sound level, L_{eq}, although an adjustment for conversion to L_{10} is provided. The method incorporates three classes of vehicles--automobiles, medium trucks, and heavy trucks. Adjustments for absorptive ground covers and finite length barriers are also included. Certain special topics such as nonuniform highway sites and determination of equivalent day-night levels, L_{dn}, are also included.

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PREFACE

This manual is the result of a one year joint project between the Offices of Research and Environmental Policy of the Federal Highway Administration. The objective of the project was to develop a logical, easy to use traffic noise prediction model for the highway traffic noise specialist. Reviews of past experiences with earlier prediction models show that the models have often been inadvertently misused, most often as a direct result of an incomplete understanding of the basic assumptions and limitations inherent in the models. Cookbook procedures are valuable only when the user has a clear understanding of the assumptions and limitations of the procedure. Without an understanding of these working bounds, cookbook procedures become inflexible tools.

In developing the FHWA Highway Traffic Noise Prediction Model, our objective was to synthesize a prediction procedure based on best available techniques and data, and to present the model in a logical, step by step format, clearly identifying our assumptions and pointing out the resulting limitations. Our basic approach was to separate the problem of traffic noise prediction into a series of adjustments, each of which has physical significance to the highway noise specialist. The approach allows the user to see the effects of vehicle noise emission levels, traffic volumes, distances, ground effects, etc., as individual effects related to the overall problem. At the same time, our approach allows the user to modify the basic model to meet the special requirements of highway sites or conditions not taken into account in the basic model.

The authors wish to express their sincere appreciation for the contributions of the many people who provided technical advice and assistance during the development of the model and during preparation of the manuscript. Special thanks are due Jim Kirschensteiner of the Office of Environmental Policy (FHWA) who developed the computer versions of the model appearing in Appendix D, Lynn Runt of the Office of Development (FHWA) who performed the numerical integrations, and Ms. Beverly Williams of the Office of Environmental Policy who typed the manuscript.

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THE FHWA HIGHWAY TRAFFIC NOISE PREDICTION MODEL

1.0 INTRODUCTION

The FHWA Highway Traffic Noise Prediction Model (hereafter referred to as the FHWA model), like several other prediction models, arrives at a predicted noise level through a series of adjustments to a reference sound level. In the FHWA model, the reference level is the energy mean emission level. Adjustments are then made to the reference energy mean emission level to account for traffic flows, for varying distances from the roadway, for finite length roadways, and for shielding. All of these variables are related by the following equation:

$$
\begin{aligned}
L_{eq}(h)_i = {} & (\overline{L_o})_{E_i} && \text{reference energy mean emission level} \\
& +10 \log \left(\frac{N_i \pi D_o}{S_i T}\right) && \text{traffic flow adjustment} \\
& +10 \log \left(\frac{D_o}{D}\right)^{1+\alpha} && \text{distance adjustment} \\
& +10 \log \left(\frac{\psi_\alpha(\phi_1, \phi_2)}{\pi}\right) && \text{finite roadway adjustment} \\
& +\Delta_s && \text{shielding adjustment}
\end{aligned} \qquad (1)
$$

where

$L_{eq}(h)_i$ is the hourly equivalent sound level of the ith class of vehicles.

$(\overline{L_o})_{E_i}$ is the reference energy mean emission level of the ith class of vehicles.

N_i is the number of vehicles in the ith class passing a specified point during some specified time period (1 hour).

D is the perpendicular distance, in metres, from the centerline of the traffic lane to the observer.

D_o is the reference distance at which the emission levels are measured. In the FHWA model, D_o is 15 metres. D_o is a special case of D.

S_i is the average speed of the ith class of vehicles and is measured in kilometres per hour (km/h).

T is the time period over which the equivalent sound level is computed (1 hour).

α is a site parameter whose values depend upon site conditions.

ψ is a symbol representing a function used for segment adjustments, i.e., an adjustment for finite length roadways.

Δ_s is the attenuation, in dB, provided by some type of shielding such as barriers, rows of houses, densely wooded areas, etc.

The first two lines of Equation 1 predict the equivalent sound level generated by a flow of vehicles of a single class traveling at a constant speed on an effectively infinite, flat roadway at a reference distance of 15 metres. The last three lines of Equation (1) represent adjustments that deal with the site conditions between the observer and the roadway.

Once computation of the $L_{eq}(h)_i$'s is complete, the total hourly equivalent sound level, $L_{eq}(h)$ can be determined. The $L_{eq}(h)$ is the sum of the acoustic contributions of the various classes of vehicles using the roadway. In the FHWA model, there are three classes of vehicles: automobiles (A), medium trucks (MT), and heavy trucks (HT). The three classes of vehicles will be defined in the next section. The total hourly equivalent sound level is computed as:

$$L_{eq}(h) = 10 \log \left(10^{\frac{L_{eq}(h)_A}{10}} + 10^{\frac{L_{eq}(h)_{MT}}{10}} + 10^{\frac{L_{eq}(h)_{HT}}{10}} \right). \quad (2)$$

When the hourly sound level exceeded 10% of the time, $L_{10}(h)$, is desired, an adjustment is used to convert the $L_{eq}(h)_i$ to $L_{10}(h)_i$. The total $L_{10}(h)$ is also computed by logarithmically summing the contribution from each class:

$$L_{10}(h) = 10 \log \left(10^{\frac{L_{10}(h)_A}{10}} + 10^{\frac{L_{10}(h)_{MT}}{10}} + 10^{\frac{L_{10}(h)_{HT}}{10}} \right). \quad (3)$$

A complete discussion of the mathematical development of this model can be found in Appendices A and B.

Figure 1 is a flow diagram that shows the computational sequence followed in the FHWA manual method in arriving at a predicted sound level.

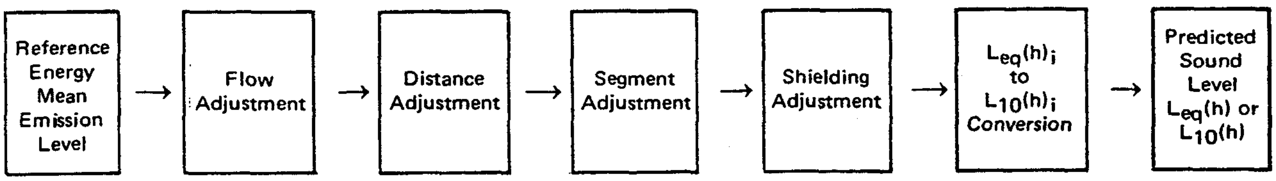


Figure 1. Flow Diagram of the Computational Sequence Used in the FHWA Model

The computational procedure shown in Figure 1 is followed in Chapter 2 where each of the variables is discussed in detail. Each variable will be discussed separately and presented in graphical form for ease of calculations. Sample problems are included to illustrate the use of each chart or charts as they are developed. Finally, a summary is included at the end of each discussion to aid the user in following the computational sequence shown in Figure 1.

Chapter 3 examines equivalent lane distances with and without barriers present at the sites. Chapter 4 presents some nomographs which can be used to quickly estimate traffic noise levels. Chapter 4 also deals with the development of a computer program for a handheld calculator. Chapter 5 briefly discusses the accuracy of the FHWA model for those situations where D is equal to or greater than 15 metres. Chapter 6 discusses noise prediction when the observer is close to the highway (D is less than 15 metres), Chapter 7 presents some problems involving multilane highways.

2.0 FHWA MODEL – MANUAL METHOD ($D \geqslant 15$ Metres)

a. Introduction

As discussed in Chapter 1, the FHWA model arrives at a predicted sound level through a series of adjustments to the reference energy mean emission level. The actual value of these adjustments depends on input data concerning traffic characteristics, topography, and roadway characteristics. In the FHWA manual method presented in this chapter, these adjustments are read from figures and tables. Thus, the procedure used in arriving at a predicted noise level using the manual method developed for the FHWA model is very similar to the manual method used in the NCHRP 117/144 model. The figures have been changed, and the basic model is drastically different, but the computational procedure is very similar.

Table 1 has been prepared to assist the user in keeping track of these adjustments. The notation in Table 1 is slightly different from that used in Equation (1). The reason for this will become apparent as each term in Equation 1 is discussed.

NAME ______________________________ PROJECT DESCRIPTION ______________________________

DATE ______________________________ ______________________________

1.	LANE NO./ROAD SEGMENT																			
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)																			
4.	S(km/h)																			
5.	D(m)																			
6.	ϕ_1 (degrees)	Fig. 5																		
7.	ϕ_2 (degrees)	Fig. 5																		
8.	$(\overline{L_o})_{E_i}$ (dBA)	Fig. 2																		
9.	10 LOG $(N_i D_o / S_i)$ (dB)	Fig. 3																		
10a.	10 LOG (D_o/D) (dBA)	Fig. 4																		
10b.	15 LOG (D_o/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_0(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6																		
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7																		
12.	ϕ_L (degrees)	Fig. 10																		
13.	ϕ_R (degrees)	Fig. 10																		
14.	δ_o (metres)	Fig. 9																		
15.	N_o	Eq. 18																		
16.	Δ_B (dBA)	Appendix B																		
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)																			
19.	$L_{eq}(h)$ (dBA)																			
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 1. Noise Prediction Worksheet

b. Reference Energy Mean Emission Level

Figure 1 indicated that the first step in the prediction procedure was to determine the reference energy mean emission level for each class of vehicles that uses the highway. This requires a knowledge of the emission levels of the individual vehicles traveling on the highway. The emission level, L_o, is defined as the A-weighted peak pass-by noise level generated by a vehicle as measured by a microphone at a specified location. In the FHWA model, the microphone is located on a line perpendicular to the centerline of the traffic lane at a distance of 15 metres from the centerline of the traffic lane. Microphone height is 1.5 metres. The intervening terrain between the traffic lane and the microphone should be flat and free of reflective surfaces. When the measurement is made, the vehicles should be operating on a straight, flat roadway under constant speed conditions and in cruise mode in the near lane. Care must be taken to insure that the measured emission levels are free from extraneous sounds. Detailed procedures for measuring noise emission levels are given in a manual under preparation by FHWA [1,12].

Unfortunately, the vehicles that use the highways do not have identical emission levels. Emission levels depend on several factors, such as the type of vehicle, engine size, speed, tire type, etc. Since it is not practical to determine the emission levels for all vehicles in each class, it becomes necessary to measure the emission levels of a large number of different types of vehicles at various speeds and statistically determine the reference energy mean emission levels. This is usually done on a computer using standard curve fitting and statistical techniques. This type of analysis has been done [2] using the data acquired in the Four-State Noise Inventory [3]. Based on this analysis and other data [2–6], vehicles can be placed in three acoustic source groups:

(1) *Automobiles (A)* — all vehicles with two axles and four wheels designed primarily for transportation of nine or fewer passengers (automobiles), or transportation of cargo (light trucks). Generally, the gross vehicle weight is less than 4,500 kilograms.

(2) *Medium trucks (MT)* — all vehicles having two axles and six wheels designed for the transportation of cargo. Generally, the gross vehicle weight is greater than 4,500 kilograms but less than 12,000 kilograms.

(3) *Heavy trucks (HT)* — all vehicles having three or more axles and designed for the transportation of cargo. Generally, the gross weight is greater than 12,000 kilograms.

The FHWA model uses the following A-weighted national reference energy mean emission levels:

$$(\overline{L_o})_{E_A} = 38.1 \log(S) - 2.4 \quad (4)$$

$$(\overline{L_o})_{E_{MT}} = 33.9 \log(S) + 16.4 \quad (5)$$

$$(\overline{L_o})_{E_{HT}} = 24.6 \log(S) + 38.5 \quad (6)$$

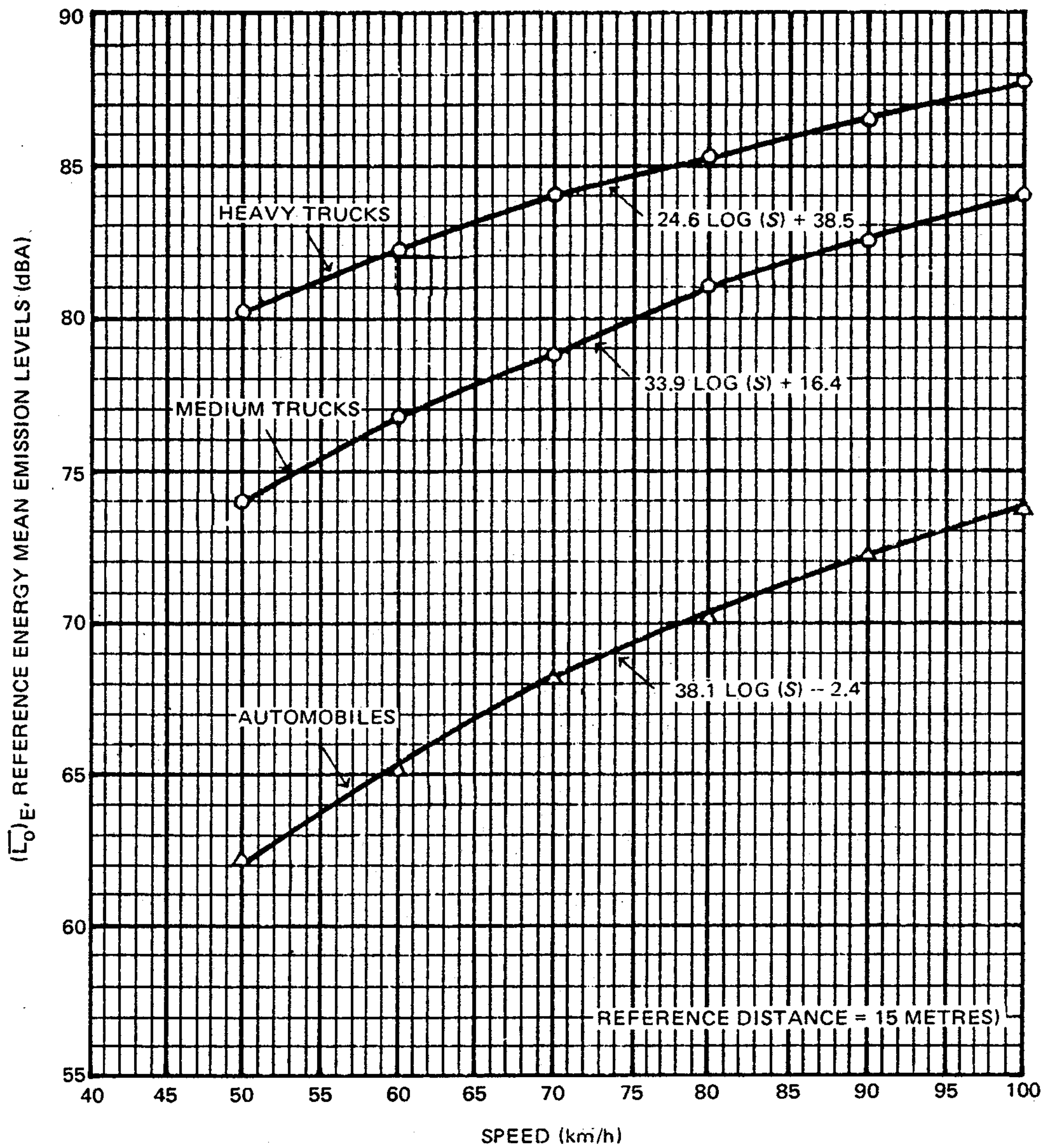
where S is the average vehicle speed of the vehicle class in km/h.

Equation (4) is from FHWA Research Report No. FHWA-RD-77-19 [4]. Equations (5) and (6) are from FHWA Research Report FHWA-RD-78-64 [2].

The reference energy mean emission levels shown here are plotted in Figure 2. It is emphasized that the truck levels are national averages based on the truck data acquired in the Four-State Noise Inventory [3].

The Four-State Noise Inventory indicated that there are regional trends in vehicle types. For example, the majority of large trucks in Florida had four axles. Consequently, the reference energy mean emission level given in Equation (6) may result in overprediction of the noise levels on Florida highways. Users of this manual may develop their own reference levels using the FHWA prescribed measurement procedures [12].

The three vehicle categories discussed here are identical to those reported in NCHRP Report 173. Although the vehicle categories are the same, the emission levels are not. The reason for this is unclear. One possible explanation is that the measurements were made at different times. The



○ SOURCE: "Statistical Analysis of FHWA Traffic Noise Data," FHWA-RD-78-64

△ SOURCE: "Update of TSC Highway Traffic Noise Prediction Code (1974)," FHWA-RD-77-19

Figure 2. National Reference Energy Mean Emission Levels as a Function of Speed

vehicle measurements shown in NCHRP Report 173 were made before 1974. The vehicle measurements in the Four-State Noise Inventory were made in 1975.

One interesting point is the distinction made in NCHRP Report 173 between emission levels and source levels. NCHRP Report 173 reported a 4 dB error between measured sound levels and predicted sound levels. This 4 dB error was subtracted from the emission levels, and these quantities were defined as source levels. The source levels given in NCHRP Report 173 and the emission levels given here have approximately the same numerical values for the emission levels of the automobiles and medium trucks. The levels for the heavy trucks are approximately the same at high speed but not at low speed. This is because the source level for heavy trucks in NCHRP 173 is independent of speed.

One word of caution. The reference mean emission levels shown in Figure 2 represent cruise conditions on a flat roadway between 50 km/h and 100 km/h. Below 50 km/h, heavy trucks' emissions increase because these vehicles cannot operate in a cruise mode at speeds less than 50 km/h.

PROBLEM 1

What are the reference energy mean emission levels for automobiles (A), medium trucks (MT), and heavy trucks (HT) at 75 km/h?

SOLUTION

Step 1. Complete Line 4, Table 1-1.

Step 2. The reference energy mean emission levels can be computed using Equations (4), (5), and (6) or read directly from Figure 1-1. Record the values on Line 8, Table 1-1 (the values shown here are based on Figure 1-1).

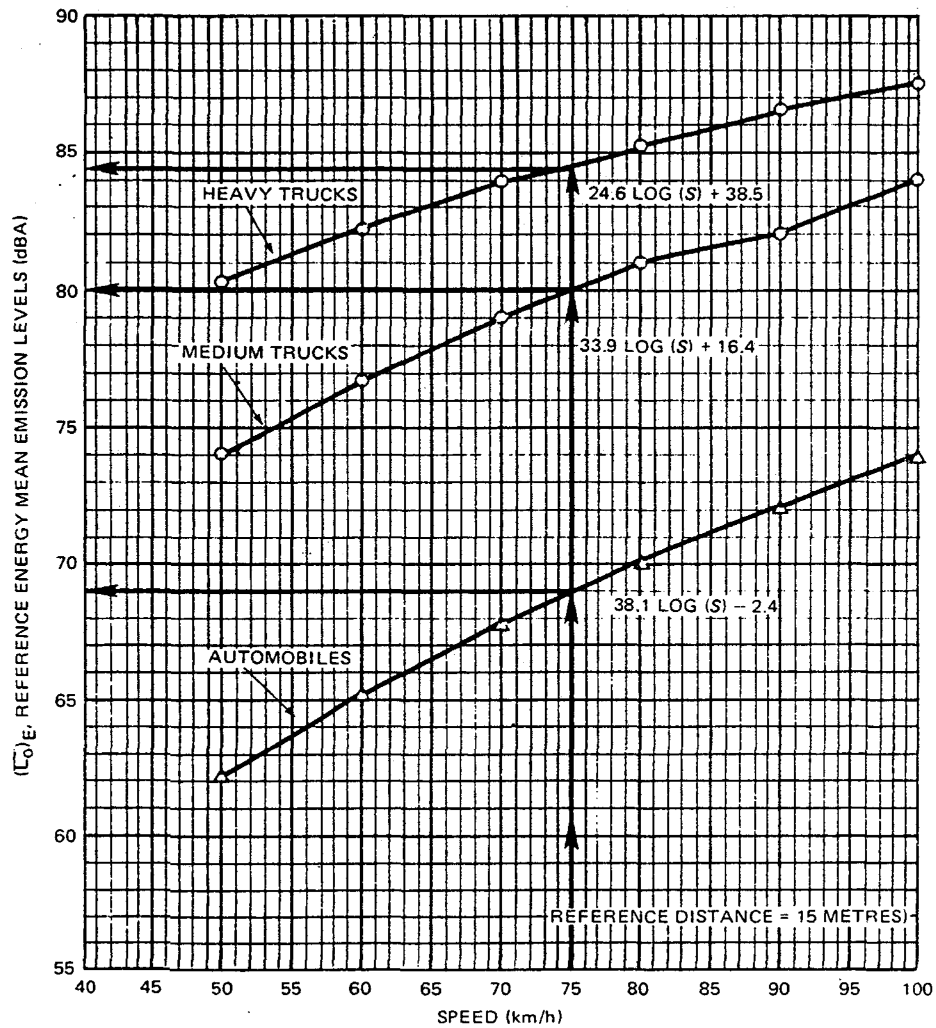


Figure 1-1. Reference Energy Mean Emission Levels as a Function of Speed

(Continued)

PROBLEM 1 (Continued)

NAME ____________________ PROJECT DESCRIPTION ____PROBLEM 1____

DATE ____________________

No.	Item	Ref.																		
1.	LANE NO./ROAD SEGMENT																			
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)																			
4.	S(km/h)		—	75	—															
5.	D(m)																			
6.	ϕ_1 (degrees)	Fig. 5																		
7.	ϕ_2 (degrees)	Fig. 5																		
8.	$(\overline{L_o})E_i$ (dBA)	Fig. 2	69.	80.	84.5															
9.	10 LOG $(N_i D_o/S_i)$ (dB)	Fig. 3																		
10a.	10 LOG (D_o/D) (dBA)	Fig. 4																		
10b.	15 LOG (D_o/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_o(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6																		
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7																		
12.	ϕ_L (degrees)	Fig. 10																		
13.	ϕ_R (degrees)	Fig. 10																		
14.	δ_o (metres)	Fig. 9																		
15.	N_o	Eq. 18																		
16.	Δ_B (dBA)	Appendix B																		
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-26
18.	$L_{eq}(h)$ (dBA)																			
19.	$L_{eq}(h)$ (dBA)																			
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 1-1. Noise Prediction Worksheet

Summary

$L_{eq}(h)_i$	$= (\overline{L_o})_{E_i}$	reference energy mean emission level (Figure 2 and line 8 of Table 1)
	+	traffic flow adjustment
	+	distance adjustment
	+	finite roadway adjustment
	+	shielding adjustment

The procedures in Section 2(b) can be used to predict the reference energy mean emission level. This is the predicted equivalent peak sound level produced by the passage of a single representative vehicle traveling at constant speed at the reference distance of 15 metres from a flat, infinitely long highway. This is not a very useful value. In Section 2(c), traffic flow adjustments will be introduced.

c. Traffic Flow Adjustments to the Reference Levels

Figure 2 is used to determine the reference energy mean emission level for a single vehicle representative of a particular class. This value must then be adjusted for traffic flows by use of the term

$$10 \log (N_i \pi D_o / TS_i) . \qquad (7)$$

This expression is valid for any consistent set of units. The units used by highways engineers are not consistent. N_i is the number of vehicles in the ith class passing a given point over a 1-hour period; D_o is equal to 15 metres; T is equal to 1-hour; and S_i is measured in kilometres per hour. Consequently, for ease of use, the expression $10 \log (N_i \pi D_o / TS_i)$ is simplified to $10 \log (N_i D_o / S_i) - 25$ (Note: $-25 = 10 \log \pi - 10 \log 1000$). Consequently, the adjustment for traffic flow reduces to

$$10 \log \left(\frac{N_i D_o}{S_i} \right) - 25 . \qquad (8)$$

Note that in Table 1, Line 17, the −25 is treated as an equation constant. The units are the same as defined above.

D_o is kept in Equation (8) for two reasons:

(1) It emphasizes that the emission levels used in the FHWA model were measured at a distance of 15 metres.

(2) It serves as an alert mechanism. When D is less than 15 metres, noise predictions must be made in accordance with the procedures in Chapter 6.

Since D_o is a constant in the term $10 \log (N_i D_o / S_i)$, the traffic flow adjustment factor varies as the logarithm of N_i / S_i. If N_i is held constant, the adjustment factor decreases with increasing speed at the rate of 3 dBA per doubling of speed. If S_i is held constant and the volume increases, the adjustment factor increases by 3 dBA for each doubling of volume.

The name given to the adjustment in this section—the traffic flow adjustment—is somewhat of a misnomer because Equation (7) has one other important function. Recall that T is the time period over which the equivalent sound level is computed. By making T equal to one hour, the reference energy mean emission level (a peak value) is converted to an hourly equivalent sound level.

The adjustment for traffic flows can be read directly from Figure 3.

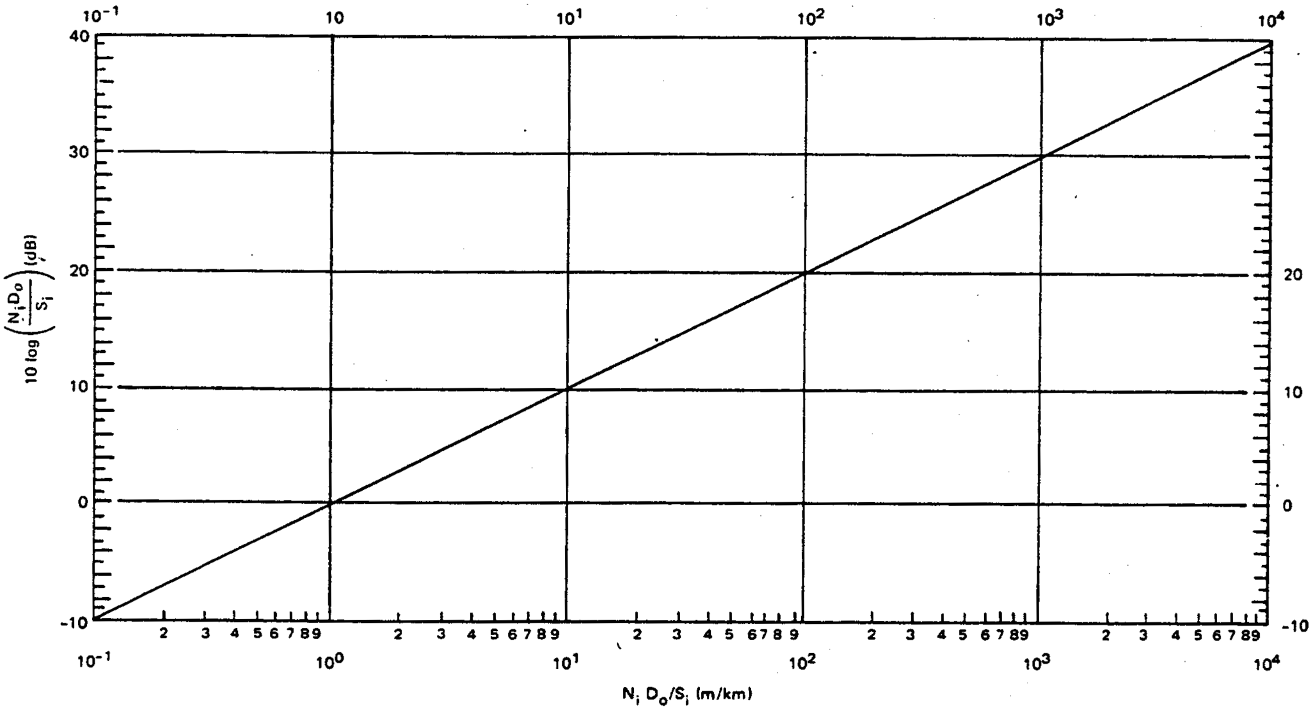


Figure 3. Adjustment for Real Traffic Flows

PROBLEM 2

A two-lane, east-west highway carries the following hourly traffic:

Vehicle Class	Eastbound Lane	Westbound Lane
A	317	281
MT	24	12
HT	22	25

The lane width is 3.66 m and the operating speed is 75 km/h. Determine the reference energy mean emission levels and the traffic flow adjustment factors for each class of vehicles.

SOLUTION

Step 1. Enter the lane designations on Line 1, Table 2-1.

Step 2. Enter the number of vehicles in each class in the proper columns in Line 3, Table 2-1.

Step 3. Enter the speed for each vehicle group in Line 4, Table 2-1.

Step 4. Determine the reference energy mean emission levels for each class of vehicles and enter these values on Line 8, Table 2-1 (values shown were read from Figure 1-1).

Step 5. Since there are three classes of vehicles in each lane, and the number of vehicles vary between classes, six traffic flow adjustment factors must be determined. Compute $N_i D_o / S_i$ for each vehicle group for each lane and enter Figure 2-1 with these values. The adjustment can then be read directly on the vertical scale. Alternately, the adjustments could be obtained directly from solving Equation (8) (note that Equation (8) includes a constant of -25). Record these values on Line 9, Table 2-1.

(Continued)

PROBLEM 2 (Continued)

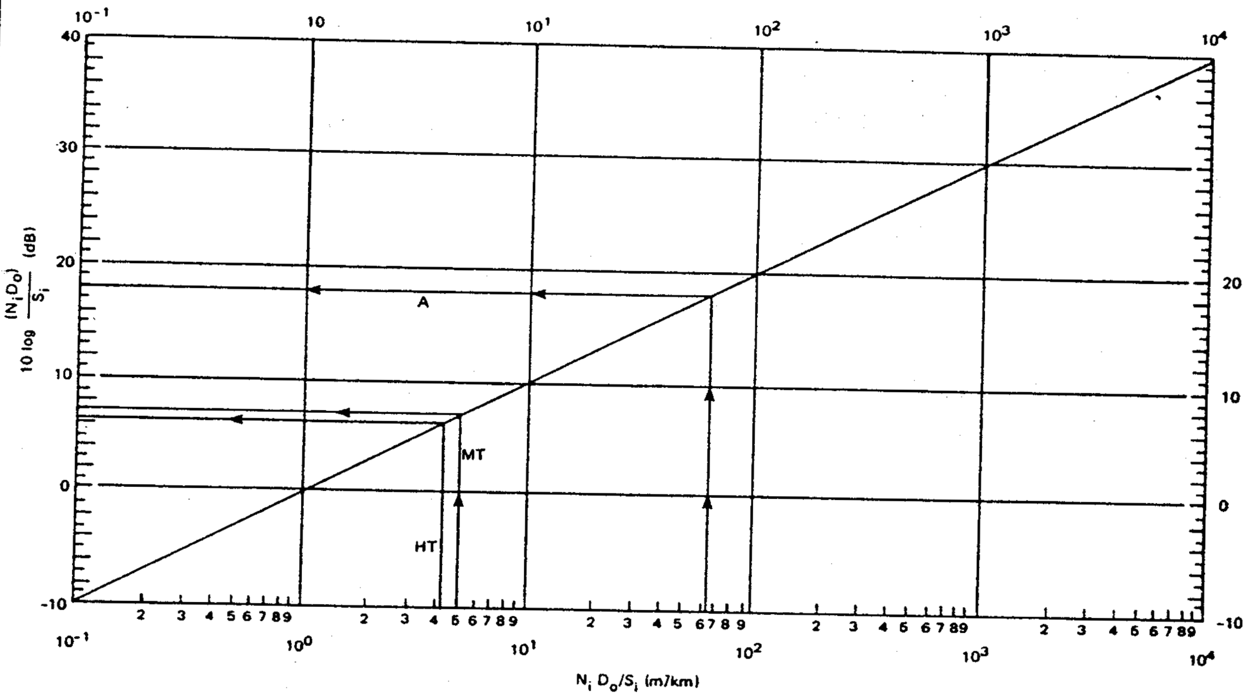


Figure 2-1. Adjustment for Real Traffic Flows

(Continued)

PROBLEM 2 (Continued)

NAME ____________________ PROJECT DESCRIPTION PROBLEM 2

DATE ____________________

1	LANE NO./ROAD SEGMENT	EB			WB														
2.	VEHICLE CLAS.	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)	317	24	22	281	12	25												
4.	S(km/h)	–	75	–	–	75	–												
5	D(m)																		
6.	ϕ_1 (degrees) Fig. 5																		
7.	ϕ_2 (degrees) Fig. 5																		
8.	$(\overline{L_o})_{E_i}$ (dBA) Fig. 2	69.	80.	84.5	69.	80.	84.5												
9.	10 LOG (N_iD_o/S_i) (dB) Fig. 3	18.	7.	6.5	17.5	4.	7.												
10a.	10 LOG (D_o/D) (dBA) Fig. 4																		
10b.	15 LOG (D_o/D) (dBA) Fig. 4																		
11a.	10 LOG $(\psi_0(\phi_1, \phi_2)/\pi)$ (dBA) Fig. 6																		
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12.	ϕ_L (degrees) Fig. 10																		
13.	ϕ_R (degrees) Fig. 10																		
14.	δ_0 (metres) Fig. 9																		
15.	N_o Eq. 18																		
16.	Δ_B (dBA) Appendix B																		
17.	CONSTANT (dB)	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)																		
19.	$L_{eq}(h)$ (dBA)																		
20.	Δ_s (dBA) Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																		
22	$L_{eq}(h)$ (dBA)																		
23.	ND/S (m/km)																		
24.	$(L_{10}-L_{eq})_i$ (dB) Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																		
26.	$L_{10}(h)$ (dBA)																		
27.	$L_{10}(h)$ (dBA)																		

Table 2-1. Noise Prediction Worksheet

Summary

$L_{eq}(h)_i = (\overline{L_o})_{E_i}$		reference energy mean emission level (Figure 2 and line 8 of Table 1)
	$+10 \log \left(\dfrac{N_i D_o}{S_i}\right)$	traffic flow adjustment (Figure 3 and line 9 of Table 1)
	+	distance adjustment
	+	finite roadway adjustment
	+	shielding
	−25	constant (line 17 of Table 1)

At this point in the development of the FHWA manual method, the user can predict the equivalent sound level at the reference distance of 15 metres from a flat, infinitely long highway produced by the passage of a group of vehicles of a particular class. In Section 2(d) distance adjustments will be introduced.

d. **Distance Adjustment to the Reference Levels**

The reference energy mean emission levels are equivalent sound levels based on single vehicle, peak pass-by noise level measurements made at a distance of 15 metres from the roadway. Predicting the noise level at distances greater than 15 metres requires that the reference energy mean emission levels be adjusted for the new distances. The distances adjustment is generally referred to as the drop-off rate and is expressed in terms of decibels per doubling of distance (dB/DD). Since the reference energy mean emission levels are equivalent sound levels, the distance adjustment factor can be expressed as

$$10 \log \left(\frac{D_o}{D}\right)^{1+\alpha} \tag{9}$$

where

- D is the perpendicular distance between the centerline of the travel lane and the observer.
- D_o is the reference distance at which the reference energy mean emission level was measured and equals 15 metres. Note that D_o is a special case of D.
- α is a site parameter whose value depends upon site conditions.

Theoretically, it can be shown that when the ground between the roadway and observer is acoustically hard, the site is reflective ($\alpha = 0$). Consequently, the distance adjustment factor reduces to

$$10 \log \left(\frac{D_o}{D}\right) \tag{10}$$

and the drop-off rate is 3 dB per doubling of distance (3 dBA/DD). Values close to this theoretical value have been measured in the field [3].

Field studies [3,5] have also shown that when the intervening ground is acoustically soft the site is absorptive ($\alpha \simeq 1/2$). In this situation, the distance adjustment factor reduces to

$$15 \log \left(\frac{D_o}{D}\right) \tag{11}$$

and the drop-off rate is 4.5 dBA per doubling of distance (4.5 dBA/DD). In this case, it appears that the 4.5 dBA/DD attenuation is made up of two components—the 3.0 dBA/DD due to geometric spreading and an excess attenuation of 1.5 dBA/DD due to ground effects.

It is important that the users of this manual understand what the values given by Equations 10 and 11 represent. Consider the situation where two sound level meters (SLM's) are located adjacent to a highway. One SLM is located at distance D and the other SLM is located at distance $2D$. As a vehicle approaches and passes the SLM's, the noise level increases up to a peak level and then decreases. If simultaneous readings of the peak levels were recorded, the difference in levels between the two SLM's would be 6 or 7.5 dBA (6.0 dBA due to divergence and 1.5 dBA due to excess attenuation if the site is absorptive). However, if comparisons were made between the equivalent sound levels computed from the pass-by envelopes, the difference in the equivalent sound levels between the SLM's would range from 3 to 4.5 dBA. Equations (10) and (11) are based on equivalent sound levels.

In the FHWA model, the user must decide the proper drop-off rate to use. Table 2 has been prepared to help the user make this decision.

As shown earlier, the 3 dBA/DD takes the form of 10 ($\log D_o/D$) and the 4.5 dBA/DD takes the form of 15 $\log (D_o/D)$. These functions are shown graphically in Figure 4.

Table 2. Criteria for Selection of Drop-Off Rate Per Doubling of Distance

Situation	Drop-Off Rate
1. All situations in which the source or the receiver are located 3 metres above the ground or whenever the line-of-sight* averages more than 3 metres above the ground.	3 dBA ($\alpha = 0$)
2. All situations involving propagation over the top of a barrier 3 metres or more in height.	3 dBA ($\alpha = 0$)
3. Where the height of the line-of-sight is less than 3 metres and	
(a) There is a clear (unobstructed) view of the highway, the ground is hard and there are no intervening structures.	3 dBA ($\alpha = 0$)
(b) The view of the roadway is interrupted by isolated buildings, clumps of bushes, scattered trees, or the intervening ground is soft or covered with vegetation.	4.5 dBA ($\alpha = 1/2$)

*The line-of-sight (L/S) is a direct line between the noise source and the observer.

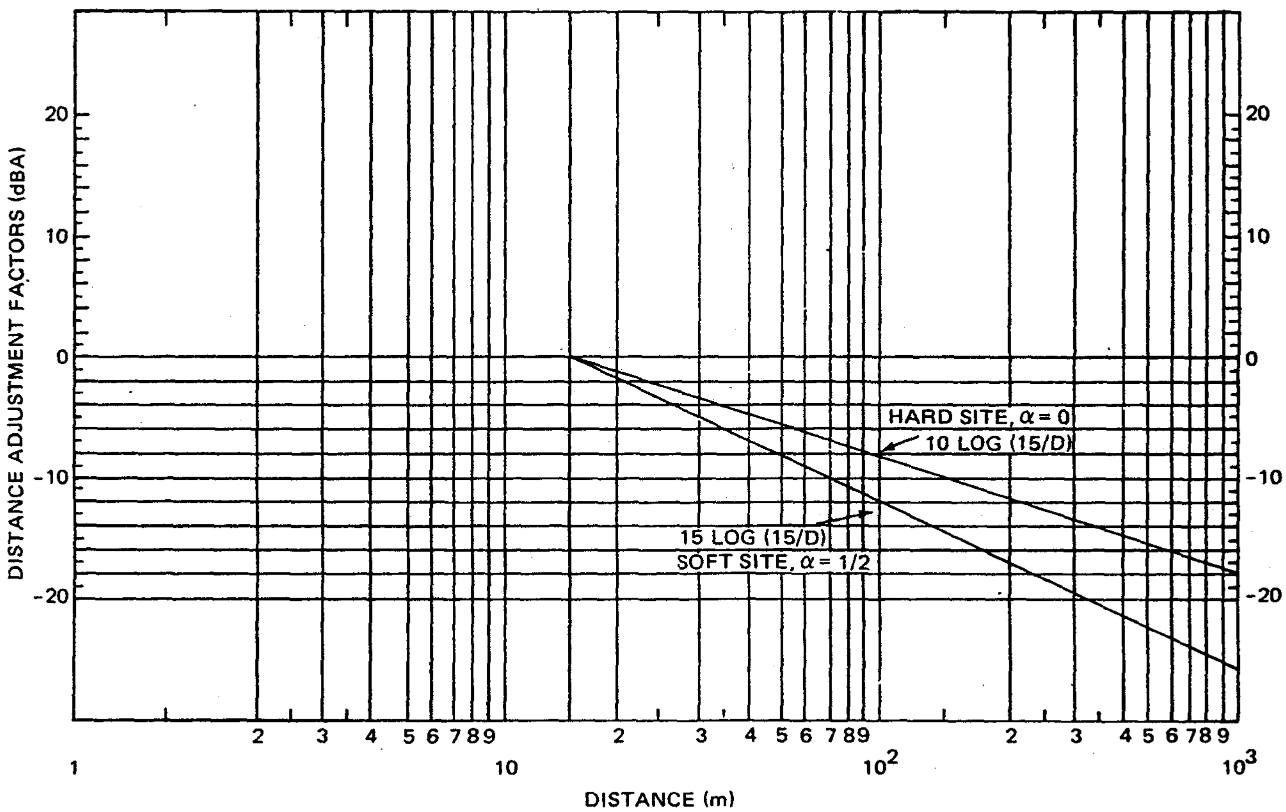


Figure 4. Adjustments for Distances Other than 15 Metres

PROBLEM 3

(a) In Problem 2, what would be the distance adjustment factors at an observer located 60 metres south of the centerline of the eastbound lane if the line-of-sight (L/S) was less 3 metres above the ground and the intervening ground was paved?

(b) What would be the distance adjustment factors if the intervening ground was covered with grass?

The lane width is 3.66 m.

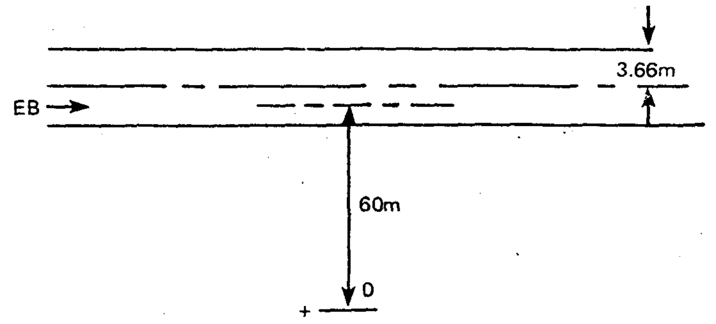


Figure 3-1. Highway Site Geometry for Problem 3

SOLUTION

Refer to Table 3-1.

Step 1. Since there are two problems, identify them in Line 1, Table 3-1.

Step 2. Determine the perpendicular distance, D, from the observer to the centerline of the EB and WB lanes. Record these values on Line 5, Table 3-1.

Step 3. Consider the problem where the L/S is less than 3 metres and the intervening ground is paved. Table 2 indicates that a drop-off rate of 3 dBA/DD is appropriate. Use Figure 3-2 and locate the line that represents a drop-off rate of 3 dBA/DD (10 log (15/D)). Using the distances, D, determined in Step 2, read the distance adjustment factors directly from the graph and record them on Line 10(a), Table 3-1. Alternately, the adjustments could be obtained directly from Equation (10).

Step 4. Consider the problem where the L/S is less than 3 metres and the intervening ground is covered with grass. Table 2 indicates that a drop-off rate of 4.5 dBA/DD is appropriate. Use Figure 3-2 and locate the line that represents 4.5 dBA/DD (15 log (15/D)). Using the distances, D, determined in Step 2, read the distance adjustments directly from the graph and record them on Line 10(b), Table 3-1. Alternately, the adjustments could have been obtained directly from Equation (11).

(Continued)

PROBLEM 3 (Continued)

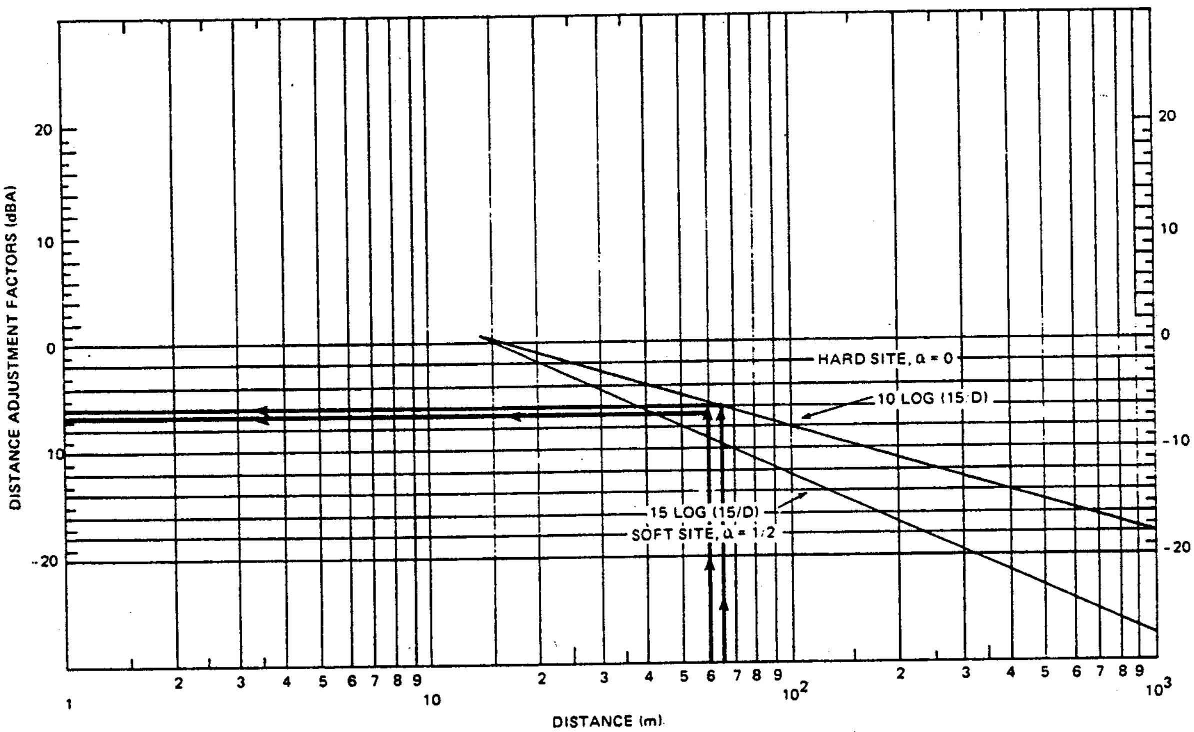


Figure 3-2. Adjustments for Distances Other than 15 Metres

(Continued)

PROBLEM 3 (Continued)

NAME ______________________ PROJECT DESCRIPTION ______ PROBLEM 3 ______

DATE ______________________

			(a) Hard Site						(b) Soft Site											
1.	LANE NO./ROAD SEGMENT			EB			WB			EB			WB							
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)																			
4.	S(km/h)																			
5.	D(m)			60			64			60			64							
6.	ϕ_1 (degrees)	Fig. 5																		
7.	ϕ_2 (degrees)	Fig. 5																		
8.	$(\overline{L_o})_{E_i}$ (dBA)	Fig. 2																		
9.	10 LOG ($N_i D_o / S_i$) (dB)	Fig. 3																		
10a.	10 LOG (D_o/D) (dBA)	Fig. 4		-6.			-6.5													
10b.	15 LOG (D_o/D) (dBA)	Fig. 4								-9			-9.5							
11a.	10 LOG ($\psi_b(\phi_1, \phi_2)/\pi$) (dBA)	Fig. 6																		
11b.	10 LOG ($\psi_{1/2}(\phi_1, \phi_2)/\pi$) (dBA)	Fig. 7																		
12.	ϕ_L (degrees)	Fig. 10																		
13.	ϕ_R (degrees)	Fig. 10																		
14.	δ_0 (metres)	Fig. 9																		
15.	N_o	Eq. 18																		
16.	Δ_B (dBA)	Appendix B																		
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)																			
19.	$L_{eq}(h)$ (dBA)																			
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 3-1. Noise Prediction Worksheet

Summary

$L_{eq}(h) = (\overline{L_o})_{E_i}$	reference energy mean emission level (Figure 2 and line 8 of Table 1)
$+10 \log \left(\frac{N_i D_o}{S_i}\right)$	traffic flow adjustment (Figure 3 and line 9 of Table 1)

$+ \begin{cases} 10 \log (D_o/D) \\ 15 \log (D_o/D) \end{cases}$	distance adjustment factor, hard site (Figure 4 and line 10(a) of Table 1) distance adjustment factor, soft site (Figure 4 and line 10(b) of Table 1)
+	finite roadways adjustment
+	shielding
−25	constant

At this point in the development of the FHWA manual method, the user can predict the hourly equivalent sound level, at any point located 15 metres or greater from a flat, infinitely long highway produced by the passage of a group of vehicles from a particular class. In Section 2(e) finite roadway adjustment will be discussed.

e. Finite Length Roadway Adjustments to the Reference Levels

Up to this point, it has been assumed that the roadway is infinitely long in both directions in relation to the observer. In many cases, this is not true, and it becomes necessary to adjust the reference level to account only for the energy contribution of the roadway that is visible to the observer. Additionally, it is often necessary to separate a roadway into sections to account for changes in topography, traffic flows, shielding, etc. In these situations, the roadway will be divided into segments of finite length [6]. The finite length roadway adjustment depends on the orientation of these highway segments relative to the observer and on ground effects.

1. *Orientation of Highway Segement*

The following procedure will be used to determine the angular relationship between the roadway segment and an observer facing the highway segment. (Refer to Figure 5)

Step 1. Draw a perpendicular line from the roadway, or the roadway extension to the observer. All angles are measured from this perpendicular.

Step 2. Draw a line from the observer to the left most end of the highway segment. The angle measured from the perpendicular drawn in Step 1 to the line connecting the observer and the left most end of the roadway segment is ϕ_1. If ϕ_1 is measured to the left of the perpendicular it is negative. If ϕ_1 is measured to the right of the perpendicular it is positive.

Step 3. Draw a line from the observer to the right most end of the highway segment. The angle measured from the perpendicular drawn in Step 1 to the line connecting the observer and the right most end of the highway segment is ϕ_2. If ϕ_2 is measured to the left of the perpendicular, it is negative, if ϕ_2 is measured to the right of the perpendicular it is positive.

Step 4. Check the angles ϕ_1 and ϕ_2 by use of the equation

$$\Delta\phi = \phi_2 - \phi_1 \tag{12}$$

where

ϕ_1 and ϕ_2 are the angles in degrees identified in Steps 1-3 above.

In all cases $\Delta\phi$ will be positive and will be numerically equal to the included angle subtended by the roadway relative to the receiver.

Based on this procedure, only three cases are possible:

Case A — ϕ_1 is negative, ϕ_2 is positive.
Case B — ϕ_1 is negative, ϕ_2 is negative.
Case C — ϕ_1 is positive, ϕ_2 is positive.

These three cases are illustrated in Figure 5.

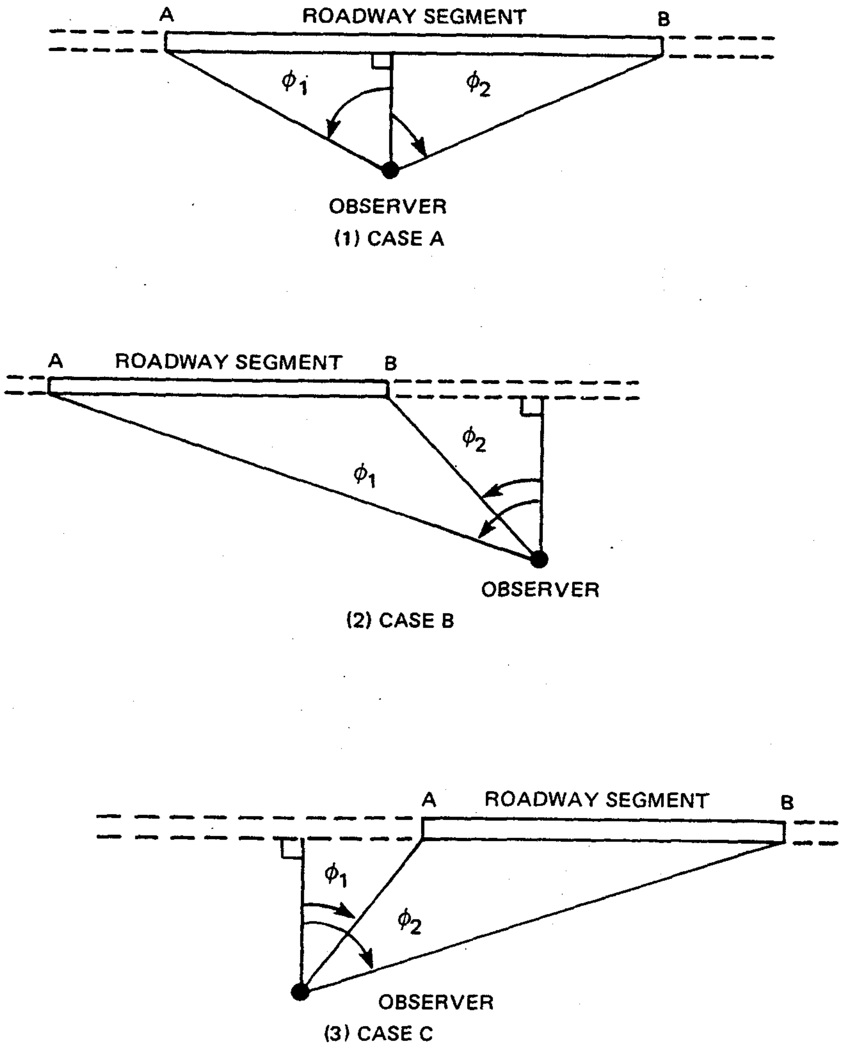


Figure 5. Angle Identification of Roadway Segments

PROBLEM 4

Determine ϕ_1 and ϕ_2 for the segments shown in Figure 4-1. Use $\Delta\phi$ to check the answers.

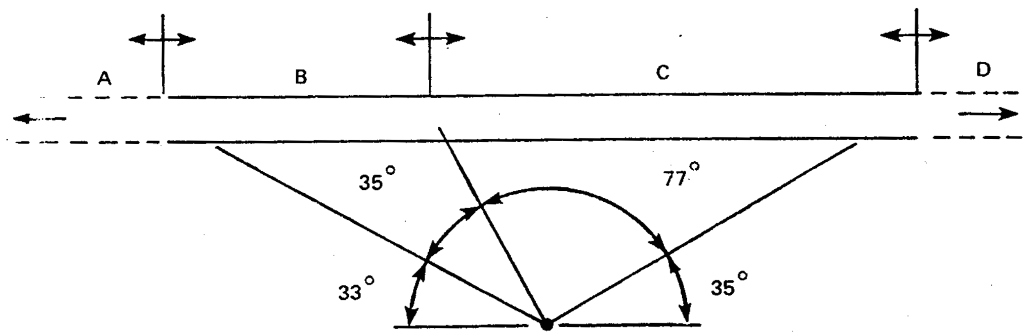


Figure 4-1. Highway Site Geometry for Problem 4

SOLUTION

Refer to Figure 5 and Table 4-1.

Step 1. The procedure established for the FHWA model requires that all angles be measured from the perpendicular line connecting the roadway and the observer. Draw a perpendicular line and remeasure the angles, as shown in Figure 4-2.

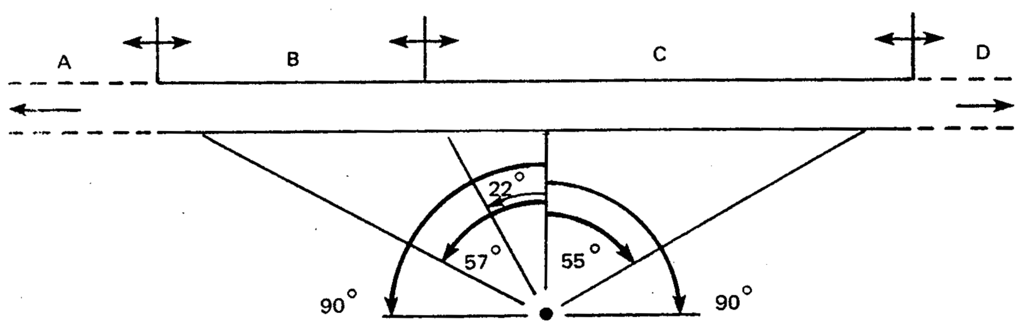


Figure 4-2. Identification of Angles for Problem 4

(Continued)

PROBLEM 4 (Continued)

Step 2. Using Figure 4-2 and the procedures for angle orientation, determine the angles and their signs.

1. Segment A: $\phi_1 = -90°$ $\phi_2 = -57°$

   Check $\Delta\phi = \phi_2 - \phi_1 = -57° - (-90°) = \underline{+33°}$

   ($\Delta\phi$ is the included angle for segment A, Figure 4-2).

2. Segment B: $\phi_1 = -57°$, $\phi_2 = -22°$

   Check $\Delta\phi = \phi_2 - \phi_1 = -22° - (-57°) = \underline{+35°}$

   ($\Delta\phi$ is the included angle for segment B).

3. Segment C: $\phi_1 = -22°$ $\phi_2 = +55°$

   Check $\Delta\phi = \phi_2 - \phi_1 = 55° - (-22°) = \underline{+77°}$

   ($\Delta\phi$ is the included angle for segment C).

4. Segment D: $\phi_1 = 55°$ $\phi_2 = 90°$

   Check $\Delta\phi = \phi_2 - \phi_1 = 90° - 55° = \underline{+35°}$

   ($\Delta\phi$ is the included angle for segment D).

Step 3. Record the angles ϕ_1 and ϕ_2 on Lines 6 and 7, Table 4-1.

NAME ________________ PROJECT DESCRIPTION PROBLEM 4

DATE ________________

1.	LANE NO./ROAD SEGMENT		Segment A			Segment B			Segment C			Segment D								
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)																			
4.	S(km/h)																			
5.	D(m)																			
6.	ϕ_1 (degrees)	Fig. 5	-90			-57			-22			+55								
7.	ϕ_2 (degrees)	Fig. 5	-57			-22			+55			+90								
8.	$(\bar{L}_o)E_i$ (dBA)	Fig. 2																		
9.	10 LOG $(N_i D_o / S_i)$ (dB)	Fig. 3																		
10a.	10 LOG (D_o/D) (dBA)	Fig. 4																		
10b.	15 LOG (D_o/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_0(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6																		
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7																		
12.	ϕ_L (degrees)	Fig. 10																		
13.	ϕ_R (degrees)	Fig. 10																		
14.	δ_o (metres)	Fig. 9																		
15.	N_o	Eq. 18																		
16.	Δ_B (dBA)	Appendix B																		
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)																			
19.	$L_{eq}(h)$ (dBA)																			
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 4-1. Noise Prediction Worksheet

2. *Ground Effects*

The problem of finite length roadways is complicated by the fact that ground effects must be taken into account. In the section on distance adjustments, it was indicated that the drop-off rate was a function of the height of the line-of-sight and the nature of the terrain between the observer and the roadway. The finite length roadway adjustment is also affected by these factors. Consequently, the finite length roadway adjustment factor takes the form of

$$10 \log \left(\frac{\psi_\alpha(\phi_1, \phi_2)}{\pi} \right) \quad (13)$$

where

$\psi_\alpha(\phi_1, \phi_2)$ is a factor that takes finite length roadways into account.

ϕ_1, ϕ_2 are the angles defined in Figure 5.

α is the site parameter.

When $\alpha = 0$, the site is reflective (i.e., the drop-off rate is 3 dBA/DD) and the term $10 \log(\psi_0(\phi_1, \phi_2)/\pi)$ reduces to $10 \log (\Delta\phi/\pi)$ where $\Delta\phi$ is defined in Equation (12).

This implies that roadways subtending equal angles contribute equal energy regardless of their position relative to the observer when the site is reflective. The function (Equation (13) is illustrated graphically in Figure 6.

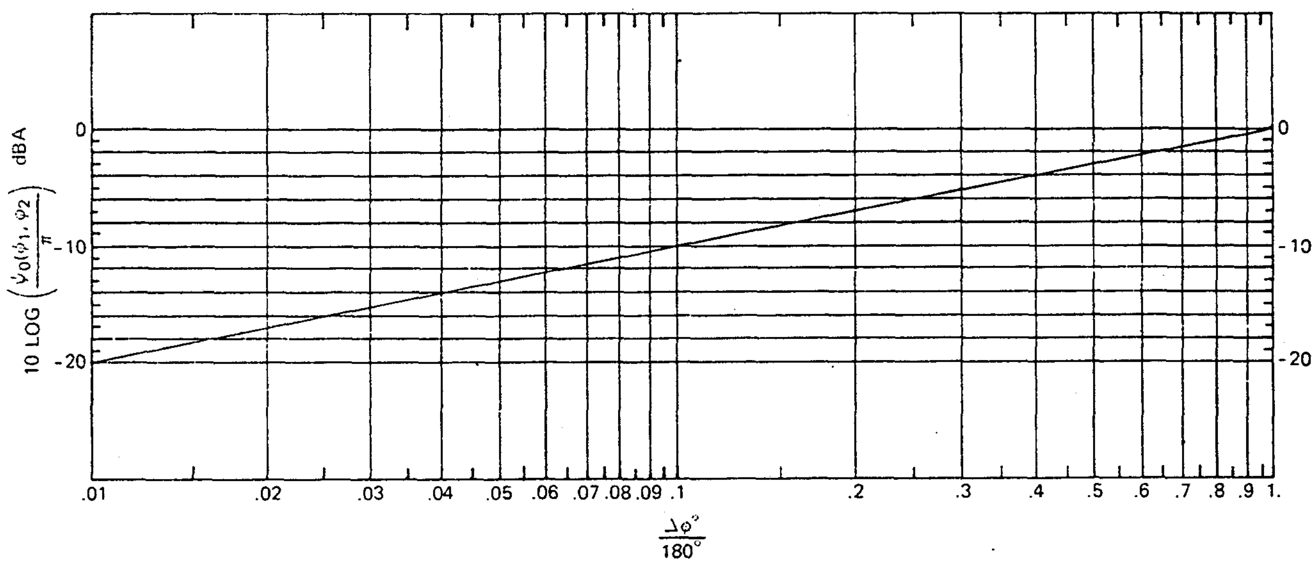


Figure 6. Adjustment Factor for Finite Length Roadways for Hard Sites ($\alpha = 0$)

When $\alpha = 1/2$, the site is absorptive (i.e., the drop-off rate is 4.5 dBA/DD). At absorbing sites, the correction $10 \log (\psi_{1/2}(\phi_1, \phi_2)/\pi)$ reduces to an integration of $\sqrt{\cos \phi}$ over the angular limits of the roadway. This integration has been performed for $\alpha = 1/2$ and the results plotted as a family of curves shown in Figure 7. One extremely important *consequence of absorption* at a highway site is that roadways subtending equal angles will not necessarily contribute equal energies. The amount of energy contributed will depend on the position of the observer relative to the roadway segment. Figure 7 also indicates that the adjustment for an infinitely long roadway is a −1.2 dBA. This results from the assumption that there are no differences in emission levels (measured at 15 metres) over hard and soft sites. (See Appendices A and C for further details.)

Although the distance adjustment and the finite length roadway adjustment were discussed separately, both values depend on the site parameter α. Under free field conditions (the observer has a unobstructed view of the highway or highway section), the same site parameter should be used to make both adjustments on the same highway or highway segment. Thus if $\alpha = 1/2$ is used for the distance adjustment, it should also be used for the finite length roadway adjustment.

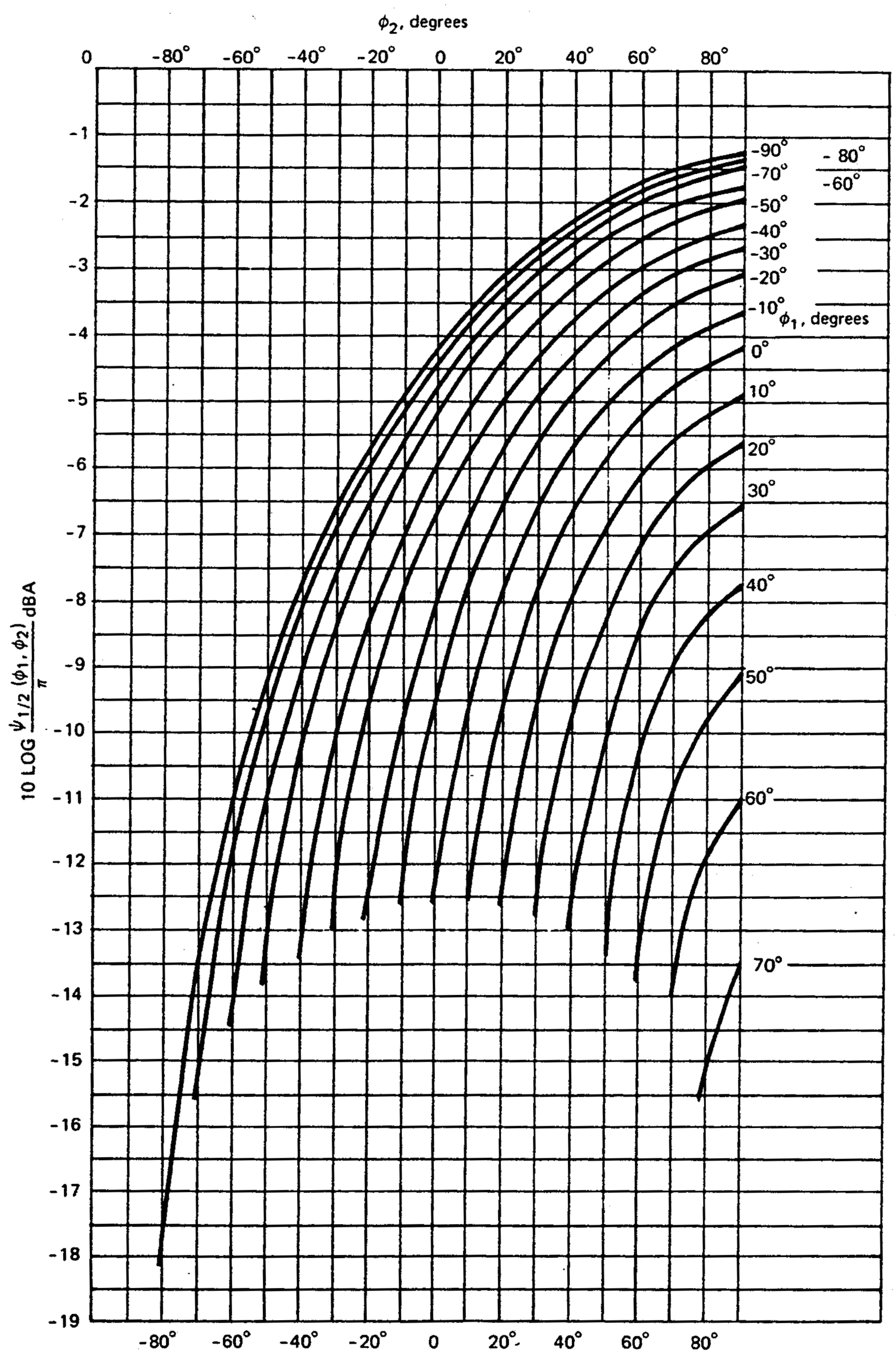


Figure 7. Adjustment Factor for Finite Length Roadways for Absorbing Sites (α = 1/2)

PROBLEM 5

(a) Using the angles ϕ_1 and ϕ_2 from Problem 4 determine the finite length roadway adjustments *assuming that the site is hard* ($\alpha = 0$).

(b) Redo Problem 5(a) assuming that the site is soft ($\alpha = 1/2$).

SOLUTION

Problem 5(a):

Step 1. Obtain ϕ_1 and ϕ_2 from Problem 4 and record these values in Table 5-1. Figure 5-1 will be used to determine the adjustment.

1. Segment A: $\phi_1 = -90°, \quad \phi_2 = -57°, \quad \Delta\phi = 33°$

$$\frac{\Delta\phi}{180} = \frac{33}{180} = .18$$

Adjustment (Figure 5-1) = $\underline{\underline{-7.5 \text{ dBA}}}$

2. Segment B: $\phi_1 = -57°, \quad \phi_2 = -22°, \quad \Delta\phi = 35°$

$$\frac{\Delta\phi}{180} = \frac{35}{180} = .19$$

Adjustment (Figure 5-1) = $\underline{\underline{-7. \text{ dBA}}}$

3. Segment C: $\phi_1 = -22°, \quad \phi_2 = +55°, \quad \Delta\phi = 77°$

$$\frac{\Delta\phi}{180} = \frac{77}{180} = .43$$

Adjustment (Figure 5-1) = $\underline{\underline{-3.5 \text{ dBA}}}$

4. Segment D: $\phi_1 = +55°, \quad \phi_2 = +90, \quad \Delta\phi = 35°$

$$\frac{\Delta\phi}{180} = \frac{35}{180} = .19$$

Adjustment (Figure 5-1) = $\underline{\underline{-7 \text{ dBA}}}$

Step 2. Record the adjustments on Line 11a, Table 5-1.

SOLUTION

Problem 5(b):

Step 1. *Obtain* ϕ_1 *and* ϕ_2 *from* Problem 4 and record these values on Table 5-2. Figure 5-2 will be used to determine the adjustment.

(Continued)

PROBLEM 5 (Continued)

1. Segment A: $\phi_1 = -90°$, $\phi_2 = -57°$

   Adjustment (Figure 5-2) = <u>-10.5 dBA</u>

2. Segment B: $\phi_1 = -57°$, $\phi_2 = -22°$

   Adjustment (Figure 5-2) = <u>-7.5 dBA</u>

3. Segment C: $\phi_1 = -22°$, $\phi_2 = +55°$

   Adjustment (Figure 5-2) = <u>-4.0 dBA</u>

4. Segment D: $\phi_1 = +55°$, $\phi_2 = +90°$

   Adjustment (Figure 5-2) = ?

This particular value is hard to read on Figure 5-2. However,

$$\frac{\psi_{1/2}(55°, 90°)}{\pi} = \frac{\psi_{1/2}(-90°, -55°)}{\pi}$$

(See Figure 5-3)

Adjustment (Figure 5-2) = <u>-10 dBA</u>

Record the adjustments on Line 11b, Table 5-2. Note that Segment B and Segment D have the same included angle but their adjustments are different.

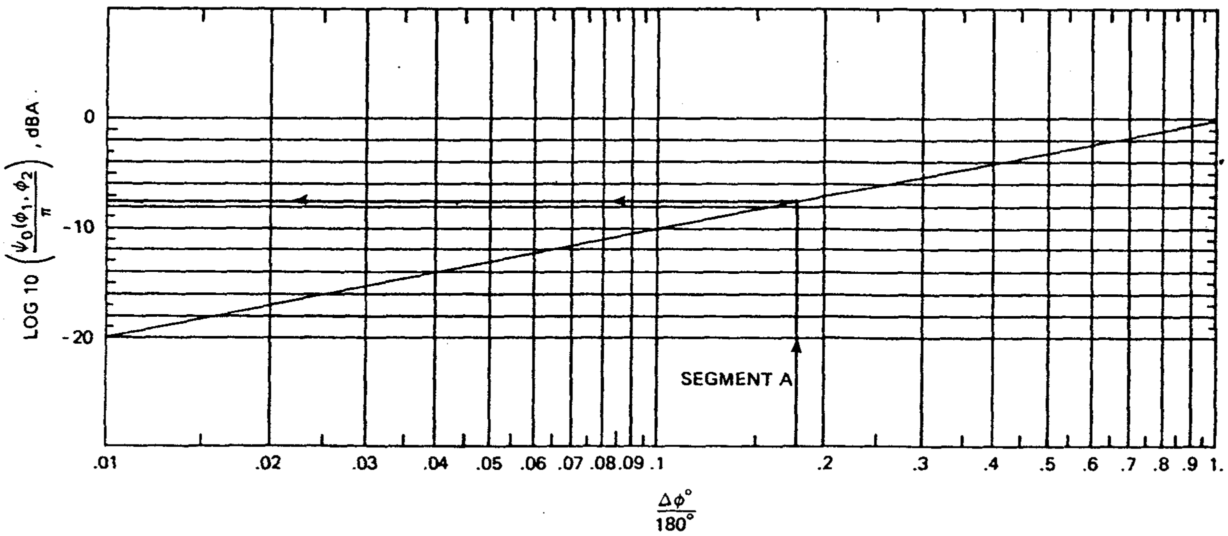


Figure 5-1. Adjustment Factor for Finite Length Roadways for Hard Sites ($\alpha = 0$)

(Continued)

PROBLEM 5 (Continued)

NAME ______________________ PROJECT DESCRIPTION PROBLEM 5a (Hard Site)

DATE ______________________

1.	LANE NO./ROAD SEGMENT		A			B			C			D								
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)																			
4.	S(km/h)																			
5.	D(m)																			
6.	ϕ_1 (degrees)	Fig. 5	-90			-57			-22			+55								
7.	ϕ_2 (degrees)	Fig. 5	-57			-22			+55			+90								
8.	$(\overline{L}_o)_{E_i}$ (dBA)	Fig. 2																		
9.	10 LOG $(N_i D_o / S_i)$ (dB)	Fig. 3																		
10a.	10 LOG (D_o/D) (dBA)	Fig. 4																		
10b.	15 LOG (D_o/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_0(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6	-7.5			-7.			-3.5			-7.								
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7																		
12.	ϕ_L (degrees)	Fig. 10																		
13.	ϕ_R (degrees)	Fig. 10																		
14.	δ_o (metres)	Fig. 9																		
15.	N_o	Eq. 18																		
16.	Δ_B (dBA)	Appendix B																		
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)																			
19.	$L_{eq}(h)$ (dBA)																			
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 5-1. Noise Prediction Worksheet

(Continued)

PROBLEM 5 (Continued)

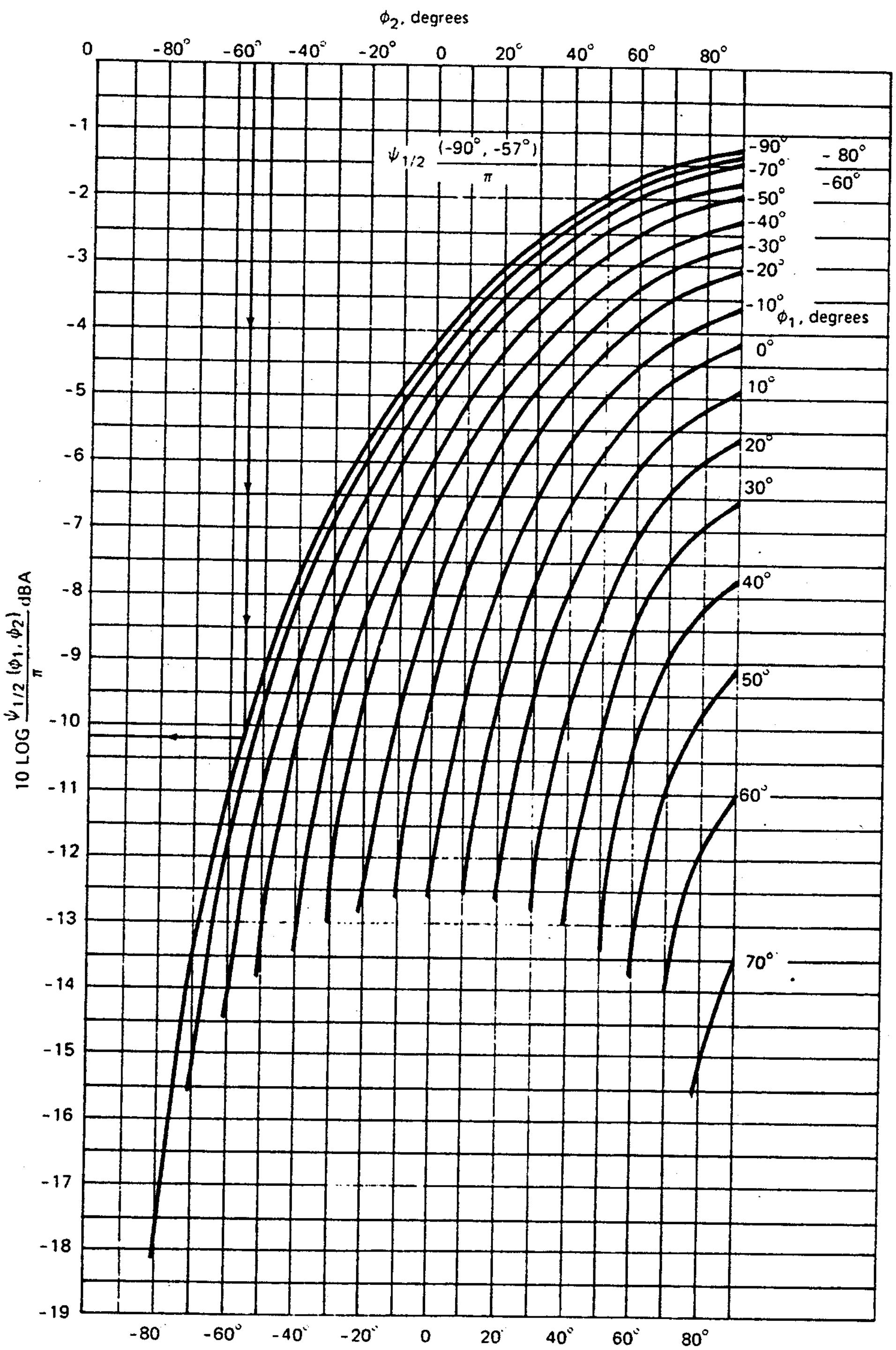


Figure 5-2. Adjustment Factor for Finite Length Roadways for Absorbing Sites ($\alpha = 1/2$)

(Continued)

PROBLEM 5 (Continued)

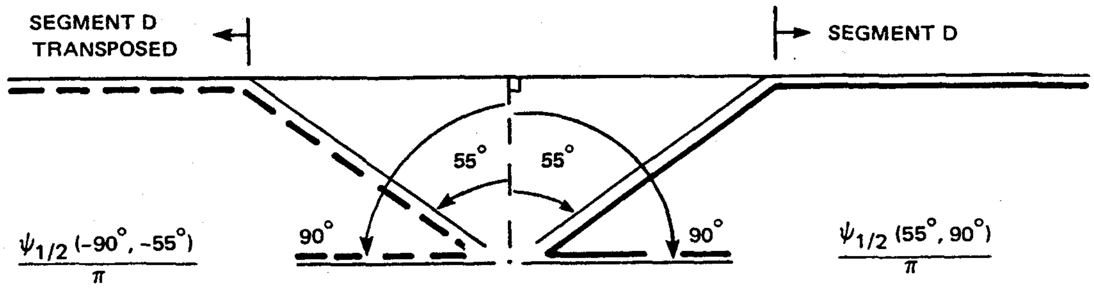


Figure 5-3

NAME ______________________ PROJECT DESCRIPTION **PROBLEM 5b (Soft Site)**

DATE ______________________

No.	Item	Ref.	A			B			C			D								
1.	LANE NO./ROAD SEGMENT		A			B			C			D								
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)																			
4.	S(km/h)																			
5.	D(m)																			
6.	ϕ_1 (degrees)	Fig. 5	-90			-57			-22			+55								
7.	ϕ_2 (degrees)	Fig. 5	-57			-22			+55			+90								
8.	$(L_o)E_i$ (dBA)	Fig. 2																		
9.	10 LOG (N_iD_o/S_i) (dB)	Fig. 3																		
10a.	10 LOG (D_o/D) (dBA)	Fig. 4																		
10b.	15 LOG (D_o/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_o(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6																		
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7	-10.5			-7.5			-4.			-10.								
12.	ϕ_L (degrees)	Fig. 10																		
13.	ϕ_R (degrees)	Fig. 10																		
14.	δ_o (metres)	Fig. 9																		
15.	N_o	Eq. 18																		
16.	Δ_B (dBA)	Appendix B																		
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)																			
19.	$L_{eq}(h)$ (dBA)																			
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 5-2. Noise Prediction Worksheet

(Continued)

PROBLEM 6

Refer to Figure 6-1 below. Using the traffic data given in Problem 2, compare the sound levels that reach the observer from Segment A and Segment B. The *L/S* is less than 3 metres above the ground and the intervening ground from Segment A has been paved over. The intervening ground from Segment B is covered with grass. The highway is infinitely long. Lane width is 3.66 metres. Use Table 1 and the Figures to solve this problem.

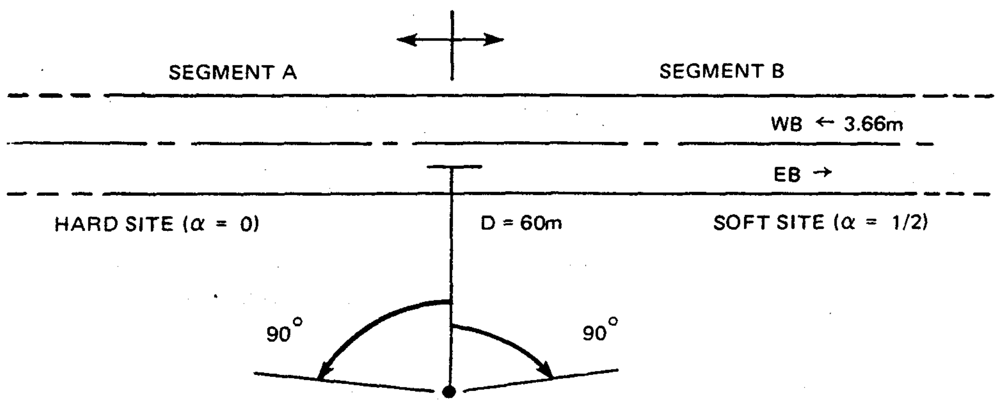


Figure 6-1

TRAFFIC DATA

Vehicle Class	Eastbound Lane V/H	Westbound Lane V/H
A	317	281
MT	24	12
HT	22	25

S = 75 km/h

SOLUTION

This problem will be solved by using Figure 1 and Table 1 as a computational guide.

Step 1. Refer to Table 6-1. Complete Lines 1-4 from the data given in the problem statement.

Step 2. Determine the perpendicular distance from the observer to the centerline of the EB Lane (60 m) and the WB Lane (64 m). Record these values on Line 5, Table 6-1.

(Continued)

Problem 6 (Continued)

Step 3. Refer to Figure 5 and Figure 6-1 and determine ϕ_1 and ϕ_2.

Segment A: $\underline{\phi_1 = -90^\circ}$ $\underline{\phi_2 = 0}$

Check $\Delta\phi = \phi_2 - \phi_1 = 0 - (-90) = +90^\circ$ $\underline{\underline{\text{OK}}}$

Segment B: $\underline{\phi_1 = 0^\circ}$ $\underline{\phi_2 = 90^\circ}$

Check $\Delta\phi = \phi_2 - \phi_1 = 90^\circ - 0^\circ = +90^\circ$ $\underline{\underline{\text{OK}}}$

Record the values for ϕ_1 and ϕ_2 on Lines 6 and 7, Table 6-1.

Step 4. Refer to Figure 2 and determine the reference energy emission levels. Record these values on Line 8, Table 6-1.

Step 5. Refer to Figure 3 and determine the traffic flow adjustments to the Reference levels. Six different adjustments must be computed for each segment.

Note $D_o = 15$ metres, $S = 75$ km/h

Record these values on Line 9, Table 6-1.

Step 6. Refer to Table 2 and Figure 4 and compute the adjustments for distances. The adjustments for Segment A are based on 10 log (D_o/D).

Record these values on Line 10(a), Table 6-1. The adjustments for Segment B are based on 15 log (D_o/D).

Record these values on Line 10(b), Table 6-1.

Step 7. Refer to Figure 6 and compute the finite length roadway adjustment for Segment A. Record these values on Line 11(a), Table 6-1. Refer to Figure 7, and compute the finite length roadway adjustment for Segment B. Record these values on Line 11(b), Table 6-1.

Step 8. Since there are no barriers in this problem Lines 12-16 are not applicable. Refer to Figure 1 and compute the $L_{eq}(h)_i$ for each class of vehicles and enter these values in Line 18, Table 6-1.

Example: Segment A, E.B.

$$L_{eq}(h)_A = 69 + 18 - 6 - 3 - 25 = \underline{53\text{ dBA}}$$

$$L_{eq}(h)_{MT} = 80 + 7 - 6 - 3 - 25 = \underline{53\text{ dBA}}$$

$$L_{eq}(h)_{HT} = 84.5 + 6.5 - 6 - 3 - 25 = \underline{57\text{ dBA}}$$

(Continued)

PROBLEM 6 (Continued)

Example: Segment B, W.B.

$$L_{eq}(h)_{A} = 69 + 17.5 - 9.5 - 4 - 25 = \underline{48\text{ dBA}}$$

$$L_{eq}(h)_{MT} = 80 + 4. - 9.5 - 4 - 25 = \underline{45.5\text{ dBA}}$$

$$L_{eq}(h)_{HT} = 84.5 + 7 - 9.5 - 4 - 25 = \underline{53\text{ dBA}}$$

Step 9. Use Equation (2) to compute the $L_{eq}(h)$ for each lane and enter these values on Line 19, Table 6-1.

Example: Segment A, W.B.

$$L_{eq}(h) = 10 \log [10^{5.2} + 10^{4.95} + 10^{5.7}] = \underline{58.7\text{ dBA}}$$

Step 10. Compute $L_{eq}(h)$ for each segment and record values on Line 22, Table 6-1. In this particular problem, the acoustics contribution of Segment A (62 dBA) is 4 dBA more than the contribution from Segment B. The total noise level heard by the observer is:

$$L_{eq}(h) = 10 \log [10^{6.21} + 10^{5.81}] = \underline{63.6\text{ dBA}}$$

Note: Throughout this manual, values from the various figures will be read to the nearest 0.5 dB. The dB addition was done on a calculator and it will be reported to the nearest 0.1 dB.

NAME ______________________ PROJECT DESCRIPTION PROBLEM 6

DATE ______________________

			Segment A						Segment B											
1.	LANE NO./ROAD SEGMENT		EB			WB			EB			WB								
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		317	24	22	281	12	25	317	24	22	281	12	25						
4.	S(km/h)		–	75	–	–	75	–	–	75	–	–	75	–						
5.	D(m)		60			64			60			64								
6.	ϕ_1 (degrees)	Fig. 5	-90			-90			0			0								
7.	ϕ_2 (degrees)	Fig. 5	0			0			90			+90								
8.	$(\overline{L_o})E_i$ (dBA)	Fig. 2	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5	69	80.	84.5						
9.	10 LOG (N_iD_o/S_i) (dB)	Fig. 3	18.	7.	6.5	17.5	4.	7.	18.	7.	6.5	17.5	4.	7.						
10a.	10 LOG (D_o/D) (dBA)	Fig. 4	-6			-6.5														
10b.	15 LOG (D_o/D) (dBA)	Fig. 4							-9.			-9.5								
11a.	10 LOG $(\psi_o(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6	-3			-3														
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7							-4.			-4.								
12.	ϕ_L (degrees)	Fig. 10																		
13.	ϕ_R (degrees)	Fig. 10																		
14.	δ_o (metres)	Fig. 9																		
15.	N_o	Eq. 18																		
16.	Δ_B (dBA)	Appendix B																		
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		53.	53.	57.	52.	49.5	57.	49.	49.	53.	48.	45.5	53.						
19.	$L_{eq}(h)$ (dBA)		59.5			58.7			55.5			54.7								
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)		62.1						$L_{eq}(h)$ = 63.5			58.1								
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 6-1. Noise Prediction Worksheet

Summary

$L_{eq}(h)_i = (\overline{L_o})_{E_i}$	reference energy mean emission level (Figure 2 and line 8 of Table 1)
$+10 \log \left(\frac{N_i D_o}{S_i}\right)$	traffic flow adjustment (Figure 3 and line 9 of Table 1)
$+\begin{cases} 10 \log \left(\frac{D_o}{D}\right) \\ \\ 15 \log \left(\frac{D_o}{D}\right) \end{cases}$	distance adjustment factor, hard site (Figure 4 and line 10(a) or Table 1) distance adjustment factor, soft site (Figure 4 and line 10(b) of Table 1)
$+\begin{cases} 10 \log \left(\frac{\Delta\phi}{\pi}\right) \\ \\ 10 \log \left(\frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi}\right) \end{cases}$	finite roadway adjustment, hard site (Figure 6 and line 11(a) of Table 1) finite roadway adjustment, soft site (Figure 7 and line 11(b) of Table 1)
$+\Delta_s$	shielding
-25	constant

Users of this manual can now predict the equivalent sound level produced by a class of vehicle traveling at constant speed on a flat highway.

f. Shielding Adjustments to the Reference Levels

So far it has been shown that, as a minimum, the equivalent sound levels generated by a stream of traffic decrease at the rate of 3 dBA/DD. This attenuation is accounted for explicitly in the FHWA model when the site parameter is zero ($\alpha = 0$). This phenomenon is illustrated in Figure 8(a).

It has also been discussed that in many situations ground effects can lead to an additional attenuation of up to 1.5 dBA/DD. This only occurs when both the source and receiver are close to the ground and the terrain between the observer and the roadway is relatively flat and soft [6,8]. As a result of this additional attenuation, the equivalent sound levels decrease at a rate of approximately 4.5 dBA/DD at soft sites. Excess attenuation is accounted for explicitly in the FHWA model when the site parameter is one-half ($\alpha = 1/2$). This is illustrated in Figure 8(b). Note that the attenuation rates shown in Figure 8(a) and Figure 8(b) are not additive—the user can only choose one, based upon site conditions.

Attenuation due to temperature gradients, winds, and atmospheric absorption also occur but these phenomenon are ignored in the FHWA method. Attenuation due to wind and temperature gradients is ignored for two reasons—(1) atmospheric conditions vary widely from hour to hour and from site to site and the (2) attenuation they provide is not permanent. Atmospheric absorption, caused by water vapor, is not important in highway work because of the long distances sound must travel before the attenuation from this mechanism becomes significant. Although atmospheric effects are not important in prediction, they can be very important when making measurements.

Attenuation due to shielding is also an important mechanism by which highway sound levels are lowered. Shielding occurs when the observer's view of a highway is obstructed or partially obstructed by an object or objects which significantly interfere with the propagation of the sound waves. Shielding can be provided by dense woods, rows of buildings, and/or barriers.

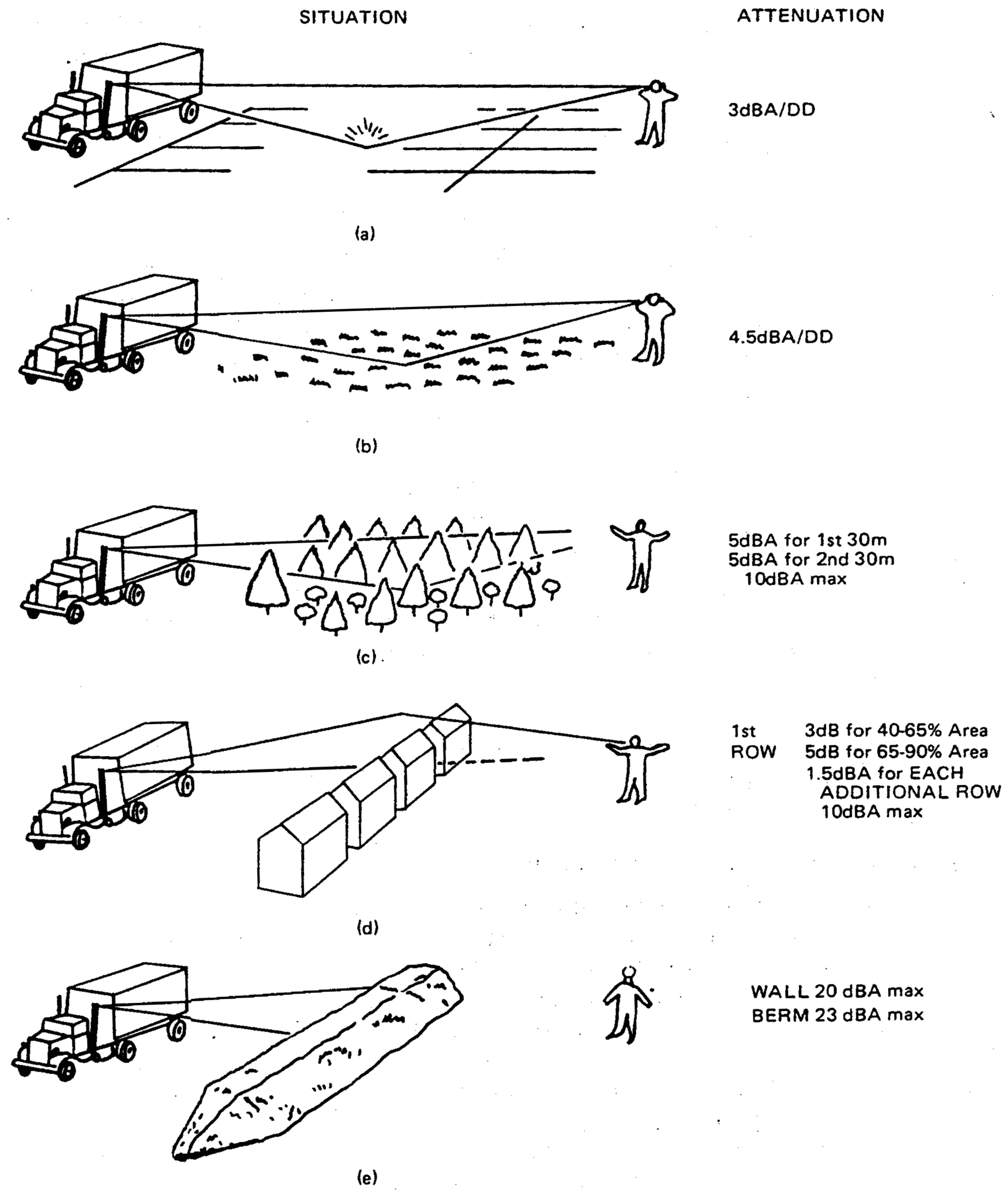


Figure 8. Attenuation of Highway Traffic Noise

1. *Dense Woods and Rows of Buildings* [6,11]

Enough information is known about dense woods and rows of buildings to account for the attenuation they provide by simple rules of thumb. If the woods are very dense, i.e., there is no clear line of sight between the observer and the source, and if the height of the trees extends at least 5 metres above the line of sight, then 5 dBA attenuation is allowed if the woods have a depth of 30 metres. An additional 5 dBA may be obtained if the depth of the woods extends for another 30 metres. 10 dBA is the maximum attenuation dense woods can provide. This is illustrated in Figure 8(c).

The amount of attenuation provided by rows of buildings depends upon the actual length of the row occupied by the buildings. 3 dBA is provided by the first row when the buildings occupy 40 to 65 percent of the length of the row and 5 dBA when the buildings occupy 65 to 90 percent of the length of the row. No attenuation is allowed for rows of houses that occupy less than 40 percent of the length of the row. 1.5 dBA additional attenuation is provided by each successive row until a total attenuation of 10 dBA for all rows is obtained. This is the maximum attenuation that this mechanism provides. This is illustrated in Figure 8(d).

The excess attenuation provided by ground effects is assumed to end when the sound waves reach the dense woods or the first row of buildings. Thus the attenuation provided by dense woods and rows of buildings is only additive to the attenuation provided by geometric spreading (3 dBA/DD). In addition, the combined effects of dense woods and rows of buildings are only additive until a maximum of 10 dBA attenuation is achieved. Thereafter the effects of additional woods and rows of buildings is ignored [6].

2. *Barriers*

Barriers include such items as berms, walls, large buildings, hills, etc., that affect sound propagation by interrupting its propagation and creating an "acoustic shadow zone." The sound level is lower in the shadow zone than in the respective free field. This is illustrated in Figure 8(e). In recent years, the construction of noise barriers has become a fairly common method of abating highway traffic noise. Although this section only addresses manmade barriers constructed specifically for highway noise abatement, the principles are applicable to large buildings, hills, depressed sections, etc.

Barriers have been constructed of a variety of materials and in three basic shapes—earth berms, freestanding walls, and combinations berm-walls. A few of the early barriers did not provide the attenuation for which they were designed. Evaluation of these barriers has pointed out several crucial features of noise barriers [7-9]:

(1) The transmitted noise must be 10 dBA less than the diffracted noise.
(2) The barriers cannot have cracks in them.
(3) The barriers must be high enough to break the line-of-sight between the observer and source and long enough to prevent noise leaks around the ends.

These problems may now be satisfactorily addressed by engineers. Two additional considerations have recently emerged that must be addressed to ensure satisfactory barrier design [8]. It appears that the shape of the barrier affects the amount of attenuation. Recent data suggests that earth berms provide about 3 dBA more attenuation than freestanding walls. Although it is not clear at this time why this is true, it probably has something to do with absorption or edge effects. The second consideration requires the introduction of an expression familiar to acoustical engineers but alien to highway engineers—field insertion loss (I.L.). Field insertion loss is simply the difference in the noise levels at the same location before and after the barrier is constructed.

$$\text{Field Insertion Loss (I.L.)} = L\ (\text{Before}) - L\ (\text{After}) \tag{14}$$

where

L represents $L_{eq}(h)$ or $L_{10}(h)$.

Thus three elements must be accounted for in barrier designs: barrier attenuation, barrier shape, and field insertion loss.

(a) *Barrier Attenuation and Barrier Shape*

The attenuation provided by a freestanding wall can be expressed as a function of the Fresnel number, the barrier shape, and the barrier length in the following form (see Appendix B),

$$\Delta_{B_i} = 10 \log \left[\frac{1}{\phi_R - \phi_L} \int_{\phi_L}^{\phi_R} 10^{\frac{-\Delta_i}{10}} d\phi \right] \tag{15}$$

where

Δ_{B_i} is the attenuation provided by the barrier for the ith class of vehicles.

ϕ_R, ϕ_L are angles that establish the relationship (position) between the barrier and the observer.

$$\Delta_i = \begin{cases} 0 & N_i \leqslant -0.1916 - 0.0635\epsilon \\ 5(1 + 0.6\epsilon) + 20 \log \dfrac{\sqrt{2\pi |N_o|_i \cos\phi}}{\tan \sqrt{2\pi |N_o|_i \cos\phi}} & (-0.1916 - 0.0635\epsilon) \leqslant N_i \leqslant 0 \\ 5(1 + 0.6\epsilon) + 20 \log \dfrac{\sqrt{2\pi (N_o)_i \cos\phi}}{\tanh \sqrt{2\pi (N_o)_i \cos\phi}} & 0 \leqslant N_i \leqslant 5.03 \\ 20(1 + 0.15\epsilon) & N_i \geqslant 5.03 \end{cases}$$

where Δ_i is the point source attenuation for the ith class of vehicles.

$N_i = (N_o)_i \cos\phi$

ϵ is a barrier shape parameter, 0 for a freestanding wall and 1 for an earth berm.

N_o is the Fresnel number determined along the perpendicular line between the source and receiver.

N_{o_i} is the Fresnel number of the ith class of vehicles determined along the perpendicular line between the source and receiver.

Mathematically the Fresnel number, N_o, is defined as

$$N_o = 2\left(\frac{\delta_o}{\lambda}\right) \tag{16}$$

where

δ_o is the pathlength difference measured along the perpendicular line between the source and receiver.

λ is the wavelength of the sound radiated by the source.

The pathlength difference, δ_0, is the difference between a perpendicular ray traveling directly to the observer and a ray diffracted over the top of the barrier,

$$\delta_o = A_o + B_o - C_o \tag{17}$$

where the distances A_o, B_o, and C_o are the distances shown in Figure 9. Note that if the height of the noise source or the observer changes, the pathlength difference will also change.

Highway traffic noise is broadband, i.e., contains energy in the frequency bands throughout the audible range and the Fresnel number will vary according to the frequency chosen. However it has been shown that the attenuation of the A-weighted sound pressure level of a typical car is almost identical to the sound attenuation of the 550 Hertz band [10]. Based on this, it is generally assumed

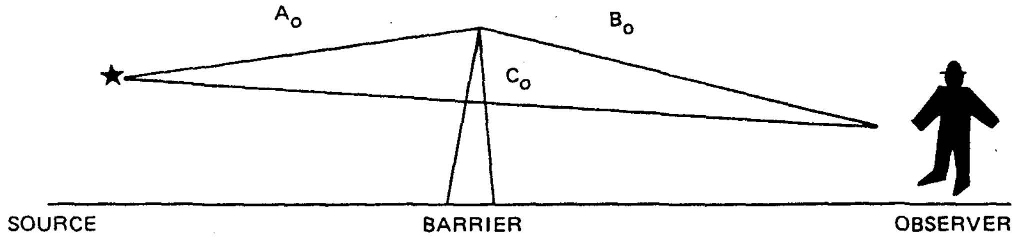


Figure 9. Pathlength Difference, δ_0

that the effective radiating frequency of highway traffic noise for all classes of vehicles is 550 Hz. Therefore, Equation (15) reduces to:

$$N_o = 2\left(\frac{\delta_o}{\lambda}\right) = 2\left(\frac{f\,\delta_o}{c}\right) = 2\left(\frac{550\,\delta_o}{343}\right) = 3.21(\delta_o)\text{ metres.} \tag{18}$$

For barrier calculations only, the vehicle noise sources are assumed to be located at the following positions:

(1) Automobiles — 0 metres above the centerline of the lane.
(2) Medium Trucks — 0.7 metres above the centerline of the lane.
(3) Heavy Trucks — 2.44 metres above the centerline of the lane.

The above positions attempt to take into account and centralize the locations of the many individual sources contributing to the overall noise radiated by medium and heavy trucks, i.e., tire, engine, exhaust, etc.

For barriers of finite length, the attenuation provided by a barrier depends on how much of the roadway is shielded from the observer. Thus, it is necessary to establish the angular relationship between the roadway and the observer and between the barrier and the observer. The angular relationship between the roadway and the observer was discussed in Section 2(e) and illustrated in Figure 5. The same procedure is used to establish the angular relationship between the barrier and the observer, except that the angles which establish the end points of the barrier are identified as ϕ_L and ϕ_R. This orientation assumes that the observer is facing the barrier. The angle measured from the perpendicular to the left most end of the barrier is ϕ_L. The angle measured from the perpenducular to the right most end of the barrier is ϕ_R. Angles measured to the left of the perpendicular are negative and angles measured to the right of the perpendicular are positive. Only three cases are possible and they are shown in Figure 10. The advantage of this procedure is that the observer can now be located at any point and the attenuation provided by the barrier can be computed.

With knowledge of N_o, ϕ_L, ϕ_R the integral in Equation (15) can be solved. This integral has been numerically integrated for a range of values of $N_o = -0.2$ to $N_o = 100$, and is presented in ten degree increments in Appendix B. The barrier attenuation values given in these tables are for free-standing walls. When using the tables to determine the attenuation due to earth berms, add 3 dBA to the values shown in the tables [8].

For infinitely long barriers, i.e., $\phi_L = -90°$ and $\phi_R = +90°$, the attenuation provided by the barrier can be read from Figure 11 for positive values of N_o. For negative values of N_o, see Figure 12. Figures 11 and 12 are based on the tables in Appendix B using $\phi_L = -90°$ and $\phi_R = +90°$.

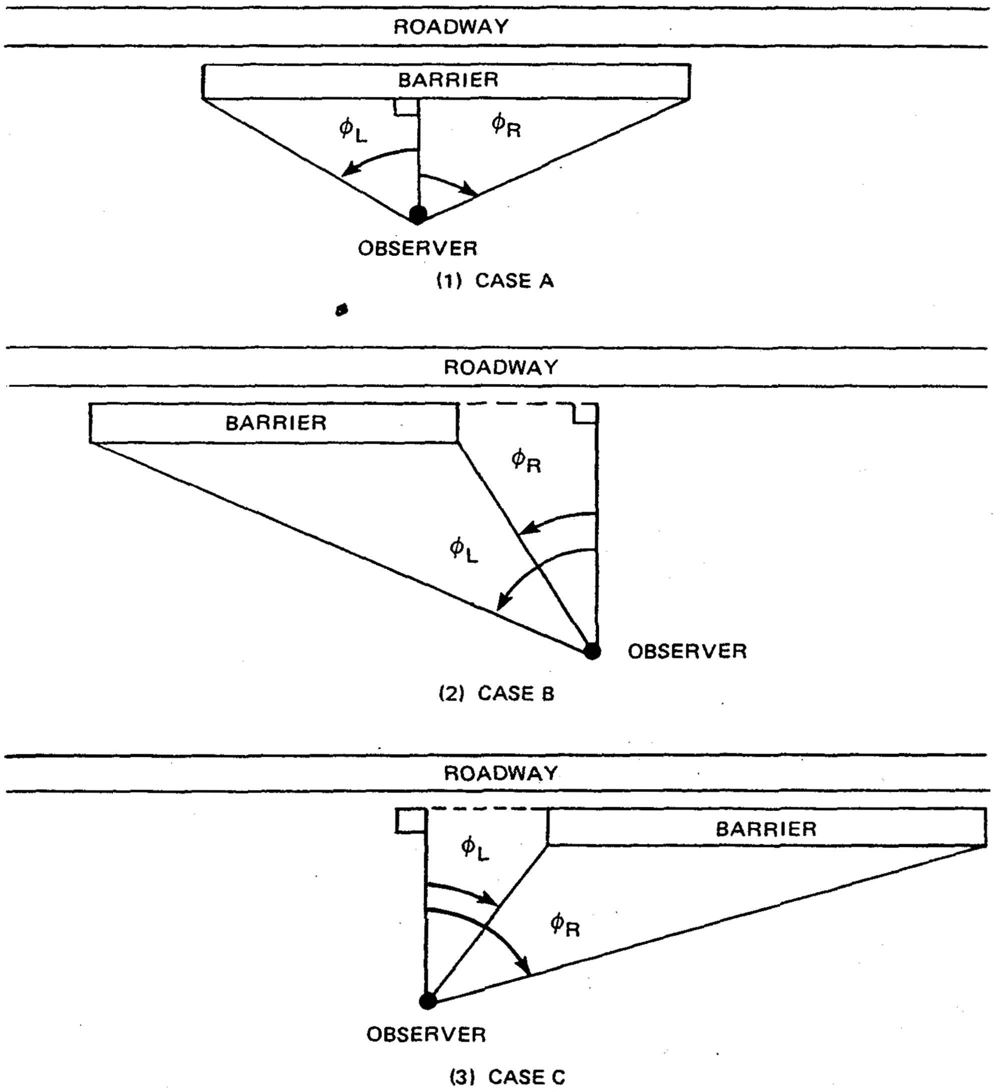


Figure 10. Angle Identification of Barriers

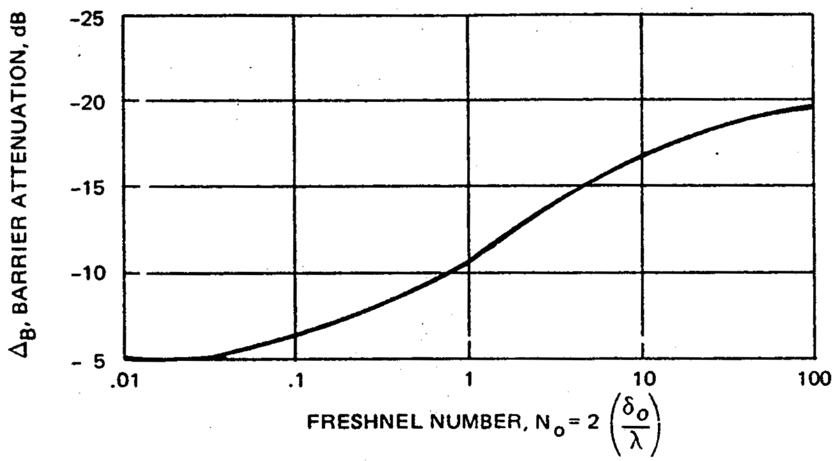


Figure 11. Barrier Attenuation vs Fresnel Number, N_o, for Infinitely Long Barriers

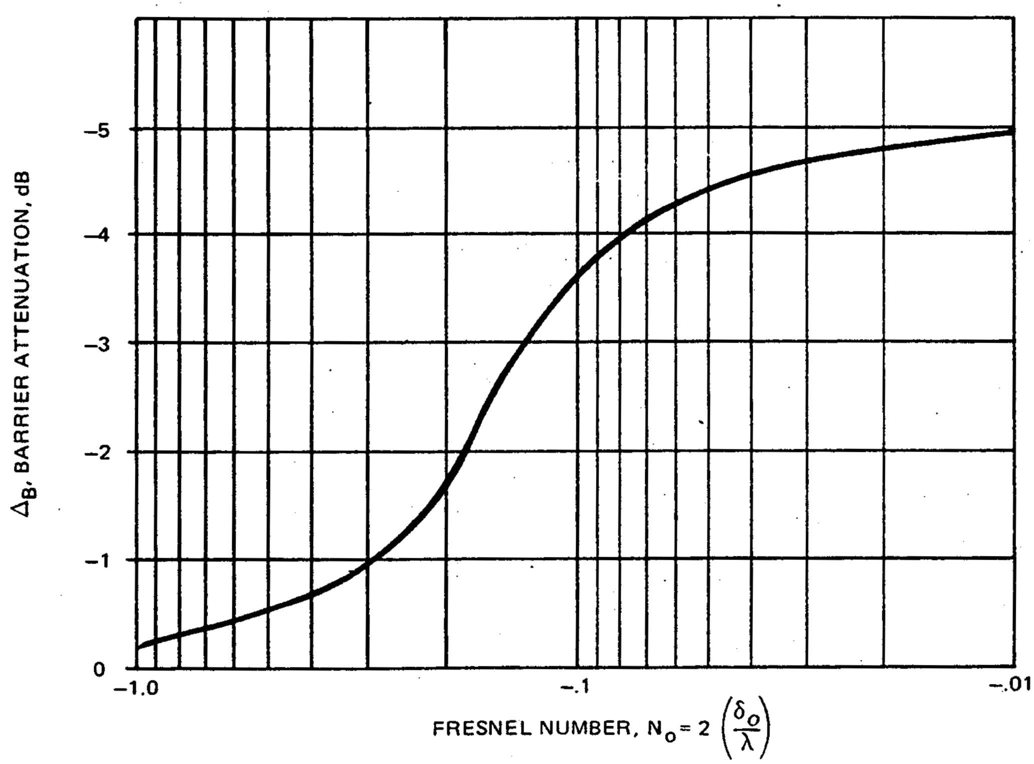


Figure 12. Barrier Attenuation vs Negative Fresnel Number, N_o, for Infinitely Long Barriers

PROBLEM 7

Refer to Figure 7-1. Compute the sound level at the observer under the following conditions:

(a) No barrier (i.e., free field).

(b) Infinitely long concrete barrier.

(c) Infinitely long earth berm.

The barrier is 4 metres high and the terrain between the roadway and the observer is paved ($\alpha = 0$).

The observer height is 1.5 m.

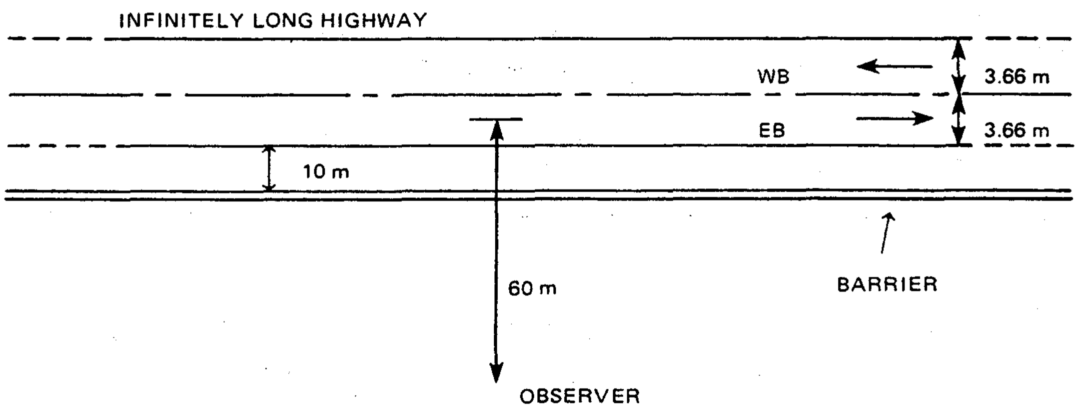


Figure 7-1. Highway Site Geometry for Problem 7

TRAFFIC DATA

Vehicle Class	EB Lane	WB Lane
A	317	281
MT	24	12
HT	22	25

SOLUTION

This problem will be solved by using Table 1 as a computational guide.

PROBLEM 7 (a)

Step 1. Refer to Table 7-1. Complete lines 1–4 from the data given in the problem statement.

Step 2. Determine the perpendicular distances from the observer to the centerline of the EB Lane (60 m) and the centerline of the WB Lane (64 m). Record these values on Line 5, Table 7-1.

(Continued)

PROBLEM 7 (Continued)

Step 3. Refer to Figure 5 and Figure 7-1 of the problem. $\phi_1 = -90°$, $\phi_2 = +90°$.

$$\text{Check } \Delta\phi = \phi_2 - \phi_1 = 90° - (-90°) = 180° \quad \text{OK}$$

Record the values for ϕ_1 and ϕ_2 on Lines 6 and 7, Table 7-1.

Step 4. Refer to Figure 2 and determine the reference energy mean emission levels. Record values on Line 8, Table 7-1.

Step 5. Refer to Figure 3 and determine the traffic flow adjustments to the reference levels. Note D_o = 15 m, S = 75 km/h. Record these values on Line 9, Table 7-1.

Step 6. Refer to Table 2 and Figure 4 and compute the adjustments for distance. The adjustments for distance are based on $10 \log D_o/D(\alpha = 0)$. Record these values on Line 10(a), Table 7-1.

Step 7. Refer to Figure 6 and compute the finite length roadway adjustments. Since $\alpha = 0$, $\phi_1 = -90°$ and $\phi_2 = +90°$, the adjustment is 0.

Step 8. Since there are no barriers in Problem 7(a), Lines 12-16 are not applicable.

Compute $L_{eq}(h)_i$ for each class of vehicles and enter these values in Line 18, Table 7-1.

Example: EB Lane

$$L_{eq}(h)_A = 69 + 18 - 6 - 25 = \underline{56 \text{ dBA}}$$

$$L_{eq}(h)_{MT} = 80 + 7 - 6 - 25 = \underline{56 \text{ dBA}}$$

$$L_{eq}(h)_{HT} = 84.5 + 6.5 - 6 - 25 = \underline{60 \text{ dBA}}.$$

Step 9. Use Equation (2), page 2 and compute $L_{eq}(h)$ for each lane and enter these values on Line 19, Table 1.

Example: EB Lane

$$L_{eq}(h) = 10 \log [10^{5.6} + 10^{5.6} + 10^{6.0}] = \underline{62.5 \text{ dBA}}$$

Step 10. Compute $L_{eq}(h)$ and enter on Line 22, Table 1.

$$L_{eq}(h) = 10 \log [10^{6.25} + 10^{6.17}] = \underline{65.1 \text{ dBA}}.$$

PROBLEM 7(b)

Step 1. Refer to Problem 7(a). The values shown in Table 7-1, Lines 1-11 are unchanged.

Step 2. Refer to Figure 10. Since the problem statement indicated that the concrete barrier was infinitely long $\phi_L = -90°$ and $\phi_R = +90°$.

Record these values on Lines 12 and 13, Table 7-1.

(Continued)

PROBLEM 7 (Continued)

Step 3. Since there are 3 classes of vehicles and 2 lanes, it is necessary to calculate 6 pathlength differences, δ_o. These distances must be computed to the nearest 1/100 of a metre. See Figure 7-2 and Figure 7-3.

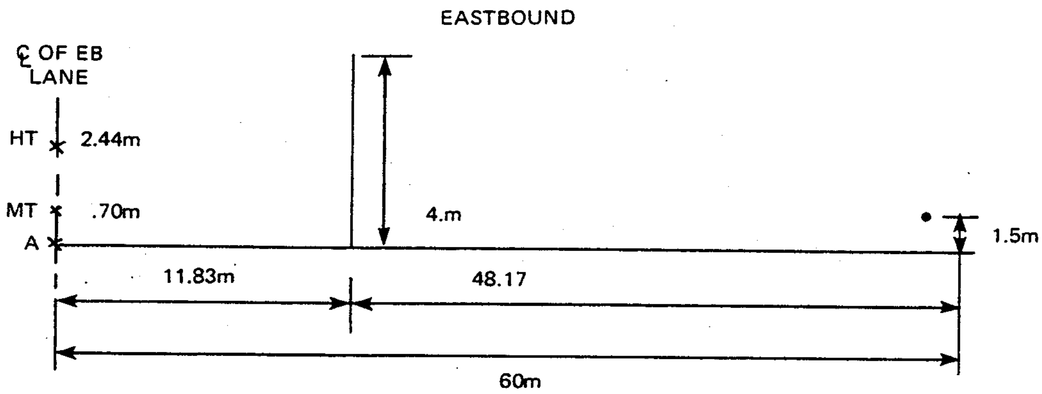


Figure 7-2. Barrier Geometry Used to Calculate Pathlength Differences (Eastbound Lanes)

$$\delta_A = \sqrt{(11.83)^2 + (4)^2} + \sqrt{(4\text{-}1.5)^2 + (48.17)^2} - \sqrt{(60)^2 + (1.5)^2}$$

$$= \underline{0.70 \text{ m}}$$

$$\delta_{MT} = \sqrt{(11.83)^2 + (4.\text{-}.7)^2} + \sqrt{(4\text{-}1.5)^2 + (48.17)^2} - \sqrt{(60)^2 + (1.5\text{-}.7)^2}$$

$$= \underline{.51 \text{ m}}$$

$$\delta_{HT} = \sqrt{(11.83)^2 + (4\text{-}2.44)^2} + \sqrt{(4\text{-}1.5)^2 + (48.17)^2} - \sqrt{(60)^2 + (2.44\text{-}1.5)^2}$$

$$= \underline{.16 \text{ m}}.$$

(Continued)

PROBLEM 7 (Continued)

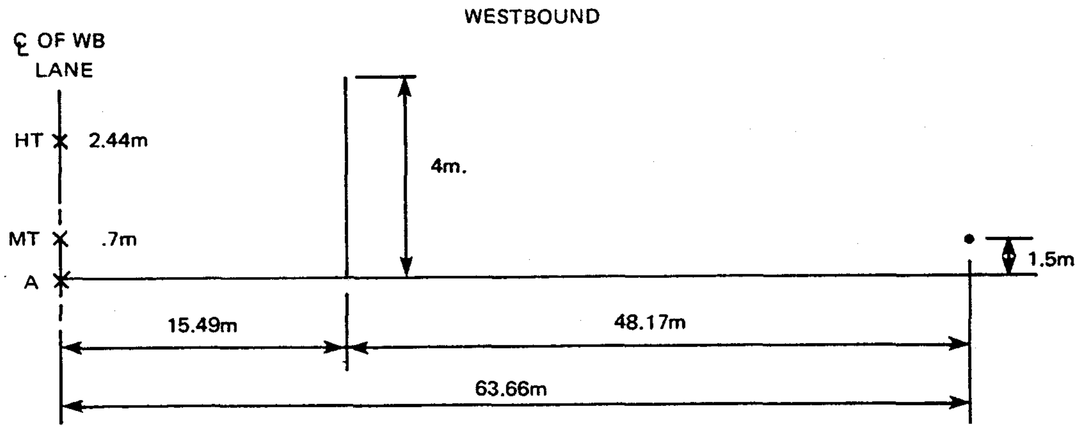


Figure 7-3. Barrier Geometry Used to Calculate Pathlength Differences (Westbound Lanes)

$$\delta_A = \sqrt{(15.49)^2 + (4)^2} + \sqrt{(48.17)^2 + (4\text{-}1.5)^2} - \sqrt{(63.66)^2 + (1.5)^2}$$

$$= \underline{.56 \text{ m}}$$

$$\delta_{MT} = \sqrt{(15.49)^2 + (4\text{-}.7)^2} + \sqrt{(48.17)^2 + (4\text{-}1.5)^2} - \sqrt{(63.66)^2 + (1.5\text{-}.7)^2}$$

$$= \underline{.41 \text{ m}}$$

$$\delta_{HT} = \sqrt{(15.49)^2 + (4\text{-}2.44)^2} + \sqrt{(48.17)^2 + (4\text{-}1.5)^2} - \sqrt{(63.66)^2 + (2.44\text{-}1.5)^2}$$

$$= \underline{.14 \text{ m}}$$

Record the pathlength difference on Line 14, Table 7-1.

Step 4. Use Equation (18) and compute the Fresnel Number, N_o, for each pathlength difference. Record these values on Line 15, Table 7-1.

EB	WB
$(N_o)_A = 3.21\,(.70) = \underline{2.25}$	$(N_o)_A = 3.21\,(.56) = \underline{1.80}$
$(N_o)_{MT} = 3.21\,(.51) = \underline{1.64}$	$(N_o)_{MT} = 3.21\,(.41) = \underline{1.32}$
$(N_o)_{HT} = 3.21\,(.16) = \underline{.51}$	$(N_o)_{HT} = 3.21\,(.14) = \underline{.45}$

Step 5. Using the data shown in Lines 12-15, Table 7-1, turn to the barrier tables in Appendix B. Use N_o to select the proper table. Locate ϕ_L in the left hand column and read horizontally to the right to the proper ϕ_R column. The value shown in the ϕ_R column is the barrier attenuation, Δ_B. If N_o falls between two tables, the correct Δ_B can be obtained by linear interpretation.

(Continued)

PROBLEM 7 (Continued)

EXAMPLE

$\phi_L = -90^\circ \quad \phi_R = +90^\circ \quad N_o \text{ (EB)} = 2.25 \quad \Delta_B = ?$

$$1.0 \left\{ \begin{array}{l} \left.\begin{array}{l} 2.0 \\ 2.25 \end{array}\right\} .25 \\ 3.0 \end{array} \right. \qquad -1.3 \left\{ \begin{array}{l} \left.\begin{array}{l} -12.3 \\ \boxed{} \end{array}\right\} x \\ -13.6 \end{array} \right.$$

(left column headed N_o, right column headed Δ_B)

$$\frac{.25}{1.0} = \frac{x}{-1.3} \qquad x = -.3$$

therefore $\Delta_B(N_o = 2.25) = -12.4 + (-.3) = \underline{-12.7 \text{ dB}}$

N_o	Δ_B
2.25	−12.6
1.64	−11.6
.51	−8.6
1.80	−11.9
1.32	−11.
.45	−8.2

Record these values on Line 16, Table 1.

Step 6. Compute the $L_{eq}(h)_i$ for each class of vehicles, and enter these values on Line 18, Table 7-1.

EXAMPLE: EB LANE

$$L_{eq}(h)_A = 69 + 18 - 6 - 12.6 - 25 = \underline{43.4 \text{ dBA}}$$

Step 7. Use Equation (2) and compute $L_{eq}(h)$ for each lane and enter these values on Line 19, Table 7-1.

EXAMPLE: EB LANE

$$L_{eq}(h) = 10 \log [10^{4.34} + 10^{4.44} + 10^{5.15}] = \underline{52.8 \text{ dBA}}$$

Step 8. Compute the noise level at the observer and enter this value on Line 22, Table 1.

$$L_{eq}(h) = 10 \log [10^{5.28} + 10^{5.26}] = \underline{55.7 \text{ dBA}}$$

(Continued)

PROBLEM 7 (Continued)

PROBLEM 7(c)

Step 1. Problem 7(c) is identical to Problem 7(b) with the exception that the barrier is now an earth berm rather than a concrete wall. Consequently 3 dB additional attenuation must be added to the values given in the barrier tables in Appendix B. The noise level at the observer is given in Table 7-1.

NAME ____________________ PROJECT DESCRIPTION PROBLEM 7

DATE ____________________

			(a) Free Field						(b) Concrete Barrier						(c) Earth Berm					
1.	LANE NO./ROAD SEGMENT		EB			WB			EB			WB			EB			WB		
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		317	24	22	281	12	25	317	24	22	281	12	25	317	24	22	281	12	25
4.	S(km/h)		–	75	–	–	75	–	–	75	–	–	75	–	–	75	–	–	75	–
5.	D(m)		60			64			60			64			60			64		
6.	ϕ_1 (degrees)	Fig. 5	-90			-90			-90			-90			-90			-90		
7.	ϕ_2 (degrees)	Fig. 5	+90			+90			+90			+90			+90			+90		
8.	$(\overline{L_o})_{E_i}$ (dBA)	Fig. 2	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5
9.	10 LOG $(N_i D_o/S_i)$ (dB)	Fig. 3	18.	7.	6.5	17.5	4.	7.	18.	7.	6.5	17.5	4.	7.	18.	7.	6.5	17.5	4.	7.
10a.	10 LOG (D_o/D) (dBA)	Fig. 4	-6.			-6.5			-6.			-6.5			-6			-6.5		
10b.	15 LOG (D_o/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_o(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6	0.			0			0			0			0			0		
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7																		
12.	ϕ_L (degrees)	Fig. 10							-90			-90			-90			-90		
13.	ϕ_R (degrees)	Fig. 10							+90			+90			+90			+90		
14.	δ_o (metres)	Fig. 9							.70	.51	.16	.56	.41	.14	.70	.51	.16	.56	.41	.14
15.	N_o	Eq. 18							2.25	1.64	.51	1.80	1.32	.45	2.25	1.64	.51	1.80	1.32	.45
16.	Δ_B (dBA)	Appendix B							-12.6	-11.6	-8.5	-11.9	-11.	-8.3	-15.6	-14.6	-11.5	-14.9	-14.	-11.3
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		56.	56.	60.	55.	52.5	60.	43.4	44.4	51.5	43.1	41.5	51.7	40.4	41.4	48.5	40.1	38.5	48.7
19.	$L_{eq}(h)$ (dBA)		62.5			61.7			52.8			52.6			49.8			49.6		
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)		65.1						55.7						52.7					
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 7-1. Noise Prediction Worksheet

Users of this manual may have noted what appears to be a paradox in the attenuation values shown in the tables in Appendix B. For example, for $N_o = 2.00$, $\phi_L = -90°$ and $\phi_R = 90°$, the attenuation is shown as −13.7 dB. If the barrier is shortened to $\phi_L = -50°$ and $\phi_R = 40°$, the attenuation is shown as −17.2 dB. It appears that the shorter barrier provides 3.5 dB more attenuation than the longer barrier. Clearly this is impossible! The explanation for this lies in the way these tables were prepared. The attenuation values shown in the tables are only applied to the portion of the roadway shielded by the barrier. This means that all roadways involving barriers of finite length must be broken down into segments. One of these segments must be shielded by the barrier. Account must then be taken of the traffic noise that comes around the ends of the barrier. This is illustrated in problem 8.

PROBLEM 8

Refer to Problem 7 and Figure 8-1. What is the sound level at the observer if the concrete barrier of Problem 7 extended from $\phi_L = -20°$ to $\phi_R = +70°$?

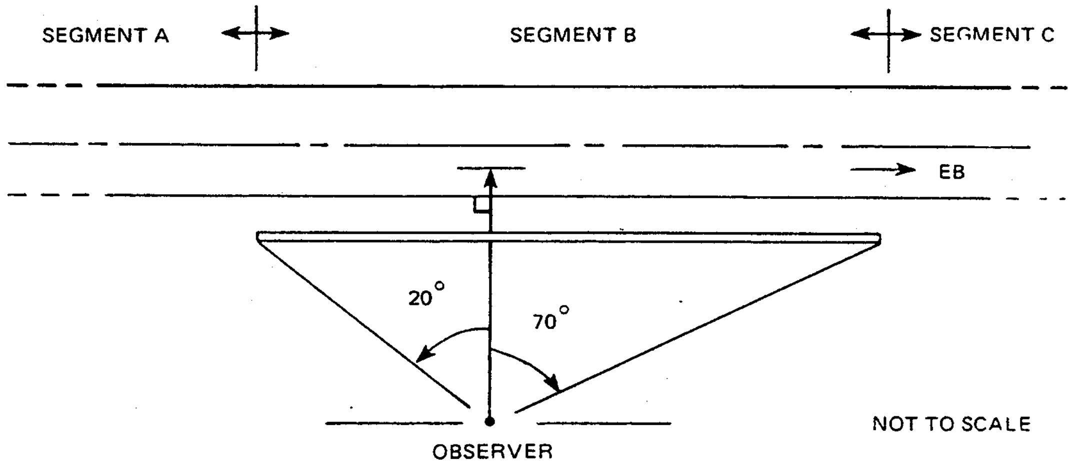


Figure 8-1. Highway Site Geometry for Problem 8

SOLUTION

The solution of this problem requires that the highway be broken down into three segments:

Segment A	$\phi_1 = -90°$,	$\phi_2 = -20°$
Segment B	$\phi_1 = -20°$,	$\phi_2 = +70°$
Segment C	$\phi_1 = +70°$,	$\phi_2 = +90°$.

Step 1. Identify the road segment on Line 1, Table 8-1, and complete Lines 6 and 7 based on Figure 8-1.

Step 2. Lines 2, 3, 4, 5, 8, 9, and 10(a) are identical to these shown in Problem 7(a). Complete these lines.

SEGMENT A

Step 1. Compute the finite length roadway adjustment for Segment A.

$10 \log (\Delta\phi/180°) = 10 \log (70°/180°) = -4$ dB. Enter this value on Line 11(a), Table 8-1.

Step 2. Complete the remainder of Table 8-1 for Segment A.

(Continued)

PROBLEM 8 (Continued)

SEGMENT B

Step 1. Compute the finite length roadway adjustment for Segment B. 10 log $(\Delta\phi/180°)$ = 10 log $(90°/180°)$ = $\underline{-3\text{ dB}}$. Enter this value on Line 11(a), Table 8-1.

Step 2. The problem indicates that a barrier extended from $\phi_L = -20°$ to $\phi_R = +70°$. Enter these values on Lines 12 and 13, Table 8-1.

Step 3. The pathlength differences and the Fresnel numbers are identical to those computed in Problem 7(b). Record these values.

Step 4. Refer to Appendix B and determine the barrier attenuations. $\phi_L = -20°$, $\phi_R = +70°$.

EXAMPLE

$$\begin{array}{lll} \underline{N_0} & & \underline{\Delta_B} \\ 2.00 & & -14.8 \\ & .25 \Big\} \; 1 & \quad x \Big\} \; -1.7 \\ 2.25 & & \\ 3.00 & & -16.5 \end{array}$$

$$\frac{.25}{1} = \frac{x}{-1.7} \qquad x = -.4$$

$$\Delta_B(N_0 = 2.25) = -14.8 + (-.4) = \underline{-15.2\text{ dB}}.$$

Record the barrier attenuations on Line 16, Table 8-1.

Step 5. Complete the remaining applicable items under Segment B and calculate the energy contribution from Segment B.

SEGMENT C

Step 1. Compute the finite length roadway adjustment: 10 log $(20°/180°)$ = $\underline{-9.5\text{ dB}}$.

Step 2. Complete the remainding applicable items under Segment C.

Step 3. Compute the hourly equivalent sound level at the observer.

$$L_{eq}(h) = 10 \log [10^{6.11} + 10^{5.14} + 10^{5.56}] = 62.5 \text{ dBA}.$$

The above result is not surprising. The barrier shielded 1/2 of the roadway. Consequently, if the barrier had eliminated all of the energy coming from Segment B, the traffic noise from the highway would have been reduced by 3 dB. The actual reduction was 65.1 − 62.5 = 2.6 dBA.

(Continued)

PROBLEM 8 (Continued)

One might ask could this problem have been solved by computing the sound level from the infinite roadway ($\phi_1 = -90°$, $\phi_2 = +90°$) and subtracting from it the barrier reduction provided by the finite barrier ($\phi_L = -20°$, $\phi_R = +70°$). The answer is *no*. The barrier reductions shown in the tables in Appendix B are to be applied to the sound level from the shielded highway segment.

NAME ____________________ PROJECT DESCRIPTION PROBLEM 8

DATE ____________________

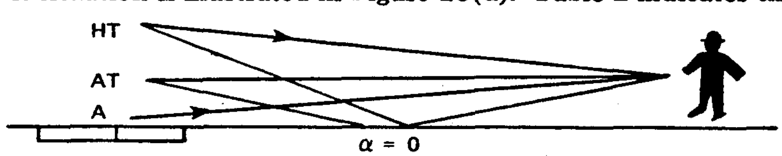
			SEGMENT A						SEGMENT B						SEGMENT C					
1.	LANE NO./ROAD SEGMENT		EB			WB			EB			WB			EB			WB		
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		317	24	22	281	12	26	317	24	22	281	12	26	317	24	22	281	12	25
4.	S(km/h)		–	76	–	–	76	–	–	76	–	–	76	–	–	76	–	–	76	–
5.	D(m)			60.			64.			60.			64.			60.			64.	
6.	ϕ_1 (degrees)	Fig. 5		-90			-90			-20			-20			+70			+70	
7.	ϕ_2 (degrees)	Fig. 5		-20			-20			+70			+70			+90			+90	
8.	$(\overline{L_o})_{E_i}$ (dBA)	Fig. 2	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5
9.	10 LOG $(N_i D_o / S_i)$ (dB)	Fig. 3	18.	7.	6.5	17.5	4.	7.	18	7.	6.5	17.5	4.	7.	18.	7.	6.5	17.5	4.	7.
10a.	10 LOG (D_o/D) (dBA)	Fig. 4		-6.			-6.5			-6.			-6.5			-6.			-6.5	
10b.	15 LOG (D_o/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_o(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6		-4.			-4.			-3.			-3.			-9.5			-9.5	
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7																		
12.	ϕ_L (degrees)	Fig. 10																		
13.	ϕ_R (degrees)	Fig. 10																		
14.	δ_o (metres)	Fig. 9							.70	.51	.16	.56	.41	.14						
15.	N_o	Eq. 18							2.26	1.64	.51	1.80	1.32	.45						
16.	Δ_B (dBA)	Appendix B							-15.2	-13.8	-9.6	-14.3	-12.9	-9.3						
17.	CONSTANT (dB)	•	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		52.	52.	56.	51.	48.5	56.	37.8	39.2	47.4	37.7	36.6	47.7	46.5	46.5	50.5	45.5	43.	50.5
19.	$L_{eq}(h)$ (dBA)			58.5			57.7			48.4			48.4			53.			52.2	
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)	Fig. 14	61.1						51.4						55.6					
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)			-						TOTAL $L_{eq}(h)$ = 62.5										
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 8-1. Noise Prediction Worksheet

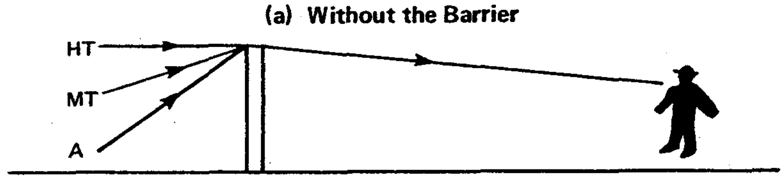
(b) *Field Insertion Loss*

As indicated in the previous section, our real interest lies in what happens to the noise levels when a barrier is constructed between the highway and an observer. As with the distance adjustment and the finite length adjustment, ground effects must be taken into account [9].

Consider the situation where the ground between the highway and the observer is reflective, i.e., $\alpha = 0$. This situation is illustrated in Figure 13(a). Table 2 indicates that under these general



(a) Without the Barrier



(b) With the Barrier

Figure 13. Effect of Constructing a Barrier When $\alpha = 0$

circumstances the drop-off rate is 3 dB/DD (Rule 3(a)). When a barrier is constructed between the highway and the observer, the top of the barrier "appears" to be the noise source to the observer. This situation is shown in Figure 13(b). Again Table 2 indicates that the drop-off rate is 3 dB/DD (Rule 2).

The situation described above occurred in problems 7 and 8. Partial results of these problems are shown in Table 3.

Table 3. Before and After Sound Levels from Problems 7 and 8 ($\alpha = 0$)

Situation	Problem 7 Infinite Barrier	Problem 8 Finite Barrier
$L_{eq}(h)$, Before Barrier	65.1 dBA	65.1 dBA
$L_{eq}(h)$, After Barrier	55.7 dBA	62.5 dBA
Net Reduction (I.L.)	9.4 dBA	2.6 dBA

These values indicate that the net reduction in sound level of building the infinite barrier is 9.4 dBA (65.1-55.7) and the net reduction in sound level of building the finite barrier is 2.6 dBA (65.1-62.5). This net reduction is often erroneously called barrier attenuation. Its proper name is field insertion loss (I.L.).

$$\text{I.L.} = L\text{ (Before)} - L\text{ (After) dB}. \tag{19}$$

In the past it was assumed that the difference between the before and after conditions could be attributed solely to barrier attenuation. It has recently been pointed out that this is only true for hard sites [8].

It was shown earlier that when the ground between the highway and the observer is absorptive, $\alpha = 1/2$, ground effects can provide an additional attenuation of 1.5 dBA/DD when both the source and receiver are close to the ground. In this situation the drop-off rate in Figure 14(a) would be 4.5 dB/DD. When a barrier is constructed between the highway and the observer, the top of the barrier again "appears" to be the noise source to the observer. This is illustrated in Figure 14(b).

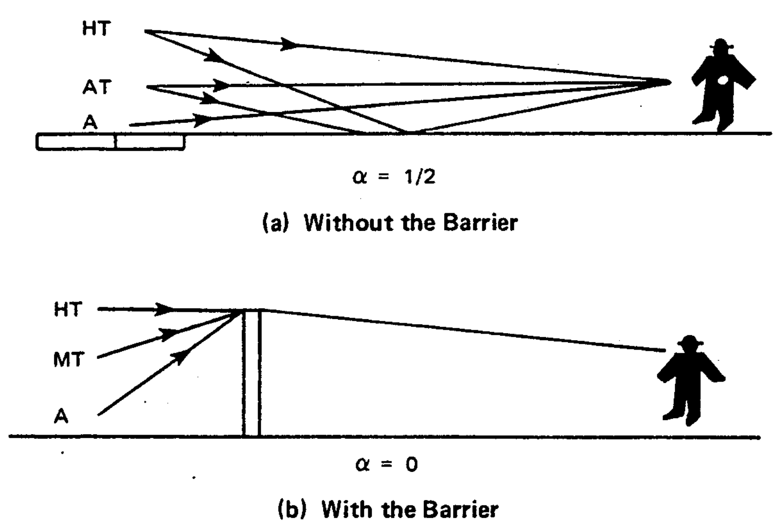


Figure 14. Effect of Constructing a Barrier When $\alpha = 1/2$

Again Table 2 indicates that the drop-off rate is 3 dB/DD (Rule 2). The 1.5 dB/DD excess attenuation has been lost. Thus a 60 metre band of grass could provide an excess attenuation of 3 dBA (5 log (15/60)). Constructing the barrier effectively raises the source height and the ground effect is lost. Consequently, if the barrier attenuation was 9 dBA, the observer at 60 metres would measure a field insertion loss of only 6 dBA (9-3).

Intuitively one would expect this phenomenon to occur only when the observer was relatively close to the barrier. As the observer moves away from the barrier, it would appear that ground effects would occur at some point. Unfortunately there is no measured data which can be used to locate this point. Consequently, it is recommended at this time that users assume that the 1.5 dBA/DD is lost for all observer locations.

PROBLEM 9

Refer to Problems 7(a) and 7(b). Compute the field insertion loss (I.L.) provided by the concrete barrier assuming that the terrain between the highway and the observer is covered with grass, i.e., $\alpha = 1/2$.

FREE FIELD

SOLUTION

Step 1. The values shown in Lines 1 through 9, Table 7-1, for Problem 7(a) will remain unchanged for this problem. Enter these values onto Table 9-1.

Step 2. Since the drop-off rate is now based on 15 log (15/D), compute the distance adjustment factors and enter these values on Line 10(b), Table 9-1.

Step 3. Refer to Figure 7. When $\phi_1 = -90°$, $\phi_2 = +90°$, there is an adjustment of −1.2 dB for infinitely long roadways. Record this value on Line 11(b), Table 9-1.

Step 4. Complete the remainder of Table 9-1 for the Free Field situation and compute the sound level at the observer.

CONCRETE BARRIER

Step 1. Since the "apparent" noise source is now at a height of 4 metres, the site should be treated as a hard site (Table 2). The values shown for Problem 7(b), Table 7-1 remain unchanged.

Step 2. The field insertion loss is given by Equation (19).

$$\text{I.L.} = L_{eq}(h) \text{ Before} - L_{eq}(h) \text{ After}$$

$$\text{I.L.} = 61.1 - 55.7 = \underline{5.4 \text{ dBA}}.$$

(Continued)

PROBLEM 9 (Continued)

NAME ______________________ PROJECT DESCRIPTION PROBLEM 9

DATE ______________________

			(a) FREE FIELD						(b) CONCRETE BARRIER											
1.	LANE NO./ROAD SEGMENT		EB			WB			EB			WB								
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		317	24	22	281	12	25	317	24	22	281	12	25						
4.	S(km/h)		—	75	—	—	75	—	—	75	—	—	75	—	—					
5.	D(m)		60			64			60			64								
6.	ϕ_1 (degrees)	Fig. 5	-90			-90			-90			-90								
7.	ϕ_2 (degrees)	Fig. 5	+90			+90			+90			+90								
8.	$(\bar{L}_o)_{E_i}$ (dBA)	Fig. 2	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5						
9.	10 LOG $(N_i D_o / S_i)$ (dB)	Fig. 3	18.	7.	6.5	17.5	4.	7.	18.	7.	6.5	17.5	4.	7.						
10a.	10 LOG (D_o/D) (dBA)	Fig. 4							-6.			-6.5								
10b.	15 LOG (D_o/D) (dBA)	Fig. 4	-9.			-9.5														
11a.	10 LOG $(\psi_o(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6							0.			0.								
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7	-1.			-1.														
12.	ϕ_L (degrees)	Fig. 10																		
13.	ϕ_R (degrees)	Fig. 10																		
14.	δ_o (metres)	Fig. 9							.70	.51	.18	.56	.41	.14						
15.	N_o	Eq. 18							2.25	1.64	.51	1.80	1.32	.45						
16.	Δ_B (dBA)	Appendix B							-12.7	-11.6	-8.5	-11.9	-11.	-8.3						
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		52.	52.	56.	51.	48.5	56.	43.3	44.4	51.5	43.1	41.5	51.7						
19.	$L_{eq}(h)$ (dBA)		58.5			57.7			52.8			52.6								
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)		61.1						55.7											
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 9-1. Noise Prediction Worksheet

PROBLEM 10

Refer to Problem 8. What is the sound level at the observer if the site is soft ($\alpha = 1/2$)? What is the field insertion loss?

SOLUTION

Computation of the field insertion loss requires knowledge of the sound levels before and after the barrier is built. The free field sound level at the observer before the barrier is built is 61.1 dBA (Problem 9).

Determination of the sound level after the barrier is built requires that the roadway be broken down into three segments.

Segment A $\phi_1 = -90°, \quad \phi_2 = -20°$

Segment B $\phi_1 = -20°, \quad \phi_2 = +70°$

Segment C $\phi_1 = +70°, \quad \phi_2 = +90°$

The values shown in Lines 1-9, Table 10-1 are identical to the values shown in Lines 1-9, Table 8-1.

SEGMENT A

Step 1. Since Segment A is unshielded, the site parameter ($\alpha = 1/2$) remains unchanged when the barrier is erected. Use Figure 4 to determine the distance adjustment and record it on Line 10(b), Table 10-1.

Step 2. Use Figure 7 to compute the finite length roadway adjustment. Record this value on Line 11(b), Table 10-1.

Step 3. Complete the remainder of Table 10-1 for Segment A.

SEGMENT B

The barrier changes the site parameter from that of a soft site ($\alpha = 1/2$) to that of a hard site. Consequently, the values shown in Table 10-1 for Segment B are identical to those shown in Table 8-1.

SEGMENT C

Step 1. Since Segment C is unshielded, the site parameter ($\alpha = 1/2$) remains unchanged when the barrier is constructed. Use Figure 4 to determine the distance adjustment. Record this value in Line 10(b), Table 10-1.

(Continued)

PROBLEM 10 (Continued)

Step 2. Use Figure 7 to determine the finite length roadway adjustment. Record this value on Line 11(b), Table 10-1.

Step 3. Complete the remainder of Table 10-1 for Segment C.

Step 4. Use Equation (2) to compute the total equivalent sound level.

$$L_{eq}(h) = 10 \log [10^{5.66} + 10^{5.14} + 10^{48.6}] = 58.2 \text{ dBA.}$$

Step 5.

$$\text{I.L.} = L_{eq}(h) \text{ Before} - L_{eq}(h) \text{ After}$$

$$= 61.1 - 58.2 = \underline{2.9 \text{ dBA}}.$$

NAME ______________________ PROJECT DESCRIPTION PROBLEM 10

DATE ______________________

			SEGMENT A						SEGMENT B						SEGMENT C					
1.	LANE NO./ROAD SEGMENT		EB			WB			EB			WB			EB			WB		
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		317	24	22	281	12	25	317	24	22	281	12	25	317	24	22	281	12	25
4.	S(km/h)		–	75	–	–	75	–	–	75	–	–	75	–	–	75	–	–	75	–
5.	D(m)		60			64			60			64			60			64		
6.	ϕ_1 (degrees)	Fig. 5	-80			-80			-20			-20			+70			+70		
7.	ϕ_2 (degrees)	Fig. 5	-20			-20			+70			+70			+80			+80		
8.	$(\overline{L_o})_{E_i}$ (dBA)	Fig. 2	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5	69.	80.	84.5
9.	10 LOG $(N_i D_o/S_i)$ (dB)	Fig. 3	18.	7.	6.5	17.5	4.	7.	18.	7.	6.5	17.5	4.	7.	18.	7.	6.5	17.5	4.	7.
10a.	10 LOG (D_o/D) (dBA)	Fig. 4							-6.			-6.5								
10b.	15 LOG (D_o/D) (dBA)	Fig. 4	-9.			-9.5									-9.			-9.5		
11a.	10 LOG $(\psi_0(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6							-3.			-3.								
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7	-5.5			-5.5									-13.5			-13.5		
12.	ϕ_L (degrees)	Fig. 10							-20			-20								
13.	ϕ_R (degrees)	Fig. 10							+70			+70								
14.	δ_o (metres)	Fig. 9							.70	.51	.16	.86	.41	.14						
15.	N_o	Eq. 18							2.25	1.64	.51	1.80	1.32	.46						
16.	Δ_B (dBA)	Appendix B							-15.2	-13.8	-9.6	-14.3	-12.9	-9.3						
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		47.5	47.5	51.5	46.5	44.	51.5	37.8	39.2	47.4	37.7	36.6	47.7	39.5	39.5	43.5	38.5	36.	43.5
19.	$L_{eq}(h)$ (dBA)		54.			53.2			48.4			48.4			46.			45.2		
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)		56.6						51.4						48.6					
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)								TOTAL $L_{eq}(h)$ = 58.2											
27.	$L_{10}(h)$ (dBA)																			

Table 10-1. Noise Prediction Worksheet

Partial results of Problems 9 and 10 are shown in Table 4.

Table 4. Before and After Sound Levels from Problems 9 and 10 ($\alpha = 1/2$)

Situation	Problem 9 Infinite Barrier	Problem 10 Finite Barrier
$L_{eq}(h)$, Before Barrier	61.1 dBA	61.1 dBA
$L_{eq}(h)$, After Barrier	55.7 dBA	58.2 dBA
Net Reduction (I.L.)	5.4 dBA	2.9 dBA

Table 3 and Table 4 show the sound levels that would result in similar situations where only the site parameter varied. The values in Table 4 indicate that the I.L. provided by the infinite barrier was 5.4 dBA (61.1-55.7) when $\alpha = 1/2$. Table 3 indicated that the I.L. provided by the infinite barrier was 9.4 dBA when $\alpha = 0$. The loss of ground effects accounts for a difference 4 dBA (9.4-5.4).

Summary

$L_{eq}(h)_i = (\overline{L_o})_{E_i}$	reference energy mean emission level (Figure 2 and line 8 of Table 1)
$+10 \log \left(\frac{N_i D_o}{S_i}\right)$	traffic flow adjustment (Figure 3 and line 9 of Table 1)
$+ \begin{cases} 10 \log \left(\frac{D_o}{D}\right) \\ 15 \log \left(\frac{D_o}{D}\right) \end{cases}$	distance adjustment factor, hard site (Figure 4 and line 10(a) of Table 1); distance adjustment factor, soft site (Figure 4 and line 10(b) of Table 1)
$+ \begin{cases} 10 \log \left(\frac{\Delta\phi}{\pi}\right) \\ 10 \log \left(\frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi}\right) \end{cases}$	finite roadway adjustment, hard site (Figure 6 and line 11(a) of Table 1); finite roadway adjustment, soft site (Figure 7 and line 11(b) of Table 1)
Δ_s	shielding
-25	constant

Users of this manual can now predict the equivalent sound level produced by a class of vehicles traveling at constant speed at a shielded or unshielded observer.

g. $L_{eq}(h)$ to $L_{10}(h)$ Conversion

Figure 15 is used to convert the $L_{eq}(h)_i$ to $L_{10}(h)_i$ for each vehicle group (A, MT, and HT). After the conversion is made, the sound level for each class is added (on an energy basis) to obtain the $L_{10}(h)$ (see Equation (3)).

The mathematical development of the equations on which Figure 15 is based is contained in Appendix F, NCHRP Report 173 [5]. As with other predictive models, the $L_{eq}(h)_i - L_{10}(h)_i$ conversion is based on the ND/S ratio (Parameter A in the NCHRP Reports 117 and 173). Figure 15 is based on the assumption that the sources—i.e., the vehicles in a particular group—have equal power and are equally spaced. These conditions lead to conservative values for $L_{10}(h)$.

The question immediately arises on the accuracy of Figure 15. To answer this question it is necessary to break the figure down into two parts and talk about low volume roadways and high volume roadways.

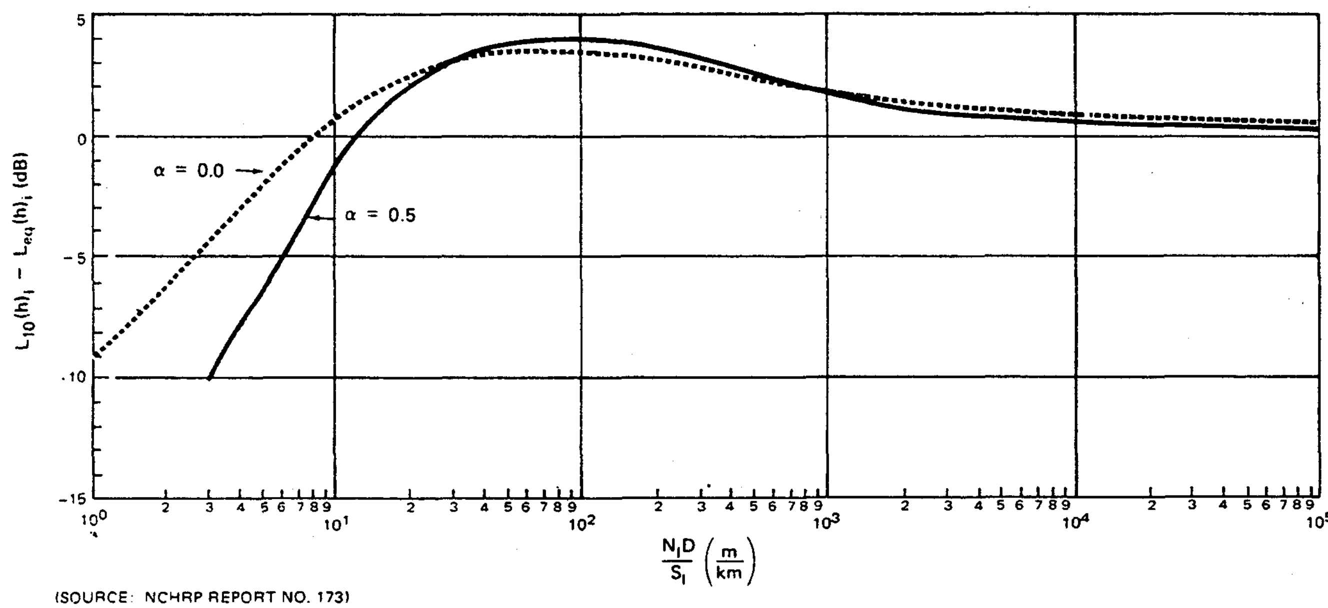


Figure 15. Adjustment Factor for Converting $L_{eq}(h)_i$ to $L_{10}(h)_i$

1. *Low Volumes Roadways*

Low volume roadways pose special problems. Past experience has shown that the difference between the measured level and the predicted level is often quite large on low volumes roadways. There are several reasons for this:

(1) The noise emission levels used in the predictive models are based on large sample populations—i.e., the reference energy mean emission levels are average values. On low volume roadways, where there are only a few vehicles of a particular group, large deviations may exist between the average values used in the model and the actual levels of the vehicles using the roadway. The FHWA model will not solve this problem. One way to know that problem 1 exists is to monitor the noise emission levels of the vehicles during the measurements to see if they conform to the average.

(2) Predictive methods, such as the NCHRP 117/144 method, which predict the noise levels in terms of a statistical descriptor, assume that the vehicles are evenly spaced on the roadway. The FHWA model solves this problem as long as the $L_{eq}(h)$ is the noise descriptor. The $L_{eq}(h)$ is a measure of the average energy and depends only on the number of vehicles passing the observer—not on the vehicle spacing.

(3) There is no assurance that the measured sound levels on low volume roadways are representative of the average condition on which the predictions are made. Figures 16 and 17 provide some insights into this area. During the 4-State Noise Inventory, continuous 50-minute noise levels were recorded on magnetic tape. In subsequent analyses of this data, the 50-minute samples were divided into five 10-minute samples. The average of the 10-minute samples were then compared with the 50-minute sample. The results of this analyses are shown in Figures 16 and 17.

Each point on these figures represents an average difference between one 50-minute sample and the averaging of the five 10-minute samples. Thus, it is quite clear that when ND/S is less than 40 m/km, the variability between the 10-minute samples and the 50-minute sample increases. The graph also suggests that the dividing line between low volume roadways and high volume roads occurs at a ND/S value between 40 and 80 m/km.

In terms of an $L_{eq}(h)$ to $L_{10}(h)$ conversion factor, the conversion factor would change for each 10-minute sample. Indeed there would be a separate value for each class of vehicles. To avoid all of these difficulties, it is recommended that when the ND/S ratio is less than 40 m/km, noise predictions be made in terms of the $L_{eq}(h)$. If this is not possible, Figure 15 can be used with the assurance that the $L_{10}(h)$ will be conservative [5].

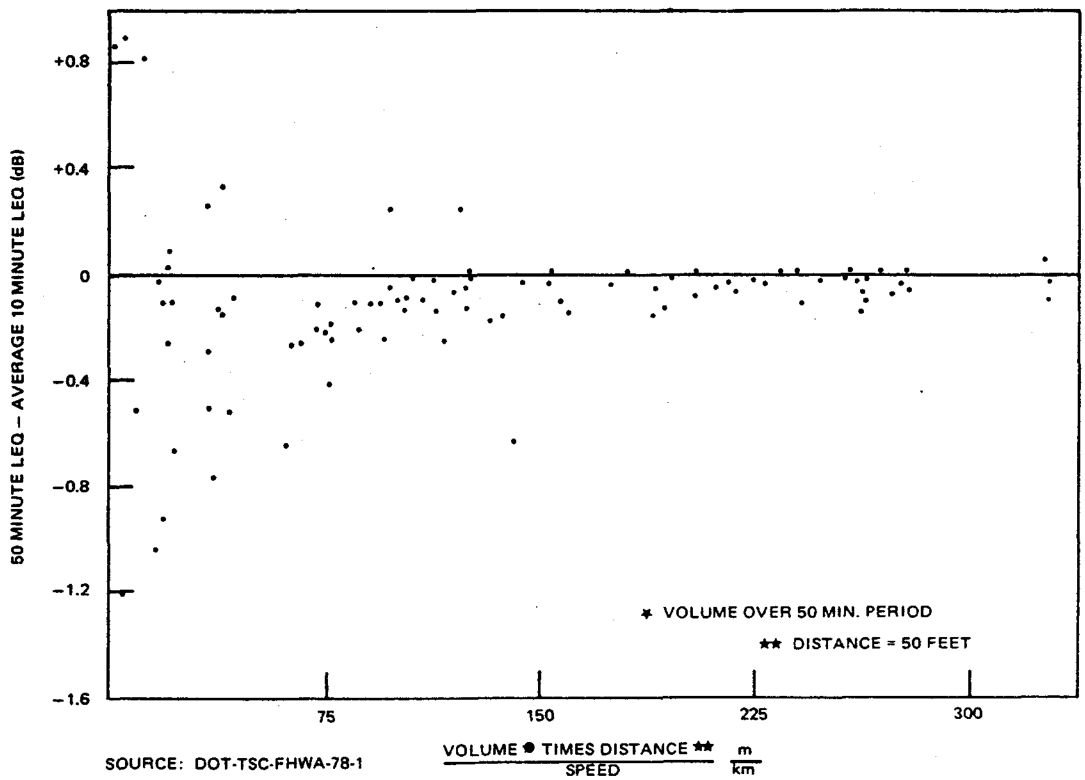


Figure 16. Data Sampling Comparison L_{eq}
(Composite all sites, all states)

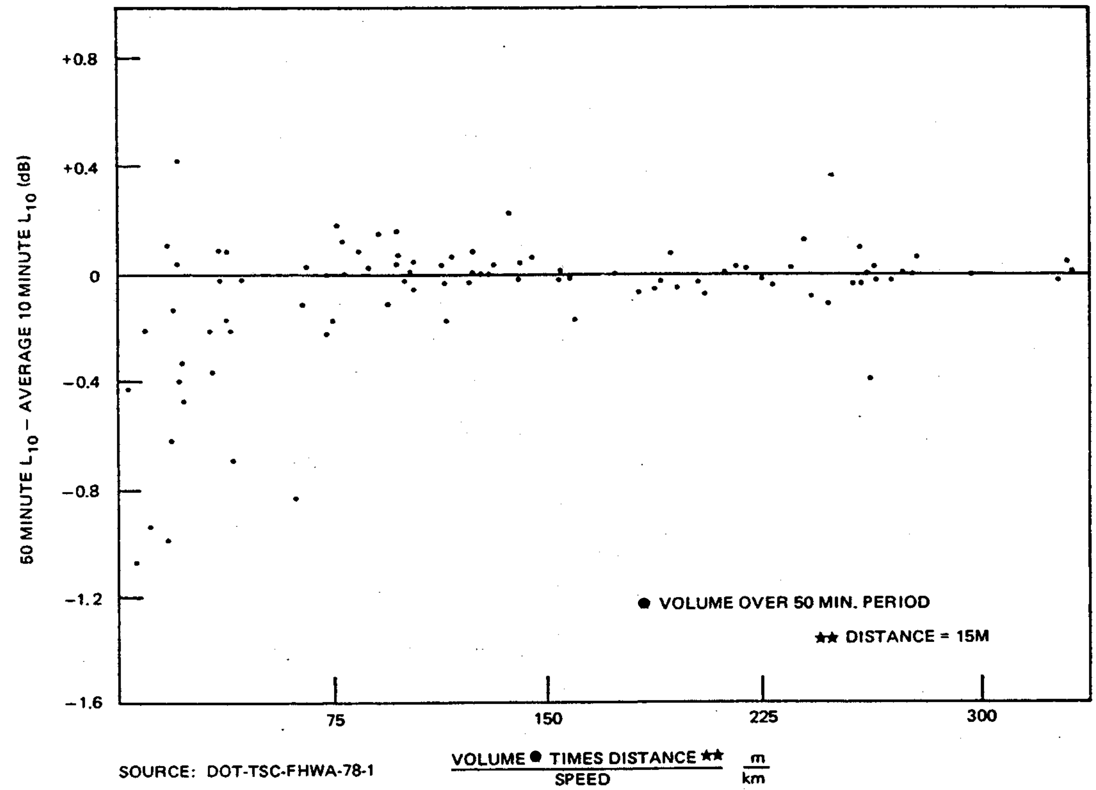


**Figure 17. Data Sampling Comparison L_{10}
Composite all sites, all states)**

2. *High Volumes Roadways*

Once the ND/S ratio is greater than 40 m/km the three problems discussed under low volume roadways are greatly reduced. Since there are now larger numbers of vehicles during the measurement period, the individual noise emission level becomes less critical and the overall effect is that the average values are approximated. The spacing of vehicles tends to become even, and the 10-minute measurement times become representative of the hourly volumes. Thus that portion of Figure 15 above ND/S of 40 m/km should be quite reasonable. The figure also suggests that as ND/S increases the difference between the $L_{eq}(h)$ and $L_{10}(h)$ approaches zero.

PROBLEM 11

The data from Problem 7(a) is reproduced on Table 11-1. Compute the $L_{10}(h)$.

SOLUTION

Step 1. Compute ND/S for each vehicle class on the EB and WB Lanes. D in this equation is the perpendicular distance from the observer to the centerline of the EB or WB Lane (Line 5). Record these values on Line 23, Table 11-1.

Step 2. Using the values obtained, shown on Line 23, use Figure 15 to determine the $(L_{10} - L_{eq})$ adjustment factors ($\alpha = 0$). Record these values on Line 24, Table 11-1.

Step 3. Compute the $L_{10}(h)_i$ for each vehicle group. (Line 18 plus Line 24).

Step 4. Use Equation (3) and compute the $L_{10}(h)$ for each lane.

Step 5. Use Equation (3) and compute the $L_{10}(h)$ heard by the observer.

NAME ____________________ PROJECT DESCRIPTION PROBLEM 11

DATE ____________________

1.	LANE NO./ROAD SEGMENT		EB			WB															
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		317	24	22	281	12	26												
4.	S(km/h)		–	75	–	–	75	–												
5.	D(m)			60.			64.													
6.	ϕ_1 (degrees)	Fig. 5																		
7.	ϕ_2 (degrees)	Fig. 5																		
8.	$(\bar{L}_o)E_i$ (dBA)	Fig. 2																		
9.	10 LOG (N_iD_o/S_i) (dB)	Fig. 3																		
10a.	10 LOG (D_o/D) (dBA)	Fig. 4																		
10b.	15 LOG (D_o/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_0(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6																		
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7																		
12.	ϕ_L (degrees)	Fig. 10																		
13.	ϕ_R (degrees)	Fig. 10																		
14.	δ_o (metres)	Fig. 9																		
15.	N_o	Eq. 18																		
16.	Δ_B (dBA)	Appendix B																		
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		56	56	60	55	52.5	60												
19.	$L_{eq}(h)$ (dBA)																			
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)		254	19	18	240	10	21												
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15	3.0	2.5	2.5	3.0	1.0	2.5												
25.	$L_{10}(h)_i$ (dBA)		59	58.5	62.5	58	53.5	62.5												
26.	$L_{10}(h)$ (dBA)			65.2			64.2													
27.	$L_{10}(h)$ (dBA)					67.7														

Table 11-1. Noise Prediction Worksheet

Summary

$L_{eq}(h)_i = (\overline{L_o})_{E_i}$	reference energy mean emission level (Figure 2 and line 8 of Table 1)
$+10 \log \left(\frac{N_i D_o}{S_i}\right)$	traffic flow adjustment (Figure 3 and line 9 of Table 1)
$+ \begin{cases} 10 \log \left(\frac{D_o}{D}\right) \\ 15 \log \left(\frac{D_o}{D}\right) \end{cases}$	distance adjustment factor, hard site (Figure 4 and line 10(a) of Table 1) distance adjustment factor, soft site (Figure 4 and line 10(b) of Table 1)
$+ \begin{cases} 10 \log \left(\frac{\Delta\phi}{\pi}\right) \\ 10 \log \left(\frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi}\right) \end{cases}$	finite roadway adjustment, hard site (Figure 6 and line 11(a) of Table 1) finite roadway adjustment, soft site (Figure 7 and line 11(b) of Table 1)
$+\Delta_S$	shielding
-25	constant

Users of this manual can now predict the $L_{eq}(h)$ or the $L_{10}(h)$ produced by a class of vehicles traveling at constant speed.

3.0 EQUIVALENT—LANE DISTANCE

a. Introduction

D was defined on page 1 as the perpendicular distance from the observer to the centerline of a traffic lane. The sample problems given so far have all dealt with two-lane highways. D, in these problems, has represented the distance from the observer to the centerline of the eastbound or near lane. D has also represented the distance from the observer to the centerline of the westbound or far lane. As the number of traffic lanes increases, computation of the noise levels on a lane-by-lane basis becomes very tedious. It has become a fairly common practice to lump the traffic without change in speed or operations on an imaginary single lane which will provide approximately the same acoustical results as an analysis done on a lane-by-lane basis [5].

This imaginary single lane is located at a distance from the observer called the single-lane equivalent distance, D_E.

b. Computation of the Single-Lane Equivalent Distance

In the free field the single-lane equivalent distance is computed as

$$D_E = \sqrt{(D_N)(D_F)} \qquad (20)$$

where

D_N is the perpendicular distance from the observer to the centerline of the near lane.

D_F is the perpendicular distance from the observer to the centerline of the far lane.

These distances are illustrated in Figure 18(a).

When a barrier is present, the single-lane equivalent distance is computed as

$$D_E = \sqrt{D_N D_F} + X \qquad (21)$$

where

D_N is the perpendicular distance from the barrier to the centerline of the near lane.

D_F is the perpendicular distance from the barrier to the centerline of the far lane.

X is the perpendicular distance from the observer to the barrier.

These distances are illustrated in Figure 18(b).

Care should be used when using equivalent lane distance, particularly in situations where:

(1) Barriers are involved.
(2) Wide medians are present.
(3) The directional distribution is not 50-50.
(4) When the observer is located within 15 metres of the centerline of the near lane.

In problems involving more than 2 lanes, the use of a equivalent lane for each directional traffic flow will eliminate any appreciable error introduced by wide medians or directional unbalance of flow.

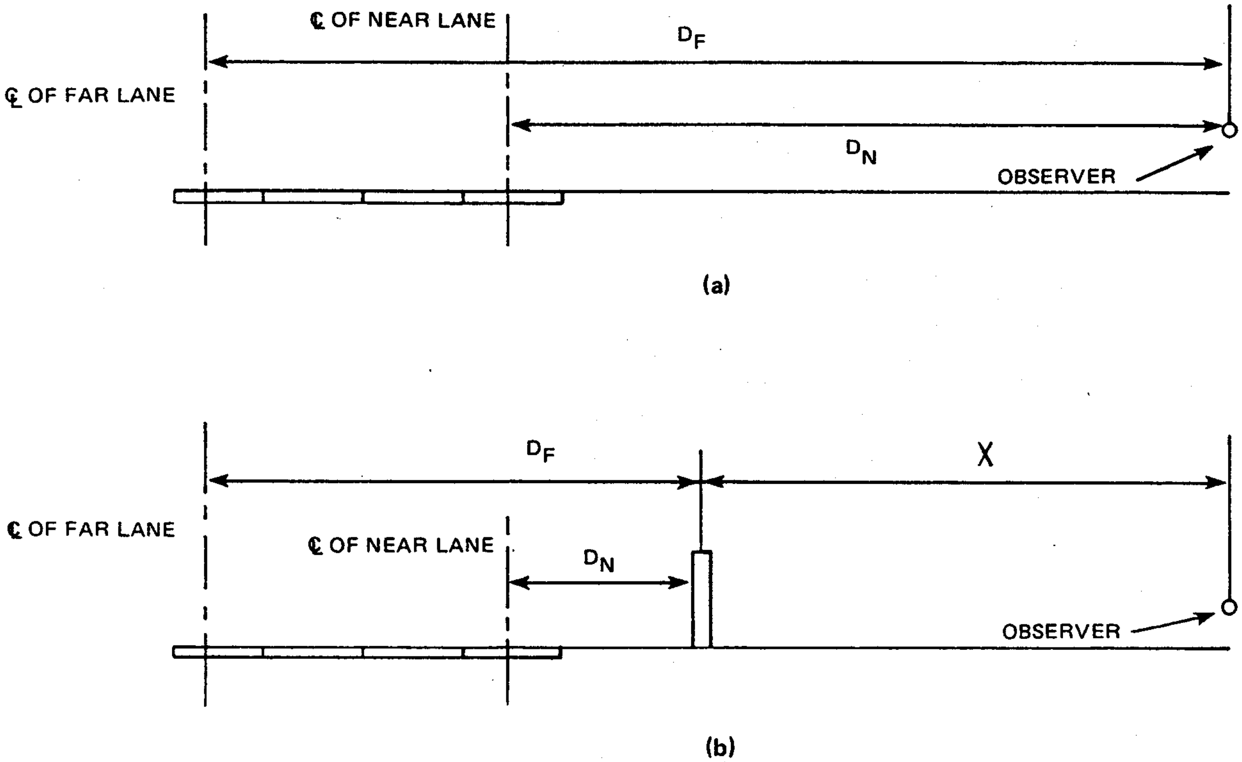


Figure 18. Equivalent Lane Distances

PROBLEM 12

A typical highway scenario is shown in the sketch below. Compute the equivalent lane distances with and without the barrier.

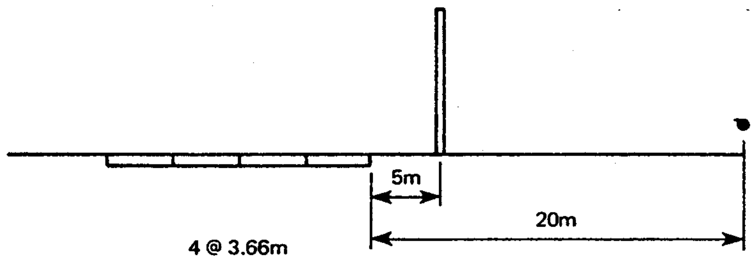


Figure 12-1

(1) D_E (The barrier is not present)

$$D_E = \sqrt{(21.83)(32.81)} = \underline{26.76 \text{ m}}$$

(2) D_E (The barrier is present)

$$D_E = \sqrt{(6.83)(17.81)} + 15$$

$$= 11.03 + 15$$

$$= \underline{26.03 \text{ m}}$$

4.0 NOMOGRAPHS AND PROGRAMMABLE HAND-HELD CALCULATORS

a. Introduction

Basically the FHWA Highway Traffic Noise Prediction Model—Manual Method consists of two equations—Equation (1) and Equation (15). In Chapter 2 these equations were reduced to a series of charts and tables which were then used to solve several example problems. These equations can also be solved by several other means. Two methods of solving these equations, nomographs and programmable hand-held calculators, are of particular value.

b. Nomographs

Although nomographs provide the least accurate noise estimates, they have many valuable uses, particularly when only a quick estimate of the noise level is needed, when the sites are relatively small, or when a quick estimate of the effects of a noise barrier is desired. Three nomographs are provided. Figures 19 and 20 are used to determine the unattenuated sound levels. Figure 21 is used to determine the attenuation provided by a barrier.

1. *The FHWA Highway Traffic Noise Prediction Nomograph (Hard Site)*

This nomograph should be used when estimating the noise level at an observer when the site is hard ($\alpha = 0$). Equation (1) for a hard site can be written as

$$L_{eq}(h)_i = (\overline{L_o})_{E_i} + 10 \log \left(\frac{N_i D_o}{S_i}\right) + 10 \log \left(\frac{D_o}{D}\right) + 10 \log \left(\frac{\phi_2 - \phi_1}{\pi}\right) - 25 . \qquad (22)$$

If $D_o = 15$ m, $\phi_1 = -90°$, $\phi_2 = +90°$, Equation (22) reduces to

$$L_{eq}(h)_i = (\overline{L_o})_{E_i} + 10 \log N_i - 10 \log S_i - 10 \log D - 1.5 . \qquad (23)$$

Recall that Equations (4), (5), and (6) are the reference energy mean emission levels

$$(\overline{L_o})_{E_A} = 38.1 \log S - 2.4 \qquad (24)$$

$$(\overline{L_o})_{E_{MT}} = 33.9 \log S + 16.4 \qquad (25)$$

$$(\overline{L_o})_{E_{HT}} = 24.6 \log S + 38.5 . \qquad (26)$$

Substitution of these values into Equation (23) results in the following equations:

$$L_{eq}(h)_A = 28.1 \log S_A + 10 \log N_A - 10 \log D - 3.9 \qquad (27)$$

$$L_{eq}(h)_{MT} = 23.9 \log S_{MT} + 10 \log N_{MT} - 10 \log D + 14.9 \qquad (28)$$

$$L_{eq}(h)_{HT} = 14.6 \log S_{HT} + 10 \log N_{HT} - 10 \log D + 37.0 . \qquad (29)$$

Figure 19 is based upon solution of the above three equations. This nomograph assumes that:

(1) The site is hard ($\alpha = 0$).
(2) The highway is infinitely long.
(3) The observer is unshielded.
(4) The vehicles travel a constant speed.

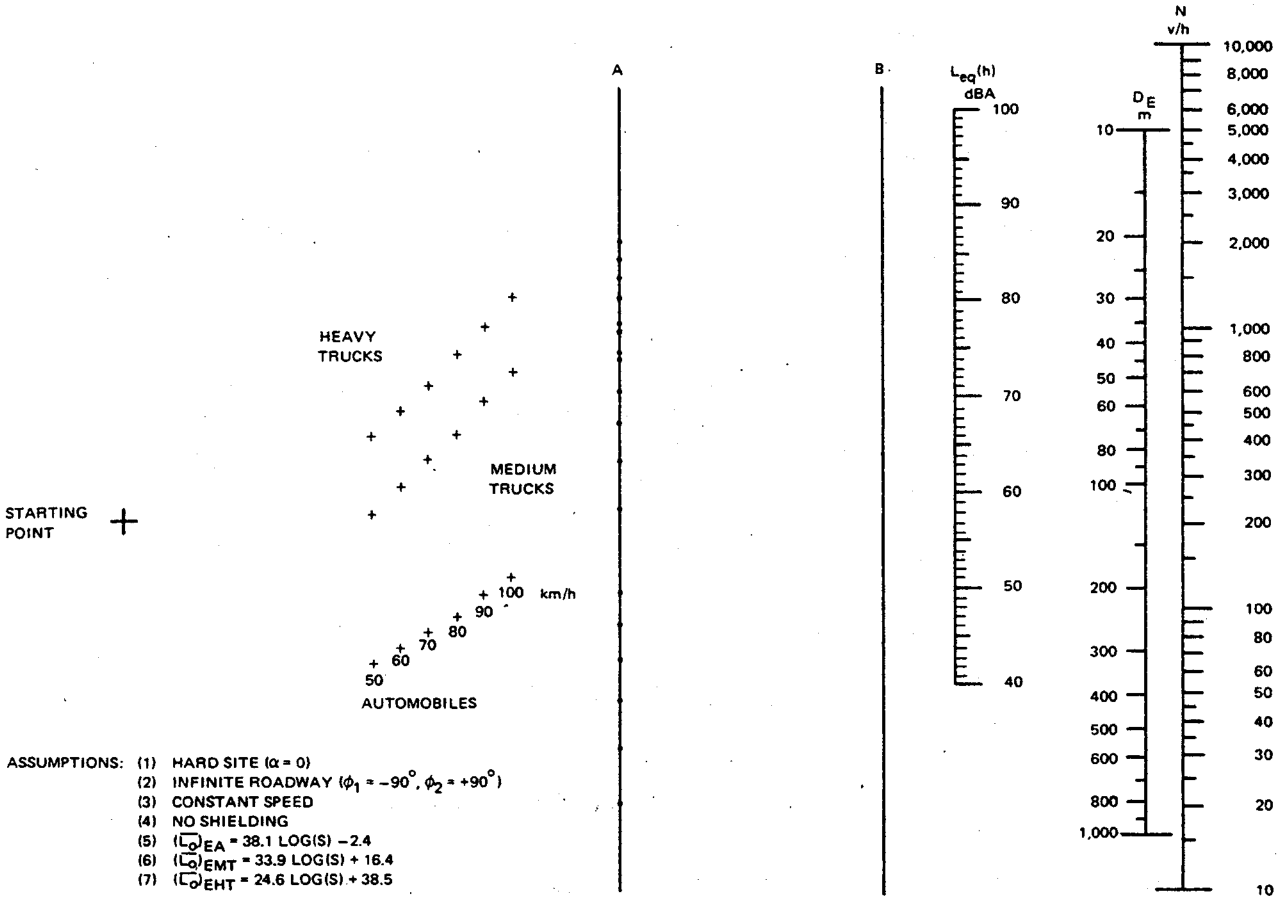


Figure 19. FHWA Highway Traffic Noise Prediction Nomograph (Hard Site)

2. *The FHWA Highway Traffic Noise Prediction Nomograph (Soft Site)*

If $\alpha = 1/2$, $D_o = 15$ m, $\phi_1 = -90°$, $\phi_2 = +90°$, Equation (1) reduces to

$$L_{eq}(h)_i = (\overline{L_o})_{E_i} + 10 \log N_i - 10 \log S_i - 15 \log D + 3.2. \qquad (30)$$

Substitution of Equations (24), (25), and (26) into Equation (30) results in

$$L_{eq}(h)_{\mathrm{A}} = 28.1 \log S_{\mathrm{A}} + 10 \log N_{\mathrm{A}} - 15 \log D + 0.8 \qquad (31)$$

$$L_{eq}(h)_{\mathrm{MT}} = 23.9 \log S_{\mathrm{MT}} + 10 \log N_{\mathrm{MT}} - 15 \log D + 19.6 \qquad (32)$$

$$L_{eq}(h)_{\mathrm{HT}} = 14.6 \log S_{\mathrm{MT}} + 10 \log N_{\mathrm{HT}} - 15 \log D + 41.7. \qquad (33)$$

Figure 20 is based upon the solutions of these three equations. This nomograph assumes:
(1) The site is soft ($\alpha = 1/2$).
(2) The highway is infinitely long.
(3) The observer is unshielded.
(4) The vehicles travel at constant speed.

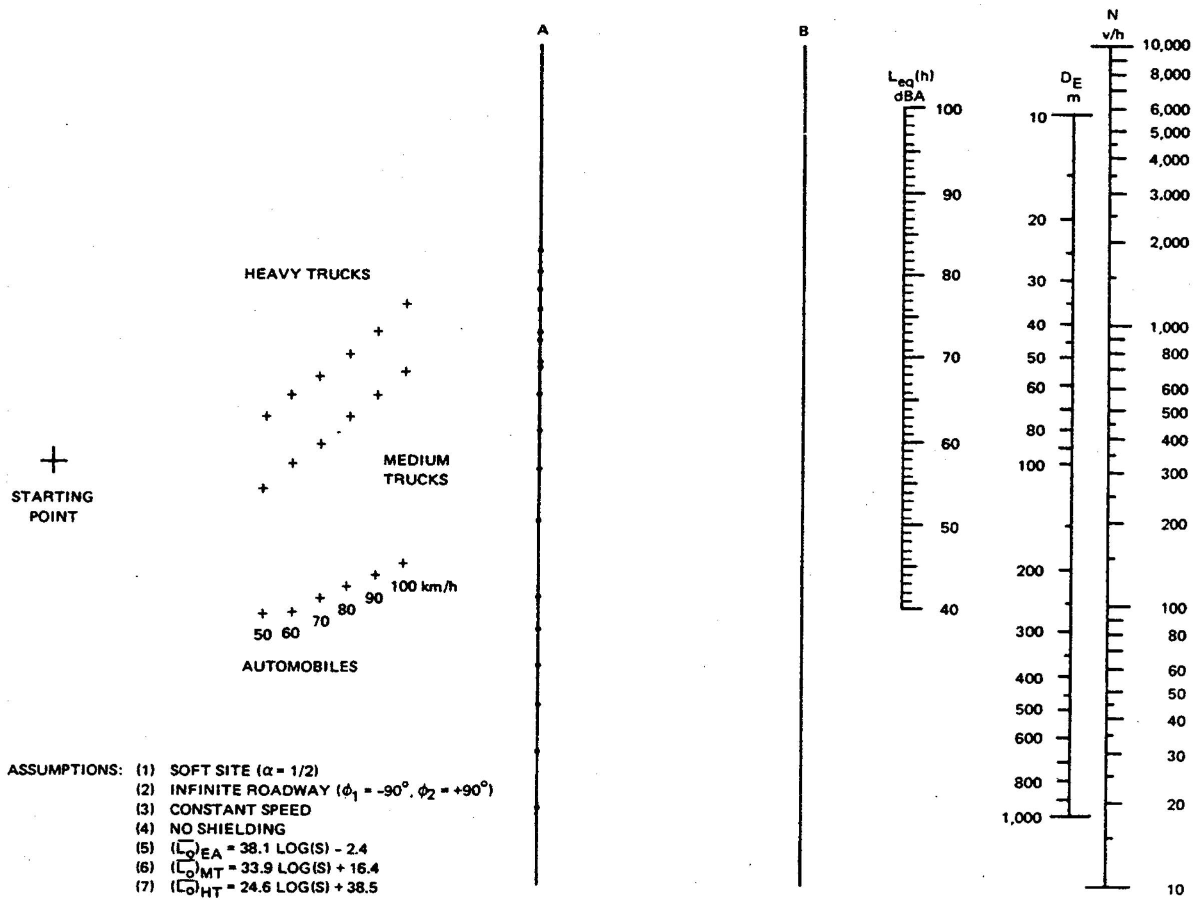


Figure 20. FHWA Highway Traffic Noise Prediction Nomograph (Soft Site)

One word should be said about the format of Figures 19 and 20. This layout was chosen because it has been widely used by noise specialists in the past. The dots shown on turn line A really represents the starting points. The purpose of the "+'s" is to locate the appropriate speed dot. Users may want to relable scale A and use turn line A as the starting point. This is slightly more accurate because the speed dots represent a logarithmic scale, and it is easier to interpolate between the dots on Line A than it is between the "+'s."

PROBLEM 13

Refer to Figure 13-1 below. Using the traffic data given in Problem 2, compare the sound levels that reach the observer from Segment A and Segment B. The *L/S* is less than 3 metres above the ground and the intervening ground from Segment A has been paved over. The intervening ground from Segment B is covered with grass. The highway is infinitely long. Lane width is 3.66 m. Use the nomographs to solve this problem.

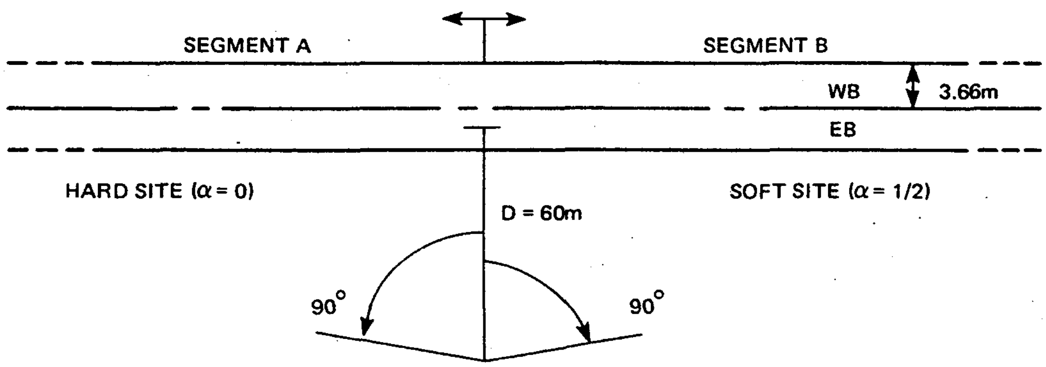


Figure 13-1

TRAFFIC DATA

Vehicle Class	Eastbound Lane V/H	Westbound Lane V/H
A	317	281
MT	24	12
HT	22	25

$S = 75$ km/h

Table 1 will again be used as a computation guide.

SEGMENT A

Step 1. Complete Lines 1 through 4, Table 13-1.

Step 2. Compute the single-lane equivalent distance, D_E.

$$D_E = \sqrt{(60)(63.66)} = 61.8\,.$$

Step 3. $\phi_1 = -90$, $\phi_2 = 0$.

Step 4. Use Figure 13-2 to determine $L_{eq}(h)_i$ for each vehicle group. Example: EB Lane — automobiles.

(Continued)

PROBLEM 13 (Continued)

1. Refer to Figure 13-2. Draw a straight line from the starting point through the 75 km/h point on the automobile speed scale. Extend the straight line to turn Line A. Note the "+'s" are used to locate the dots on Line A.
2. Draw a second straight line from the intersection point A-1 to 598 vph point on the volume scale. Mark the intersection of this line with turn Line B as B-1.
3. Draw a third straight line from point B-1 to the 62 metre point on the D_E scale. The intersection of the third line with the $L_{eq}(h)$ scale gives the predicted $L_{eq}(h)_A$.

Step 5. Repeat Step 4 for each of the vehicle classes

$$\left.\begin{aligned} L_{eq}(h)_{\mathrm{A}} &= 59\ \mathrm{dBA} \\ L_{eq}(h)_{\mathrm{MT}} &= 57\ \mathrm{dBA} \\ L_{eq}(h)_{\mathrm{HT}} &= 63\ \mathrm{dBA} \end{aligned}\right\} L_{eq}(h) = 65.2\ \mathrm{dBA}.$$

Step 6. The values shown above are for an infinitely long highway where the site is hard. Therefore, reduce each value by 10 log (90/180) = −3 dBA and enter this value on Line 18, Table 13-1.

Step 7. Compute the $L_{eq}(h)$ from Segment A.

$$L_{eq}(h) = 10 \log [10^{5.6} + 10^{5.4} + 10^{6.0}] = 62.2\ \mathrm{dBA}.$$

(From Problem 6, $L_{eq}(h)$ = 62.1 dBA.)

SEGMENT B

Step 1. Repeat Steps 1–4 from Segment A except that Figure 13-3 must be used.

$$\left.\begin{aligned} L_{eq}(h)_{\mathrm{A}} &= 54.5\ \mathrm{dBA} \\ L_{eq}(h)_{\mathrm{MT}} &= 53.\ \mathrm{dBA} \\ L_{eq}(h)_{\mathrm{HT}} &= 58.5\ \mathrm{dBA} \end{aligned}\right\} L_{eq}(h) = 60.8\ \mathrm{dBA}.$$

Step 2. The values shown in Step 1 above are for an infinitely long highway where the site is soft. Use Figure 7 to adjust these values for a finite length roadway.

1. $\phi_1 = -90$, $\phi_2 = +90$. Adjustment = −1.2 dBA. (Built into nomograph.)
2. $\phi_1 = 0$, $\phi_2 = +90$. Adjustment = −4.2 dBA.
3. (−4.2) − (−1.2) = −3.0 dBA.

Reduce the values shown in Step 1 by 3. dBA.

(Continued)

PROBLEM 13 (Continued)

Step 3. Compute the $L_{eq}(h)$ from Segment B.

$$L_{eq}(h) = 10 \log [10^{5.15} + 10^{5.00} + 10^{5.55}] = \underline{57.8 \text{ dBA}} .$$

(From Problem 6, $L_{eq}(h)_B = 58.1$ dBA.)

COMPUTE $L_{eq}(h)$ FROM ROADWAY

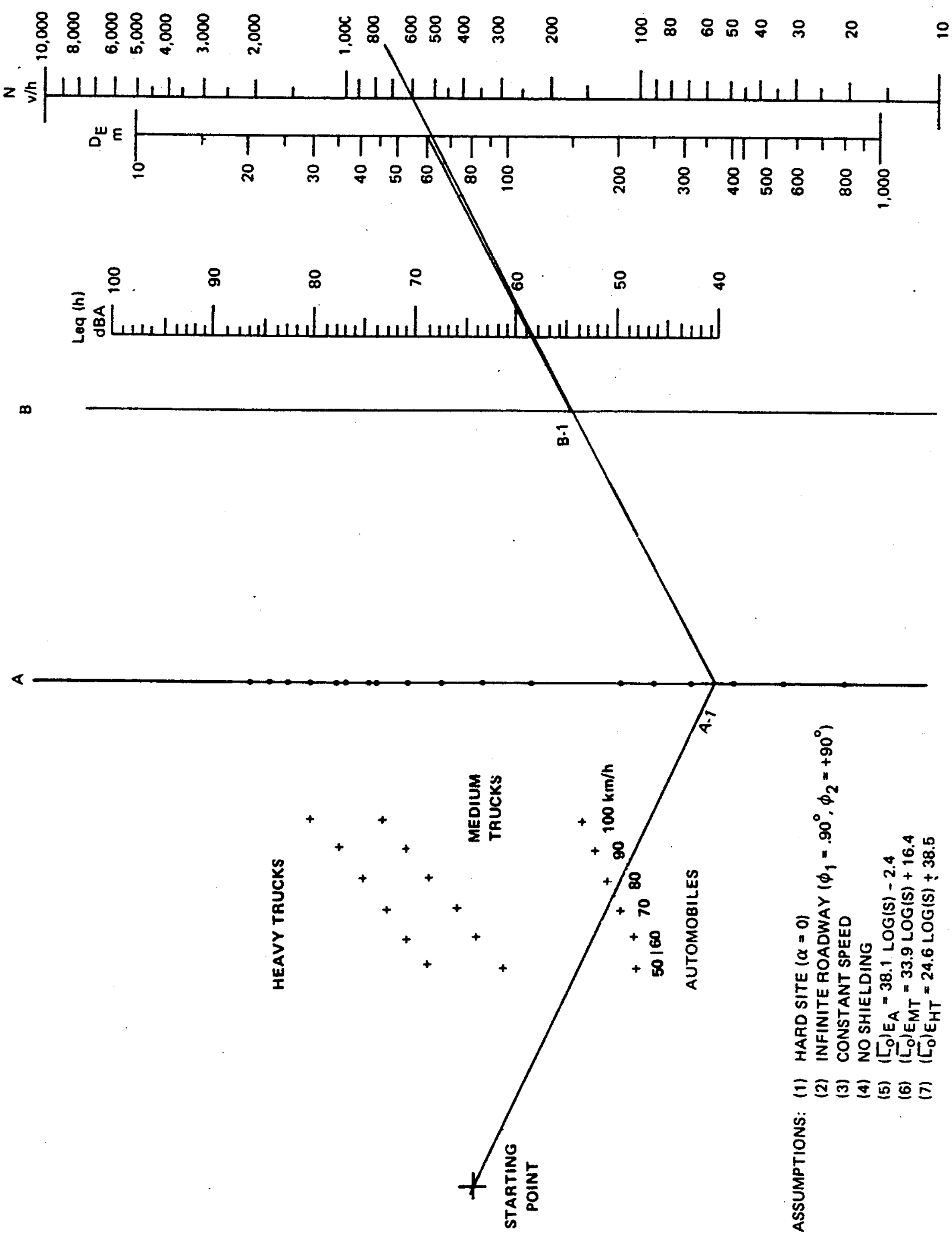
Step 1. Compute the $L_{eq}(h)$ heard by the observer.

$$L_{eq}(h) = 10 \log [10^{6.22} + 10^{5.78}] = 63.6 \text{ dBA} .$$

(From Problem 6, $L_{eq}(h) = 63.6$ dBA.)

(Continued)

PROBLEM 13 (Continued)



ASSUMPTIONS:
(1) HARD SITE (α = 0)
(2) INFINITE ROADWAY ($\phi_1 = -90°$, $\phi_2 = +90°$)
(3) CONSTANT SPEED
(4) NO SHIELDING
(5) $(\overline{L_o})_{E_A}$ = 38.1 LOG(S) - 2.4
(6) $(\overline{L_o})_{E_{MT}}$ = 33.9 LOG(S) + 16.4
(7) $(\overline{L_o})_{E_{HT}}$ = 24.6 LOG(S) + 38.5

Figure 13-2. FHWA Highway Traffic Noise Prediction Nomograph (Hard Site)

(Continued)

.PROBLEM 13 (Continued)

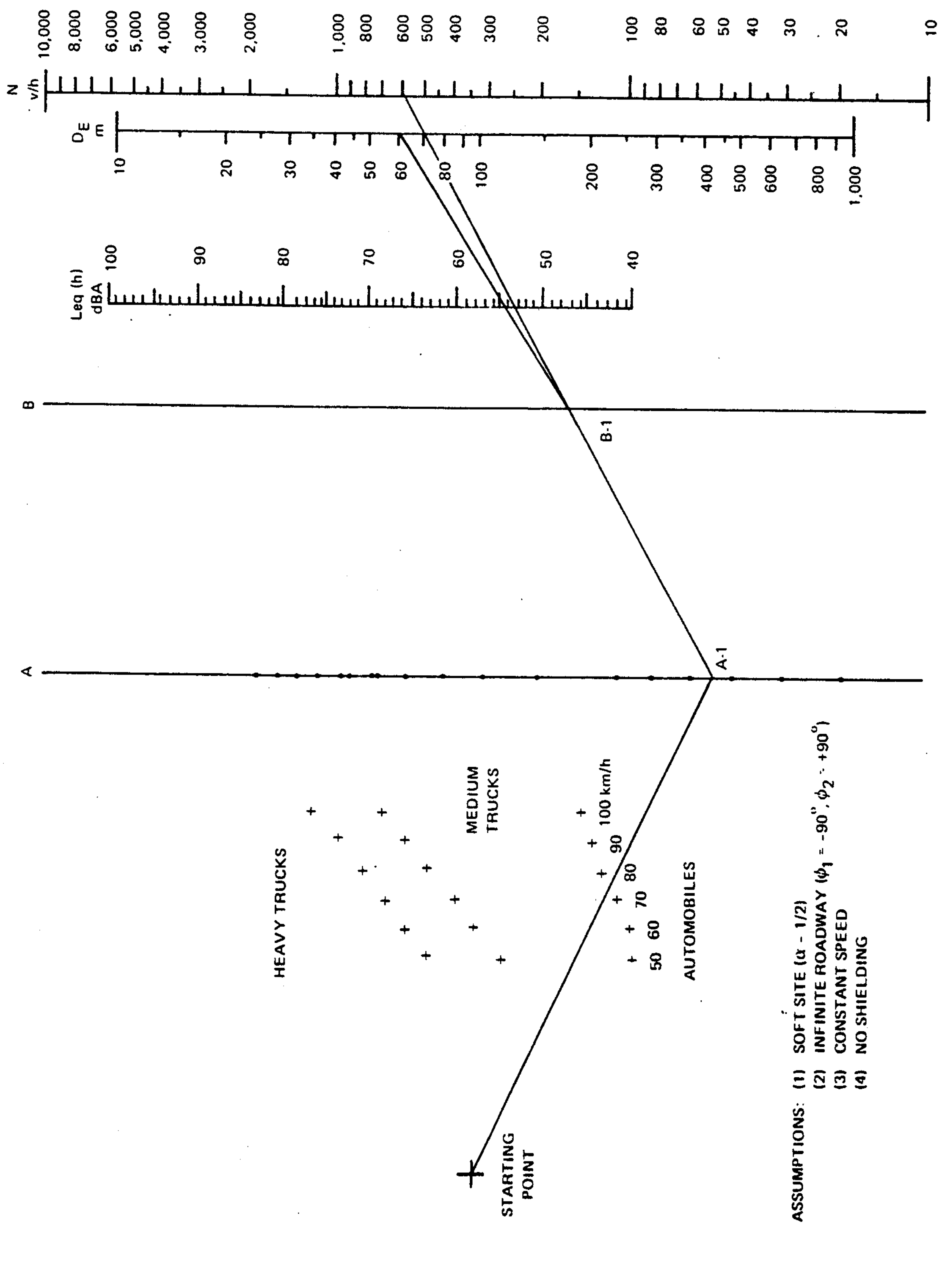


Figure 13-3. FHWA Highway Traffic Noise Prediction Nomograph (Soft Site)

(Continued)

PROBLEM 13 (Continued)

NAME ____________________ PROJECT DESCRIPTION PROBLEM 13

DATE ____________________

			SEGMENT A			SEGMENT B														
1.	LANE NO./ROAD SEGMENT																			
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		598	36	47	598	36	47												
4.	S(km/h)		–	75	–	–	75	–												
5.	D(m)			61.8			61.8													
6.	ϕ_1 (degrees)	Fig. 5		-90			0													
7.	ϕ_2 (degrees)	Fig. 5		0			+90													
8.	$(\overline{L_o})E_i$ (dBA)	Fig. 2																		
9.	10 LOG $(N_i D_o / S_i)$ (dB)	Fig. 3																		
10a.	10 LOG (D_o/D) (dBA)	Fig. 4																		
10b.	15 LOG (D_o/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_0(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6		-3																
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7					-3													
12.	ϕ_L (degrees)	Fig. 10																		
13.	ϕ_R (degrees)	Fig. 10																		
14.	δ_o (metres)	Fig. 9																		
15.	N_o	Eq. 18																		
16.	Δ_B (dBA)	Appendix B																		
17.																				
18.	$L_{eq}(h)$ (dBA)	Nomograph	59	57	63	54.5	53	58.5												
19.	$L_{eq}(h)$ (dBA)		56	54	60	51.5	50	55.5												
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)			62.2			57.8													
22.	$L_{eq}(h)$ (dBA)				63.6															
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 13-1. Noise Prediction Worksheet

3. *Barrier Nomograph*

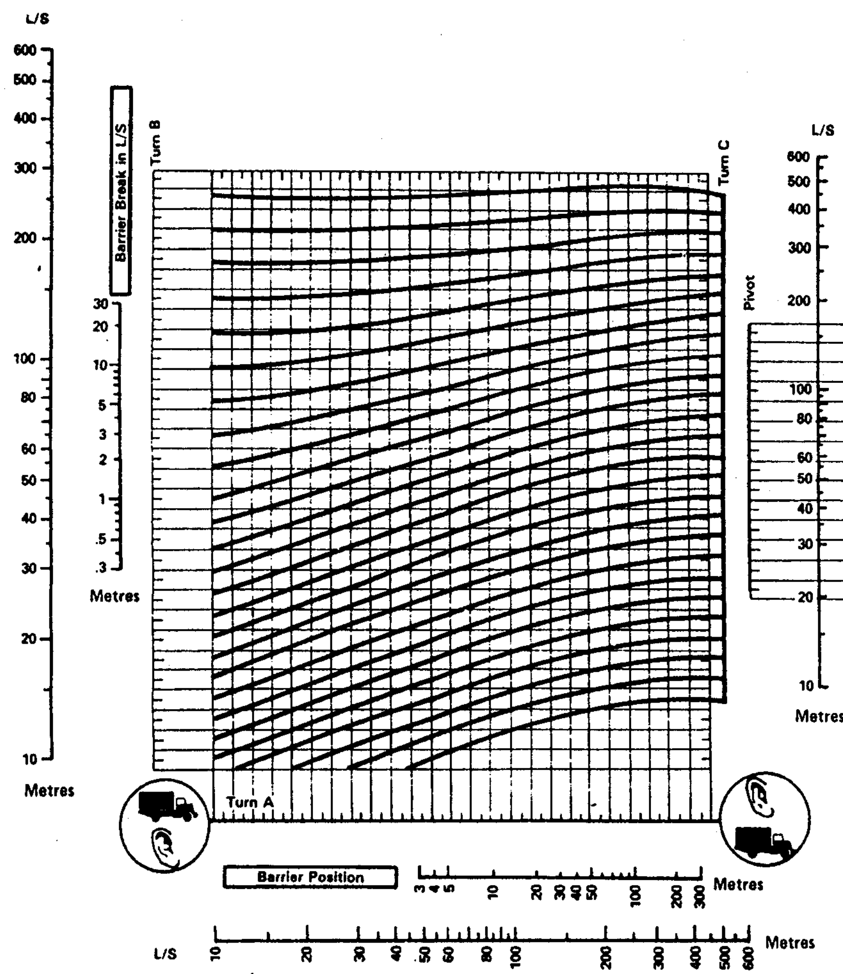
The Barrier Nomograph (Figure 21) is identical, except for the metric scales, to the Barrier Nomographs contained in References 6 and 8. Both the Barrier Nomograph (Figure 21) and the FHWA manual method start with the same basic expression—an integration of the point source attenuation function for an infinitely long barrier.

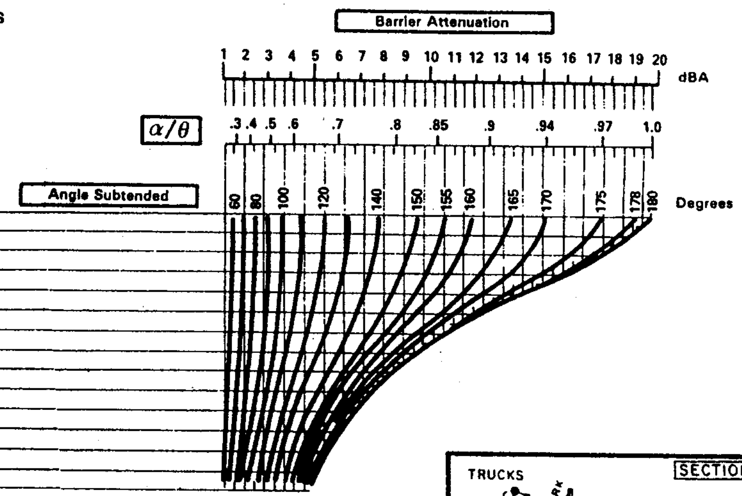
$$\text{Attenuation} = 10 \log \left\{ \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} 10^{-\Delta/10}\, d\phi \right\} \tag{34}$$

The major difference between the barrier nomograph and the FHWA method is in the treatment of finite barriers.

The manual method is applicable to a straight roadway of any length protected by a parallel, constant-height barrier. The FHWA method locates the barrier end points by the angles ϕ_L, ϕ_R relative to the position of the observer (see Figure 10). Spreading losses over the top of the barrier are purely geometric, i.e., 3 dBA/DD. Spreading losses around the ends of the barrier may include ground effects—i.e., 3 dBA/DD or 4.5 dBA/DD is used, depending on site conditions. The barrier attenuation values shown in the tables in Appendix B are to be applied to the noise levels emanating from the shielded highway section—i.e., the roadway must be broken down into segments, one of which is shielded by the barrier.

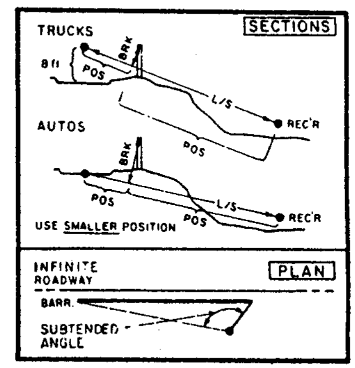
The barrier nomograph assumes a straight and infinitely long highway with a parallel and constant-height barrier. The barrier nomograph translates all finite barriers, regardless of actual position to $\phi_L = -90°$, $\phi_R = \Delta\phi - 90°$. This means that a barrier located by the angles ϕ_L, ϕ_R would be treated as a barrier located at $-90°$, $\Delta\phi - 90°$ where $\Delta\phi = \phi_L - \phi_R$. For example, a barrier located by the angles $\phi_L = -25°$, $\phi_R = 40°$ would be treated as if it were located at $\phi_L = -90°$, $\phi_R = -25°$. A barrier located by the angles $\phi_L = -45$, $\phi_R = +45°$, or a barrier located at $\phi_L = 0°$, $\phi_R = 90°$ would both be treated as if they were located at $\phi_L = -90°$, $\phi_R = 0°$. The barrier nomograph also assumes that the spreading losses over the top of the barrier are the rate of 3 dBA/DD and the spreading losses around the ends are at the rate of 4.5 dBA/DD. Since the nomograph assumes an infinitely long highway and the relation of the observer to the barrier is fixed, the attenuation provided by the barrier is applied to the noise levels coming from the infinitely long highway. The highway does not have to be broken down into sections. The nomograph only provides an estimate of the attenuation.





Assumptions:

1. Spreading losses over the top of the barrier are 3 dB/DD.
2. Spreading losses from leakage around the ends are 4.5 dB/DD.
3. The nomograph translates all finite barriers, regardless of position, to $\phi_L = -\pi/2$, $\phi_R = \Delta\phi - \pi/2$



Project:

Barrier Description:

Engineer:

Date:

Figure 21. Barrier Nomograph

PROBLEM 14

Refer to Figure 14-1. Compute the sound level at the observer under the following conditions:

a. No barrier (i.e., free field).

b. Infinitely long concrete barrier.

c. Finite concrete barrier when $\phi_L = -20^\circ$, $\phi_R = 70^\circ$.

The barrier is 4 metres high and the terrain between the roadway and the observer is covered with grass. ($\alpha = 1/2$). Use equivalent lane distance, and the nomographs to solve this problem.

The observer height is 1.5 m.

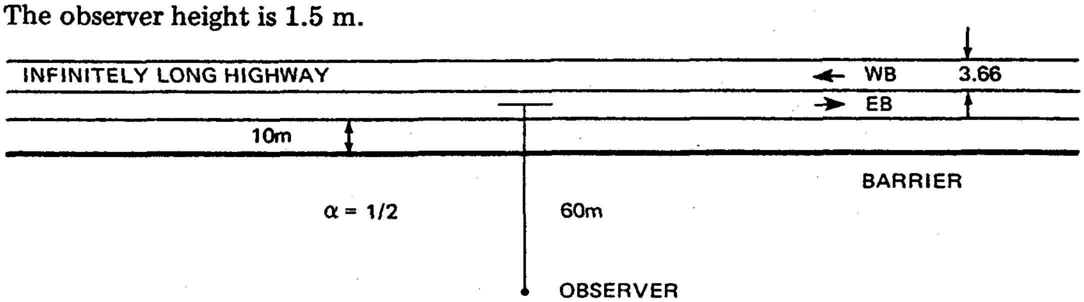


Figure 14-1

TRAFFIC DATA

Vehicle Class	EB	WB
A	317	281
MT	24	12
HT	22	25

$S = 75$ km/h.

a. *Compute the free field sound levels.*

Step 1. Use Figure 20—"FHWA Highway Traffic Noise Prediction Nomograph (Soft Site)," to compute the sound level at the observer without the barrier.

$$D_E = \sqrt{(60)(63.7)} = 62\text{ m}.$$

Step 2. $L_{eq}(h) = 60.8$ dBA. (From Problem 9, $L_{eq}(h) = 61.1$ dBA.)

b. *Compute the sound levels with the infinitely long concrete barrier.*

Step 1. Prepare a cross-sectional view of the highway of the highway and compute D_E.

(Continued)

PROBLEM 14 (Continued)

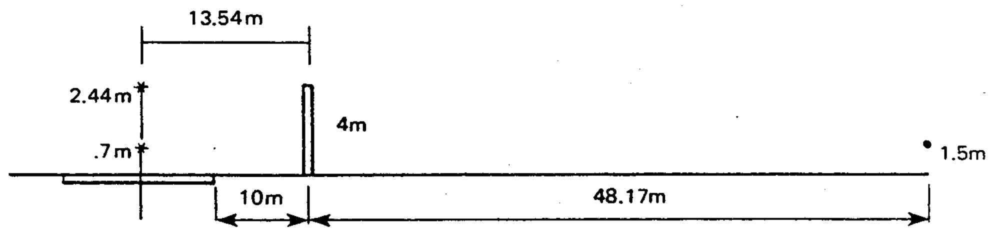


Figure 14-2

$$D_E = \sqrt{(11.83)(15.49)} + 48.17 = 61.71\,\text{m}.$$

SOLUTION

Step 1. Determine the perpendicular break in the L/S.

$$\delta_A \cong 4 - \left(\frac{x}{13.54} :: \frac{1.5}{61.7}\right) \cong 4 - .33 \cong \underline{3.67\text{ m}}$$

$$\delta_{MT} \cong 3.3 - \left(\frac{x}{13.54} :: \frac{.8}{61.7}\right) \cong 3.12\text{ m}$$

$$\delta_{HT} \cong 2.5 - \left(\frac{x}{48.17} :: \frac{.94}{61.7}\right) \cong 1.77\text{ m}.$$

Step 2. Use Figure 14-3 and determine the attenuation provided by the barrier. The values are shown in Table 14-1.

1. Starting at the bottom, draw a line from the L/S scale (62 m) through the barrier position scale (13.5 m) to Turn A. The intersection at the line with Turn A is marked A-1. From point A-1, project a line vertically upward.
2. Starting at the left, draw a line from the L/S scale (62 m) through the barrier break in L/S (3.67 m) to Turn B. The intersection of this line with Turn B is marked B-1. From point B-1, project a line horizontally to the right.
3. The intersection of the line from A-1 and the line from B-1 locate the top of the barrier on an attenuation curve. Follow the attenuation curve on which the top of the barriers lie upward and to the right to Turn C. The intersection of this line with Turn C is marked C-1.
4. From C-1 draw a line to the L/S scale (62 m). The intersection of this line with the pivot line is marked P-1. From P-1, project a line horizontally to the right until it intersects with the curve corresponding to the proper Angle Subtended.
5. At the intersection with the Angle Subtended curve, project upward to the Barrier Attenuation Scale.

$$\Delta_B \text{ (Automobiles)} = -13.5\text{ dB}.$$

(Continued)

PROBLEM 14 (Continued)

Repeat Step 1 for medium trucks and heavy trucks.

Δ_B (Medium Trucks) = <u>11.8 dB</u>

Δ_B (Heavy Trucks) = <u>9.3 dB</u>.

Step 3. Determine the sound level at the observer.

Note: Since the site is soft, ground effects ($\alpha = 1/2$) have to be taken into account. (Use Figure 19.)

$L_{eq}(h)_A = 59 - 13.5 = 45.5$ dBA

$L_{eq}(h)_{MT} = 57 - 11.8 = 45.2$ dBA

$L_{eq}(h)_{HT} = 63 - 9.3 = 53.7$ dBA

$L_{eq}(h) = 54.8$ dBA (From Problem 9, $L_{eq}(h) = 55.7$ dBA).

c. *Compute the sound levels with the finite barrier.*

Step 1. Since $\phi_L = -20°$ and $\phi_R = 70°$ the angle subtended is 90°.

Step 2. Use Figure 21 and determine the barrier attenuation using $\Delta\phi = 90°$. $\Delta_B = 3$ dB.

Step 3. Determine the sound level at the observer. This problem is fairly complicated because the site was initially soft ($\alpha = 1/2$). The roadway must now be broken down into three segments as was the case with Problem 10. Figure 20 is used to calculate the sound levels from Segments A and C. Figure 19 is used to calculate the sound level from Segment B. Since the barrier attenuation values shown in the barrier nomograph are applied to the infinite roadway values, the sound levels from the three segments must be added before the barrier attenuation is subtracted.

Segment A	$L_{eq}(h) = 56.5$ dBA	(Figure 20)
Segment B	$L_{eq}(h) = 62.2$ dBA	(Figure 19)
Segment C	$L_{eq}(h) = 48.6$ dBA	(Figure 20)

$$L_{eq}(h) = 10 \log [10^{5.65} + 10^{6.22} + 10^{4.86}] = \underline{63.4 \text{ dBA}}.$$

Therefore, the sound level at the observer is

$$L_{eq}(h) = 63.4 - 3 = \underline{60.4 \text{ dBA}}.$$

(From Problem 10, $L_{eq}(h) = 58.6$ dBA.)

(Continued)

PROBLEM 14 (Continued)

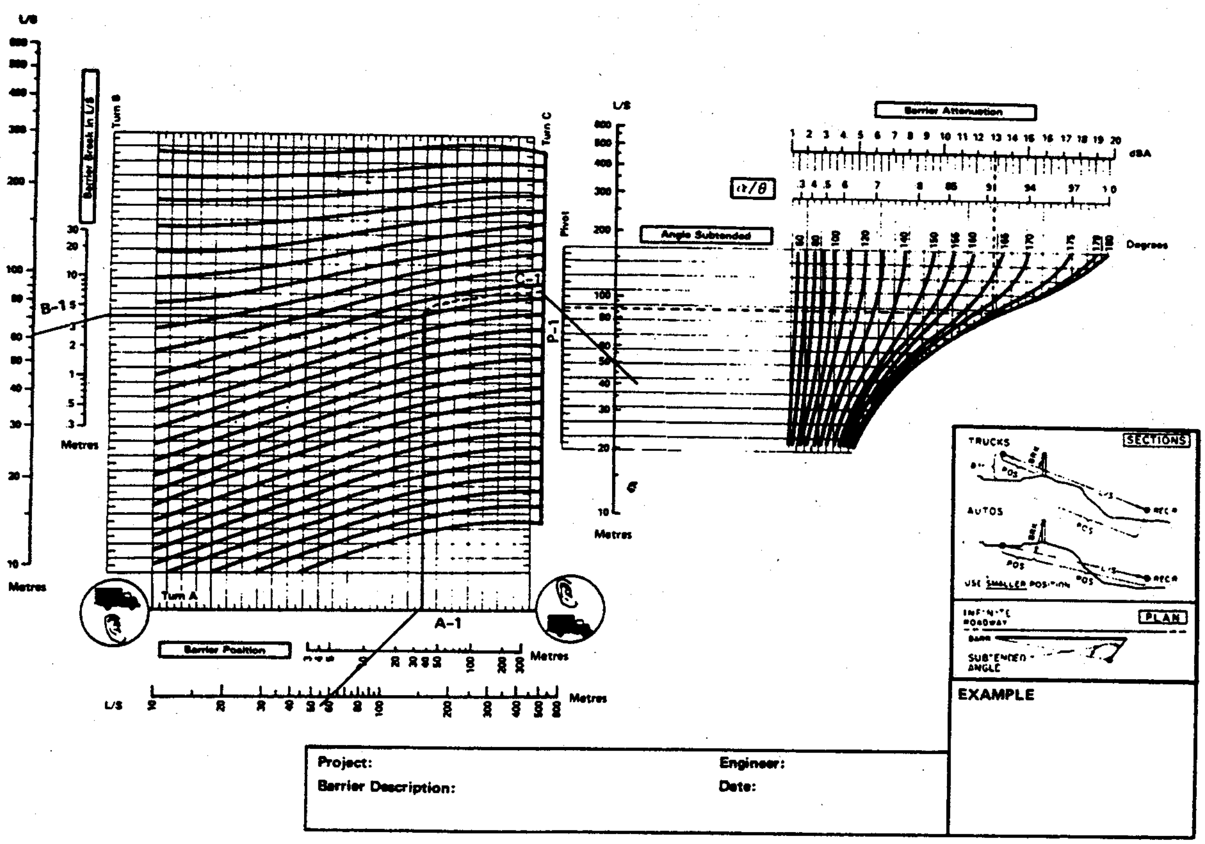


Figure 14-3. Barrier Nomograph

(Continued)

PROBLEM 14 (Continued)

NAME ______________________ PROJECT DESCRIPTION PROBLEM 14

DATE ______________________

			(a) FREE FIELD			(b) INFINITE BARRIER			(c) FINITE BARRIER											
1.	LANE NO./ROAD SEGMENT																			
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		598	36	47	598	36	47	598	36	47									
4.	S(km/h)		—	75	—	—	75	—	—	75	—									
5.	D(m)			62			62			62										
6.	ϕ_1 (degrees)	Fig. 5		-90			-90			-90										
7.	ϕ_2 (degrees)	Fig. 5		+90			+90			+90										
8.	$(\overline{L_o})_{E_i}$ (dBA)	Fig. 2																		
9.	10 LOG $(N_i D_o / S_i)$ (dB)	Fig. 3																		
10a.	10 LOG (D_o/D) (dBA)	Fig. 4																		
10b.	15 LOG (D_o/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_o(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6																		
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7																		
12.	ϕ_L (degrees)	Fig. 10								-20										
13.	ϕ_R (degrees)	Fig. 10								+70										
14.	δ_o (metres)	Fig. 9																		
15.	N_o	Eq. 18																		
16.	Δ_B (dBA)	Appendix B				-13.5	-11.8	-9.3	-3	-3	-3					(NOMOGRAPH VALUES)				
17.	CONSTANT (dB)																			
18.	$L_{eq}(h)$ (dBA)		54.5	53.	58.5	45.5	45.2	53.7	53.5	59.2	45.6									
19.	$L_{eq}(h)$ (dBA)			60.8			54.8			60.4										
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 14-1. Noise Prediction Worksheet

c. Programmable Hand-Held Calculators

The use of programmable hand-held calculators to solve Equations (1) and (15) has several distinct advantages. The calculators can be used to solve the equation directly to 0.1 of a decibel. Thus, they are more accurate. The use of the calculators eliminates the need to obtain values from several charts and tables. This reduces the potential for making an error. Finally, hand-held calculators are very quick, and make it possible to alter some variables without changing all of the other input data. Thus the time required to get an answer is further reduced. Figures 22 and 23 are Flow diagrams that can be used as a guide in writing a program.

Appendix D contains a listing of a program for one such programmable hand-held calculator. Equipment manufacturers are continually improving the capability and efficiency of these calculators. The program shown in Appendix D could be improved considerably by using a calculator with more storage capacity. Such calculators are available for less than $400.

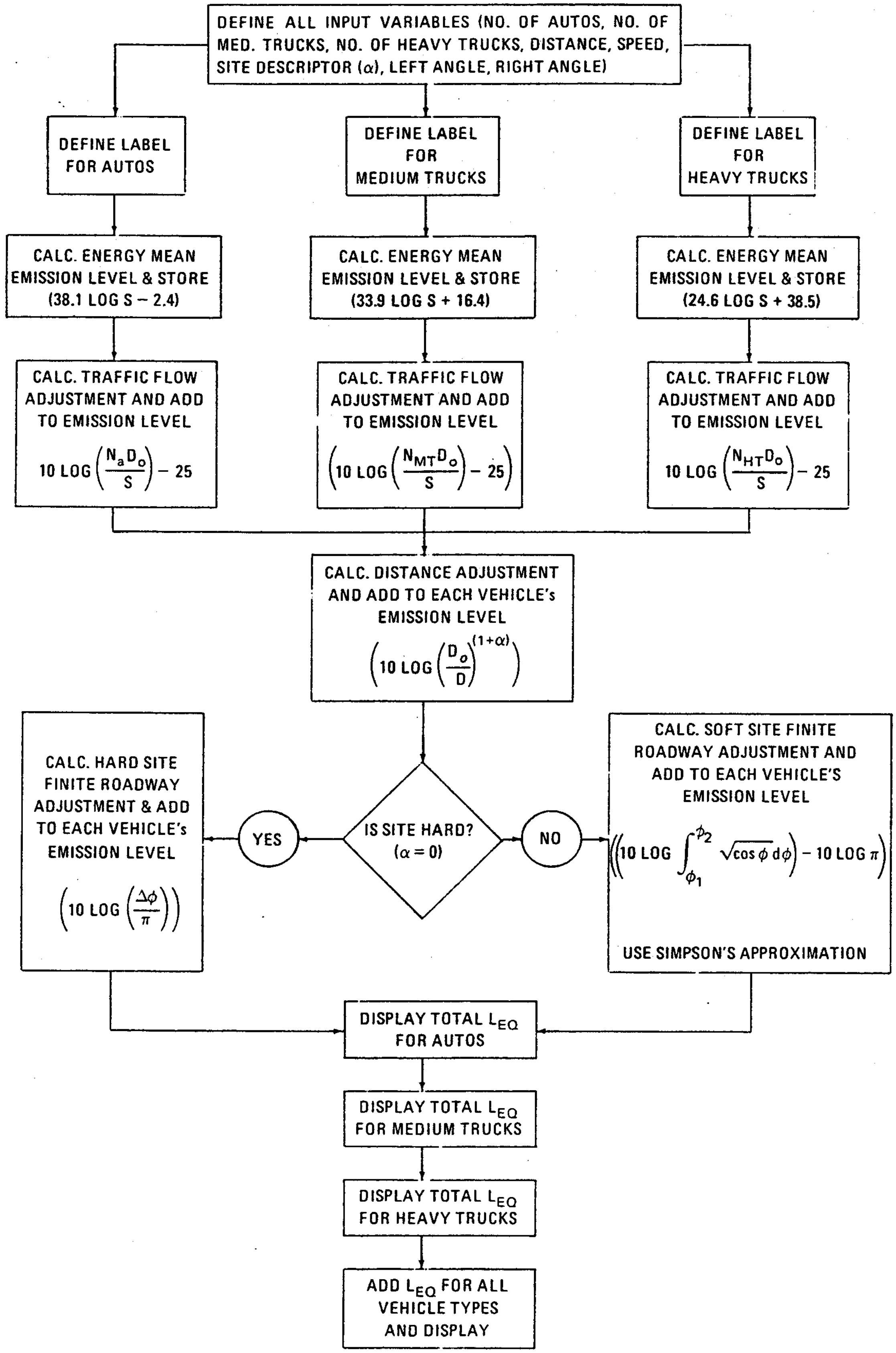


Figure 22. Flow Chart for Free Field Calculations

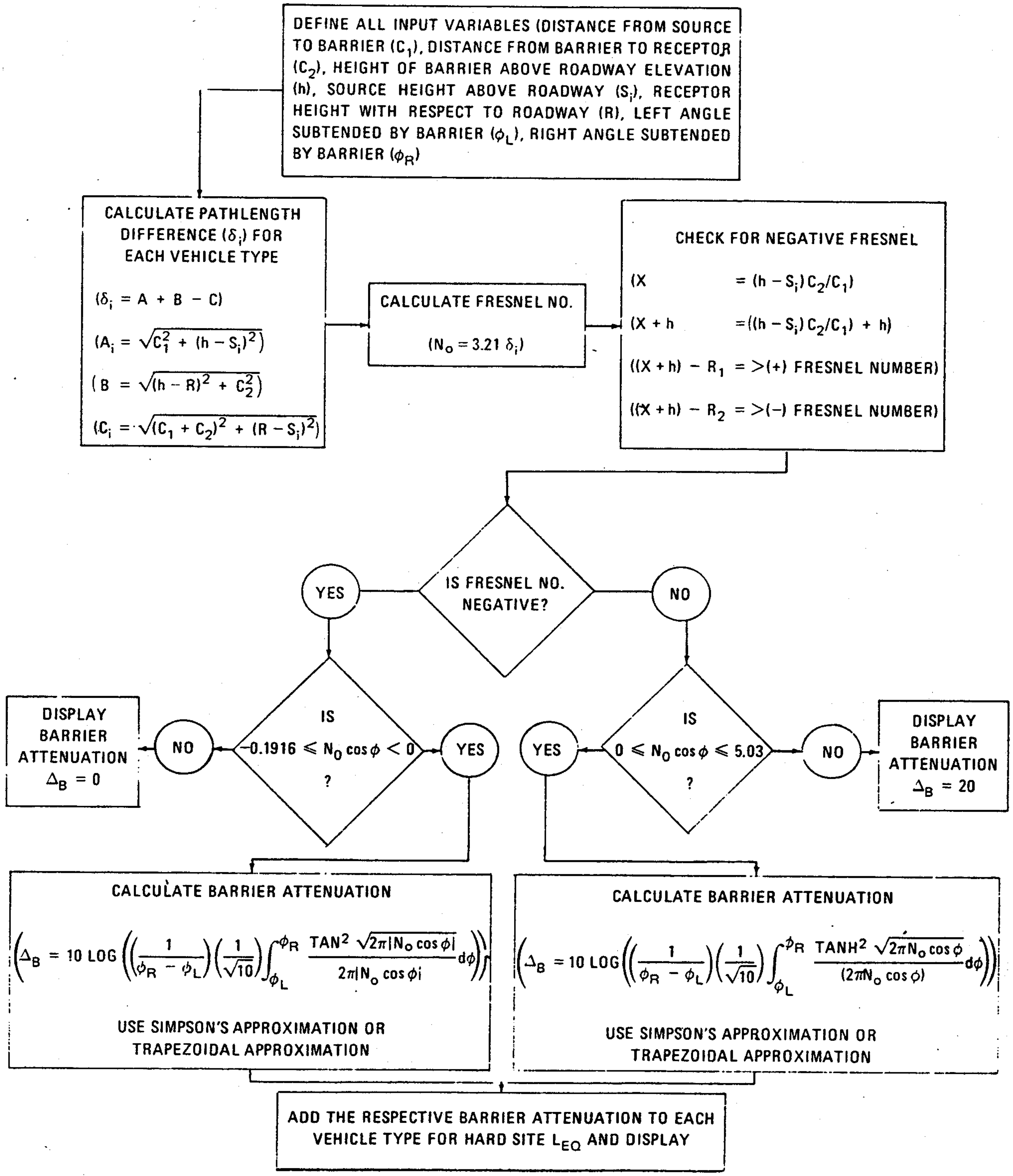


Figure 23. Flow Chart for Barrier Attenuation Calculations

PROBLEM 15

Redo Problems 9 and 10 using the equations developed in Chapter 2.

SOLUTION

Figures 22 and 23 show the equations as used in the development of the program shown in Appendix D.

The values shown in Tables 15-1 and 15-2 are accurate to 0.1 of a decibel.

Problem 9 (reworked using hand-held calculator).

Step 1. Free Field: $L_{eq}(h)$ = 61.0 dBA.

Step 2. Infinite Barrier: $L_{eq}(h)$ = 55.8 dBA.

Step 3. Insertion Loss: I.L. = 61. − 55.8 = 9.2 dBA.

Problem 10 (reworked using hand-held calculator).

Step 4. Finite Barrier: $L_{eq}(h)$ = 58.2 dBA.

Step 5. Insertion Loss: I.L. = 61.0 − 58.2 = 2.8 dBA.

NAME ______________________ PROJECT DESCRIPTION PROBLEM 15

DATE ______________________

			(a) FREE FIELD						(b) INFINITE BARRIER														
1.	LANE NO./ROAD SEGMENT			EB			WB			EB			WB								
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		317	24	22	281	12	25	317	24	22	281	12	25						
4.	S(km/h)		–	75	–	–	75	–	–	75	–	–	75	–						
5.	D(m)			60			63.66			60			63.66							
6.	ϕ_1 (degrees)	Fig. 5		-90			-90			-90			-90							
7.	ϕ_2 (degrees)	Fig. 5		+90			+90			+90			+90							
8.	$(\overline{L_o})E_i$ (dBA)	Fig. 2	69.	80.	84.6	69.	80	84.6	69.	80.	84.6	69.	80	84.6						
9.	10 LOG (N_iD_o/S_i) (dB)	Fig. 3	18.	6.8	6.4	17.5	3.8	7.	18.	6.8	6.4	17.5	3.8	7.0						
10a.	10 LOG (D_o/D) (dBA)	Fig. 4								-6.0			-6.3							
10b.	15 LOG (D_o/D) (dBA)	Fig. 4		-9.			-9.4													
11a.	10 LOG $(\psi_0(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6								0.0			0.0							
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7		-1.2			-1.2													
12.	ϕ_L (degrees)	Fig. 10								-90			-90							
13.	ϕ_R (degrees)	Fig. 10								+90			+90							
14.	δ_o (metres)	Fig. 9							.70	.51	.16	.56	.41	.14						
15.	N_o	Eq. 18							2.26	1.64	.51	1.78	1.31	.44						
16.	Δ_B (dBA)	Appendix B							-12.6	-11.6	-8.6	-11.9	-11.0	-8.2						
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		51.8	51.6	55.8	50.9	48.2	56.0	43.4	44.2	51.4	43.3	41.5	52.1						
19.	$L_{eq}(h)$ (dBA)			58.3			57.7			52.7			53.0							
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)					61.0						55.8								
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 15-1. Noise Prediction Worksheet

(Continued)

PROBLEM 15 (Continued)

NAME ______________________ PROJECT DESCRIPTION PROBLEM 15

DATE ______________________

			SEGMENT A						SEGMENT B						SEGMENT C					
1.	LANE NO./ROAD SEGMENT		EB			WB			EB			WB			EB			WB		
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		317	24	22	281	12	26	317	24	22	281	12	26	317	24	22	281	12	26
4.	S(km/h)		–	75	–	–	75	–	–	75	–	–	75	–	–	75	–	–	75	–
5.	D(m)		60			63.86			60			63.66			60			63.66		
6.	ϕ_1 (degrees)	Fig. 5	-90			-90			-20			-20			+70			+70		
7.	ϕ_2 (degrees)	Fig. 5	-20			-20			+70			+70			+90			+90		
8.	$(\overline{L_o})_{E_i}$ (dBA)	Fig. 2	69.	80.	84.6	69.	80.	84.6	69.	80.	84.6	69.	80.	84.6	69.	80.	84.6	69.	80.	84.6
9.	10 LOG (N_iD_o/S_i) (dB)	Fig. 3	18.	6.8	6.4	17.5	3.8	7.	18.0	6.8	6.4	17.5	3.8	7.	18.	6.8	6.4	17.5	3.8	7.
10a.	10 LOG (D_o/D) (dBA)	Fig. 4							-6.			-6.3								
10b.	15 LOG (D_o/D) (dBA)	Fig. 4	-9.			-9.4									-9.			-9.4		
11a.	10 LOG $(\psi_0(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6							-3.			-3.0								
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7	-5.7			-5.7									-13.6			-13.6		
12.	ϕ_L (degrees)	Fig. 10							-20			-20								
13.	ϕ_R (degrees)	Fig. 10							+70			+70								
14.	δ_o (metres)	Fig. 9							.70	.51	.16	.56	.41	.14						
15.	N_o	Eq. 18							2.26	1.64	.61	1.78	1.31	.44						
16.	Δ_B (dBA)	Appendix B							-15.3	-14.	-9.7	-14.3	-13.1	-9.2						
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		47.4	47.1	51.4	46.4	43.7	51.5	37.7	38.8	47.3	37.9	36.4	48.1	39.4	39.1	43.4	38.5	35.7	43.6
19.	$L_{eq}(h)$ (dBA)		53.8			53.2			48.3			48.8			45.9			45.3		
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)		56.5						51.6						48.6					
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)								TOTAL $L_{eq}(h)$ = 58.2											
27.	$L_{10}(h)$ (dBA)																			

Table 15-2. Noise Prediction Worksheet

d. Summary

Three different computational procedures have been presented for arriving at a predicted sound level using the FHWA Highway Traffic Noise Prediction Model—a manual method, nomographs, and a program for a hand-held calculator. Tables 5 and 6 are summaries of the sound levels predicted by the computational procedures in Problems 9 through 15. Comparisons of the values shown in Tables 5 and 6 indicate that the three methods provide almost identical answers. Although the problems used here are simple examples, the manual method and the use of programmable hand-held calculators should always provide the same answers. This is true because the program for the hand-held calculators is based on the manual method and contains the same assumptions.

The nomographs for predicting the sound level in the absence of barriers are also accurate. However, the barrier nomograph (Figure 21) has assumptions in it that are not consistent with the barrier procedure used in the manual method. Although the differences shown in Tables 5 and 6 are insignificant, there may be situations where the barrier nomograph would introduce significant error. The barrier nomograph should never be used for final design.

Table 5. Comparison of Predicted Sound Levels for Problems 9, 14, and 15 (Infinite Barrier), dBA Based on Different Computational Procedures

MANUAL METHOD Problem 9 ($\alpha = 1/2$)		NOMOGRAPHS Problem 14 ($\alpha = 1/2$)		CALCULATOR Problem 15 ($\alpha = 1/2$)	
Free Field	Infinite Barrier	Free Field	Infinite Barrier	Free Field	Infinite Barrier
61.1	55.7	60.8	54.8	61.0	55.8

Table 6. Comparison of Predicted Sound Levels for Problems 10, 14, and 15 (Finite Barrier), dBA Based on Different Computational Procedures

MANUAL METHOD Problem 10 ($\alpha = 1/2$)		NOMOGRAPHS Problem 14 ($\alpha = 1/2$)		CALCULATOR Problem 15 ($\alpha = 1/2$)	
Free Field	Finite Barrier	Free Field	Finite Barrier	Free Field	Finite Barrier
61.1	58.2	60.8	60.4	61.0	58.2

5.0 ACCURACY OF THE FHWA METHOD

a. Introduction

The final test of any noise prediction method is accuracy. How well do the predicted noise levels for a particular location compare with the measured noise levels for that location? If the predicted noise levels were equal to the measured noise levels, the predicted values would correlate perfectly with the measured data—i.e., the correlation coefficient (r) would equal one ($r = 1$). The mean difference between measured sound levels and predicted sound levels ($\bar{x}$) would equal zero ($\bar{x} = 0$). The standard deviation (s) of the differences between measured sound levels and predicted sound levels (x's) would equal zero ($s = 0$). At that location, it could be concluded that the prediction method performed perfectly. If the location were changed, or if any condition at the location changed that would affect the variables used in the prediction method, the accuracy of the prediction method could also be affected.

Consequently, before any positive statement is made about the accuracy of the method, it must be tested under a wide variety of conditions at a large number of locations. The FHWA noise prediction model has undergone only limited evaluation. The following sections discuss the evaluation which has been done.

b. Accuracy Based on Data Collected in Four State Noise Inventory [3]

Figures 24 and 25 are plots of the measured sound levels versus predicted sound levels at Site #2 in Florida. This data was collected over a 24-hour period in which traffic speeds remained fairly constant but traffic volumes and truck percentages varied considerably.

Noise level measurements were made over a 24-hour period at a distance of 15 m, 30 m, and 60 m from the centerline of the near traffic lane. Data was also collected on noise emission levels of the automobiles, medium trucks, and heavy trucks.

The predicted values shown in Figure 24 are based upon national noise emission levels. The predicted values shown in Figure 25 are based on the noise emission levels of vehicle, measured at 5 sites in Florida, one of which included Site #2.

Table 7 shows the results of the evaluation using the national emission levels. Table 8 shows the results of the evaluation using the Florida emission levels in the FHWA method.

The data in Tables 7 and 8 illustrate three points that one could have intuitively suspected:

1. The FHWA model is not perfect.
2. The FHWA model is slightly more accurate in Florida using Florida's noise emission levels.
3. The accuracy of the FHWA model decreases with increasing distance from the roadway.

However the overall accuracy is quite good at this site.

c. Accuracy Based on Data Contained in Research Report FHWA-RD-76-54 "Noise Experience Attenuation: Field Experiences"

Because of the large amount of measured data contained in this report, only a partial evaluation of this data has been done to date. The data analysis shown in Research Report FHWA-RD-76-54 is based on the NCHRP 174 procedure. This procedure and the one contained in the FHWA model are almost identical. Consequently, the results should be the same. The problems in Chapter 7 are based on the data contained in Research Report FHWA-RD-76-54.

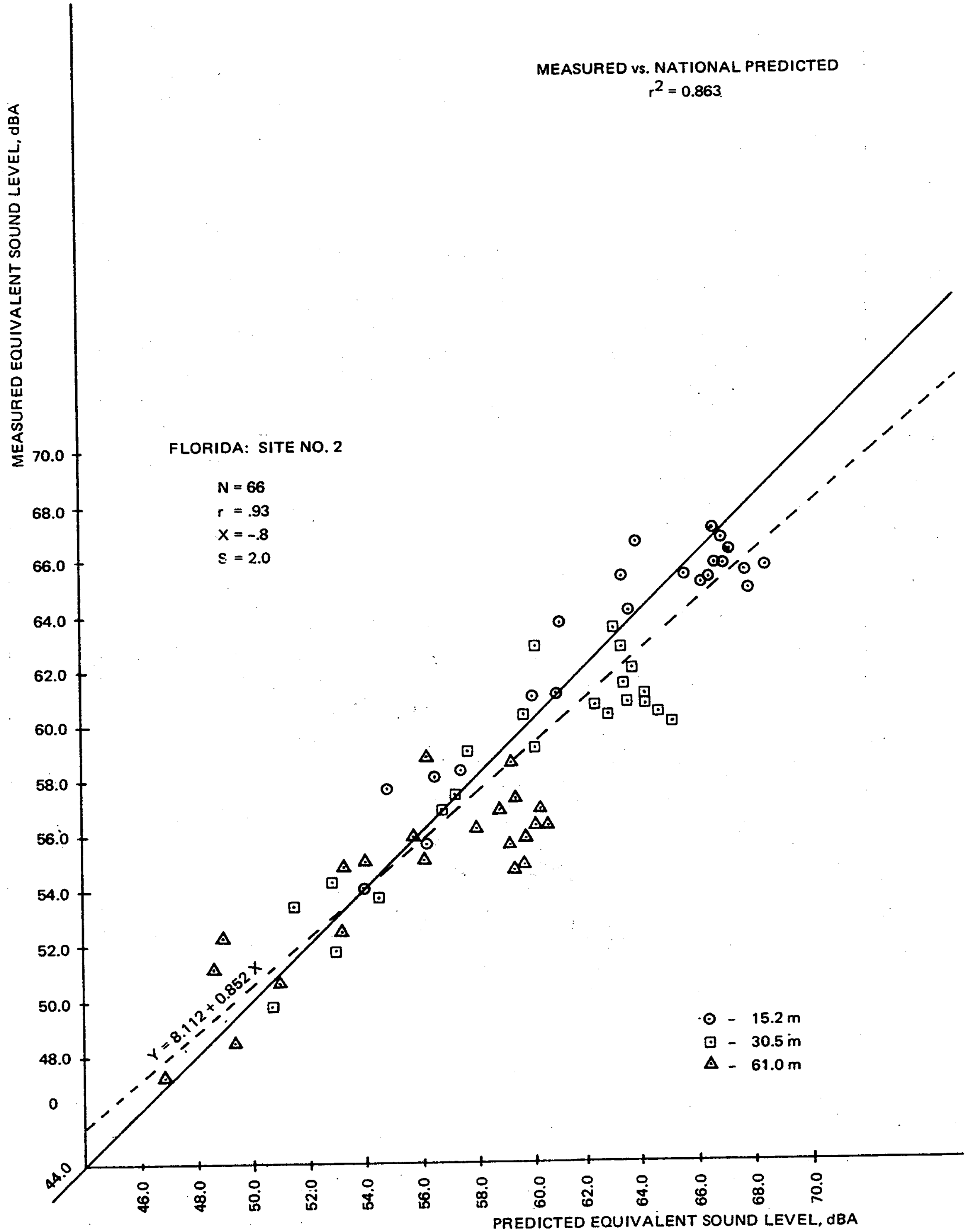


Figure 24. Comparison of the Florida Site 2 Data with Predicted Values Using National Noise Emission Levels

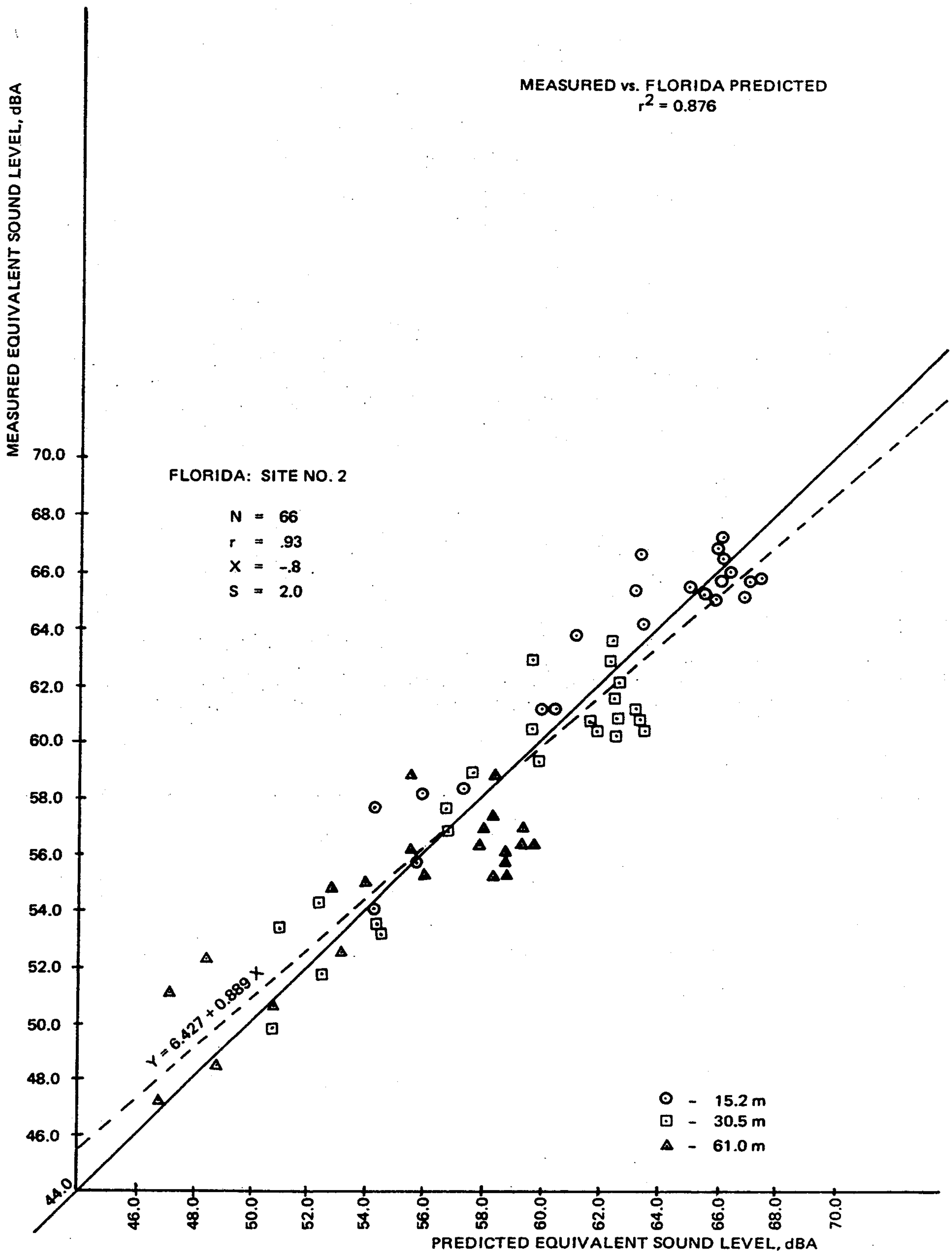


Figure 25. Comparison of the Florida Site 2 Data with Predicted Values Using Florida Emission Levels

Table 7. Evaluation of FHWA Prediction Method at Site 2, Florida Using National Noise Emission Levels

Location	Sample Size	*r*	$\bar{x}$	*s*
15 m	22	.94	−.05	1.64
30 m	22	.93	−.95	1.82
60 m	22	.86	−1.3	2.39
All locations	66	.93	−.78	2.02

Table 8. Evaluation of FHWA Prediction Method at Site 2, Florida Using Florida Noise Emission Levels

Location	Sample Size	*r*	$\bar{x}$	*s*
15 m	22	.95	+.58	1.39
30 m	22	.93	−.23	1.63
60 m	22	.86	−.57	2.31
All locations	66	.94	−.09	1.86

6.0 FHWA MODEL—MANUAL METHOD ($D < 15$ Metres)

a. Introduction

The discussion of the FHWA model up to this point has been limited to situations where D is equal to or greater than 15 metres. Over the past several years, questions have been raised concerning situations where D is less than 15 metres. Appendix A treats one general case where this occurs. In this case, the observer is located along the extension of the roadway. D can range from 15 metres down to 0 metres, but the observer must be located far enough from the roadway to insure that the vehicles still act as moving point sources. This occurs whenever the distance from the observer to the closest approach point of the vehicles is greater than 15 metres. (In NCHRP Report 174, this situation occurs when the angle between the observer and roadway extension is less than 5.0°.) Two situations where this occurs are shown in Figure 26.

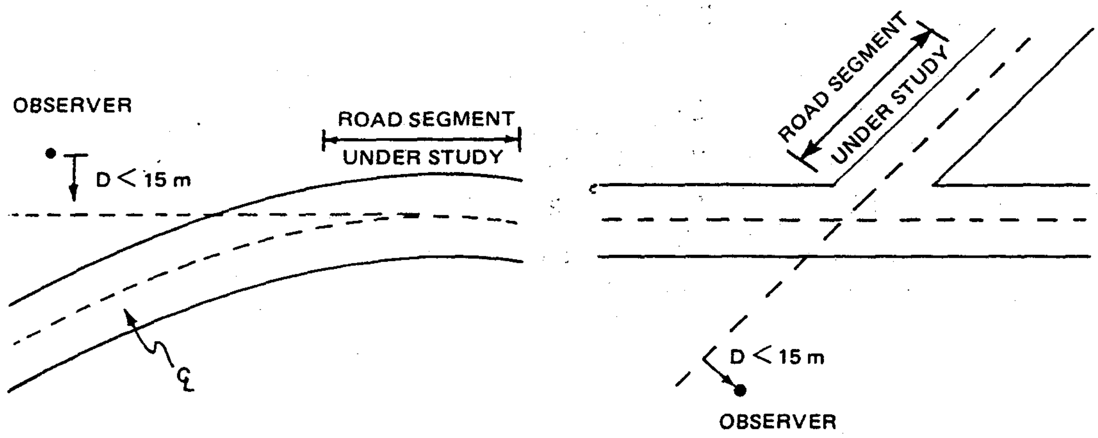


Figure 26. Situations were $D < 15$ Meters but the Vehicles are Still Treated as Point Sources

b. When D is Less Than 15 Metres and when Observer is Not Immediately Adjacent to the Highway or Highway Section

Although D can vary from 15 metres to 0 metres (the observer is on the extended centerline), the observer is often quite removed from the roadway. The sound level in this situation is computed using the following general equation:

$$L_{eq}(h)_i = (\overline{L_o})_{E_i} + 10 \log \left(\frac{N_i D_o}{S_i}\right)$$

$$+10 \log \left\{ \frac{1}{1+\alpha} \left[\left(\frac{D_o}{R_n}\right)^{1+\alpha} - \left(\frac{D_o}{R_f}\right)^{1+\alpha} \right] \right\} - 30 \qquad (35)$$

where

R_n is the distance in metres between the centerline of the near end of the roadway segment and the observer.

R_f is the distance in metres between the centerline of the far end of the roadway segment and the observer.

When $\alpha = 0$, Equation (21) reduces to

$$L_{eq}(h)_i = (\overline{L_o})_{E_i} + 10 \log \left(\frac{N_i D_o}{S_i}\right) + 10 \log \left[\left(\frac{D_o}{R_n}\right) - \left(\frac{D_o}{R_f}\right)\right] - 30 \quad (36)$$

for a reflective site.

When $\alpha = 1/2$, Equation (21) reduces to

$$L_{eq}(h)_i = (\overline{L_o})_{E_i} + 10 \log \left(\frac{N_i D_o}{S_i}\right)$$

$$+10 \log \left\{\frac{2}{3}\left[\left(\frac{D_o}{R_n}\right)^{3/2} - \left(\frac{D_o}{R_f}\right)^{3/2}\right]\right\} - 30 \quad (37)$$

for an absorptive site.

The total $L_{eq}(h)$ from all sources is then computed by decibel addition.

c. Accuracy

The accuracy of Equations (36) and (37) has not been established. There is a good possibility that a calibration constant will be needed to account for vehicle shielding. This is particularly true when D approaches 0. In this case the leading vehicle may significantly shield the noise generated by the vehicles behind it. It is expected that Equations (36) and (37) are conservative, perhaps overly so.

PROBLEM 16

What is the noise level generated by the traffic on the section of one lane ramp shown in Figure 16-1 at the observer. $S = 50$ km/h. Hourly volumes are 400 automobiles, 40 medium trucks, and 20 heavy trucks. The site is acoustically hard.

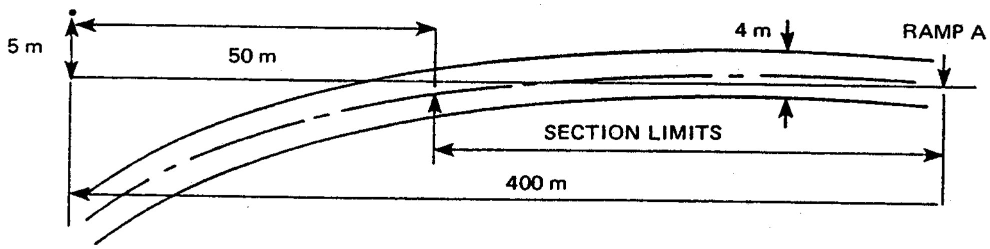


Figure 16-1

SOLUTION

Refer to Table 16-1.

Step 1. Complete Lines 1 through 4, Table 16-1.

Step 2. $D = 5$ metres. Record on Line 4, Table 16-1.

Step 3. Since D is less than 15 metres, the position of the ramp will be specified as R_n and R_f. $R_n \cong 50$ m and $R_f \cong 400$ m. Record these values on Lines 6 and 7, Table 16-1.

Step 4. Use Figure 2 and $S = 50$ km/h to determine the reference energy mean emission level. Enter this value on Line 8, Table 16-1.

Step 5. Use Figure 3 to determine the traffic flow adjustment factors; record these values on Line 9, Table 11-1.

Step 6. The distance adjustment factor and the finite length segment adjustment are included in the expression:

$$10 \log \left[\left(\frac{D_o}{R_n}\right) - \left(\frac{D_o}{R_f}\right)\right]$$

therefore adjustment factor

$$= 10 \log \left[\left(\frac{15}{50}\right) - \left(\frac{15}{400}\right)\right]$$

$$= 10 \log (.26)$$

$$= -5.8 \text{ dB}.$$

Record this value on Line 10(a), Table 16-1.

Step 7. Add up the values in each column and complete the $L_{eq}(h)$ at the observer.

$$L_{eq}(h) = 10 \log [10^{4.73} + 10^{4.90} + 10^{5.23}] = 54.8 \text{ dBA}.$$

(Continued)

PROBLEM 16 (Continued)

NAME ______________________ PROJECT DESCRIPTION PROBLEM 16

DATE ______________________

1.	LANE NO./ROAD SEGMENT	Ramp																	
2.	VEHICLE CLAS.	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)	400	40	20															
4.	S(km/h)	–	80	–															
5.	D(m)	5																	
6.	R_n Fig. 5	50																	
7.	R_f Fig. 5	400																	
8.	$(\bar{L}_o)E_i$ (dBA) Fig. 2	62.3	74.0	80.3															
9.	10 LOG $(N_i D_o/S_i)$ (dB) Fig. 3	20.8	10.8	7.8															
10a.	10 LOG (D_o/D) (dBA) Fig. 4	-6.8																	
10b.	15 LOG (D_o/D) (dBA) Fig. 4																		
11a.	10 LOG $(\psi_o(\phi_1, \phi_2)/\pi)$ (dBA) Fig. 6																		
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA) Fig. 7																		
12.	ϕ_L (degrees) Fig. 10																		
13.	ϕ_R (degrees) Fig. 10																		
14.	δ_o (metres) Fig. 9																		
15.	N_o Eq. 18																		
16.	Δ_B (dBA) Appendix B																		
17.	CONSTANT (dB)	-30	-30	-30															
18.	$L_{eq}(h)$ (dBA)	47.3	49.0	52.3															
19.	$L_{eq}(h)$ (dBA)	54.8																	
20.	Δ_s (dBA) Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																		
22.	$L_{eq}(h)$ (dBA)																		
23.	ND/S (m/km)																		
24.	$(L_{10}-L_{eq})_i$ (dB) Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																		
26.	$L_{10}(h)$ (dBA)																		
27.	$L_{10}(h)$ (dBA)																		

Table 16-1. Noise Prediction Worksheet

7.0 PROBLEMS

Most of the problems in this section are based on situations where actual measurements have been made. Table 1 is used in each problem as a computational guide.

PROBLEM 17

Refer to Research Report FHWA-RD-76-54, "Noise Barrier Attenuation: Field Experience." Compute the noise level at (1) the reference station and (2) Station 1, height equal 10 feet, for run no. 4 at site 01. See Figure 17-1. Use one equivalent lane. Please note that in the metric conversion there is some rounding error in the distances.

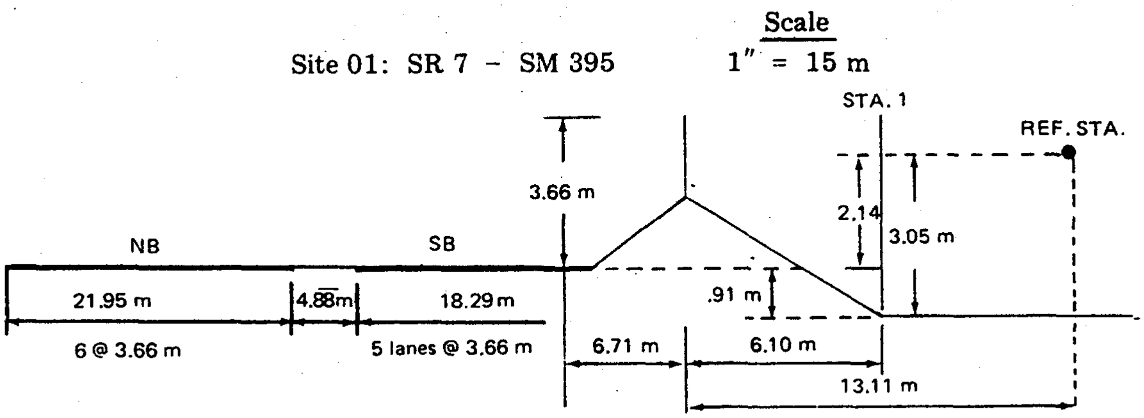


Figure 17-1

TRAFFIC DATA

(Page C-2, Report FHWA-RD-76-4)

Run No. 4

NB	SB
V_A = 3241 vph	V_A = 3252 vph
V_{HT} = 305 vph	V_{HT} = 378 vph

Speed = 85 km/h

V_A (Total) = 6493 vph

V_{HT} (Total) = 683 vph

SOLUTION

Compute the noise level at the reference station. Refer to Table 1.

Step 1. Complete Lines 1 through 4, Table 1.

Step 2. Since the reference station is beyond the limits of the barrier, Equation (20) is to compute the equivalent lane distance. Although it is not discussed in the report, it is assumed that the western most lane is an acceleration or deacceleration lane, and it is ignored.

$$D_E = \sqrt{(D_N)(D_F)}$$

$$= \sqrt{(13.11 + 6.71 + 1.83)(13.11 + 6.71 + 18.29 + 4.88 + 18.29 - 1.83)}$$

$$= \sqrt{(21.65)(59.45)} = 35.88 \text{ m}.$$

(Continued)

PROBLEM 17 (Continued)

Note: The author of Report FHWA-RD-76-4 did not use centerline distances for the computation of D_E. Therefore, there will be some discrepancies between the computed values shown here and those in the report.

Step 3. Refer to Figure 5. Infinite highway $\phi_1 = -90°$, $\phi_2 = +90°$.

Step 4. Refer to Figure 2, and determine the reference mean noise emission level at 85 km/h.

Step 5. Refer to Figure 3 and compute the traffic flow adjustment factor (D_0 = 15 m, S_o = 85 km/h).

Step 6. Refer to Figure 4 and compute the distance adjustment factor using 15 log (D_0/D).

Step 7. Refer to Figure 7 for the finite length adjustment factor for soft sites.

Step 8.

$L_{eq}(h)$ = 76.2 dBA calculated

$L_{eq}(h)$ = 75.9 dBA measured (Page D-2)

$L_{10}(h)$ = 78.9 dBA calculated

$L_{10}(h)$ = 78.8 dBA measured (Page D-2).

Compute the field insertion loss at Station 1, height = 3.05 m, using traffic data from Run 04.

SOLUTION

Computation of the *I.L.* requires two computations: the noise level at Station 1 before the barrier is built and the noise level after the barrier is built.

Before the Barrier

Step 1. Refer to Table 1. Complete Lines 1 through 4, Table 1.

Step 2. Computation of D here assumes that the barrier is not present.

$$D_E = \sqrt{(6.10 + 6.71 + 1.83)(6.10 + 6.71 + 18.29 + 4.88 + (18.29 - 1.83))}$$

$$= \sqrt{(14.64)(52.44)} = 27.71 \text{ m.}$$

Step 3. The distance adjustment factor is based on 4.5 dB/DD since it is assumed that (1) the barrier has not been built and (2) the report indicates that the site is soft.

(Continued)

PROBLEM 17 (Continued)

Step 4.

$L_{eq}(h)$ = $\underline{77.9 \text{ dBA}}$ calculated

$$L_{eq}(h) = 75.9 - 15 \log\left(\frac{89}{118}\right)$$

(See Page 18, Report FHWA-RD-76-54)

= $\underline{77.7 \text{ dBA}}$ measured

$L_{10}(h)$ = $\underline{79.6 \text{ dBA}}$ calculated

$$L_{10}(h) = 78.8 - 15 \log\left(\frac{89}{118}\right) = \underline{80.6 \text{ dBA}} \quad \text{measured.}$$

After the Barrier is Built

Step 1. Construction of the barrier now requires that the equivalent lane be based on the barrier's location

$$D_E = \sqrt{(6.71 + 1.83)(6.71 + 18.29 + 4.88 + 16.46)} + 6.10 \text{ m}$$

$$= \sqrt{(8.54)(46.36)} + 6.10$$

$$= 19.89 + 6.10 = \underline{25.99 \text{ m}}.$$

Step 2. Construction of the barrier has effectively raised the height of the noise source. The distance adjustment factor is now based on 10 log (D_0/D).

Step 3. The finite length adjustment factor is now based on 10 log $(\Delta\phi/\pi) = 0$.

Step 4. Since the barrier is infinitely long, $\phi_L = -90°$ and $\phi_R = +90°$.

Step 5. Compute the pathlength differences.

$$\delta_A = \sqrt{19.89)^2 + (3.66)^2} + \sqrt{(3.66 - 2.13)^2 + (6.10)^2}$$

$$-\sqrt{(2.13)^2 + (25.99)^2} = .44 \text{ m}$$

$$\delta_{HT} = \sqrt{(19.89)^2 + (3.66 - 2.44)^2} + \sqrt{(3.66 - 2.13)^2 + (6.10)^2}$$

$$-\sqrt{(2.44 - 2.13)^2 + (25.99)^2} = .22 \text{ m}.$$

(Continued)

PROBLEM 17 (Continued)

Step 6. Compute the Fresnel numbers

$$N_0 = 3.21\delta$$

$$\text{A:} \quad N_0 = 3.21(.44) = 1.41$$

$$\text{HT:} \quad N_0 = 3.21(.22) = .71$$

Step 7. Compute the barrier attenuation, Δ_B (auto)

$$1. \left\{ \begin{array}{l} 1.0 \\ 1.41 \\ 2.0 \end{array} \right. \begin{array}{l} \left.\begin{array}{l} \\ \end{array}\right\} .41 \\ \end{array} \begin{array}{l} \rightarrow -10.3 \\ \\ \rightarrow -12.3 \end{array} \quad \left\{ x \right. \quad \left\{ 2.0 \right. \qquad \Delta_B(\text{Auto}) = \underline{-11.1 \text{ dBA}}$$

$$\Delta_B(\text{HT}) = \underline{-9.3 \text{ dBA}}.$$

Step 8.

$L_{eq}(h) = \underline{70.9}$ calculated

$L_{eq}(h) = \underline{67.6}$ measured

The calculated value is 3.3 dBA higher than the measured value. Two possible causes are now under investigation.

(1) The source height for trucks – 2.44 metres – may be too high.

(2) The barrier attenuation in the table is based on a thin-screen barrier. The wall-berm combination may act more like a berm in which Case 3 dBA should have been added to the attenuation given in the barrier attenuation tables.

$$I.L. = 77.9 - 70.7 = 7.2 \text{ dBA} \quad \underline{\text{predicted}}$$

$$I.L. = 75.9 - 15 \log\left(\frac{90.86}{117.66}\right) - 67.6 = 10 \text{ dBA} \quad \underline{\text{measured}}$$

(Continued)

PROBLEM 17 (Continued)

NAME ______________________ PROJECT DESCRIPTION PROBLEM 17

DATE ______________________

			REF. STA.						W/O BARRIER						W/BARRIER					
1.	LANE NO./ROAD SEGMENT		STA. RUN 4						STATION 1 RUN 4											
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		6493		683															
4.	S(km/h)		–	85	–															
5.	D(m)		35.88						27.71						25.99					
6.	ϕ_1 (degrees)	Fig. 5	-90																	
7.	ϕ_2 (degrees)	Fig. 5	+90																	
8.	$(\overline{L_o})E_i$ (dBA)	Fig. 2	71.1		86.				71.1		86.				71.1		86.			
9.	10 LOG (N_iD_o/S_i) (dB)	Fig. 3	30.6		20.8				30.6		20.8				30.6		20.8			
10a.	10 LOG (D_o/D) (dBA)	Fig. 4													-2.4					
10b.	15 LOG (D_o/D) (dBA)	Fig. 4	-5.7						-4											
11a.	10 LOG $(\psi_o(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6													0					
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7	-1.1						-1.1											
12.	ϕ_L (degrees)	Fig. 10													-90					
13.	ϕ_R (degrees)	Fig. 10													+90					
14.	δ_o (metres)	Fig. 9													.44		-.22			
15.	N_o	Eq. 18													1.41		-.71			
16.	Δ_B (dBA)	Appendix B													-11.1		- 9.3			
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		69.9		75				71.6		76.7				63.2		70.1			
19.	$L_{eq}(h)$ (dBA)		76.2						77.9						70.9					
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)		2740		288				2115		223				1986		209			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15	1.5		+3				+1.5		+3.5				+2		+3			
25.	$L_{10}(h)_i$ (dBA)		71.4		78.3				73.1		80.2				65.2		73.1			
26.	$L_{10}(h)$ (dBA)		78.9						81.0						73.8					
27.	$L_{10}(h)$ (dBA)																			

Table 17-1. Noise Prediction Worksheet

PROBLEM 18

What would be the *I.L.* at Station 1 (Problem 17) if the barrier occupied the position shown in Figure 18-1 below.

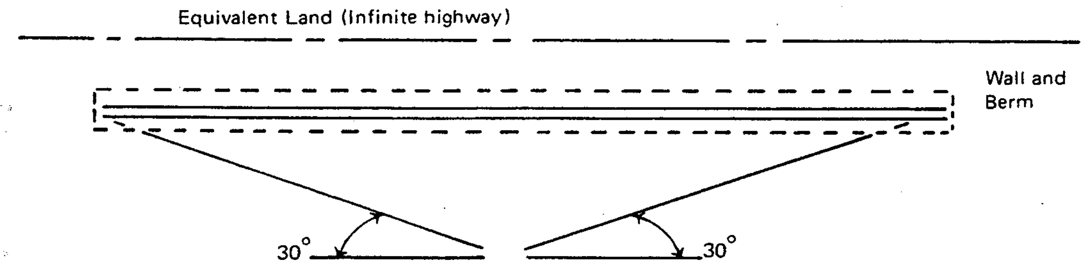


Figure 18-1

SOLUTION

Two sets of calculations must be made. The first set deals with the sound level at the station without the barrier. This level is identical to the level computed for Problem 17 without the barrier. In the second set of calculations, the sound level after the barrier is built must be computed. To do this the roadway must be broken down into 3 segments. Refer to Figure and the sketch above.

Segment I	$\phi_1 = -90°$	$\phi_2 = -60°$
Segment II	$\phi_1 = -60°$	$\phi_2 = +60°$
Segment III	$\phi_1 = +60°$	$\phi_2 = +90°$

<u>Sound Level at Station 1 Without the Barrier</u>

See Table 1. This level is identical to that computed in Problem 17 for Station 1 without the barrier.

SEGMENTS I AND III

Refer to Figure 5, Figure 7, and sketch of the problem. All angles are measured from the perpendicular between the observer and the roadway. Thus in Segment I, $\phi_1 = -90°$, $\phi_2 = -60°$. In Segment III, $\phi_1 = 60°$, $\phi_2 = 90°$. Figure 7 indicates that the adjustment factor for finite length roadways for absorbing sites is −11.0 dBA in both cases. This is because the segments have the same relative position. Note that for a 30° segment located anywhere else, the adjustment is different.

For example if $\phi_1 = -30$, $\phi_2 = 0$, then the adjustment is −8.0 dB.

See Table 18-1 for values.

(Continued)

SEGMENT II

Step 1. $D = 25.99$ (Based on barrier position).

Step 2. See Figure 5. $\phi_1 = -60°$, $\phi_2 = +60°$.

Step 3. Because of the barrier, use 10 log (D_o/D) for the distance adjustment factor.

Step 4. Finite length roadway adjustment

$$10 \log \left(\frac{120}{180}\right) = -1.8 \text{ dB}.$$

Step 5. See Figure 10. $\phi_L = -60$, $\phi_R = +60$.

Step 6. See Problem 17 (with barrier).

Step 7. Barrier tables. $\phi_L = -60$, $\phi_R = +60$

Δ_B (Auto):

1. and 1.41 differ by .41; 1. and 2.0 differ by 1.0

−12.2 and ☐ differ by x; −12.2 and −15.0 differ by −2.8

1.	−12.2	
	☐	
1.41	−15.0	
2.0		

$$\frac{x}{-2.8} = \frac{.41}{1.} \qquad x = -1.2$$

therefore Δ_B (Auto) = −13.4 dB

Δ_B (H. Trucks) = −10.9 dB.

Step 8.

$$L_{eq}(h) = 10 \log [10^{6.80} + 10^{6.74} + 10^{6.80}] = 72.6 \text{ dBA}$$

$$\boxed{I.L. = 77.9 - 72.6 = 5.3 \text{ dBA}}$$

(Continued)

PROBLEM 18 (Continued)

NAME ______________________ PROJECT DESCRIPTION PROBLEM 18

DATE ______________________

			W/O BARRIER			SEGMENT I			SEGMENT II			SEGMENT III								
1.	LANE NO./ROAD SEGMENT		STA. 1, RUN 4 HT 3.05 m						W/BARRIER											
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		6493		683															
4.	S(km/h)		–	85	–															
5.	D(m)			27.71			27.71			25.99			27.71							
6.	ϕ_1 (degrees)	Fig. 5		-90			-90			-60			+60							
7.	ϕ_2 (degrees)	Fig. 5		+90			-60			+60			+90							
8.	$(\overline{L_o})_{E_i}$ (dBA)	Fig. 2	71.1		86.															
9.	10 LOG $(N_i D_o / S_i)$ (dB)	Fig. 3	30.6		20.8															
10a.	10 LOG (D_o/D) (dBA)	Fig. 4								-2.4										
10b.	15 LOG (D_o/D) (dBA)	Fig. 4		-4			-4						-4.							
11a.	10 LOG $(\psi_o(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6								-1.8										
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7		-1.1			-11.0						-11.0							
12.	ϕ_L (degrees)	Fig. 10								-60										
13.	ϕ_R (degrees)	Fig. 10								+60										
14.	δ_o (metres)	Fig. 9							.44		.22									
15.	N_o	Eq. 18	.						1.41		.71									
16.	Δ_B (dBA)	Appendix B							-13.4		-10.9									
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		71.6		76.7	61.7		66.8	59.1		66.7	61.7		66.8						
19.	$L_{eq}(h)$ (dBA)			77.9			68.			67.4			68.							
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)									72.6										
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 18-1. Noise Prediction Worksheet

PROBLEM 19

Refer to Research Report FHWA-RD-76-54, "Noise Barrier Attenuation: Field Experience," Site 02, I605-STA-769 (Page B-3). Compute the noise level at the reference station based on Run 2. Compute the *I.L.* at Station 1, Height—9.0′ for Run 2. This is a hard site.

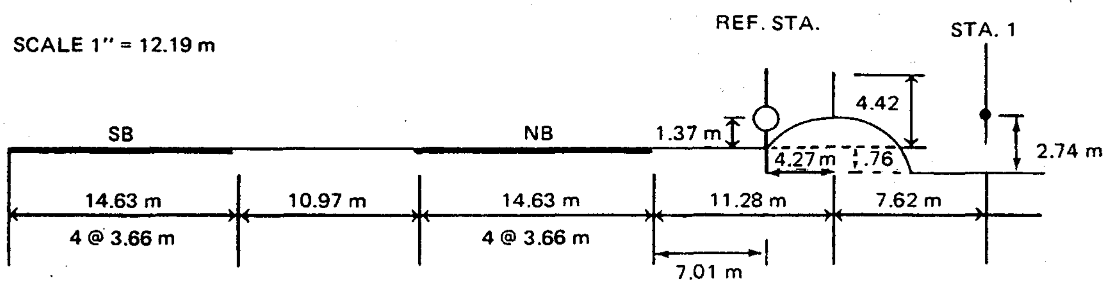


Figure 19-1

TRAFFIC DATA

(Page C-3) Run 02

SB	NB
V_A = 4056 vph	V_A = 3527 vph
V_{HT} = 66 vph	V_{HT} = 61 vph

S = 103 km/h (Note: Use 100 km/h)

V_A (Total) = 7583 vph

V_{HT}(Total) = 127 vph.

(a) Compute the Noise at the Reference Station

See Table 19-1.

$L_{eq}(h)$ = 79.6 dBA calculated

$L_{eq}(h)$ = 78.5 dBA measured (Page D-3)

(b) Compute the *I.L.* at Station 1, Height = 9′

$L_{eq}(h)$ = 77.3 dBA calculated without barrier

$L_{eq}(h)$ = 75.9 dBA measured without barrier

$L_{eq}(h)$ = 65.1 dBA calculated with barrier

$L_{eq}(h)$ = 63.2 dBA measured with barrier

(c) *I.L.* = 77.3 − 65.1 = 12.2 dBA calculated

I.L. = 75.9 − 63.2 = 12.7 dBA measured

Note: Since this is a hard site, the barrier attenuation and the field insertion loss are equal.

(Continued)

PROBLEM 19 (Continued)

NAME ______________________________ PROJECT DESCRIPTION ___PROBLEM 19___

DATE ______________________________

			REF. LEVEL						STA. 1 W/O						STA. 1, W/BARRIER					
1.	LANE NO./ROAD SEGMENT		RUN 2						BARRIER, RUN 2						RUN 2, HT = 9'					
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		7883		127															
4.	S(km/h)		–	100	–															
5.	D(m)		20.04						34.46						33.14					
6.	ϕ_1 (degrees)	Fig. 5	-90																	
7.	ϕ_2 (degrees)	Fig. 5	+90																	
8.	$(\overline{L_o})E_i$ (dBA)	Fig. 2	73.8		87.7															
9.	10 LOG (N_iD_o/S_i) (dB)	Fig. 3	30.6		12.8															
10a.	10 LOG (D_o/D) (dBA)	Fig. 4	-1.3						-3.6						-3.4					
10b.	15 LOG (D_o/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_o(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6	0						0						0					
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7																		
12.	ϕ_L (degrees)	Fig. 10													-87.4					
13.	ϕ_R (degrees)	Fig. 10													+87.4					
14.	δ_o (metres)	Fig. 9													.70		.49			
15.	N_o	Eq. 18													2.30		1.61			
16.	Δ_B (dBA)	Appendix B													-13.2		-11.7			
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		78.1		74.2				75.8		71.8				62.6		60.2			
19.	$L_{eq}(h)$ (dBA)		79.6						77.3						64.6					
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)		1520		25				2613		44				2513		42			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15	+2		+3				+1.5		+3				+1.5		+3			
25.	$L_{10}(h)_i$ (dBA)		80.1		77.2				77.3		74.8				64.1		63.2			
26.	$L_{10}(h)$ (dBA)		81.1						79.2						66.7					
27.	$L_{10}(h)$ (dBA)																			

Table 19-1. Noise Prediction Worksheet

PROBLEM 20

Refer to Research Report FHWA-RD-76-54, "Noise Barrier Attenuation: Field Experience." Site 06: 194-STA-213. Use two equivalent lanes, soft site. Note: Berms add 3 dBA to the attenuation.

(a) Compute the noise level at the reference station based on Run 3.

(b) Compute the insertion loss at Station 2, height = 1.52 m, Run 3 assuming that the earth berm is infinitely long.

(c) Compute the insertion loss at Station 2, height = 1.52 m, Run 3 for an earth berm that subtends the following angles $\phi_L = -50°$, $\phi_R = +70°$.

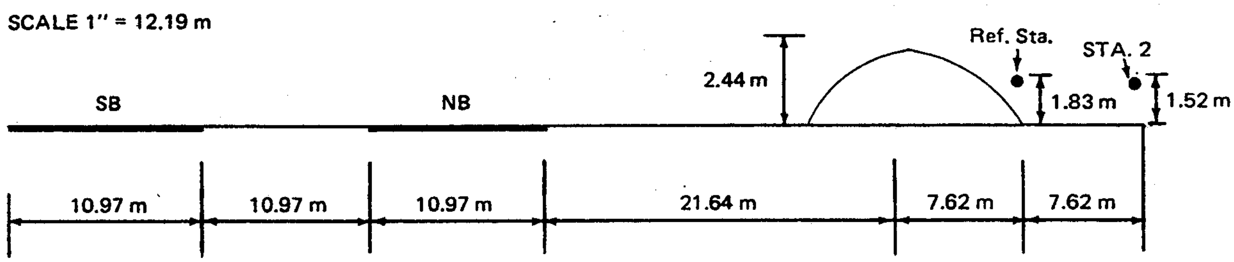


Figure 20-1

SOLUTION

See Table 20-1.

(a) Reference Station

$L_{eq}(h)$ = 72.1 dBA calculated

$L_{eq}(h)$ = 71.8 dBA measured.

(b) $L_{eq}(h)$ (Before) = 70.9 dBA calculated

$L_{eq}(h)$ (Before) = 70.7 dBA measured

$L_{eq}(h)$ (After) = 65.8 dBA calculated

$L_{eq}(h)$ (After) = 63.4 dBA measured

$I.L.$ = 70.9 − 65.8 = 5.1 dBA calculated

$I.L.$ = 70.7 − 63.4 = 7.3 dBA measured

(c) $L_{eq}(h) = 10 \log [10^{6.3} + 10^{6.38} + 10^{5.85}] = 67.1$ dBA

$I.L.$ = 70.9 − 67.1 = 3.8 dBA calculated.

(Continued)

PROBLEM 20 (Continued)

NAME ______________________________ PROJECT DESCRIPTION PROBLEM 20

DATE ______________________________

			REFERENCE STATION						STATION 2, HT = 1.52 m						STATION 2, HT = 1.52 m					
1.	LANE NO./ROAD SEGMENT		NB-RUN 3			SB-RUN 3														
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		498		192	568		96												
4.	S(km/h)		–	100	–	–	100	–												
5.	D(m)		34.55			56.57			42.21			64.21			42.12			64.18		
6.	ϕ_1 (degrees)	Fig. 5	-90			-90														
7.	ϕ_2 (degrees)	Fig. 5	+90			+90														
8.	$(\overline{L_o})E_i$ (dBA)	Fig. 2	73.8		87.7	73.8		87.7												
9.	10 LOG (N_iD_o/S_i) (dB)	Fig. 3	18.7		14.6	19.2		11.6												
10a.	10 LOG (D_o/D) (dBA)	Fig. 4													-4.5			-6.3		
10b.	15 LOG (D_o/D) (dBA)	Fig. 4	-5.4			-8.6			-6.7			-9.5								
11a.	10 LOG $(\psi_o(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6													0			0		
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7	-1.2			-1.2			-1.2			-1.2								
12.	ϕ_L (degrees)	Fig. 10													-90			-90		
13.	ϕ_R (degrees)	Fig. 10													+90			+90		
14.	δ_o (metres)	Fig. 9													.11		.02	.07		.02
15.	N_o	Eq. 18													.35		.06	.22		.06
16.	Δ_B (dBA)	Appendix B													-10.7		-8.6	-10		-8.6
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		60.9		70.7	58.2		64.5	59.6		69.4	57.3		63.6	52.3		64.2	51.7		59.4
19.	$L_{eq}(h)$ (dBA)		71.1			65.4			69.8			64.5			64.5			60.1		
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)		72.1						70.9						65.8					
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 20-1. Noise Prediction Worksheet

(Continued)

PROBLEM 20 (Continued)

NAME ______________________ PROJECT DESCRIPTION **PROBLEM 20(C) FINITE LENGTH BARRIER**

DATE ______________________

			SEGMENT I						SEGMENT II						SEGMENT III					
1.	LANE NO./ROAD SEGMENT		NB			SB			NB			SB			NB			SB		
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		498		192	568		96												
4.	S(km/h)		–	100	–	–	100	–												
5.	D(m)		42.21			64.21			42.12			64.18			42.21			64.21		
6.	ϕ_1 (degrees)	Fig. 5	-90			-90			-50			-50			70			70		
7.	ϕ_2 (degrees)	Fig. 5	-50			-50			70			70			90			90		
8.	$(\overline{L_o})_{E_i}$ (dBA)	Fig. 2	73.8		87.7	73.8		87.7												
9.	10 LOG $(N_i D_o / S_i)$ (dB)	Fig. 3	18.7		14.6	19.2		11.6												
10a.	10 LOG (D_o/D) (dBA)	Fig. 4							-4.5			-6.3								
10b.	15 LOG (D_o/D) (dBA)	Fig. 4	-6.7			-9.5									-6.7			-9.5		
11a.	10 LOG $(\psi_0(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6							-1.8			-1.8								
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7	-9.2			-9.2									-13.6			-13.6		
12.	ϕ_L (degrees)	Fig. 10							-50			-50								
13.	ϕ_R (degrees)	Fig. 10							+70			+70								
14.	δ_o (metres)	Fig. 9							.11		.02	.07		.02						
15.	N_o	Eq. 18							.35		.06	.22		.06						
16.	Δ_B (dBA)	Appendix B							-11.6		-8.8	-10.6		-8.8						
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		51.6		61.4	49.4		55.6	49.6		62.2	49.4		57.4	47.1		56.9	44.9		51.2
19.	$L_{eq}(h)$ (dBA)		61.8			56.6			62.4			58.			57.4			52.1		
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)		63.						63.8						58.5					
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 20-2. Noise Prediction Worksheet

REFERENCES

1. "Sound Procedures for Measuring Highway Noise," Report No. FHWA-DP-45-1, Federal Highway Administration, Washington, D.C. 20590, May 1978.
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4. "Update of TSC Highway Traffic Noise Prediction Code (1974)," Research Report FHWA-RD-77-19, Federal Highway Administration, Washington, D.C. 20590, January 1977.
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9. "Noise Barrier Attenuation: Field Experience," Research Report FHWA-RD-76-54, Federal Highway Administration, Washington, D.C. 20590, February 1976.
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11. "Attenuation of Highway Noise by Narrow Forest Belts," Report No. FHWA-RD-77-140, Federal Highway Administration, Washington, D.C. 20590, March 1978.
12. "Determination of Reference Energy Mean Emission Levels," Report No. FHWA-OEP/HEV-78-1, Federal Highway Administration, Washington, D. C. 20590, July 1978.

Appendix A

TRAFFIC NOISE MODEL FOR UNIFORMLY FLOWING (CONSTANT SPEED) TRAFFIC

The object of this appendix is to present a means whereby, given certain traffic flow information, it is possible to calculate or predict the equivalent sound level, L_{eq}, for uniformly flowing traffic. This objective will be accomplished through the development of an L_{eq} noise prediction model. In developing this model, the following steps will be taken:

Step 1 — An expression will be derived that specifies the position of a single vehicle on a flat, infinitely long highway, as it passes an observer adjacent to the highway.

Step 2 — Using first principles of acoustics, the equivalent sound level for a single vehicle will determined.

Step 3 — Noise level statistics for real traffic flows will be incorporated to expand the single vehicle model to cover actual traffic situations.

Step 4 — A correction factor for finite length roadways will be derived.

Step 5 — An excess attenuation factor will be developed to take ground cover effects into account.

Step 6 — The final step will be to summarize the L_{eq} noise model in two equations and illustrate their use through an example.

Step 1. Single Vehicle on a Single-Lane Highway

Consider a single vehicle traveling with a constant speed, S, past an observer situated next to a straight, flat, infinitely long, single-lane roadway as illustrated in Figure A-1. In the illustration, D is the perpendicular distance from the observer to the roadway centerline, and R is the distance between the observer and the vehicle. Since it is assumed that the vehicle is traveling with constant speed, R will vary continuously with time.

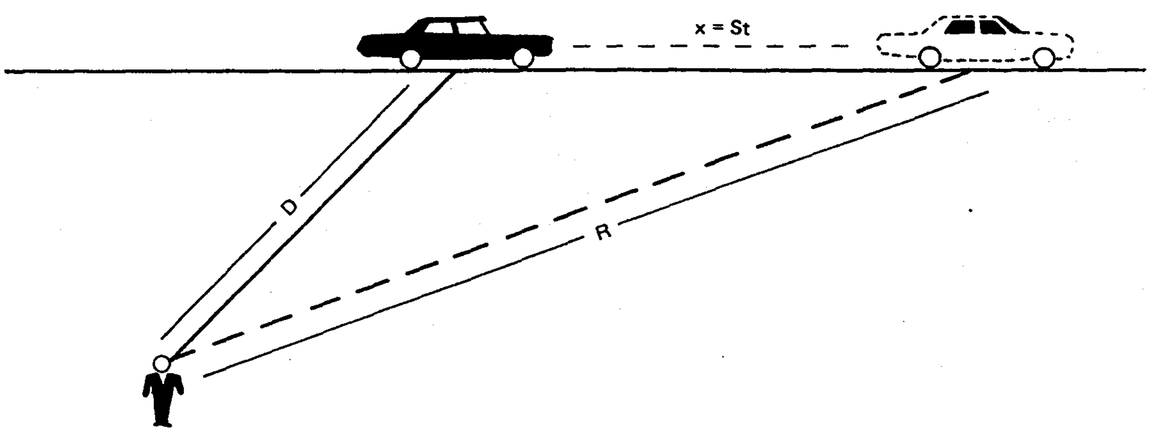


Figure A-1. Relationship Between Observer and Vehicle

To mathematically specify its time dependence, consider the plan view of the site shown in Figure A-2. For convenience, the time frame is defined such that t (t is the time in seconds) is equal to zero when the vehicle is closest to the observer, that is, $t = 0$ when $R = D$. When $t > 0$ the vehicle has moved some distance x, which is simply the speed of the vehicle, S, multiplied by the time, t. Thus the observer-vehicle distance is given by the expression,

$$R = \sqrt{D^2 + x^2} = \sqrt{D^2 + (St)^2}\ . \qquad \text{(A-1)}$$

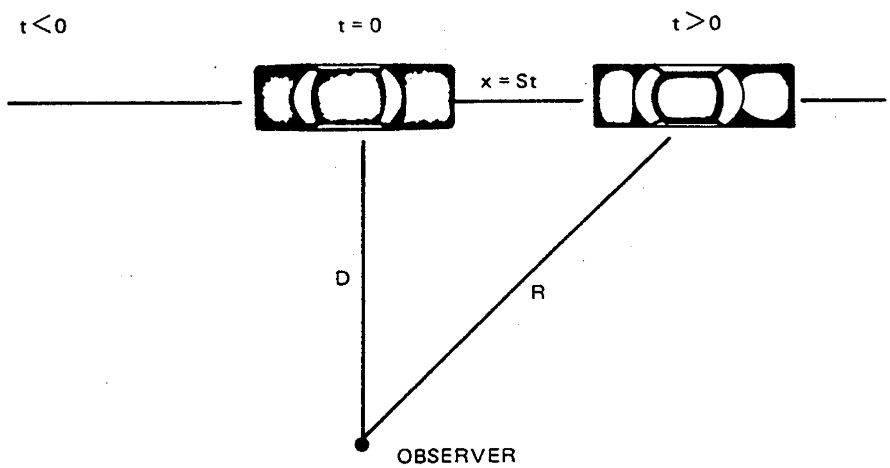


Figure A-2. Plan View of Relationship Between Observer and Vehicle

Step 2. Equivalent Sound Level for a Single Vehicle

Having specified the source-observer distance relationship for this simple site, some acoustic considerations may now be introduced. The first major assumption is the noise characteristics of the single vehicle are adequately represented by an acoustic point source. With this assumption, first principles show that the relationship between the mean square sound pressure, $\langle P^2 \rangle$, at some distance R, and the reference mean square pressure, $\langle P_o^2 \rangle$, radiated by the point source vehicle at some reference distance D_o is given by

$$\langle P^2 \rangle = \langle P_o^2 \rangle \frac{D_o^2}{R^2} = \langle P_o^2 \rangle \frac{D_o^2}{D^2 + (St)^2}\ . \qquad \text{(A-2)}$$

To insure the validity of the point source vehicle model, limits must be placed on the minimum reference distance D_o. Intuitively, as the observer gets closer and closer to the vehicle (decreasing D_o), the vehicle looks less and less like a point source and more and more like an extended source. When this begins to happen, the mathematical statement of the point source assumption (Equation (A-2)) breaks down and is no longer valid. Practically, the reference distance should not be less than 15 metres, and as a matter of practice 15 metres is usually the distance at which the reference measurements are taken. By applying this restriction, it is implied that the minimum observer distance, D, should also be 15 metres.

To calculate the time dependent sound pressure level, L, for the moving vehicle, recall the definition of sound pressure level,

$$L \triangleq 10 \log \frac{\langle P^2 \rangle}{\langle P_{ref}^2 \rangle} \text{ dB (decibel)} \qquad \text{(A-3)}$$

where $\triangleq$ means 'defined"; P_{ref} is the reference pressure and is equal to 2×10^{-5} pascal (Pa).

Applying this definition to the mean square pressure radiated by a point source vehicle (Equation (A-2)), the sound pressure level, L, at the observer is given by:

$$L = 10 \log \frac{\langle P^2 \rangle}{\langle P_{ref}^2 \rangle} = 10 \log \left[\frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} \frac{D_o^2}{D^2 + (St)^2} \right]. \quad \text{(A-4)}$$

Using the rule $\log (AB) = \log A + \log B$, Equation (A-4) may be written

$$L = 10 \log \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} + 10 \log \frac{D_o^2}{D^2 + (St)^2} \quad \text{(A-5)}$$

and finally,

$$L = L_o + 10 \log \frac{D_o^2}{D^2 + (St)^2} \quad \text{(A-6a)}$$

where

$$L_o \triangleq 10 \log \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle}. \quad \text{(A-6b)}$$

In highway work, L_o, is called the noise emission level of the vehicle and is referenced to the distance D_o. In general L will depend on the vehicle class (car, truck, bus, etc.) and the vehicle speed. Equation (A-6) gives the sound pressure level that would be measured by the observer situated D metres away from the roadway. D_o and L_o are constants, and since $R^2 = D^2 + S^2t^2$, Equation (A-6) is essentially of the form

$$L = \text{constant} + 10 \log \frac{1}{R^2}.$$

As the source-observer distance R increases, the sound level L decreases. For each doubling of source-receiver distance, L will decrease by 6 decibels, i.e., $10 \log (1/2^2) = -6$ dB.

EXAMPLE PROBLEM NUMBER 1

Problem: Suppose the emission level L_o at 15 metres for an automobile traveling at 80 km/h is 67 dBA. Investigate the sound level as a function of distance and time. Determine at what source-receiver distance the vehicle's sound level will be 10 dBA below an existing sound level of 50 dBA. (The sound pressure level and the sound level have the same meaning.)

Solution: The sound level for a single vehicle is given by Equation (A-6),

$$L = L_o + 10 \log \frac{D_o^2}{D^2 + (St)^2}$$

(Continued)

and from the information in the problem, we know

$$L_o = 67 \text{ dBA}$$

$$D_o = 15 \text{ m}$$

$$S = 80 \text{ km/h} = 22.2 \text{ m/s}$$

so that

$$L = 67 + 10 \log \frac{15^2}{D^2 + (22.2\,t)^2}$$

Using the relation $\log (A/B) = \log A - \log B$, the last expression becomes

$$L = 67 + 10 \log 15^2 - 10 \log [D^2 + (22.2\,t)^2]$$

$$L = 90.5 - 10 \log [D^2 + (22.2t)^2] \text{ dBA}.$$

(a) In terms of source-receiver distance, replace $[D^2 + (22.2t)^2]$ by R^2,

$$L = 90.5 - 10 \log R^2 .$$

When $R = 75$ m the sound level is

$$L = 90.5 - 10 \log (75)^2 = 53.0 \text{ dBA}$$

and when this distance is doubled, $R = 150$

$$L = 90.5 - 10 \log (150)^2 = 47.0 \text{ dBA}$$

which illustrates the 6 dB doubling of distance attenuation rate inherent in a point source.

(b) In terms of time and vehicle speed we return to

$$L = 90.5 - 10 \log [D^2 + (22.2t)^2] .$$

If the observer is 30 m from the roadway,

$$L = 90.5 - 10 \log [30^2 + (22.2t)^2] .$$

When $t = 0$,

$$L = 90.5 - 10 \log [30^2] = 61.0 \text{ dBA},$$

(Continued)

EXAMPLE PROBLEM NUMBER 1 (Continued)

and after 15 seconds

$$L = 90.5 - 10 \log [30^2 + (22.2 \times 15)^2] = 40.0 \text{ dBA}.$$

When $t = 0$ and the observer is 15 m from the roadway the sound level and the noise emission level are equal,

$$L = 90.5 - 10 \log [15^2] = 67.0 \text{ dBA}.$$

(c) To determine the distance at which the vehicle's instantaneous level is 10 dBA below the existing sound level of 50 dBA, calculate R when $L = 50 - 10 = 40$ dBA,

$$L = 90.5 - 10 \log R^2$$

$$40 = 90.5 - 10 \log R^2$$

$$\log R^2 = \frac{90.5 - 40}{10} = 5.05$$

$$R = \sqrt{10^{5.05}} \simeq 335 \text{ m}.$$

Thus, when $R = 335$ m, $L = 40$ dBA.

It is important to realize at this point in the analytical development, that the decrease in sound level radiated by the point source vehicle with increasing source-observer distances is due solely to geometric spreading of the sound waves and does not include any sound level attenuation resulting from atmospheric absorption or ground cover effects. As seen in the first example, geometric spreading results in a 6 dB decrease in the instantaneous sound level per doubling of the source-receiver distance when the vehicle is treated as a point source.

EXAMPLE PROBLEM NUMBER 2

Problem: Using the information provided in Example Problem 1, plot the time history of the sound level between $t = -15$ seconds and $t = +15$ seconds for an observer situated 15 m from the roadway. Take the existing sound level into account.

Solution: From Problem 1, extract the expression relating the level and time,

$$L = 90.5 - 10 \log [D^2 + (22.2t)^2]$$

where D will now equal 15 m. Table A-1 shows the calculation of the total sound level at various times taking into account the existing sound level. These values are used to construct Figure A-3.

(Continued)

EXAMPLE PROBLEM NUMBER 2 (Continued)

Table A-1. Computation of Instantaneous Sound Pressure Levels for Various Times

Time Seconds	$L = 90.5 - 10 \log [15^2 + 22.2^2 t^2]$ dBA	Existing Level, DBA	Total Level, dBA
0	67.0	50	67.1
.5	65.1	50	65.2
1.0	61.9	50	62.2
1.5	59.2	50	59.7
2.0	57.1	50	57.9
2.5	55.3	50	56.4
3.0	53.8	50	55.3
4.0	51.4	50	53.8
5.0	49.5	50	52.8
6.0	48.0	50	52.1
7.0	46.6	50	51.6
8.0	45.5	50	51.3
9.0	44.5	50	51.1
10.0	43.6	50	50.9
11.0	42.7	50	50.7
13.0	41.3	50	50.5
15.0	40.0	50	50.4

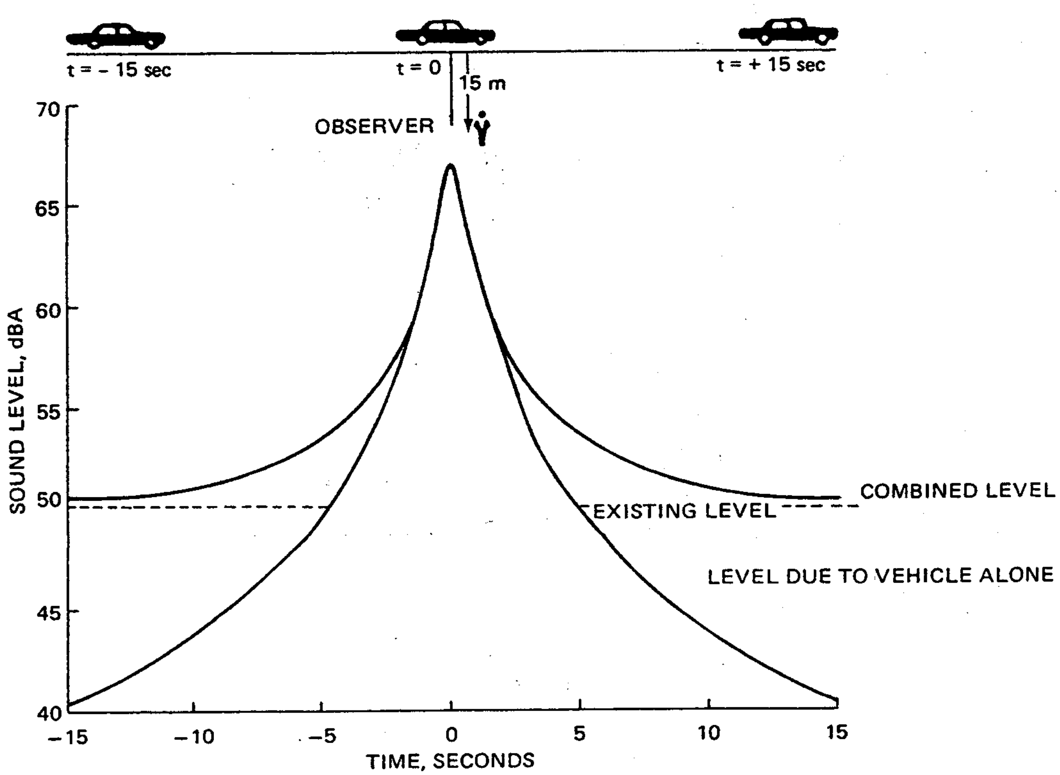


Figure A-3. Combined Sound Level Envelope Recorded by an Observer 15 m from the Roadway

Figure A-3 shows that the presence of the existing sound level can significantly alter the sound envelop of the passing vehicle.

Equation (A-6) permits the calculation of the sound pressure level at any observer location as the vehicle moves along the roadway. A quantity of considerably more interest, however, is the equivalent sound level associated with the traverse of the vehicle. The equivalent sound level is representative of the level of average intensity for the time period under consideration. Specifically, the equivalent sound level of the mean square pressure $\langle P^2 \rangle$ is defined as

$$L_{eq} \triangleq 10 \log \frac{1}{t_2' - t_1'} \int_{t_1'}^{t_2'} \frac{\langle P^2 \rangle}{\langle P_{ref}^2 \rangle} \, dt \quad \text{dB} \tag{A-7}$$

where $t_2' - t_1'$ is the time interval of interest. Before this noise metric (the equivalent sound level) is applied to the highway problem, consider calculation of the equivalent sound level in the case of a transient noise in the presence of a continuous but constant ambient sound level (similar to Example Problem 2 in which the level due to the vehicle (transient) was observed in the presence of the existing level). With reference to Figure A-4, the mean square pressure, $\langle P^2 \rangle$ is approximately

$$\langle P^2 \rangle \cong \begin{cases} \langle P^2 \rangle_{ex} + \langle P^2 \rangle_{tr} & t_1 < t < t_2 \\ \langle P^2 \rangle_{ex} & \text{elsewhere} \end{cases} \tag{A-7a}$$

where $\langle P^2 \rangle_{ex}$ is the existing sound level and $\langle P^2 \rangle_{tr}$ is the transient sound level. The equivalent sound level over the period (t_1', t_2') is calculated as

$$L_{eq} = 10 \log \frac{1}{t_2' - t_1'} \int_{t_1'}^{t_2'} \frac{\langle P^2 \rangle}{\langle P_{ref}^2 \rangle} \, dt \tag{A-7b}$$

$$L_{eq} \cong 10 \log \frac{1}{t_2' - t_1'} \left[\int_{t_1'}^{t_1} \frac{\langle P^2 \rangle_{ex}}{\langle P_{ref}^2 \rangle} \, dt + \int_{t_1}^{t_2} \frac{\langle P^2 \rangle_{ex} + \langle P^2 \rangle_{tr}}{\langle P_{ref}^2 \rangle} \, dt + \int_{t_2}^{t_2'} \frac{\langle P^2 \rangle_{ex}}{\langle P_{ref}^2 \rangle} \, dt \right] . \tag{A-7c}$$

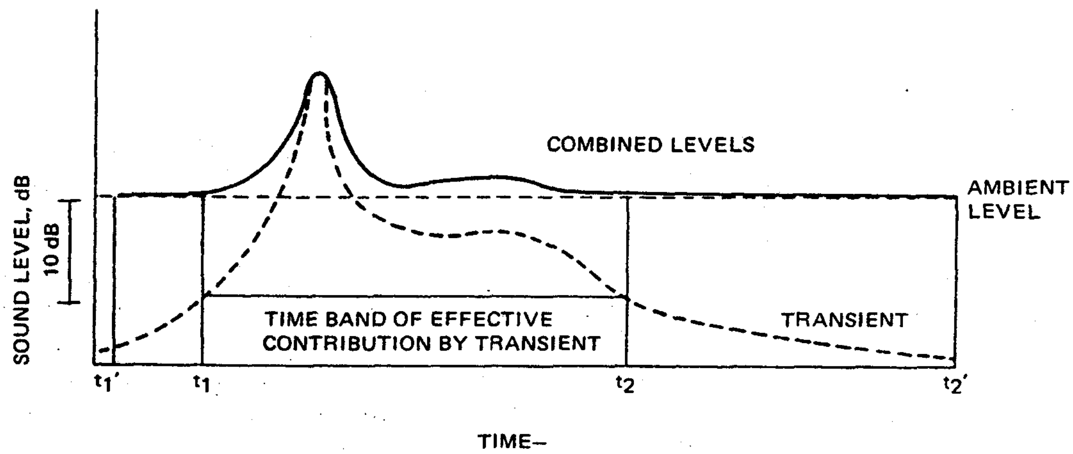


Figure A-4. Combined Sound Level Envelope Showing the Influence of the Existing Sound Level on the Transient Sound Level Envelope

Since the existing mean square pressures are constant, they may be taken outside each integral, so that

$$L_{eq} \cong 10 \log \frac{1}{t_2' - t_1'} \left[(t_1 - t_1') \frac{\langle P^2 \rangle_{ex}}{\langle P_{ref}^2 \rangle} + (t_2' - t_2) \frac{\langle P^2 \rangle_{ex}}{\langle P_{ref}^2 \rangle} \right.$$

$$\left. + (t_2 - t_1) \frac{\langle P^2 \rangle_{ex}}{\langle P_{ref}^2 \rangle} + \int_{t_1}^{t_2} \frac{\langle P^2 \rangle_{tr}}{\langle P_{ref}^2 \rangle} dt \right] . \tag{A-7d}$$

Combining terms,

$$L_{eq} \cong 10 \log \frac{1}{t_2' - t_1'} \left[(t_2' - t_1') \frac{\langle P^2 \rangle_{ex}}{\langle P_{ref}^2 \rangle} + \int_{t_1}^{t_2} \frac{\langle P^2 \rangle_{tr}}{\langle P_{ref}^2 \rangle} dt \right] , \tag{A-7e}$$

or

$$L_{eq} \cong 10 \log \left[\frac{\langle P^2 \rangle_{ex}}{\langle P_{ref}^2 \rangle} + \frac{1}{t_2' - t_1'} \int_{t_1}^{t_2} \frac{\langle P^2 \rangle_{tr}}{\langle P_{ref}^2 \rangle} dt \right] . \tag{A-7f}$$

This last expression indicates that the total equivalent sound level is calculated by computing the contribution from the transient signal between (t_1, t_2) averaged over the time interval of interest, $T = t_2' - t_1'$ and adding it, on an energy basis, to the existing sound level.

Applying this principle, the equivalent sound level associated with the traverse of a point source vehicle between the points $x_1 = St_1$ and $x_2 = St_2$ can be calculated. For the averaging interval T, which will be greater than or equal to the interval $t_2 - t_1$, the equivalent sound level is

$$L_{eq} = 10 \log \frac{1}{T} \int_{t_1}^{t_2} \frac{\langle P^2 \rangle}{\langle P_{ref}^2 \rangle} dt \tag{A-8}$$

$$L_{eq} = 10 \log \frac{1}{T} \int_{t_1}^{t_2} \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} \frac{D_o^2}{D^2 + (St)^2} dt . \tag{A-8a}$$

As a rule, the greatest portion of acoustic energy received by the observer from the moving vehicle takes place when the vehicle is closest to the observer, usually a few seconds either side of $t = 0$. (Inspection of the graph in Figure A-3 of Problem 2 shows this to be true.) As the receiver moves further away from the roadway, this time band becomes wider, that is, the vehicle contributes significant amounts of energy relative to its peak level over a longer period of time. This concept is illustrated in Figure A-5. Note that it takes the 15 m receiver's level 3.5 seconds to drop 15 dBA below its peak value of 75 dBA, about 6.9 seconds for the 30 m level to drop 15 dBA below its 69 dBA peak and much greater than 10 seconds for the level at 120 m to fall 15 dBA below its 56.9 dBA peak. If one considers integration as a summation, it is clear from the figure that it takes increasingly greater lengths of time for the more distance receivers to record the significant portions of a passing vehicle's sound level. A mathematical statement of this observation is that when

$$t_1 < 0 < t_2 \quad \text{and} \quad \left| \frac{St}{D} \right|_{t_1, t_2} >> 1 \tag{A-8b}$$

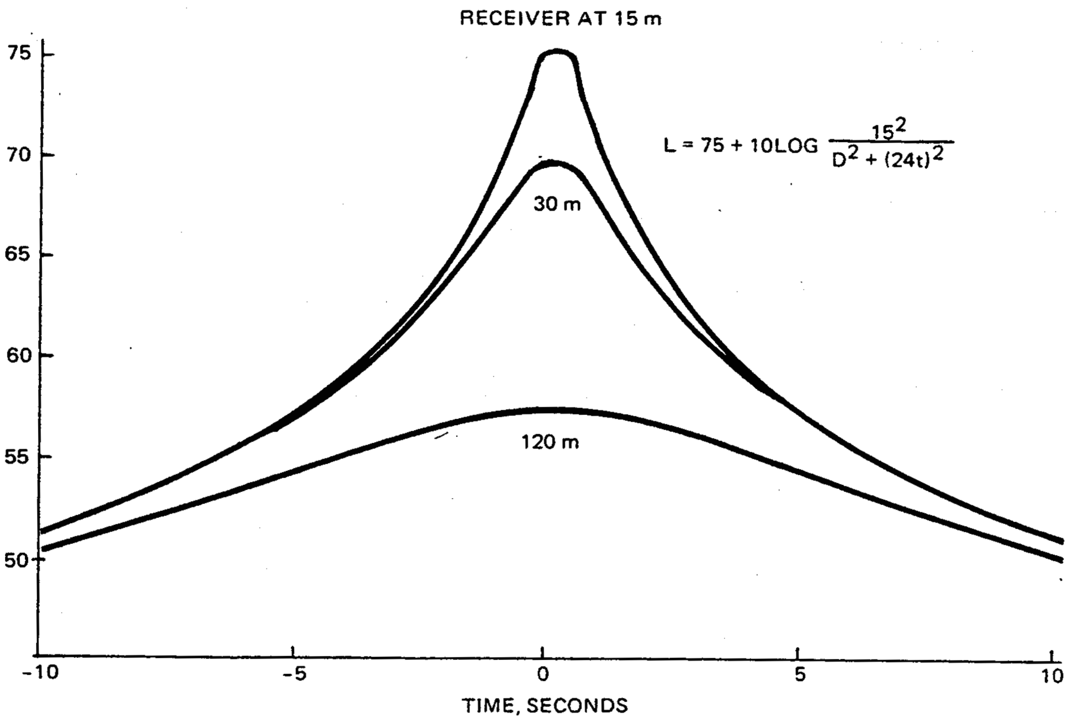


Figure A-5(a). Sound Level and Envelope Recorded by Observers 15 m, 30 m and 120 m from the Roadway

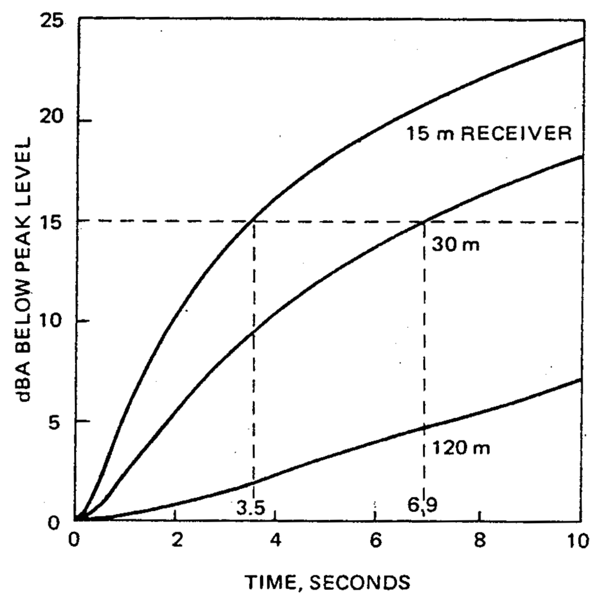


Figure A-5(b). Graph of Difference Between Peak Pass-By Sound Levels and the Time Dependent Levels as a Function of Time for Receivers at 15 m, 30 m, and 120 m

the following approximation may be used,

$$\int_{t_1}^{t_2} \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} \frac{D_o^2}{D^2 + (St)^2}\, dt \cong \int_{-\infty}^{\infty} \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} \frac{D_o^2}{D^2 + (St)^2}\, dt. \tag{A-8c}$$

Thus, for a sufficiently long averaging time, T, the following equation may be written

$$L_{eq} = 10 \log \frac{1}{T} \int_{-\infty}^{\infty} \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} \frac{D_o^2}{D^2 + (St)^2}\, dt. \tag{A-9}$$

Bringing the constant terms outside the integral and factoring out an S^2

$$L_{eq} = 10 \log \frac{1}{T} \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} \frac{D_o^2}{S^2} \int_{-\infty}^{\infty} \frac{dt}{(D/S)^2 + t^2}. \tag{A-10}$$

Using integral tables

$$\int_{-\infty}^{\infty} \frac{dt}{a^2 + t^2} = \frac{\pi}{a}.$$

Let $a = (D/S)$ in Equation (A-10), there results

$$L_{eq} = 10 \log \left[\frac{1}{T} \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} \frac{D_o^2}{S^2} \cdot \frac{S\pi}{D} \right]. \tag{A-11}$$

After canceling terms, (A-11) may be expanded,

$$L_{eq} = 10 \log \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} + 10 \log \frac{\pi D_o}{ST} + 10 \log \left(\frac{D_o}{D} \right). \tag{A-12}$$

Recalling the definition of the noise emission level for a single vehicle, Equation (A-12) can be re-written as

$$\boxed{L_{eq} = L_o + 10 \log \frac{\pi D_o}{ST} + 10 \log \left(\frac{D_o}{D} \right).} \tag{A-13}$$

The last result is an expression which permits one to calculate the equivalent sound level for a single vehicle traversing an "effectively infinite" roadway. The phase "effectively infinite" is used because of the approximation made in evaluating the integral in Equation (A-8). This expression is valid for any consistent set of units.

EXAMPLE PROBLEM NUMBER 3

Problem: Using the information in Example Problems 1 and 2, calculate the equivalent sound level for 15 minutes, and one hour for an observer 40 m from the roadway. Calculate the minimum stand-off distance for a 5 minute L_{eq} to be below 40 dBA.

Solution: Using Equation (A-13) insert the proper quantities

$$L_{eq} = L_o + 10 \log \frac{\pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right)$$

$$L_{eq} = 67 + 10 \log \frac{15\pi}{T\,22.2} + 10 \log \left(\frac{15}{40}\right)$$

$$L_{eq} = 66.0 - 10 \log T.$$

(a) For the 15 minute L_{eq}, check the validity of the inequality

$$\left|\frac{St}{D}\right|_{t_1, t_2} >> 1$$

if the L_{eq} is symmetric about the passage of the vehicle then,

$$\left|\frac{S\left(t = \frac{T}{2}\right)}{D}\right| = \frac{22.2 \times \frac{15}{2} \times 60}{40} \simeq 250 >> 1.$$

Therefore,

$$L_{eq} = 66.0 - 10 \log T$$

may be used to calculate the 15 minute equivalent sound level. Note that the equivalent sound level now only depends on the time period of interest.

$$L_{eq} = 66.0 - 10 \log (15 \times 60) = 36.5 \text{ dBA}$$

$$L_{eq} = 66.0 - 10 \log (60 \times 60) = 30.4 \text{ dBA}.$$

These L_{eq} values just calculated are artifically low. When the contribution from the ambient (50 dBA) is added to these values,

$$L_{eq} = 10 \log [10^{3.65} + 10^5] = 50.2 \text{ dBA}$$

$$L_{eq} = 10 \log [10^{3.04} + 10^5] = 50.0 \text{ dBA}.$$

It is important to remember that these L_{eq} values are based on the passage of one vehicle during the time interval.

(Continued)

EXAMPLE PROBLEM NUMBER 3 (Continued)

(b) To calculate the minimum stand-off distance, first check the validity of the inequality

$$\left|\frac{S\left(t = \frac{T}{2}\right)}{D}\right| >> 1\,; \qquad \left|\frac{22.2\left(\frac{5}{2} \times 60\right)}{D}\right| = \left|\frac{3{,}330}{D}\right| >> 1$$

which is valid for D, say less than 65 m, so proceed to solve Equation (A-13) for D,

$$L_{eq} = L_o + 10 \log \frac{\pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right)$$

$$L_{eq} = L_o + 10 \log \left(\frac{D_o^2 \pi}{SDT}\right)$$

$$\frac{L_{eq} - L_o}{10} = \log \left(\frac{D_o^2 \pi}{SDT}\right); \qquad \frac{\pi D_o^2}{SDT} = 10^{\frac{L_{eq} - L_o}{10}}$$

$$\therefore D = \frac{\pi D_o^2}{ST}\, 10^{\frac{L_o - L_{eq}}{10}}$$

Substituting the proper values

$$D \doteq \frac{\pi\, 15^2}{22.2\,(5 \times 60)}\, 10^{\frac{67-40}{10}} \simeq 53 \text{ m}.$$

Step 3. Noise Level Statistics for Uniformly Flowing Traffic

In steps 1 and 2 the instantaneous and equivalent sound pressure levels were derived for a single point source vehicle. The single vehicle model must now be expanded to a multivehicle model capable of addressing real traffic flows.

Following essentially the same development as before, the first requirement is to specify the total sound pressure level for a flow of, say N, vehicles. Since uncorrelated noise sources are added on an energy basis (or in practical terms, a $\langle P^2 \rangle$ basis), the total mean square pressures associated with the N vehicles is

$$\langle P^2 \rangle_{TOT} = \langle P^2 \rangle_1 + \langle P^2 \rangle_2 + \cdots + \langle P^2 \rangle_N = \sum_{i=1}^{N} \langle P^2 \rangle_i\,. \qquad \text{(A-14)}$$

Now, the mean square pressure from each vehicle will have the general form expressed in Equation (A-2), so for the ith vehicle in the flow

$$\langle P^2 \rangle_i = \langle P_o^2 \rangle_i \frac{D_o^2}{D^2 + (S_i t_i')^2} \qquad \text{(A-15)}$$

where $\langle P_o^2 \rangle$ is the reference mean square pressure, S_i is the ith vehicle's speed, and t_i' is the time frame for the ith vehicle, arranged so that when $t_i' = 0$, the ith vehicle is closest to the observer. Because the vehicles are usually randomly spaced along the roadway, the time frame for each vehicle will be different, that is they pass the coordinate origin at different times. If t_i is the time at which the ith vehicle passes the origin, (A-15) may be recast in the form

$$\langle P^2 \rangle_i = \langle P_o^2 \rangle_i \frac{D_o^2}{D^2 + S_i^2 (t - t_i)^2} \tag{A-16}$$

where $t_i' = t - t_i$. Thus the total mean square pressure is

$$\langle P^2 \rangle_{TOT} = \sum_{i=1}^{N} \langle P_o^2 \rangle_i \frac{D_o^2}{D^2 + S_i^2 (t - t_i)^2} . \tag{A-17}$$

For a sufficiently long averaging time T (the requirement being that all N vehicles pass the observer in the interval T), the equivalent sound pressure level is obtained from

$$L_{eq} = 10 \log \frac{1}{T} \int_{-\infty}^{\infty} \frac{\langle P^2 \rangle_{TOT}}{\langle P_{ref}^2 \rangle} dt. \tag{A-18}$$

Substituting Equation (A-17) into Equation (A-18)

$$L_{eq} = 10 \log \frac{1}{T} \int_{-\infty}^{\infty} \left[\sum_{i=1}^{N} \frac{\langle P_o^2 \rangle_i}{\langle P_{ref}^2 \rangle} \frac{D_o^2}{D^2 + S_i^2 (t - t_i)^2} \right] dt. \tag{A-19}$$

Exchange the order of integration and summation, and make the substitutions $\xi_i = t - t_i$, $d\xi_i = dt$

$$L_{eq} = 10 \log \frac{D_o^2}{T} \sum_{i=1}^{N} \frac{\langle P_o^2 \rangle_i}{\langle P_{ref}^2 \rangle} \int_{-\infty}^{\infty} \frac{d\xi_i}{D^2 + S_i^2 \xi_i^2} \tag{A-20}$$

recalling again that

$$\int_{-\infty}^{\infty} \frac{dt}{a^2 + t^2} = \frac{\pi}{a}$$

where $a = (D/S_i)$, the above expression simplies to

$$L_{eq} = 10 \log \frac{D_o^2}{T} \sum_{i=1}^{N} \frac{\langle P_o^2 \rangle_i}{\langle P_{ref}^2 \rangle} \frac{1}{S_i^2} \frac{\pi S_i}{D} \tag{A-21}$$

or

$$L_{eq} = 10 \log \frac{D_o^2 \pi}{DT} \sum_{i=1}^{N} \frac{\langle P_o^2 \rangle_i}{\langle P_{ref}^2 \rangle} \frac{1}{S_i} . \tag{A-22}$$

If the vehicle speeds are identical for each of the N vehicles passing the observer in the integration interval T, and if the reference mean square pressures are also identical for each vehicle, (A-22) becomes

$$L_{eq} = 10 \log \frac{D_o^2 \pi}{DT} \frac{N}{S} \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} \tag{A-23}$$

EXAMPLE PROBLEM NUMBER 4

Problem: To illustrate the vehicle spacing model in an example, consider three vehicles passing an observer situated 30 m from the roadway. Traveling at different speeds, the emission levels are as indicated:

Vehicle	Speed, km/h (m/s)	Emission Level, dBA
1	89 (24.7)	75
2	80 (22.2)	72
3	77 (21.4)	71

Suppose when the second vehicle is closest to the observer, vehicle 3 had already passed three seconds before and vehicle 1 is due to pass in four seconds. Investigate the individual and combined sound level envelopes recorded by the observer. Also illustrate the distance relationship among the vehicles as a function of time.

Solution: As implied by Equation (A-15), the time dependent sound level of each vehicle will be of the form

$$L_i = (L_o)_i + 10 \log \left[\frac{15^2}{30^2 + S_i^2 (t_i')^2} \right] .$$

Then from Equation (A-16), for vehicle 1 due to pass in four seconds

$$L_1 = 75 + 10 \log \left[\frac{15^2}{30^2 + 24.7^2 (t-4)^2} \right] .$$

For number 2, closest to the observer

$$L_2 = 72 + 10 \log \left[\frac{15^2}{30^2 + 22.2^2 t^2} \right]$$

and for vehicle 3 which passed three seconds before,

$$L_3 = 71 + 10 \log \left[\frac{15^2}{30^2 + 21.4^2 (t+3)^2} \right] .$$

The observer will record the combined level of the three vehicles,

$$L_{TOT} = 10 \log \left[10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} + 10^{\frac{L_3}{10}} \right] \text{dBA} .$$

(Continued)

EXAMPLE PROBLEM NUMBER 4 (Continued)

Figure A-6(a) iiiustrates the distance relationship among the three vehicles as a function of time. Figure A-6(b) illustrates the individual and combined sound level envelopes.

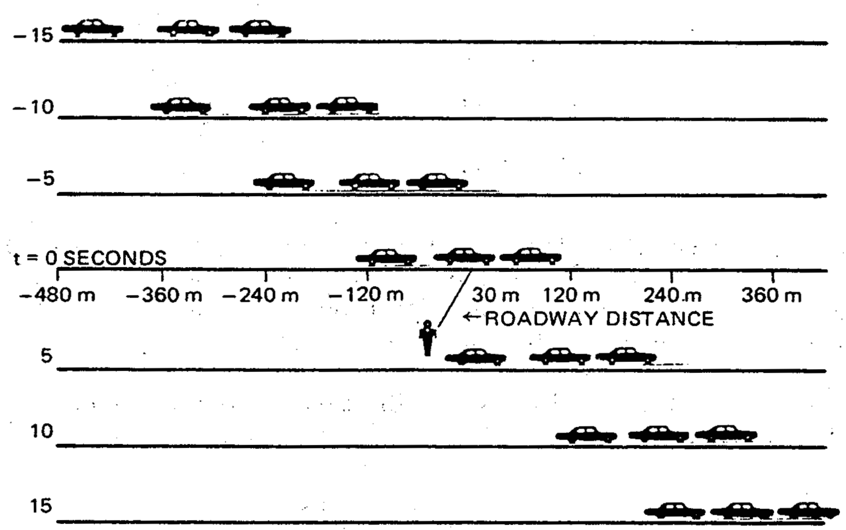


Figure A-6(a). Illustration of the Approximate Time-Distance Relationship of the Vehicles in Example Problem 4

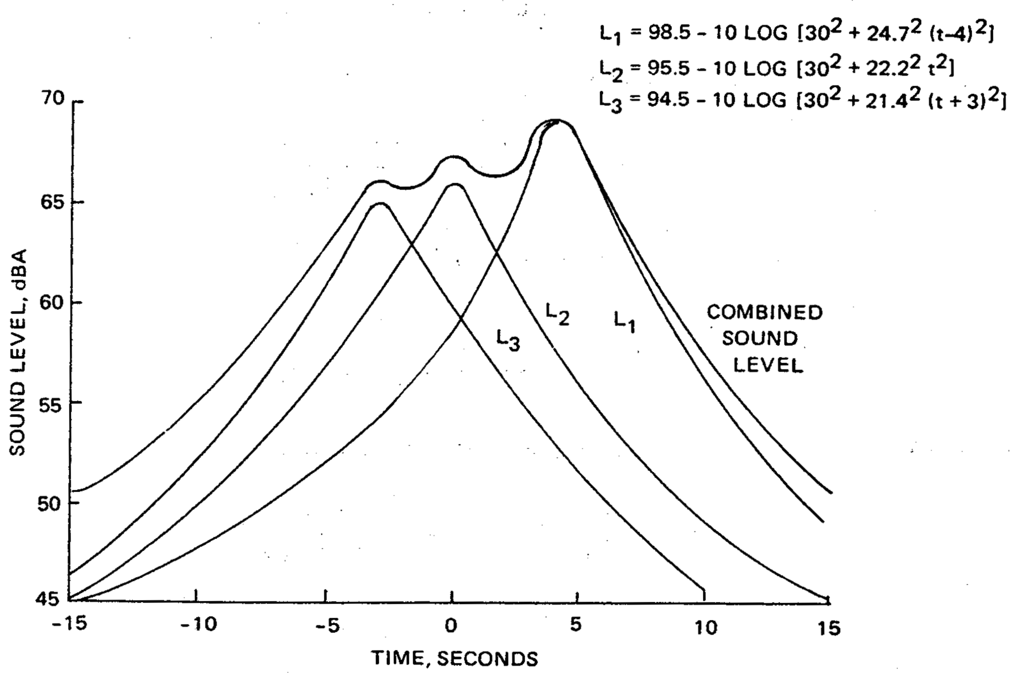


Figure A-6(b). Sound Level Time History of Three Passing Vehicles

which upon expansion gives

$$L_{eq} = L_o + 10 \log \frac{N\pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right). \qquad \text{(A-24)}$$

Thus, given an identical speed S for N identically noisy vehicles passing an observer situated D metres from the roadway, Equation (A-24) permits the calculation of the equivalent sound level under these conditions. Comparison of Equation (A-13) and (A-24) shows that for identically noisy vehicles,

$$L_{eq_N} = L_{eq} + 10 \log N \qquad \text{(A-25)}$$

where

L_{eq_N} = equivalent sound level for N identical vehicles passing the observer in the time interval T

L_{eq} = equivalent sound level over the time period T for a single vehicle

N = Number of identically noisy vehicles.

Equation (A-25) shows that the noise metric L_{eq_N} is independent of the spacing between vehicles. Since the noise sources were assumed to be uncorrelated and since L_{eq} is a measure of average energy, the result should have been anticipated.

EXAMPLE PROBLEM NUMBER 5

Problem: Calculate the hourly equivalent sound level for a flow of 1580 identical vehicles traveling at 72 km/h (20 m/s) if their noise emission level is 68 dBA and the receiver is 56 m from the roadway.

Solution: Using (A-24), calculate L_{eq} as

$$L_{eq} = L_o + 10 \log \frac{N\pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right)$$

$$L_{eq} = 68 + 10 \log \frac{1580\pi \times 15}{(60 \times 60)20} + 10 \log \left(\frac{15}{56}\right)$$

$$L_{eq} = 62.4 \text{ dBA}.$$

The identical vehicle noise model of Equation (A-24) and (A-25) suffers from the fact that real traffic flows never consist of identically noisy vehicles. To accommodate real traffic flows on a practical basis, it is necessary to deal with the statistics of the noise emission level distributions of real traffic flows. In this model, traffic flow will be separated into three distinct classes: automobiles, medium trucks, and heavy trucks. Within each class the speed dependent noise emission levels are assumed to be normally distributed with mean $\bar{L}_o$ and standard deviation σ_o. Figure A-7 shows example emission level distributions at different speeds. To shorten the following presentation, the equations will be developed for only one vehicle class, realizing that with proper substitution of the mean levels and standard deviations, the equations will be applicable to the other vehicle classes.

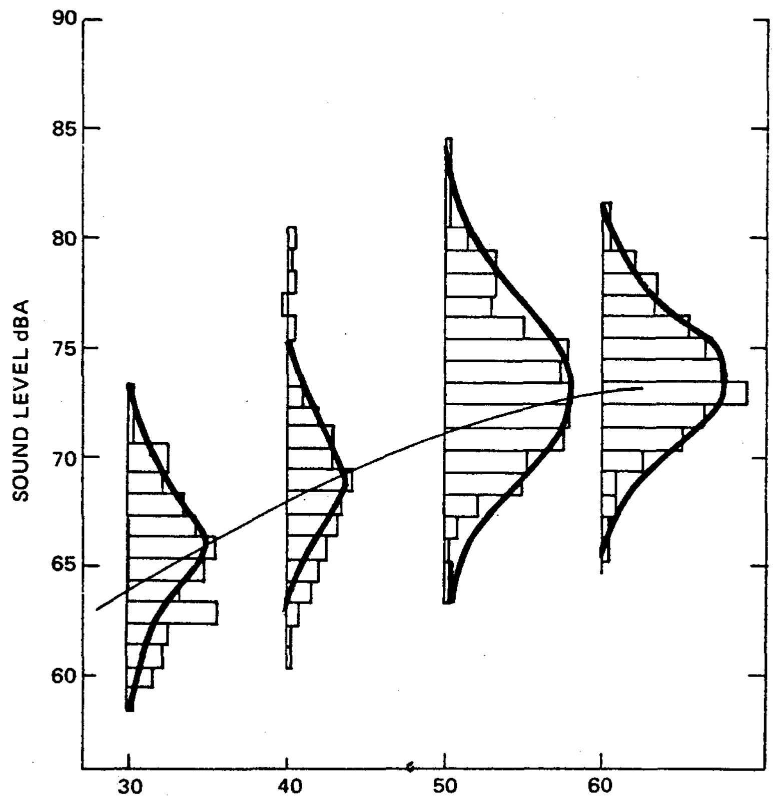


Figure A-7. Example Noise Emission Levels as a Function of Speed

Returning to Equation (A-22), assume that all N vehicles within this class are traveling at the same average speed, therefore,

$$L_{eq} = 10 \log \frac{\pi D_o^2}{TDS} \sum_{i=1}^{N} \frac{\langle P_o^2 \rangle_i}{\langle P_{\text{ref}}^2 \rangle} . \qquad \text{(A-26)}$$

It is obviously not practical to determine the noise emission level for each vehicle in the flow. This problem must be approached from a statistical aspect. In the statistical sense, we want to know the expected value of the sum, that is, what is the average value of $\Sigma[\langle P_o^2 \rangle_i / \langle P_{\text{ref}} \rangle]$. The expected value of an arbitrary function $H(X)$ of a continuous random variable X with probability density function $f_X(x)$ is given by

$$E\{H(X)\} = \int_{-\infty}^{\infty} H(x) f_X(x)\, dx \qquad \text{(A-27)}$$

where $E\{\ \}$ denotes the expected value of the argument. The problem is to determine

$$E \left\{ \sum_{i=1}^{N} \frac{\langle P_o^2 \rangle_i}{\langle P_{\text{ref}}^2 \rangle} \right\} = ?$$

Since it has already been assumed that the noise emission levels are normally distributed within each vehicle class, the probability density function is given by

$$f_X(x) = f_{\mathcal{L}_o}(L_o) = \frac{1}{\sigma_o \sqrt{2\pi}}\, e^{-\frac{(L_o - \bar{L}_o)^2}{2\sigma_o^2}} \qquad \text{(A-28)}$$

where

L_o = Speed dependent noise emission level of the *i*th vehicle.

$\bar{L}_o$ = Speed dependent mean noise emission level for the vehicle class.

σ_o = Speed dependent standard deviation for the vehicle class.

In order to deal with a *mean square pressure* sum (A-26) and *sound level* distributions, the mean pressures must be expressed in terms of sound levels (that is to avoid comparing apples and oranges). To make this transformation,

$$L_o = 10 \log \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle}$$

and

$$10^{\frac{L_o}{10}} = \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle}$$

so that the mean square pressure sum may be written in terms of levels,

$$E\left\{ \sum_{i=1}^{N} \frac{\langle P_o^2 \rangle_i}{\langle P_{ref}^2 \rangle} \right\} = E\left\{ \sum_{i=1}^{N} 10^{\left(\frac{L_o}{10}\right)_i} \right\}. \tag{A-29}$$

A fundamental theorem of expections shows that

$$E\{H(X) + G(X)\} = E\{H(X)\} + E\{G(X)\}.$$

Apply this theorem to the problem,

$$E\left\{ \sum_{i=1}^{N} 10^{\left(\frac{L_o}{10}\right)_i} \right\} = \sum_{i=1}^{N} E\left\{ 10^{\left(\frac{L_o}{10}\right)_i} \right\} = NE\left\{ 10^{\frac{L_o}{10}} \right\} \tag{A-30}$$

where L_o now represents an arbitrary sample emission level from the vehicle population. Invoking the expectation theorem (A-27), the probability density function in (A-28), and the result in (A-30)

$$NE\left\{ 10^{\frac{L_o}{10}} \right\} = \frac{N}{\sigma_o \sqrt{2\pi}} \int_{-\infty}^{\infty} 10^{\frac{L_o}{10}} e^{-\frac{(L_o - \bar{L}_o)^2}{2\sigma_o^2}} dL_o. \tag{A-31}$$

Using the relationship

$$10^{\frac{L_o}{10}} = e^{\left(\frac{\ln 10}{10}\right) L_o} \tag{A-32}$$

Equation (A-31) becomes

$$NE\left\{ 10^{\frac{L_o}{10}} \right\} = \frac{N}{\sigma_o \sqrt{2\pi}} \int_{-\infty}^{\infty} e^{\left(\frac{\ln 10}{10}\right) L_o} e^{-\frac{(L_o - \bar{L}_o)^2}{2\sigma_o^2}} dL_o. \tag{A-33}$$

With a little algebra the exponents in the integrand can be written as

$$e^{\left(\frac{\ln 10}{10}\right)L_o} e^{-\frac{(L_o-\bar{L}_o)^2}{2\sigma_o^2}} = e^{\left(\frac{\ln 10}{10}\right)L_o} e^{-\frac{(L_o^2+\bar{L}_o^2-2\bar{L}_oL_o)}{2\sigma_o^2}} \quad \text{(A-33a)}$$

$$= e^{-\left[\frac{L_o^2}{2\sigma_o^2}-\left(\frac{\bar{L}_o}{\sigma_o^2}+\frac{\ln 10}{10}\right)L_o+\frac{\bar{L}_o^2}{2\sigma_o^2}\right]} . \quad \text{(A-33b)}$$

Thus, it is necessary to now evaluate the integral

$$\frac{N}{\sigma_o\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\left[\frac{L_o^2}{2\sigma_o^2}-\left(\frac{\bar{L}_o}{\sigma_o^2}+\frac{\ln 10}{10}\right)L_o+\frac{\bar{L}_o^2}{2\sigma_o^2}\right]} dL_o = ? \quad \text{(A-34)}$$

Consultation of integral tables gives the relationship

$$\int_{-\infty}^{\infty} e^{-(ax^2+bx+c)}\, dx = \sqrt{\frac{\pi}{a}}\, e^{\left(\frac{b^2-4ac}{4a}\right)} .$$

Inspection of the integral indicates that the following substitutions should be made

$$x = L_o, \quad a = \frac{1}{2\sigma_o^2}, \quad b = -\left(\frac{\bar{L}_o}{\sigma_o^2}+\frac{\ln 10}{10}\right), \quad c = \frac{\bar{L}_o^2}{2\sigma_o^2} , \quad \text{(A-35)}$$

Then the integral is

$$\text{integral} = \sqrt{\frac{\pi}{\frac{1}{2\sigma_o^2}}} \exp\left[\frac{\left(\frac{\bar{L}_o}{\sigma_o^2}+\frac{\ln 10}{10}\right)^2 - 4\left(\frac{1}{2\sigma_o^2}\right)\frac{\bar{L}_o^2}{2\sigma_o^2}}{4\left(\frac{1}{2\sigma_o^2}\right)}\right]$$

$$= a_o\sqrt{2\pi}\, \exp\left\{\left[\frac{\bar{L}_o^2}{\sigma_o^4} + \left(\frac{\ln 10^2}{10}\right) + 2\,\frac{\bar{L}_o}{\sigma_o^2}\left(\frac{\ln 10}{10}\right) - \frac{\bar{L}_o^2}{\sigma_o^4}\right]\frac{\sigma_o^2}{2}\right\}$$

$$= \sigma_o\sqrt{2\pi}\, \exp\left[\frac{1}{2}\left(\frac{\ln 10^2}{10}\right)\sigma_o^2 + \left(\frac{\ln 10}{10}\right)\bar{L}_o\right]$$

$$= \sigma_o\sqrt{2\pi}\, e^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2\sigma_o^2}\, e^{\left(\frac{\ln 10}{10}\right)\bar{L}_o} . \quad \text{(A-36)}$$

Recalling the multiplicative constants indicated in Equation (A-34) which had been momentarily dropped,

$$NE\left\{10^{\frac{L_o}{10}}\right\} = \frac{N}{\sigma_o\sqrt{2\pi}}\, \sigma_o\sqrt{2\pi}\, e^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2\sigma_o^2}\, e^{\left(\frac{\ln 10}{10}\right)\bar{L}_o} . \quad \text{(A-37)}$$

This result can now be substituted in (A-26)

$$L_{eq} = 10 \log \frac{1}{T} \left(\frac{\pi D}{S}\right) \left(\frac{D_o}{D}\right)^2 \sum_{i=1}^{N} \frac{\langle P_o^2 \rangle_i}{\langle P_{ref}^2 \rangle}$$

$$= 10 \log \frac{1}{T} \left(\frac{\pi D}{S}\right) \left(\frac{D_o}{D}\right)^2 N e^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2 \sigma_o^2} e^{\left(\frac{\ln 10}{10}\right)\bar{L}_o} \tag{A-38}$$

with a little rearranging and recognizing that

$$10 \log e^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2 \sigma_o^2} = 0.115 \sigma_o^2 \tag{A-39}$$

and that

$$10 \log e^{\left(\frac{\ln 10}{10}\right)\bar{L}_o} = \bar{L}_o$$

Equation (A-38) will reduce to

$$\boxed{L_{eq} = \bar{L}_o + 0.115 \sigma_o^2 + 10 \log \frac{N \pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right).} \tag{A-40}$$

This result is fairly important. Equation (A-40) permits the calculation of the equivalent sound level generated by a flow of vehicles from a single class traveling on a flat, single lane, infinite highway. When more than one vehicle class uses the highway, the total equivalent sound level is calculated by appropriately summing the L_{eq}'s from each class, that is

$$L_{eq_{TOT}} = 10 \log \left[10^{\left(\frac{L_{eq}}{10}\right)_{\text{cars}}} + 10^{\left(\frac{L_{eq}}{10}\right)_{\substack{\text{med.}\\\text{trucks}}}} + 10^{\left(\frac{L_{eq}}{10}\right)_{\substack{\text{heavy}\\\text{trucks}}}} \right]. \tag{A-41}$$

EXAMPLE PROBLEM NUMBER 6

Problem: A highway noise survey showed the 15 m automobile mean emission level to be 74 dBA with a standard deviation of 2.5 dBA at 88 km/h with the medium truck valued to be 84 dBA and 3.2 dBA at 80 km/h respectively. Calculate the hourly equivalent sound level for a flow of 1250 automobiles and 200 medium trucks per hour for receivers at 30 and 60 metres.

Solution: Solution of this problem requires separate calculation of the automobile and medium truck equivalent levels with the final solution obtained by logrithmic summing:

Automobiles—

$$L_{eq} = L_o + 0.115\, \sigma_o^2 + 10 \log \frac{N \pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right)$$

$$= 74 + 0.115\,(2.5)^2 + 10 \log \frac{1250\pi(15)}{(3600)24.4} + 10 \log \frac{15}{D}$$

(Continued)

EXAMPLE PROBLEM NUMBER 6 (Continued)

$$\therefore L_{eq} = 84.7 - 10 \log D \text{ dBA}.$$

Medium Trucks—

$$L_{eq} = 84 + 0.115(3.2)^2 + 10 \log \frac{200\pi(15)}{(3600)22.2} + 10 \log \frac{15}{D}$$

$$\therefore L_{eq} = 87.7 - 10 \log D \text{ dBA}.$$

Total L_{eq} —

$$L_{eq_{TOT}} = 10 \log \left[10^{\frac{84.7 - 10 \log D}{10}} + 10^{\frac{87.7 - 10 \log D}{10}} \right]$$

$$L_{eq_{TOT}} = 89.5 - 10 \log D \text{ dBA}.$$

For a receiver at 30 m,

$$L_{eq_{TOT}} = 89.5 - 10 \log (30) = 74.7 \text{ dBA}$$

and for a receiver at 60 m,

$$L_{eq_{TOT}} = 89.5 - 10 \log (60) = 71.7 \text{ dBA}.$$

This 3 dB attenuation rate per doubling of distance is in contrast to the 6 dB rate encountered before and results from the integration of the point source levels. The point source model has effectively been turned into a line source model.

Step 4. Roadways of Finite Length When There Are No Excess Propagation Losses

The development to this point has assumed that the restraints on calculation of the equivalent sound level (see page A-8)

$$t_1 < 0 < t_2 \quad \text{and} \quad \left| \frac{tS}{D} \right|_{t_1, t_2} \gg 1$$

have been met. These conditions being fulfilled, it is quite acceptable to make the approximation

$$\int_{t_1}^{t_2} \frac{dt}{D^2 + (St)^2} \cong \int_{-\infty}^{\infty} \frac{dt}{D^2 + (St)^2}.$$

With this approximation, the roadway is assumed to be infinitely long in both directions. However, there are many cases in which this approximation will not be valid. Examples would include curved roadways, roadway sections hidden by topography, sections where there are significant changes in traffic volume, speed, mix, etc.

This problem of sectioned roadways will now be solved. Referring to Figure A-8 for a distribution of N single class vehicles traveling with the same average speed over the segment, the equivalent sound level is given by

$$L_{eq} = 10 \log \left[\frac{1}{T} \sum_{i=1}^{N} \int_{t_1+t_i}^{t_2+t_i} \frac{\langle P_o^2 \rangle_i}{\langle P_{ref}^2 \rangle} \frac{D_o^2}{D^2 + S^2(t-t_i)^2} \, dt \right]. \tag{A-42}$$

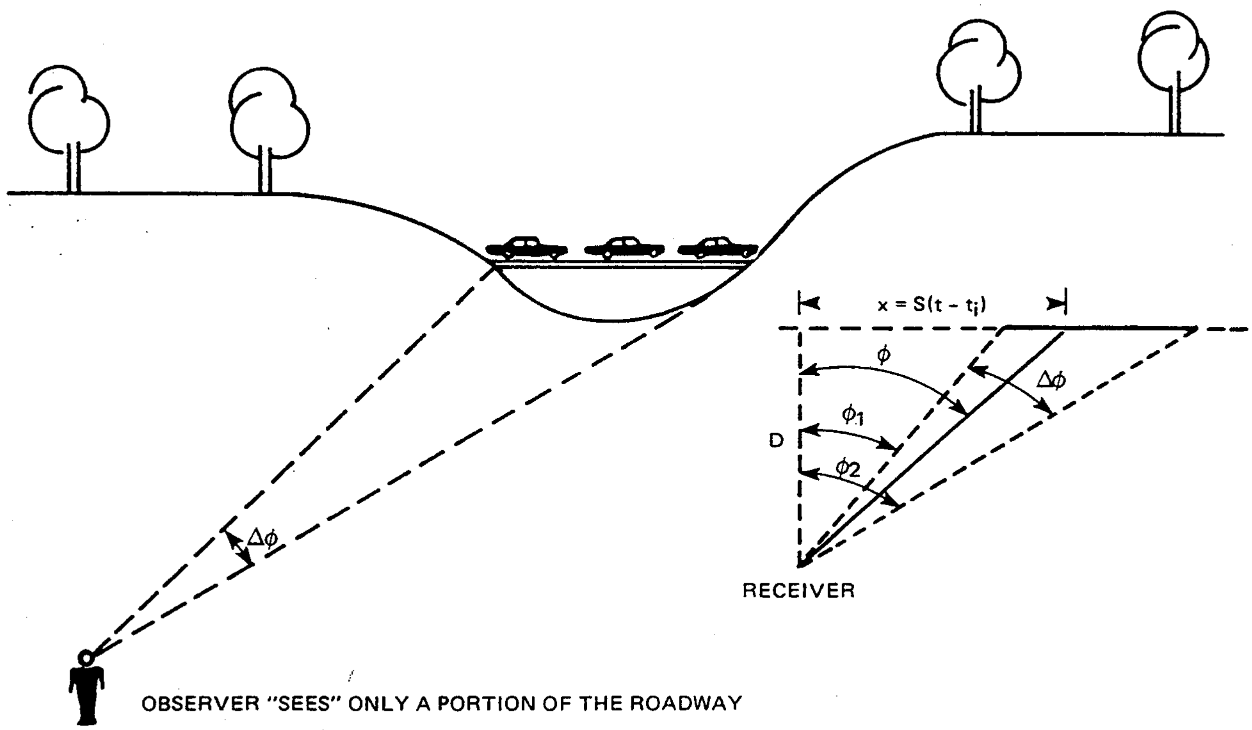


Figure A-8. Finite Roadway (Segment)

In (A-42), the limits of integration are arranged so that each vehicle passes through the segment, i.e.,

$$S(t-t_i)|_{t=t_2+t_i} = St_2$$

and

$$S(t-t_i)|_{t=t_1+t_i} = St_1 .$$

To simplify evaluation of the integral, make the substitution

$$S(t-t_i) = D \tan \phi \tag{A-43}$$

in which ϕ is defined as the angle in Figure A-8. Since $S\,dt = D \sec^2 \phi \, d\phi$, the integral is transformed to

$$\int_{t_1+t_i}^{t_2+t_i} \frac{dt}{D^2 + S^2(t-t_i)^2} = \int_{\phi_1}^{\phi_2} \frac{\frac{D}{S} \sec^2 \phi}{D^2 + D^2 \tan^2 \phi} \, d\phi . \tag{A-44}$$

To further the simplification, use the trigonometric identity $\tan^2\phi + 1 = \sec^2\phi$

$$\frac{D}{S}\int_{\phi_1}^{\phi_2} \frac{\sec^2\phi}{D^2(1+\tan^2\phi)}\,d\phi = \frac{1}{DS}\int_{\phi_1}^{\phi_2} \frac{\sec^2\phi}{\sec^2\phi}\,d\phi \tag{A-45}$$

and after cancelling

$$\frac{1}{DS}\int_{\phi_1}^{\phi_2} d\phi = \frac{\phi_2 - \phi_1}{DS} = \frac{\Delta\phi}{DS}. \tag{A-46}$$

Returning to Equation (A-42)

$$L_{eq} = 10\log\left[\frac{1}{T}\,\frac{D_o^2\Delta\phi}{DS}\sum_{i=1}^{N}\frac{\langle P_o^2\rangle_i}{\langle P_{\mathrm{ref}}^2\rangle}\right]. \tag{A-47}$$

Implementing the previous statistical treatment for the summation (i.e., Equations (A-29), A-38))

$$L_{eq} = 10\log\left[\frac{1}{T}\,\frac{D_o^2\Delta\phi}{DS}\,Ne^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2\sigma_o^2}\,10^{\frac{\bar{L}_o}{10}}\right] \tag{A-48}$$

and with a little arranging

$$L_{eq} = 10\log\left[10^{\frac{\bar{L}_o}{10}}\,e^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2\sigma_o^2}\,\frac{N\pi D}{S}\left(\frac{D_o}{D}\right)^2\frac{1}{T}\,\frac{\Delta\phi}{\pi}\right]. \tag{A-49}$$

so that

$$\boxed{L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10\log\frac{N\pi D_o}{TS} + 10\log\left(\frac{D_o}{D}\right) + 10\log\frac{\Delta\phi}{\pi}.} \tag{A-50}$$

Note again that the equivalent level is independent of the vehicle spacing.

The criteria for determining when a road is infinite now boils down to how well the approximation

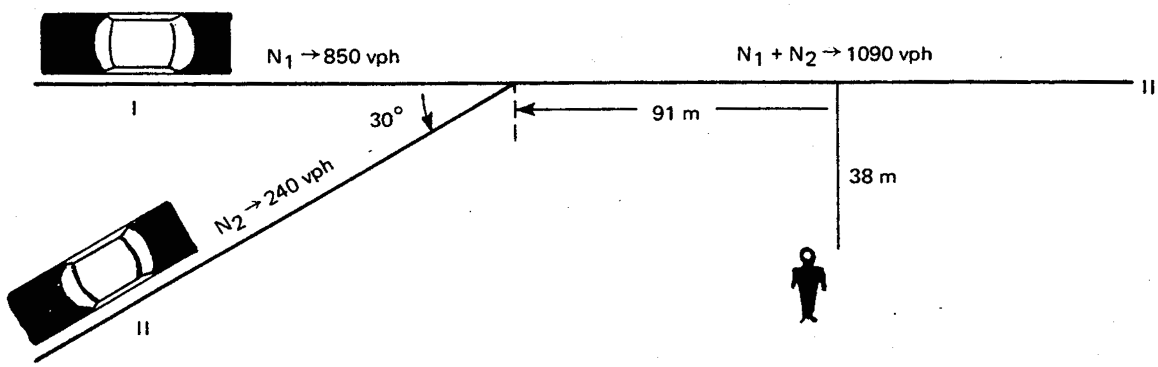
$$10\log\frac{\Delta\phi}{\pi} \simeq 0$$

holds. For example, when the roadway subtends 145°, the correction for noninfiniteness is

$$10\log\frac{145}{180} = -0.94\text{ dB}.$$

EXAMPLE PROBLEM NUMBER 7

Problem: Consider the scenario indicated in the illustration where automobiles are the only vehicles present.

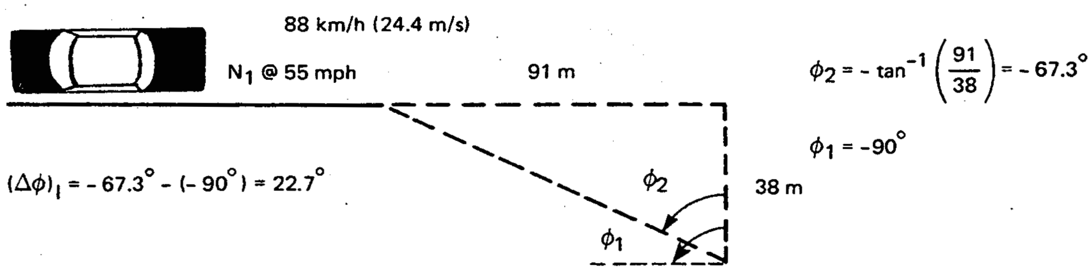


Suppose for automobiles,

$$\bar{L}_o + 0.115\,\sigma_o^2 = 32 + 30 \log S$$

where S is the vehicle speed in metres/second. If the speeds on the indicated roadway Segments I, II, and III are 88, 56, and 80 km/h respectively, calculate the hourly equivalent level contributed by each segment to the observer; also calculate the total L_{eq}.

Solution: Considering the first segment,



Using Equation (A-50)

$$L_{eq} = L_o + 115\,\sigma_o^2 + 10 \log \frac{N \pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right) + 10 \log \frac{\Delta\phi}{\pi}$$

$$L_{eq} = 32 + 30 \log S_1 + 10 \log \frac{N_1 \pi D_o}{TS_1} + 10 \log \left(\frac{D_o}{D_1}\right) + 10 \log \frac{\Delta\phi_1}{\pi}$$

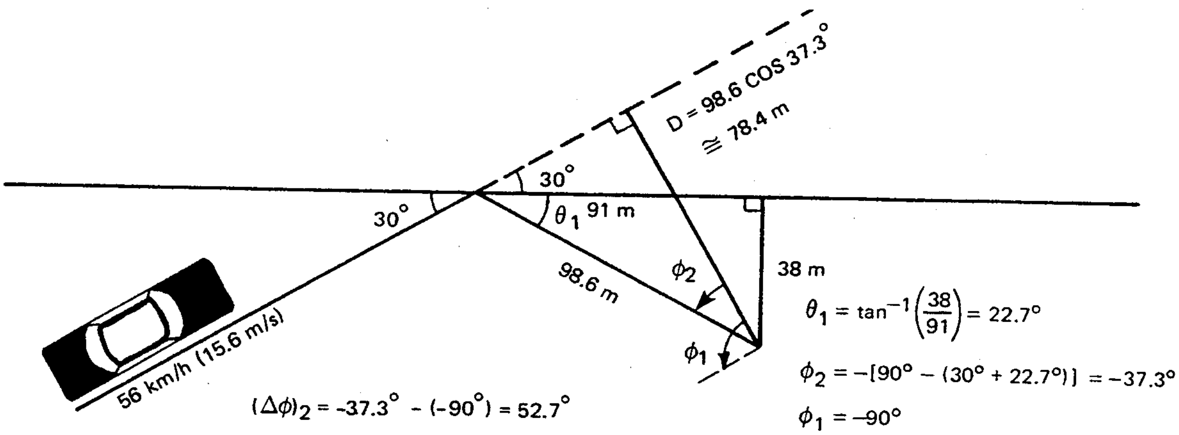
$$L_{eq} = 32 + 30 \log (24.4) + 10 \log \frac{N_1 \pi \times 15}{3600(24.4)} + 10 \log \left(\frac{15}{38}\right) + 10 \log \frac{22.7^\circ}{180^\circ}$$

$$L_{eq} = 27.9 + 10 \log N_1 .$$

(Continued)

EXAMPLE PROBLEM NUMBER 7 (Continued)

For Segment II

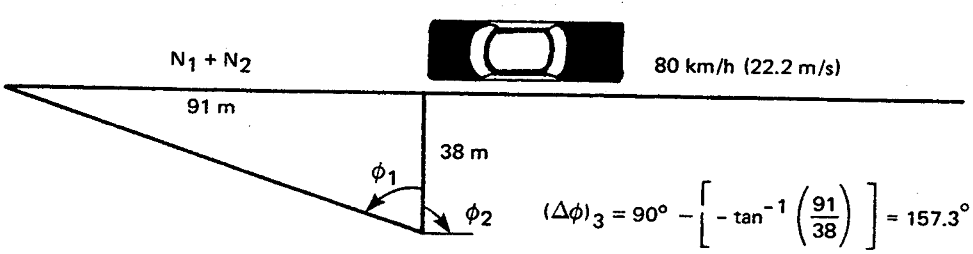


$$L_{eq} = 32 + 30 \log S_2 + 10 \log \frac{N_2 \pi D_o}{T S_2} + 10 \log \left(\frac{D_o}{D_2}\right) + 10 \log \frac{\Delta\phi_2}{\pi}$$

$$L_{eq} = 32 + 30 \log (15.6) + 10 \log \frac{N_2 \pi \times 15}{(3600) 15.6} + 10 \log \left(\frac{15}{78.4}\right) + 10 \log \frac{52.7}{180^\circ}$$

$$L_{eq} = 24.5 + 10 \log N_2 .$$

For Segment III



$$L_{eq} = 32 + 30 \log S_3 + 10 \log \frac{N_3 \pi D_o}{T S_3} + 10 \log \left(\frac{D_o}{D_3}\right) + 10 \log \frac{\Delta\phi_3}{\pi}$$

$$L_{eq} = 32 + 30 \log (22.2) + 10 \log \frac{(N_1 + N_2) \pi \times 15}{3600 (22.2)} + 10 \log \frac{15}{38}$$

$$+10 \log \frac{157.3^\circ}{180^\circ}$$

$$L_{eq} = 35.5 + 10 \log (N_1 + N_2) .$$

(Continued)

EXAMPLE PROBLEM NUMBER 7 (Continued)

For vehicle flows of 850 and 240 vehicles per hour for Segment I and Segment II, respectively

1. $L_{eq} = 27.9 + 10 \log (850) = 57.2$ dBA
2. $L_{eq} = 24.5 + 10 \log (240) = 48.3$ dBA
3. $L_{eq} = 35.5 + 10 \log (850 + 240) = 65.9$ dBA

hence,

$$L_{eq_{TOT}} = 10 [10^{5.72} + 10^{4.83} + 10^{6.59}] = 66.5 \text{ dBA}.$$

Step 5. Excess Attenuation

In deriving the model in Equation (A-50), it was assumed that the sound level attenuation with increasing receiver-source distance was entirely due to geometric spreading of the sound waves over a hard flat site. Under certain conditions, this spreading loss (3 dB per distance doubling) is observed in the field. However at many highway sites, field data has shown this rate to be too low. The observed increase in sound level attenuation rate is primarily due to local environmental factors (ground cover effects, atmospheric absorption, etc.) and must be considered in the model. To mathematically specify this effect, the original acoustic expression for the point source vehicle must be reexamined,

$$\langle P^2 \rangle = \langle P_o^2 \rangle \frac{D_o^2}{R^2} \tag{A-51}$$

and a modification of the form is postulated:

$$\langle P^2 \rangle_{\text{observed}} = \langle P^2 \rangle_{\substack{\text{geometric} \\ \text{spreading}}} \times \begin{bmatrix} \text{Excess} \\ \text{Attenuation} \\ \text{Factor} \end{bmatrix}. \tag{A-52}$$

Specifically the form is modified to

$$\langle P^2 \rangle_\alpha = \langle P_o^2 \rangle \frac{D_o^2}{R^2} \left(\frac{D_o}{R} \right)^\alpha \tag{A-53}$$

where α is a parameter dependent on the ground cover at the particular site. The sound level is now calculated by dividing through by the reference mean square pressure and making the logarithmic transformation,

$$L_\alpha = 10 \log \frac{\langle P^2 \rangle_\alpha}{\langle P_{\text{ref}}^2 \rangle} = 10 \log \frac{\langle P_o^2 \rangle}{\langle P_{\text{ref}}^2 \rangle} \frac{D_o^2}{R^2} \left(\frac{D_o}{R} \right)^\alpha . \tag{A-54}$$

Expanding,

$$L_\alpha = 10 \log \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} + 10 \log \left(\frac{D_o}{R}\right)^2 + 10 \log \left(\frac{D_o}{R}\right)^\alpha . \tag{A-55}$$

Since the sound level for a point source exhibiting only geometric spreading is $L = L_o + 10 \log D_o^2/R^2$, Equation (A-55) may be condensed to give

$$L_\alpha = L + 10 \log \left(\frac{D_o}{R}\right)^\alpha . \tag{A-56}$$

When $R = D_o$, Equation (A-56) shows that the sound levels at the sites with excess attenuation are equal to the hard, flat site without excess attenuation no matter what the value of α, that is

$$L_\alpha = L + 10 \log \left(\frac{D_o}{R}\right)^\alpha \quad \text{if} \quad R = D_o$$

then

$$L_\alpha = L .$$

This attenuation model does not recognize any site dependent differences in noise emission levels. To better appreciate the effects of the site parameter α, L_α is plotted in Figure A-9 as a function of t for several values of α.

To calculate the equivalent sound level of a site characterized by α, it is permissible to utilize previous developments.

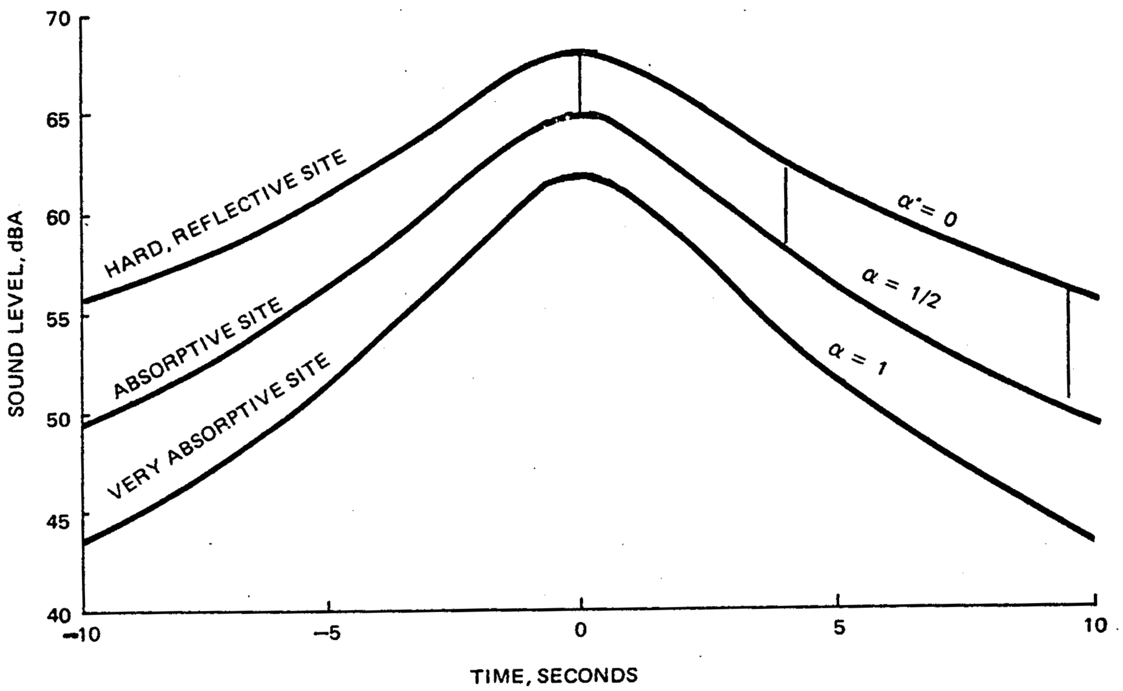


Figure A-9. Sound Level Recorded by an Observer 60 m from the Roadway for Three Different Site Types—Hard Site, Absorptive Site, and Very Absorptive Site

Equation (A-42) can be modified to account for the excess attenuation,

$$L_{eq} = 10 \log \left[\frac{1}{T} N e^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2 \bar{\sigma}_o^2} \; 10^{\frac{\bar{L}_o}{10}} \int_{t_1}^{t_2} \left(\frac{D_o}{R}\right)^{\alpha+2} dt \right] \qquad \text{(A-57)}$$

and since $R = \sqrt{D^2 + (St)^2}$, the above becomes, after expanding,

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N}{T} + 10 \log \int_{t_1}^{t_2} \frac{D_o^{\alpha+2}}{(D^2 + S^2 t^2)^{\frac{\alpha+2}{2}}} \, dt . \qquad \text{(A-58)}$$

(As indicated before, headway spacing does not affect the equivalent sound level, thus the problem can be cast in terms of all vehicles passing the origin at the same time.) Working only with the integral, it is convenient to make the substitution $St = D \tan \phi$ and $S\,dt = D \sec^2 \phi \, d\phi$

$$\int_{t_1}^{t_2} \frac{D_o^{\alpha+2}}{(D^2 + S^2 t^2)^{\frac{\alpha+2}{2}}} \, dt = D_o^{\alpha+2} \int_{\phi_1}^{\phi_2} \frac{\frac{D}{S} \sec^2 \phi \, d\phi}{(D^2 + D^2 \tan^2 \phi)^{\frac{\alpha+2}{2}}} \, d\phi . \qquad \text{(A-59)}$$

Since $D^2 + D^2 \tan^2 \phi = D^2 \sec^2 \phi$, the right side of (A-59) becomes

$$D_o^{\alpha+2} \frac{D}{S} \int_{\phi_1}^{\phi_2} \frac{\sec^2 \phi \, d\phi}{(D^2 \sec^2 \phi)^{\frac{\alpha+2}{2}}} = \frac{D_o^{\alpha+2}}{SD^{\alpha+1}} \int_{\phi_1}^{\phi_2} \frac{d\phi}{(\sec \phi)^{\alpha}} \qquad \text{(A-60)}$$

and since $\sec \phi = (\cos \phi)^{-1}$

$$\int_{t_1}^{t_2} \frac{D_o^{\alpha+2}}{(D^2 + S^2 t^2)^{\frac{\alpha+2}{2}}} \, dt = \frac{D_o^{\alpha+2}}{SD^{\alpha+1}} \psi_\alpha(\phi_1, \phi_2) \qquad \text{(A-61)}$$

where

$$\psi_\alpha(\phi_1, \phi_2) \triangleq \int_{\phi_1}^{\phi_2} (\cos \phi)^\alpha \, d\phi . \qquad \text{(A-61a)}$$

Substitution (A-61) in (A-58)

$$L_{eq} = \bar{L}_o + 0.115\sigma_c^2 + 10 \log \frac{N}{T} + 10 \log \frac{D_o^{\alpha+2}}{SD^{\alpha+1}} \psi_\alpha(\phi_1, \phi_2) \qquad \text{(A-62)}$$

and with a little rearranging

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N\pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right)$$

$$+10 \log \left(\frac{D_o}{D}\right)^\alpha + 10 \log \frac{\psi_\alpha(\phi_1, \phi_2)}{\pi} . \qquad \text{(A-63)}$$

The first line in (A-63) is recognized as the equivalent sound level generated by a flow of vehicles from a single class traversing an effectively infinite, flat roadway (Equation (A-40)). The second line of terms represents distance and visible road length adjustments to be applied when the sites have excess attenuation.

Various field studies have indicated that a reasonable range for the site parameter α is between 0 and 1. When $\alpha = 0$, the site is reflecting (i.e., hard), Equation (A-63) will collapse to (A-50). There is strong evidence indicating most absorbing sites may be characterized by $\alpha \simeq 1/2$. For a point source this implies a 7½ dB sound level drop-off rate, i.e.

$$\Delta_{ps} = 10 \log (1/2)^{1/2+2} = -7.5 \text{ dB}$$

and a 4.5 dB decrease per distance doubling for the L_{eq} level,

$$\Delta_{L_{eq}} = 10 \log (1/2)^{1/2+1} = -4.5 \text{ dB}.$$

Adopting a value of $\alpha = 1/2$ for absorbing sites,

$$\frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi} = \frac{1}{\pi} \int_{\phi_1}^{\phi_2} \sqrt{\cos \phi}\; d\phi . \qquad \text{(A-64)}$$

This integral is rather difficult to evaluate and so a graph of the factor is presented in Figure A-10 as a function of ϕ_2 with ϕ_1 as a parameter. With $\alpha = 1/2$, the equivalent sound level is now given by

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N\pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right)$$
$$+10 \log \left(\frac{D_o}{D}\right)^{1/2} + 10 \log \frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi}. \qquad \text{(A-65)}$$

If similar terms are combined,

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N\pi D_o}{TS} + 15 \log \left(\frac{D_o}{D}\right)$$
$$+10 \log \frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi} \text{ dB} \qquad \text{(A-66)}$$

for the absorptive site. When $\alpha = 0$, the equivalent sound level is given by

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N\pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right)$$
$$+10 \log \frac{\Delta\phi}{\pi} \text{ dB} \qquad \text{(A-67)}$$

for the nonattenuated site which is the same as Equation (A-50).

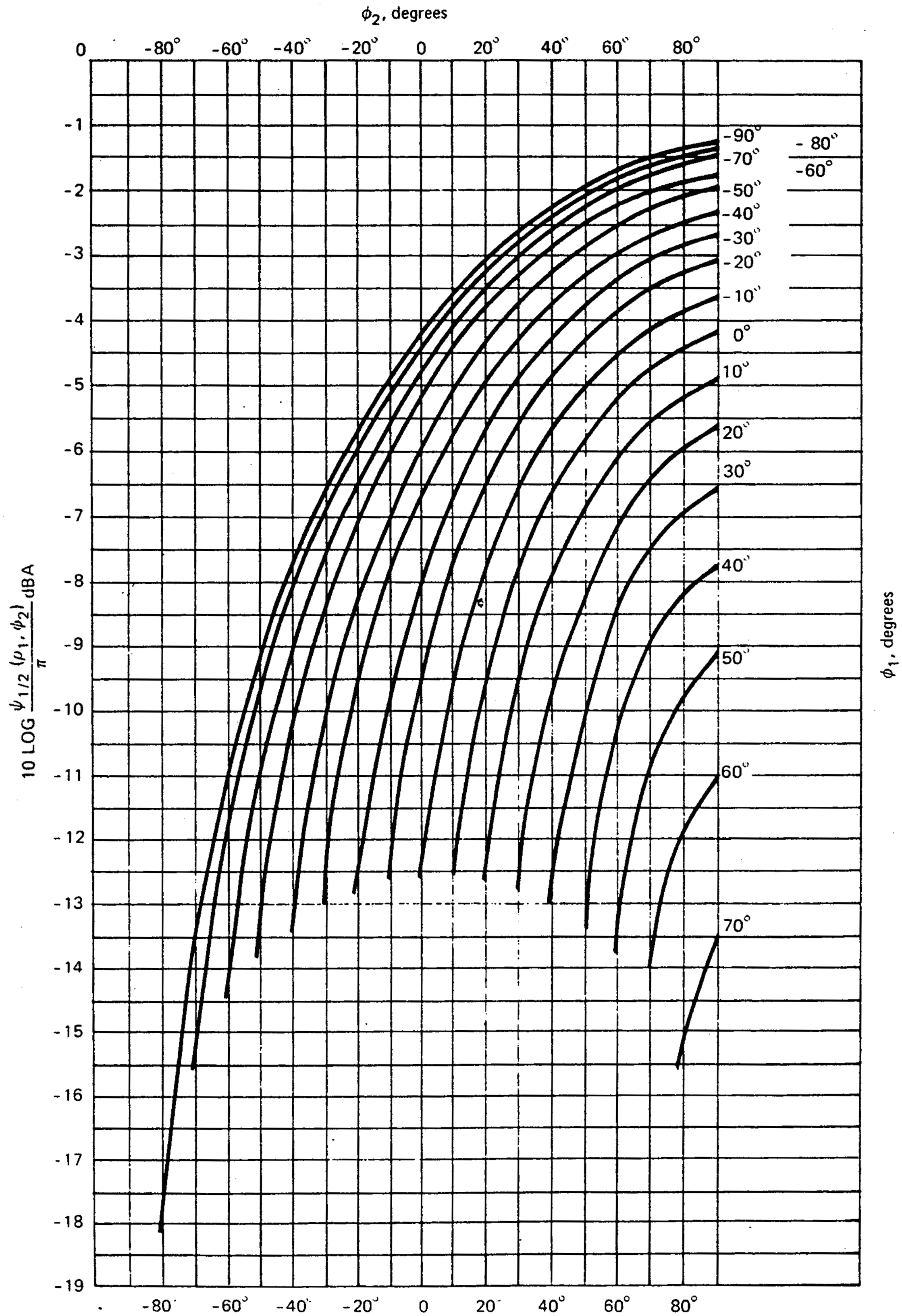


Figure A-10. Adjustment Factor for Finite Length Roadways for Absorbing Sites

In using (A-66) and A-67) to calculate equivalent sound levels for roadway segments, it is necessary to properly identify the angles of the segment relative to the receiver. Proper angle identification requires use of the rule:

RULE: Roadway angles are left-justified

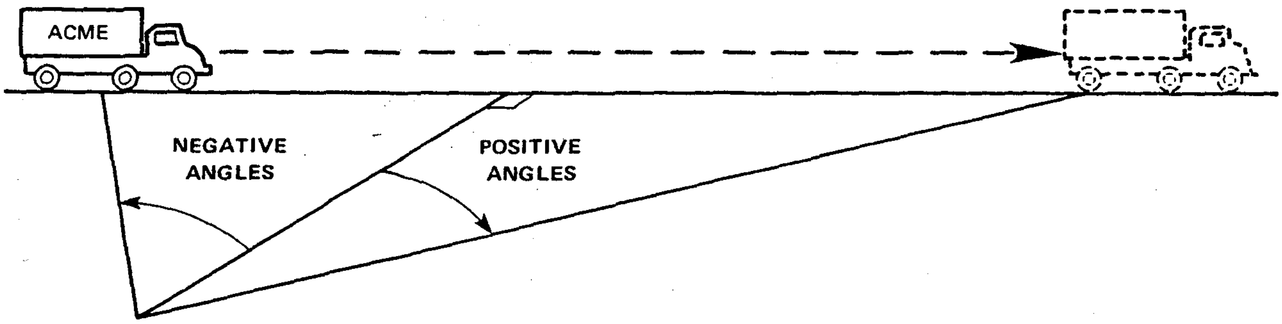
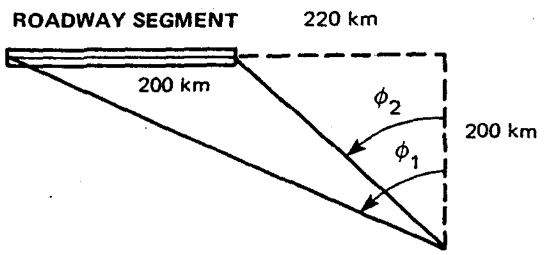


Figure A-11. Proper Angle Identification of Roadway Segments

EXAMPLE PROBLEM NUMBER 9

Problem: Determine the segment adjustments for the following 3 scenarios, using the rule indicated in Figure A-11.

1. Completely negative segment



$$\phi_1 = -\tan^{-1}\left(\frac{200 + 220}{200}\right) = -64.5^\circ$$

$$\phi_2 = -\tan^{-1}\left(\frac{220}{200}\right) = -47.7^\circ$$

Thus the segment adjustment for the negative segment is

$$10 \log \frac{\phi_2 - \phi_1}{\pi} = 10 \log \frac{-47.7^\circ - (-64.5^\circ)}{180^\circ} = 10 \log \left(\frac{16.8}{180}\right) = -10.3 \text{ dB}$$

for the reflective site and

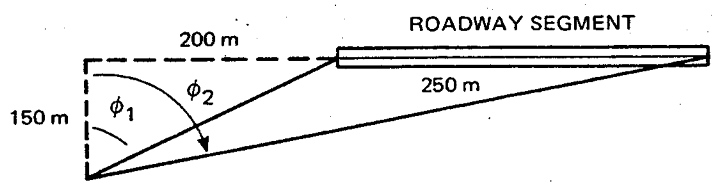
$$10 \log \frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi} = 10 \log \frac{\psi_{1/2}(-64.5^\circ, -47.7^\circ)}{\pi} = -11.6 \text{ dB}$$

for an absorptive site.

(Continued)

EXAMPLE PROBLEM NUMBER 9 (Continued)

2. Completely positive segment



$$\phi_1 = +\tan^{-1}\left(\frac{200}{150}\right) = 53.1°$$

$$\phi_2 = +\tan^{-1}\left(\frac{200 + 250}{150}\right) = 71.6°$$

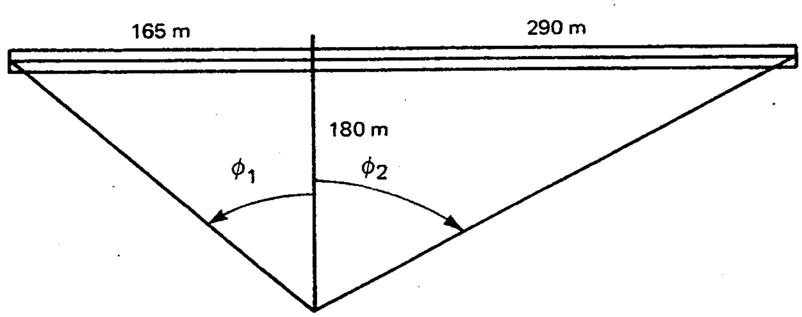
reflective site

$$10 \log \left(\frac{\Delta\phi}{\pi}\right) = 10 \log \frac{71.6° - 53.1°}{180°} = 10 \log \left(\frac{18.5°}{180°}\right) = -9.9 \text{ dB}$$

absorptive site

$$10 \log \frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi} = 10 \log \frac{\psi_{1/2}(53.1°, 73.6°)}{\pi} = -11.2 \text{ dB}.$$

3. Mixed segment



$$\phi_1 = -\tan^{-1}\left(\frac{165}{180}\right) = -42.5°$$

$$\phi_2 = +\tan^{-1}\left(\frac{290}{180}\right) = +58.2°$$

reflective site

$$10 \log \frac{\Delta\phi}{\pi} = 10 \log \frac{58.2° - (-42.5°)}{180°} = 10 \log \left(\frac{100.7°}{180°}\right) = -2.5 \text{ dB}$$

absorptive site

$$10 \log \frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi} = 10 \log \frac{\psi_{1/2}(-42.5°, 58.2°)}{\pi} = -2.8 \text{ dB}.$$

EXAMPLE PROBLEM NUMBER 10

Problem: Repeat Example Problem Number 7 only now assume the site is absorbing ($\alpha = 1/2$).

Solution: Since all parameters other than site type remain the same, subtract the non-absorbing angular correction and attenuation rate and write immediately,

Segment I:

$$L_{eq} = 57.2 + \left[-10 \log \frac{\Delta\phi_1}{\pi} - 10 \log \frac{D_o}{D_1}\right]$$

for $\alpha = 0$

$$+ \left[15 \log \frac{D_o}{D_1} + 10 \log \frac{\psi_{1/2}(-90°, -67.3°)}{\pi}\right]$$

for $\alpha = 1/2$

$$L_{eq} = 57.2 + 9.0 + 4.0 - 6.1 - 12.8 = 51.3 \text{ dBA}.$$

Segment II:

$$L_{eq} = 48.3 - 10 \log \frac{\Delta\phi_2}{\pi} + 5 \log \frac{D_o}{D_2} + 10 \log \frac{\psi_{1/2}(-90°, -37.3°)}{\pi}$$

$$L_{eq} = 48.3 + 5.3 - 3.6 - 7.4 = 42.6 \text{ dBA}.$$

Segment III:

$$L_{eq} = 65.9 - 10 \log \frac{\Delta\phi_3}{\pi} + 5 \log \frac{D_o}{D_3} + 10 \log \frac{\psi_{1/2}(-67.3°, 90°)}{\pi}$$

since $\psi_{1/2}(\phi_1, \phi_2) = \psi_{1/2}(-\phi_2, -\phi_1)$, we rewrite the above expression,

$$L_{eq} = 65.9 - 10 \log \frac{\Delta\phi_3}{\pi} + 5 \log \frac{D_o}{D_3} + 10 \log \frac{\psi_{1/2}(-90°, 67.3°)}{\pi}$$

$$L_{eq} = 65.9 + 0.6 - 2.0 - 1.5 = 63.0 \text{ dBA}.$$

$$L_{eq_{TOT}} = 10 \log [10^{5.13} + 10^{4.26} + 10^{6.3}] = 63.3 \text{ dBA}.$$

(Continued)

EXAMPLE PROBLEM NUMBER 10 (Continued)

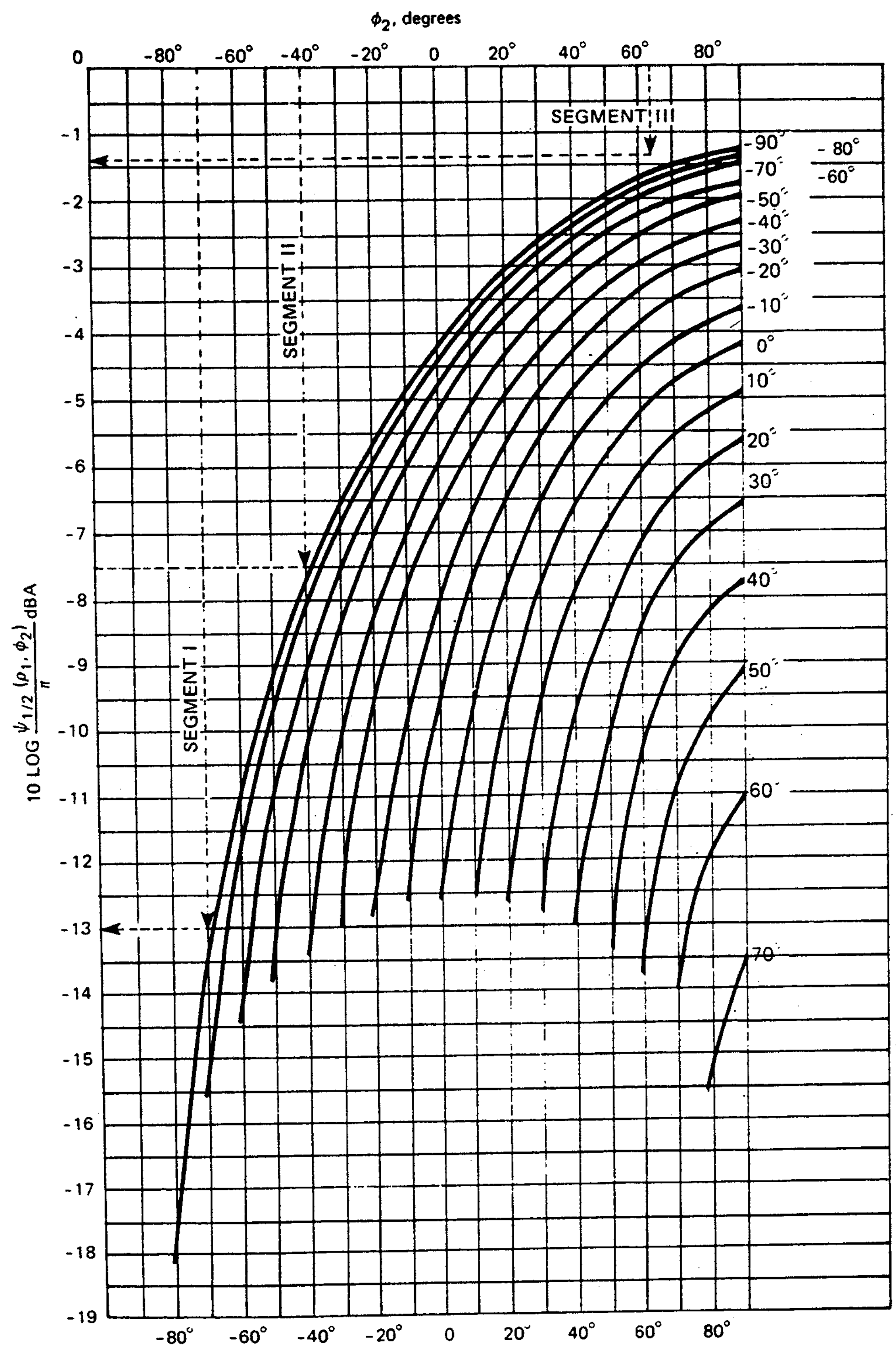


Figure A-12. Adjustment Factor for Finite Length Roadways for Absorbing Sites—Example Problem 10

Two Special Cases

One restriction given in step 2 which limits the application of Equations (A-66) and (A-67) is that no receiver may be physically closer than 15 m to the roadway. There may be situations however in which a receiver is close, $D << |St|$, to an extended portion of a roadway segment (case 1). In special case 1 (see Figure A-13) ϕ is in the neighborhood of $\pm\pi/2$ and the subtended angle of the roadway segment is small. In case 1, the roadway segment adjustment chart does not contain sufficient detail to permit determination of the adjustment.

In case 2, the receiver is located on the extension of the roadway segment (see Figure A-14). In these situations $D = 0$ and it is not valid to talk in terms of subtended angles. As a result Equations (A-66) and (A-67) are not correct for case 2.

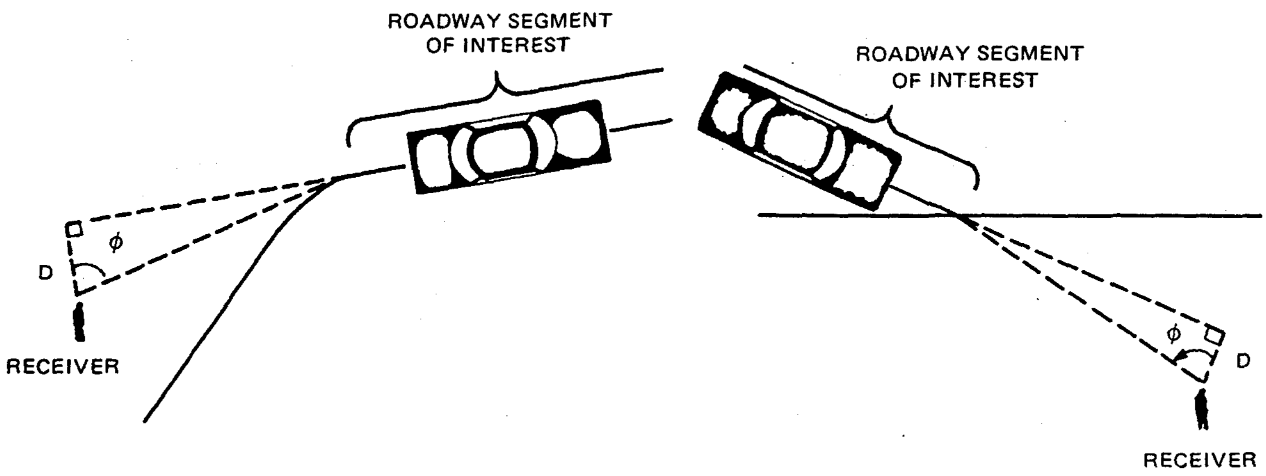


Figure A-13. Case 1: Two Situations in Which a Receiver is Very Close to an Extended Portion of a Roadway Segment

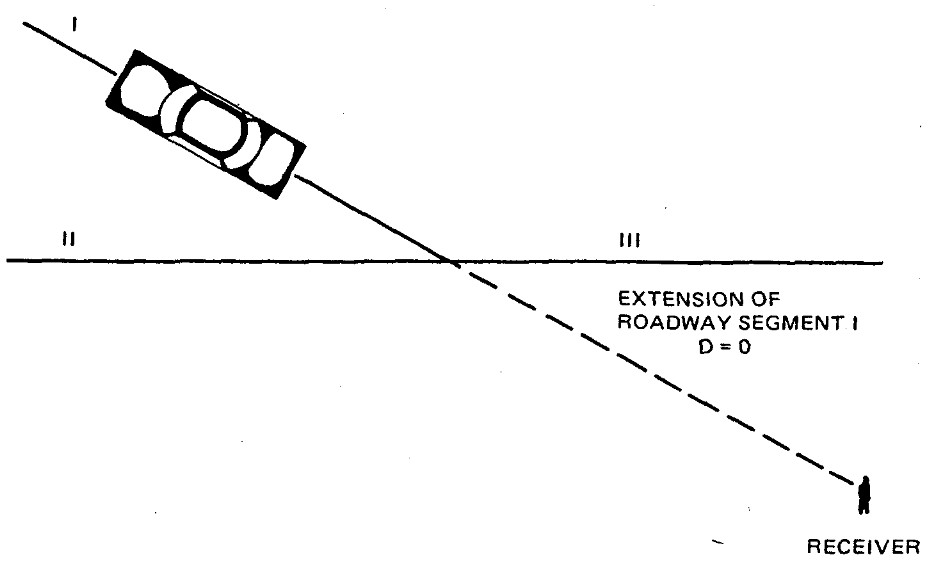


Figure A-14. Case 2: Example of Situation in Which the Receiver is on the Extension of a Roadway Segment

It is possible to handle cases 1 and 2 simultaneously by reorganizing (A-58),

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N}{T} + 10 \log \int_{t_1}^{t_2} \frac{D_o^{\alpha+2}}{(D^2 + S^2t^2)^{\frac{\alpha+2}{2}}} dt \qquad \text{(A-58)}$$

when $D << |St|$. With this condition, (A-58) becomes

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N}{T} + 10 \log \int_{t_1}^{t_2} \left(\frac{D_o}{St}\right)^{\alpha+2} dt. \qquad \text{(A-68)}$$

Performing the integration

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{ND_o}{ST} + 10 \log \frac{1}{1 + \alpha} \left[\left(\frac{D_o}{St_1}\right)^{1+\alpha} - \left(\frac{D_o}{St_2}\right)^{1+\alpha}\right]. \qquad \text{(A-69)}$$

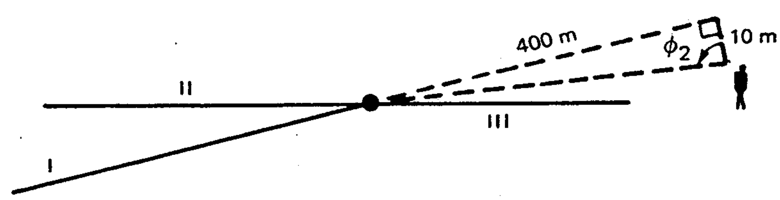
By defining St_1 as the distance, R_n, between the receiver and the near end of the roadway segment, and St_2 as the distance, R_f, between the receiver and the far end of the roadway segment, (A-69) becomes

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{ND_o}{ST} + 10 \log \frac{1}{1 + \alpha} \left[\left(\frac{D_o}{R_n}\right)^{1+\alpha} - \left(\frac{D_o}{R_f}\right)^{1+\alpha}\right] \qquad \text{(A-70)}$$

which is the desired result. Equation (A-70) is useful for situations in which $0 \leqslant D << |St|$.

EXAMPLE PROBLEM NUMBER 11

Problem: Consider the highway site illustrated below. Calculate the equivalent sound level for Segment I for both an attenuating and nonattenuating site for a single class of vehicles.



Solution: Since the problem does not specify vehicle volume, speed, or time period for L_{eq}, leave the answer explicity in terms of N, S, and T. From the illustration,

$$\phi_1 = -90^\circ \qquad \phi_2 = -\tan^{-1}\left(\frac{400}{10}\right) = -88.6^\circ$$

$$R_f = \infty \qquad R_n = \sqrt{400^2 + 10^2} \cong 400 \text{ m}.$$

(Continued)

EXAMPLE PROBLEM NUMBER 11 (Continued)

Since the angles are very close to $-\pi/2$ and $R_n >> D$, it is appropriate to use (A-70),

$$L_{eq} = \bar{L}_o + 0.115\,\sigma_o^2 + 10 \log \frac{ND_o}{ST} + 10 \log \frac{1}{1+\alpha}\left[\left(\frac{D_o}{R_n}\right)^{1+\alpha} - \left(\frac{D_o}{R_f}\right)^{1+\alpha}\right].$$

(a) Absorptive Site, $\alpha = 1/2$

$$L_{eq} = \bar{L}_o + 0.115\,\sigma_o^2 + 10 \log \frac{N \times 15}{ST} + 10 \log \frac{1}{1+1/2}\left[\left(\frac{15}{400}\right)^{3/2} - \left(\frac{15}{\infty}\right)^{3/2}\right]$$

$$L_{eq} = \bar{L}_o + 0.115\,\sigma_o^2 + 10 \frac{N}{ST} - 11.4 \text{ dB}.$$

(b) Hard Site, $\alpha = 0$

$$L_{eq} = \bar{L}_o + 0.115\,\sigma_o^2 + 10 \log \frac{N \times 15}{ST} + 10 \log \left[\left(\frac{D_o}{400}\right) - \left(\frac{D_o}{\infty}\right)\right]$$

$$L_{eq} = \bar{L}_o + 0.115\,\sigma_o^2 + 10 \log \frac{N}{ST} - 2.5 \text{ dB}.$$

Step 6. Summary

In steps 1 through 5 a model to predict the equivalent sound level for freely flowing traffic was developed. In developing the model, three major assumptions were made:

(1) vehicles are adequately represented by acoustic point sources,

(2) vehicle emission levels within a vehicle group are normally distributed, and

(3) propagation losses are adequately modeled by including an excess attenuation factor $(D_o/R)^{1/2}$.

Field observation consistent with these assumptions have been made in a number of separate studies. Accepting these assumptions, the hourly equivalent sound level was shown to be given by

$$L_{eq}(h) = (\bar{L}_o)_E + 10 \log \frac{ND_o}{S} + \begin{cases} 15 \log \dfrac{D_o}{D} \\ 10 \log \dfrac{D_o}{D} \end{cases} + \begin{cases} 10 \log \dfrac{\psi_{1/2}(\phi_1, \phi_2)}{\pi} \\ 10 \log \dfrac{\Delta\phi}{\pi} \end{cases} - 25 \text{ dBA} \qquad \text{(A-71)}$$

where $(\bar{L}_o)_E$ is the reference energy mean emission level for a class of vehicles and is given by

$$(\bar{L}_o)_E = \bar{L}_o + 0.115\sigma_o^2$$

$\bar{L}_o$ = arithmetic mean emission level

σ_o = standard deviation around the arithmetic mean emission levels

N is the number of vehicles traversing a roadway segment defined by the angles (ϕ_1, ϕ_2) in one hour at the average speed S in km/h

D_o is the reference distance in metres at which $\bar{L}_o$ was determined

D is the perpendicular distance in metres from the centerline of the traffic lane to the receiver

$\Delta\phi$ is the subtended angle of the roadway, $\phi_2 - \phi_1$, relative to the receiver

$\dfrac{\psi_{1/2}(\phi_1,\phi_2)}{\pi} = \dfrac{1}{\pi}\displaystyle\int_{\phi_1}^{\phi_2} \sqrt{\cos\phi}\, d\phi$ is the segment adjustment factor to account for ground absorption effects.

On the special cases of very small or near zero observer distances, the hourly equivalent sound level was shown to be given by

$$L_{eq}(h) = (\bar{L}_o)_E + 10 \log \frac{ND_o}{S} + \begin{cases} 10 \log \dfrac{2}{3}\left[\left(\dfrac{D_o}{R_n}\right)^{3/2} - \left(\dfrac{D_o}{R_f}\right)^{3/2}\right] \\[2ex] 10 \log \left[\left(\dfrac{D_o}{R_n}\right) - \left(\dfrac{D_o}{R_f}\right)\right] \end{cases} - 30 \text{ dBA} \tag{A-72}$$

where

R_n is the distance in metres from the observer to the near end of the centerline of the traffic lane segment.

R_f is the distance in metres from the observer to the far end of the centerline of the traffic lane segment.

EXAMPLE PROBLEM NUMBER 12

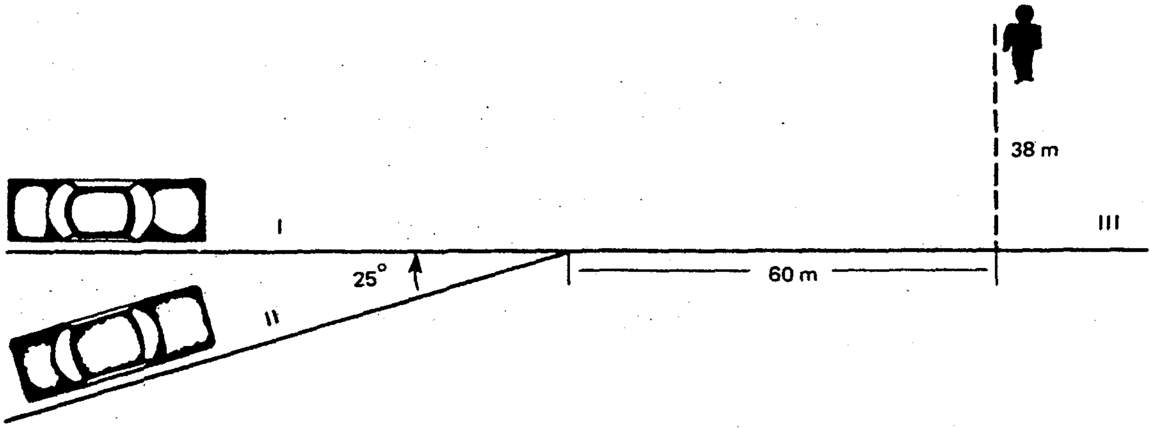
Problem: Consider the highway site shown in the figure below. Calculate the hourly equivalent level at the receiver if:

(a) the site is reflective, $\alpha = 0$

(b) the site is absorptive, $\alpha = 1/2$

Assume the vehicle speeds on Segment III are the same as on Segment I.

(Continued)



On Segment I, the flow and reference energy mean emission levels are:

680 automobiles = 69 dBA at 88 km/h (D_0 = 15 m)
110 medium trucks = 80 dBA at 80 km/h
42 heavy trucks = 85 dBA at 80 km/h

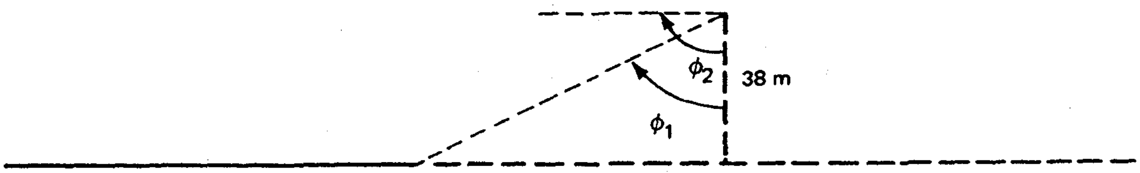
On Segment II the flow and reference energy mean emission levels are:

240 automobiles = 68 dBA at 80 km/h
50 medium trucks = 79 dBA at 72 km/h
15 heavy trucks = 84 dBA at 72 km/h

Solution:

(a) Hard Site

Segment I



$$\phi_1 = \tan^{-1}\left(\frac{60}{38}\right) = 57.7°$$

$$\phi_2 = 90°$$

$$\Delta\phi = \phi_2 - \phi_1 = 90° - 57.7° = 32.3°$$

(Continued)

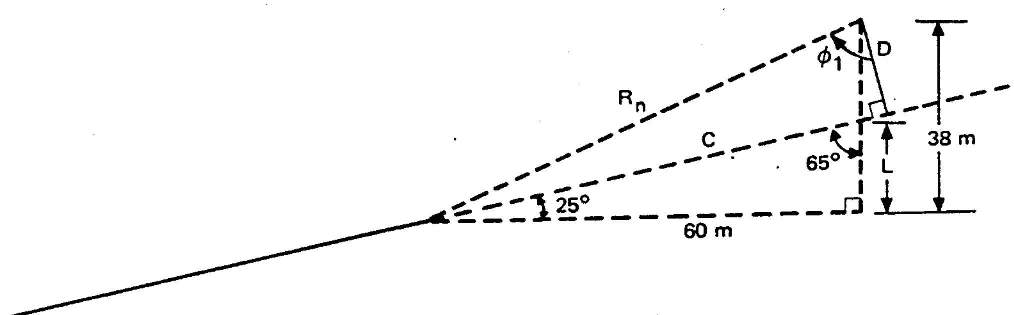
EXAMPLE PROBLEM NUMBER 12 (Continued)

Segment I:

	Automobiles	Medium Trucks	Heavy Trucks
Volume, N	680	110	42
Speed, km/h	88	80	80
D, metres	38	38	38
$(\bar{L}_o)_E$	69	80	85
$10 \log (ND_o/S)$	20.6	13.1	9.0
$10 \log (D_o/D)$	−4.0	−4.0	−4.0
$10 \log (\Delta\phi/\pi)$	−7.5	−7.5	−7.5
+ constant	−25.0	−25.0	−25.0
L_{eq}	53.1	56.6	57.5

$$L_{eq}(h)_I = 60.9 \text{ dBA}$$

Segment II:



$L = 60 \tan 25° = 28.0$ m $\qquad \phi_1 = \cos^{-1}\left(\frac{9.1}{71}\right) = 82.6°$

$D = (38 - 28) \sin 65° = 9.1$ m $\qquad \phi_2 = 90°$

$R_n = \sqrt{60^2 + 38^2} = 71.0$ $\qquad C = \sqrt{71^2 - 9.1^2} = 70.4$ m

$R_f = \infty$

Since $D << |St|$, that is $9.1 << 70.4$ it is appropriate to use the L_{eq} expression involving R_n, R_f.

(Continued)

EXAMPLE PROBLEM NUMBER 12 (Continued)

$$\text{Segment Factor} \quad F(R_n, R_f)_o = 10 \log \left[\left(\frac{D_o}{R_n} \right) - \left(\frac{D_o}{R_f} \right) \right]$$

$$F(R_n, R_f)_o = 10 \log \left[\left(\frac{15}{71} \right) - \left(\frac{15}{\infty} \right) \right] = -6.8 \text{ dB}$$

	Automobiles	Medium Trucks	Heavy Trucks
Volume, N	240	50	15
Speed, km/h	80	72	72
D, metres	9.1	9.1	9.1
$(\bar{L}_o)_E$	68	79	84
$10 \log (ND_o/S)$	16.5	10.2	4.9
$F(R_n, R_f)_o$	−6.8	−6.8	−6.8
+ constant	−30.0	−30.0	−30.0
L_{eq}	47.7	52.4	52.1

$$L_{eq}(h)_{II} = 56.0 \text{ dBA}$$

Segment III:

	Automobiles	Medium Trucks	Heavy Trucks
Volume, N	920	160	57
Speed, km/h	88	80	80
D, metres	38	38	38
$(\bar{L}_o)_E$	69	80	85
$10 \log (ND_o/S)$	22.0	14.8	10.3
$10 \log (D_o/D)$	−4.0	−4.0	−4.0
$10 \log (\Delta\phi/\pi)$	−.9	−.9	−.9
+ constant	−25.0	−25.0	−25.0
L_{eq}	61.1	64.9	65.4

$$L_{eq}(h)_{III} = 68.9 \text{ dBA}$$

To calculate the equivalent sound level at the receiver due to all three segments, calculate

(Continued)

EXAMPLE PROBLEM NUMBER 12 (Continued)

$$L_{eq}(h) = 10 \log \left[10^{\frac{L_{eq}(h)_I}{10}} + 10^{\frac{L_{eq}(h)_{II}}{10}} + 10^{\frac{L_{eq}(h)_{III}}{10}} \right]$$

$$L_{eq}(h) = 10 \log [10^{6.09} + 10^{5.60} + 10^{6.89}] = 69.7 \text{ dBA}$$

$$L_{eq}(h) \simeq 70 \text{ dBA}.$$

(b) Absorptive Site

Using the information from part (a), construct the tables

Segment I:

	Automobiles	Medium Trucks	Heavy Trucks
$(\bar{L}_o)_E$	69	80	85
$10 \log (ND_o/S)$	20.6	13.1	9.0
$15 \log (D_o/D)$	−6.1	−6.1	−6.1
$10 \log \frac{\psi_{1/2}(58,90)}{\pi}$	−10.6	−10.6	−10.6
+ constant	−25.0	−25.0	−25.0
L_{eq}	47.9	51.4	52.3

$$L_{eq}(h)_I = 55.7 \text{ dBA}$$

Segment II:

$$\text{Segment Factor} \quad F(R_n, R_f)_{1/2} = 10 \log \frac{2}{3} \left[\left(\frac{D_o}{R_n}\right)^{3/2} - \left(\frac{D_o}{R_f}\right)^{3/2} \right]$$

$$F(R_n, R_f)_{1/2} = 10 \log \frac{2}{3} \left[\left(\frac{15}{71}\right)^{3/2} - \left(\frac{15}{\infty}\right)^{3/2} \right] = -11.9 \text{ dB}$$

	Automobiles	Medium Trucks	Heavy Trucks
$(\bar{L}_o)_E$	68	79	84
$10 \log (ND_o/S)$	16.5	10.2	4.9
$F(R_n, R_f)_{1/2}$	−11.9	−11.9	−11.9
+ constant	−30.0	−30.0	−30.0
L_{eq}	42.6	47.3	47.0

$$L_{eq}(h)_{II} = 50.9 \text{ dBA}$$

(Continued)

EXAMPLE PROBLEM NUMBER 12 (Continued)

Segment III:

	Automobiles	Medium Trucks	Heavy Trucks
$(\bar{L}_o)_E$	69	80	85
$10 \log (ND_o/S)$	22.0	14.8	10.3
$15 \log (D_o/D)$	−6.1	−6.1	−6.1
$10 \log \frac{\psi_{1/2}(-90,58)}{\pi}$	−1.7	−1.7	−1.7
+ constant	−25.0	−25.0	−25.0
L_{eq}	58.2	62.0	62.5

$$L_{eq}(h)_{III} = 66.0 \text{ dBA}$$

Thus the total L_{eq} at the receiver for the absorbing site is

$$L_{eq}(h) = 66.5 \text{ dBA} \simeq 67 \text{ dBA}$$

Note: Decimal points are shown for illustrative purposes only. Numbers should be rounded off to the nearest half dBA.

Appendix B

TRAFFIC NOISE BARRIERS: ATTENUATION AND INSERTION LOSS

INTRODUCTION

Appendix B is intended to provide the tools with which the highway engineer may obtain estimates of how well a wall or berm will perform in the field. For detailed designs the reader is referred to "Fundamentals and Abatement of Highway Traffic Noise" [1], "Noise Barrier Design Handbook" [2], and "User's Manual for the Prediction of Road Traffic Noise Computer Program—MOD 4" [3].

The thrust of Appendix B is on the *calculation* of barrier effects rather than the *measurement* of barrier effects. The barrier model utilized is based on an analytic approximation [4] to laboratory data with field verification [5]. The treatment of barrier effects is consistent with the equivalent energy methodology of Appendix A.

The information in Appendix B is presented in three steps:

(1) definitions and principles
(2) barrier attenuation of equivalent sound levels
(3) example problem.

Step 1. Definitions and Barrier Principles

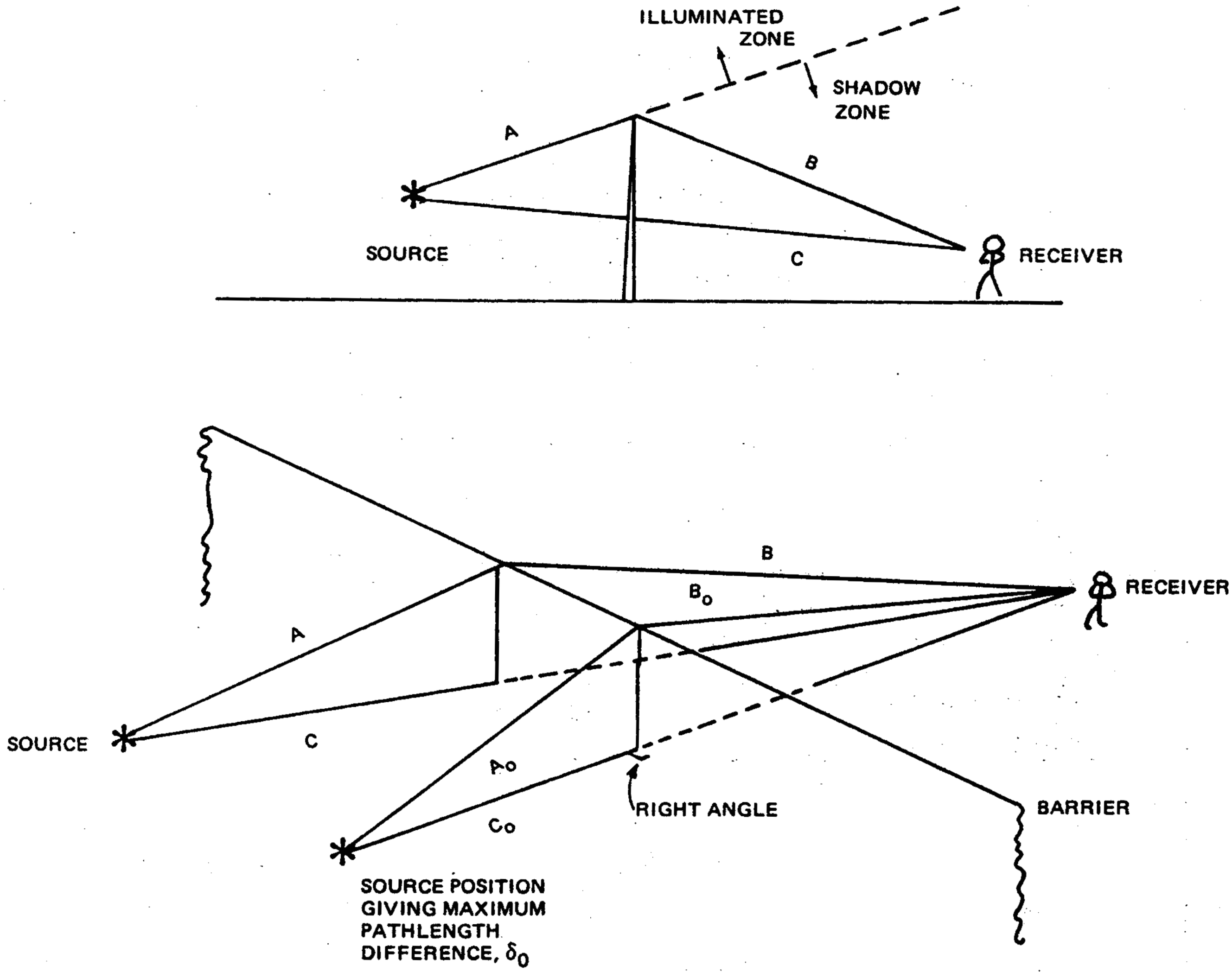
In the context of this report the term barrier is considered to include walls and berms. Barriers affect sound by interrupting its propagation and creating an *acoustic shadow zone.* (See Figure B-1.) The sound level in the shadow zone is lower than the respective free field sound level. In the illuminated zone, the sound level may or may not be lower than the free field level depending upon how far the receiver is into the zone. The reduction in sound level depends on the source angle, angle of diffraction, frequency of sound radiated by the source and the path length difference. For most practical situations the reduction in sound level (attenuation) provided by a barrier may be expressed as a function of a single variable called the Fresnel number. The Fresnel number, N, is defined by

$$N \triangleq 2\frac{\delta}{\lambda} = 2\frac{f\delta}{c} \qquad \text{(B-1)}$$

where δ is the pathlength difference (see Figure B-1), λ is the wavelength of sound radiated by the source, f is the frequency of sound radiated by the source, and c is the speed of sound (343 m/s).

For a point source located behind an infinitely long barrier, the attenuation, Δ, is given in terms of the Fresnel number, N, by

$$\Delta = \begin{cases} 0 & N \leqslant -0.1916 - 0.0635\epsilon \\ 5(1+0.6\epsilon) + 20\log\dfrac{\sqrt{2\pi|N|}}{\tan\sqrt{2\pi|N|}} & (-0.1916 - 0.0635\epsilon) \leqslant N \leqslant 0 \\ 5(1+0.6\epsilon) + 20\log\dfrac{\sqrt{2\pi N}}{\tanh\sqrt{2\pi N}} & 0 \leqslant N \leqslant 5.03 \\ 20(1+0.15\epsilon) & N \geqslant 5.03 \end{cases} \qquad \text{(B-2)}$$



δ = PATHLENGTH DIFFERENCE
$\delta = \pm(A + B - C)$

δ_o = MAXIMUM PATHLENGTH DIFFERENCE
$\delta_o = \pm(A_o + B_o - C_o)$

+ FOR RECEIVERS IN SHADOW ZONE
− FOR RECEIVERS IN ILLUMINATED ZONE

Figure B-1. General Source/Receiver/Barrier Geometry

where

ϵ = 0 for a wall

ϵ = 1 for a berm.

From field experiments, berms appeared to perform about 3 dB better than predicted when they were mathematically treated as a wall. Thus, the ϵ factor was included in (B-2) to take this observed performance difference into account.

Step 2. Attenuation of Equivalent Sound Levels by a Barrier

Consider the source-receiver-barrier geometry shown in Figure B-2. The problem is to determine the sound level at the receiver due to the roadway-barrier segment (ϕ_L, ϕ_R). When treating

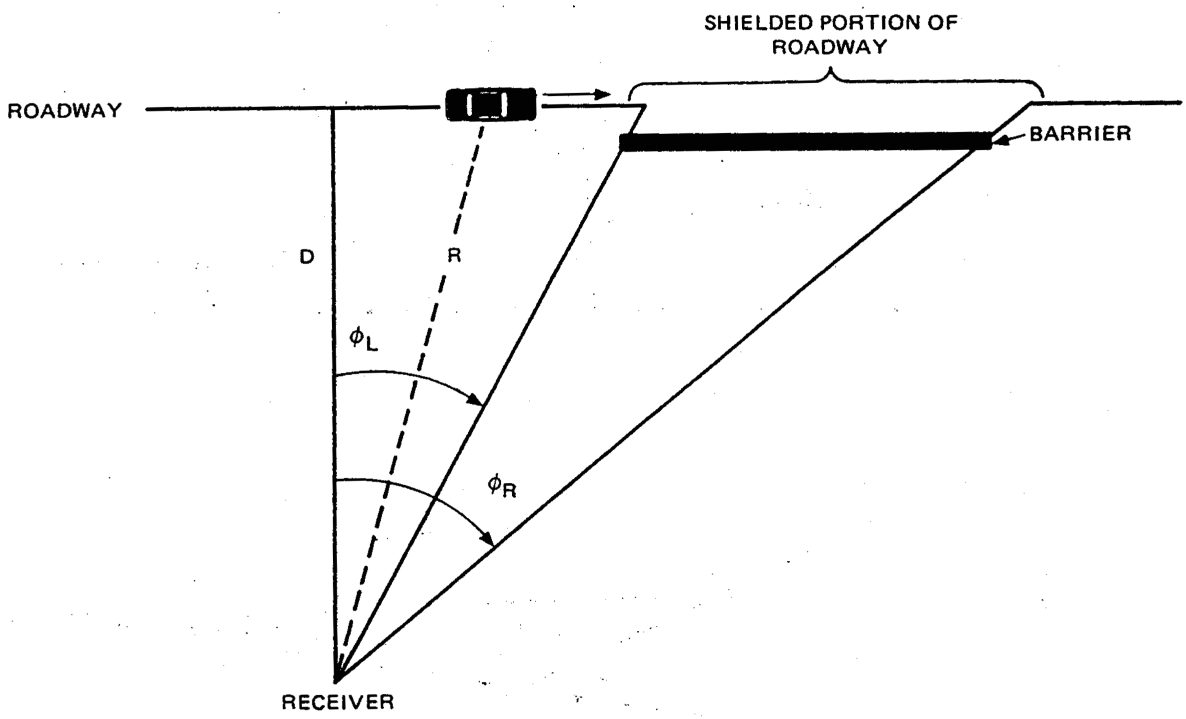


Figure B-2. Source/Receiver/Barrier Geometry Used for the Determination of Barrier Attenuation

roadway-barrier scenarios, it is assumed that ground effects for the shielded portions are negligible ($\alpha = 0$). In the absence of the barrier and with negligible ground effects, the mean square pressure $\langle P^2 \rangle$ due to a single vehicle source is given by

$$\langle P^2 \rangle = \langle P_o^2 \rangle \left(\frac{D_o}{R}\right)^2 \qquad \text{(B-3)}$$

where

D_o = reference distance

R = source-receiver distance

$\langle P_o^2 \rangle$ = mean square pressure measured at reference distance.

The effect of the barrier is that each sound ray will be attenuated by the factor $10^{-\Delta/10}$, that is

$$\langle P^2 \rangle = \langle P_o^2 \rangle \left(\frac{D_o}{R}\right)^2 10^{-\frac{\Delta}{10}}. \qquad \text{(B-4)}$$

where Δ is given by Equation (B-2).

Using the identical methods and techniques developed in Appendix A for calculating equivalent sound levels for a flow of vehicles, (B-4) is integrated over position (time) to give

$$L_{eq}(h)_i = (\bar{L}_o)_{E_i} + 10 \log \frac{N_i D_o}{S_i} + 10 \log \left(\frac{D_o}{D}\right) + 10 \log \frac{1}{\pi} \int_{\phi_L}^{\phi_R} 10^{-\frac{\Delta}{10}} \, d\phi - 25 \qquad \text{(B-5)}$$

where

$L_{eq}(h)_i$ is the hourly equivalent sound level for the ith class of vehicles

$(\bar{L}_o)_{E_i}$	is the reference energy mean emission level for the class of vehicles
N_i	is the number of vehicles in the ith class traversing the roadway in one hour
D_o	is the reference distance, taken as 15 m
S_i	is the average speed of the ith class of vehicles (km/h)
D	is the perpendicular distance from the centerline of the traffic lane to the receiver, m
Δ	is the attenuation of point source levels (Equation (B-2)) provided by a wall or berm

$10 \log \frac{1}{\pi} \int_{\phi_L}^{\phi_R} 10^{-\frac{\Delta}{10}} \, d\phi$ is the attenuation in equivalent sound level provided by a wall or berm subtending the angles ϕ_L and ϕ_R relative to the receiver.

In order to put (B-5) in form more compatible with the results of Appendix A, the right side of (B-5) is multiplied by the factor $10 \log [\Delta\phi(1/\Delta\phi)]$ where $\Delta\phi = \phi_R - \phi_L$,

$$L_{eq}(h)_i = (\bar{L}_o)_{E_i} + 10 \log \frac{N_i D_o}{S_i} + 10 \log \left(\frac{D_o}{D}\right) + 10 \log \frac{\Delta\phi}{\pi}$$

$$+10 \log \frac{1}{\Delta\phi} \int_{\phi_L}^{\phi_R} 10^{-\frac{\Delta}{10}} \, d\phi - 25. \qquad \text{(B-6)}$$

If the equivalent level attenuation term is designated Δ_B, the hourly equivalent sound level for a receiver near a roadway segment (ϕ_L, ϕ_R) shielded by a barrier subtending the angles ϕ_L, ϕ_R is

$$L_{eq}(h)_i = (\bar{L}_o)_{E_i} + 10 \log \frac{N_i D_o}{S_i} + 10 \log \left(\frac{D_o}{D}\right) + 10 \log \frac{\Delta\phi}{\pi} + \Delta_B - 25. \qquad \text{(B-7)}$$

It is important to note that (B-7) is used only for $L_{eq}(h)_i$ contributions from shielded segments. If the roadway element has unshielded portions as in Figure B-3, segments I and III, their contributions are *separately* calculated using earlier results according to

$$L_{eq}(h)_i = (\bar{L}_o)_{E_i} + 10 \log \frac{N_i D_o}{S_i} + 10 \log \left(\frac{D_o}{D}\right)^{1+\alpha} + 10 \log \frac{\psi_\alpha(\phi_1, \phi_2)}{\pi} - 25 \qquad \text{(B-8)}$$

the results of which would be appropriately added to the shielded $L_{eq}(h)_i$ value to obtain the total equivalent sound level.

Two *problems* remain: (1) performing the indicated integration in (B-6) requires that the functional relationship between N and ϕ be determined, and (2) deciding if Δ_B is the same for all classes of vehicles for a given site geometry.

The ϕ dependence of N is determined by the approximate relationship

$$N \cong N_o \cos \phi \qquad \text{(B-9)}$$

in which N_o is the Fresnel number determined along the *perpendicular* between the receiver and the source (line).

For barrier calculations only, the source vehicles are treated as being located at the following positions:

automobiles	0 metres above the centerline of the lane
medium trucks	0.7 metres above the centerline of the lane
heavy trucks	2.44 metres above the centerline of the lane.

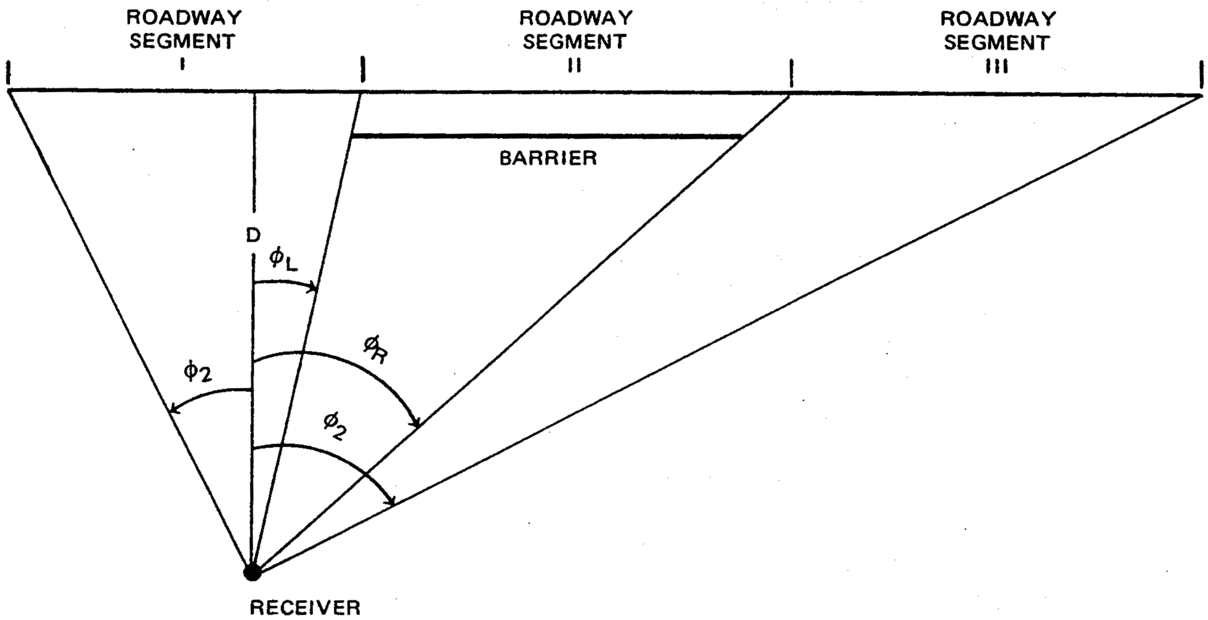


Figure B-3. Finite Roadway/Finite Barrier Geometry for Insertion Loss Calculations

These elevated positions take into account the many individual noise sources contributing to the overall noise radiated by medium and heavy trucks. Since the source positions vary, Δ_B will vary, and hence, must be *indexed to indicate vehicle class, i.e.,* Δ_{B_i}. Then,

$$L_{eq}(h)_i = (\bar{L}_o)_{E_i} + 10 \log \frac{N_i D_o}{S_i} + 10 \log \left(\frac{D_o}{D}\right) + 10 \log \frac{\Delta\phi}{\pi} + \Delta_{B_i} - 25 \qquad \text{(B-10)}$$

where

$$\Delta_{B_i} = 10 \log \frac{1}{\Delta\phi} \int_{\phi_L}^{\phi_R} 10^{-\frac{\Delta_i}{10}} \, d\phi . \qquad \text{(B-11)}$$

$$\Delta_i = \begin{cases} 0 & N_i \leqslant -0.1916 - 0.0635\epsilon \\ 5(1+0.6\epsilon) + 20 \log \dfrac{\sqrt{2\pi |N_o|_i \cos\phi}}{\tan \sqrt{2\pi |N_o|_i \cos\phi}} & (-0.1916 - 0.0635\epsilon) \leqslant N_i \leqslant 0 \\ 5(1+0.6\epsilon) + 20 \log \dfrac{\sqrt{2\pi (N_o)_i \cos\phi}}{\tanh \sqrt{2\pi (N_o)_i \cos\phi}} & 0 \leqslant N_i \leqslant 5.03 \\ 20(1+0.15\epsilon) & N_i \geqslant 5.03 . \end{cases} \qquad \text{(B-12)}$$

and

$N_i = (N_0)_i \cos\phi$

i = automobiles, medium trucks, heavy trucks.

To put (B-11) and (B-12) in a more useable form note that

$$3\epsilon = 10\log(10^{0.3\epsilon})$$

$$5(1+0.6\epsilon) = 10\log 10^{\frac{5+3\epsilon}{10}} = 10\log(\sqrt{10}\ 10^{0.3\epsilon})$$

$$20(1+0.15\epsilon) = 10\log 10^{\frac{20+3\epsilon}{10}} = 10\log(100\times 10^{0.3\epsilon})$$

which when combined with the log terms in (B-12) gives

$$\Delta_i = \begin{cases} 20\log(1) & N_i \leqslant -0.1916 - 0.0635\epsilon \\ 10\log\left[\dfrac{\sqrt{10}\ 10^{0.3\epsilon}\ 2\pi|N_o|_i\cos\phi}{\tan^2\sqrt{2\pi|N_o|_i\cos\phi}}\right] & (-0.1916-0.0635\epsilon) \leqslant N_i \leqslant 0 \\ 10\log\left[\dfrac{\sqrt{10}\ 10^{0.3\epsilon}\ 2\pi(N_o)_i\cos\phi}{\tanh^2\sqrt{2\pi(N_o)_i\cos\phi}}\right] & 0 \leqslant N_i \leqslant 5.03 \\ 10\log[100\times 10^{0.3\epsilon}] & N_i \geqslant 5.03. \end{cases} \quad \text{(B-13)}$$

The integrand in (B-11) involves the antilog of negative $\Delta_i/10$, so that (B-11) may be rewritten using the result (B-13)

$$B_i = 10\log\frac{1}{\phi_R-\phi_L}\int_{\phi_L}^{\phi_R}\left\{\begin{matrix} 1 & N_i \leqslant -0.1916 - 0.0635\epsilon \\ \left[\dfrac{10^{-0.3\epsilon}\tan^2\sqrt{2\pi|N_o|_i\cos\phi}}{\sqrt{10}\ 2\pi|N_o|_i\cos\phi}\right] & (-0.1916-0.0635\epsilon) \leqslant N_i \leqslant 0 \\ \left[\dfrac{10^{-0.3\epsilon}\tanh^2\sqrt{2\pi(N_o)_i\cos\phi}}{\sqrt{10}\ 2\pi(N_o)_i\cos\phi}\right] & 0 \leqslant N_i \leqslant 5.03 \\ \dfrac{10^{-0.3\epsilon}}{10^0} & N_i \geqslant 5.03. \end{matrix}\right\} d\phi$$

(B-13)

The integral in (B-14) has been numerically integrated for a range of values of N_o, $-0.2 \leqslant N_o \leqslant 100$, and is presented in ten degree increments in a series of tables appearing at the end of this appendix.

Insertion Loss

Insertion loss, *IL*, is the direct measure of the field effectiveness of a barrier. Insertion loss is simply the difference in sound levels at a receiver before and after construction of the barrier,

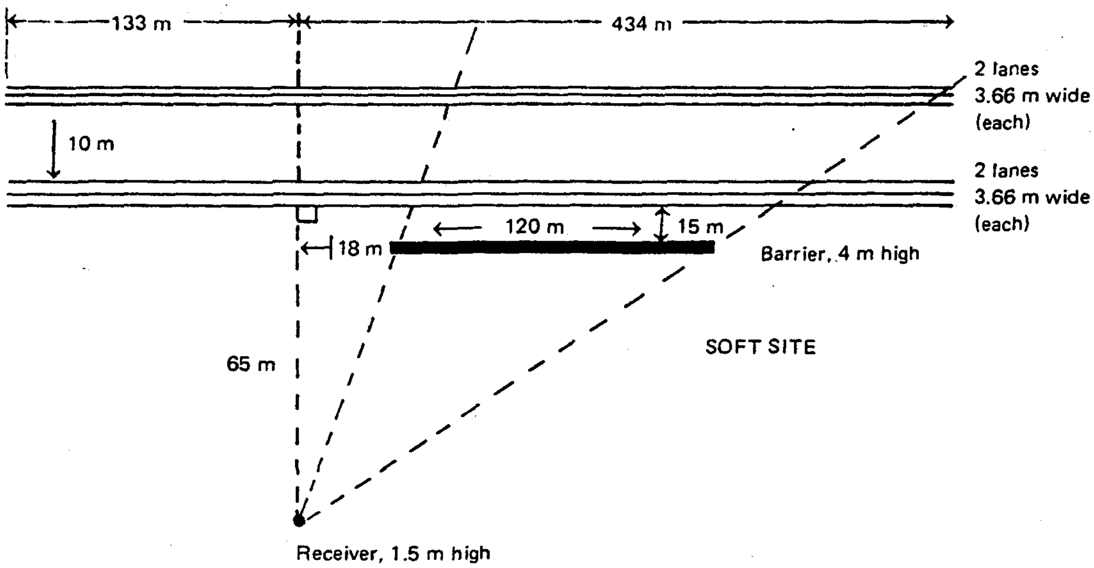
$$IL = \begin{pmatrix}\text{Sound level before} \\ \text{barrier construction}\end{pmatrix} - \begin{pmatrix}\text{Sound level after} \\ \text{barrier construction}\end{pmatrix}. \quad \text{(B-14)}$$

In general, insertion loss will depend upon the barrier's attenuation Δ_B, transmission loss characteristics, leaks, and propagation effects. Insertion loss is the quantity around which barriers should be designed.

EXAMPLE PROBLEM NUMBER 1

Problem: Using the finite roadway, finite barrier geometry illustrated below and the traffic information in the accompanying table, determine (1) the traffic noise level at the receiver before construction of the barrier, (2) the level at the receiver after construction of the barrier, and (3) the field insertion loss provided by the barrier.

ROADWAY SITE (Not to Scale)



Traffic Information

Vehicle Class	N (vph) All Lanes	S (km/h)	$(L_0)_E$ (dBA)
Automobiles	2450	88	72
Medium Trucks	195	84	82
Heavy Trucks	160	82	86

Solution:

Using the Noise Prediction Worksheet, fill in the traffic data.

Calculation of Equivalent Lane Distances

1. No Barrier

$$D_E = [(\text{Receiver—near lane} \ ℄ \ \text{distance}) \times (\text{Receiver—far lane} \ ℄ \ \text{distance})]^{1/2}$$

$$D_E = \left[\left(65 + \frac{3.66}{2}\right)\left(65 + 3.66 + 3.66 + 10 + 3.66 + \frac{3.66}{2}\right)\right]^{1/2}$$

$$D_E = 76.61 \text{ m}.$$

(Continued)

EXAMPLE PROBLEM NUMBER 1 (Continued)

2. With Barrier

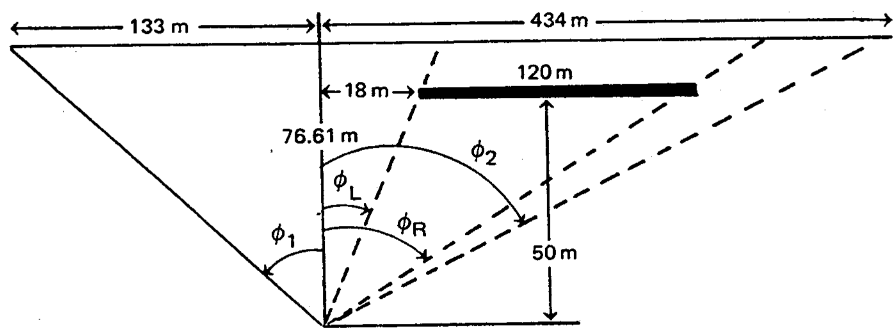
D_E = Receiver-barrier distance (perpendicular)

$+[(\text{Barrier—near lane } \mathbb{C}\text{ distance}) \times (\text{Barrier—far lane } \mathbb{C}\text{ distance})]^{1/2}$

$$D_E = 50 + \left[\left(15 + \frac{3.66}{2}\right)\left(15 + 3.66 + 10 + 3.66 + \frac{3.66}{2}\right)\right]^{1/2}$$

D_E = 75.23 m.

Calculation of Roadway Segment Angles



$$\phi_1 = -\tan^{-1}\left(\frac{133}{76.61}\right) \simeq -60°$$

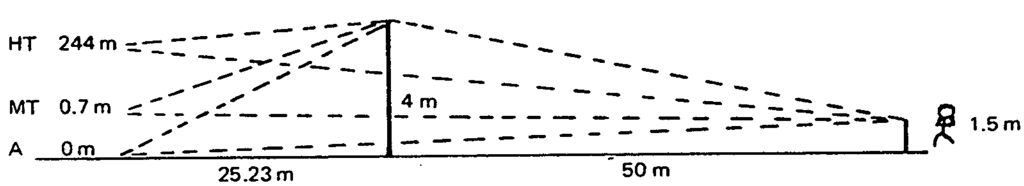
$$\phi_L = \tan^{-1}\left(\frac{18}{50}\right) \simeq 20°$$

$$\phi_R = \tan^{-1}\left(\frac{18 + 120}{50}\right) \simeq 70°$$

$$\phi_2 = \tan^{-1}\left(\frac{434}{76.61}\right) \simeq 80°$$

Calculation of δ_o, N_o

Redrawing the barrier in a cross-section



A $\delta_o = \sqrt{25.23^2 + 4^2} + \sqrt{(4-1.5)^2 + 50^2} - \sqrt{1.5^2 + 75.23^2} = 0.36$ m

MT $\delta_o = \sqrt{25.23^2 + (4-0.7)^2} + \sqrt{25^2 + 50^2} - \sqrt{(1.5-0.7)^2 + 75.23^2} = 0.27$ m

HT $\delta_o = \sqrt{25.23^2 + (4-2.44)^2} + \sqrt{2.5^2 + 50^2} - \sqrt{(2.44-1.5)^2 + 75.23^2} = 0.10$ m

(Continued)

EXAMPLE PROBLEM NUMBER 1 (Continued)

$$N_o = 2\frac{\delta_o}{\lambda} = 2\frac{f\delta_o}{c}$$

f is usually taken as 550 Hz

c = 343 m/s

$$N_o = \frac{2(550)}{343}\delta_o = 3.21\,\delta_o$$

A $N_o = 3.21(0.36) = 1.16$

MT $N_o = 3.21(0.27) = 0.87$

HT $N_o = 3.21(0.10) = 0.32.$

Calculation of Δ_B

Using the attenuation tables at the end of Appendix B

A $N_o = 1.16$ $\phi_L = 20°$ $N_o = 1$ $\Delta_B = -11.39$

$\phi_R = 70°$ $N_o = 2$ $\Delta_B = -14.09$

By linear interpolation $\Delta_B \simeq -11.39 - 0.16(14.09 - 11.39)$

$$\Delta_B \simeq -11.8$$

MT $N_o = 0.87$ $N_o = 0.8,$ $\Delta_B = -10.60$

$N_o = 0.9,$ $\Delta_B = -11.01$

$$\Delta_B \simeq -10.60 - 0.7(11.01 - 10.60)$$

$$\Delta_B \simeq -10.9$$

HT $N_o = 0.32$ $N_o = 0.3,$ $\Delta_B = -7.83$

$N_o = 0.4,$ $\Delta_B = -8.52$

$$\Delta_B \simeq -7.83 - 0.2(8.52 - 7.83)$$

$$\Delta_B \simeq -8.0$$

From the Noise Prediction Worksheet,

noise level at the receiver before construction of the barrier

$$\boxed{L^b_{eq}(h) = 66.7 \text{ dBA}}$$

(Continued)

EXAMPLE PROBLEM NUMBER 1 (Continued)

noise level at the receiver after construction of the barrier

$$\boxed{L^{a}_{eq}(h) = 65.5 \text{ dBA}}$$

$$I.L. = L^{b}_{eq}(h) - L^{a}_{eq}(h) = 66.7 - 65.5$$

$$\boxed{I.L. = 1.2 \text{ dBA}}$$

NAME ______________________ PROJECT DESCRIPTION EXAMPLE B-1

DATE ______________________

1.	LANE NO./ROAD SEGMENT		I			II (Before)			II (After)			III								
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		2450	195	160	2450	195	160	2450	195	160	2450	195	160						
4.	S(km/h)		88	84	82	88	84	82	88	84	82	88	84	82						
5.	D(m)		–	76.61	–	–	76.61	–	–	75.23	–	–	76.61	–						
6.	ϕ_1 (degrees)	Fig. 5	–80			20			20			70								
7.	ϕ_2 (degrees)	Fig. 5	20			70			70			80								
8.	$(\overline{L_o})E_i$ (dBA)	Fig. 2	72	82	86	72	82	86	72	82	86	72	82	86						
9.	10 LOG $(N_i D_o / S_i)$ (dB)	Fig. 3	26.2	15.4	14.7	26.2	15.4	14.7	26.2	15.4	14.7	26.2	15.4	14.7						
10a.	10 LOG (D_o/D) (dBA)	Fig. 4							–7.0	–7.0	–7.0									
10b.	15 LOG (D_o/D) (dBA)	Fig. 4	–10.6	–10.6	–10.6	–10.6	–10.6	–10.6				–10.6	–10.6	–10.6						
11a.	10 LOG $(\psi_0(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6							–5.6	–6.6	–5.6									
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7	–3.6	–3.6	–3.6	–6.2	–6.2	–6.2				–15.0	–25.0	–15.0						
12.	ϕ_L (degrees)	Fig. 10							20											
13.	ϕ_R (degrees)	Fig. 10							70											
14.	δ_o (metres)	Fig. 9							0.36	0.27	0.10									
15.	N_o	Eq. 18							1.16	0.87	0.32									
16.	Δ_B (dBA)	Appendix B							–11.8	–10.9	–8.0									
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)		59.0	58.2	61.5	56.4	55.6	58.9	18.8	48.9	55.1	47.6	46.8	50.1						
19.	$L_{eq}(h)$ (dBA)		64.6			62.0			56.8			53.2								
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)		Before 66.7						After 65.5											
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table B-1-1. Noise Prediction Worksheet

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = –0.01

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	–80	–70	–60	–50	–40	–30	–20	–10	0	10	20	30	40	50	60	70	80	90
–90	–5.0	–5.0	–5.0	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9
–80	–	–5.0	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9
–70	–	–	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.9	–4.8	–4.8	–4.8	–4.8	–4.9	–4.9	–4.9	–4.9
–60	–	–	–	–4.9	–4.9	–4.9	–4.9	–4.9	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.9	–4.9	–4.9
–50	–	–	–	–	–4.9	–4.9	–4.9	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.9	–4.9
–40	–	–	–	–	–	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.9	–4.9
–30	–	–	–	–	–	–	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.9	–4.9
–20	–	–	–	–	–	–	–	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.9	–4.9
–10	–	–	–	–	–	–	–	–	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.9	–4.9	–4.9
0	–	–	–	–	–	–	–	–	–	–4.8	–4.8	–4.8	–4.8	–4.8	–4.8	–4.9	–4.9	–4.9
10	–	–	–	–	–	–	–	–	–	–	–4.8	–4.8	–4.8	–4.8	–4.9	–4.9	–4.9	–4.9
20	–	–	–	–	–	–	–	–	–	–	–	–4.8	–4.8	–4.9	–4.9	–4.9	–4.9	–4.9
30	–	–	–	–	–	–	–	–	–	–	–	–	–4.8	–4.9	–4.9	–4.9	–4.9	–4.9
40	–	–	–	–	–	–	–	–	–	–	–	–	–	–4.9	–4.9	–4.9	–4.9	–4.9
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–4.9	–4.9	–4.9	–4.9
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–4.9	–4.9	–5.0
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–5.0	–5.0
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–5.0

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.02

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.0	−4.9	−4.9	−4.9	−4.8	−4.8	−4.8	−4.8	−4.8	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.8
−80	–	−4.9	−4.9	−4.8	−4.8	−4.8	−4.8	−4.8	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7
−70	–	–	−4.8	−4.8	−4.8	−4.8	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7
−60	–	–	–	−4.8	−4.8	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7
−50	–	–	–	–	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7
−40	–	–	–	–	–	−4.7	−4.7	−4.7	−4.7	−4.6	−4.6	−4.6	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7
−30	–	–	–	–	–	–	−4.7	−4.7	−4.6	−4.6	−4.6	−4.6	−4.6	−4.7	−4.7	−4.7	−4.7	−4.7
−20	–	–	–	–	–	–	–	−4.6	−4.6	−4.6	−4.6	−4.6	−4.6	−4.7	−4.7	−4.7	−4.7	−4.7
−10	–	–	–	–	–	–	–	–	−4.6	−4.6	−4.6	−4.6	−4.6	−4.7	−4.7	−4.7	−4.7	−4.7
0	–	–	–	–	–	–	–	–	–	−4.6	−4.6	−4.6	−4.7	−4.7	−4.7	−4.7	−4.7	−4.7
10	–	–	–	–	–	–	–	–	–	–	−4.6	−4.7	−4.7	−4.7	−4.7	−4.7	−4.8	−4.8
20	–	–	–	–	–	–	–	–	–	–	–	−4.7	−4.7	−4.7	−4.7	−4.7	−4.8	−4.8
30	–	–	–	–	–	–	–	–	–	–	–	–	−4.7	−4.7	−4.7	−4.8	−4.8	−4.8
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.7	−4.8	−4.8	−4.8	−4.8
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.8	−4.8	−4.8	−4.9
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.8	−4.9	−4.9
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.9	−4.9
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.0

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.03

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.0	−4.9	−4.9	−4.8	−4.8	−4.7	−4.7	−4.7	−4.6	−4.6	−4.6	−4.6	−4.6	−4.6	−4.6	−4.6	−4.6	−4.6
−80	–	−4.9	−4.8	−4.8	−4.7	−4.7	−4.7	−4.6	−4.6	−4.6	−4.6	−4.6	−4.6	−4.6	−4.6	−4.6	−4.6	−4.6
−70	–	–	−4.8	−4.7	−4.7	−4.6	−4.6	−4.6	−4.6	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.6	−4.6	−4.6
−60	–	–	–	−4.7	−4.6	−4.6	−4.6	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.6	−4.6
−50	–	–	–	–	−4.6	−4.6	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.6	−4.6
−40	–	–	–	–	–	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.6	−4.6
−30	–	–	–	–	–	–	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.5	−4.6	−4.6
−20	–	–	–	–	–	–	–	−4.4	−4.4	−4.4	−4.4	−4.4	−4.5	−4.5	−4.5	−4.5	−4.6	−4.6
−10	–	–	–	–	–	–	–	–	−4.4	−4.4	−4.4	−4.4	−4.5	−4.5	−4.5	−4.5	−4.6	−4.6
0	–	–	–	–	–	–	–	–	–	−4.4	−4.4	−4.5	−4.5	−4.5	−4.5	−4.6	−4.6	−4.6
10	–	–	–	–	–	–	–	–	–	–	−4.4	−4.5	−4.5	−4.5	−4.5	−4.6	−4.6	−4.7
20	–	–	–	–	–	–	–	–	–	–	–	−4.5	−4.5	−4.5	−4.6	−4.6	−4.7	−4.7
30	–	–	–	–	–	–	–	–	–	–	–	–	−4.5	−4.6	−4.6	−4.6	−4.7	−4.7
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.6	−4.6	−4.7	−4.7	−4.8
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.7	−4.7	−4.8	−4.8
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.8	−4.8	−4.9
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.9	−4.9
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.0

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, $N_0 = -0.04$

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−4.9	−4.9	−4.8	−4.7	−4.7	−4.6	−4.6	−4.5	−4.5	−4.5	−4.5	−4.4	−4.4	−4.4	−4.4	−4.5	−4.5	−4.5
−80	–	−4.8	−4.7	−4.7	−4.6	−4.6	−4.5	−4.5	−4.5	−4.4	−4.4	−4.4	−4.4	−4.4	−4.4	−4.4	−4.5	−4.5
−70	–	–	−4.7	−4.6	−4.6	−4.5	−4.5	−4.4	−4.4	−4.4	−4.4	−4.4	−4.4	−4.4	−4.4	−4.4	−4.4	−4.5
−60	–	–	–	−4.6	−4.5	−4.5	−4.4	−4.4	−4.4	−4.3	−4.3	−4.3	−4.3	−4.3	−4.4	−4.4	−4.4	−4.4
−50	–	–	–	–	−4.5	−4.4	−4.4	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.4	−4.4	−4.4
−40	–	–	–	–	–	−4.4	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.4	−4.4	−4.4
−30	–	–	–	–	–	–	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.4	−4.4	−4.4
−20	–	–	–	–	–	–	–	−4.3	−4.2	−4.2	−4.2	−4.3	−4.3	−4.3	−4.3	−4.4	−4.4	−4.5
−10	–	–	–	–	–	–	–	–	−4.2	−4.2	−4.2	−4.3	−4.3	−4.3	−4.3	−4.4	−4.4	−4.5
0	–	–	–	–	–	–	–	–	–	−4.2	−4.2	−4.3	−4.3	−4.3	−4.4	−4.4	−4.5	−4.5
10	–	–	–	–	–	–	–	–	–	–	−4.3	−4.3	−4.3	−4.3	−4.4	−4.4	−4.5	−4.5
20	–	–	–	–	–	–	–	–	–	–	–	−4.3	−4.3	−4.4	−4.4	−4.5	−4.5	−4.6
30	–	–	–	–	–	–	–	–	–	–	–	–	−4.4	−4.4	−4.5	−4.5	−4.6	−4.6
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.5	−4.5	−4.6	−4.6	−4.7
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.6	−4.6	−4.7	−4.7
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.7	−4.7	−4.8
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.8	−4.9
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.9

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.05

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−4.9	−4.8	−4.8	−4.7	−4.6	−4.5	−4.5	−4.4	−4.4	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.3	−4.4
−80	–	−4.8	−4.7	−4.6	−4.5	−4.5	−4.4	−4.4	−4.3	−4.3	−4.3	−4.2	−4.2	−4.2	−4.3	−4.3	−4.3	−4.3
−70	–	–	−4.6	−4.5	−4.5	−4.4	−4.3	−4.3	−4.3	−4.2	−4.2	−4.2	−4.2	−4.2	−4.2	−4.3	−4.3	−4.3
−60	–	–	–	−4.5	−4.4	−4.3	−4.3	−4.3	−4.2	−4.2	−4.2	−4.2	−4.2	−4.2	−4.2	−4.2	−4.3	−4.3
−50	–	–	–	–	−4.3	−4.3	−4.2	−4.2	−4.1	−4.1	−4.1	−4.1	−4.1	−4.1	−4.2	−4.2	−4.2	−4.3
−40	–	–	–	–	–	−4.2	−4.2	−4.1	−4.1	−4.1	−4.1	−4.1	−4.1	−4.1	−4.2	−4.2	−4.2	−4.3
−30	–	–	–	–	–	–	−4.1	−4.1	−4.1•	−4.1	−4.1	−4.1	−4.1	−4.1	−4.2	−4.2	−4.2	−4.3
−20	–	–	–	–	–	–	–	−4.1	−4.0	−4.0	−4.0	−4.1	−4.1	−4.1	−4.2	−4.2	−4.3	−4.3
−10	–	–	–	–	–	–	–	–	−4.0	−4.0	−4.0	−4.1	−4.1	−4.1	−4.2	−4.2	−4.3	−4.3
0	–	–	–	–	–	–	–	–	–	−4.0	−4.0	−4.1	−4.1	−4.1	−4.2	−4.3	−4.3	−4.4
10	–	–	–	–	–	–	–	–	–	–	−4.1	−4.1	−4.1	−4.2	−4.2	−4.3	−4.4	−4.4
20	–	–	–	–	–	–	–	–	–	–	–	−4.1	−4.2	−4.2	−4.3	−4.3	−4.4	−4.5
30	–	–	–	–	–	–	–	–	–	–	–	–	−4.2	−4.3	−4.3	−4.4	−4.5	−4.5
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.3	−4.4	−4.5	−4.5	−4.6
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.5	−4.5	−4.6	−4.7
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.6	−4.7	−4.8
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.8	−4.8
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.9

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.06

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−4.9	−4.8	−4.7	−4.6	−4.5	−4.4	−4.4	−4.3	−4.2	−4.2	−4.2	−4.1	−4.1	−4.1	−4.1	−4.2	−4.2	−4.2
−80	–	−4.7	−4.6	−4.5	−4.4	−4.4	−4.3	−4.2	−4.2	−4.1	−4.1	−4.1	−4.1	−4.1	−4.1	−4.1	−4.2	−4.2
−70	–	–	−4.5	−4.4	−4.3	−4.3	−4.2	−4.1	−4.1	−4.1	−4.0	−4.0	−4.0	−4.0	−4.1	−4.1	−4.1	−4.2
−60	–	–	–	−4.3	−4.3	−4.2	−4.1	−4.1	−4.0	−4.0	−4.0	−4.0	−4.0	−4.0	−4.0	−4.1	−4.1	−4.1
−50	–	–	–	–	−4.2	−4.1	−4.0	−4.0	−4.0	−3.9	−3.9	−3.9	−3.9	−4.0	−4.0	−4.0	−4.1	−4.1
−40	–	–	–	–	–	−4.0	−4.0	−3.9	−3.9	−3.9	−3.9	−3.9	−3.9	−3.9	−4.0	−4.0	−4.1	−4.1
−30	–	–	–	–	–	–	−3.9	−3.9	−3.9	−3.8	−3.8	−3.9	−3.9	−3.9	−4.0	−4.0	−4.1	−4.1
−20	–	–	–	–	–	–	–	−3.8	−3.8	−3.8	−3.8	−3.8	−3.9	−3.9	−4.0	−4.0	−4.1	−4.2
−10	–	–	–	–	–	–	–	–	−3.8	−3.8	−3.8	−3.8	−3.9	−3.9	−4.0	−4.1	−4.1	−4.2
0	–	–	–	–	–	–	–	–	–	−3.8	−3.8	−3.9	−3.9	−4.0	−4.0	−4.1	−4.2	−4.2
10	–	–	–	–	–	–	–	–	–	–	−3.8	−3.9	−3.9	−4.0	−4.1	−4.1	−4.2	−4.3
20	–	–	–	–	–	–	–	–	–	–	–	−3.9	−4.0	−4.0	−4.1	−4.2	−4.3	−4.4
30	–	–	–	–	–	–	–	–	–	–	–	–	−4.0	−4.1	−4.2	−4.3	−4.4	−4.4
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.2	−4.3	−4.3	−4.4	−4.5
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.3	−4.4	−4.5	−4.6
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.5	−4.6	−4.7
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.7	−4.8
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.9

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.07

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−4.9	−4.8	−4.7	−4.5	−4.4	−4.3	−4.2	−4.2	−4.1	−4.0	−4.0	−4.0	−4.0	−4.0	−4.0	−4.0	−4.1	−4.1
−80	–	−4.7	−4.5	−4.4	−4.3	−4.2	−4.1	−4.1	−4.0	−4.0	−3.9	−3.9	−3.9	−3.9	−3.9	−4.0	−4.0	−4.1
−70	–	–	−4.4	−4.3	−4.2	−4.1	−4.0	−4.0	−3.9	−3.9	−3.8	−3.8	−3.8	−3.9	−3.9	−3.9	−4.0	−4.0
−60	–	–	–	−4.2	−4.1	−4.0	−4.0	−3.9	−3.8	−3.8	−3.8	−3.8	−3.8	−3.8	−3.8	−3.9	−3.9	−4.0
−50	–	–	–	–	−4.0	−3.9	−3.9	−3.8	−3.8	−3.7	−3.7	−3.7	−3.7	−3.8	−3.8	−3.9	−3.9	−4.0
−40	–	–	–	–	–	−3.9	−3.8	−3.7	−3.7	−3.7	−3.7	−3.7	−3.7	−3.7	−3.8	−3.8	−3.9	−4.0
−30	–	–	–	–	–	–	−3.7	−3.7	−3.6	−3.6	−3.6	−3.6	−3.7	−3.7	−3.8	−3.8	−3.9	−4.0
−20	–	–	–	–	–	–	–	−3.6	−3.6	−3.6	−3.6	−3.6	−3.7	−3.7	−3.8	−3.8	−3.9	−4.0
−10	–	–	–	–	–	–	–	–	−3.6	−3.6	−3.6	−3.6	−3.7	−3.7	−3.8	−3.9	−4.0	−4.0
0	–	–	–	–	–	–	–	–	–	−3.6	−3.6	−3.6	−3.7	−3.8	−3.8	−3.9	−4.0	−4.1
10	–	–	–	–	–	–	–	–	–	–	−3.6	−3.7	−3.7	−3.8	−3.9	−4.0	−4.1	−4.2
20	–	–	–	–	–	–	–	–	–	–	–	−3.7	−3.8	−3.9	−4.0	−4.0	−4.1	−4.2
30	–	–	–	–	–	–	–	–	–	–	–	–	−3.9	−3.9	−4.0	−4.1	−4.2	−4.3
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.0	−4.1	−4.2	−4.3	−4.4
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.2	−4.3	−4.4	−4.5
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.4	−4.5	−4.7
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.7	−4.8
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.9

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = –0.08

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	–80	–70	–60	–50	–40	–30	–20	–10	0	10	20	30	40	50	60	70	80	90
–90	–4.9	–4.7	–4.6	–4.5	–4.3	–4.2	–4.1	–4.0	–3.9	–3.9	–3.8	–3.8	–3.8	–3.8	–3.8	–3.9	–3.9	–3.9
–80	–	–4.6	–4.5	–4.4	–4.2	–4.1	–4.0	–3.9	–3.8	–3.8	–3.7	–3.7	–3.7	–3.7	–3.8	–3.8	–3.8	–3.9
–70	–	–	–4.4	–4.2	–4.1	–4.0	–3.9	–3.8	–3.7	–3.7	–3.7	–3.6	–3.6	–3.7	–3.7	–3.7	–3.8	–3.9
–60	–	–	–	–4.1	–4.0	–3.9	–3.8	–3.7	–3.7	–3.6	–3.6	–3.6	–3.6	–3.6	–3.7	–3.7	–3.8	–3.8
–50	–	–	–	–	–3.9	–3.8	–3.7	–3.6	–3.6	–3.5	–3.5	–3.5	–3.5	–3.6	–3.6	–3.7	–3.7	–3.8
–40	–	–	–	–	–	–3.7	–3.6	–3.5	–3.5	–3.5	–3.5	–3.5	–3.5	–3.5	–3.6	–3.6	–3.7	–3.8
–30	–	–	–	–	–	–	–3.5	–3.5	–3.4	–3.4	–3.4	–3.4	–3.5	–3.5	–3.6	–3.6	–3.7	–3.8
–20	–	–	–	–	–	–	–	–3.4	–3.4	–3.4	–3.4	–3.4	–3.5	–3.5	–3.6	–3.7	–3.7	–3.8
–10	–	–	–	–	–	–	–	–	–3.4	–3.4	–3.4	–3.4	–3.5	–3.5	–3.6	–3.7	–3.8	–3.9
0	–	–	–	–	–	–	–	–	–	–3.4	–3.4	–3.4	–3.5	–3.6	–3.7	–3.7	–3.8	–3.9
10	–	–	–	–	–	–	–	–	–	–	–3.4	–3.5	–3.5	–3.6	–3.7	–3.8	–3.9	–4.0
20	–	–	–	–	–	–	–	–	–	–	–	–3.5	–3.6	–3.7	–3.8	–3.9	–4.0	–4.1
30	–	–	–	–	–	–	–	–	–	–	–	–	–3.7	–3.8	–3.9	–4.0	–4.1	–4.2
40	–	–	–	–	–	–	–	–	–	–	–	–	–	–3.9	–4.0	–4.1	–4.2	–4.3
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–4.1	–4.2	–4.4	–4.5
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–4.4	–4.5	–4.6
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–4.6	–4.7
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–4.9

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, $N_0 = -0.09$

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	-80	-70	-60	-50	-40	-30	-20	-10	0	10	20	30	40					
-90	-4.9	-4.7	-4.6	-4.4	-4.3	-4.1	-4.0	-3.9	-3.8	-3.7	-3.7	-3.6	-3.6	-3.6	-3.7	-3.7	-3.7	-3.8
-80	–	-4.6	-4.4	-4.3	-4.1	-4.0	-3.9	-3.8	-3.7	-3.6	-3.6	-3.5	-3.5	-3.6	-3.6	-3.6	-3.7	-3.7
-70	–	–	-4.3	-4.1	-4.0	-3.9	-3.7	-3.6	-3.6	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.6	-3.6	-3.7
-60	–	–	–	-4.0	-3.9	-3.7	-3.6	-3.5	-3.5	-3.4	-3.4	-3.4	-3.4	-3.4	-3.5	-3.5	-3.6	-3.7
-50	–	–	–	–	-3.7	-3.6	-3.5	-3.4	-3.4	-3.3	-3.3	-3.3	-3.3	-3.4	-3.4	-3.5	-3.6	-3.6
-40	–	–	–	–	–	-3.5	-3.4	-3.3	-3.3	-3.2	-3.2	-3.2	-3.3	-3.3	-3.4	-3.5	-3.5	-3.6
-30	–	–	–	–	–	–	-3.3	-3.2	-3.2	-3.2	-3.2	-3.2	-3.2	-3.3	-3.4	-3.5	-3.5	-3.6
-20	–	–	–	–	–	–	–	-3.2	-3.1	-3.1	-3.1	-3.2	-3.2	-3.3	-3.4	-3.5	-3.6	-3.7
-10	–	–	–	–	–	–	–	–	-3.1	-3.1	-3.1	-3.2	-3.2	-3.3	-3.4	-3.5	-3.6	-3.7
0	–	–	–	–	–	–	–	–	–	-3.1	-3.1	-3.2	-3.3	-3.4	-3.5	-3.6	-3.7	-3.8
10	–	–	–	–	–	–	–	–	–	–	-3.2	-3.2	-3.3	-3.4	-3.5	-3.6	-3.8	-3.9
20	–	–	–	–	–	–	–	–	–	–	–	-3.3	-3.4	-3.5	-3.6	-3.7	-3.9	-4.0
30	–	–	–	–	–	–	–	–	–	–	–	–	-3.5	-3.6	-3.7	-3.9	-4.0	-4.1
40	–	–	–	–	–	–	–	–	–	–	–	–	–	-3.7	-3.9	-4.0	-4.1	-4.3
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-4.0	-4.1	-4.3	-4.4
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-4.3	-4.4	-4.6
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-4.6	-4.7
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-4.9

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.10

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−4.8	−4.7	−4.5	−4.3	−4.2	−4.0	−3.9	−3.7	−3.6	−3.6	−3.5	−3.5	−3.4	−3.5	−3.5	−3.5	−3.6	−3.6
−80	–	−4.5	−4.3	−4.2	−4.0	−3.9	−3.7	−3.6	−3.5	−3.4	−3.4	−3.4	−3.3	−3.4	−3.4	−3.4	−3.5	−3.6
−70	–	–	−4.2	−4.0	−3.9	−3.7	−3.6	−3.5	−3.4	−3.3	−3.3	−3.3	−3.3	−3.3	−3.3	−3.4	−3.4	−3.5
−60	–	–	–	−3.9	−3.7	−3.6	−3.4	−3.3	−3.3	−3.2	−3.2	−3.2	−3.2	−3.2	−3.3	−3.3	−3.4	−3.5
−50	–	–	–	–	−3.6	−3.4	−3.3	−3.2	−3.1	−3.1	−3.1	−3.1	−3.1	−3.1	−3.2	−3.3	−3.4	−3.5
−40	–	–	–	–	–	−3.3	−3.2	−3.1	−3.0	−3.0	−3.0	−3.0	−3.0	−3.1	−3.2	−3.3	−3.3	−3.4
−30	–	–	–	–	–	–	−3.1	−3.0	−3.0	−2.9	−2.9	−3.0	−3.0	−3.1	−3.2	−3.3	−3.4	−3.5
−20	–	–	–	–	–	–	–	−2.9	−2.9	−2.9	−2.9	−2.9	−3.0	−3.1	−3.2	−3.3	−3.4	−3.5
−10	–	–	–	–	–	–	–	–	−2.9	−2.9	−2.9	−2.9	−3.0	−3.1	−3.2	−3.3	−3.4	−3.6
0	–	–	–	–	–	–	–	–	–	−2.9	−2.9	−3.0	−3.0	−3.1	−3.3	−3.4	−3.5	−3.6
10	–	–	–	–	–	–	–	–	–	–	−2.9	−3.0	−3.1	−3.2	−3.3	−3.5	−3.6	−3.7
20	–	–	–	–	–	–	–	–	–	–	–	−3.1	−3.2	−3.3	−3.4	−3.6	−3.7	−3.9
30	–	–	–	–	–	–	–	–	–	–	–	–	−3.3	−3.4	−3.6	−3.7	−3.9	−4.0
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.6	−3.7	−3.9	−4.0	−4.2
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.9	−4.0	−4.2	−4.3
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.2	−4.3	−4.5
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.5	−4.7
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.8

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.12

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−4.8	−4.6	−4.4	−4.2	−4.0	−3.8	−3.6	−3.4	−3.3	−3.2	−3.1	−3.1	−3.1	−3.1	−3.1	−3.2	−3.2	−3.3
−80	–	−4.4	−4.2	−4.0	−3.8	−3.6	−3.4	−3.3	−3.1	−3.0	−3.0	−2.9	−2.9	−3.0	−3.0	−3.1	−3.1	−3.2
−70	–	–	−4.0	−3.8	−3.6	−3.4	−3.2	−3.1	−3.0	−2.9	−2.8	−2.8	−2.8	−2.9	−2.9	−3.0	−3.1	−3.2
−60	–	–	–	−3.6	−3.4	−3.2	−3.1	−2.9	−2.8	−2.8	−2.7	−2.7	−2.7	−2.8	−2.8	−2.9	−3.0	−3.1
−50	–	–	–	–	−3.2	−3.1	−2.9	−2.8	−2.7	−2.6	−2.6	−2.6	−2.6	−2.7	−2.8	−2.9	−3.0	−3.1
−40	–	–	–	–	–	−2.9	−2.8	−2.7	−2.6	−2.5	−2.5	−2.5	−2.6	−2.6	−2.7	−2.8	−2.9	−3.1
−30	–	–	–	–	–	–	−2.6	−2.5	−2.5	−2.4	−2.4	−2.5	−2.5	−2.6	−2.7	−2.8	−2.9	−3.1
−20	–	–	–	–	–	–	–	−2.4	−2.4	−2.4	−2.4	−2.4	−2.5	−2.6	−2.7	−2.8	−3.0	−3.1
−10	–	–	–	–	–	–	–	–	−2.3	−2.3	−2.4	−2.4	−2.5	−2.6	−2.8	−2.9	−3.0	−3.2
0	–	–	–	–	–	–	–	–	–	−2.3	−2.4	−2.5	−2.6	−2.7	−2.8	−3.0	−3.1	−3.3
10	–	–	–	–	–	–	–	–	–	–	−2.4	−2.5	−2.7	−2.8	−2.9	−3.1	−3.3	−3.4
20	–	–	–	–	–	–	–	–	–	–	–	−2.6	−2.8	−2.9	−3.1	−3.2	−3.4	−3.6
30	–	–	–	–	–	–	–	–	–	–	–	–	−2.9	−3.1	−3.2	−3.4	−3.6	−3.8
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.2	−3.4	−3.6	−3.8	−4.0
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.6	−3.8	−4.0	−4.2
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.0	−4.2	−4.4
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.4	−4.6
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.8

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.14

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−4.8	−4.5	−4.3	−4.0	−3.8	−3.5	−3.3	−3.1	−2.9	−2.8	−2.7	−2.7	−2.6	−2.7	−2.7	−2.8	−2.8	−2.9
−80	–	−4.3	−4.1	−3.8	−3.6	−3.3	−3.1	−2.9	−2.7	−2.6	−2.5	−2.5	−2.5	−2.5	−2.6	−2.7	−2.7	−2.8
−70	–	–	−3.8	−3.6	−3.3	−3.1	−2.9	−2.7	−2.6	−2.5	−2.4	−2.4	−2.4	−2.4	−2.5	−2.6	−2.7	−2.8
−60	–	–	–	−3.3	−3.1	−2.9	−2.7	−2.5	−2.4	−2.3	−2.2	−2.2	−2.3	−2.3	−2.4	−2.5	−2.6	−2.7
−50	–	–	–	–	−2.9	−2.7	−2.5	−2.3	−2.2	−2.1	−2.1	−2.1	−2.1	−2.2	−2.3	−2.4	−2.5	−2.7
−40	–	–	–	–	–	−2.5	−2.3	−2.2	−2.1	−2.0	−2.0	−2.0	−2.1	−2.1	−2.3	−2.4	−2.5	−2.6
−30	–	–	–	–	–	–	−2.1	−2.0	−1.9	−1.9	−1.9	−1.9	−2.0	−2.1	−2.2	−2.4	−2.5	−2.7
−20	–	–	–	–	–	–	–	−1.9	−1.8	−1.8	−1.8	−1.9	−2.0	−2.1	−2.2	−2.4	−2.5	−2.7
−10	–	–	–	–	–	–	–	–	−1.8	−1.8	−1.8	−1.9	−2.0	−2.1	−2.3	−2.5	−2.6	−2.8
0	–	–	–	–	–	–	–	–	–	−1.8	−1.8	−1.9	−2.1	−2.2	−2.4	−2.6	−2.7	−2.9
10	–	–	–	–	–	–	–	–	–	–	−1.9	−2.0	−2.2	−2.3	−2.5	−2.7	−2.9	−3.1
20	–	–	–	–	–	–	–	–	–	–	–	−2.1	−2.3	−2.5	−2.7	−2.9	−3.1	−3.3
30	–	–	–	–	–	–	–	–	–	–	–	–	−2.5	−2.7	−2.9	−3.1	−3.3	−3.5
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−2.9	−3.1	−3.3	−3.6	−3.8
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.3	−3.6	−3.8	−4.0
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.8	−4.1	−4.3
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.3	−4.5
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.8

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.16

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−4.7	−4.5	−4.2	−3.9	−3.6	−3.3	−3.0	−2.7	−2.5	−2.4	−2.3	−2.2	−2.2	−2.2	−2.3	−2.3	−2.4	−2.5
−80	–	−4.2	−3.9	−3.6	−3.3	−3.0	−2.7	−2.5	−2.3	−2.2	−2.1	−2.0	−2.0	−2.1	−2.1	−2.2	−2.3	−2.4
−70	–	–	−3.6	−3.3	−3.0	−2.8	−2.5	−2.3	−2.1	−2.0	−1.9	−1.9	−1.9	−1.9	−2.0	−2.1	−2.2	−2.3
−60	–	–	–	−3.1	−2.8	−2.5	−2.3	−2.1	−1.9	−1.8	−1.7	−1.7	−1.7	−1.8	−1.9	−2.0	−2.1	−2.3
−50	–	–	–	–	−2.5	−2.3	−2.0	−1.8	−1.7	−1.6	−1.6	−1.6	−1.6	−1.7	−1.8	−1.9	−2.1	−2.2
−40	–	–	–	–	–	−2.0	−1.8	−1.6	−1.5	−1.4	−1.4	−1.4	−1.5	−1.6	−1.7	−1.9	−2.0	−2.2
−30	–	–	–	–	–	–	−1.6	−1.5	−1.3	−1.3	−1.3	−1.3	−1.4	−1.6	−1.7	−1.9	−2.0	−2.2
−20	–	–	–	–	–	–	–	−1.3	−1.2	−1.2	−1.2	−1.3	−1.4	−1.6	−1.7	−1.9	−2.1	−2.3
−10	–	–	–	–	–	–	–	–	−1.2	−1.2	−1.2	−1.3	−1.4	−1.6	−1.8	−2.0	−2.2	−2.4
0	–	–	–	–	–	–	–	–	–	−1.2	−1.2	−1.3	−1.5	−1.7	−1.9	−2.1	−2.3	−2.5
10	–	–	–	–	–	–	–	–	–	–	−1.3	−1.5	−1.6	−1.8	−2.1	−1.3	−2.5	−2.7
20	–	–	–	–	–	–	–	–	–	–	–	−1.6	−1.8	−2.0	−2.3	−2.5	−2.7	−3.0
30	–	–	–	–	–	–	–	–	–	–	–	–	−2.0	−2.3	−2.5	−2.8	−3.0	−3.3
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−2.5	−2.8	−3.0	−3.3	−3.6
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.1	−3.3	−3.6	−3.9
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.6	−3.9	−4.2
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.2	−4.5
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.7

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, $N_0 = -0.18$

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−4.7	−4.4	−4.0	−3.7	−3.3	−3.0	−2.6	−2.3	−2.1	−1.9	−1.8	−1.7	−1.7	−1.7	−1.8	−1.9	−2.0	−2.1
−80	–	−4.1	−3.7	−3.4	−3.0	−2.7	−2.4	−2.1	−1.8	−1.7	−1.6	−1.5	−1.5	−1.5	−1.6	−1.7	−1.8	−2.0
−70	–	–	−3.4	−3.1	−2.7	−2.4	−2.1	−1.8	−1.6	−1.4	−1.3	−1.3	−1.3	−1.4	−1.5	−1.6	−1.7	−1.9
−60	–	–	–	−2.8	−2.4	−2.1	−1.8	−1.6	−1.4	−1.2	−1.1	−1.1	−1.2	−1.2	−1.4	−1.5	−1.6	−1.8
−50	–	–	–	–	−2.1	−1.8	−1.5	−1.3	−1.1	−1.0	−1.0	−1.0	−1.0	−1.1	−1.2	−1.4	−1.5	−1.7
−40	–	–	–	–	–	−1.5	−1.3	−1.1	−0.9	−0.8	−0.8	−0.8	−0.9	−1.0	−1.2	−1.3	−1.5	−1.7
−30	–	–	–	–	–	–	−1.0	−0.8	−0.7	−0.6	−0.7	−0.7	−0.8	−1.0	−1.1	−1.3	−1.5	−1.7
−20	–	–	–	–	–	–	–	−0.7	−0.6	−0.5	−0.6	−0.7	−0.8	−1.0	−1.1	−1.3	−1.6	−1.8
−10	–	–	–	–	–	–	–	–	−0.5	−0.5	−0.5	−0.6	−0.8	−1.0	−1.2	−1.4	−1.7	−1.9
0	–	–	–	–	–	–	–	–	–	−0.5	−0.6	−0.7	−0.9	−1.1	−1.4	−1.6	−1.8	−2.1
10	–	–	–	–	–	–	–	–	–	–	−0.7	−0.8	−1.1	−1.3	−1.6	−1.8	−2.1	−2.3
20	–	–	–	–	–	–	–	–	–	–	–	−1.0	−1.3	−1.5	−1.8	−2.1	−2.4	−2.6
30	–	–	–	–	–	–	–	–	–	–	–	–	−1.5	−1.8	−2.1	−2.4	−2.7	−3.0
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−2.1	−2.4	−2.7	−3.0	−3.3
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−2.8	−3.1	−3.4	−3.7
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.4	−3.7	−4.0
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.1	−4.4
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.7

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.20

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−4.7	−4.3	−3.9	−3.5	−3.1	−2.7	−2.3	−1.9	−1.6	−1.4	−1.3	−1.2	−1.2	−1.2	−1.3	−1.4	−1.5	−1.4
−80	–	−4.0	−3.6	−3.2	−2.8	−2.3	−2.0	−1.6	−1.4	−1.2	−1.1	−1.0	−1.0	−1.1	−1.1	−1.3	−1.4	−1.5
−70	–	–	−3.2	−2.8	−2.4	−2.	−1.6	−1.3	−1.1	−1.0	−0.8	−0.8	−0.8	−0.9	−1.0	−1.1	−1.3	−1.4
−60	–	–	–	−2.5	−2.1	−1.7	−1.3	−1.0	−0.8	−0.7	−0.6	−0.6	−0.6	−0.7	−0.8	−1.0	−1.1	−1.3
−50	–	–	–	–	−1.7	−1.3	−1.0	−0.7	−0.6	−0.5	−0.4	−0.4	−0.5	−0.6	−0.7	−0.9	−1.1	−1.2
−40	–	–	–	–	–	−1.0	−0.7	−0.5	−0.3	−0.3	−0.2	−0.2	−0.3	−0.5	−0.6	−0.8	−1.0	−1.2
−30	–	–	–	–	–	–	−0.4	−0.2	−0.1	−0.1	−0.1	−0.1	−0.2	−0.4	−0.6	−0.8	−1.0	−1.2
−20	–	–	–	–	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.1	−0.2	−0.4	−0.6	−0.8	−1.1	−1.3
−10	–	–	–	–	–	–	–	–	0.0	0.0	−0.0	−0.1	−0.3	−0.5	−0.7	−1.0	−1.2	−1.4
0	–	–	–	–	–	–	–	–	–	0.0	−0.0	−0.1	−0.3	−0.6	−0.8	−1.1	−1.4	−1.4
10	–	–	–	–	–	–	–	–	–	–	−0.0	−0.2	−0.5	−0.7	−1.0	−1.3	−1.6	−1.9
20	–	–	–	–	–	–	–	–	–	–	–	−0.4	−0.7	−1.0	−1.3	−1.6	−2.0	−2.3
30	–	–	–	–	–	–	–	–	–	–	–	–	−1.0	−1.3	−1.7	−2.0	−2.3	−2.7
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−1.7	−2.1	−2.4	−2.8	−3.1
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−2.5	−2.8	−3.2	−3.5
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.2	−3.6	−3.9
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.0	−4.3
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.7

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.30

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^z	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−4.5	−3.9	−3.2	−2.4	−1.8	−1.5	−1.2	−1.0	−0.9	−0.8	−0.7	−0.7	−0.6	−0.6	−0.6	−0.7	−0.8	−0.9
−80	–	−3.4	−2.7	−1.9	−1.4	−1.0	−0.9	−0.7	−0.6	−0.6	−0.5	−0.4	−0.4	−0.4	−0.4	−0.5	−0.6	−0.8
−70	–	–	−1.2	−1.3	−0.8	−0.6	−0.5	−0.4	−0.3	−0.3	−0.3	−0.2	−0.2	−0.2	−0.2	−0.3	−0.5	−0.7
−60	–	–	–	−0.7	−0.3	−0.2	−0.2	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.2	−0.4	−0.6
−50	–	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.2	−0.4	−0.6
−40	–	–	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	0.0	0.0	0.0	0.0	−0.1	−0.2	−0.4	−0.6
−30	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.2	−0.4	−0.7
−20	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3	−0.5	−0.7
−10	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3	−0.6	−0.8
0	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3	−0.6	−0.9
10	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	−0.1	−0.4	−0.7	−1.0
20	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	−0.2	−0.5	−0.9	−1.2
30	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	−0.2	−0.6	−1.0	−1.5
40	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	−0.3	−0.8	−1.4	−1.8
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−0.7	−1.3	−1.9	−2.4
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−2.1	−2.7	−3.2
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.4	−3.9
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.5

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.40

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−4.3	−3.4	−2.4	−1.6	−1.3	−1.0	−0.9	−0.7	−0.7	−0.6	−0.5	−0.5	−0.4	−0.4	−0.4	−0.4	−0.5	−0.7
−80	–	−2.7	−1.6	−1.0	−0.7	−0.6	−0.5	−0.4	−0.4	−0.3	−0.3	−0.3	−0.2	−0.2	−0.2	−0.2	−0.4	−0.5
−70	–	–	−0.8	−0.4	−0.2	−0.2	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.2	−0.4
−60	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.1	−0.2	−0.4
−50	–	–	–	–	−0.0	−0.0	−0.0	−0.0	0.0	−0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.2	−0.4
−40	–	–	–	–	–	−0.0	−0.0	−0.0	−0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.2	−0.4
−30	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3	−0.5
−20	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3	−0.5
−10	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3	−0.6
0	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.4	−0.7
10	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	−0.1	−0.4	−0.7
20	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	−0.1	−0.5	−0.9
30	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	−0.2	−0.6	−1.0
40	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	−0.2	−0.7	−1.3
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	−0.4	−1.0	−1.6
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−0.8	−1.6	−2.4
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−2.7	−3.4
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−4.3

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = –0.50

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	–80	–70	–60	–50	–40	–30	–20	–10	0	10	20	30	40	50	60	70	80	90
–90	–4.1	–2.9	–1.8	–1.2	–1.0	–0.8	–0.7	–0.6	–0.5	–0.5	–0.4	–0.4	–0.3	–0.3	–0.3	–0.3	–0.4	–0.5
–80	–	–2.0	–0.9	–0.6	–0.4	–0.3	–0.3	–0.2	–0.2	–0.2	–0.2	–0.2	–0.1	–0.1	–0.1	–0.1	–0.2	–0.4
–70	–	–	–0.1	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.1	–0.3
–60	–	–	–	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.1	–0.3
–50	–	–	–	–	–0.0	–0.0	–0.0	–0.0	–0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.0	–0.1	–0.3
–40	–	–	–	–	–	–0.0	–0.0	–0.0	–0.0	–0.0	0.0	0.0	0.0	0.0	0.0	–0.0	–0.1	–0.3
–30	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.0	–0.2	–0.4
–20	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.0	–0.2	–0.4
–10	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.0	–0.2	–0.5
0	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	–0.0	–0.2	–0.5
10	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	–0.0	–0.2	–0.6
20	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	–0.0	–0.3	–0.7
30	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	–0.0	–0.3	–0.8
40	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	–0.0	–0.4	–1.0
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	–0.0	–0.6	–1.2
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–0.1	–0.9	–1.8
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–2.0	–2.9
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–4.1

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.60

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−3.9	−2.3	−1.4	−1.0	−0.8	−0.6	−0.5	−0.5	−0.4	−0.4	−0.3	−0.3	−0.3	−0.3	−0.2	−0.2	−0.3	−0.4
−80	–	−1.2	−0.5	−0.4	−0.3	−0.2	−0.2	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.3
−70	–	–	0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.1	−0.2
−60	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.1	−0.2
−50	–	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3
−40	–	–	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3
−30	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3
−20	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3
−10	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.4
0	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.4
10	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.5
20	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	−0.2	−0.5
30	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	−0.2	−0.6
40	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	−0.3	−0.8
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	−0.3	−0.8
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	−0.5	−1.4
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−1.2	−2.3
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.9

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, $N_0 = -0.70$

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−3.7	−1.9	−1.2	−0.8	−0.7	−0.5	−0.5	−0.4	−0.4	−0.3	−0.3	−0.3	−0.2	−0.2	−0.2	−0.2	−0.2	−0.4
−80	–	−0.6	−0.3	−0.2	−0.2	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.0	−0.0	−0.0	−0.0	−0.1	−0.2
−70	–	–	0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.2
−60	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.2
−50	–	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.2
−40	–	–	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.2
−30	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3
−20	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3
−10	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.3
0	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.4
10	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	−0.4
20	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	−0.1	−0.5
30	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	−0.1	−0.5
40	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	−0.2	−0.7
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	−0.2	−0.8
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	−0.3	−1.2
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−0.6	−1.9
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.7

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −0.80

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−3.4	−1.6	−1.0	−0.7	−0.6	−0.5	−0.4	−0.3	−0.3	−0.3	−0.3	−0.2	−0.2	−0.2	−0.2	−0.2	−0.2	−0.3
−80	–	−0.3	−0.2	−0.1	−0.1	−0.1	−0.1	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.2
−70	–	–	0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.2
−60	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.2
−50	–	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.2
−40	–	–	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.2
−30	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.2
−20	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.3
−10	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.3
0	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.3
10	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.3
20	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	−0.1	−0.4
30	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	−0.1	−0.5
40	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	−0.1	−0.6
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	−0.1	−0.7
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	−0.2	−1.0
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−0.3	−1.6
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−3.4

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = –0.90

LEFTMOST BARRIER ANGLE, ϕ_L^o \ RIGHTMOST BARRIER ANGLE, ϕ_R^o	–80	–70	–60	–50	–40	–30	–20	–10	0	10	20	30	40	50	60	70	80	90
–90	–3.2	–1.4	–0.9	–0.6	–0.5	–0.4	–0.4	–0.3	–0.3	–0.2	–0.2	–0.2	–0.2	–0.2	–0.2	–0.2	–0.2	–0.3
–80	–	–0.1	–0.1	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.2
–70	–	–	0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.2
–60	–	–	–	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.0	–0.2
–50	–	–	–	–	–0.0	–0.0	–0.0	–0.0	–0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.0	–0.2
–40	–	–	–	–	–	–0.0	–0.0	–0.0	–0.0	–0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.0	–0.2
–30	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.0	–0.2
–20	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.0	–0.2
–10	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.0	–0.2
0	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–0.0	–0.3
10	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	–0.0	–0.3
20	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	–0.0	–0.4
30	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	–0.0	–0.4
40	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	–0.0	–0.5
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	–0.0	–0.6
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	–0.1	–0.9
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–0.1	–1.4
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–3.2

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −1.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−2.9	−1.2	−0.8	−0.6	−0.4	−0.4	−0.3	−0.3	−0.2	−0.2	−0.2	−0.2	−0.2	−0.2	−0.1	−0.1	−0.1	−0.2
−80	–	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.1
−70	–	–	0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.1
−60	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.1
−50	–	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.2
−40	–	–	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.2
−30	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.2
−20	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.2
−10	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.2
0	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.2
10	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	−0.0	−0.3
20	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	−0.0	−0.3
30	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	−0.0	−0.4
40	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	−0.0	−0.4
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	−0.0	−0.6
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	−0.0	−0.8
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−0.0	−1.2
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−2.9

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = −2.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−1.2	−0.6	−0.4	−0.3	−0.2	−0.2	−0.2	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1
−80	–	0.0	0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.1
−70	–	–	0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.1
−60	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.1
−50	–	–	–	−0.0	−0.0	−0.0	−0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1
−40	–	–	–	–	–	−0.0	−0.0	−0.0	−0.0	−0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1
−30	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1
−20	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1
−10	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1
0	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1
10	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1
20	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	0.0	−0.1
30	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	0.0	−0.2
40	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	0.0	−0.2
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	0.0	−0.3
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	0.0	−0.4
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.0	−0.6
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−1.2

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.01

LEFTMOST BARRIER ANGLE, ϕ_L^o \ RIGHTMOST BARRIER ANGLE, ϕ_R^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.0	−5.0	−5.0	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1
−80	–	−5.0	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1
−70	–	–	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1
−60	–	–	–	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1	−5.2	−5.2	−5.2	−5.2	−5.2	−5.1	−5.1	−5.1	−5.1
−50	–	–	–	–	−5.1	−5.1	−5.1	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.1	−5.1	−5.1
−40	–	–	–	–	–	−5.1	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.1	−5.1	−5.1
−30	–	–	–	–	–	–	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.1	−5.1	−5.1
−20	–	–	–	–	–	–	–	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.1	−5.1	−5.1
−10	–	–	–	–	–	–	–	–	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.2	−5.1	−5.1	−5.1
0	–	–	–	–	–	–	–	–	–	−5.2	−5.2	−5.2	−5.2	−5.2	−5.1	−5.1	−5.1	−5.1
10	–	–	–	–	–	–	–	–	–	–	−5.2	−5.2	−5.2	−5.2	−5.1	−5.1	−5.1	−5.1
20	–	–	–	–	–	–	–	–	–	–	–	−5.2	−5.2	−5.1	−5.1	−5.1	−5.1	−5.1
30	–	–	–	–	–	–	–	–	–	–	–	–	−5.1	−5.1	−5.1	−5.1	−5.1	−5.1
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.1	−5.1	−5.1	−5.1	−5.1
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.1	−5.1	−5.1	−5.1
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.1	−5.1	−5.0
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.1	−5.0
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.0

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.02

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	–80	–70	–60	–50	–40	–30	–20	–10	0	10	20	30	40	50	60	70	80	90
–90	–5.0	–5.1	–5.1	–5.1	–5.1	–5.2	–5.2	–5.2	–5.2	–5.2	–5.2	–5.3	–5.3	–5.3	–5.3	–5.2	–5.2	–5.2
–80	–	–5.1	–5.1	–5.1	–5.2	–5.2	–5.2	–5.2	–5.2	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.2	–5.2
–70	–	–	–5.2	–5.2	–5.2	–5.2	–5.2	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.2
–60	–	–	–	–5.2	–5.2	–5.2	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3
–50	–	–	–	–	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3
–40	–	–	–	–	–	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3
–30	–	–	–	–	–	–	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3
–20	–	–	–	–	–	–	–	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.2
–10	–	–	–	–	–	–	–	–	–5.4	–5.4	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.2
0	–	–	–	–	–	–	–	–	–	–5.4	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.2	–5.2
10	–	–	–	–	–	–	–	–	–	–	–5.3	–5.3	–5.3	–5.3	–5.3	–5.3	–5.2	–5.2
20	–	–	–	–	–	–	–	–	–	–	–	–5.3	–5.3	–5.3	–5.3	–5.2	–5.2	–5.2
30	–	–	–	–	–	–	–	–	–	–	–	–	–5.3	–5.3	–5.2	–5.2	–5.2	–5.2
40	–	–	–	–	–	–	–	–	–	–	–	–	–	–5.3	–5.2	–5.2	–5.2	–5.1
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–5.2	–5.2	–5.1	–5.1
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–5.2	–5.1	–5.1
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–5.1	–5.1
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–5.0

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.03

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	–80	–70	–60	–50	–40	–30	–20	–10	0	10	20	30	40	50	60	70	80	90
–90	–5.0	–5.1	–5.1	–5.2	–5.2	–5.3	–5.3	–5.3	–5.3	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4	–5.3
–80	–	–5.1	–5.2	–5.2	–5.3	–5.3	–5.3	–5.3	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4
–70	–	–	–5.2	–5.3	–5.3	–5.3	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4	–5.4
–60	–	–	–	–5.3	–5.3	–5.4	–5.4	–5.4	–5.4	–5.4	–5.5	–5.5	–5.5	–5.4	–5.4	–5.4	–5.4	–5.4
–50	–	–	–	–	–5.4	–5.4	–5.4	–5.4	–5.5	–5.5	–5.5	–5.5	–5.5	–5.5	–5.4	–5.4	–5.4	–5.4
–40	–	–	–	–	–	–5.4	–5.5	–5.5	–5.5	–5.5	–5.5	–5.5	–5.5	–5.5	–5.5	–5.4	–5.4	–5.4
–30	–	–	–	–	–	–	–5.5	–5.5	–5.5	–5.5	–5.5	–5.5	–5.5	–5.5	–5.5	–5.4	–5.4	–5.4
–20	–	–	–	–	–	–	–	–5.5	–5.5	–5.5	–5.5	–5.5	–5.5	–5.5	–5.5	–5.4	–5.4	–5.4
–10	–	–	–	–	–	–	–	–	–5.5	–5.5	–5.5	–5.5	–5.5	–5.5	–5.4	–5.4	–5.4	–5.4
0	–	–	–	–	–	–	–	–	–	–5.5	–5.5	–5.5	–5.5	–5.5	–5.4	–5.4	–5.4	–5.3
10	–	–	–	–	–	–	–	–	–	–	–5.5	–5.5	–5.5	–5.4	–5.4	–5.4	–5.3	–5.3
20	–	–	–	–	–	–	–	–	–	–	–	–5.5	–5.5	–5.4	–5.4	–5.4	–5.3	–5.3
30	–	–	–	–	–	–	–	–	–	–	–	–	–5.4	–5.4	–5.4	–5.3	–5.3	–5.3
40	–	–	–	–	–	–	–	–	–	–	–	–	–	–5.4	–5.3	–5.3	–5.3	–5.2
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–5.3	–5.3	–5.2	–5.2
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–5.2	–5.2	–5.1
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–5.1	–5.1
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–5.0

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.04

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.1	−5.1	−5.2	−5.2	−5.3	−5.3	−5.4	−5.4	−5.4	−5.5	−5.5	−5.5	−5.5	−5.5	−5.5	−5.5	−5.5	−5.4
−80	–	−5.2	−5.2	−5.3	−5.3	−5.4	−5.4	−5.5	−5.5	−5.5	−5.5	−5.5	−5.5	−5.5	−5.5	−5.5	−5.5	−5.5
−70	–	–	−5.3	−5.4	−5.4	−5.4	−5.5	−5.5	−5.5	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.5	−5.5	−5.5
−60	–	–	–	−5.4	−5.4	−5.5	−5.5	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.5	−5.5
−50	–	–	–	–	−5.5	−5.5	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.5	−5.5
−40	–	–	–	–	–	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.5	−5.5
−30	–	–	–	–	–	–	−5.6	−5.6	−5.7	−5.7	−5.7	−5.7	−5.6	−5.6	−5.6	−5.6	−5.5	−5.5
−20	–	–	–	–	–	–	–	−5.7	−5.7	−5.7	−5.7	−5.7	−5.6	−5.6	−5.6	−5.6	−5.5	−5.5
−10	–	–	–	–	–	–	–	–	−5.7	−5.7	−5.7	−5.7	−5.6	−5.6	−5.6	−5.6	−5.5	−5.5
0	–	–	–	–	–	–	–	–	–	−5.7	−5.7	−5.7	−5.6	−5.6	−5.6	−5.5	−5.5	−5.4
10	–	–	–	–	–	–	–	–	–	–	−5.7	−5.6	−5.6	−5.6	−5.6	−5.5	−5.5	−5.4
20	–	–	–	–	–	–	–	–	–	–	–	−5.6	−5.6	−5.6	−5.5	−5.5	−5.4	−5.4
30	–	–	–	–	–	–	–	–	–	–	–	–	−5.6	−5.5	−5.5	−5.4	−5.4	−5.3
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.5	−5.4	−5.4	−5.3	−5.3
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.4	−5.4	−5.3	−5.2
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.3	−5.2	−5.2
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.2	−5.1
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.1

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_o = 0.05

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.1	−5.2	−5.2	−5.3	−5.4	−5.4	−5.5	−5.5	−5.5	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.6	−5.5
−80	–	−5.2	−5.3	−5.4	−5.4	−5.5	−5.5	−5.6	−5.6	−5.6	−5.6	−5.7	−5.7	−5.7	−5.6	−5.6	−5.6	−5.6
−70	–	–	−5.4	−5.4	−5.5	−5.5	−5.6	−5.6	−5.7	−5.7	−5.7	−5.7	−5.7	−5.7	−5.7	−5.7	−5.6	−5.6
−60	–	–	–	−5.5	−5.6	−5.6	−5.6	−5.7	−5.7	−5.7	−5.7	−5.7	−5.7	−5.7	−5.7	−5.7	−5.6	−5.6
−50	–	–	–	–	−5.6	−5.7	−5.7	−5.7	−5.7	−5.8	−5.8	−5.8	−5.8	−5.7	−5.7	−5.7	−5.7	−5.6
−40	–	–	–	–	–	−5.7	−5.7	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.7	−5.7	−5.7	−5.6
−30	–	–	–	–	–	–	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.7	−5.7	−5.7	−5.6
−20	–	–	–	–	–	–	–	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.7	−5.7	−5.6	−5.6
−10	–	–	–	–	–	–	–	–	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.7	−5.7	−5.6	−5.6
0	–	–	–	–	–	–	–	–	–	−5.8	−5.8	−5.8	−5.8	−5.7	−5.7	−5.7	−5.6	−5.5
10	–	–	–	–	–	–	–	–	–	–	−5.8	−5.8	−5.8	−5.7	−5.7	−5.6	−5.6	−5.5
20	–	–	–	–	–	–	–	–	–	–	–	−5.8	−5.7	−5.7	−5.6	−5.6	−5.5	−5.5
30	–	–	–	–	–	–	–	–	–	–	–	–	−5.7	−5.7	−5.6	−5.5	−5.5	−5.4
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.6	−5.6	−5.5	−5.4	−5.4
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.5	−5.4	−5.4	−5.3
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.4	−5.3	−5.2
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.2	−5.2
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.1

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.06

LEFTMOST BARRIER ANGLE, ϕ_L^o \ RIGHTMOST BARRIER ANGLE, ϕ_R^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.1	−5.2	−5.3	−5.3	−5.4	−5.5	−5.5	−5.6	−5.6	−5.7	−5.7	−5.7	−5.7	−5.7	−5.7	−5.7	−5.7	−5.6
−80	–	−5.3	−5.4	−5.4	−5.5	−5.6	−5.6	−5.7	−5.7	−5.7	−5.8	−5.8	−5.8	−5.8	−5.8	−5.7	−5.7	−5.7
−70	–	–	−5.4	−5.5	−5.6	−5.7	−5.7	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.7	−5.7
−60	–	–	–	−5.6	−5.7	−5.7	−5.8	−5.8	−5.8	−5.9	−5.9	−5.9	−5.9	−5.9	−5.8	−5.8	−5.8	−5.7
−50	–	–	–	–	−5.7	−5.8	−5.8	−5.9	−5.9	−5.9	−5.9	−5.9	−5.9	−5.9	−5.9	−5.8	−5.8	−5.7
−40	–	–	–	–	–	−5.8	−5.9	−5.9	−5.9	−5.9	−5.9	−5.9	−5.9	−5.9	−5.9	−5.8	−5.8	−5.7
−30	–	–	–	–	–	–	−5.9	−5.9	−6.0	−6.0	−6.0	−6.0	−5.9	−5.9	−5.9	−5.8	−5.8	−5.7
−20	–	–	–	–	–	–	–	−6.0	−6.0	−6.0	−6.0	−6.0	−5.9	−5.9	−5.9	−5.8	−5.8	−5.7
−10	–	–	–	–	–	–	–	–	−6.0	−6.0	−6.0	−6.0	−5.9	−5.9	−5.9	−5.8	−5.7	−5.7
0	–	–	–	–	–	–	–	–	–	−6.0	−6.0	−6.0	−5.9	−5.9	−5.8	−5.8	−5.7	−5.6
10	–	–	–	–	–	–	–	–	–	–	−6.0	−5.9	−5.9	−5.9	−5.8	−5.7	−5.7	−5.6
20	–	–	–	–	–	–	–	–	–	–	–	−5.9	−5.9	−5.8	−5.8	−5.7	−5.6	−5.5
30	–	–	–	–	–	–	–	–	–	–	–	–	−5.8	−5.8	−5.7	−5.6	−5.6	−5.5
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.7	−5.7	−5.6	−5.5	−5.4
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.6	−5.5	−5.4	−5.3
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.4	−5.4	−5.3
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.3	−5.2
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.1

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.07

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.1	−5.2	−5.3	−5.4	−5.5	−5.6	−5.6	−5.7	−5.7	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.8	−5.7
−80	–	−5.3	−5.4	−5.5	−5.6	−5.7	−5.7	−5.8	−5.8	−5.9	−5.9	−5.9	−5.9	−5.9	−5.9	−5.9	−5.8	−5.8
−70	–	–	−5.5	−5.6	−5.7	−5.7	−5.8	−5.9	−5.9	−5.9	−6.0	−6.0	−6.0	−6.0	−5.9	−5.9	−5.9	−5.8
−60	–	–	–	−5.7	−5.8	−5.8	−5.9	−5.9	−6.0	−6.0	−6.0	−6.0	−6.0	−6.0	−6.0	−5.9	−5.9	−5.8
−50	–	–	–	–	−5.8	−5.9	−6.0	−6.0	−6.0	−6.0	−6.1	−6.1	−6.0	−6.0	−6.0	−6.0	−5.9	−5.8
−40	–	–	–	–	–	−6.0	−6.0	−6.0	−6.1	−6.1	−6.1	−6.1	−6.1	−6.0	−6.0	−6.0	−5.9	−5.8
−30	–	–	–	–	–	–	−6.1	−6.1	−6.1	−6.1	−6.1	−6.1	−6.1	−6.1	−6.0	−6.0	−5.9	−5.8
−20	–	–	–	–	–	–	–	−6.1	−6.1	−6.1	−6.1	−6.1	−6.1	−6.1	−6.0	−6.0	−5.9	−5.8
−10	–	–	–	–	–	–	–	–	−6.2	−6.2	−6.1	−6.1	−6.1	−6.0	−6.0	−5.9	−5.9	−5.8
0	–	–	–	–	–	–	–	–	–	−6.2	−6.1	−6.1	−6.1	−6.0	−6.0	−5.9	−5.8	−5.7
10	–	–	–	–	–	–	–	–	–	–	−6.1	−6.1	−6.0	−6.0	−5.9	−5.9	−5.8	−5.7
20	–	–	–	–	–	–	–	–	–	–	–	−6.1	−6.0	−6.0	−5.9	−5.8	−5.7	−5.6
30	–	–	–	–	–	–	–	–	–	–	–	–	−6.0	−5.9	−5.8	−5.7	−5.7	−5.6
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.8	−5.8	−5.7	−5.6	−5.5
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.7	−5.6	−5.5	−5.4
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.5	−5.4	−5.3
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.3	−5.2
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.1

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER $N_0 = 0.08$

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.1	−5.2	−5.4	−5.5	−5.6	−5.6	−5.7	−5.8	−5.8	−5.9	−5.9	−5.9	−5.9	−5.9	−5.9	−5.9	−5.9	−5.8
−80	–	−5.4	−5.5	−5.6	−5.7	−5.7	−5.8	−5.9	−5.9	−6.0	−6.0	−6.0	−6.0	−6.0	−6.0	−6.0	−5.9	−5.9
−70	–	–	−5.6	−5.7	−5.8	−5.8	−5.9	−6.0	−6.0	−6.1	−6.1	−6.1	−6.1	−6.1	−6.1	−6.0	−6.0	−5.9
−60	–	–	–	−5.8	−5.9	−5.9	−6.0	−6.1	−6.1	−6.1	−6.1	−6.1	−6.1	−6.1	−6.1	−6.1	−6.0	−5.9
−50	–	–	–	–	−5.9	−6.0	−6.1	−6.1	−6.2	−6.2	−6.2	−6.2	−6.2	−6.2	−6.1	−6.1	−6.0	−5.9
−40	–	–	–	–	–	−6.1	−6.1	−6.2	−6.2	−6.2	−6.2	−6.2	−6.2	−6.2	−6.1	−6.1	−6.0	−5.9
−30	–	–	–	–	–	–	−6.2	−6.2	−6.3	−6.3	−6.3	−6.3	−6.2	−6.2	−6.1	−6.1	−6.0	−5.9
−20	–	–	–	–	–	–	–	−6.3	−6.3	−6.3	−6.3	−6.3	−6.2	−6.2	−6.1	−6.1	−6.0	−5.9
−10	–	–	–	–	–	–	–	–	−6.3	−6.3	−6.3	−6.3	−6.2	−6.2	−6.1	−6.1	−6.0	−5.9
0	–	–	–	–	–	–	–	–	–	−6.3	−6.3	−6.3	−6.2	−6.2	−6.1	−6.0	−5.9	−5.8
10	–	–	–	–	–	–	–	–	–	–	−6.3	−6.2	−6.2	−6.1	−6.1	−6.0	−5.9	−5.8
20	–	–	–	–	–	–	–	–	–	–	–	−6.2	−6.1	−6.1	−6.0	−5.9	−5.8	−5.7
30	–	–	–	–	–	–	–	–	–	–	–	–	−6.1	−6.0	−5.9	−5.8	−5.7	−5.6
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.9	−5.9	−5.8	−5.7	−5.6
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.8	−5.7	−5.6	−5.5
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.6	−5.5	−5.4
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.4	−5.2
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.1

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.09

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.1	−5.3	−5.4	−5.5	−5.6	−5.7	−5.8	−5.9	−5.9	−6.0	−6.0	−6.0	−6.0	−6.1	−6.0	−6.0	−6.0	−5.9
−80	–	−5.4	−5.5	−5.6	−5.7	−5.8	−5.9	−6.0	−6.0	−6.1	−6.1	−6.1	−6.1	−6.1	−6.1	−6.1	−6.0	−6.0
−70	–	–	−5.7	−5.8	−5.9	−5.9	−6.0	−6.1	−6.1	−6.2	−6.2	−6.2	−6.2	−6.2	−6.2	−6.1	−6.1	−6.0
−60	–	–	–	−5.9	−6.0	−6.0	−6.1	−6.2	−6.2	−6.2	−6.3	−6.3	−6.3	−6.2	−6.2	−6.2	−6.1	−6.0
−50	–	–	–	–	−6.1	−6.1	−6.2	−6.2	−6.3	−6.3	−6.3	−6.3	−6.3	−6.3	−6.2	−6.2	−6.1	−6.1
−40	–	–	–	–	–	6.2	−6.3	−6.3	−6.3	−6.4	−6.4	−6.4	−6.3	−6.3	−6.3	−6.2	−6.1	−6.0
−30	–	–	–	–	–	–	−6.3	−6.4	−6.4	−6.4	−6.4	−6.4	−6.4	−6.3	−6.3	−6.2	−6.1	−6.0
−20	–	–	–	–	–	–	–	−6.4	−6.4	−6.4	−6.4	−6.4	−6.4	−6.3	−6.3	−6.2	−6.1	−6.0
−10	–	–	–	–	–	–	–	–	−6.4	−6.4	−6.4	−6.4	−6.4	−6.3	−6.2	−6.2	−6.1	−6.0
0	–	–	–	–	–	–	–	–	–	−6.4	−6.4	−6.4	−6.3	−6.3	−6.2	−6.1	−6.0	−5.9
10	–	–	–	–	–	–	–	–	–	–	−6.4	−6.4	−6.3	−6.2	−6.2	−6.1	−6.0	−5.9
20	–	–	–	–	–	–	–	–	–	–	–	−6.3	−6.3	−6.2	−6.1	−6.0	−5.9	−5.8
30	–	–	–	–	–	–	–	–	–	–	–	–	−6.2	−6.1	−6.0	−5.9	−5.8	−5.7
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−6.1	−6.0	−5.9	−5.7	−5.6
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.9	−5.8	−5.6	−5.5
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.7	−5.5	−5.4
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.4	−5.3
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.1

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.10

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.2	−5.3	−5.4	−5.6	−5.7	−5.8	−5.9	−5.9	−6.0	−6.1	−6.1	−6.1	−6.2	−6.2	−6.1	−6.1	−6.1	−6.0
−80	–	−5.5	−5.6	−5.7	−5.8	−5.9	−6.0	−6.1	−6.1	−6.2	−6.2	−6.2	−6.2	−6.2	−6.2	−6.2	−6.1	−6.1
−70	–	–	−5.7	−5.8	−5.9	−6.0	−6.1	−6.2	−6.2	−6.3	−6.3	−6.3	−6.3	−6.3	−6.3	−6.2	−6.2	−6.1
−60	–	–	–	−6.0	−6.1	−6.2	−6.2	−6.3	−6.3	−6.4	−6.4	−6.4	−6.4	−6.4	−6.3	−6.3	−6.2	−6.1
−50	–	–	–	–	−6.2	−6.2	−6.3	−6.4	−6.4	−6.4	−6.5	−6.5	−6.4	−6.4	−6.4	−6.3	−6.2	−6.2
−40	–	–	–	–	–	−6.3	−6.4	−6.4	−6.5	−6.5	−6.5	−6.5	−6.5	−6.4	−6.4	−6.3	−6.2	−6.2
−30	–	–	–	–	–	–	−6.5	−6.5	−6.5	−6.5	−6.5	−6.5	−6.5	−6.5	−6.4	−6.3	−6.2	−6.1
−20	–	–	–	–	–	–	–	−6.5	−6.6	−6.6	−6.6	−6.5	−6.5	−6.5	−6.4	−6.3	−6.2	−6.1
−10	–	–	–	–	–	–	–	–	−6.6	−6.6	−6.6	−6.5	−6.5	−6.4	−6.4	−6.3	−6.2	−6.1
0	–	–	–	–	–	–	–	–	–	−6.6	−6.6	−6.5	−6.5	−6.4	−6.3	−6.2	−6.1	−6.0
10	–	–	–	–	–	–	–	–	–	–	−6.5	−6.5	−6.4	−6.4	−6.3	−6.2	−6.1	−5.9
20	–	–	–	–	–	–	–	–	–	–	–	−6.5	−6.4	−6.3	−6.2	−6.1	−6.0	−5.9
30	–	–	–	–	–	–	–	–	–	–	–	–	−6.3	−6.2	−6.2	−6.0	−5.9	−5.8
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−6.2	−6.1	−5.9	−5.8	−5.7
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−6.0	−5.8	−5.7	−5.6
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.7	−5.6	−5.4
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.5	−5.3
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.2

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.20

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.3	−5.6	−5.8	−6.0	−6.2	−6.4	−6.6	−6.7	−6.8	−6.9	−7.0	−7.0	−7.1	−7.1	−7.0	−7.0	−6.9	−6.8
−80	–	−5.9	−6.1	−6.3	−6.5	−6.7	−6.8	−6.9	−7.0	−7.1	−7.2	−7.2	−7.2	−7.2	−7.2	−7.1	−7.0	−6.9
−70	–	–	−6.4	−6.6	−6.8	−6.9	−7.0	−7.2	−7.2	−7.3	−7.4	−7.4	−7.4	−7.4	−7.3	−7.2	−7.1	−7.0
−60	–	–	–	−6.8	−7.0	−7.1	−7.2	−7.3	−7.4	−7.5	−7.5	−7.5	−7.5	−7.5	−7.4	−7.3	−7.2	−7.0
−50	–	–	–	–	−7.1	−7.3	−7.4	−7.5	−7.5	−7.6	−7.6	−7.6	−7.6	−7.5	−7.5	−7.4	−7.2	−7.1
−40	–	–	–	–	–	−7.4	−7.5	−7.6	−7.7	−7.7	−7.7	−7.7	−7.7	−7.6	−7.5	−7.4	−7.2	−7.1
−30	–	–	–	–	–	–	−7.6	−7.7	−7.7	−7.8	−7.8	−7.7	−7.7	−7.6	−7.5	−7.4	−7.2	−7.0
−20	–	–	–	–	–	–	–	−7.8	−7.8	−7.8	−7.8	−7.8	−7.7	−7.6	−7.5	−7.4	−7.2	−7.0
−10	–	–	–	–	–	–	–	–	−7.8	−7.8	−7.8	−7.8	−7.7	−7.6	−7.5	−7.3	−7.1	−6.9
0	–	–	–	–	–	–	–	–	–	−7.8	−7.8	−7.7	−7.7	−7.5	−7.4	−7.2	−7.0	−6.8
10	–	–	–	–	–	–	–	–	–	–	−7.8	−7.7	−7.6	−7.5	−7.3	−7.2	−6.9	−6.7
20	–	–	–	–	–	–	–	–	–	–	–	−7.6	−7.5	−7.4	−7.2	−7.0	−6.8	−6.6
30	–	–	–	–	–	–	–	–	–	–	–	–	−7.4	−7.3	−7.1	−6.9	−6.7	−6.4
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−7.1	−7.0	−6.8	−6.5	−6.2
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−6.8	−6.6	−6.3	−6.0
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−6.4	−6.1	−5.8
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.9	−5.6
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.3

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.30

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.4	−5.8	−6.2	−6.5	−6.7	−7.0	−7.2	−7.3	−7.5	−7.6	−7.7	−7.8	−7.8	−7.8	−7.8	−7.7	−7.6	−7.5
−80	–	−6.3	−6.6	−6.9	−7.1	−7.3	−7.5	−7.7	−7.8	−7.9	−8.0	−8.0	−8.1	−8.1	−8.0	−7.9	−7.8	−7.6
−70	–	–	−6.9	−7.2	−7.5	−7.7	−7.8	−8.0	−8.1	−8.2	−8.2	−8.3	−8.3	−8.3	−8.2	−8.1	−7.9	−7.7
−60	–	–	–	−7.5	−7.7	−7.9	−8.1	−8.2	−8.3	−8.4	−8.4	−8.5	−8.4	−8.4	−8.3	−8.2	−8.0	−7.8
−50	–	–	–	–	−8.0	−8.1	−8.3	−8.4	−8.5	−8.6	−8.6	−8.6	−8.6	−8.5	−8.4	−8.3	−8.1	−7.8
−40	–	–	–	–	–	−8.3	−8.5	−8.6	−8.6	−8.7	−8.7	−8.7	−8.6	−8.6	−8.4	−8.3	−8.1	−7.8
−30	–	–	–	–	–	–	−8.6	−8.7	−8.7	−8.8	−8.8	−8.7	−8.7	−8.6	−8.5	−8.3	−8.0	−7.8
−20	–	–	–	–	–	–	–	−8.8	−8.8	−8.8	−8.8	−8.8	−8.7	−8.6	−8.4	−8.2	−8.0	−7.7
−10	–	–	–	–	–	–	–	–	−8.9	−8.9	−8.8	−8.8	−8.7	−8.6	−8.4	−8.2	−7.9	−7.6
0	–	–	–	–	–	–	–	–	–	−8.9	−8.8	−8.7	−8.6	−8.5	−8.3	−8.1	−7.8	−7.5
10	–	–	–	–	–	–	–	–	–	–	−8.8	−8.7	−8.6	−8.4	−8.2	−8.0	−7.7	−7.3
20	–	–	–	–	–	–	–	–	–	–	–	−8.6	−8.5	−8.3	−8.1	−7.8	−7.5	−7.2
30	–	–	–	–	–	–	–	–	–	–	–	–	−8.3	−8.1	−7.9	−7.7	−7.3	−7.0
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−8.0	−7.7	−7.5	−7.1	−6.7
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−7.5	−7.2	−6.9	−6.5
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−6.9	−6.6	−6.2
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−6.3	−5.8
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.4

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.40

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	–80	–70	–60	–50	–40	–30	–20	–10	0	10	20	30	40	50	60	70	80	90
–90	–5.6	–6.1	–6.5	–6.9	–7.2	–7.4	–7.7	–7.9	–8.0	–8.2	–8.3	–8.4	–8.4	–8.4	–8.4	–8.4	–8.2	–8.0
–80	–	–6.6	–7.0	–7.4	–7.7	–7.9	–8.1	–8.3	–8.5	–8.6	–8.7	–8.7	–8.8	–8.8	–8.7	–8.6	–8.5	–8.2
–70	–	–	–7.5	–7.8	–8.1	–8.3	–8.5	–8.7	–8.8	–8.9	–9.0	–9.0	–9.0	–9.0	–8.9	–8.8	–8.6	–8.4
–60	–	–	–	–8.2	–8.4	–8.6	–8.8	–9.0	–9.1	–9.2	–9.2	–9.2	–9.2	–9.2	–9.1	–8.9	–8.7	–8.4
–50	–	–	–	–	–8.7	–8.9	–9.1	–9.2	–9.3	–9.4	–9.4	–9.4	–9.4	–9.3	–9.2	–9.0	–8.8	–8.4
–40	–	–	–	–	–	–9.1	–9.3	–9.4	–9.5	–9.5	–9.5	–9.5	–9.5	–9.4	–9.2	–9.0	–8.8	–8.4
–30	–	–	–	–	–	–	–9.4	–9.5	–9.6	–9.6	–9.6	–9.6	–9.5	–9.4	–9.2	–9.0	–8.7	–8.4
–20	–	–	–	–	–	–	–	–9.6	–9.7	–9.7	–9.7	–9.6	–9.5	–9.4	–9.2	–9.0	–8.7	–8.3
–10	–	–	–	–	–	–	–	–	–9.7	–9.7	–9.7	–9.6	–9.5	–9.4	–9.2	–8.9	–8.6	–8.2
0	–	–	–	–	–	–	–	–	–	–9.7	–9.7	–9.6	–9.5	–9.3	–9.1	–8.8	–8.5	–8.0
10	–	–	–	–	–	–	–	–	–	–	–9.6	–9.5	–9.4	–9.2	–9.0	–8.7	–8.3	–7.9
20	–	–	–	–	–	–	–	–	–	–	–	–9.4	–9.3	–9.1	–8.8	–8.5	–8.1	–7.7
30	–	–	–	–	–	–	–	–	–	–	–	–	–9.1	–8.9	–8.6	–8.3	–7.9	–7.4
40	–	–	–	–	–	–	–	–	–	–	–	–	–	–8.7	–8.4	–8.1	–7.7	–7.2
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–8.2	–7.8	–7.4	–6.9
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–7.5	–7.0	–6.5
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–6.6	–6.1
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–5.6

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.50

LEFTMOST BARRIER ANGLE, ϕ_L^o \ RIGHTMOST BARRIER ANGLE, ϕ_R^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.7	−6.3	−6.8	−7.2	−7.5	−7.8	−8.1	−8.3	−8.5	−8.7	−8.8	−8.9	−9.0	−9.0	−9.0	−8.9	−8.8	−8.5
−80	–	−7.0	−7.4	−7.8	−8.2	−8.4	−8.7	−8.9	−9.1	−9.2	−9.3	−9.4	−9.4	−9.4	−9.3	−9.2	−9.1	−8.8
−70	–	–	−8.0	−8.3	−8.6	−8.9	−9.1	−9.3	−9.5	−9.6	−9.6	−9.7	−9.7	−9.7	−9.6	−9.5	−9.2	−8.9
−60	–	–	–	−8.7	−9.0	−9.3	−9.5	−9.6	−9.8	−9.9	−9.9	−9.9	−9.9	−9.9	−9.8	−9.6	−9.3	−9.0
−50	–	–	–	–	−9.3	−9.6	−9.7	−9.9	−10.0	−10.1	−10.1	−10.1	−10.1	−10.0	−9.9	−9.7	−9.4	−9.0
−40	–	–	–	–	–	−9.8	−10.0	−10.1	−10.2	−10.2	−10.3	−10.2	−10.2	−10.1	−9.9	−9.7	−9.4	−9.0
−30	–	–	–	–	–	–	−10.1	−10.2	−10.3	−10.3	−10.3	−10.3	−10.2	−10.1	−9.9	−9.7	−9.4	−8.9
−20	–	–	–	–	–	–	–	−10.3	−10.4	−10.4	−10.4	−10.3	−10.3	−10.1	−9.9	−9.6	−9.3	−8.8
−10	–	–	–	–	–	–	–	–	−10.5	−10.5	−10.4	−10.3	−10.2	−10.1	−9.9	−9.6	−9.2	−8.7
0	–	–	–	–	–	–	–	–	–	−10.5	−10.4	−10.3	−10.2	−10.0	−9.8	−9.5	−9.1	−8.5
10	–	–	–	–	–	–	–	–	–	–	−10.3	−10.2	−10.1	−9.9	−9.6	−9.3	−8.9	−8.3
20	–	–	–	–	–	–	–	–	–	–	–	−10.1	−10.0	−9.7	−9.5	−9.1	−8.7	−8.1
30	–	–	–	–	–	–	–	–	–	–	–	–	−9.8	−9.6	−9.3	−8.9	−8.4	−7.8
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−9.3	−9.0	−8.6	−8.2	−7.5
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−8.7	−8.3	−7.8	−7.2
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−8.0	−7.4	−6.8
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−7.0	−6.3
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.7

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.60

RIGHTMOST BARRIER ANGLE, ϕ_R^o (columns); LEFTMOST BARRIER ANGLE, ϕ_L^o (rows)

ϕ_L^o \ ϕ_R^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−5.8	−6.5	−7.0	−7.5	−7.9	−8.2	−8.5	−8.7	−9.0	−9.1	−9.3	−9.4	−9.4	−9.5	−9.5	−9.4	−9.2	−9.0
−80	–	−7.3	−7.8	−8.2	−8.6	−8.9	−9.2	−9.4	−9.6	−9.7	−9.8	−9.9	−9.9	−9.9	−9.9	−9.8	−9.6	−9.2
−70	–	–	−8.4	−8.8	−9.1	−9.4	−9.7	−9.9	−10.0	−10.1	−10.2	−10.3	−10.3	−10.3	−10.2	−10.0	−9.8	−9.4
−60	–	–	–	−9.3	−9.6	−9.8	−10.0	−10.2	−10.4	−10.5	−10.5	−10.5	−10.5	−10.5	−10.4	−10.2	−9.9	−9.5
−50	–	–	–	–	−9.9	−10.2	−10.3	−10.5	−10.6	−10.7	−10.7	−10.7	−10.7	−10.6	−10.5	−10.3	−9.9	−9.5
−40	–	–	–	–	–	−10.4	−10.6	−10.7	−10.8	−10.9	−10.9	−10.9	−10.8	−10.7	−10.5	−10.3	−9.9	−9.4
−30	–	–	–	–	–	–	−10.8	−10.9	−10.9	−11.0	−11.0	−10.9	−10.9	−10.7	−10.5	−10.3	−9.9	−9.4
−20	–	–	–	–	–	–	–	−11.0	−11.0	−11.1	−11.0	−11.0	−10.9	−10.7	−10.5	−10.2	−9.8	−9.3
−10	–	–	–	–	–	–	–	–	−11.1	−11.1	−11.1	−11.0	−10.9	−10.7	−10.5	−10.1	−9.7	−9.1
0	–	–	–	–	–	–	–	–	–	−11.1	−11.0	−10.9	−10.8	−10.6	−10.4	−10.0	−9.6	−9.0
10	–	–	–	–	–	–	–	–	–	–	−11.0	−10.9	−10.7	−10.5	−10.2	−9.9	−9.4	−8.7
20	–	–	–	–	–	–	–	–	–	–	–	−10.8	−10.6	−10.3	−10.0	−9.7	−9.2	−8.5
30	–	–	–	–	–	–	–	–	–	–	–	–	−10.4	−10.2	−9.8	−9.4	−8.9	−8.2
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−9.9	−9.6	−9.1	−8.6	−7.9
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−9.3	−8.8	−8.2	−7.5
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−8.4	−7.8	−7.0
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−7.3	6.5
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−5.8

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.70

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−6.0	−6.7	−7.3	−7.8	−8.2	−8.6	−8.9	−9.1	−9.3	−9.5	−9.7	−9.8	−9.9	−9.9	−9.9	−9.8	−9.6	−9.3
−80	–	−7.6	−8.2	−8.6	−9.0	−9.3	−9.6	−9.8	−10.0	−10.2	−10.3	−10.4	−10.4	−10.4	−10.4	−10.3	−10.0	−9.6
−70	–	–	−8.8	−9.2	−9.6	−9.9	−10.2	−10.4	−10.5	−10.7	−10.7	−10.8	−10.8	−10.8	−10.7	−10.5	−10.3	−9.8
−60	–	–	–	−9.7	−10.1	−10.3	−10.6	−10.7	−10.9	−11.0	−11.1	−11.1	−11.1	−11.0	−10.9	−10.7	−10.4	−9.9
−50	–	–	–	–	−10.4	−10.7	−10.9	−11.0	−11.2	−11.2	−11.3	−11.3	−11.3	−11.2	−11.0	−10.8	−10.4	−9.9
−40	–	–	–	–	–	−10.9	−11.1	−11.3	−11.4	−11.4	−11.4	−11.4	−11.4	−11.3	−11.1	−10.8	−10.4	−9.9
−30	–	–	–	–	–	–	−11.3	−11.4	−11.5	−11.6	−11.6	−11.5	−11.4	−11.3	−11.1	−10.8	−10.4	−9.8
−20	–	–	–	–	–	–	–	−11.6	−11.6	−11.6	−11.6	−11.6	−11.4	−11.3	−11.1	−10.7	−10.3	−9.7
−10	–	–	–	–	–	–	–	–	−11.7	−11.7	−11.6	−11.6	−11.4	−11.2	−11.0	−10.7	−10.2	−9.5
0	–	–	–	–	–	–	–	–	–	−11.7	−11.6	−11.5	−11.4	−11.2	−10.9	−10.5	−10.0	−9.3
10	–	–	–	–	–	–	–	–	–	–	−11.6	−11.4	−11.3	−11.0	−10.7	−10.4	−9.8	−9.1
20	–	–	–	–	–	–	–	–	–	–	–	−11.3	−11.1	−10.9	−10.6	−10.2	−9.6	−8.9
30	–	–	–	–	–	–	–	–	–	–	–	–	−10.9	−10.7	−10.3	−9.9	−9.3	−8.6
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−10.4	−10.1	−9.6	−9.0	−8.2
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−9.7	−9.2	−8.6	−7.8
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−8.8	−8.2	−7.3
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−7.6	−6.7
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−6.0

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.80

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−6.1	−6.9	−7.5	−8.1	−8.5	−8.9	−9.2	−9.5	−9.7	−9.9	−10.0	−10.2	−10.2	−10.3	−10.3	−10.2	−10.0	−9.7
−80	–	−7.9	−8.5	−9.0	−9.4	−9.7	−10.0	−10.3	−10.5	−10.6	−10.7	−10.8	−10.9	−10.9	−10.8	−10.7	−10.5	−10.0
−70	–	–	−9.2	−9.6	−10.0	−10.3	−10.6	−10.8	−11.0	−11.1	−11.2	−11.3	−11.3	−11.3	−11.2	−11.0	−10.7	−10.2
−60	–	–	–	−10.2	−10.5	−10.8	−11.0	−11.2	−11.4	−11.5	−11.5	−11.6	−11.6	−11.5	−11.4	−11.2	−10.8	−10.3
−50	–	–	–	–	−10.9	−11.2	−11.4	−11.5	−11.7	−11.7	−11.8	−11.8	−11.8	−11.7	−11.5	−11.3	−10.9	−10.3
−40	–	–	–	–	–	−11.4	−11.6	−11.8	−11.9	−11.9	−12.0	−11.9	−11.9	−11.8	−11.6	−11.3	−10.9	−10.2
−30	–	–	–	–	–	–	−11.8	−11.9	−12.0	−12.1	−12.1	−12.0	−11.9	−11.8	−11.6	−11.3	−10.8	−10.2
−20	–	–	–	–	–	–	–	−12.1	−12.1	−12.1	−12.1	−12.1	−12.0	−11.8	−11.5	−11.2	−10.7	−10.0
−10	–	–	–	–	–	–	–	–	−12.2	−12.2	−12.1	−12.1	−11.9	−11.7	−11.5	−11.1	−10.6	−9.9
0	–	–	–	–	–	–	–	–	–	−12.2	−12.1	−12.0	−11.9	−11.7	−11.4	−11.0	−10.5	−9.7
10	–	–	–	–	–	–	–	–	–	–	−12.1	−11.9	−11.8	−11.5	−11.2	−10.8	−10.3	−9.5
20	–	–	–	–	–	–	–	–	–	–	–	−11.8	−11.6	−11.4	−11.0	−10.6	−10.0	−9.2
30	–	–	–	–	–	–	–	–	–	–	–	–	−11.4	−11.2	−10.8	−10.3	−9.7	−8.9
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−10.9	−10.5	−10.0	−9.4	−8.5
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−10.2	−9.6	−9.0	−8.1
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−9.2	−8.5	−7.5
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−7.9	−6.9
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−6.1

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 0.90

LEFTMOST BARRIER ANGLE, ϕ_L^o \ RIGHTMOST BARRIER ANGLE, ϕ_R^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−6.2	−7.1	−7.7	−8.3	−8.8	−9.1	−9.5	−9.8	−10.0	−10.2	−10.4	−10.5	−10.6	−10.6	−10.6	−10.6	−10.4	−10.0
−80	–	−8.2	−8.8	−9.3	−9.7	−10.1	−10.4	−10.6	−10.8	−11.0	−11.1	−11.2	−11.3	−11.3	−11.2	−11.1	−10.8	−10.4
−70	–	–	−9.5	−10.0	−10.4	−10.7	−11.0	−11.2	−11.4	−11.5	−11.6	−11.7	−11.7	−11.7	−11.6	−11.4	−11.1	−10.6
−60	–	–	–	−10.6	−10.9	−11.2	−11.5	−11.7	−11.8	−11.9	−12.0	−12.0	−12.0	−11.9	−11.8	−11.6	−11.2	−10.6
−50	–	–	–	–	−11.3	−11.6	−11.8	−12.0	−12.1	−12.2	−12.2	−12.2	−12.2	−12.1	−11.9	−11.7	−11.3	−10.6
−40	–	–	–	–	–	−11.9	−12.1	−12.2	−12.3	−12.4	−12.4	−12.4	−12.3	−12.2	−12.0	−11.7	−11.3	−10.6
−30	–	–	–	–	–	–	−12.3	−12.4	−12.5	−12.5	−12.5	−12.5	−12.4	−12.2	−12.0	−11.7	−11.2	−10.5
−20	–	–	–	–	–	–	–	−12.5	−12.6	−12.6	−12.6	−12.5	−12.4	−12.2	−12.0	−11.6	−11.1	−10.4
−10	–	–	–	–	–	–	–	–	−12.7	−12.7	−12.6	−12.5	−12.4	−12.2	−11.9	−11.5	−11.0	−10.2
0	–	–	–	–	–	–	–	–	–	−12.7	−12.6	−12.5	−12.3	−12.1	−11.8	−11.4	−10.8	−10.0
10	–	–	–	–	–	–	–	–	–	–	−12.5	−12.4	−12.2	−12.0	−11.7	−11.2	−10.6	−9.8
20	–	–	–	–	–	–	–	–	–	–	–	−12.3	−12.1	−11.8	−11.5	−11.0	−10.4	−9.5
30	–	–	–	–	–	–	–	–	–	–	–	–	−11.9	−11.6	−11.2	−10.7	−10.1	−9.1
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−11.3	−10.9	−10.4	−9.7	−8.8
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−10.6	−10.0	−9.3	−8.3
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−9.5	−8.8	−7.7
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−8.2	−7.1
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−6.2

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 1.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−6.3	−7.2	−7.9	−8.5	−9.0	−9.4	−9.7	−10.0	−10.3	−10.5	−10.7	−10.8	−10.9	−11.0	−11.0	−10.9	−10.7	−10.3
−80	–	−8.4	−9.1	−9.6	−10.1	−10.4	−10.7	−11.0	−11.2	−11.4	−11.5	−11.6	−11.7	−11.7	−11.6	−11.5	−11.2	−10.7
−70	–	–	−9.9	−10.4	−10.8	−11.1	−11.4	−11.6	−11.8	−11.9	−12.0	−12.1	−12.1	−12.1	−12.0	−11.8	−11.5	−10.9
−60	–	–	–	−10.9	−11.3	−11.6	−11.9	−12.1	−12.2	−12.3	−12.4	−12.4	−12.4	−12.3	−12.2	−12.0	−11.6	−11.0
−50	–	–	–	–	−11.7	−12.0	−12.2	−12.4	−12.5	−12.6	−12.7	−12.7	−12.6	−12.5	−12.3	−12.1	−11.7	−11.0
−40	–	–	–	–	–	−12.3	−12.5	−12.6	−12.7	−12.8	−12.8	−12.8	−12.7	−12.6	−12.4	−12.1	−11.7	−10.9
−30	–	–	–	–	–	–	−12.7	−12.8	−12.9	−12.9	−12.9	−12.9	−12.8	−12.7	−12.4	−12.1	−11.6	−10.8
−20	–	–	–	–	–	–	–	−13.0	−13.0	−13.0	−13.0	−12.9	−12.8	−12.7	−12.4	−12.0	−11.5	−10.7
−10	–	–	–	–	–	–	–	–	−13.1	−13.1	−13.0	−12.9	−12.8	−12.6	−12.3	−11.9	−11.4	−10.5
0	–	–	–	–	–	–	–	–	–	−13.1	−13.0	−12.9	−12.7	−12.5	−12.2	−11.8	−11.2	−10.3
10	–	–	–	–	–	–	–	–	–	–	−13.0	−12.8	−12.6	−12.4	−12.1	−11.6	−11.0	−10.0
20	–	–	–	–	–	–	–	–	–	–	–	−12.7	−12.5	−12.2	−11.9	−11.4	−10.7	−9.7
30	–	–	–	–	–	–	–	–	–	–	–	–	−12.3	−12.0	−11.6	−11.1	−10.4	−9.4
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−11.7	−11.3	−10.8	−10.1	−9.0
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−10.9	−10.4	−9.6	−8.5
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−9.9	−9.1	−7.9
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−8.4	−7.2
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−6.3

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 2.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−7.2	−8.6	−9.5	−10.2	−10.8	−11.3	−11.7	−12.1	−12.3	−12.6	−12.8	−13.0	−13.1	−13.2	−13.2	−13.2	−13.0	−12.3
−80	–	−10.5	−11.3	−12.0	−12.5	−12.9	−13.2	−13.5	−13.8	−14.0	−14.1	−14.2	−14.3	−14.3	−14.3	−14.1	−13.8	−13.0
−70	–	–	−12.4	−13.0	−13.4	−13.8	−14.1	−14.3	−14.5	−14.7	−14.8	−14.9	−14.9	−14.9	−14.8	−14.5	−14.1	−13.2
−60	–	–	–	−13.6	−14.1	−14.4	−14.7	−14.9	−15.0	−15.2	−15.2	−15.3	−15.3	−15.2	−15.0	−14.8	−14.3	−13.2
−50	–	–	–	–	−14.5	−14.8	−15.1	−15.2	−15.4	−15.5	−15.5	−15.5	−15.5	−15.4	−15.2	−14.9	−14.3	−13.2
−40	–	–	–	–	–	−15.1	−15.4	−15.5	−15.6	−15.7	−15.7	−15.7	−15.6	−15.5	−15.3	−14.9	−14.3	−13.1
−30	–	–	–	–	–	–	−15.6	−15.7	−15.8	−15.8	−15.8	−15.8	−15.7	−15.5	−15.3	−14.9	−14.2	−13.0
−20	–	–	–	–	–	–	–	−15.9	−15.9	−15.9	−15.9	−15.8	−15.7	−15.5	−15.2	−14.8	−14.1	−12.8
−10	–	–	–	–	–	–	–	–	−16.0	−16.0	−15.9	−15.8	−15.7	−15.5	−15.2	−14.7	−14.0	−12.6
0	–	–	–	–	–	–	–	–	–	−16.0	−15.9	−15.8	−15.6	−15.4	−15.0	−14.5	−13.8	−12.3
10	–	–	–	–	–	–	–	–	–	–	−15.9	−15.7	−15.5	−15.2	−14.9	−14.3	−13.5	−12.1
20	–	–	–	–	–	–	–	–	–	–	–	−15.6	−15.4	−15.1	−14.7	−14.1	−13.2	−11.7
30	–	–	–	–	–	–	–	–	–	–	–	–	−15.1	−14.8	−14.4	−13.8	−12.9	−11.3
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−14.5	−14.1	−13.4	−12.5	−10.8
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−13.6	−13.0	−12.0	−10.2
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−12.4	−11.3	−9.5
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−10.5	−8.6
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−7.2

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 3.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	-80	-70	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80	90
-90	-8.0	-9.5	-10.6	-11.4	-12.0	-12.5	-13.0	-13.3	-13.6	-13.9	-14.2	-14.3	-14.5	-14.6	-14.6	-14.6	-14.4	-13.6
-80	–	-12.0	-12.9	-13.6	-14.1	-14.5	-14.9	-15.2	-15.4	-15.6	-15.8	-15.9	-16.0	-16.0	-16.0	-15.8	-15.4	-14.4
-70	–	–	-14.0	-14.6	-15.1	-15.5	-15.8	-16.0	-16.3	-16.4	-16.5	-16.6	-16.6	-16.6	-16.5	-16.3	-15.8	-14.6
-60	–	–	–	-15.3	-15.8	-16.1	-16.4	-16.6	-16.8	-16.9	-17.0	-17.0	-17.0	-16.9	-16.8	-16.5	-16.0	-14.6
-50	–	–	–	–	-16.2	-16.6	-16.8	-17.0	-17.1	-17.2	-17.3	-17.3	-17.2	-17.1	-16.9	-16.6	-16.0	-14.6
-40	–	–	–	–	–	-16.9	-17.1	-17.3	-17.4	-17.4	-17.5	-17.4	-17.4	-17.2	-17.0	-16.6	-16.0	-14.5
-30	–	–	–	–	–	–	-17.3	-17.5	-17.5	-17.6	-17.6	-17.5	-17.4	-17.3	-17.0	-16.6	-15.9	-14.3
-20	–	–	–	–	–	–	–	-17.6	-17.7	-17.7	-17.7	-17.6	-17.5	-17.3	-17.0	-16.5	-15.8	-14.2
-10	–	–	–	–	–	–	–	–	-17.7	-17.7	-17.7	-17.6	-17.4	-17.2	-16.9	-16.4	-15.6	-13.9
0	–	–	–	–	–	–	–	–	–	-17.7	-17.7	-17.5	-17.4	-17.1	-16.8	-16.3	-15.4	-13.6
10	–	–	–	–	–	–	–	–	–	–	-17.6	-17.5	-17.3	-17.0	-16.6	-16.0	-15.2	-13.3
20	–	–	–	–	–	–	–	–	–	–	–	-17.3	-17.1	-16.8	-16.4	-15.8	-14.9	-13.0
30	–	–	–	–	–	–	–	–	–	–	–	–	-16.9	-16.6	-16.1	-15.5	-14.5	-12.5
40	–	–	–	–	–	–	–	–	–	–	–	–	–	-16.2	-15.8	-15.1	-14.1	-12.0
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-15.3	-14.6	-13.6	-11.4
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-14.0	-12.9	-10.6
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-12.0	-9.5
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-8.0

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 4.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−8.6	−10.3	−11.4	−12.2	−12.9	−13.4	−13.9	−14.3	−14.6	−14.9	−15.1	−15.3	−15.5	−15.6	−15.7	−15.6	−15.4	−14.6
−80	–	−13.1	−14.0	−14.7	−15.3	−15.7	−16.1	−16.4	−16.6	−16.8	−17.0	−17.1	−17.2	−17.2	−17.2	−17.0	−16.6	−15.4
−70	–	–	−15.2	−15.9	−16.3	−16.7	−17.0	−17.3	−17.5	−17.6	−17.8	−17.8	−17.9	−17.8	−17.7	−17.5	−17.0	−15.6
−60	–	–	–	−16.6	−17.0	−17.3	−17.6	−17.8	−18.0	−18.1	−18.2	−18.3	−18.2	−18.2	−18.0	−17.7	−17.2	−15.7
−50	–	–	–	–	−17.5	−17.8	−18.0	−18.2	−18.4	−18.5	−18.5	−18.5	−18.5	−18.4	−18.2	−17.8	−17.2	−15.6
−40	–	–	–	–	–	−18.1	−18.3	−18.5	−18.6	−18.7	−18.7	−18.7	−18.6	−18.5	−18.2	−17.9	−17.2	−15.5
−30	–	–	–	–	–	–	−18.6	−18.7	−18.8	−18.8	−18.8	−18.8	−18.7	−18.5	−18.3	−17.8	−17.1	−15.3
−20	–	–	–	–	–	–	–	−18.8	−18.9	−18.9	−18.9	−18.8	−18.7	−18.5	−18.2	−17.8	−17.0	−15.1
−10	–	–	–	–	–	–	–	–	−19.0	−19.0	−18.9	−18.8	−18.7	−18.5	−18.1	−17.6	−16.8	−14.9
0	–	–	–	–	–	–	–	–	–	−19.0	−18.9	−18.8	−18.6	−18.4	−18.0	−17.5	−16.6	−14.6
10	–	–	–	–	–	–	–	–	–	–	−18.8	−18.7	−18.5	−18.2	−17.8	−17.3	−16.4	−14.3
20	–	–	–	–	–	–	–	–	–	–	–	−18.6	−18.3	−18.0	−17.6	−17.0	−16.1	−13.9
30	–	–	–	–	–	–	–	–	–	–	–	–	−18.1	−17.8	−17.3	−16.7	−15.7	−13.4
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−17.5	−17.0	−16.3	−15.3	−12.9
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−16.6	−15.9	−14.7	−12.2
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−15.2	−14.0	−11.4
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−13.1	−10.3
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−8.6

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 5.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−9.1	−10.9	−12.1	−12.9	−13.6	−14.1	−14.6	−15.0	−15.3	−15.6	−15.9	−16.1	−16.3	−16.4	−16.5	−16.4	−16.3	−15.3
−80	–	−14.0	−15.0	−15.7	−16.2	−16.7	−17.0	−17.3	−17.6	−17.8	−18.0	−18.1	−18.2	−18.2	−18.1	−18.0	−17.6	−16.3
−70	–	–	−16.2	−16.8	−17.3	−17.7	−18.0	−18.2	−18.5	−18.6	−18.7	−18.8	−18.8	−18.8	−18.7	−18.5	−18.0	−16.4
−60	–	–	–	−17.5	−18.0	−18.3	−18.6	−18.8	−19.0	−19.1	−19.2	−19.2	−19.2	−19.1	−19.0	−18.7	−18.1	−16.5
−50	–	–	–	–	−18.5	−18.8	−19.0	−19.2	−19.3	−19.4	−19.5	−19.5	−19.4	−19.3	−19.1	−18.8	−18.2	−16.4
−40	–	–	–	–	–	−19.1	−19.3	−19.5	−19.6	−19.7	−19.7	−19.7	−19.6	−19.4	−19.2	−18.8	−18.2	−16.3
−30	–	–	–	–	–	–	−19.5	−19.7	−19.8	−19.8	−19.8	−19.8	−19.7	−19.5	−19.2	−18.8	−18.1	−16.1
−20	–	–	–	–	–	–	–	−19.8	−19.9	−19.9	−19.9	−19.8	−19.7	−19.5	−19.2	−18.7	−18.0	−15.9
−10	–	–	–	–	–	–	–	–	−19.9	−19.9	−19.9	−19.8	−19.7	−19.4	−19.1	−18.6	−17.8	−15.6
0	–	–	–	–	–	–	–	–	–	−19.9	−19.9	−19.8	−19.6	−19.3	−19.0	−18.5	−17.6	−15.3
10	–	–	–	–	–	–	–	–	–	–	−19.8	−19.7	−19.5	−19.2	−18.8	−18.2	−17.3	−15.0
20	–	–	–	–	–	–	–	–	–	–	–	−19.5	−19.3	−19.0	−18.6	−18.0	−17.0	−14.6
30	–	–	–	–	–	–	–	–	–	–	–	–	−19.1	−18.8	−18.3	−17.7	−16.7	−14.1
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−18.5	−18.0	−17.3	−16.2	−13.6
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−17.5	−16.8	−15.7	−12.9
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−16.2	−15.0	−12.1
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−14.0	−10.9
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−9.1

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 6.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−9.5	−11.4	−12.6	−13.5	−14.2	−14.7	−15.2	−15.6	−15.9	−16.2	−16.4	−16.6	−16.8	−16.9	−17.0	−17.0	−16.8	−15.9
−80	–	−14.8	−15.7	−16.4	−17.0	−17.4	−17.8	−18.0	−18.2	−18.4	−18.5	−18.6	−18.7	−18.8	−18.7	−18.6	−18.2	−16.8
−70	–	–	−17.0	−17.6	−18.1	−18.5	−18.7	−18.9	−19.1	−19.2	−19.2	−19.3	−19.4	−19.4	−19.3	−19.1	−18.6	−17.0
−60	–	–	–	−18.3	−18.8	−19.1	−19.3	−19.4	−19.5	−19.6	−19.6	−19.7	−19.7	−19.7	−19.5	−19.3	−18.7	−17.0
−50	–	–	–	–	−19.2	−19.5	−19.7	−19.8	−19.8	−19.8	−19.9	−19.9	−19.9	−19.8	−19.7	−19.4	−18.8	−16.9
−40	–	–	–	–	–	−19.9	−19.9	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.7	−19.4	−18.7	−16.8
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.7	−19.3	−18.6	−16.6
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.6	−19.2	−18.5	−16.4
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−19.8	−19.6	−19.2	−18.4	−16.2
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−19.8	−19.5	−19.1	−18.2	−15.9
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−19.8	−19.4	−18.9	−18.0	−15.6
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−19.9	−19.7	−19.3	−18.7	−17.8	−15.2
30	–	–	–	–	–	–	–	–	–	–	–	–	−19.9	−19.5	−19.1	−18.5	−17.4	−14.7
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−19.2	−18.8	−18.1	−17.0	−14.2
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−18.3	−17.6	−16.4	−13.5
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−17.0	−15.7	−12.6
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−14.8	−11.4
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−9.5

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, $N_0 = 7.00$

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−9.9	−11.9	−13.1	−14.0	−14.7	−15.2	−15.7	−16.0	−16.3	−16.6	−16.8	−17.0	−17.2	−17.3	−17.4	−17.4	−17.3	−16.3
−80	–	−15.4	−16.4	−17.1	−17.6	−18.0	−18.3	−18.5	−18.7	−18.8	−18.8	−18.9	−19.0	−19.1	−19.1	−19.0	−18.7	−17.3
−70	–	–	−17.6	−18.3	−18.7	−19.0	−19.2	−19.3	−19.4	−19.5	−19.5	−19.6	−19.6	−19.6	−19.6	−19.4	−19.0	−17.4
−60	–	–	–	−19.0	−19.4	−19.6	−19.7	−19.8	−19.8	−19.8	−19.8	−19.9	−19.9	−19.9	−19.8	−19.6	−19.1	−17.4
−50	–	–	–	–	−19.9	−19.9	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.6	−19.1	−17.3
−40	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.6	−19.1	−17.2
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.6	−19.0	−17.0
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.8	−19.5	−18.9	−16.8
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.8	−19.5	−18.8	−16.6
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−19.8	−19.4	−18.7	−16.3
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−19.8	−19.3	−18.5	−16.0
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−19.7	−19.2	−18.3	−15.7
30	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−19.9	−19.6	−19.0	−18.0	−15.2
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−19.9	−19.4	−18.7	−17.6	−14.7
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−19.0	−18.3	−17.1	−14.0
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−17.6	−16.4	−13.1
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−15.4	−11.9
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−9.9

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 8.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−10.3	−12.3	−13.5	−14.4	−15.1	−15.6	−16.0	−16.4	−16.6	−16.9	−17.1	−17.3	−17.4	−17.6	−17.7	−17.7	−17.6	−16.6
−80	–	−16.0	−17.0	−17.7	−18.1	−18.5	−18.7	−18.8	−19.0	−19.1	−19.2	−19.2	−19.3	−19.3	−19.4	−19.3	−19.0	−17.6
−70	–	–	−18.2	−18.8	−19.2	−19.4	−19.5	−19.6	−19.6	−19.7	−19.7	−19.7	−19.8	−19.8	−19.8	−19.6	−19.3	−17.7
−60	–	–	–	−19.6	−19.8	−19.9	−19.9	−19.9	−19.9	−19.9	−19.9	−19.9	−20.0	−20.0	−19.9	−19.8	−19.4	−17.7
−50	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.8	−19.3	−17.6
−40	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.8	−19.3	−17.4
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.7	−19.2	−17.3
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.7	−19.2	−17.1
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.7	−19.1	−16.9
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.6	−19.0	−16.6
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−19.9	−19.6	−18.8	−16.4
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−19.9	−19.5	−18.7	−16.0
30	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−19.9	−19.4	−18.5	−15.6
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−19.8	−19.2	−18.1	−15.1
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−19.6	−18.8	−17.7	−14.4
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−18.2	−17.0	−13.5
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−16.0	−12.3
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−10.3

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 9.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−10.6	−12.6	−13.9	−14.8	−15.4	−15.9	−16.3	−16.6	−16.9	−17.1	−17.3	−17.5	−17.7	−17.8	−17.9	−17.9	−17.8	−16.9
−80	–	−16.5	−17.5	−18.1	−18.5	−18.8	−19.0	−19.1	−19.2	−19.3	−19.4	−19.4	−19.5	−19.5	−19.5	−19.5	−19.2	−17.8
−70	–	–	−18.7	−19.3	−19.5	−19.6	−19.7	−19.7	−19.8	−19.8	−19.8	−19.8	−19.9	−19.9	−19.9	−19.8	−19.5	−17.9
−60	–	–	–	−19.9	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.5	−17.9
−50	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.5	−17.8
−40	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.5	−17.7
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.8	−19.4	−17.5
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.8	−19.4	−17.3
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.8	−19.3	−17.1
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.8	−19.2	−16.9
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−19.7	−19.1	−16.6
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−19.7	−19.0	−16.3
30	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−19.6	−18.8	−15.9
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−19.5	−18.5	−15.4
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−19.9	−19.3	−18.1	−14.8
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−18.7	−17.5	−13.9
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−16.5	−12.6
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−10.6

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 10.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−10.9	−12.9	−14.2	−15.1	−15.7	−16.2	−16.6	−16.9	−17.1	−17.4	−17.5	−17.7	−17.8	−18.0	−18.1	−18.1	−18.1	−17.1
−80	–	−17.0	−17.9	−18.5	−18.8	−16.0	−19.2	−19.3	−19.4	−19.4	−19.5	−19.5	−19.6	−19.6	−19.6	−19.6	−19.4	−18.1
−70	–	–	−19.2	−19.6	−19.7	−19.8	−19.8	−19.9	−19.9	−19.9	−19.9	−19.9	−19.9	−19.9	−19.9	−19.9	−19.6	−18.1
−60	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.6	−18.1
−50	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.6	−18.0
−40	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.6	−17.8
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.5	−17.7
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.5	−17.5
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.4	−17.4
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−194.	−17.1
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−19.3	−16.9
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−19.8	−19.2	−16.6
30	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−19.8	−19.0	−16.2
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−19.7	−18.8	−15.7
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−19.6	−18.5	−15.1
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−19.2	−17.9	−14.2
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−17.0	−12.9
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−10.9

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 20.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−12.9	−15.1	−16.2	−16.9	−17.3	−17.7	−17.9	−18.2	−18.3	−18.5	−18.6	−18.7	−18.8	−18.9	−18.9	−19.0	−19.0	−18.3
−80	–	−19.6	−19.8	−19.9	−19.9	−19.9	−19.9	−19.9	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.0
−70	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.0
−60	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.9
−50	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.9
−40	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.8
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.7
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.6
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.5
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.3
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−18.2
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−19.9	−17.9
30	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−19.9	−17.7
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−19.9	−17.3
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−19.9	−16.9
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−19.8	−16.2
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−19.6	−15.1
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−12.9

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 30.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−14.1	−16.1	−17.1	−17.6	−18.0	−18.3	−18.5	−18.7	−18.8	−18.9	−19.0	−19.1	−19.1	−19.2	−19.2	−19.3	−19.3	−18.8
−80	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.3
−70	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.3
−60	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.2
−50	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.2
−40	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.1
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.1
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.0
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.9
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.8
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.7
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.5
30	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−18.3
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−18.0
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−17.6
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−17.1
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−16.1
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−14.1

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 40.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−14.8	−16.7	−17.5	−18.0	−18.4	−18.6	−18.8	−18.9	−19.0	−19.1	−19.2	−19.2	−19.3	−19.3	−19.4	−19.4	−19.5	−19.0
−80	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−70	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
−60	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
−50	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.3
−40	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.3
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.2
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.2
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.1
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.0
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.9
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.8
30	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−18.6
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−18.4
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−18.0
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−17.5
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−16.7
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−14.8

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 50.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−15.3	−17.1	−17.8	−18.3	−18.6	−18.8	−18.9	−19.1	−19.2	−19.2	−19.3	−19.4	−19.4	−19.4	−19.5	−19.5	−19.5	−19.2
−80	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−70	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−60	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−50	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
−40	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.3
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.2
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.2
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.1
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−18.9
30	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−18.8
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−18.6
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−18.3
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−17.8
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−17.1
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−15.3

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 60.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−15.7	−17.3	−18.1	−18.5	−18.7	−18.9	−19.1	−19.2	−19.2	−19.3	−19.4	−19.4	−19.5	−19.5	−19.5	−19.6	−19.6	−19.2
−80	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−70	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−60	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−50	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−40	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.3
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.2
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.2
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.1
30	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−18.9
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−18.7
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−18.5
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−18.1
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−17.3
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−15.7

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 70.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−15.9	−17.5	−18.2	−18.6	−18.8	−19.0	−19.1	−19.2	−19.3	−19.4	−19.4	−19.5	−19.5	−19.5	−19.6	−19.6	−19.6	−19.3
−80	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−70	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−60	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−50	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−40	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.3
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.2
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.1
30	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−19.0
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−18.8
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−18.6
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−18.2
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−17.5
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−15.9

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 80.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−16.1	−17.6	−18.3	−18.7	−18.9	−19.1	−19.2	−19.3	−19.4	−19.4	−19.5	−19.5	−19.5	−19.6	−19.6	−19.6	−19.6	−19.4
−80	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−10.6
−70	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−60	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−50	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−40	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.3
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.2
30	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−19.1
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−18.9
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−18.7
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−18.3
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−17.6
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−16.1

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 90.00

RIGHTMOST BARRIER ANGLE, ϕ_R^o

LEFTMOST BARRIER ANGLE, ϕ_L^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−16.3	−17.7	−18.4	−18.7	−19.0	−19.1	−19.2	−19.3	−19.4	−19.4	−19.5	−19.5	−19.6	−19.6	−19.6	−19.6	−19.7	−19.4
−80	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.7
−70	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−60	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−50	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−40	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.3
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.2
30	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−19.1
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−19.0
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−18.7
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−18.4
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−17.7
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−16.3

NOISE ATTENUATION BY A BARRIER DEFINED BY (N_0, ϕ_L, ϕ_R)

MAXIMUM FRESNEL NUMBER, N_0 = 100.00

LEFTMOST BARRIER ANGLE, ϕ_L^o \ RIGHTMOST BARRIER ANGLE, ϕ_R^o	−80	−70	−60	−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90
−90	−16.4	−17.8	−18.4	−18.8	−19.0	−19.1	−19.3	−19.3	−19.4	−19.5	−19.5	−19.6	−19.6	−19.6	−19.6	−19.7	−19.7	−19.4
−80	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.7
−70	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.7
−60	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−50	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−40	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−30	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.6
−20	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
−10	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.5
0	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.4
10	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.3
20	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−20.0	−19.3
30	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−20.0	−19.1
40	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−20.0	−19.0
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−20.0	−18.8
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−20.0	−18.4
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−17.8
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−16.4

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Appendix C

ROADWAY SEGMENT ADJUSTMENTS—SOFT SITES

At a soft site, the adjustment to the equivalent sound level for a roadway segment defined by the angles (ϕ_1, ϕ_2) is

$$\text{Segment adjustment} = 10 \log \frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi} = 10 \log \frac{1}{\pi} \int_{\phi_1}^{\phi_2} \sqrt{\cos\phi}\ d\phi . \qquad \text{(C-1)}$$

The indicated integration has been performed numerically and the segment adjustment appears in Figure 7 of the text as a family of curves with ϕ_1 as a parameter and ϕ_2 as the independent variable.

Because of the inherent difficulties with graphic representation of the segment adjustment, Figure 7 becomes difficult to use in a number of situations. To extend the usefulness of Figure 7, the even function property of the cosine function is used to derive the following relationship

$$\psi_{1/2}(\phi_1, \phi_2) = \psi_{1/2}(-\phi_2, -\phi_1) . \qquad \text{(C-2)}$$

The property of the segment adjustment in (C-2) allows the user to reflect the roadway segment into the portion of Figure 7 which gives the finest delineation of the adjustment. For example, determining the adjustment for a roadway segment subtending the angles (65°, 90°) is rather diffucult since an interpolation between the 60° and 70° curves is required. Using (C-2) the roadway segment is reflected, (65°, 90°) → (−90°, −65°), making determination of the adjustment considerably more easy and accurate.

Equation (C-2) is easily proven when the even property of the cosine function, i.e., $\cos(-\phi) = \cos\phi$, is invoked. The proof begins by switching the limits of integration

$$\psi_{1/2}(\phi_1, \phi_2) = \int_{\phi_1}^{\phi_2} \sqrt{\cos\phi}\ d\phi = -\int_{\phi_2}^{\phi_1} \sqrt{\cos\phi}\ d\phi .$$

Now let $-\theta = \phi$, and $-d\theta = d\phi$,

$$\psi_{1/2}(\phi_1, \phi_2) = -\int_{-\phi_2}^{-\phi_1} \sqrt{\cos(-\theta)}\ (-d\theta) = \int_{-\phi_2}^{-\phi_1} \sqrt{\cos\theta}\ d\theta .$$

Since θ is actually a dummy variable, we have the final result

$$\psi_{1/2}(\phi_1, \phi_2) = \psi_{1/2}(-\phi_2, -\phi_1) .$$

The results of the numerical integrations used to develop Figure 7 appear in Tables C-1 and C-2 in 5° increments. These tables may be used instead of Figure 7 to determine segment adjustments.

Table C-1. Adjustment Factor for Finite Length Roadways for Absorbing Sites, dB

RIGHTMOST ROADWAY ANGLE, ϕ_2^o (columns); LEFTMOST ROADWAY ANGLE, ϕ_1^o (rows)

	−85	−80	−75	−70	−65	−60	−55	−50	−45	−40	−35	−30	−25	−20	−15	−10	−5	0
−90	−22.6	−18.1	−15.5	−13.6	−12.2	−11.0	−10.0	−9.2	−8.4	−7.7	−7.1	−6.6	−6.1	−5.7	−5.3	−4.9	−4.5	−4.2
−85	–	−20.0	−16.4	−14.2	−12.6	−11.3	−10.2	−9.3	−8.6	−7.9	−7.3	−6.7	−6.2	−5.8	−5.3	−4.9	−4.6	−4.2
−80	–	–	−18.9	−15.5	−13.4	−11.9	−10.7	−9.7	−8.9	−8.2	−7.5	−6.9	−6.4	−5.9	−5.5	−5.1	−4.7	−4.4
−75	–	–	–	−18.2	−14.9	−12.9	−11.5	−10.3	−9.4	−8.5	−7.8	−7.2	−6.6	−6.1	−5.7	−5.3	−4.9	−4.5
−70	–	–	–	–	−17.7	−14.4	−12.5	−11.1	−10.0	−9.0	−8.3	−7.6	−7.0	−6.4	−5.9	−5.5	−5.1	−4.7
−65	–	–	–	–	–	−17.2	−14.1	−12.2	−10.8	−9.7	−8.8	−8.0	−7.4	−6.8	−6.2	−5.8	−5.3	−4.9
−60	–	–	–	–	–	–	−16.9	−13.8	−11.9	−10.5	−9.5	−8.6	−7.8	−7.2	−6.6	−6.1	−5.6	−5.2
−55	–	–	–	–	–	–	–	−16.6	−13.5	−11.7	−10.3	−9.3	−8.4	−7.7	−7.0	−6.5	−6.0	−5.5
−50	–	–	–	–	–	–	–	–	−16.4	−13.3	−11.5	−10.1	−9.1	−8.2	−7.5	−6.9	−6.3	−5.9
−45	–	–	–	–	–	–	–	–	–	−16.2	−13.1	−11.3	−10.0	−9.0	−8.1	−7.4	−6.8	−6.3
−40	–	–	–	–	–	–	–	–	–	–	−16.1	−13.0	−11.2	−9.9	−8.9	−8.0	−7.3	−6.7
−35	–	–	–	–	–	–	–	–	–	–	–	−15.9	−12.9	−11.1	−9.8	−8.8	−7.9	−7.3
−30	–	–	–	–	–	–	–	–	–	–	–	–	−15.8	−12.8	−11.0	−9.7	−8.7	−7.9
−25	–	–	–	–	–	–	–	–	–	–	–	–	–	−15.7	−12.7	−10.9	−9.6	−8.6
−20	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−15.7	−12.6	−10.9	−9.6
−15	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−15.6	−12.6	−10.8
−10	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−15.6	−12.6
−5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−15.6
0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
10	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
15	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
20	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
25	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
30	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
35	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
40	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
45	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
50	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
55	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
60	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
65	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
75	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
85	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Table C-2. Adjustment Factor for Finite Length Roadways for Absorbing Sites, dB

RIGHTMOST ROADWAY ANGLE, ϕ_2^o (columns); LEFTMOST ROADWAY ANGLE, ϕ_1^o (rows)

	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
−90	−3.9	−3.6	−3.3	−3.1	−2.9	−2.6	−2.4	−2.3	−2.1	−1.9	−1.8	−1.7	−1.5	−1.4	−1.3	−1.3	−1.2	−1.2
−85	−3.9	−3.7	−3.4	−3.1	−2.9	−2.7	−2.5	−2.3	−2.1	−2.0	−1.8	−1.7	−1.6	−1.5	−1.4	−1.3	−1.2	−1.2
−80	−4.0	−3.8	−3.5	−3.2	−3.0	−2.8	−2.6	−2.4	−2.2	−2.0	−1.9	−1.8	−1.6	−1.5	−1.4	−1.4	−1.3	−1.3
−75	−4.2	−3.9	−3.6	−3.3	−3.1	−2.9	−2.7	−2.5	−2.3	−2.1	−2.0	−1.8	−1.7	−1.6	−1.5	−1.4	−1.4	−1.3
−70	−4.4	−4.1	−3.8	−3.5	−3.2	−3.0	−2.8	−2.6	−2.4	−2.2	−2.1	−1.9	−1.8	−1.7	−1.6	−1.5	−1.5	−1.4
−65	−4.6	−4.2	−3.9	−3.7	−3.4	−3.2	−2.9	−2.7	−2.5	−2.4	−2.2	−2.1	−1.9	−1.8	−1.7	−1.6	−1.6	−1.5
−60	−4.8	−4.5	−4.1	−3.9	−3.6	−3.3	−3.1	−2.9	−2.7	−2.5	−2.3	−2.2	−2.1	−1.9	−1.8	−1.8	−1.7	−1.7
−55	−5.1	−4.7	−4.4	−4.1	−3.8	−3.5	−3.3	−3.1	−2.9	−2.7	−2.5	−2.3	−2.2	−2.1	−2.0	−1.9	−1.8	−1.8
−50	−5.4	−5.0	−4.7	−4.3	−4.0	−3.7	−3.5	−3.3	−3.0	−2.8	−2.7	−2.5	−2.4	−2.2	−2.1	−2.0	−2.0	−1.9
−45	−5.8	−5.3	−5.0	−4.6	−4.3	−4.0	−3.7	−3.5	−3.2	−3.0	−2.9	−2.7	−2.5	−2.4	−2.3	−2.2	−2.1	−2.1
−40	−6.2	−5.7	−5.3	−4.9	−4.6	−4.2	−4.0	−3.7	−3.5	−3.3	−3.1	−2.9	−2.7	−2.6	−2.5	−2.4	−2.3	−2.3
−35	−6.7	−6.1	−5.7	−5.3	−4.9	−4.5	−4.2	−4.0	−3.7	−3.5	−3.3	−3.1	−2.9	−2.8	−2.7	−2.6	−2.5	−2.4
−30	−7.2	−6.6	−6.1	−5.6	−5.2	−4.9	−4.5	−4.2	−4.0	−3.7	−3.5	−3.3	−3.2	−3.0	−2.9	−2.8	−2.7	−2.6
−25	−7.8	−7.2	−6.6	−6.1	−5.6	−5.2	−4.9	−4.6	−4.3	−4.0	−3.8	−3.6	−3.4	−3.2	−3.1	−3.0	−2.9	−2.9
−20	−8.6	−7.8	−7.1	−6.6	−6.1	−5.6	−5.3	−4.9	−4.6	−4.3	−4.1	−3.9	−3.7	−3.5	−3.3	−3.2	−3.1	−3.1
−15	−9.6	−8.6	−7.8	−7.1	−6.6	−6.1	−5.7	−5.3	−5.0	−4.7	−4.4	−4.1	−3.9	−3.8	−3.6	−3.5	−3.4	−3.3
−10	−10.8	−9.6	−8.6	−7.8	−7.2	−6.6	−6.1	−5.7	−5.3	−5.0	−4.7	−4.5	−4.2	−4.1	−3.9	−3.8	−3.7	−3.6
−5	−12.6	−10.8	−9.6	−8.6	−7.8	−7.2	−6.7	−6.2	−5.8	−5.4	−5.1	−4.8	−4.6	−4.4	−4.2	−4.0	−3.9	−3.9
0	−15.6	−12.6	−10.8	−9.6	−8.6	−7.9	−7.3	−6.7	−6.3	−5.9	−5.5	−5.2	−4.9	−4.7	−4.5	−4.4	−4.2	−4.2
5	–	−15.6	−12.6	−10.9	−9.6	−8.7	−7.9	−7.3	−6.8	−6.3	−6.0	−5.6	−5.3	−5.1	−4.9	−4.7	−4.6	−4.5
10	–	–	−15.6	−12.6	−10.9	−9.7	−8.8	−8.0	−7.4	−6.9	−6.5	−6.1	−5.8	−5.5	−5.3	−5.1	−4.9	−4.9
15	–	–	–	−15.7	−12.7	−11.0	−9.8	−8.9	−8.1	−7.5	−7.0	−6.6	−6.2	−5.9	−5.7	−5.5	−5.3	−5.3
20	–	–	–	–	−15.7	−12.8	−11.1	−9.9	−9.0	−8.2	−7.7	−7.2	−6.8	−6.4	−6.1	−5.9	−5.8	−5.7
25	–	–	–	–	–	−15.8	−12.9	−11.2	−10.0	−9.1	−8.4	−7.8	−7.4	−7.0	−6.6	−6.4	−6.2	−6.1
30	–	–	–	–	–	–	−15.9	−13.0	−11.3	−10.1	−9.3	−8.6	−8.0	−7.6	−7.2	−6.9	−6.7	−6.6
35	–	–	–	–	–	–	–	−16.1	−13.1	−11.5	−10.3	−9.5	−8.8	−8.3	−7.8	−7.5	−7.3	−7.1
40	–	–	–	–	–	–	–	–	−16.2	−13.3	−11.7	−10.5	−9.7	−9.0	−8.5	−8.2	−7.9	−7.7
45	–	–	–	–	–	–	–	–	–	−16.4	−13.5	−11.9	−10.8	−10.0	−9.4	−8.9	−8.6	−8.4
50	–	–	–	–	–	–	–	–	–	–	−16.6	−13.8	−12.2	−11.1	−10.3	−9.7	−9.3	−9.2
55	–	–	–	–	–	–	–	–	–	–	–	−16.9	−14.1	−12.5	−11.5	−10.7	−10.2	−10.0
60	–	–	–	–	–	–	–	–	–	–	–	–	−17.2	−14.4	−12.9	−11.9	−11.3	−11.0
65	–	–	–	–	–	–	–	–	–	–	–	–	–	−17.7	−14.9	−13.4	−12.6	−12.2
70	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−18.2	−15.5	−14.2	−13.6
75	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−18.9	−16.4	−15.5
80	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−20.0	−18.1
85	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	−22.6

Appendix D

PROGRAM FOR CALCULATING TRAFFIC NOISE LEVELS USING THE FHWA TRAFFIC NOISE PREDICTION MODEL (TI-59)

A computer program based on hand-held calculator has been developed and is available from FHWA. The program is based upon the flow diagram shown in Figures 22 and 23.

It was decided at the last minute not to include the program because it will require frequent updating that can best be handied through FHWA Technical Advisory Series. (Refer to FHWA Technical Advisory T 5040.5, "Hand-Held Calculator Listings for the FHWA Highway Traffic Noise Prediction Model.")

Appendix E

RELATIONSHIP BETWEEN NOISE LEVEL AND LEVEL OF SERVICE

INTRODUCTION

In most highway traffic noise analyses, the noise impacts of the highway are normally based upon the traffic condition that produces the highest noise level. Many people have argued that this is not the best way. The noise evaluation should be based on the traffic situation that is most annoying to the highway neighbor. This is probably true. Unfortunately this time period is often very difficult to identify or forecast. Another difficulty is forecasting the traffic that will be carried by the highway during that annoying period. Determination of the traffic condition that will produce the highest noise level is relatively simple.

RELATIONSHIP BETWEEN LEVEL OF SERVICE AND NOISE LEVEL

The capacity of a highway depends upon the interrelationships between the type of highway, its geometrics, and the traffic conditions. These characteristics will then establish the noise level generated by the traffic operating on the highway. This can be illustrated rather easily by examples. Tables E-1 through E-5 show the noise levels that would be produced by a single lane of traffic operating under various levels of service with increasing heavy-truck traffic. These tables assume freeway conditions, level roadway, an average highway speed of 113 km/h, and ideal geometrics. The site is hard ($\alpha = 0$) and the observer is located 15 metres from the highway.

Case 1. T (Percent Heavy Trucks) = 0

The values shown for the automobile volume and the speeds for each level of service are taken directly from the Highway Capacity Manual (E-1).

Table E-1. Noise Levels versus Level of Service (T = 0%).

Level of Service	Capacity (v/h)		Speed (km/h)	$L_{eq}(h)_i$		$L_{eq}(h)$ (dBA)
	A	HT		A	HT	
A	700		100	69.0		69.0
B	1000		90	69.3		69.3
C	1500		80	69.6		69.6
D	1800		65	67.9		67.9
E	2000		50	65.1		65.1
F	—	—	—	—	—	—

Case 2. T = 1%

In terms of capacity, one truck in the situation described here is equivalent to two automobiles. This must be taken into account in computing the new capacity. Thus, for level of Service A, the truck volume is 700 (.01) = 7 vph. The automobile volume becomes 700 − 7 (2) = 686 vph.

Note that this 2 for 1 exchange in terms of capacity changes greatly depending on the highway. The speeds shown in Table E-1 for the different levels of service must be maintained.

Note that at 1% heavy trucks, automobile noise dominates at all levels of service.

Table E-2. Noise Levels versus Level of Service (T = 1%)

Level of Service	Capacity (v/h)		Speed (km/h)	$L_{eq}(h)_i$		$L_{eq}(h)$ (dBA)
	A	HT		A	HT	
A	686	7	100	68.9	62.9	70.0
B	980	10	90	69.2	63.8	70.3
C	1470	15	80	69.5	64.8	70.8
D	1764	18	65	67.8	64.3	69.4
E	1960	20	50	65.0	63.1	67.2
F	—	—	—	—	—	—

Case 3

Table E-3 shows that at 2% heavy trucks, the trucks begin to dominate the noise level at level of service E.

Table E-3. Noise Level versus Level of Service (T = 2%)

Level of Service	Capacity (v/h)		Speed (km/h)	$L_{eq}(h)_i$		$L_{eq}(h)$ (dBA)
	A	HT		A	HT	
A	672	14	100	68.8	65.9	70.7
B	960	20	90	69.1	66.8	71.1
C	1440	30	80	69.4	67.8	71.7
D	1728	36	65	67.7	67.3	70.5
E	1920	40	50	64.9	66.1	68.6
F	—	—	—	—	—	—

Case 4

Table E-4 shows that at 3% heavy trucks, the trucks dominate at Level of Service C, D & E.

Table E-4. Noise Level versus Level of Service (T = 3%)

Level of Service	Capacity (v/h)		Speed (km/h)	$L_{eq}(h)_i$		$L_{eq}(h)$ (dBA)
	A	HT		A	HT	
A	658	21	100	68.7	67.7	71.3
B	940	30	90	69.0	68.6	71.8
C	1410	45	80	69.3	69.6	72.5
D	1592	54	65	67.6	69.1	71.4
E	1880	60	50	64.8	67.8	69.6
F	—	—	—	—	—	—

Case 5

Table E-5 shows that at 4% heavy trucks, the trucks dominate at all levels of service.

Table E-5. Noise Level versus Level of Service (T = 4%)

Level of Service	Capacity (v/h)		Speed (km/h)	$L_{eq}(h)_i$		$L_{eq}(h)$ (dBA)
	A	HT		A	HT	
A	644	28	100	68.6	68.9	71.8
B	920	40	90	68.9	69.8	72.4
C	1380	60	80	69.2	70.8	73.1
D	1656	72	65	67.5	70.3	72.1
E	1840	80	50	64.8	69.1	70.5
F	—	—	—	—	—	—

Reference

E-1. "Highway Capacity Manual — 1965," Highway Research Board Special Report 87, National Academy of Sciences, Washington, D.C., 1965.

Appendix F

COMPUTATION OF $L_{eq}(T)$ AND LDN

INTRODUCTION

Although the $L_{eq}(h)$ or the $L_{10}(h)$ is used for highway work, there may be times when the equivalent sound level for some other time period is of interest. The FHWA model can be modified rather easily to handle different time periods. This is done by reevaluating the traffic flow adjustment factor, (the FHWA model cannot be modified to compute L_{10} values for any other time period)

$$10 \log (N_i \pi D_o / TS_i) . \tag{F-1}$$

COMPUTATION OF $L_{eq}(T)$

Suppose the equivalent sound level over a 24-hour period, $L_{eq}(24)$ is desired. One way to do this is to compute the $L_{eq}(h)$ for each hourly period during the 24 hours and add them together on an energy basis. Unfortunately, we are unable to predict the future traffic volumes on an hour-by-hour basis. However, if we let N_i represent the average annual daily traffic (AADT) for the ith class of vehicles, and if S_i represents the average highway speed over a 24 hour period, the traffic flow adjustment factor becomes

$$10 \log \left[\frac{\left(N_{(\text{AADT})_i}\right)(\pi)(D_o \text{ metres})}{(S_i \text{ km/h})\,(24 \text{ hours})} \right] . \tag{F-2}$$

This reduces to

$$10 \log \left[\frac{\left(N_{(\text{AADT})_i}\right)(D_o)}{S_i} \right] - 38.8 . \tag{F-3}$$

Substitution of Equation (F-3) into the Equation (1) will give $L_{eq}(24)$.

$$L_{eq}(24)_i = (\bar{L}_o)_{E_i} + 10 \log \left(\frac{N_{(\text{AADT})_i} D_o}{S_i} \right) + 10 \log \left(\frac{D_o}{D} \right)^{1+\alpha}$$

$$+10 \log \left[\frac{\psi_\alpha(\phi_1, \phi_2)}{\pi} \right] - 38.8 . \tag{F-4}$$

$$L_{dn} = 10 \log \left\{ \frac{1}{24} \left[15 \left(10^{\frac{L_d}{10}} \right) + 9 \left(10^{\frac{L_n + 10}{10}} \right) \right] \right\} \tag{F-5}$$

COMPUTATION OF L_{DN}

The same reasoning used in Computation of $L_{eq}(T)$ is used here.

L_d = Equivalent sound level from 7:00 a.m. to 10:00 p.m. – 15 hours

L_n = Equivalent sound level from 10:00 p.m. to 7:00 a.m. – 9 hours

$$L_{d_i} = (\bar{L}_o)_{E_i} + 10 \log \left(\frac{N_i \pi D_o}{S_i(15)}\right) \frac{1 \text{ km}}{1000 \text{ mm}} + 10 \log \left(\frac{D_o}{D}\right)^{1+\alpha}$$

$$+10 \log \left[\frac{\psi_\alpha(\phi_1, \phi_2)}{\pi}\right] \quad \text{or} \tag{F-6}$$

$$L_{d_i} = (\bar{L}_o)_{E_i} + 10 \log \left(\frac{N_i D_o}{S_i}\right) + 10 \log \left(\frac{D_o}{D}\right)^{1+\alpha}$$

$$+10 \log \left[\frac{\psi_\alpha(\phi_1, \phi_2)}{\pi}\right] - 36.8 \tag{F-7}$$

where

N_i = Volume of the ith class from 7:00 a.m. to 10:00 p.m.

S_i = Average speed of the ith class from 7:00 a.m. to 10:00 p.m.

$$L_{n_i} = (\bar{L}_o)_{E_i} + 10 \log \left(\frac{N_i D_o}{S_i}\right) + 10 \log \left(\frac{D_o}{D}\right)^{1+\alpha} + 10 \log \left[\frac{\psi_\alpha(\phi_1, \phi_2)}{\pi}\right] - 34.6 \tag{F-8}$$

where

N_i = Volume of the ith class from 10:00 p.m. to 7:00 a.m.

S_i = Average speed of the ith class from 10:00 p.m. to 7:00 a.m.

Appendix G

COMPUTATION OF NOISE LEVELS WHEN $D < 15$ METRES AND THE OBSERVER IS ADJACENT TO THE ROADWAY

INTRODUCTION

Many situations arise where D is less than 15 metres and the observer is located adjacent to the roadway as shown in Figure G-1. Although the method of analysis suggested here has not been verified in the field, the procedure seems reasonable.

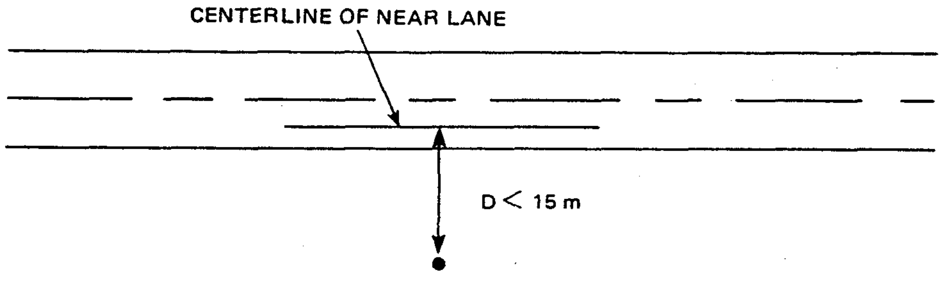


Figure G-1. Situations Where *D* is Less than 15 Metres

WHEN THE MODEL CAN BE USED

One of the basic assumptions in the FHWA model is that traffic noise decreases at a uniform rate as the noise propagates away from the highway. It was indicated in Chapter 2 that the FHWA model uses a rate of 3 dB/DD or 4.5 dB/DD (based on average energy) depending on site conditions. This uniform rate only occurs when the observer is located in the acoustic far field. In the FHWA model, it is assumed that the far field begins 15 metres from the centerline of the near lane. This is illustrated in Figure G-2.

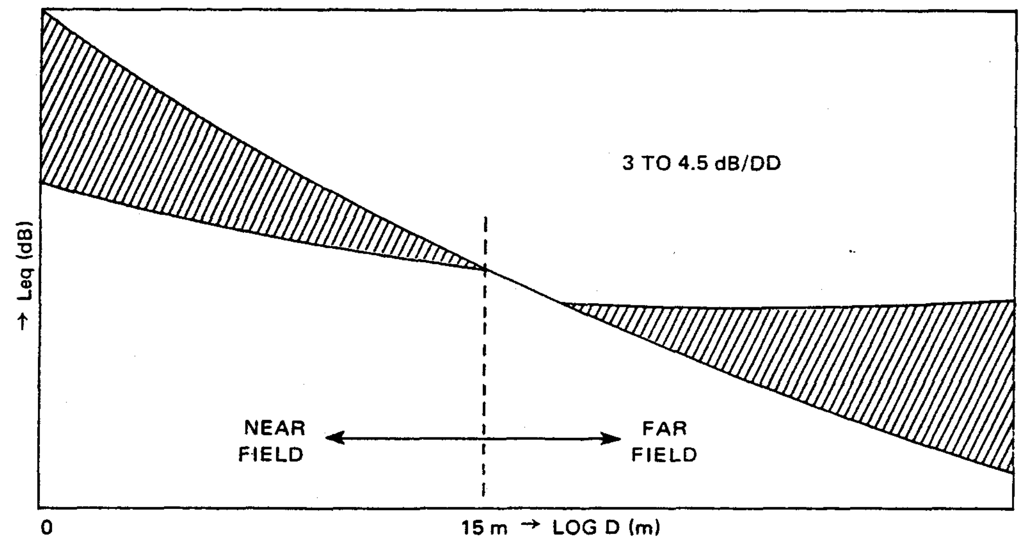


Figure G-2. Noise Levels Versus Distance

Location of where the far field begins is strongly influenced by the size of the noise source. There is some evidence to suggest that for automobiles and medium trucks, D is approximately equal to 7.5 metres. An evaluation of the data in Table G-1 shows that when only automobiles and medium trucks are present (Location A), the drop-off rate from 7.5 metres to 15 metres is 4.1 dB/DD. Since $\alpha = 1/2$, the expected rate would be 4.5 dB/DD. This suggests that automobiles and medium trucks are point sources at 7.5 metres.

Table G-1. Measured Sound Levels at 7.5 and 15 Metres (Source: FHWA Region 15)

Location	Facility	S (km/h)	A (v/h)	MT (v/h)	HT (v/h)	$L_{eq}(h)$			$L_{10}(h)$		
						7.5 m	15 m	Drop-Off Rate (dB/DD)	7.5 m	15 m	Drop-Off Rate (dB/DD)
A	4-lane, no median $\alpha = 1/2$	56	339	42	0	68.6	64.5	4.1	73.2	68.9	4.1
B	4-lane, median $\alpha = 1/2$	52	1572	48	90	75.5	73.4	2.1	78.7	76.9	1.8
C	6-lane, median $\alpha = 1/2$	58	960	72	270	77.2	74.	3.2	80.	76.9	3.1

At locations B and C, heavy trucks are present, and the expected decrease from 7.5 metres to 15 metres is not observed. This would imply that at 7.5 metres the observer is in the acoustic near field of the heavy trucks. This result is not surprising when one compares the length of a heavy truck to 15 metres.

Figure G-2 shows that the sound level does not increase at a uniform rate in the near field. Rough field measurements indicate that the emission level from trucks remains constant within several metres of the edge of the roadway.

Thus it appears that for roadways that carry automobiles and medium trucks, Equation (1) can be used without introducing significant error as long as D is greater than 7.5 metres.

WHEN MEASUREMENTS ARE NEEDED

Future noise levels for all situations involving heavy trucks and all situations where D is less than 7.5 metres should be based upon measured data. To do this, users will have to develop their own data bases. The development of these bases poses several problems, primarily with equipment, measurement procedures, and data analyses. For example, at distances very close to the roadway, the sound levels will change very rapidly over a wide dynamic range. Accurate analysis of these sound levels generally requires that the data be recorded and analyzed by mechanical means. Data will also have to be developed on volumes, mixes, and speeds that occur during the measurement period.

On the positive side, the data acquired at one site should be applicable to other sites. It seems reasonable to assume that when D is less than 15 metres, the highway is infinitely long (the roadway must be visible to the observer from 60 metres in either direction for $D = 15$ m) and corrections for specific site conditions can be ignored (less than 1 dB).

In developing a plot of sound levels versus vehicles, user may want to try the following equations (it has never been field tested).

$$L_{eq}\ (\text{future}) = L_{eq}\ (\text{measured}) - 10 \log \left(\frac{N_E D_E}{S}\right)_{\text{Existing}} + 10 \log \left(\frac{N_E D_E}{S}\right)_{\text{Future}}$$

where

N_E is the number of equivalent automobiles

D_E is the equivalent land distance, and

S is the speed.

To calculate N_E assume that the relative noise level relationship shown in Figure 2 exists between the vehicles when D is less than 15 metres. Then

$$N_E = N_A + 10 N_{\text{MT}} + 32\ N_{\text{HT}}.$$

If the future speed increases the L_{eq} (measured) should be adjusted upward based on Figure 2.

Appendix H

GRADES

INTRODUCTION

The reference energy mean emission levels shown in Figure 2 are based on vehicles operating under cruise conditions on level terrain. The effects of grades upon these emission levels have not been studied. However, NCHRP Report 117 and NCHRP Report 174 describe procedures which can be used to account for the effects of grades. The two procedures give different results and neither appear to be based upon any substantial field study. The adjustment given from these procedures is applied in the same manner. A positive adjustment is made only to the truck levels, $L_{eq}(h)_{HT}$, and it is never negative, i.e., there is no adjustment for a downhill grade.

NCHRP Report 117 suggests that the correction can be applied to the noise level based on the total truck volume. The NCHRP Report 174 suggests that the traffic be split and the adjustment applied to the levels produced by the trucks going up the gradient. It is recommended here that the traffic be split and the correction from the NCHRP Report 117 method (Table H-1) be added to the $L_{eq}(h)$ for heavy trucks going up the grade (i.e., the correction is to be added to the volume shown on line 18, Table 1 for heavy trucks).

Note that after the grades exceed 7%, trucks cannot operate at constant speed and Equation (1) is not valid.

NCHRP REPORT 117 METHOD

Table H-1. Noise Level Adjustments for Trucks on Grades

Gradient (%)	Adjustment (dB)
$\leqslant 2$	0
3 to 4	+2
5 to 6	+3
>7	+5

NCHRP REPORT 174 METHOD

The adjustments for grade are based upon the following equation:

$$\Delta_G = 7.3 - 3.3 \log S + G \qquad \text{(H-1)}$$

where

S is the speed in km/h

G is the percent grade.

Table H-2 is based upon Equation (H-1). The values appear to be too high and their use is not recommended until they have been verified by the user in the field.

Table H-2. Noise Level Adjustments for Trucks on Grades

Grade	Speed (km/h)					
	50	60	70	80	90	100
1	2.7	2.4	2.2	2	1.8	1.7
2	3.7	3.4	3.2	3	2.8	2.7
3	4.7	4.4	4.2	4	3.8	3.7
4	5.7	5.4	5.2	5	4.8	4.7
5	6.7	6.4	6.2	6	5.8	5.7
6	7.7	7.4	7.2	7	6.8	6.7
7	8.7	8.4	8.2	8	7.8	7.7

Appendix I

INTERRUPTED FLOW (STOP-AND-GO TRAFFIC)

INTRODUCTION

A review of the literature indicated that a recent English study has been reported by Gilbert [I-1]. In this study an equation was evaluated for predicting curbside noise from interrupted flow. The equation was of the form

$$L = 55.7 + 9.18 \log Q (1 + .09 H) - 4.20 \log Vy + 2.31 T$$

where

Q is the traffic volume (vph)

H is the proportion of vehicles exceeding 1.525 Mg (%)

y is the roadway width (m)

V is the mean speed of traffic (km/h), and

T is the index of dispersion.

Alternate forms of the equation are suggested, and users may want to obtain the reference and study it in detail. No detailed study on the effects of interrupted flow was found in the U.S. The NCHRP 117 provides some guidelines and these are reproduced in Table I-1. Since no reference is cited, these should be treated as rules of thumb.

Table I-1. Adjustment for Interrupted Flow

Vehicle Type	Adjustment (dB)	
	L_{50}	L_{10}
A	0	+2
HT	0	+4

The NCHRP Report 117 assumes that interrupted flow imposed by a traffic control signal influences the operating noise of a vehicle over a distance of 1000 feet centered at the center of the signal area. This is probably based upon the fact that a truck accelerating from a stopped condition would produce a maximum noise level over this distance while accelerating to cruise condition. This distance is a function of both the grade and how heavily the truck is loaded.

SUGGESTED TECHNIQUE

This is another procedure that has not been verified in the field but seems reasonable. This procedure is based upon an examination of Equation (1) from the standpoint of stop-and-go traffic. All of the variables in Equation (1) are valid for interrupted flow except for the reference energy mean emission levels and the traffic flow adjustment factor.

Reference Energy Mean Emission Levels

Interrupted flow involved speed below 50 km/h. At these speeds heavy trucks will be accelerating. The noise levels associated with accelerating conditions are peak levels. Thus for heavy trucks use a reference level of 87 dBA. For automobiles and medium trucks use the reference levels at 50 km/h. Assume that these values are independent of speed.

Traffic Flow Adjustment Factor

This adjustment factor assumes that the vehicles operate at constant speed. This value should be replaced by the mean speed of the vehicles taking into account the traffic signal. Hopefully, with the above two changes the FHWA model will provide a reasonable estimate of the noise level.

Reference

I-1. Gilbert, D., "Noise from Road Traffic (Interrupted Flow)," Journal of Sound and Vibration, 51(2), 171-181, 1977.

Appendix J

ADAPTION OF THE L_{eq} METHODOLOGY TO DEAL WITH SPECIAL HIGHWAY SITES

INTRODUCTION

In Appendix A a methodology was presented for determining the equivalent sound level at highway sites whose excess attenuation effects may be completely characterized by the site parameter α. The Appendix A L_{eq} methodology began by expressing the mean square pressure at the receiver in terms of reference mean square pressure and a distance adjustment factor,

$$\left\{\begin{matrix}\text{mean square pressure}\\ \text{at receiver}\end{matrix}\right\} = \left\{\begin{matrix}\text{reference mean square}\\ \text{pressure measured at } D_o\end{matrix}\right\} \times \left\{\begin{matrix}\text{distance adjustment}\\ \text{factor}\end{matrix}\right\}$$

$$\langle P^2 \rangle = \langle P_o^2 \rangle \left(\frac{D_o}{R}\right)^{2+\alpha} . \qquad \text{(J-1)}$$

The single vehicle equivalent sound level was then calculated by expressing the source-receiver distance R in terms of the angle ϕ and then integrating the mean square pressure over the roadway segment,

$$L_{eq} = 10 \log \frac{1}{T} \int_{t_1}^{t_2} \frac{\langle P^2(t) \rangle}{\langle P_{ref}^2 \rangle} dt = 10 \log \frac{1}{T} \int_{\phi_1}^{\phi_2} \frac{\langle P^2(\phi) \rangle}{\langle P_{ref}^2 \rangle} \frac{D}{S} \sec^2 \phi \, d\phi \qquad \text{(J-2)}$$

where $P_{ref} = 2 \times 10^{-5}$ Pa.

The limitation of the L_{eq} model of Appendix A is that the highway site must be homogeneous, that is, the excess attenuation effects must be completely characterized by a single value of α. Some highway sites, however, may consist of sections, each with their own propagation parameter. The purpose of this appendix is to demonstrate through examples how the basic methodology of Appendix A may be tailored to fit the specific characteristics of highway sites that are not homogeneous.

EXAMPLE J-1 — GROUND STRIPS PARALLEL TO THE ROADWAY

Consider the highway site in Figure J-1 in which the receiver is separated from the roadway by two ground strips. The excess attenuation effects of the first strip of width D_1 are characterized by the ground cover parameter α_1, while the second strip of width D_2 has its excess attenuation effects characterized by the ground cover parameter α_2.

The first step in solving this problem is to draw a sound ray from the source to the receiver as in Figure J-2. Propagation over that portion of the sound ray R_1 is characterized by geometric spreading and excess attenuation characterized by α_1. At R_1, the mean square pressure $\langle P^2 \rangle_{R_1}$ is given by

$$\langle P^2 \rangle_{R_1} = \langle P_o^2 \rangle \left(\frac{D_o}{R_1}\right)^{2+\alpha_1} . \qquad \text{(J-3)}$$

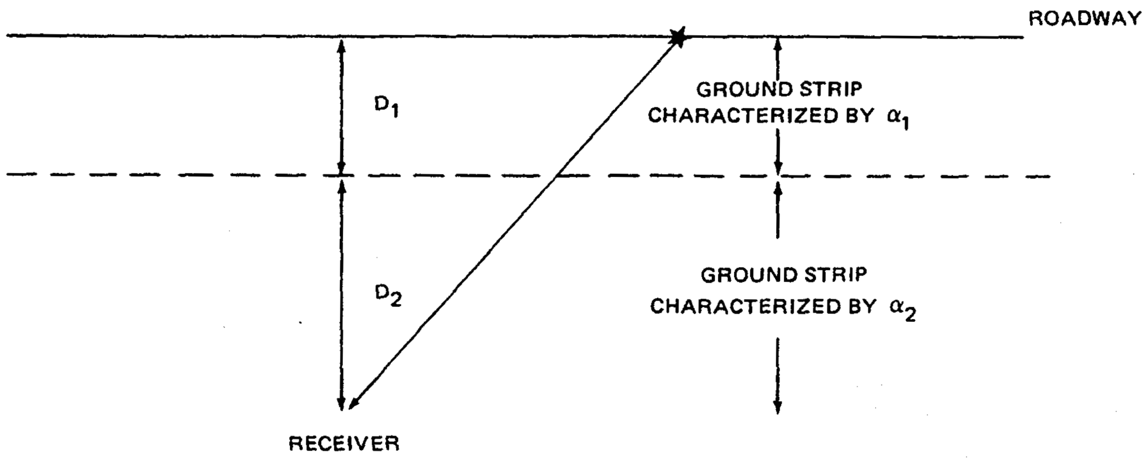
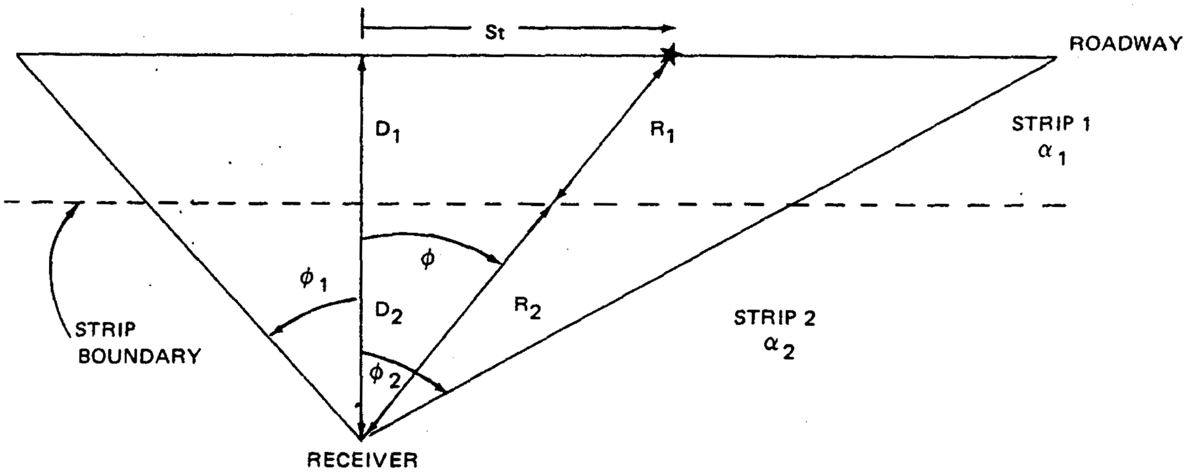


Figure J-1. Highway Site Consisting of Two Absorptive Ground Strips Parallel to the Roadway



D = Stand-off Distance = $D_1 + D_2$

R = Source-Receiver Distance = $\sqrt{D^2 + (St)^2}$

$R = R_1 + R_2$

$R \cos\phi = D \qquad R_1 \cos\phi = D_1$

Figure J-2. Roadway-Receiver Geometry for a Highway Site With Two Ground Strips Parallel to the Roadway

The mean square pressure at the receiver $\langle P^2 \rangle$ is equal to the mean square pressure at R_1 times the appropriate distance adjustment factor, .

$$\langle P^2 \rangle = \langle P^2 \rangle_{R_1} \left(\frac{R_1}{R}\right)^{2+\alpha_2} \tag{J-4}$$

Substitution of (J-3) into (J-4) gives

$$\langle P^2 \rangle = \langle P_o^2 \rangle \left(\frac{D_o}{R_1}\right)^{2+\alpha_1} \left(\frac{R_1}{R}\right)^{2+\alpha_2} \tag{J-5}$$

which may be written in the form

$$\langle P^2 \rangle = \langle P_o^2 \rangle \left(\frac{D_o}{R}\right)^2 \left(\frac{D_o}{R_1}\right)^{\alpha_1} \left(\frac{R_1}{R}\right)^{\alpha_2} . \tag{J-6}$$

From the site and ray geometry in Figure J-2, R_1 and R may be expressed in terms of the variable ϕ, which when substituted in (J-6) gives

$$\langle P^2 \rangle = \langle P_o^2 \rangle \left(\frac{D_o}{D} \cos\phi\right)^2 \left(\frac{D_o}{D_1} \cos\phi\right)^{\alpha_1} \left(\frac{D_1}{D}\right)^{\alpha_2} . \tag{J-7}$$

To calculate the single vehicle equivalent sound level, the mean square pressure at the receiver, (J-7), is integrated over the roadway angles using (J-2),

$$L_{eq} = 10 \log \frac{1}{T} \int_{\phi_1}^{\phi_2} \frac{\langle P^2(\phi) \rangle}{\langle P_{ref}^2 \rangle} \frac{D}{S} \sec^2 \phi \, d\phi \tag{J-2}$$

$$L_{eq} = 10 \log \left[\frac{1}{T} \int_{\phi_1}^{\phi_2} \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} \left(\frac{D_o}{D} \cos\phi\right)^2 \left(\frac{D_o}{D_1} \cos\phi\right)^{\alpha_1} \left(\frac{D_1}{D}\right)^{\alpha_2} \frac{D}{S} \sec^2 \phi \, d\phi \right] . \tag{J-8}$$

Combining similar terms and bringing the constant terms outside the integral, (J-8) reduces to

$$L_{eq} = 10 \log \left[\frac{1}{T} \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} \left(\frac{D_o}{D}\right)^2 \left(\frac{D_o}{D_1}\right)^{\alpha_1} \left(\frac{D_1}{D}\right)^{\alpha_2} \left(\frac{D}{S}\right) \int_{\phi_1}^{\phi_2} (\cos\phi)^{\alpha_1} \, d\phi \right] , \tag{J-9}$$

or

$$L_{eq} = 10 \log \left[\frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} \left(\frac{D_o}{ST}\right) \left(\frac{D_o}{D}\right) \left(\frac{D_o}{D_1}\right)^{\alpha_1} \left(\frac{D_1}{D}\right)^{\alpha_2} \frac{\psi_{\alpha_1}(\phi_1, \phi_2)}{\pi} \pi \right] . \tag{J-10}$$

The first term in the brackets corresponds to the emission level, so that expanding (J-10) results in

$$L_{eq} = L_o + 10 \log \frac{D_o}{ST} + 10 \log \left(\frac{D_o}{D}\right) + 10 \log \left(\frac{D_o}{D_1}\right)^{\alpha_1} + 10 \log \left(\frac{D_1}{D}\right)^{\alpha_2}$$

$$+10 \log \frac{\psi_{\alpha_1}(\phi_1, \phi_2)}{\pi} + 5 . \tag{J-11}$$

Equation (J-11) is valid for a single vehicle. For a given class of vehicles, (J-11) is modified using the results of Appendix A, so that

$$L_{eq} = (\bar{L}_o)_E + 10 \log \frac{ND_o}{ST} + 10 \log \left(\frac{D_o}{D}\right) + 10 \log \left(\frac{D_o}{D_1}\right)^{\alpha_1} + 10 \log \left(\frac{D_1}{D}\right)^{\alpha_2}$$

$$+10 \log \frac{\psi_{\alpha_1}(\phi_1, \phi_2)}{\pi} + 5 \tag{J-12}$$

which is the final result.

EXAMPLE 2—GROUND STRIPS NORMAL TO THE ROADWAY

Consider the highway site of Figure J-3 in which the ground strips are normal to the roadway. Strip 1 is characterized by the ground cover parameter α_1 while strip 2 is characterized by the ground cover parameter α_2. The receiver is located y_0 metres from the boundary of the strips. Since y_0 is measured along the *St* axis, y_0 will have a sign associated with it. On the figure y_0 is to the right of the receiver and thus y_0 is positive. If the receiver had been located in strip 1, y_0 would be measured to the left of the receiver and would be negative.

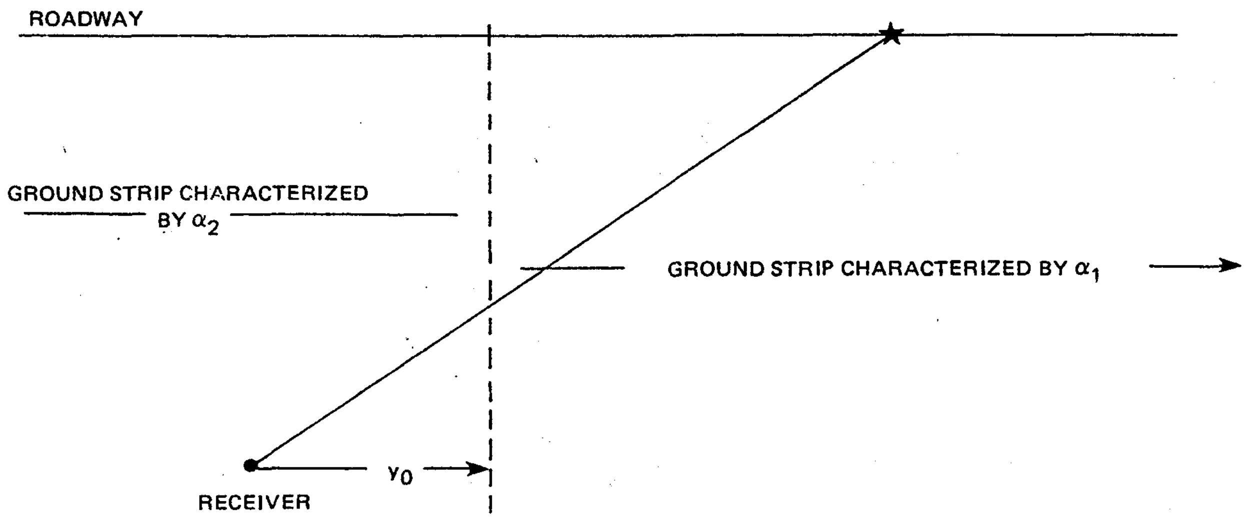


Figure J-3. Highway Site Consisting of Two Absorptive Ground Strips Normal to the Roadway

The roadway segment defined by the angles (ϕ_1, ϕ_L) in Figure J-4 is homogeneous in that excess propagation effects are determined by α_2. Its contribution to the total equivalent sound level is calculated using the results of Appendix A, hence

$$L_{eq} = (\bar{L}_o)_E + 10 \log \frac{ND_o}{ST} + 10 \log \left(\frac{D_o}{D}\right)^{1+\alpha_2} + 10 \log \frac{\psi_{\alpha_2}(\phi_1, \phi_L)}{\pi} + 5. \qquad \text{(J-13)}$$

The L_{eq} contribution from the roadway segment (ϕ_L, ϕ_R) remains to be determined. The method of solution is identical to that used in example J-1. First the mean square pressure at R_1 is expressed in terms of the reference mean square pressure and a distance adjustment factor. Then the mean square pressure at R_1 is adjusted to account for propagation over R_2. The mean square pressure at R_1 is

$$\langle P^2 \rangle_{R_1} = \langle P_o^2 \rangle \left(\frac{D_o}{R_1}\right)^{2+\alpha_1} \qquad \text{(J-14)}$$

and the mean square pressure at the receiver is

$$\langle P^2 \rangle = \langle P^2 \rangle_{R_1} \left(\frac{R_1}{R}\right)^{2+\alpha_2} = \langle P_o^2 \rangle \left(\frac{D_o}{R_1}\right)^{2+\alpha_1} \left(\frac{R_1}{R}\right)^{2+\alpha_2}. \qquad \text{(J-15)}$$

Combining terms, Equation (J-15) becomes

$$\langle P^2 \rangle = \langle P_o^2 \rangle \left(\frac{D_o}{R}\right)^2 \left(\frac{D_o}{R_1}\right)^{\alpha_1} \left(\frac{R_1}{R}\right)^{\alpha_2}. \qquad \text{(J-16)}$$

From Figure J-4, the geometric relations

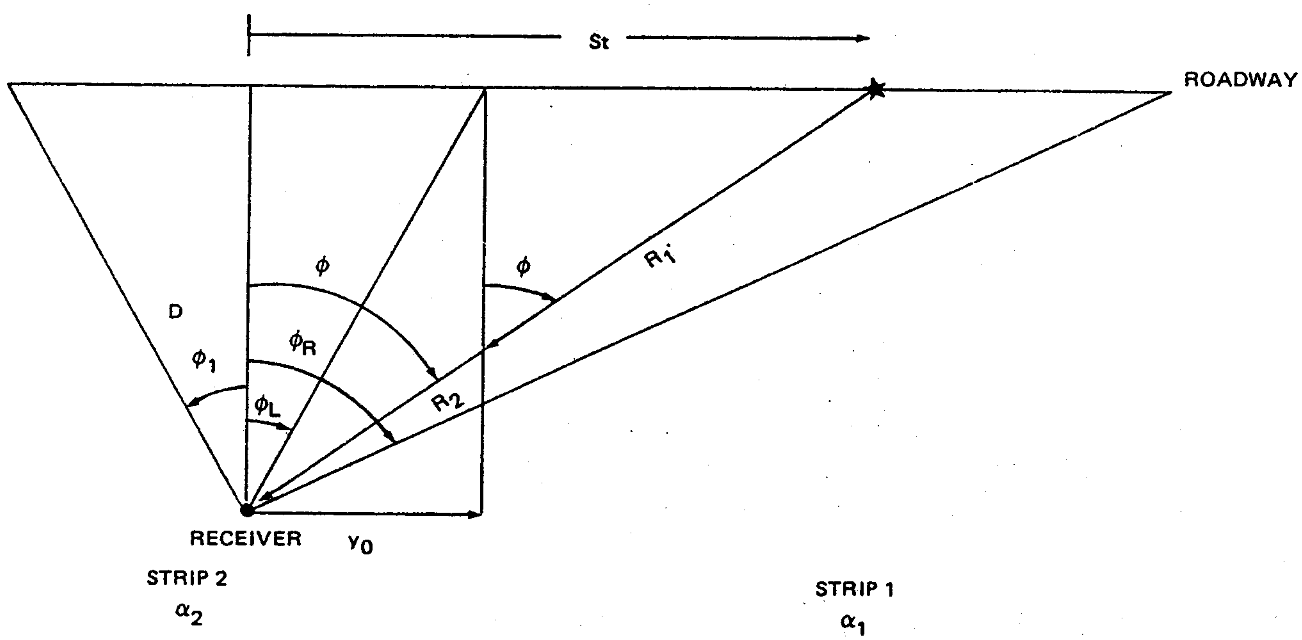
$$R = \frac{D}{\cos\phi} \quad \text{and} \quad R_1 = R\left(1 - \frac{y_o}{D}\cot\phi\right)$$

are employed in (J-16),

$$\langle P^2 \rangle = \langle P_o^2 \rangle \left(\frac{D_o}{D}\cos\phi\right)^2 \left[\frac{D_o\cos\phi}{D\left(1 - \frac{y_o}{D}\right)\cot\phi}\right]^{\alpha_1} \left(1 - \frac{y_o}{D}\cot\phi\right)^{\alpha_2} \qquad \text{(J-17)}$$

which simplifies to

$$\langle P^2 \rangle = \langle P_o^2 \rangle \left(\frac{D_o}{D}\cos\phi\right)^2 \left(\frac{D_o}{D}\cos\phi\right)^{\alpha_1} \left(1 - \frac{y_o}{D}\cot\phi\right)^{\alpha_2 - \alpha_1} \qquad \text{(J-18)}$$



$$R_1 \sin\phi = St - y_o \qquad St = D\tan\phi \qquad R = D/\cos\phi$$

$$R_1 = \frac{D\tan\phi - y_o}{\sin\phi} = \frac{D}{\cos\phi} - \frac{y_o}{\sin\phi} = \frac{D}{\cos\phi}\left(1 - \frac{y_o}{D}\cot\phi\right)$$

$$\therefore\ R_1 = R\left(1 - \frac{y_o}{D}\cot\phi\right)$$

Figure J-4. Roadway-Receiver Geometry for Two Absorptive Strips Normal to the Roadway

To calculate the equivalent sound level, Equation (J-2) is used,

$$L_{eq} = 10\log\frac{1}{T}\int_{\phi_L}^{\phi_R} \frac{\langle P^2(\phi)\rangle}{\langle P_{ref}^2\rangle}\frac{D}{S}\sec^2\phi\, d\phi$$

so that

$$L_{eq} = 10 \log \left[\frac{1}{T} \int_{\phi_L}^{\phi_R} \frac{\langle P_o^2 \rangle}{\langle P_{\text{ref}}^2 \rangle} \left(\frac{D_o}{D} \cos\phi \right)^2 \left(\frac{D_o}{D} \cos\phi \right)^{\alpha_1} \left(1 - \frac{y_o}{D} \cot\phi \right)^{\alpha_2 - \alpha_1} \frac{D}{S} \sec^2\phi \, d\phi \right] . \tag{J-19}$$

Bringing the constants outside the integral and combining similar terms, (J-19) becomes

$$L_{eq} = 10 \log \left[\frac{\langle P_o^2 \rangle}{\langle P_{\text{ref}}^2 \rangle} \frac{D_o}{ST} \left(\frac{D_o}{D} \right)^{1+\alpha_1} \int_{\phi_L}^{\phi_R} (\cos\phi)^{\alpha_1} \left(1 - \frac{y_o}{D} \cot\phi \right)^{\alpha_2 - \alpha_1} d\phi \right] . \tag{J-20}$$

Expanding (J-20), the single vehicle equivalent sound level is

$$L_{eq} = L_o + 10 \log \frac{D_o}{ST} + 10 \log \left(\frac{D_o}{D} \right)^{1+\alpha_1}$$
$$+10 \log \frac{1}{\pi} \int_{\phi_L}^{\phi_R} (\cos\phi)^{\alpha_1} \left(1 - \frac{y_o}{D} \cot\phi \right)^{\alpha_2 - \alpha_1} d\phi + 5 . \tag{J-21}$$

For a class of vehicles, (J-22) is modified to give the following result.

$$L_{eq} = (\bar{L}_o)_E + 10 \log \frac{ND_o}{ST} + 10 \log \left(\frac{D_o}{D} \right)^{1+\alpha_1}$$
$$+10 \log \frac{1}{\pi} \int_{\phi_L}^{\phi_R} (\cos\phi)^{\alpha_1} \left(1 - \frac{y_o}{D} \cot\phi \right)^{\alpha_2 - \alpha_1} d\phi + 5 . \tag{J-22}$$

Evaluation of the integral in (J-22) is best accomplished using numerical integration routines. The total equivalent sound level due to the roadway segment (ϕ_1, ϕ_R) is then the decibel sum of Equations (J-13) and (J-22).

EXAMPLE J-3—BARRIER ATTENUATION AT ABSORPTIVE HIGHWAY SITES

In Appendix B, the hourly equivalent sound level due to a roadway segment shielded by a barrier subtending the angles (ϕ_L, ϕ_R) was given as

$$L_{eq}(h)_i = (\bar{L}_o)_{E_i} + 10 \log \frac{N_i D_o}{S_i} + 10 \log \frac{D_o}{D} + 10 \log \frac{\phi_R - \phi_L}{\pi} + \Delta_{B_i} - 25 \tag{B-10}$$

where Δ_{B_i} is the reduction in equivalent sound level due to the barrier for the ith class of vehicles. In developing (B-10) it was assumed that in the presence of the barrier, excess attenuation effects are lost. This is an oversimplification of a very complex physical phenomenon. In a more rigorous analysis of the problem, absorption due to the ground could not be neglected. However, including ground effects in the presence of a barrier is a difficult undertaking and research is currently underway to provide practical, design-oriented procedures for these situations.

In the absence of formal solutions to the problem of a barrier resting on an absorptive ground plane, an interim solution may be obtained by application of the methodologies employed in Appendices A and B. Consider the shielded roadway segment in Figure J-5. Using the same procedures in Examples J-1 and J-2, the mean square pressure at the receiver is

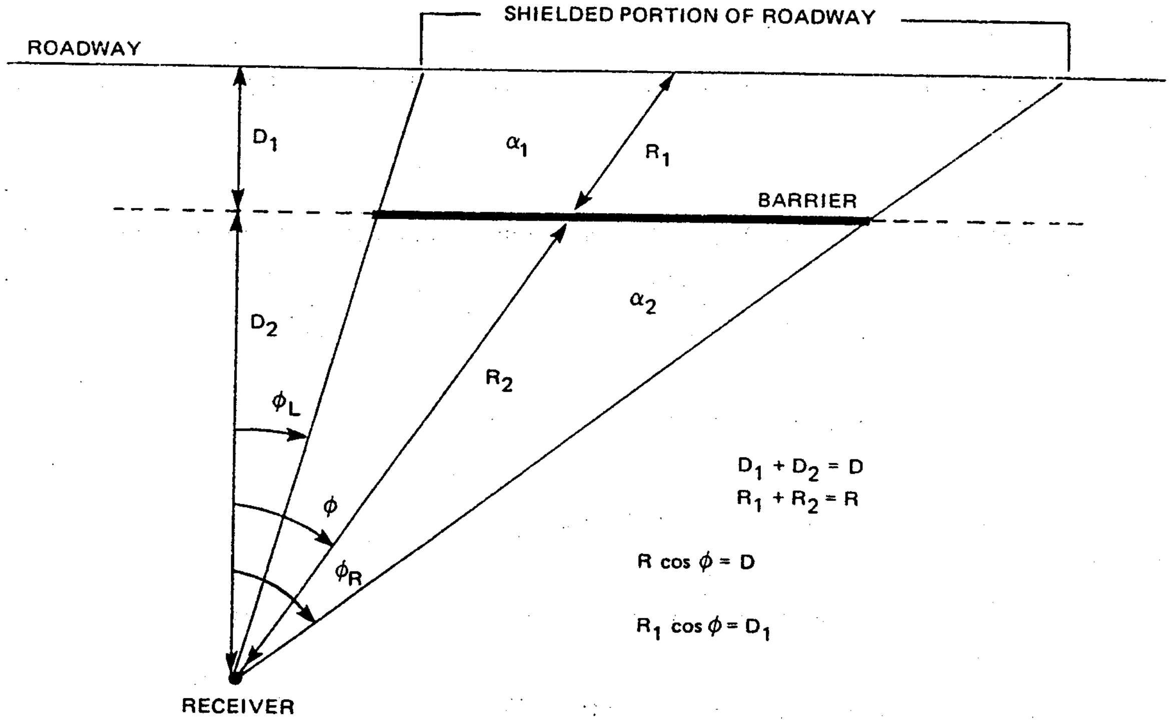


Figure J-5. Roadway-Barrier-Receiver Geometry for a Finite Barrier in the Presence of Absorptive Ground Strips Parallel to the Roadway

$$\langle P^2 \rangle_i = \langle P_o^2 \rangle_i \left(\frac{D_o}{R_1}\right)^{2+\alpha_1} 10^{-\Delta_i/10} \left(\frac{R_1}{R}\right)^{2+\alpha_2} \tag{J-23}$$

in which $-\Delta_i$ is the attenuation in point source levels for the ith class of vehicles and is given by Equation (B-12). Using the relations $D_1 = R_1 \cos\phi$ and $D = R \cos\phi$ it is possible to express (J-23) in terms of angle,

$$\langle P^2 \rangle_i = \langle P_o^2 \rangle_i \left(\frac{D_o}{D_1} \cos\phi\right)^{2+\alpha_1} \left(\frac{D_1}{D}\right)^{2+\alpha_2} 10^{-\Delta_i/10} \,. \tag{J-24}$$

Equation (J-2) is used to calculate the single vehicle equivalent sound level due to the segment,

$$L_{eq_i} = 10 \log \frac{1}{T} \int_{\phi_L}^{\phi_R} \frac{\langle P^2(\phi) \rangle_i}{\langle P_{ref}^2 \rangle} \frac{D}{S_i} \sec^2 \phi \, d\phi \,,$$

so that

$$L_{eq_i} = 10 \log \left[\frac{1}{T} \int_{\phi_L}^{\phi_R} \frac{\langle P_o^2 \rangle_i}{\langle P_{ref}^2 \rangle} \left(\frac{D_o}{D_1} \cos\phi\right)^{2+\alpha_1} \left(\frac{D_1}{D}\right)^{2+\alpha_2} 10^{-\Delta_i/10} \frac{D}{S_i} \sec^2 \phi \, d\phi \right]. \tag{J-25}$$

Taking the constant terms outside the integral and combining similar terms in (J-25) results in

$$L_{eq_i} = 10 \log \left[\frac{\langle P_o^2 \rangle_i}{\langle P_{ref}^2 \rangle} \frac{D_o}{S_i T} \left(\frac{D_o}{D}\right) \left(\frac{D_o}{D_1}\right)^{\alpha_1} \left(\frac{D_1}{D}\right)^{\alpha_2} \int_{\phi_L}^{\phi_R} (\cos\phi)^{\alpha_1} \, 10^{-\Delta_i/10} \, d\phi \right]. \tag{J-26}$$

To put (J-26) in a form compatible with earlier results, the right side is multiplied through by

$$10 \log \left[\left(\frac{\phi_R - \phi_L}{\pi} \right) \left(\frac{\pi}{\phi_R - \phi_L} \right) \right]$$

is added to the right side, so that

$$L_{eq_i} = (L_o)_i + 10 \log \frac{D_o}{S_i T} + 10 \log \frac{D_o}{D} + 10 \log \left(\frac{D_o}{D_1} \right)^{\alpha_1} + 10 \log \left(\frac{D_1}{D} \right)^{\alpha_2}$$

$$+10 \log \frac{\phi_R - \phi_L}{\pi} + 10 \log \frac{\pi}{\phi_R - \phi_L} \int_{\phi_L}^{\phi_R} (\cos \phi)^{\alpha_1} \, 10^{-\Delta_i/10} \, d\phi . \qquad \text{(J-27)}$$

Since $10 \log \pi = 5$,

$$L_{eq_i} = (L_o)_i + 10 \log \frac{D_o}{S_i T} + 10 \log \frac{D_o}{D} + 10 \log \left(\frac{D_o}{D_1} \right)^{\alpha_1} + 10 \log \left(\frac{D_1}{D} \right)^{\alpha_2}$$

$$+10 \log \frac{\Delta \phi}{\pi} + 10 \log \frac{1}{\Delta \phi} \int_{\phi_L}^{\phi_R} (\cos \phi)^{\alpha_1} \, 10^{-\Delta_i/10} \, d\phi + 5 . \qquad \text{(J-28)}$$

For a class of vehicles, Equation (J-28) is modified to yield

$$L_{eq_i} = (\bar{L}_o)_{E_i} + 10 \log \frac{N_i D_o}{S_i T} + 10 \log \left(\frac{D_o}{D} \right) + 10 \log \left(\frac{D_o}{D_1} \right)^{\alpha_1} + 10 \log \left(\frac{D_1}{D} \right)^{\alpha_2}$$

$$+10 \log \frac{\Delta \phi}{\pi} + 10 \log \frac{1}{\Delta \phi} \int_{\phi_L}^{\phi_R} (\cos \phi)^{\alpha_1} \, 10^{-\Delta_i/10} \, d\phi + 5 \qquad \text{(J-29)}$$

which is the final result. Evaluation of the integral is best accomplished using numerical integration routines.

Appendix K

HEAVY TRUCK SOURCE HEIGHTS USED IN BARRIER ATTENUATION CALCULATIONS

INTRODUCTION

In Appendix B it was recommended that for barrier attenuation calculations heavy trucks be located 2.44 metres above the centerline of the pavement and that the truck be treated as if all its sound were radiated at 550 Hz. This single position—single frequency representation of a heavy truck is an attempt to simplify and reduce the number of calculations required to determine the attenuation of equivalent sound levels due to a barrier. It is the purpose of this appendix to indicate, through an example calculation, that the gain in accuracy by resolving a heavy truck into its component sources each with their own spectrum is minimal and that for a manual prediction procedure, the increase in accuracy does not justify the additional calculations.

EXAMPLE CALCULATIONS

The sensitivity of barrier attenuation to changes in source height can be determined analytically. The resulting relationship however is complex and unwieldy. In order to put the accuracy trade-offs between single and multiple source heavy truck models into perspective, the source-barrier-receiver scenarios of Figure K-1 were analyzed to determine equivalent sound levels at the receivers. In the analysis, three source models were used:

(1) In the first model, the heavy truck was treated as a single source located 2.44 m above the pavement with a effective radiation frequency of 550 Hz.

(2) The second heavy truck model consisted of the single source 2.44 m above the pavement with the source strength consisting of the octave band spectrum labeled "TOTAL" in Figure K-2. Attenuation calculations were then made octave band by octave band. The attenuated octave band levels were then A-weighted and logarithmically combined to give the A-weighted sound level at the receiver.

(3) In the third heavy truck model, the heavy truck was resolved into tire noise (0 m), engine noise (1.2 m), and exhaust noise (3.6 m). Each source was assigned its own octave band spectrum as shown in Figure K-2. Source by source, octave band by octave band attenuation calculations were then made. The attenuated octave band levels were A-weighted and

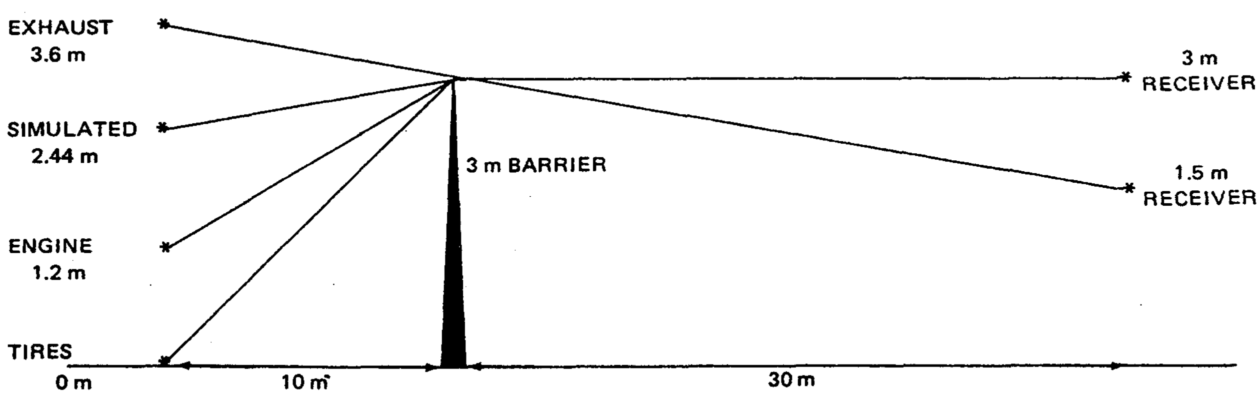


Figure K-1. Source-Barrier-Receiver Geometry Used to Examine the Effects of Source Height on Barrier Attenuation

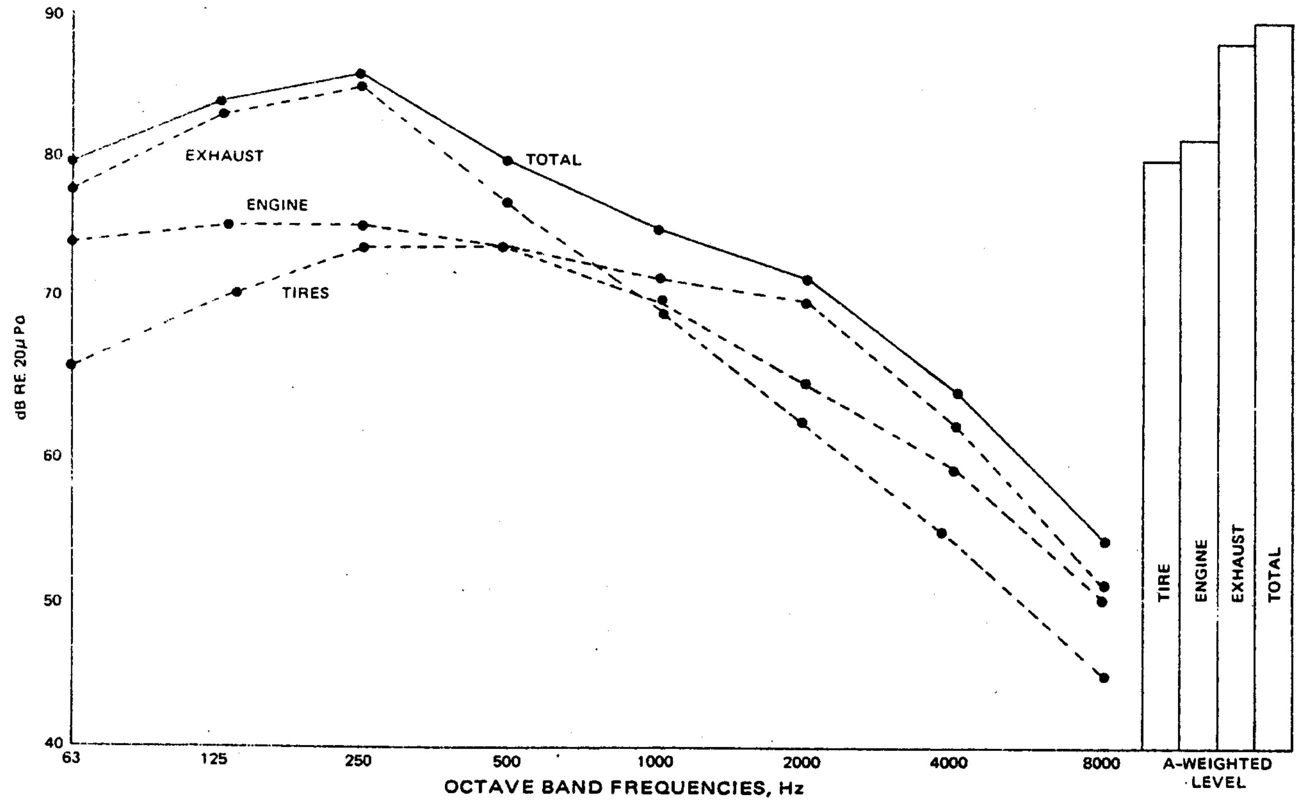


Figure K-2. Individual and Total Heavy Truck Noise Spectra Used in Example Calculations (Source Fundamentals and Abatement of Highway Traffic Noise," FHWA-HHI-HEV-73-7976-1)

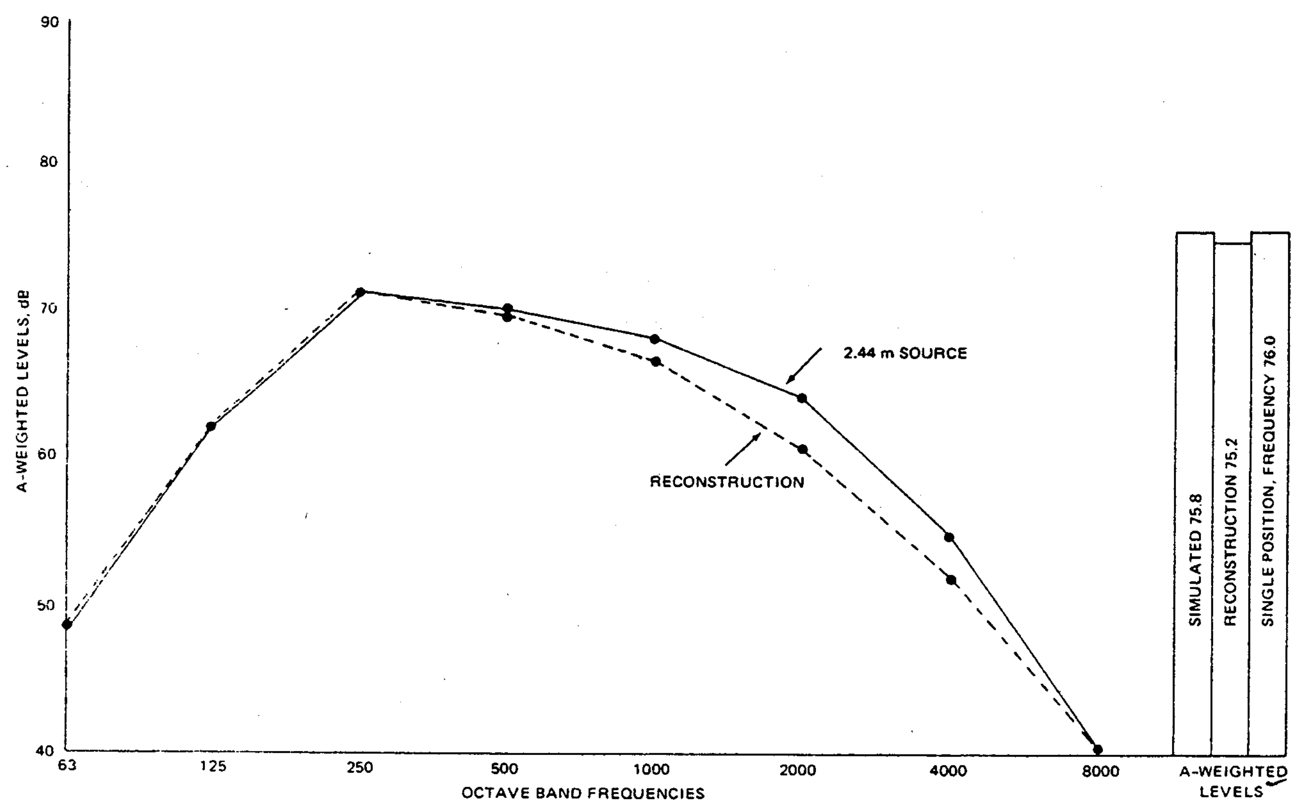


Figure K-3. Octave Band and A-Weighted Sound Levels Behind the Barrier at the 1.5 m Receiver

logarithmically combined to produce the reconstructed A-weighted octave band levels at the receiver. The A-weighted levels at the receiver were then combined to give the A-weighted level at the receiver.

The site geometry for this example was selected to insure that the exhaust stack of the truck was clearly visible by the 3 m receiver and just barely visible by the 1.5 m receiver. Both receivers are in the shadow zone of the 2.44 m source height.

Examination of the resulting A-weighted levels in Figures K-3 and K-4 shows that the largest discrepancy, 1.1 dBA, occurs at the 3 m receiver. Comparison of the simulated source (single position, octave band spectrum) and the single position, single frequency (550 Hz) A-weighted levels shows them to be quite close (0.2 dBA). Certainly in a manual procedure where the objective is to estimate the effectiveness of a barrier, the additional calculations required by resolution of the source into its frequency components and source components is not justified. In a computer based barrier design situation, the additional calculations are worthwhile. The question remains, however, as to what are the proper locations and octave band levels for the resolved heavy truck sources? The answer to this question is the object of current research.

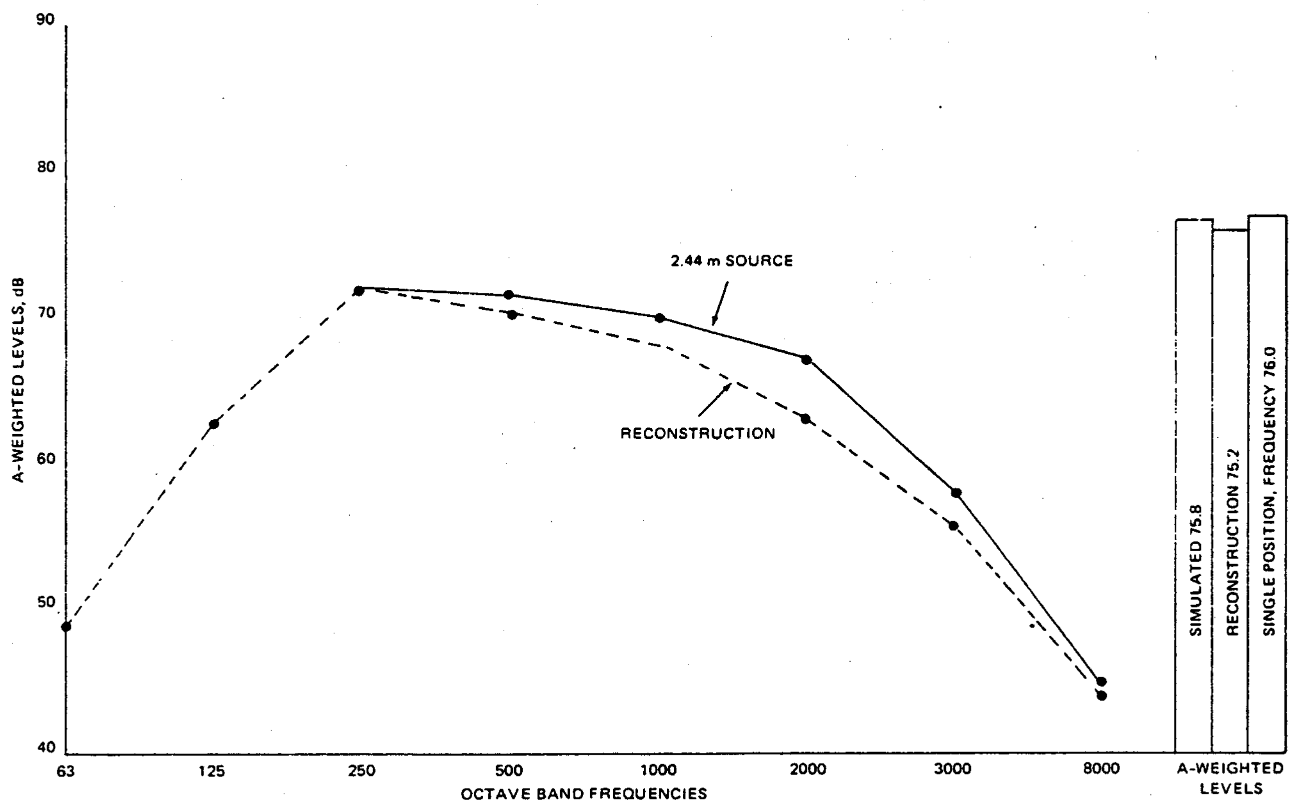
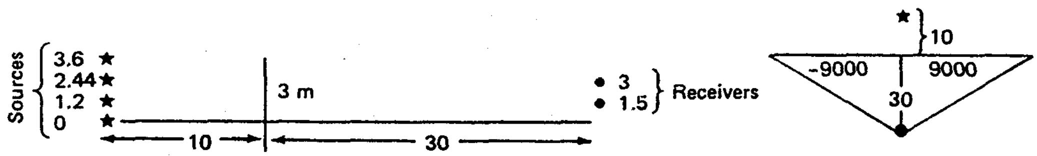


Figure K-4. Octave Band and A-Weighted Sound Levels Behind the Barrier at the 3 m Receiver

EXAMPLE CALCULATIONS



Tires = 0 m Source Height			Engine = 1.2 m		Exhaust = 3.6 m	
Frequency, Hz	Barrier Attenuation, dB		Barrier Attenuation, dB		Barrier Attenuation, dB	
	0 m Receiver	3 m Receiver	0 m	3 m	0 m	3 m
63	−6.56	−6.20	−5.76	−5.48	−5.00	−4.94
125	−7.65	−7.09	−6.39	−5.90	−5.00	−4.88
250	−9.19	−8.44	−7.41	−6.64	−4.99	−4.77
500	−11.09	−10.19	−8.86	−7.78	−4.99	−4.52
1,000	−13.26	−12.25	−10.71	−9.36	−4.97	−3.96
2,000	−15.59	−14.52	−12.83	−11.30	−4.95	−2.58
4,000	−17.38	−16.65	−15.14	−13.48	−4.90	−0.86
8,000	−18.57	−18.10	−17.09	−15.80	−4.79	−0.39

Simulated Truck — 2.44 m Source Height		
Frequency, Hz	Barrier Attenuation, dB	
	0 m Receiver	3 m Receiver
63	−5.18	−5.05
125	−5.34	−5.10
250	−5.65	−5.19
500	−6.22	−5.38
1,000	−7.14	−5.72
2,000	−8.50	−6.33
4,000	−10.26	−7.32
8,000	−12.33	−8.75
550	−6.32	−5.41

1.5 m RECEIVER

Freq.	TIRE NOISE			ENGINE NOISE		
	Level	Δ	Level B.B.	Level	Δ	Level B.B.
63	66	6.6	59.4	74.5	5.8	68.7
125	70.5	7.6	62.9	75.5	6.4	69.1
250	74	9.2	64.8	75.5	7.4	68.1
500	74	11.1	62.9	74	8.9	65.1
1	72	13.3	58.7	70.5	10.7	59.8
2	70.5	15.6	54.9	65	12.8	52.2
4	62	17.4	44.6	59	15.1	43.9
8	51	18.6	32.4	50	17.1	32.9
T	79.7	10.7	69.0	81.4	7.2	74.2

Freq.	STACK NOISE			SIMULATED		
	Level	Δ	Level B.B.	Level	Δ	Level B.B.
63	78	5.0	73	79.8	5.2	74.6
125	83	5.0	78	83.9	5.3	78.6
250	85	5.0	80	85.8	5.6	80.2
500	77	5.0	72	80.0	6.2	73.8
1	70	5.0	65	75.7	7.1	68.6
2	62	5.0	57	72.0	8.5	63.5
4	54	4.9	49.1	64.2	10.3	53.9
8	45	4.8	40.2	54.1	12.3	41.8
T	88.1	5.0	83.1	89.4	5.6	83.8

LEVEL BEHIND BARRIER—RECONSTRUCTION

Freq.	Level in Front	Level B.B.	$\epsilon = L_{RE} - L_{SIM}$
63	79.8	74.5	−0.1
125	83.9	78.6	0
250	85.8	80.4	+0.2
500	80.0	73.2	−0.6
1	75.7	66.9	−1.7
2	72.0	59.9	−3.6
4	64.2	51.3	−2.6
8	54.1	41.5	−0.3
T	89.4	83.8	0

3 m RECEIVER

Freq.	TIRE NOISE			ENGINE NOISE		
	Level	Δ	Level B.B.	Level	Δ	Level B.B.
63	66	6.2	59.8	74.5	5.5	69
125	70.5	7.1	63.4	75.5	5.9	69.6
250	74	8.4	65.6	75.5	6.6	58.9
500	74	10.2	63.8	74	7.8	66.2
1	72	12.2	59.8	70.5	9.4	61.1
2	70.5	14.5	56	65	11.3	53.7
4	62	16.5	45.4	59	13.5	45.5
8	51	18.1	32.9	50	15.8	34.2
T	79.7	9.5	70.2	81.4	6.5	74.9

Freq.	STACK NOISE			SIMULATED		
	Level	Δ	Level B.B.	Level	Δ	Level B.B.
63	78	−4.9	73.1	79.8	5.0	74.8
125	83	4.9	78.1	83.9	5.1	78.8
250	85	4.8	80.2	85.8	5.2	80.6
500	77	4.5	72.5	80	5.4	74.6
1	70	4.0	66	75.7	5.7	70
2	62	2.6	59.4	72	6.3	65.7
4	54	0.9	53.1	64.2	7.3	56.9
8	45	0.4	44.6	54.1	8.7	45.4
T	88.1	4.8	83.3	89.4	5.2	84.2

RECONSTRUCTED LEVELS

Freq.	Level B.B.	$\epsilon = L_R - L_{SIM}$
63	74.7	−0.1
125	78.8	0
250	80.6	0
500	73.9	−0.7
1	67.9	−2.1
2	61.8	−3.9
4	54.4	−2.5
8	45.2	−0.2
T	84.0	−0.2

A-WEIGHTING CORRECTIONS — 1.5 m RECEIVER

Frequency	Correction	TIRES		ENGINE	
		Level B.B.	Corrected Level	Level B.B.	Corrected Level
63	−26.2	59.4	33.2	68.7	42.5
125	−16.1	62.9	46.8	69.1	53
250	−8.6	64.8	56.2	68.1	59.5
500	−3.2	62.9	59.7	65.1	61.9
1	0	58.7	58.7	59.8	59.8
2	1.2	54.9	56.1	52.2	53.4
4	1.0	44.6	45.6	43.9	44.9
8	−1.1	32.4	31.3	32.9	31.8
T			64.1		65.9

Frequency	Correction	EXHAUST			
		Level B.B.	Corrected Level	Level B.B.	Corrected Level
63	−26.2	73	46.8	74.6	48.4
125	−16.1	78	61.9	78.6	62.5
250	−8.6	80	71.4	80.2	71.6
500	−3.2	72	68.8	73.8	70.6
1	0	65	65	68.6	68.6
2	1.2	57	58.2	63.5	64.7
4	1.0	49.1	50.1	53.9	54.9
8	−1.1	40.2	39.1	41.8	40.7
T	−1.1		74.3		75.8

RECONSTRUCTED LEVEL

Frequency	Level B.B.	$\epsilon_A = L_{R_A} - L_{S_A}$
63	48.3	−0.1
125	62.5	0
250	71.8	0.2
500	70	−0.6
1	66.9	−1.7
2	61.1	−3.6
4	52.3	−2.6
8	40.4	−0.3
T	75.2	−0.6

A-WEIGHTING CORRECTIONS—3 m RECEIVER

Frequency	Correction	TIRE		ENGINE	
		Level B.B.	Corrected Level	Level B.B.	Corrected Level
63	−26.2	59.8	33.6	69	42.8
125	−16.1	63.4	47.3	69.6	53.5
250	−8.6	65.6	57	68.9	60.3
500	−3.2	63.8	60.6	66.2	63
1	0	59.8	59.8	61.1	61.1
2	1.2	56	57.2	53.7	54.9
4	1.0	45.4	46.4	45.5	46.5
8	−1.1	32.9	31.8	34.2	33.1
T			65.1		66.9

Frequency	Correction	EXHAUST			
		Level B.B.	Corrected Level	Level B.B.	Corrected Level
63	−26.2	73.1	46.9	74.8	48.6
125	−16.1	78.1	62	78.8	62.7
250	−8.6	80.2	71.6	80.6	72
500	−3.2	72.5	69.3	74.6	71.4
1	0	66	66	70	70
2	1.2	59.4	60.6	65.7	66.9
4	1.0	53.1	54.1	56.9	57.9
8	−1.1	44.6	43.5	45.4	44.3
T					76.6

RECONSTRUCTED LEVEL

Frequency	Level B.B.
63	48.5
125	62.7
250	72
500	70.7
1	67.9
2	63
4	55.4
8	44.1
T	75.8

Appendix L

TABLES, FIGURES, AND NOMOGRAPHS

This appendix contains all of the tables, figures and nomographs needed to predict a noise level from highway traffic using the FHWA model.

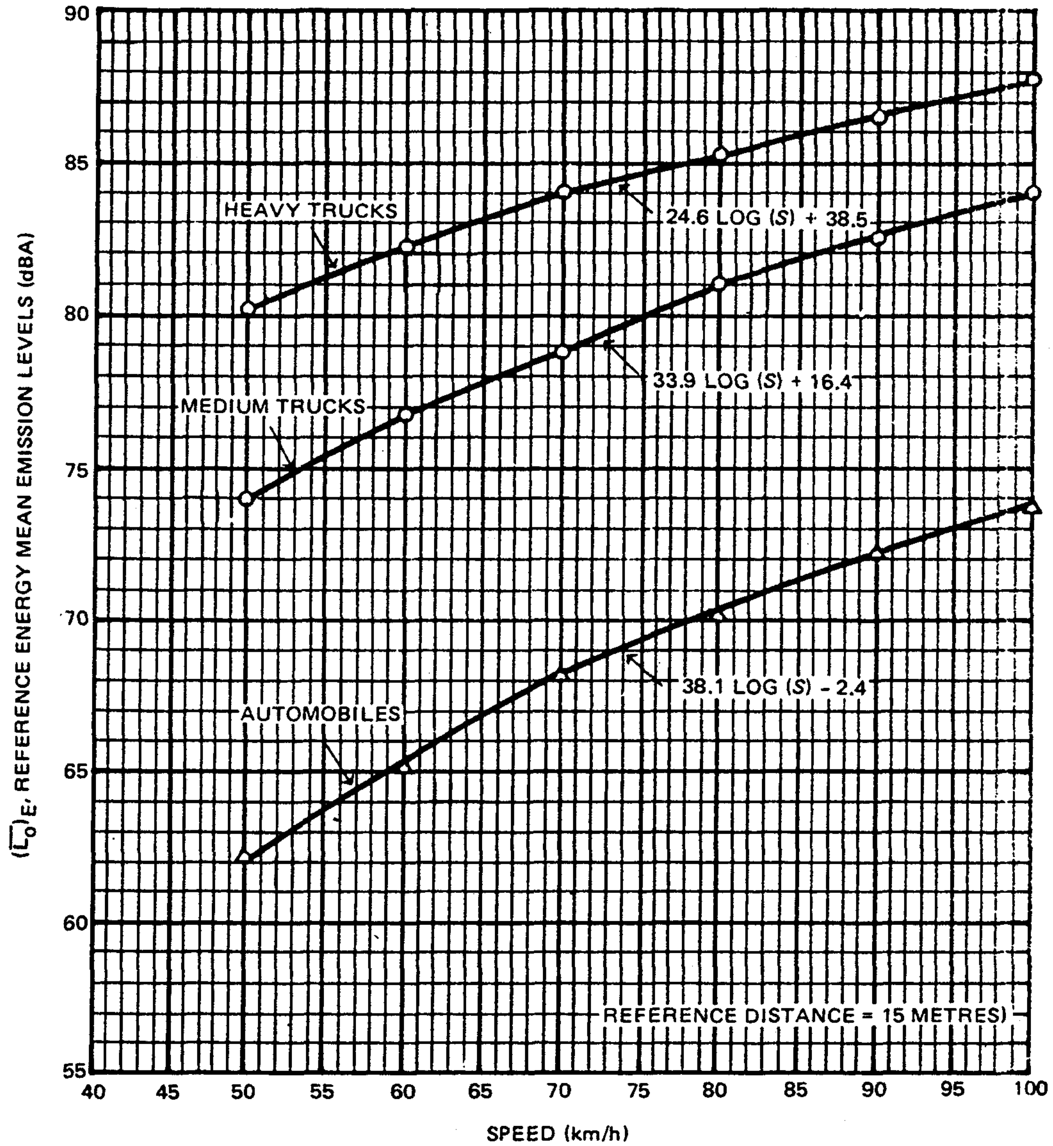
NAME ______________________

DATE ______________________

PROJECT DESCRIPTION ______________________

1.	LANE NO./ROAD SEGMENT																			
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)																			
4.	S(km/h)																			
5.	D(m)																			
6.	ϕ_1 (degrees)	Fig. 5																		
7.	ϕ_2 (degrees)	Fig. 5																		
8.	$(\overline{L_o})_{E_i}$ (dBA)	Fig. 2																		
9.	10 LOG $(N_i D_o / S_i)$ (dB)	Fig. 3																		
10a.	10 LOG (D_o/D) (dBA)	Fig. 4																		
10b.	15 LOG (D_o/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_o(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 6																		
11b.	10 LOG $(\psi_{1/2}(\phi_1, \phi_2)/\pi)$ (dBA)	Fig. 7																		
12.	ϕ_L (degrees)	Fig. 10																		
13.	ϕ_R (degrees)	Fig. 10																		
14.	δ_o (metres)	Fig. 9																		
15.	N_o	Eq. 18																		
16.	Δ_B (dBA)	Appendix B																		
17.	CONSTANT (dB)		-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25	-25
18.	$L_{eq}(h)$ (dBA)																			
19.	$L_{eq}(h)$ (dBA)																			
20.	Δ_s (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)																			
24.	$(L_{10}-L_{eq})_i$ (dB)	Fig. 15																		
25.	$L_{10}(h)_i$ (dBA)																			
26.	$L_{10}(h)$ (dBA)																			
27.	$L_{10}(h)$ (dBA)																			

Table 1. Noise Prediction Worksheet



○ SOURCE: "Statistical Analysis of FHWA Traffic Noise Data," FHWA-RD-78-64

△ SOURCE: "Update of TSC Highway Traffic Noise Prediction Code (1974)," FHWA-RD-77-19

Figure 2. Reference Energy Mean Emission Levels as a Function of Speed

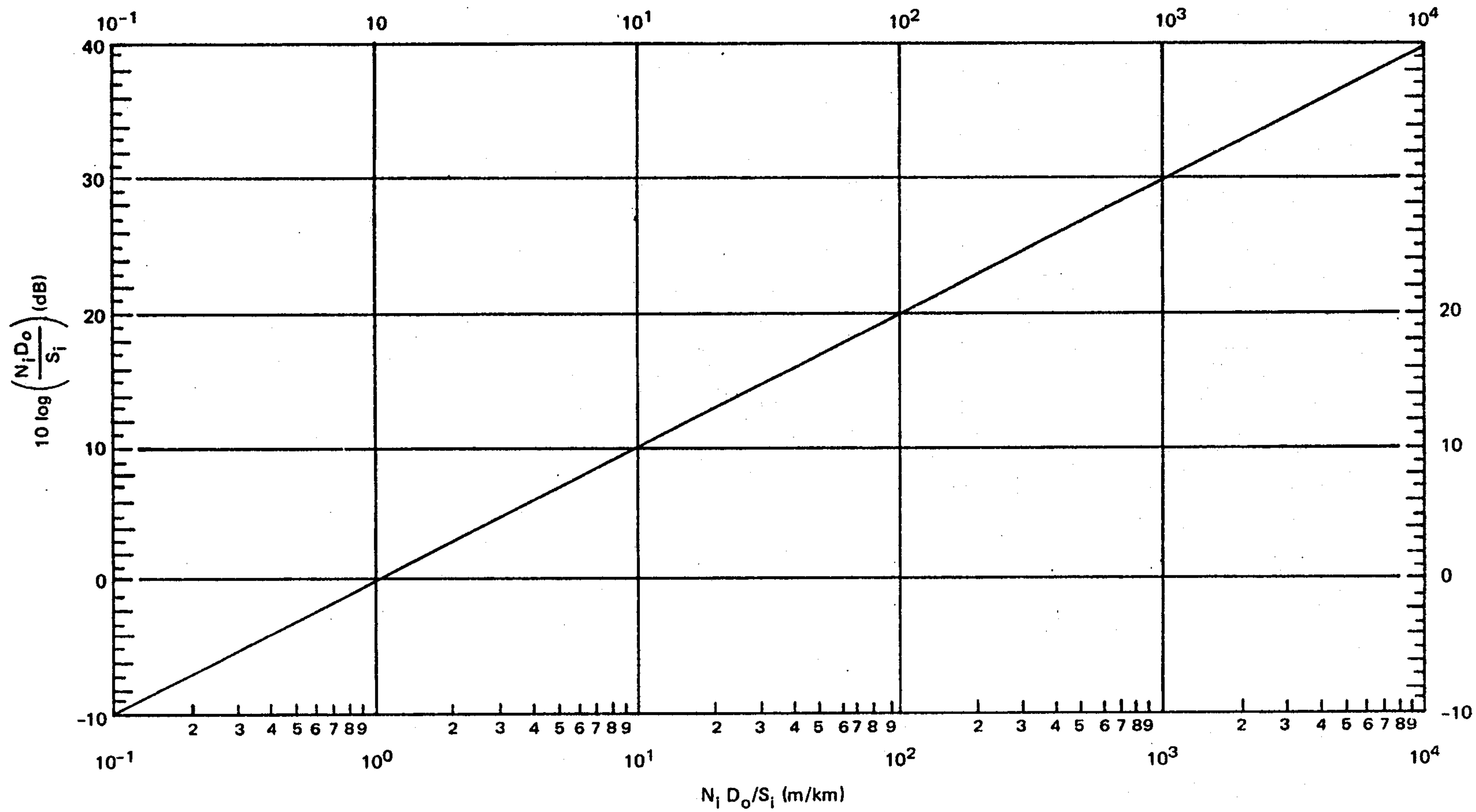


Figure 3. Adjustment for Real Traffic Flows

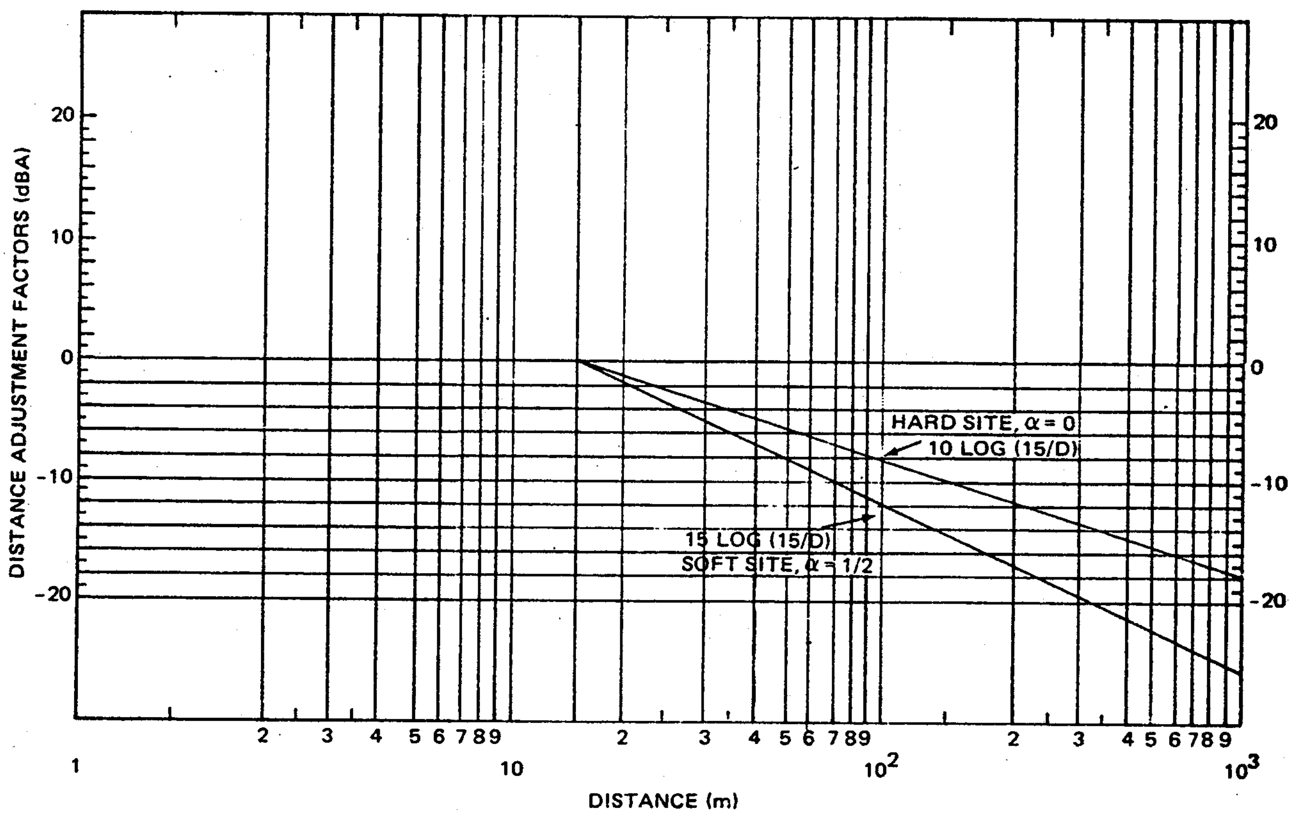


Figure 4. Adjustments for Distances Other Than 15 Metres

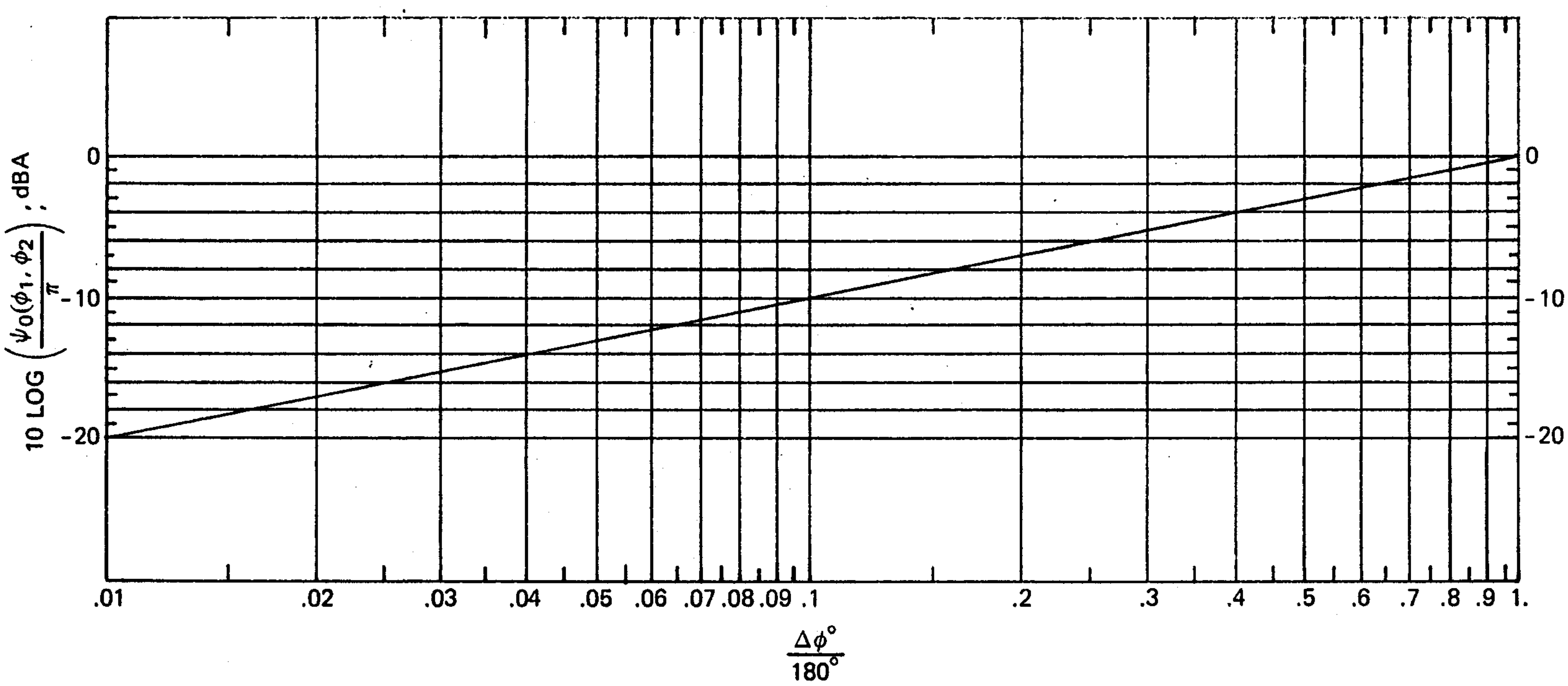


Figure 6. Adjustment Factor for Finite Length Roadways for Hard Site ($\alpha = 0$)

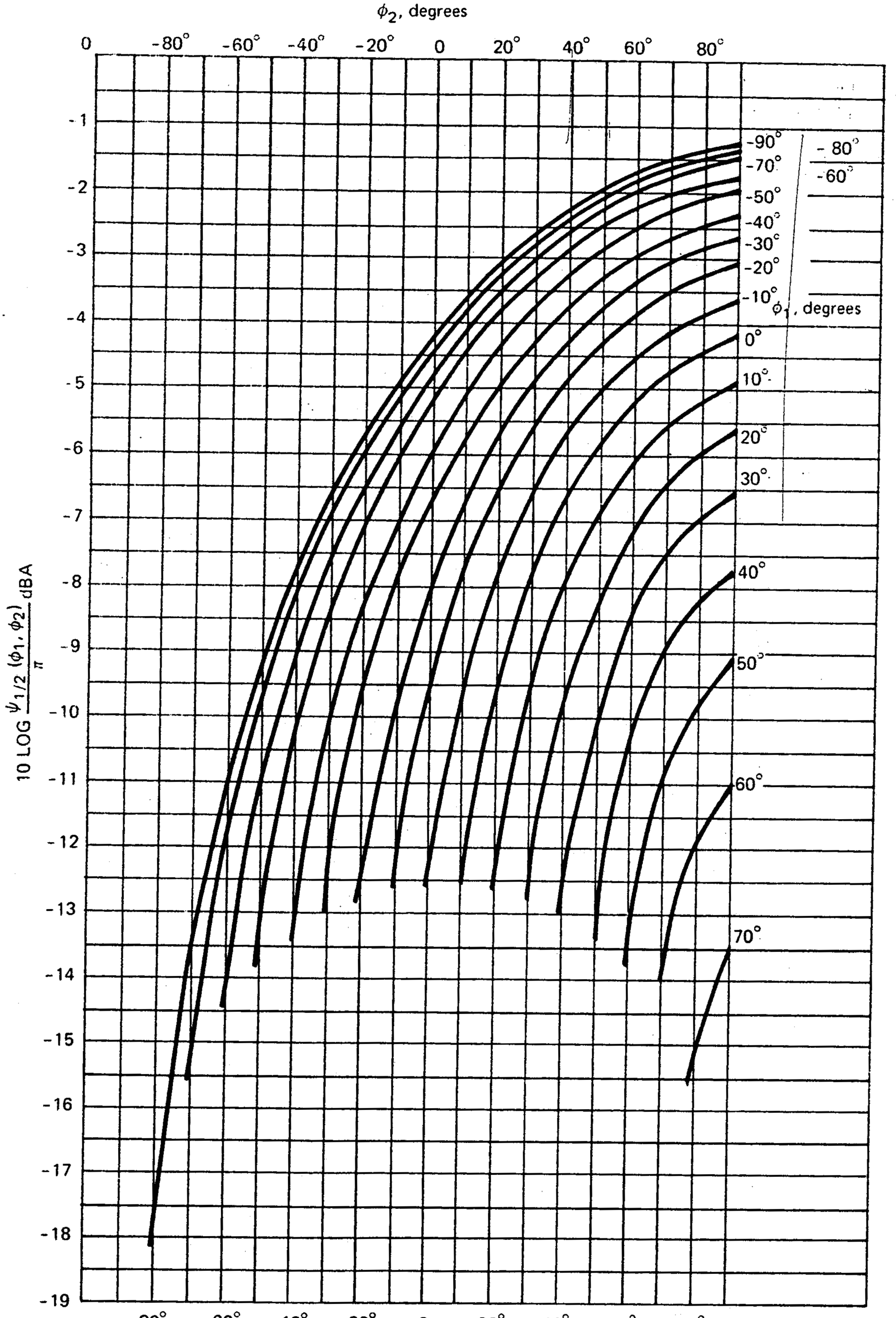
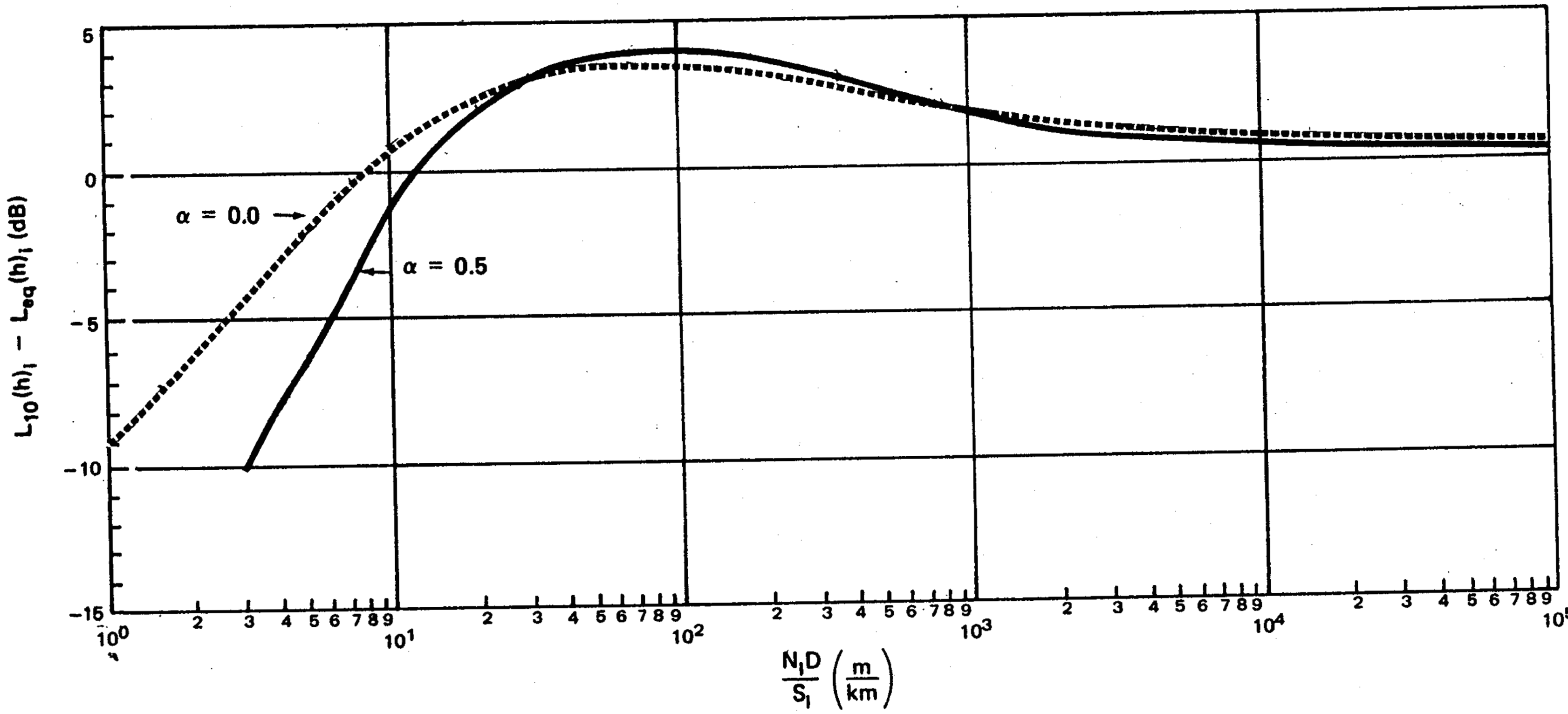


Figure 7. Adjustment Factor for Finite Length Roadways for Absorbing Sites ($\alpha = 1/2$)



(SOURCE: NCHRP REPORT NO. 173)

Figure 15. Adjustment Factor for Converting $L_{eq}(h)_i$ to $L_{10}(h)_i$

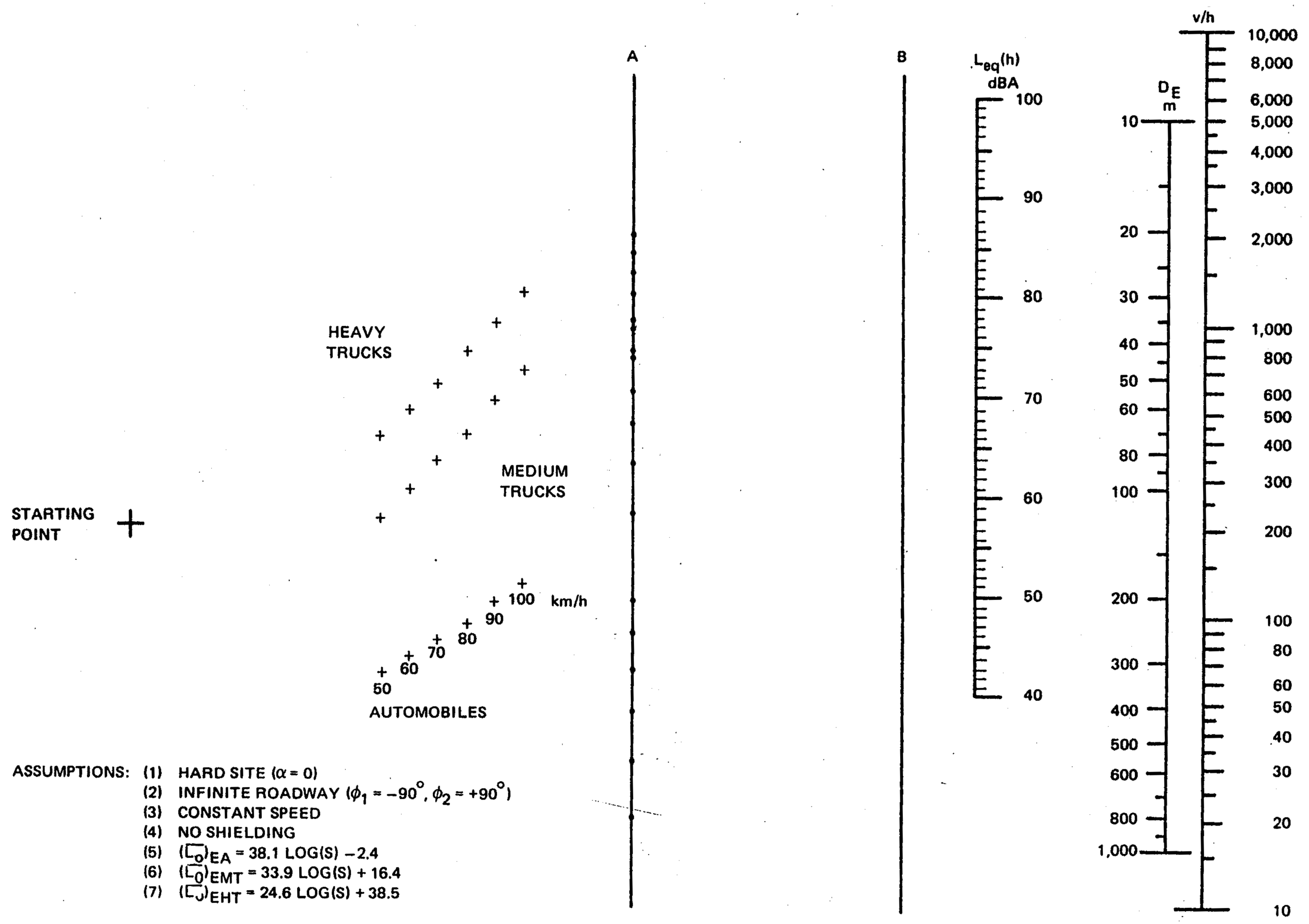


Figure 19. FHWA Highway Traffic Noise Prediction Nomograph (Hard Site)

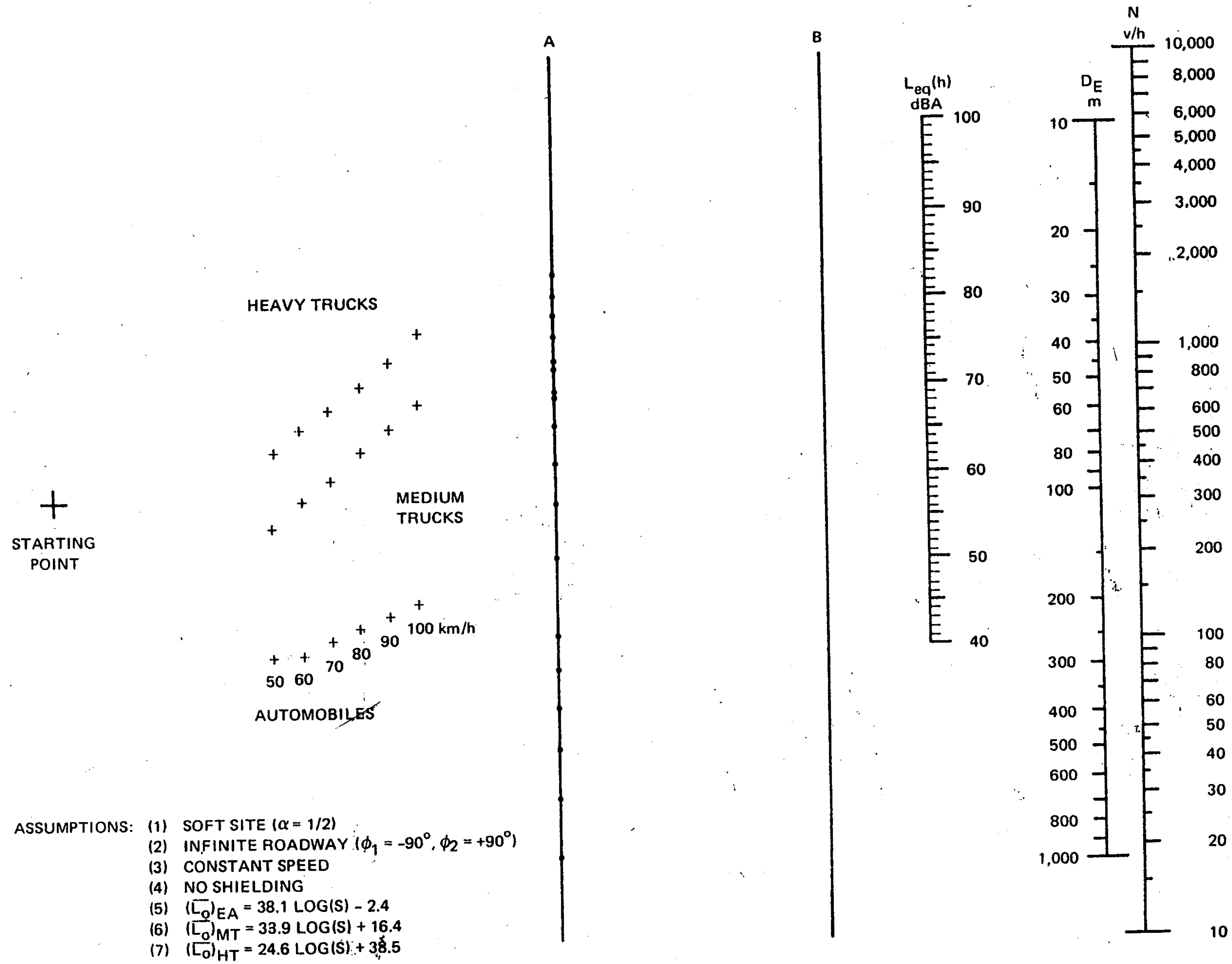
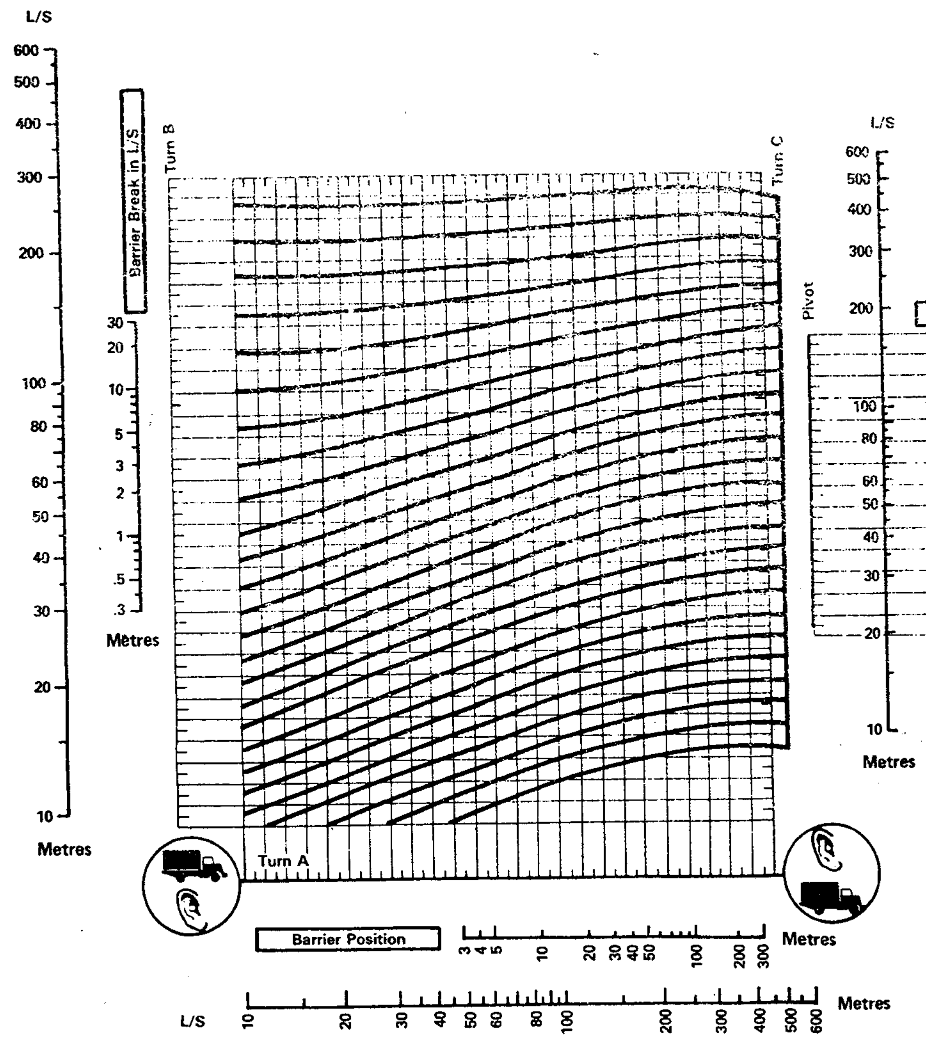
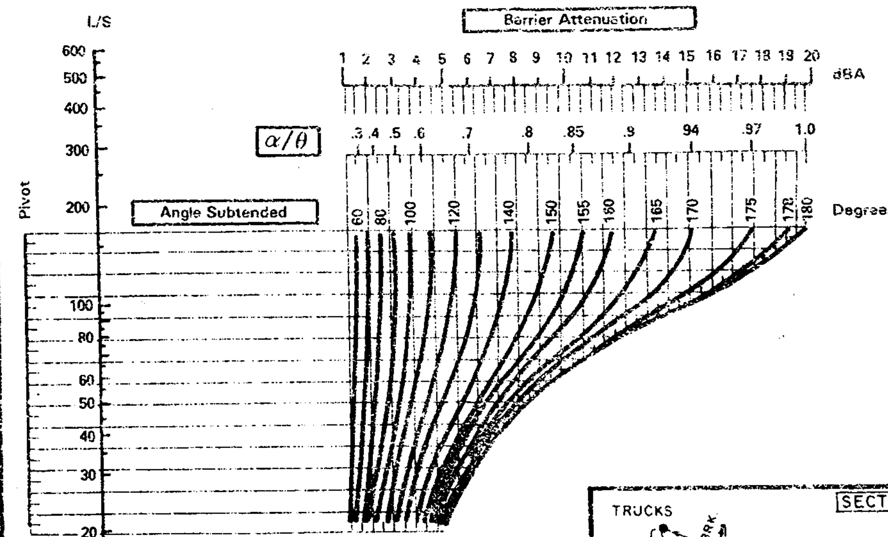


Figure 20. FHWA Highway Traffic Noise Prediction Nomograph (Soft Site)

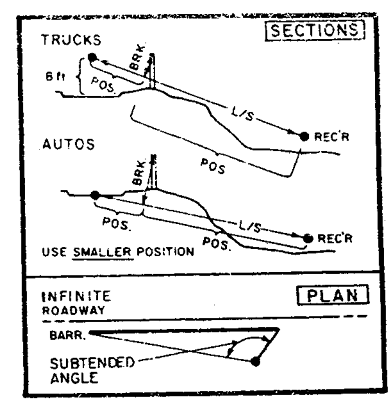
*U.S. GOVERNMENT PRINTING OFFICE: 1991.312.687/55546





Assumptions:

1. Spreading losses over the top of the barrier are 3 dB/DD.
2. Spreading losses from leakage around the ends are 4.5 dB/DD.
3. The nomograph translates all finite barriers, regardless of position, to $\Phi_L = -\pi/2$, $\Phi_R = \Delta\Phi - \pi/2$



Project:

Barrier Description:

Engineer:

Date:

Figure 21. Barrier Nomograph

Figure 21. Barrier Nomograph

L-11

FEDERALLY COORDINATED PROGRAM OF HIGHWAY RESEARCH AND DEVELOPMENT (FCP)

The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote to these projects.*

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

6. Prototype Development and Implementation of Research

This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

7. Improved Technology for Highway Maintenance

Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.

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* The complete 7-volume official statement of the FCP is available from the National Technical Information Service (NTIS), Springfield, Virginia 22161 (Order No. PB 242057, price $45 postpaid). Single copies of the introductory volume are obtainable without charge from Program Analysis (HRD-2), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.