FHWA-RD-77-108
FHWA HIGHWAY TRAFFIC NOISE
PREDICTION MODEL

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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

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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.

Timothy M. Barry, Sc.D.
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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:

$$
\begin{aligned}
L_{eq}(h)_i = {} & (\overline{L_o})_{E_i} && \text{reference energy mean emission level} \\
& +10\log\left(\frac{N_i \pi D_o}{S_i T}\right) && \text{traffic flow adjustment} \\
& +10\log\left(\frac{D_o}{D}\right)^{1+\alpha} && \text{distance adjustment} \\
& +10\log\left(\frac{\psi_\alpha(\phi_1, \phi_2)}{\pi}\right) && \text{finite roadway adjustment} \\
& +\Delta_s && \text{shielding adjustment} \qquad (1)
\end{aligned}
$$

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:

$$L_{eq}(h) = 10 \log \left(10^{\frac{L_{eq}(h)_A}{10}} + 10^{\frac{L_{eq}(h)_{MT}}{10}} + 10^{\frac{L_{eq}(h)_{HT}}{10}} \right). \qquad (2)$$

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:

$$L_{10}(h) = 10 \log \left(10^{\frac{L_{10}(h)_A}{10}} + 10^{\frac{L_{10}(h)_{MT}}{10}} + 10^{\frac{L_{10}(h)_{HT}}{10}} \right). \qquad (3)$$

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.

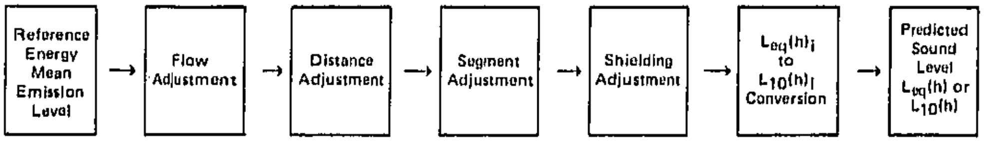


Figure 1. Flow Diagram of the Computational Sequence Used in the FHWA Model

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. 6																		
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_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.	$L_{eq}(h)_i$ (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:

$$(\overline{L_o})_{E_A} = 38.1 \log (S) - 2.4 \tag{4}$$

$$(\overline{L_o})_{E_{MT}} = 33.9 \log (S) + 16.4 \tag{5}$$

$$(\overline{L_o})_{E_{HT}} = 24.6 \log (S) + 38.5 \tag{6}$$

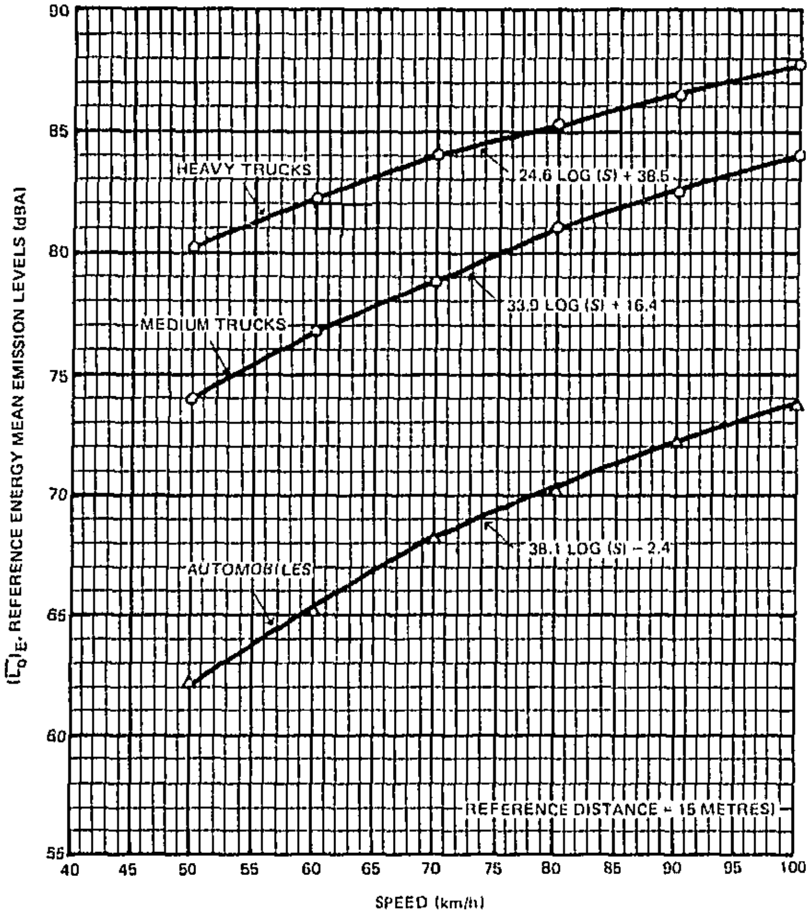
where S is the average vehicle speed of the vehicle class in km/h.

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).

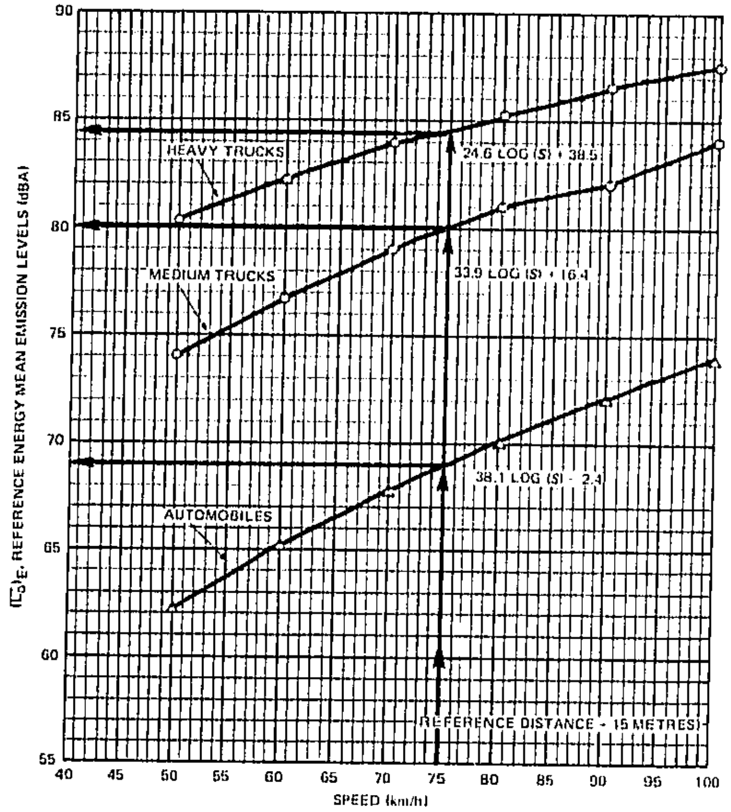


Figure 1-1. Reference Energy Mean Emission Levels as a Function of Speed

(Continued)

PROBLEM 1 (Continued)

NAME ______________________
DATE ______________________

PROJECT DESCRIPTION PROBLEM 1

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.	$(\bar{L}_o)_{E_i}$ (dBA)	Fig. 2	69.	80.	84.5															
9.	10 LOG ($N_i D_0/S_i$) (dB)	Fig. 3																		
10a.	10 LOG (D_0/D) (dBA)	Fig. 4																		
10b.	15 LOG (D_0/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.	$\bar{\delta}_0$ (metres)	Fig. 9																		
15.	N_0	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.	$L_{eq}(h)_i$ (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

$$10 \log (N_i \pi D_o / T S_i) \, . \tag{7}$$

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 $10 \log (N_i \pi D_o / T S_i)$ 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

$$10 \log \left(\frac{N_i D_o}{S_i} \right) - 25 \, . \tag{8}$$

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.

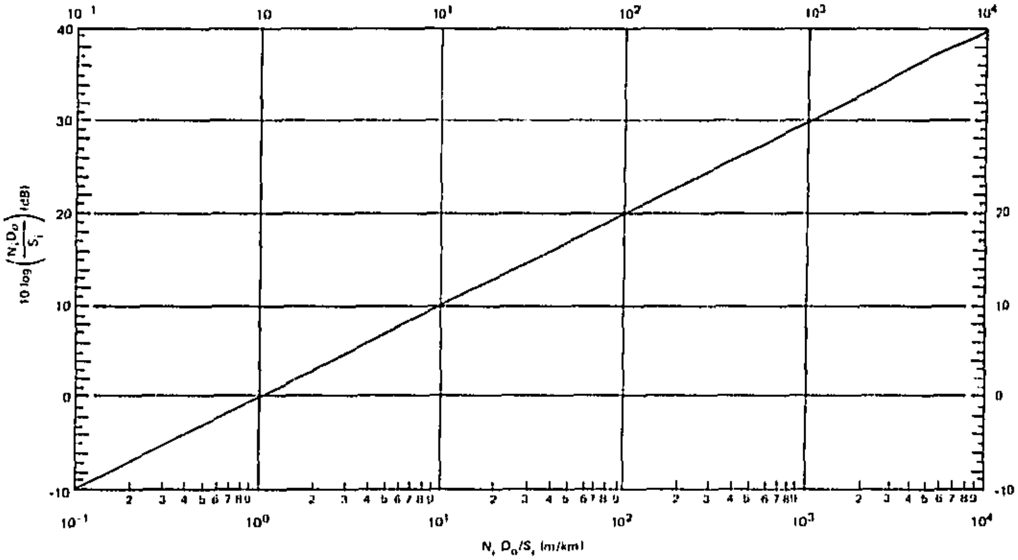


Figure 3. Adjustment for Real Traffic Flows

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)

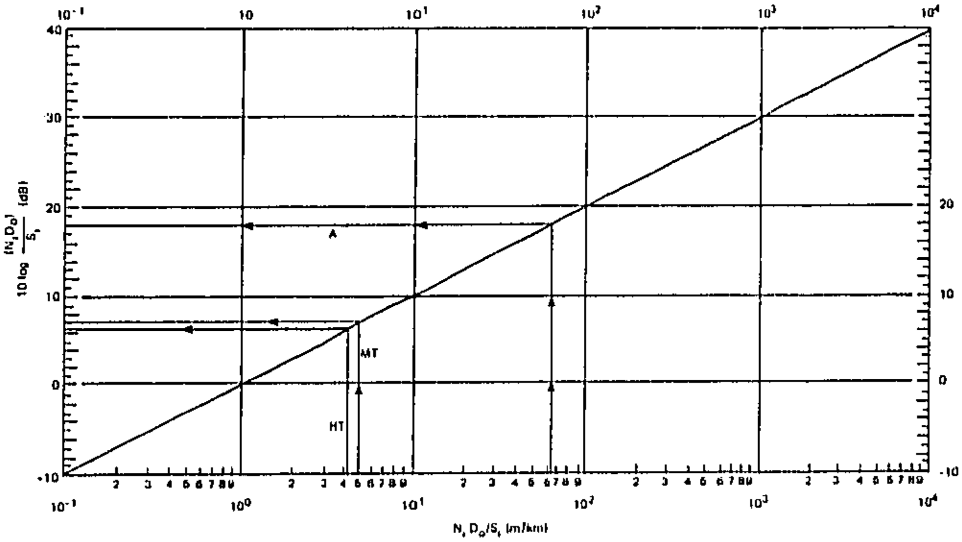


Figure 2-1. Adjustment for Real Traffic Flows

(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 $(\psi_\alpha(\phi_1, \phi_2)/\pi)$ (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 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)
$+10 \log \left(\frac{N_i D_o}{S_i}\right)$	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

$$10 \log \left(\frac{D_o}{D}\right)^{1+\alpha} \qquad (9)$$

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

$$10 \log \left(\frac{D_o}{D}\right) \qquad (10)$$

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

$$15 \log \left(\frac{D_o}{D}\right) \qquad (11)$$

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.

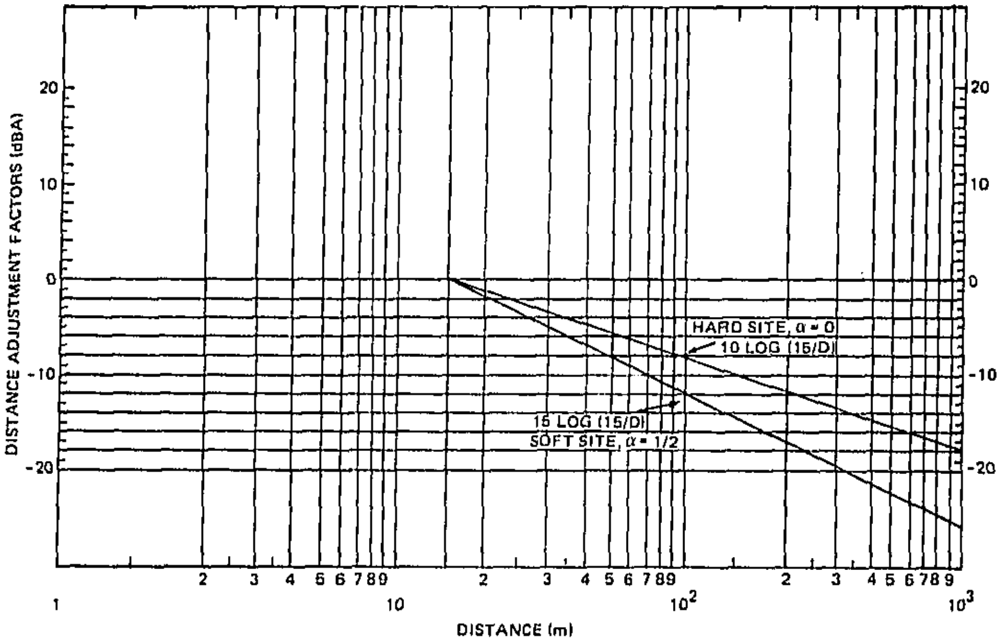


Figure 4. Adjustments for Distances Other than 15 Metres

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.

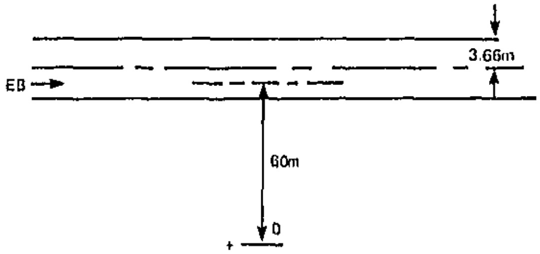


Figure 3-1. Highway Site Geometry for Problem 3

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)

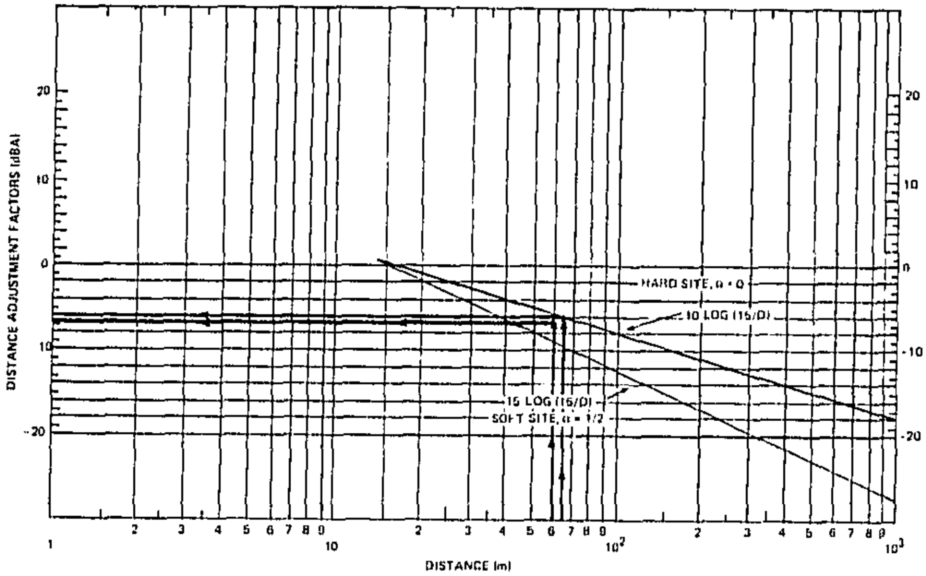


Figure 3-2. Adjustments for Distances Other than 15 Metres

(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 $(\psi_0(\phi_1, \phi_2)/\pi)$ (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 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 Segment*

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

$$\Delta\phi = \phi_2 - \phi_1 \qquad (12)$$

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.

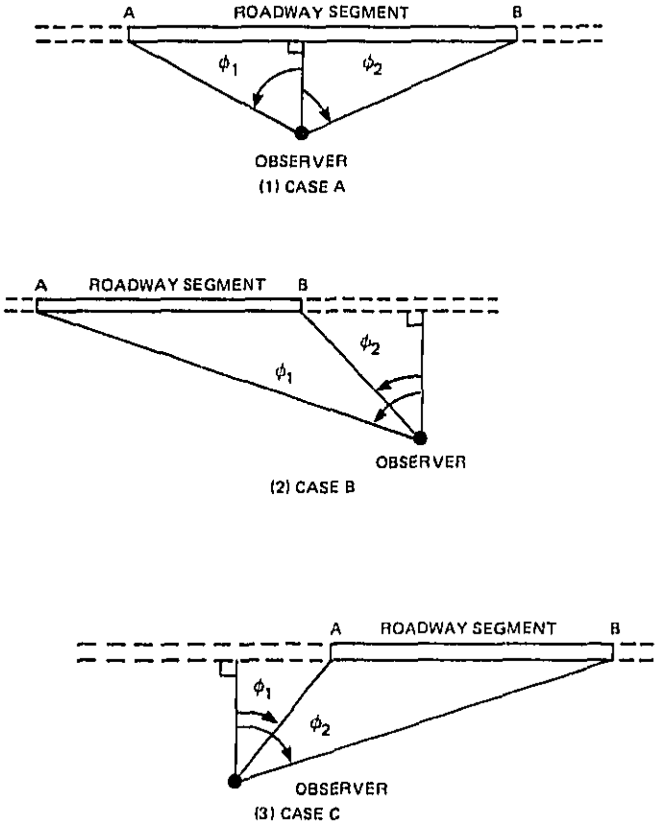


Figure 5. Angle Identification of Roadway Segments

PROBLEM 4

Determine ϕ_1 and ϕ_2 for the segments shown in Figure 4-1. Use $\Delta\phi$ to check the answers.

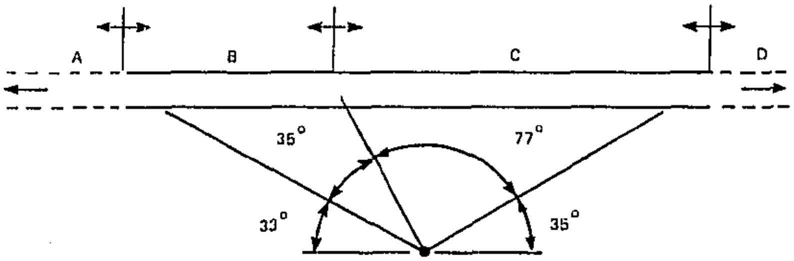


Figure 4-1. Highway Site Geometry for Problem 4

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.

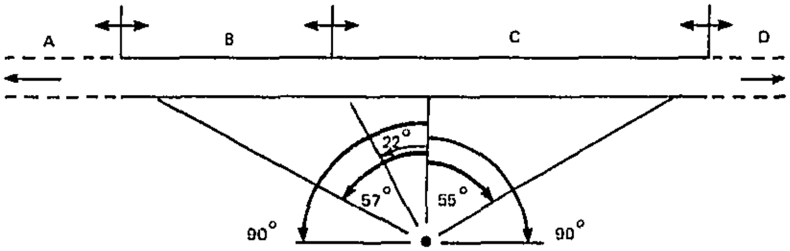


Figure 4-2. Identification of Angles for Problem 4

(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: $\phi_1 = -90^\circ \quad \phi_2 = -57^\circ$

$$\text{Check } \Delta\phi = \phi_2 - \phi_1 = -57^\circ - (-90^\circ) = \underline{+33^\circ}$$

($\Delta\phi$ is the included angle for segment A, Figure 4-2).

2. Segment B: $\phi_1 = -57^\circ, \quad \phi_2 = -22^\circ$

$$\text{Check } \Delta\phi = \phi_2 - \phi_1 = -22^\circ - (-57^\circ) = \underline{+35^\circ}$$

($\Delta\phi$ is the included angle for segment B).

3. Segment C: $\phi_1 = -22^\circ \quad \phi_2 = +55^\circ$

$$\text{Check } \Delta\phi = \phi_2 - \phi_1 = 55^\circ - (-22^\circ) = \underline{+77^\circ}$$

($\Delta\phi$ is the included angle for segment C).

4. Segment D: $\phi_1 = 55^\circ \quad \phi_2 = 90^\circ$

$$\text{Check } \Delta\phi = \phi_2 - \phi_1 = 90^\circ - 55^\circ = \underline{+35^\circ}$$

($\Delta\phi$ 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.	$(\overline{L_o})E_i$ (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 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

$$10 \log \left(\frac{\psi_\alpha(\phi_1, \phi_2)}{\pi} \right) \tag{13}$$

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.

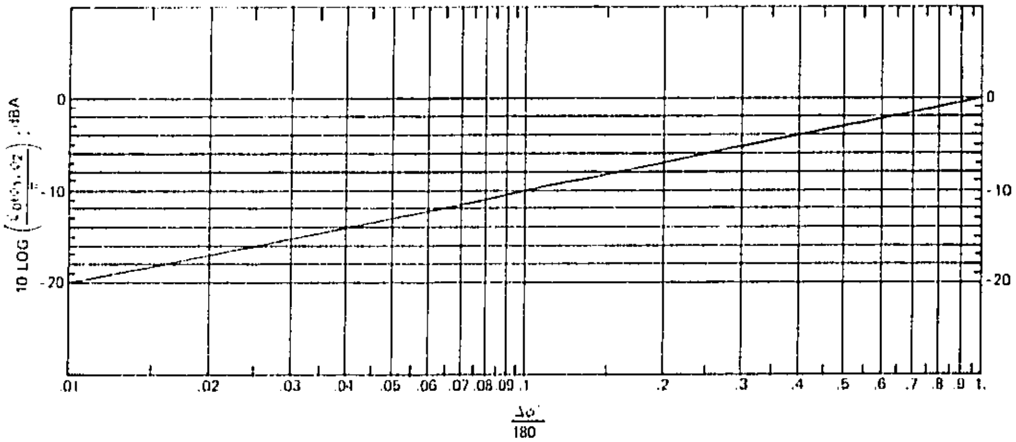


Figure 6. Adjustment Factor for Finite Length Roadways for Hard Sites ($\alpha = 0$)

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.

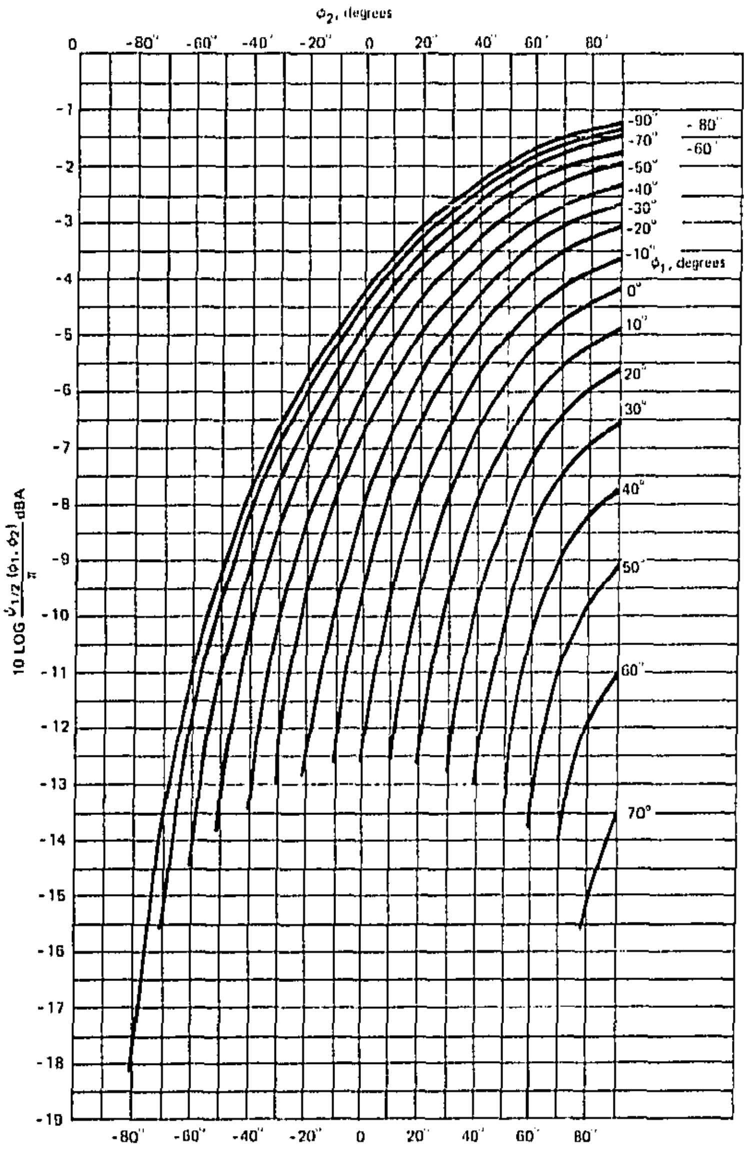


Figure 7. Adjustment Factor for Finite Length Roadways for Absorbing Sites ($\alpha = 1/2$)

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: $\phi_1 = -90°$, $\phi_2 = -57°$, $\Delta\phi = 33°$

$$\frac{\Delta\phi}{180} = \frac{33}{180} = .18$$

Adjustment (Figure 5-1) = $\underline{\underline{-7.5 \text{ dBA}}}$

2. Segment B: $\phi_1 = -57°$, $\phi_2 = -22°$, $\Delta\phi = 35°$

$$\frac{\Delta\phi}{180} = \frac{35}{180} = .19$$

Adjustment (Figure 5-1) = $\underline{\underline{-7. \text{ dBA}}}$

3. Segment C: $\phi_1 = -22°$, $\phi_2 = +55°$, $\Delta\phi = 77°$

$$\frac{\Delta\phi}{180} = \frac{77}{180} = .43$$

Adjustment (Figure 5-1) = $\underline{\underline{-3.5 \text{ dBA}}}$

4. Segment D: $\phi_1 = +55°$, $\phi_2 = +90$, $\Delta\phi = 35°$

$$\frac{\Delta\phi}{180} = \frac{35}{180} = .19$$

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) = −10.5 dBA

2. Segment B: $\phi_1 = -57°$, $\phi_2 = -22°$

   Adjustment (Figure 5-2) = −7.5 dBA

3. Segment C: $\phi_1 = -22°$, $\phi_2 = +55°$

   Adjustment (Figure 5-2) = −4.0 dBA

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) = −10 dBA

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.

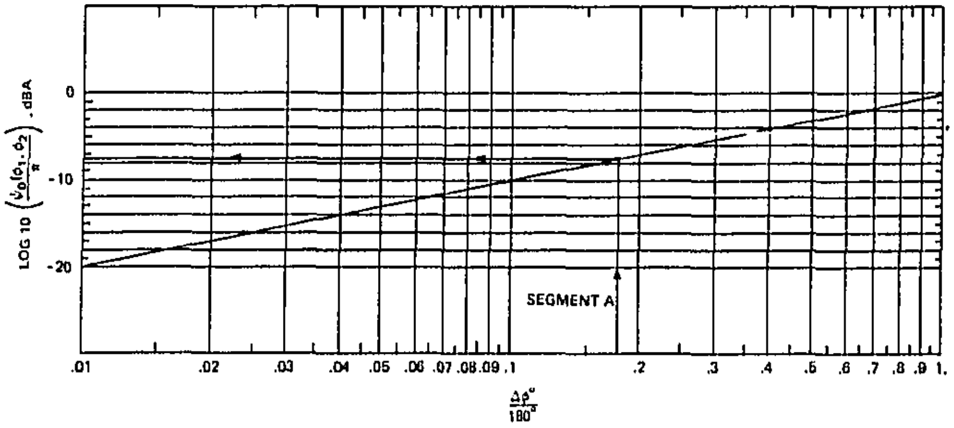


Figure 5-1. Adjustment Factor for Finite Length Roadways for Hard Sites (α = 0)

(Continued)

PROBLEM 5 (Continued)

NAME ____________________
DATE ____________________

PROJECT DESCRIPTION PROBLEM 5a (Hard Site)

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			-67			-22			+55								
7.	ϕ_2 (degrees)	Fig. 5	-67			-22			+55			+90								
8.	$(\overline{L_o})_{E_i}$ (dBA)	Fig. 2																		
9.	10 LOG $(N_i D_0/S_i)$ (dB)	Fig. 3																		
10a.	10 LOG (D_0/D) (dBA)	Fig. 4																		
10b.	15 LOG (D_0/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_\alpha(\phi_1, \phi_2)/\pi)$ (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_0 (metres)	Fig. 9																		
15.	N_0	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)

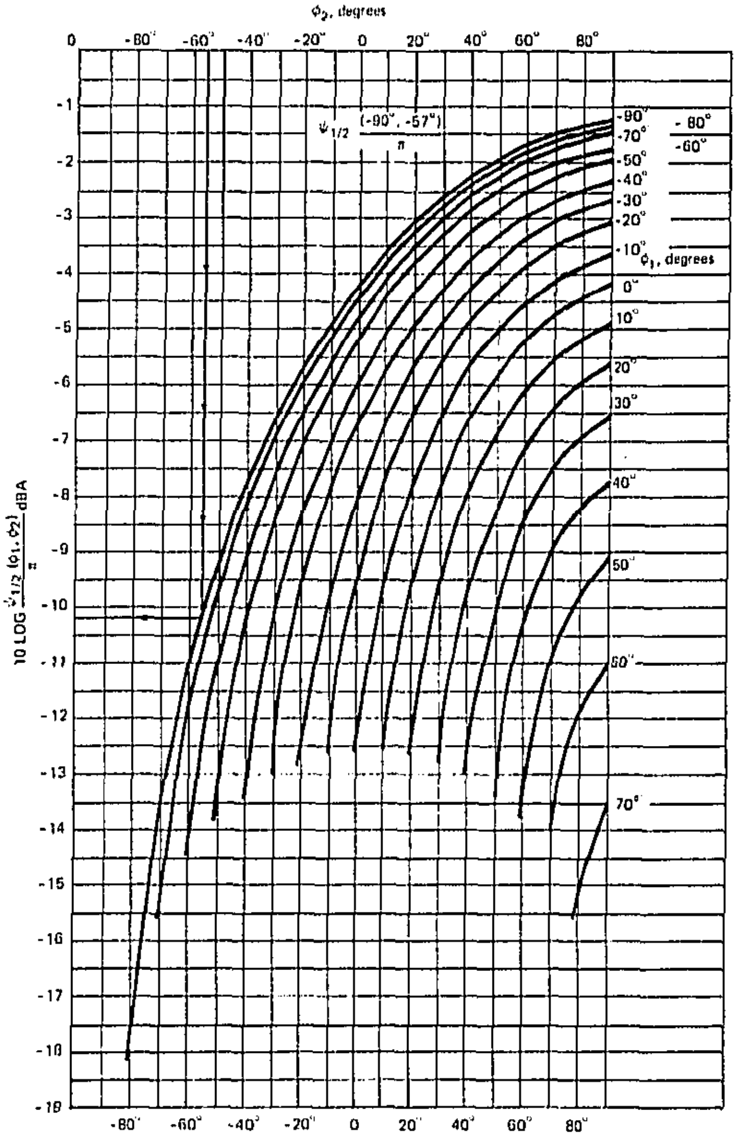


Figure 5-2. Adjustment Factor for Finite Length Roadways for Absorbing Sites ($\alpha = 1/2$)

(Continued)

PROBLEM 5 (Continued)

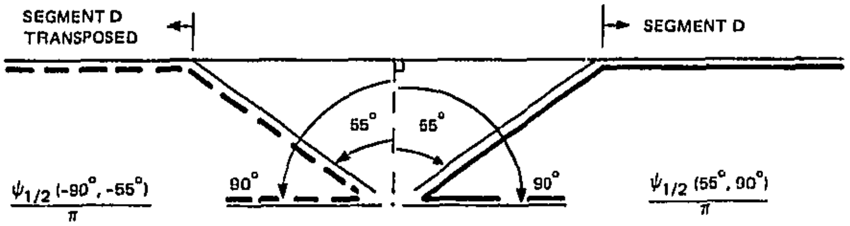


Figure 5-3

NAME ______________________

DATE ______________________

PROJECT DESCRIPTION PROBLEM 5b (Soft Site)

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			-67			-22			+55								
7.	ϕ_2(degrees)	Fig. 5	-67			-22			+55			+90								
8.	$(\overline{L_o})_{E_i}$ (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	-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_i (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.

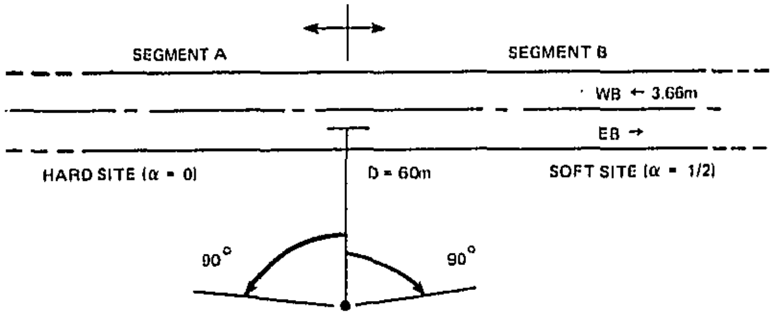


Figure 6-1

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 $(N_i D_o/S_i)$ (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 $(\psi_a(\phi_1, \phi_2)/\pi)$ (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.	$L_{eq}(h)_i$ (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) = 63.6			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.

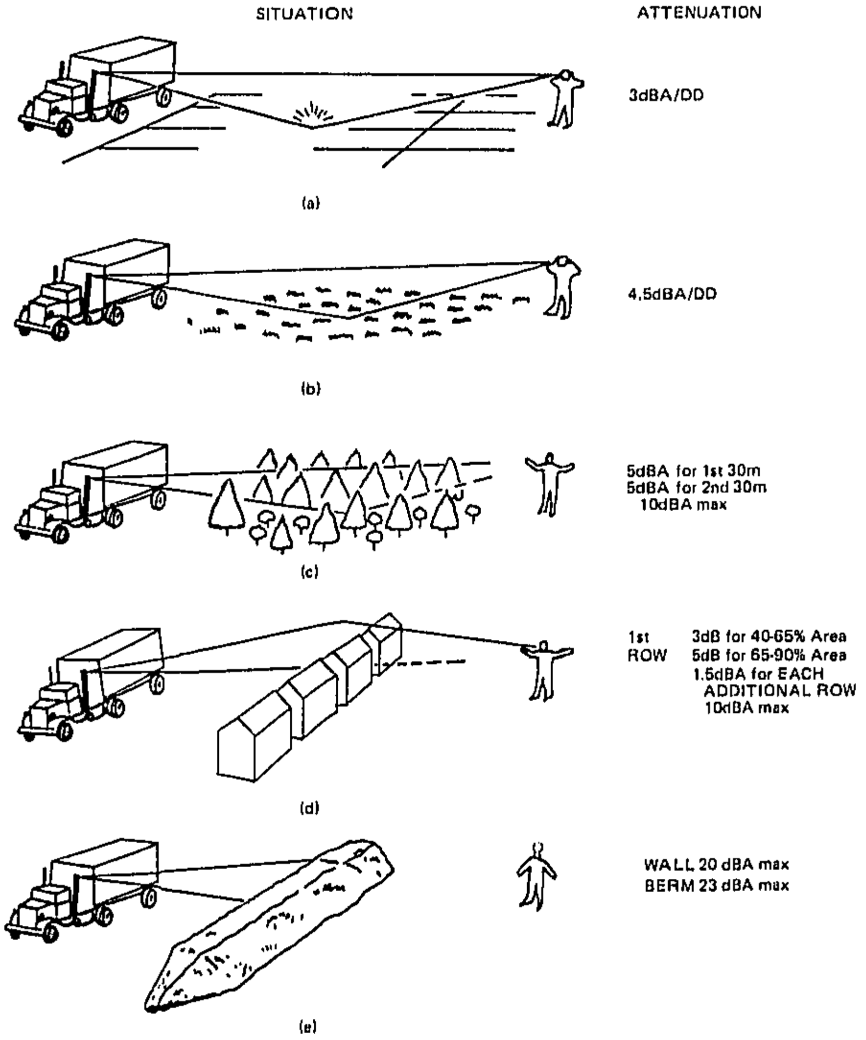


Figure 8. Attenuation of Highway Traffic Noise

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.

$$\text{Field Insertion Loss (I.L.)} = L\ (\text{Before}) - L\ (\text{After}) \qquad (14)$$

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

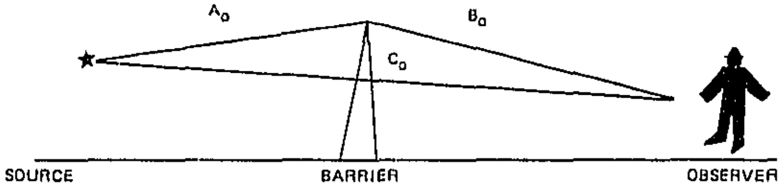


Figure 9. Pathlength Difference, δ_o

that the effective radiating frequency of highway traffic noise for all classes of vehicles is 550 Hz. Therefore, Equation (15) reduces to:

$$N_o = 2\left(\frac{\delta_o}{\lambda}\right) = 2\left(\frac{f\,\delta_o}{c}\right) = 2\left(\frac{550\,\delta_o}{343}\right) = 3.21(\delta_o) \text{ metres.} \qquad (18)$$

For barrier calculations only, the vehicle noise sources are assumed to be located at the following positions:

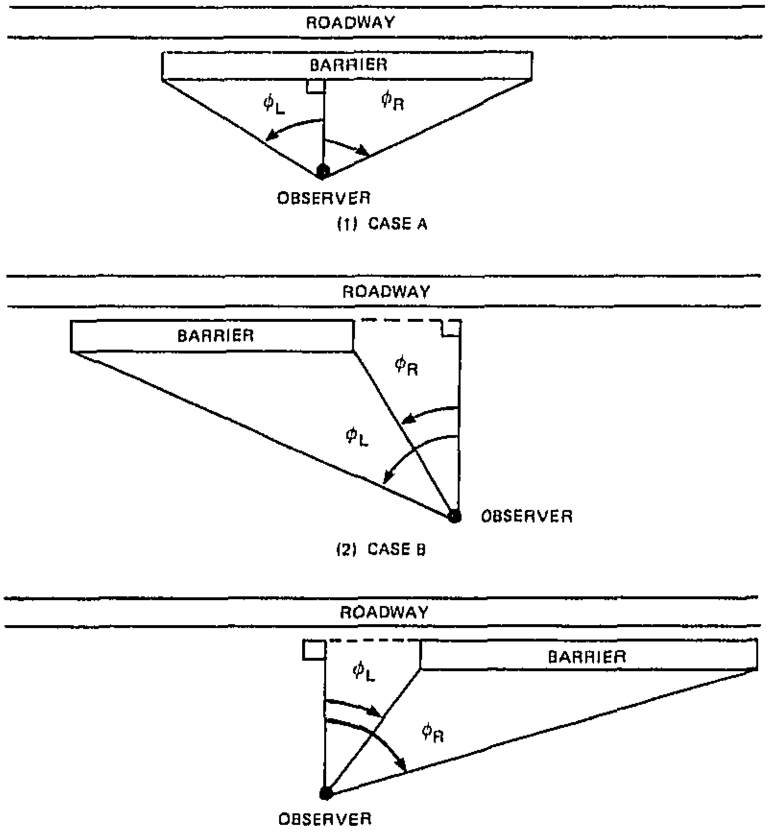
(1) Automobiles – 0 metres above the centerline of the lane.
(2) Medium Trucks – 0.7 metres above the centerline of the lane.
(3) Heavy Trucks – 2.44 metres above the centerline of the lane.

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 $\phi_R = +90°$.



(1) CASE A

(2) CASE B

(3) CASE C

Figure 10. Angle Identification of Barriers

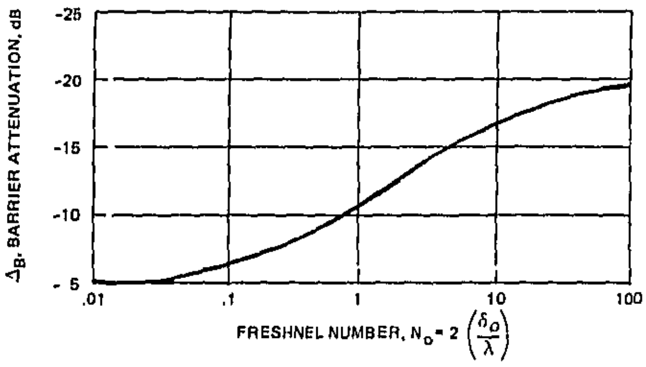


Figure 11. Barrier Attenuation vs Fresnel Number, N_o, for Infinitely Long Barriers

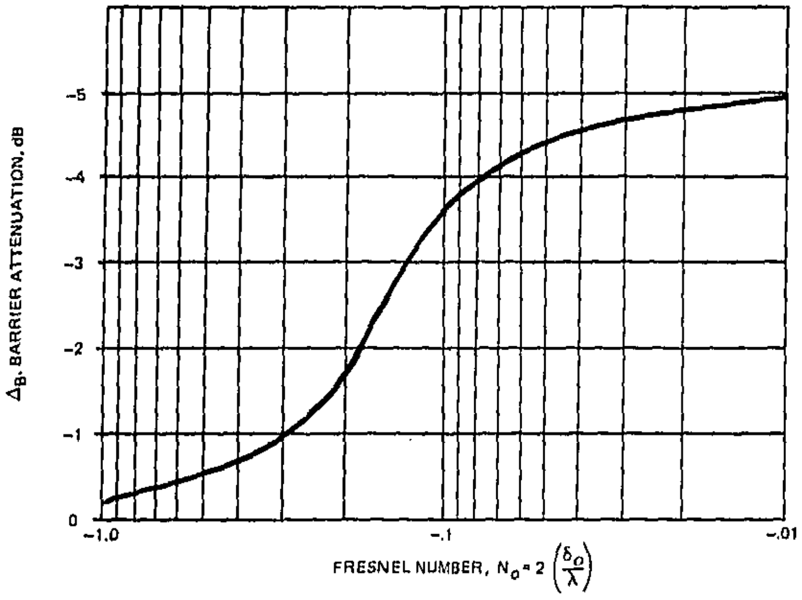


Figure 12. Barrier Attenuation vs Negative Fresnel Number, N_o, for Infinitely Long Barriers

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.

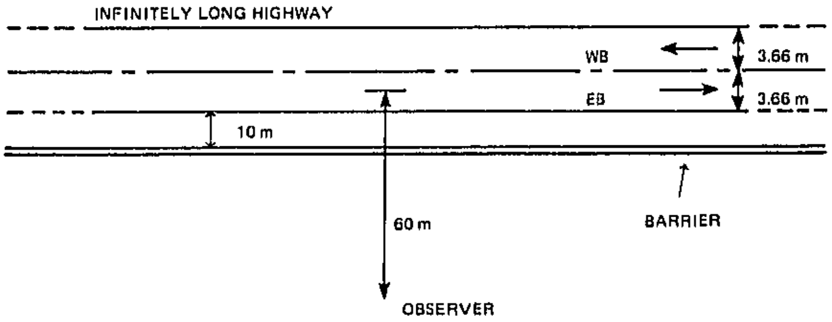


Figure 7-1. Highway Site Geometry for Problem 7

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.

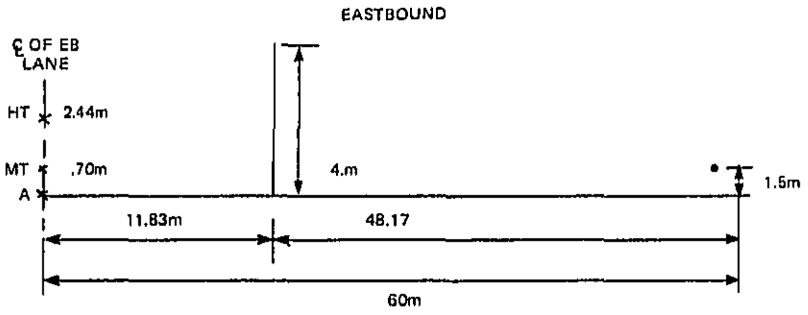


Figure 7-2. Barrier Geometry Used to Calculate Pathlength Differences (Eastbound Lanes)

$$\delta_A = \sqrt{(11.83)^2 + (4)^2} + \sqrt{(4\text{-}1.5)^2 + (48.17)^2} - \sqrt{(60)^2 + (1.5)^2}$$

$$= \underline{0.70\ \mathrm{m}}$$

$$\delta_{MT} = \sqrt{(11.83)^2 + (4.\text{-}.7)^2} + \sqrt{(4\text{-}1.5)^2 + (48.17)^2} - \sqrt{(60)^2 + (1.5\text{-}.7)^2}$$

$$= \underline{.51\ \mathrm{m}}$$

$$\delta_{HT} = \sqrt{(11.83)^2 + (4\text{-}2.44)^2} + \sqrt{(4\text{-}1.5)^2 + (48.17)^2} - \sqrt{(60)^2 + (2.44\text{-}1.5)^2}$$

$$= \underline{.16\ \mathrm{m}}\,.$$

(Continued)

PROBLEM 7 (Continued)

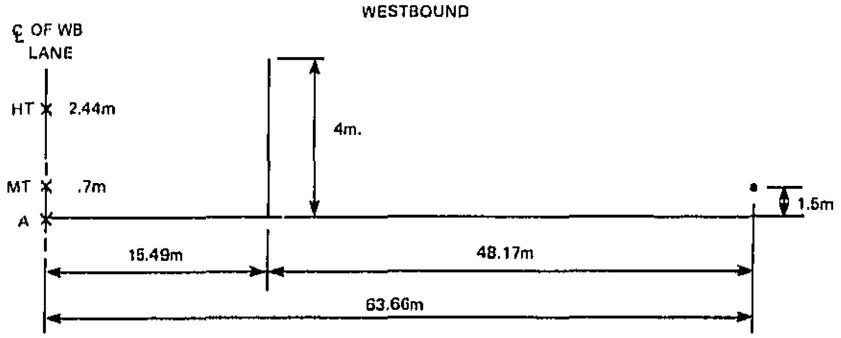


Figure 7-3. Barrier Geometry Used to Calculate Pathlength Differences (Westbound Lanes)

$$\delta_A = \sqrt{(15.49)^2 + (4)^2} + \sqrt{(48.17)^2 + (4\text{-}1.5)^2} - \sqrt{(63.66)^2 + (1.5)^2}$$

$$= \underline{.56\ \text{m}}$$

$$\delta_{MT} = \sqrt{(15.49)^2 + (4\text{-}.7)^2} + \sqrt{(48.17)^2 + (4\text{-}1.5)^2} - \sqrt{(63.66)^2 + (1.5\text{-}.7)^2}$$

$$= \underline{.41\ \text{m}}$$

$$\delta_{HT} = \sqrt{(15.49)^2 + (4\text{-}2.44)^2} + \sqrt{(48.17)^2 + (4\text{-}1.5)^2} - \sqrt{(63.66)^2 + (2.44\text{-}1.5)^2}$$

$$= \underline{.14\ \text{m}}$$

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

$\phi_L = -90°$ $\phi_R = +90°$ N_o (EB) $= 2.25$ $\Delta_B = ?$

$$\begin{array}{cc} \underline{N_o} & \underline{\Delta_B} \\ 1.0\left\{\begin{array}{l}\left.\begin{array}{l}2.0\\2.25\end{array}\right\}.25\\3.0\end{array}\right. & \qquad -1.3\left\{\begin{array}{l}\left.\begin{array}{l}-12.3\\\boxed{}\end{array}\right\}x\\-13.6\end{array}\right. \end{array}$$

$$\frac{.25}{1.0} = \frac{x}{-1.3} \qquad x = -.3$$

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.	$(\overline{L_0})_{E_i}$ (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 $(N_i D_0/S_i)$ (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_0/D) (dBA)	Fig. 4	-6.			-6.5			-6.			-6.5			-6			-6.5		
10b.	15 LOG (D_0/D) (dBA)	Fig. 4																		
11a.	10 LOG $(\psi_0(\phi_1, \phi_2)/\pi)$ (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_i (metres)	Fig. 9							.70	.51	.16	.56	.41	.14	.70	.51	.16	.56	.41	.14
15.	N_0	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	-11.0	-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.	$L_{eq}(h)_i$ (dBA)		56.	58.	60.	56.	62.5	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 $N_0 = 2.00$, $\phi_L = -90°$ 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 $\phi_R = +70°$?

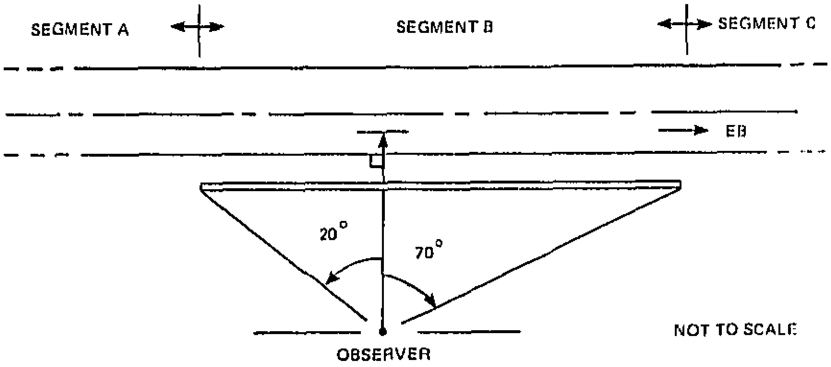


Figure 8-1. Highway Site Geometry for Problem 8

SOLUTION

The solution of this problem requires that the highway be broken down into three segments:

$$\begin{array}{lll} \text{Segment A} & \phi_1 = -90°, & \phi_2 = -20° \\ \text{Segment B} & \phi_1 = -20°, & \phi_2 = +70° \\ \text{Segment C} & \phi_1 = +70°, & \phi_2 = +90°. \end{array}$$

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 $(\Delta\phi/180^\circ) = 10 \log (90^\circ/180^\circ) = \underline{-3 \text{ dB}}$. Enter this value on Line 11(a), Table 8-1.

Step 2. The problem indicates that a barrier extended from $\phi_L = -20^\circ$ to $\phi_R = +70^\circ$. 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. $\phi_L = -20^\circ$, $\phi_R = +70^\circ$.

EXAMPLE

$$\begin{array}{ccc} \underline{N_0} & \qquad & \underline{\Delta_B} \\ \left.\begin{array}{l}\left.\begin{array}{r}2.00\\2.25\end{array}\right\} .25\\ 3.00\end{array}\right\} 1 & \qquad & \left.\begin{array}{l}\left.\begin{array}{r}-14.8\\ \end{array}\right\} x\\ -16.5\end{array}\right\} -1.7 \end{array}$$

$$\frac{.25}{1} = \frac{x}{-1.7} \qquad x = -.4$$

$$\Delta_B(N_0 = 2.25) = -14.8 + (-.4) = \underline{-15.2 \text{ dB}}.$$

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 $(20^\circ/180^\circ) = \underline{-9.5 \text{ dB}}$.

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 ______________________

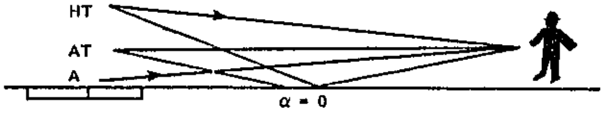
			SEGMENT A						SEGMENT B						SEGMENT C					
1.	LANE NO./ROAD SEGMENT		EB			WB			EB			WB			EB			WB		
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		317	24	22	281	12	26	317	24	22	281	12	26	317	24	22	281	12	26
4.	S(km/h)		–	75	–	–	75	–	–	75	–	–	75	–	–	75	–	–	75	–
5.	D(m)		60.			64.			60.			64.			60.			64.		
6.	ϕ_1 (degrees)	Fig. 5	-90			-90			-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_iD_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 $(\psi_0(\phi_1,\phi_2)/\pi)$ (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	.19	.56	.41	.14						
15.	N_o	Eq. 18							2.26	1.64	.61	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)		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 ($\alpha = 0$)

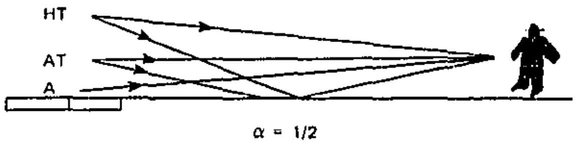
Situation	Problem 7 Infinite Barrier	Problem 8 Finite Barrier
$L_{eq}(h)$, Before Barrier	65.1 dBA	65.1 dBA
$L_{eq}(h)$, After Barrier	55.7 dBA	62.5 dBA
Net Reduction (I.L.)	9.4 dBA	2.6 dBA

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.).

$$\text{I.L.} = L\,(\text{Before}) - L\,(\text{After})\ \text{dB}\,. \tag{19}$$

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).



(a) Without the Barrier

(b) With the Barrier

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 ______________________
DATE ______________________

PROJECT DESCRIPTION PROBLEM 9

			(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	26	317	24	22	281	12	26												
4.	S(km/h)		–	76	–	–	76	–	–	76	–	–	76.	–	–											
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.	$(\overline{L_o})_{E_i}$ (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.	6.6	17.6	4.	7.	18.	7.	6.6	17.6	4.	7.												
10a.	10 LOG (D_o/D) (dBA)	Fig. 4							-6.			-6.5														
10b.	15 LOG (D_o/D) (dBA)	Fig. 4	-9.			-9.6																				
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	.61	.18	.66	.41	.14												
15.	N_o	Eq. 18							2.26	1.84	.61	1.80	1.32	.46												
16.	Δ_B (dBA)	Appendix B							-12.7	-11.6	-8.6	-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	51.6	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	34	22	281	12	28	317	34	22	281	12	28	317	34	22	281	12	28
4.	S(km/h)		–	78	–	–	78	–	–	78	–	–	78	–	–	78	–	–	78	–
5.	D(m)		60			64			60			64			60			64		
6.	ϕ_1 (degrees)	Fig. 5	-80			-80			-30			-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 $(N_i D_0/S_i)$ (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_0/D) (dBA)	Fig. 4							-6.			-6.6								
10b.	15 LOG (D_0/D) (dBA)	Fig. 4	-9.			-9.6									-9.			-9.6		
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			-13.6		
12.	ϕ_L (degrees)	Fig. 10							-30			-20								
13.	ϕ_R (degrees)	Fig. 10							+70			+70								
14.	δ_0 (metres)	Fig. 9							.70	.61	.16	.88	.41	.14						
15.	N_0	Eq. 18							2.28	1.84	.61	1.80	1.32	.46						
16.	Δ_B (dBA)	Appendix B							-15.2	-13.8	-9.5	-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	46.6	44.	51.6	37.8	39.2	47.4	37.7	38.6	47.7	39.8	39.5	43.5	38.5	38.	43.6
19.	$L_{eq}(h)$ (dBA)		54.			53.2			48.4			48.4			46.			45.2		
20.	Δ_t (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. 16																		
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

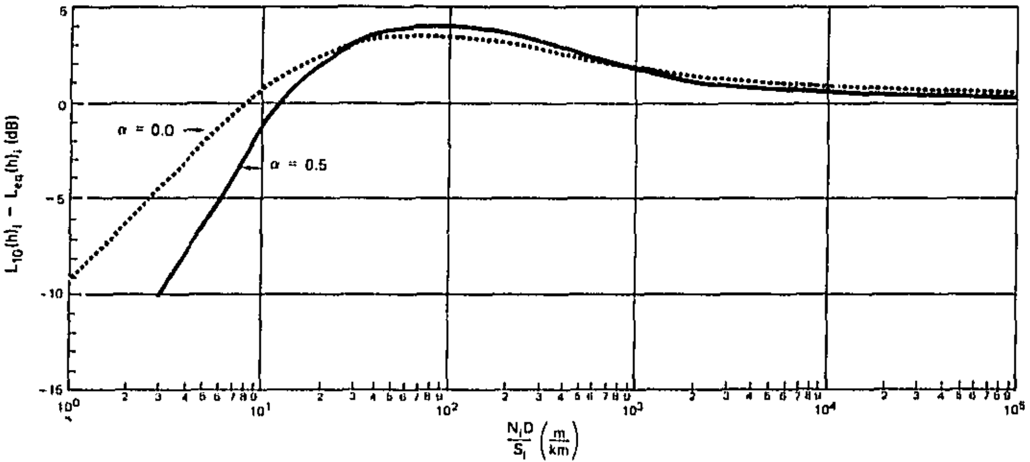
Users of this manual can now predict the equivalent sound level produced by a class of vehicles traveling at constant speed at a shielded or unshielded observer.

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.



(SOURCE: NCHRP REPORT NO. 173)

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:

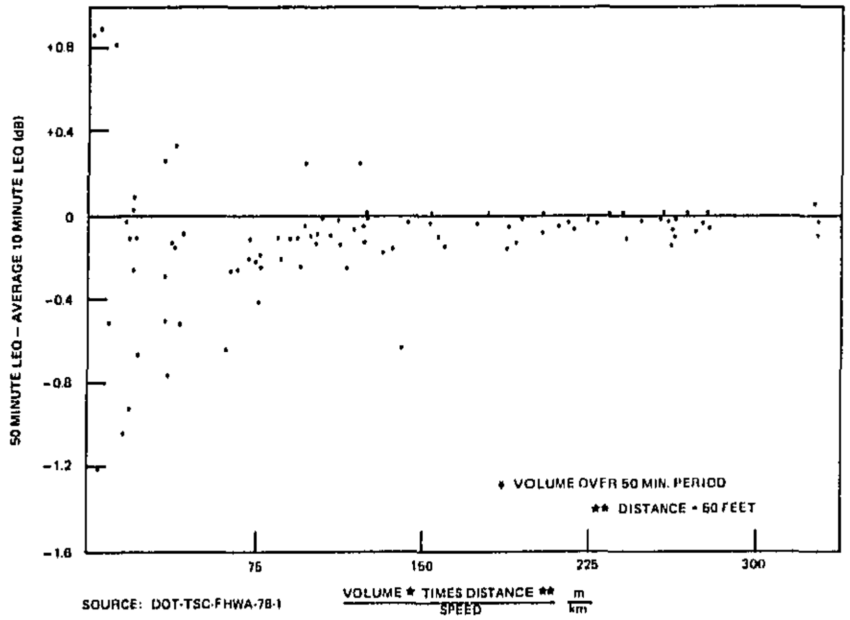
(1) The noise emission levels used in the predictive models are based on large sample populations—i.e., the reference energy mean emission levels are average values. On low volume roadways, where there are only a few vehicles of a particular group, large deviations may exist between the average values 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.

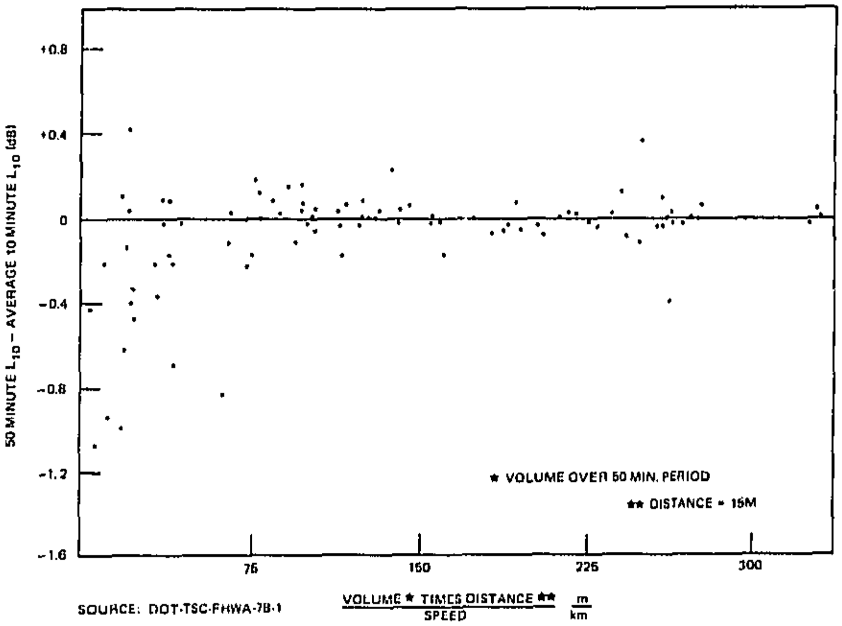
Each point on these figures represents an average difference between one 50-minute sample and the averaging of the five 10-minute samples. Thus, it is quite clear that when ND/S is less than 40 m/km, the variability between the 10-minute samples and the 50-minute sample increases. The graph also suggests 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].



SOURCE: DOT-TSC-FHWA-78-1

Figure 16. Data Sampling Comparison L_{eq}
(Composite all sites, all states)



SOURCE: DOT-TSC-FHWA-78-1

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 ______________________
DATE ______________________
PROJECT DESCRIPTION PROBLEM 11

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)		60.			64.														
6.	ϕ_1 (degrees)	Fig. 6																		
7.	ϕ_2 (degrees)	Fig. 6																		
8.	$(\overline{L_o})E_i$ (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_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)		56	56	60	56	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	59	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)
$+10\log\left(\frac{N_i D_c}{S_i}\right)$	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.

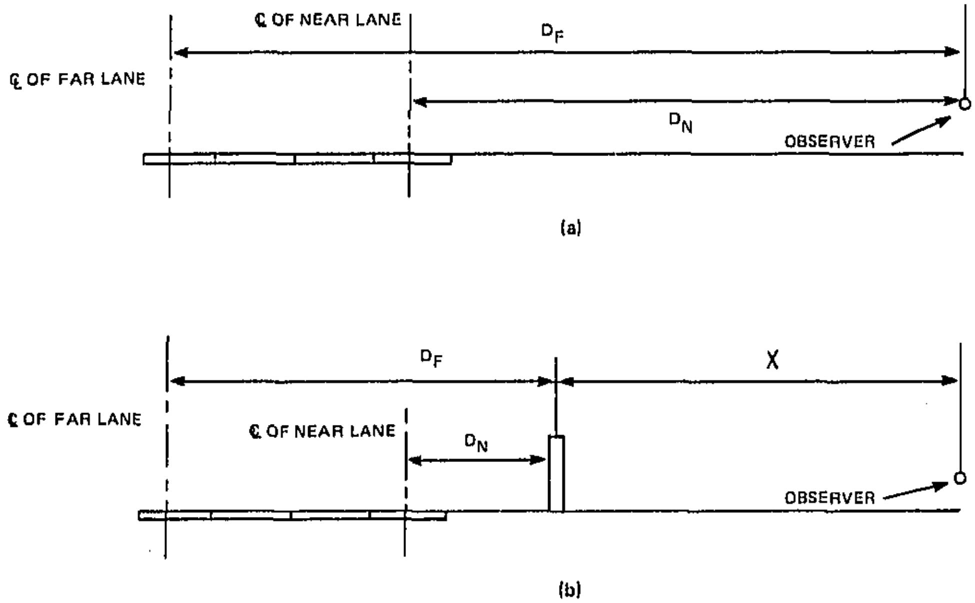


Figure 18. Equivalent Lane Distances

PROBLEM 12

A typical highway scenario is shown in the sketch below. Compute the equivalent lane distances with and without the barrier.

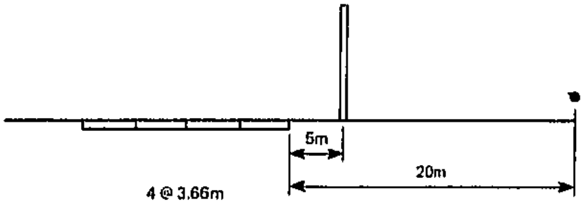


Figure 12-1

(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)

$$\begin{aligned} D_E &= \sqrt{(6.83)(17.81)} + 15 \\ &= 11.03 + 15 \\ &= \underline{26.03\ \text{m}} \end{aligned}$$

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.

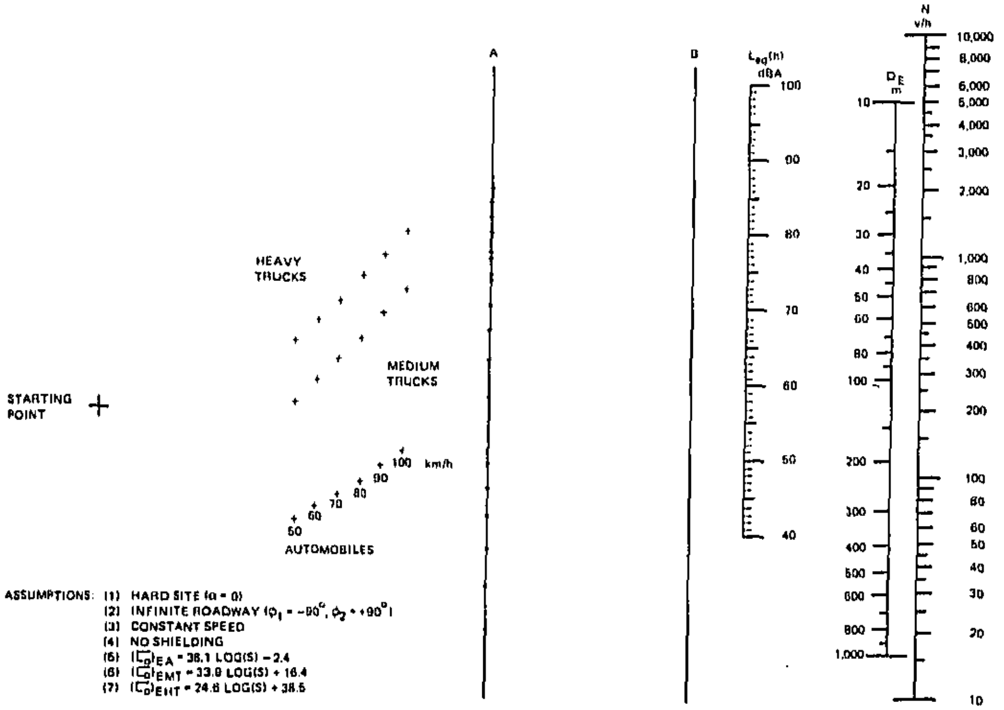


Figure 19. FHWA Highway Traffic Noise Prediction Nomograph (Hard Site)

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

$$L_{eq}(h)_{\rm A} = 28.1 \log S_{\rm A} + 10 \log N_{\rm A} - 15 \log D + 0.8 \qquad (31)$$

$$L_{eq}(h)_{\rm MT} = 23.9 \log S_{\rm MT} + 10 \log N_{\rm MT} - 15 \log D + 19.6 \qquad (32)$$

$$L_{eq}(h)_{\rm HT} = 14.6 \log S_{\rm MT} + 10 \log N_{\rm HT} - 15 \log D + 41.7. \qquad (33)$$

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.

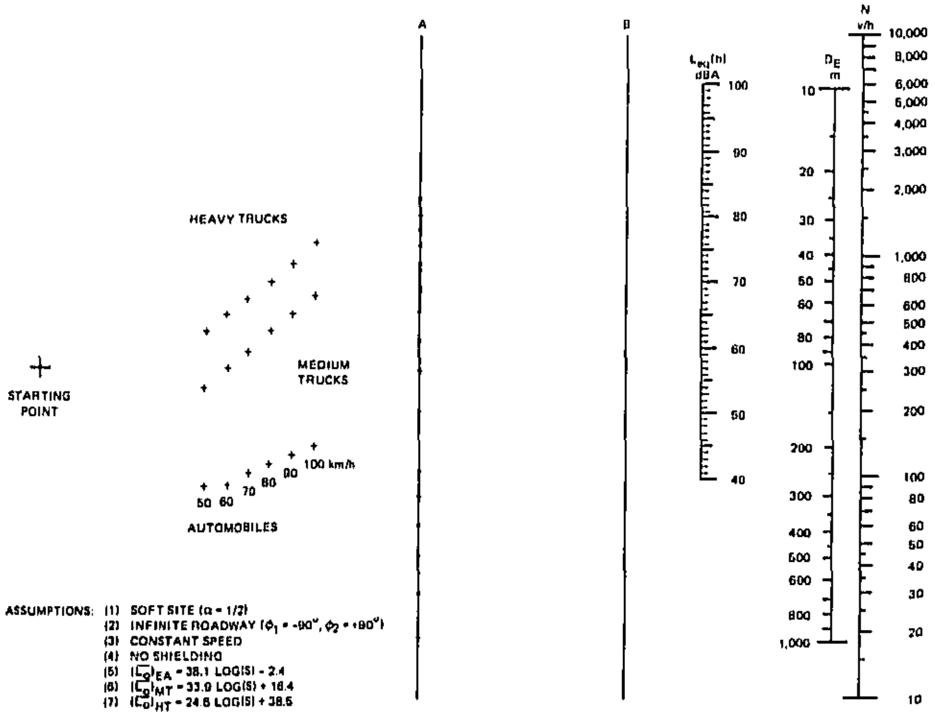


Figure 20. FHWA Highway Traffic Noise Prediction Nomograph (Soft Site)

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.

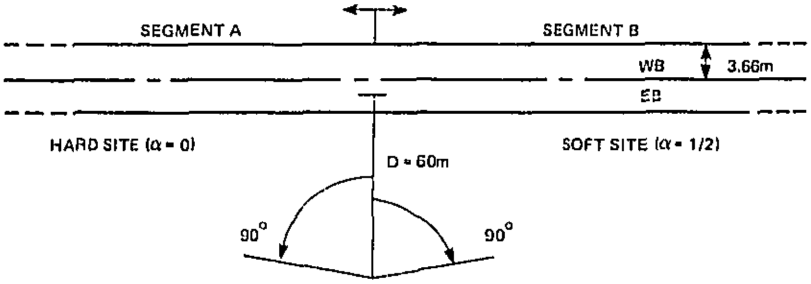


Figure 13-1

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.

$$L_{eq}(h) = 10 \log \left[10^{5.6} + 10^{5.4} + 10^{6.0}\right] = 62.2\ \mathrm{dBA}.$$

(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)

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.)

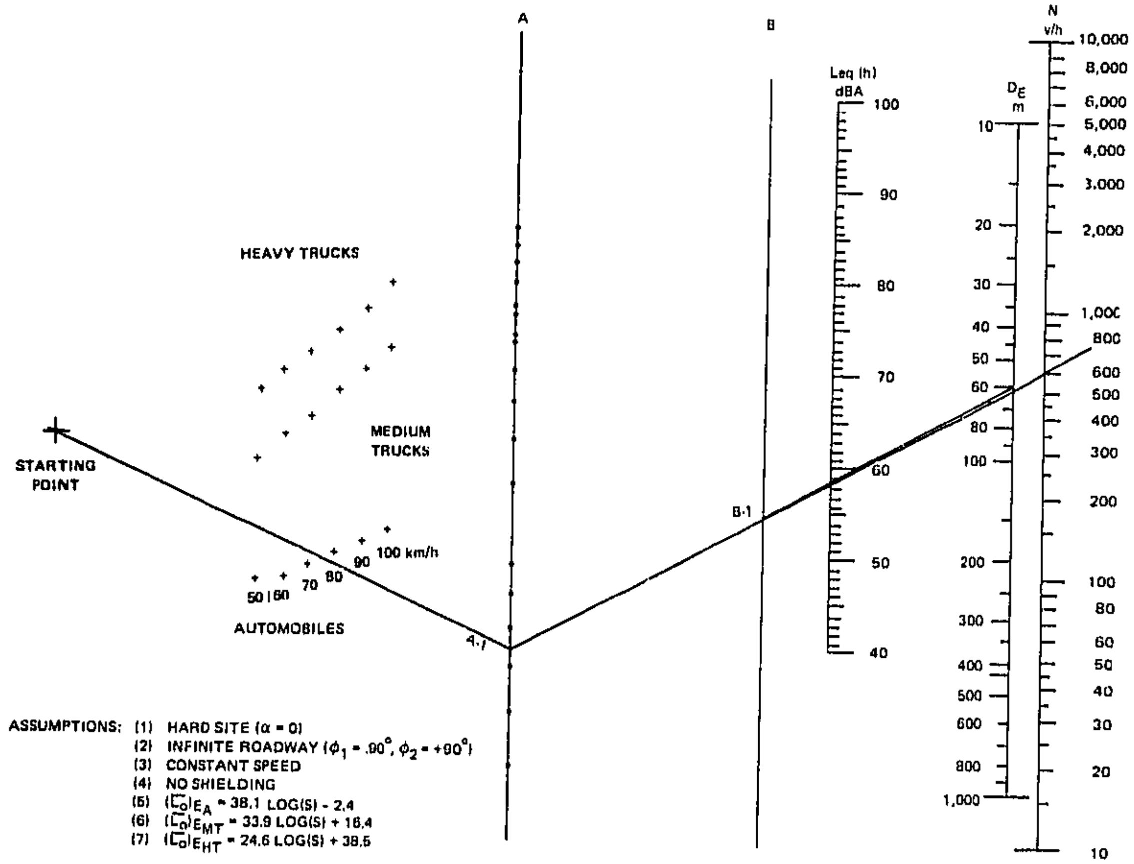
COMPUTE $L_{eq}(h)$ FROM ROADWAY

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)



ASSUMPTIONS: (1) HARD SITE ($\alpha = 0$)
(2) INFINITE ROADWAY ($\phi_1 = -90°$, $\phi_2 = +90°$)
(3) CONSTANT SPEED
(4) NO SHIELDING
(5) $(\overline{L}_o)E_A = 38.1 \text{ LOG(S)} - 2.4$
(6) $(\overline{L}_o)E_{MT} = 33.9 \text{ LOG(S)} + 16.4$
(7) $(\overline{L}_o)E_{HT} = 24.6 \text{ LOG(S)} + 38.5$

Figure 13-2. FHWA Highway Traffic Noise Prediction Nomograph (Hard Site)

(Continued)

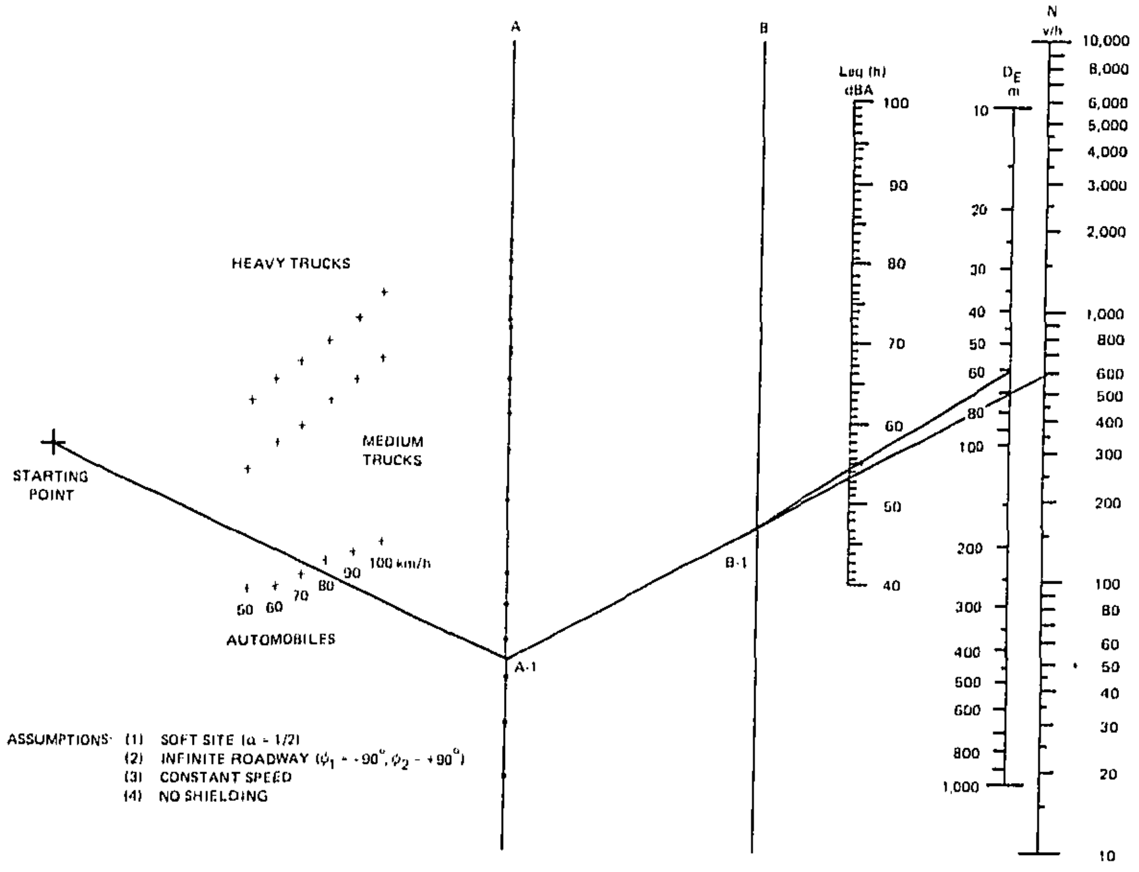


Figure 13-3. FHWA Highway Traffic Noise Prediction Nomograph (Soft Site)

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)		[illegible]	36	47	606	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. 6	0			+90														
8.	$(\overline{L_0})E_i$ (dBA)	Fig. 2																		
9.	10 LOG (N_iD_0/S_i) (dB)	Fig. 3																		
10a.	10 LOG (D_0/D) (dBA)	Fig. 4																		
10b.	15 LOG (D_0/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_0 (metres)	Fig. 9																		
15.	N_0	Eq. 10																		
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. 16																		
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*

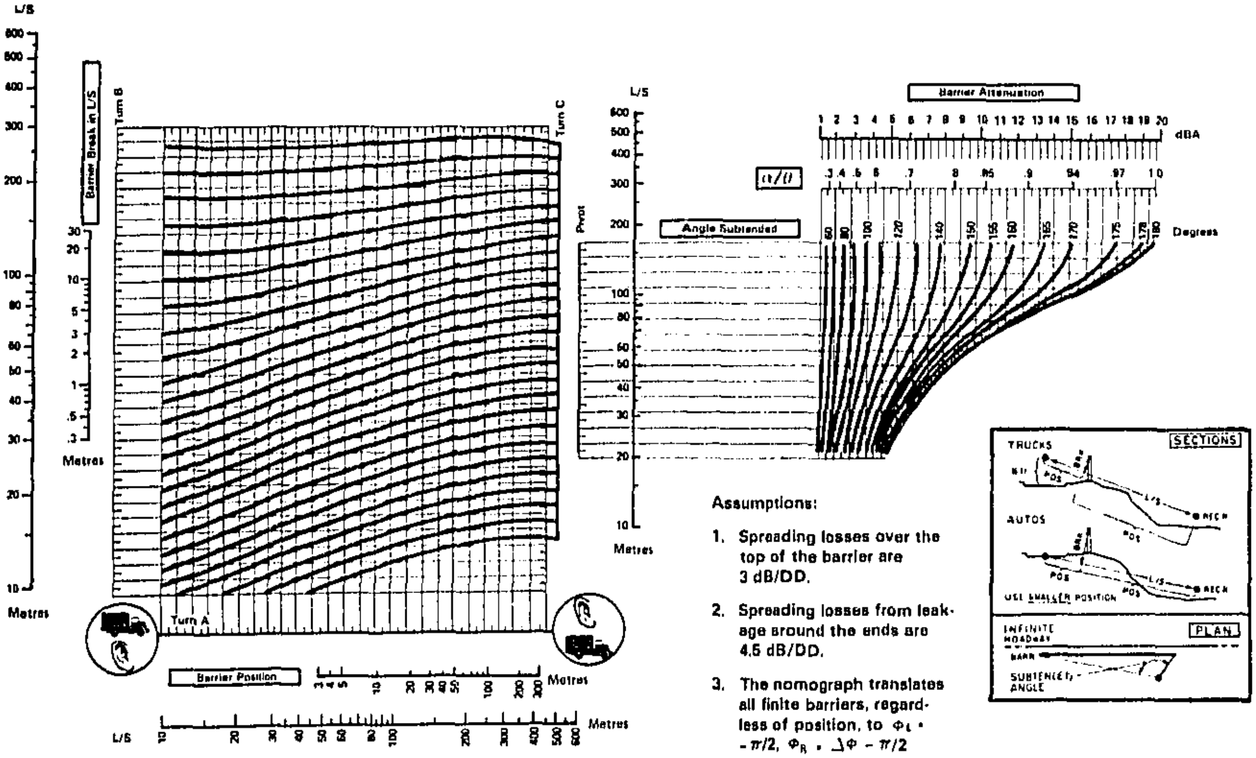
The Barrier Nomograph (Figure 21) is identical, except for the metric scales, to the Barrier Nomographs contained in References 6 and 8. Both the Barrier Nomograph (Figure 21) and the FHWA manual method start with the same basic expression—an integration of the point source attenuation function for an infinitely long barrier.

$$\text{Attenuation} = 10 \log \left\{ \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} 10^{-\Delta/10} \, d\phi \right\} . \qquad (34)$$

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 $\phi_L = -20°$, $\phi_R = 70°$.

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.

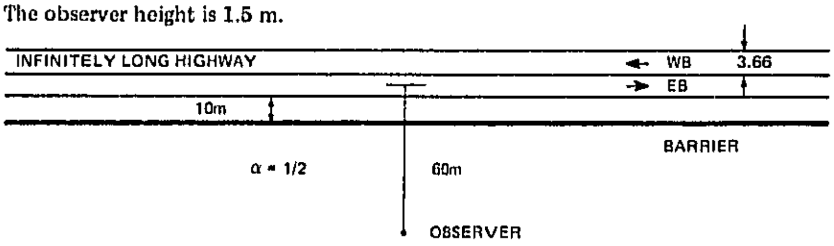


Figure 14-1

TRAFFIC DATA

Vehicle Class	EB	WB
A	317	281
MT	24	12
HT	22	25

$$S = 75 \text{ km/h}.$$

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)

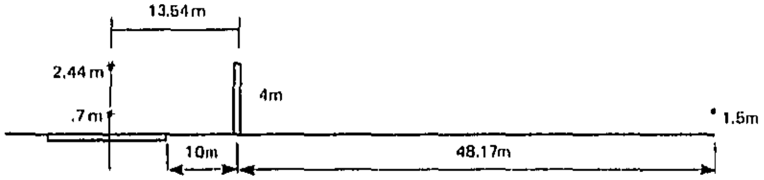


Figure 14-2

$$D_E = \sqrt{(11.83)(15.49)} + 48.17 = 61.71\,\text{m}\,.$$

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)

Repeat Step 1 for medium trucks and heavy trucks.

Δ_B (Medium Trucks) = 11.8 dB

Δ_B (Heavy Trucks) = 9.3 dB.

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.)

$$L_{eq}(h)_{\mathrm{A}} = 59 - 13.5 = 45.5 \text{ dBA}$$

$$L_{eq}(h)_{\mathrm{MT}} = 57 - 11.8 = 45.2 \text{ dBA}$$

$$L_{eq}(h)_{\mathrm{HT}} = 63 - 9.3 = 53.7 \text{ dBA}$$

$$L_{eq}(h) = 54.8 \text{ dBA (From Problem 9, } L_{eq}(h) = 55.7 \text{ dBA).}$$

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)

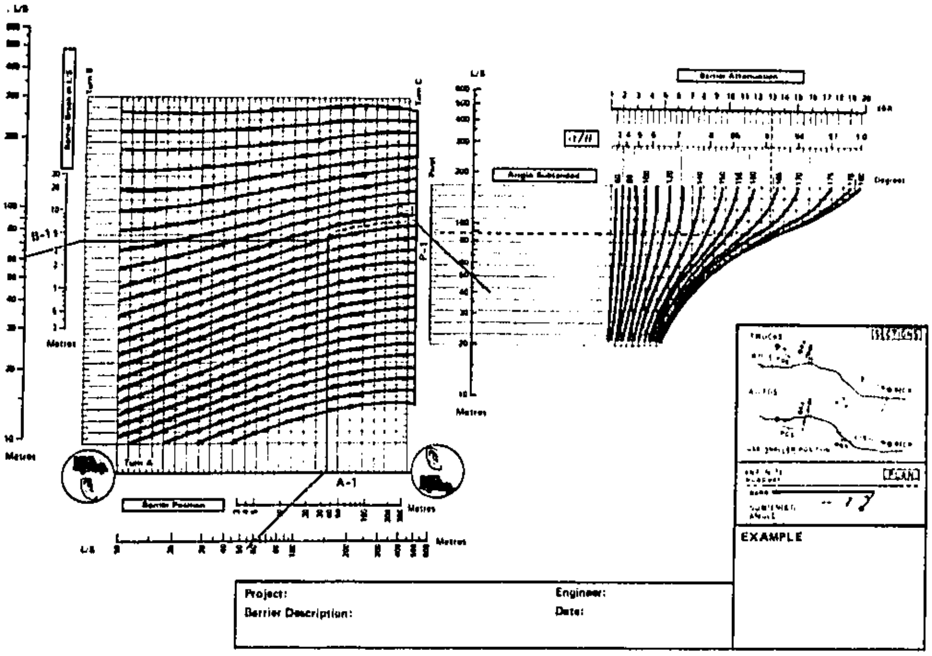


Figure 14-3. Barrier Nomograph

(Continued)

PROBLEM 14 (Continued)

NAME ______________________

DATE ______________________

PROJECT DESCRIPTION PROBLEM 14

1.	LANE NO./ROAD SEGMENT		(a) FREE FIELD			(b) INFINITE BARRIER			(c) FINITE BARRIER						
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A
3.	N(vph)		698	36	47	698	36	47	698	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.	$(\bar{L}_o)E_i$ (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 $(\psi_\alpha(\phi_1,\phi_2)/\pi)$ (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.	$L_{eq}(h)_i$ (dBA)		54.5	53.	56.5	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. 16													
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.

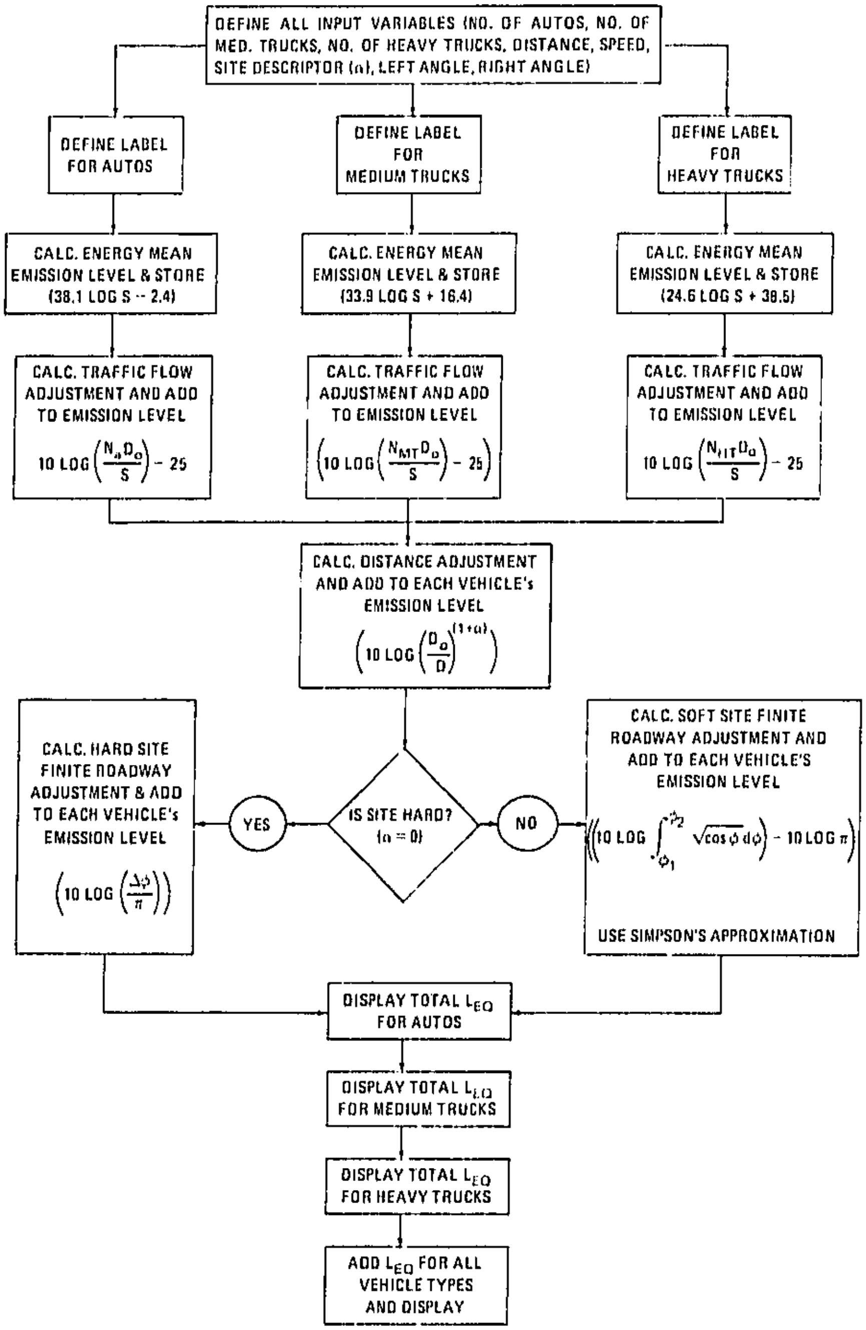


Figure 22. Flow Chart for Free Field Calculations

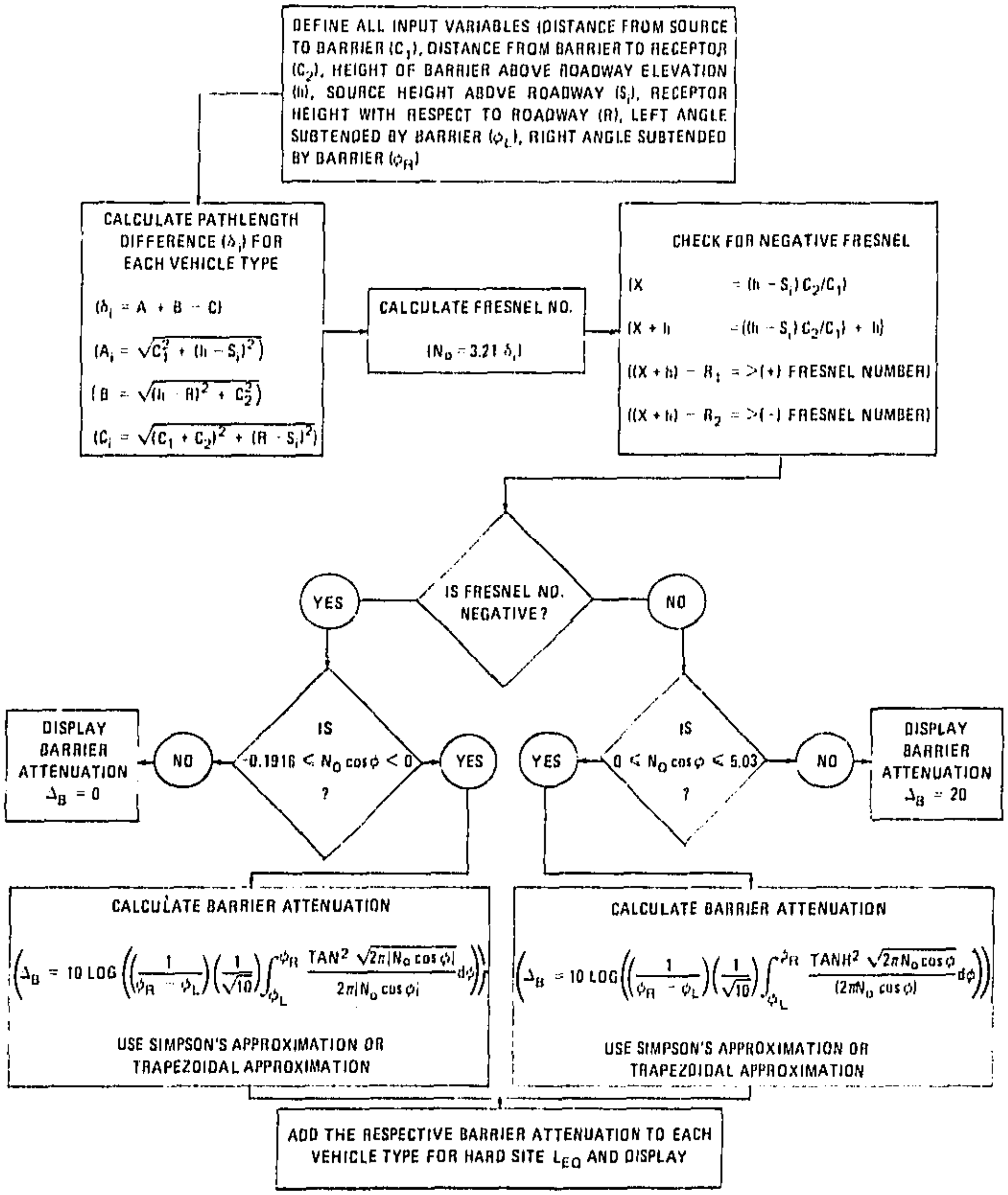


Figure 23. Flow Chart for Barrier Attenuation Calculations

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	28	317	24	22	281	12	28						
4.	S(km/h)		–	78	–	–	78	–	–	78	–	–	78	–						
5.	D(m)		60			63.60			60			63.60								
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 $(N_i D_0/S_i)$ (dB)	Fig. 3	19.	8.8	8.4	17.5	3.8	7.	19.	8.8	8.4	17.6	3.8	7.0						
10a.	10 LOG (D_0/D) (dBA)	Fig. 4							-6.0			-6.3								
10b.	15 LOG (D_0/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_0 (metres)	Fig. 9							.70	.61	.16	.68	.41	.14						
15.	N_0	Eq. 18							2.28	1.64	.81	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.	$L_{eq}(h)_i$ (dBA)		51.8	51.6	55.6	50.9	48.2	56.0	43.4	44.2	51.4	43.3	41.6	52.1						
19.	$L_{eq}(h)$ (dBA)		58.3			57.7			52.7			53.0								
20.	Δ_i (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	28	317	24	22	281	12	28	317	24	22	281	12	28
4.	S(km/h)		–	75	–	–	75	–	–	75	–	–	75	–	–	75	–	–	75	–
5.	D(m)		60			63.66			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 $(N_i D_o / S_i)$ (dB)	Fig. 3	18.	6.6	6.4	17.5	3.8	7.	18.0	6.6	6.4	17.5	3.8	7.	18.	6.6	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	.81	.18	.86	.41	.14						
15.	N_o	Eq. 18							2.78	1.84	.81	1.78	1.31	.44						
16.	Δ_B (dBA)	Appendix B							-15.3	-14.	-9.7	-14.3	-13.1	-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)		47.4	47.1	51.4	46.4	43.7	51.6	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)		53.6			53.2			48.3			48.8			45.9			45.3		
20.	Δ_t (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)		56.6						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 $L_{eq}(h)$ = 56.2											
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.

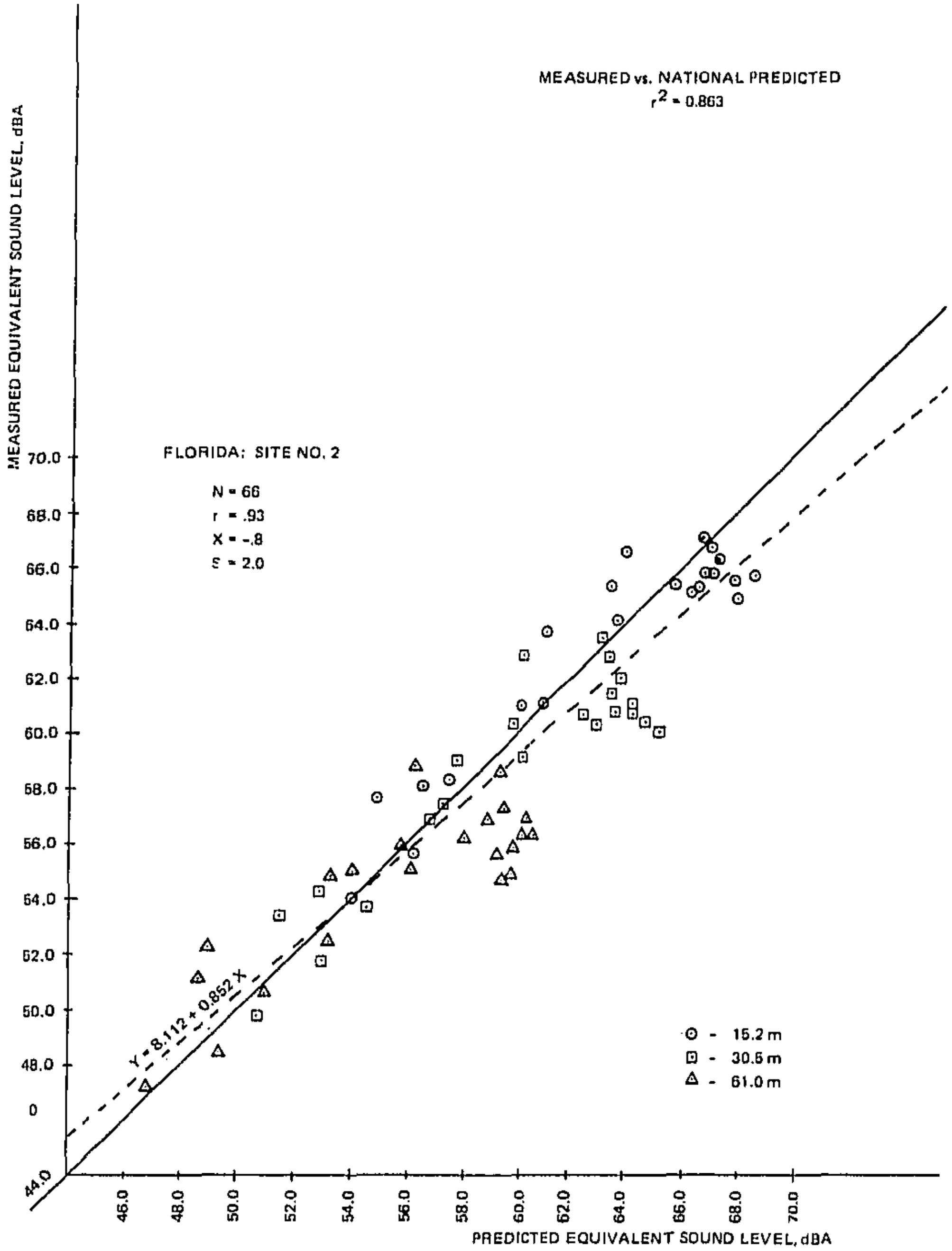


Figure 24. Comparison of the Florida Site 2 Data with Predicted Values Using National Noise Emission Levels

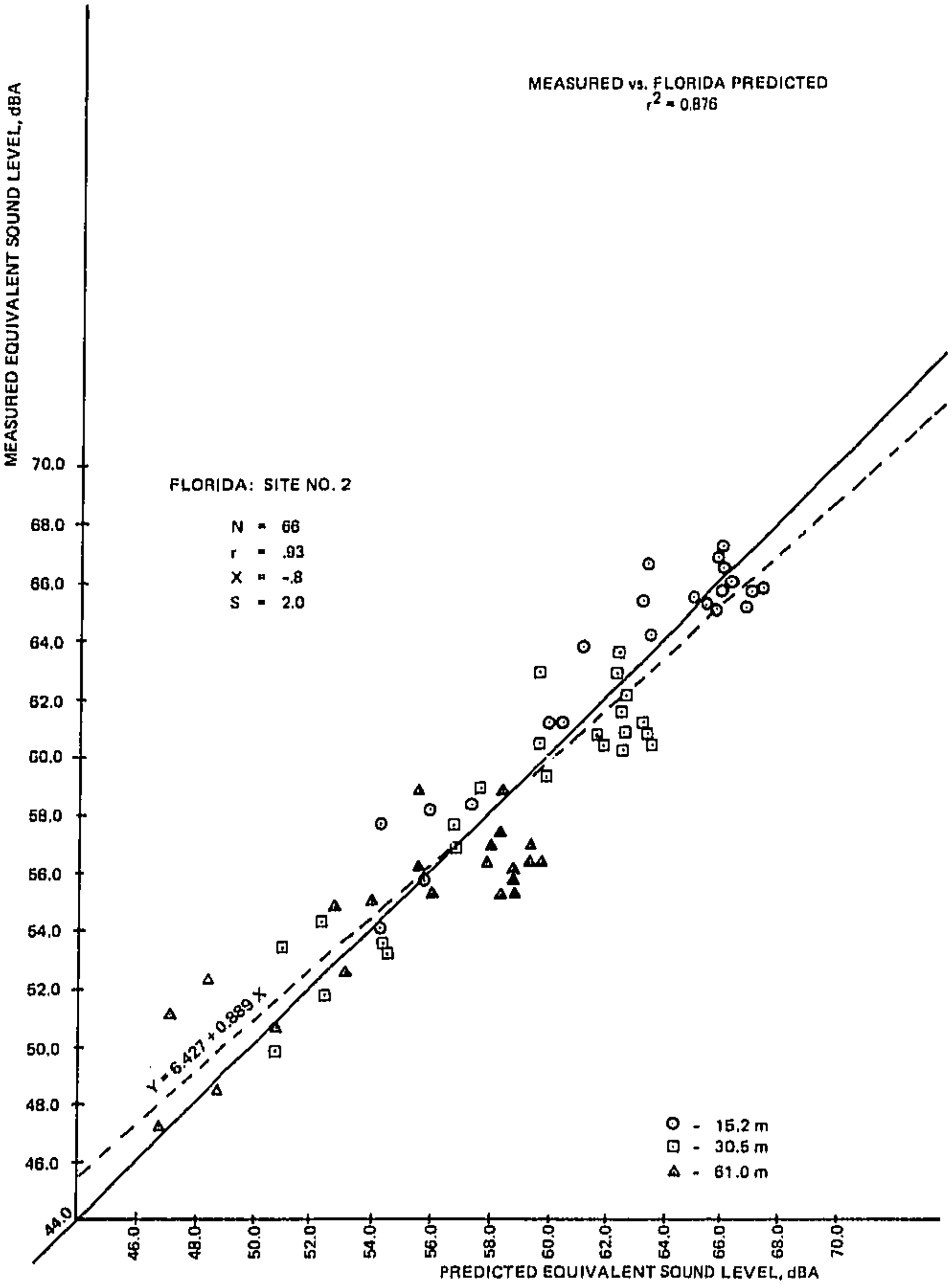


Figure 25. Comparison of the Florida Site 2 Data with Predicted Values Using Florida Emission Levels

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.

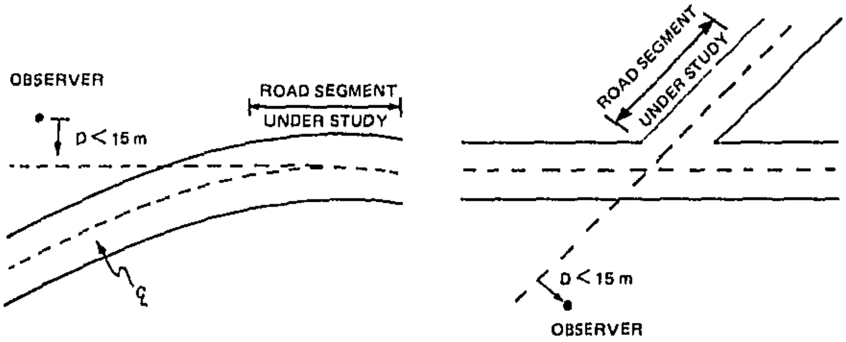


Figure 26. Situations were $D < 15$ Meters but the Vehicles are Still Treated as Point Sources

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

$$L_{eq}(h)_i = (\overline{L_o})_{E_i} + 10 \log \left(\frac{N_i D_o}{S_i}\right) + 10 \log \left[\left(\frac{D_o}{R_n}\right) - \left(\frac{D_o}{R_f}\right)\right] - 30 \qquad (36)$$

for a reflective site.

When $\alpha = 1/2$, Equation (21) reduces to

$$L_{eq}(h)_i = (\overline{L_o})_{E_i} + 10 \log \left(\frac{N_i D_o}{S_i}\right)$$

$$+10 \log \left\{\frac{2}{3}\left[\left(\frac{D_o}{R_n}\right)^{3/2} - \left(\frac{D_o}{R_f}\right)^{3/2}\right]\right\} - 30 \qquad (37)$$

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.

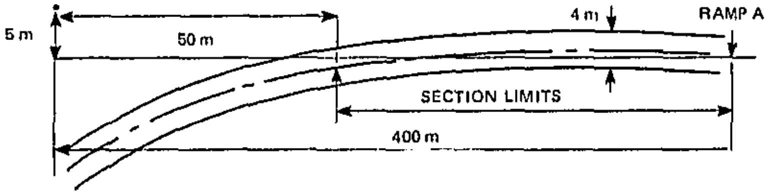


Figure 16-1

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 ______________________
DATE ______________________

PROJECT DESCRIPTION PROBLEM 16

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)		–	50	–															
5.	D (m)		[illegible]																	
6.	R_n	Fig. 5	60																	
7.	R_f	Fig. 5	400																	
8.	$(\overline{L_o})_{E_i}$ (dBA)	Fig. 2	62.3	74.0	80.3															
9.	10 LOG $(N_i D_0/S_i)$ (dB)	Fig. 3	20.8	10.8	7.8															
10a.	10 LOG (D_0/D) (dBA)	Fig. 4	-5.8																	
10b.	15 LOG (D_0/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.	d_0 (metres)	Fig. 9																		
15.	N_0	Eq. 18																		
16.	Δ_B (dBA)	Appendix B																		
17.	CONSTANT (dB)		-30	-30	-30															
18.	$L_{eq}(h)_i$ (dBA)		47.3	49.0	52.3															
19.	$L_{eq}(h)$ (dBA)		54.8																	
20.	Δ_r (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.

Site 01: SR 7 – SM 395

Scale
1" = 15 m

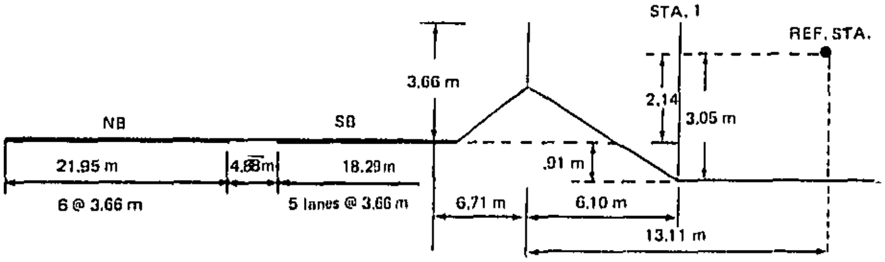


Figure 17-1

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 $\phi_1 = -90^\circ$, $\phi_2 = +90^\circ$.

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.

$$L_{eq}(h) = \underline{77.9\ \text{dBA}}\quad \text{calculated}$$

$$L_{eq}(h) = 75.9 - 15 \log\left(\frac{89}{118}\right)$$

(See Page 18, Report FHWA-RD-76-54)

$$= \underline{77.7\ \text{dBA}}\quad \text{measured}$$

$$L_{10}(h) = \underline{79.6\ \text{dBA}}\quad \text{calculated}$$

$$L_{10}(h) = 78.8 - 15 \log\left(\frac{89}{118}\right) = \underline{80.6\ \text{dBA}}\quad \text{measured.}$$

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)

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)

$$1.\ \left\{\begin{array}{l} \left.\begin{array}{l} 1.0 \\ 1.41 \end{array}\right\} \begin{array}{l} \rightarrow\ -10.3 \\ .41 \end{array} \\ 2.0 \qquad \rightarrow\ -12.3 \end{array}\right. \quad \left\{\begin{array}{l} x \\ \end{array}\right. \left\{\begin{array}{l} \\ 2.0 \\ \\ \end{array}\right. \qquad \Delta_B(\text{Auto}) = \underline{-11.1\ \text{dBA}}$$

$$\Delta_B(\text{HT}) = \underline{-9.3\ \ \text{dBA}}\ .$$

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 ______________________

DATE ______________________

PROJECT DESCRIPTION PROBLEM 17

		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		883															
4.	S(km/h)	–	88	–															
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 $(N_i D_o / S_i)$ (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 $(\psi_0(\phi_1, \phi_2)/\pi)$ (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		268				3116		323				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.

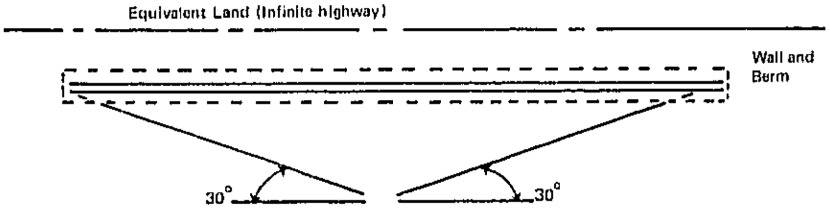


Figure 18-1

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	$\phi_1 = +60°$	$\phi_2 = +90°$.

Sound Level at Station 1 Without the Barrier

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)

PROBLEM 18 (Continued)

SEGMENT II

Step 1. $D = 25.99$ (Based on barrier position).

Step 2. See Figure 5. $\phi_1 = -60^\circ$, $\phi_2 = +60^\circ$.

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. $\phi_L = -60$, $\phi_R = +60$

$$\Delta_B(\text{Auto}):\quad \left.\begin{array}{l} \left.\begin{array}{l}1.\\ \\ 1.41\end{array}\right\}.41 \\ 2.0 \end{array}\right\} 1.0 \qquad \left.\begin{array}{l}\left.\begin{array}{l}-12.2\\ \boxed{}\end{array}\right\}x\\ -15.0\end{array}\right\}-2.8$$

$$\frac{x}{-2.8} = \frac{.41}{1.} \qquad x = -1.2$$

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 3.09 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			25.90			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		88.															
9.	10 LOG (N_iD_o/S_i) (dB)	Fig. 3	30.6		20.0															
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 $(\psi_\alpha(\phi_1, \phi_2)/\pi)$ (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. 16																		
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.

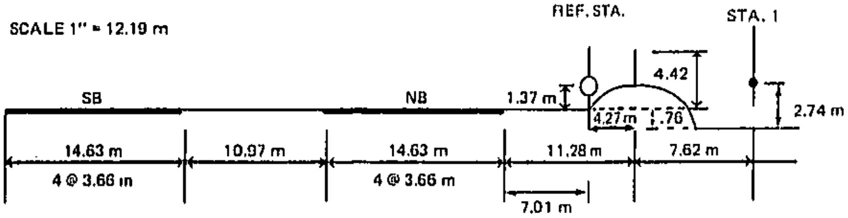


Figure 19-1

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 = 8'					
2.	VEHICLE CLAS.		A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT	A	MT	HT
3.	N(vph)		7963		127															
4.	S(km/h)		–	100	–															
5.	D(m)		20.04						24.46						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	73.6		87.7															
9.	10 LOG $(N_i D_o / S_i)$ (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 $(\psi_0(\phi_1, \phi_2)/\pi)$ (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_0 (metres)	Fig. 9													.70		.49			
15.	N_0	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				76.8		71.8				82.6		80.2			
19.	$L_{eq}(h)$ (dBA)		79.6						77.3						84.6					
20.	Δ_r (dBA)	Fig. 8																		
21.	$L_{eq}(h)$ (dBA)																			
22.	$L_{eq}(h)$ (dBA)																			
23.	ND/S (m/km)		1520		25				2613		44				2613		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				84.1		83.2			
26.	$L_{10}(h)$ (dBA)		81.1						79.2						86.7					
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 $\phi_L = -50°$, $\phi_R = +70°$.

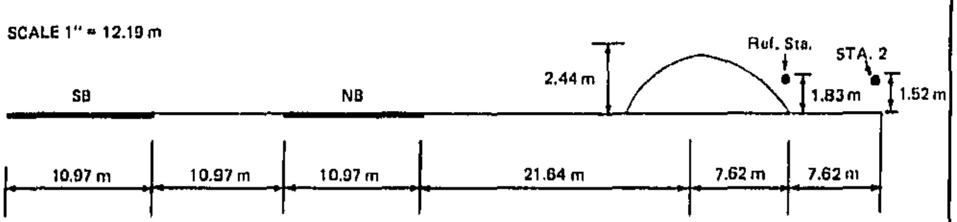


Figure 20-1

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 = 1.62 m						STATION 2, HT = 1.62 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	558		96												
4.	S(km/h)		–	100	–	–	100	–												
5.	D(m)		34.66			56.57			42.21			64.21			42.17			64.18		
6.	ϕ_1 (degrees)	Fig. 6	-90			-90														
7.	ϕ_2 (degrees)	Fig. 6	+90			+90														
8.	$(\bar{L}_o)_{E_i}$ (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		14.8	10.2		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 $(\psi_0(\phi_1, \phi_2)/\pi)$ (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		.08	.22		.08
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.	$L_{eq}(h)_i$ (dBA)		60.9		70.7	68.2		64.5	50.6		69.4	67.3		63.6	52.3		64.2	51.7		59.4
19.	$L_{eq}(h)$ (dBA)		71.1			68.4			69.8			64.6			64.5			60.1		
20.	Δ_i (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. 16																		
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)		480		192	866		98												
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			-60			-60			70			70		
7.	ϕ_2 (degrees)	Fig. 5	-60			-60			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_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	-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							-60			-60								
13.	ϕ_R (degrees)	Fig. 10							+70			+70								
14.	δ_o (metres)	Fig. 9							.11		.02	.07		.02						
15.	N_o	Eq. 18							.35		.08	.72		.08						
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.	$L_{eq}(h)_i$ (dBA)		61.6		61.4	49.4		65.6	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.						63.6						56.5					
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.
5. "Highway Noise—Generation and Control," National Cooperative Highway Research Program Report 173, Transportation Research Board, Washington, D.C., 1976.
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8. "Noise Barrier Design Handbook," Research Report FHWA-RD-76-58, Federal Highway Administration, Washington, D.C. 20590, February 1976.
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10. "Manual for Highway Noise Prediction," Report No. DOT-TSC-FHWA-72-1, Federal Highway Administration, Washington, D.C. 20590, March 1972.
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.

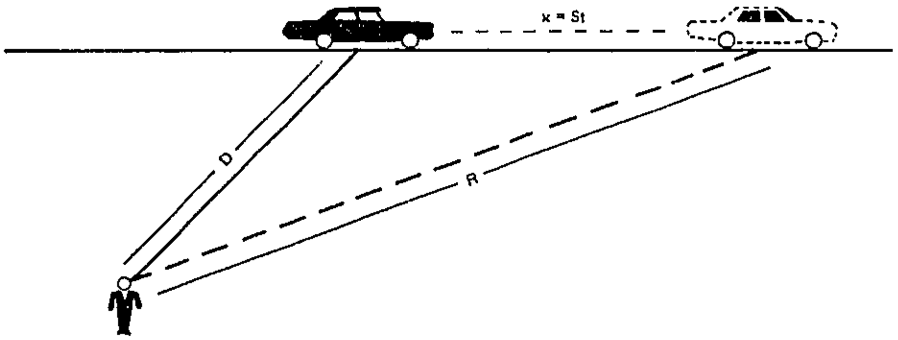


Figure A-1. Relationship Between Observer and Vehicle

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,

$$R = \sqrt{D^2 + x^2} = \sqrt{D^2 + (St)^2}\,. \qquad \text{(A-1)}$$

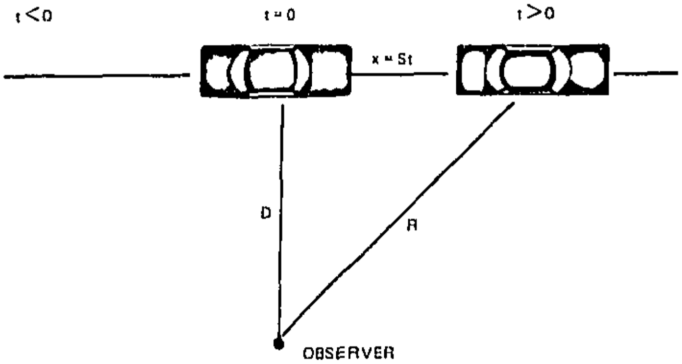


Figure A-2. Plan View of Relationship Between Observer and Vehicle

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:

$$L = 10 \log \frac{\langle P^2 \rangle}{\langle P_{ref}^2 \rangle} = 10 \log \left[\frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} \frac{D_o^2}{D^2 + (St)^2} \right]. \tag{A-4}$$

Using the rule $\log (AB) = \log A + \log B$, Equation (A-4) may be written

$$L = 10 \log \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} + 10 \log \frac{D_o^2}{D^2 + (St)^2} \tag{A-5}$$

and finally,

$$L = L_o + 10 \log \frac{D_o^2}{D^2 + (St)^2}. \tag{A-6a}$$

where

$$L_o \triangleq 10 \log \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle}. \tag{A-6b}$$

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)

EXAMPLE PROBLEM NUMBER 1 (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,

$$L = 90.5 - 10 \log R^2$$

$$40 = 90.5 - 10 \log R^2$$

$$\log R^2 = \frac{90.5 - 40}{10} = 5.05$$

$$R = \sqrt{10^{5.05}} \approx 335 \text{ m}.$$

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

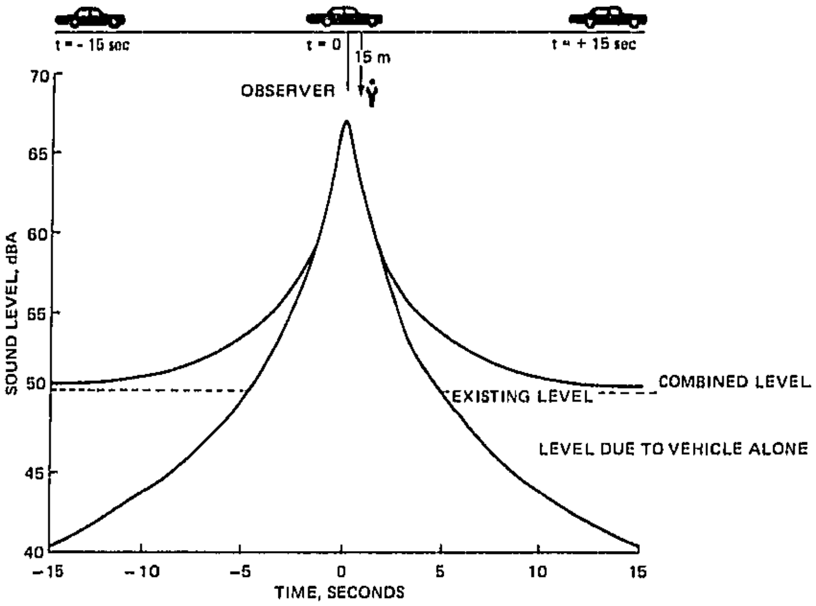


Figure A-3. Combined Sound Level Envelope Recorded by an Observer 15 m from the Roadway

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

$$L_{eq} \triangleq 10 \log \frac{1}{t_2' - t_1'} \int_{t_1'}^{t_2'} \frac{\langle P^2 \rangle}{\langle P^2_{\mathrm{ref}} \rangle}\, dt \quad \mathrm{dB} \tag{A-7}$$

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

$$\langle P^2 \rangle \cong \begin{cases} \langle P^2 \rangle_{\mathrm{ex}} + \langle P^2 \rangle_{\mathrm{tr}} & t_1 < t < t_2 \\ \langle P^2 \rangle_{\mathrm{ex}} & \text{elsewhere} \end{cases} \tag{A-7a}$$

where $\langle P^2 \rangle_{\mathrm{ex}}$ is the existing sound level and $\langle P^2 \rangle_{\mathrm{tr}}$ is the transient sound level. The equivalent sound level over the period (t_1', t_2') is calculated as

$$L_{eq} = 10 \log \frac{1}{t_2' - t_1'} \int_{t_1'}^{t_2'} \frac{\langle P^2 \rangle}{\langle P^2_{\mathrm{ref}} \rangle}\, dt \tag{A-7b}$$

$$L_{eq} \cong 10 \log \frac{1}{t_2' - t_1'} \left[\int_{t_1'}^{t_1} \frac{\langle P^2 \rangle_{\mathrm{ex}}}{\langle P^2_{\mathrm{ref}} \rangle}\, dt + \int_{t_1}^{t_2} \frac{\langle P^2 \rangle_{\mathrm{ex}} + \langle P^2 \rangle_{\mathrm{tr}}}{\langle P^2_{\mathrm{ref}} \rangle}\, dt + \int_{t_2}^{t_2'} \frac{\langle P^2 \rangle_{\mathrm{ex}}}{\langle P^2_{\mathrm{ref}} \rangle}\, dt \right]. \tag{A-7c}$$

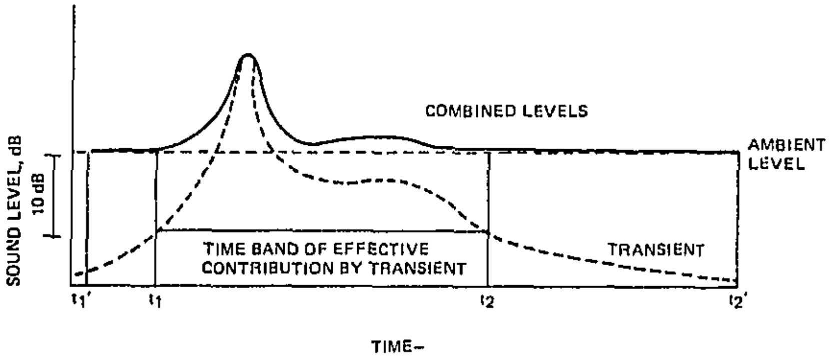


Figure A-4. Combined Sound Level Envelope Showing the Influence of the Existing Sound Level on the Transient Sound Level Envelope

Since the existing mean square pressures are constant, they may be taken outside each integral, so that

$$L_{eq} \cong 10 \log \frac{1}{t_2' - t_1'} \left[(t_1 - t_1') \frac{\langle P^2 \rangle_{ex}}{\langle P^2_{ref} \rangle} + (t_2' - t_2) \frac{\langle P^2 \rangle_{ex}}{\langle P^2_{ref} \rangle} + (t_2 - t_1) \frac{\langle P^2 \rangle_{ex}}{\langle P^2_{ref} \rangle} + \int_{t_1}^{t_2} \frac{\langle P^2 \rangle_{tr}}{\langle P^2_{ref} \rangle} \, dt \right]. \tag{A-7d}$$

Combining terms,

$$L_{eq} \cong 10 \log \frac{1}{t_2' - t_1'} \left[(t_2' - t_1') \frac{\langle P^2 \rangle_{ex}}{\langle P^2_{ref} \rangle} + \int_{t_1}^{t_2} \frac{\langle P^2 \rangle_{tr}}{\langle P^2_{ref} \rangle} \, dt \right], \tag{A-7e}$$

or

$$L_{eq} \cong 10 \log \left[\frac{\langle P^2 \rangle_{ex}}{\langle P^2_{ref} \rangle} + \frac{1}{t_2' - t_1'} \int_{t_1}^{t_2} \frac{\langle P^2 \rangle_{tr}}{\langle P^2_{ref} \rangle} \, dt \right]. \tag{A-7f}$$

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

$$L_{eq} = 10 \log \frac{1}{T} \int_{t_1}^{t_2} \frac{\langle p^2 \rangle}{\langle P^2_{ref} \rangle} \, dt \tag{A-8}$$

$$L_{eq} = 10 \log \frac{1}{T} \int_{t_1}^{t_2} \frac{\langle P_0^2 \rangle}{\langle P^2_{ref} \rangle} \frac{D_0^2}{D^2 + (St)^2} \, dt. \tag{A-8a}$$

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

$$t_1 < 0 < t_2 \quad \text{and} \quad \left| \frac{St}{D} \right|_{t_1, t_2} >> 1 \tag{A-8b}$$

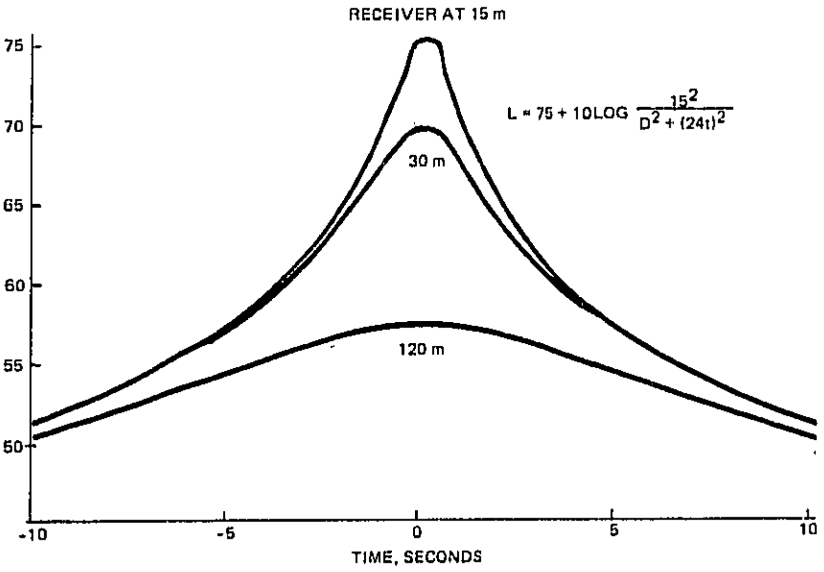


Figure A-5(a). Sound Level and Envelope Recorded by Observers 15 m, 30 m and 120 m from the Roadway

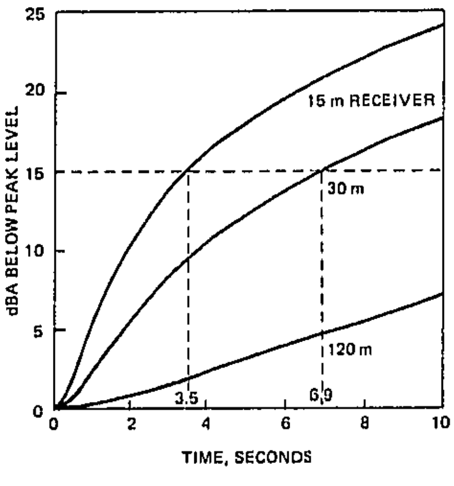


Figure A-5(b). Graph of Difference Between Peak Pass-By Sound Levels and the Time Dependent Levels as a Function of Time for Receivers at 15 m, 30 m, and 120 m the following approximation may be used,

$$\int_{t_1}^{t_2} \frac{\langle P_o^2 \rangle}{\langle P_{\text{ref}}^2 \rangle} \frac{D_o^2}{D^2 + (St)^2}\, dt \cong \int_{-\infty}^{\infty} \frac{\langle P_o^2 \rangle}{\langle P_{\text{ref}}^2 \rangle} \frac{D_o^2}{D^2 + (St)^2}\, dt . \tag{A-8c}$$

Thus, for a sufficiently long averaging time, T, the following equation may be written

$$L_{eq} = 10 \log \frac{1}{T} \int_{-\infty}^{\infty} \frac{\langle P_o^2 \rangle}{\langle P_{\text{ref}}^2 \rangle} \frac{D_o^2}{D^2 + (St)^2}\, dt . \tag{A-9}$$

Bringing the constant terms outside the integral and factoring out an S^2

$$L_{eq} = 10 \log \frac{1}{T} \frac{\langle P_o^2 \rangle}{\langle P_{\text{ref}}^2 \rangle} \frac{D_o^2}{S^2} \int_{-\infty}^{\infty} \frac{dt}{(D/S)^2 + t^2} . \tag{A-10}$$

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

$$L_{eq} = 10 \log \left[\frac{1}{T} \frac{\langle P_o^2 \rangle}{\langle P_{\text{ref}}^2 \rangle} \frac{D_o^2}{S^2} \cdot \frac{S\pi}{D} \right] . \tag{A-11}$$

After canceling terms, (A-11) may be expanded,

$$L_{eq} = 10 \log \frac{\langle P_o^2 \rangle}{\langle P_{\text{ref}}^2 \rangle} + 10 \log \frac{\pi D_o}{ST} + 10 \log \left(\frac{D_o}{D} \right) . \tag{A-12}$$

Recalling the definition of the noise emission level for a single vehicle, Equation (A-12) can be rewritten 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,

$$\left|\frac{S\left(t = \frac{T}{2}\right)}{D}\right| = \frac{22.2 \times \frac{15}{2} \times 60}{40} \approx 250 >> 1.$$

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,

$$L_{eq} = L_o + 10 \log \frac{\pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right)$$

$$L_{eq} = L_o + 10 \log \left(\frac{D_o^2 \pi}{SDT}\right)$$

$$\frac{L_{eq} - L_o}{10} = \log\left(\frac{D_o^2 \pi}{SDT}\right); \quad \frac{\pi D_o^2}{SDT} = 10^{\frac{L_{eq}-L_o}{10}}$$

$$\therefore\ D = \frac{\pi D_o^2}{ST}\, 10^{\frac{L_o - L_{eq}}{10}} .$$

Substituting the proper values

$$D = \frac{\pi\, 15^2}{22.2\,(5 \times 60)}\, 10^{\frac{67-40}{10}} \simeq 53 \text{ m} .$$

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

$$\langle P^2\rangle_{\mathrm{TOT}} = \langle P^2\rangle_1 + \langle P^2\rangle_2 + \cdots + \langle P^2\rangle_N = \sum_{i=1}^{N} \langle P^2\rangle_i . \tag{A-14}$$

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

$$\langle P^2\rangle_i = \langle P_o^2\rangle_i\, \frac{D_o^2}{D^2 + (S_i t_i')^2} \tag{A-15}$$

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

$$\langle P^2\rangle_{\mathrm{TOT}} = \sum_{i=1}^{N} \langle P_o^2\rangle_i \frac{D_o^2}{D^2 + S_i^2(t-t_i)^2} . \tag{A-17}$$

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

$$L_{eq} = 10 \log \frac{1}{T} \int_{-\infty}^{\infty} \frac{\langle P^2\rangle_{\mathrm{TOT}}}{\langle P_{\mathrm{ref}}^2\rangle}\, dt. \tag{A-18}$$

Substituting Equation (A-17) into Equation (A-18)

$$L_{eq} = 10 \log \frac{1}{T} \int_{-\infty}^{\infty} \left[\sum_{i=1}^{N} \frac{\langle P_o^2\rangle_i}{\langle P_{\mathrm{ref}}^2\rangle} \frac{D_o^2}{D^2 + S_i^2(t-t_i)^2} \right] dt . \tag{A-19}$$

Exchange the order of integration and summation, and make the substitutions $\xi_i = t - t_i$, $d\xi_i = dt$

$$L_{eq} = 10 \log \frac{D_o^2}{T} \sum_{i=1}^{N} \frac{\langle P_o^2\rangle_i}{\langle P_{\mathrm{ref}}^2\rangle} \int_{-\infty}^{\infty} \frac{d\xi_i}{D^2 + S_i^2 \xi_i^2} \tag{A-20}$$

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

$$L_{eq} = 10 \log \frac{D_o^2}{T} \sum_{i=1}^{N} \frac{\langle P_o^2\rangle_i}{\langle P_{\mathrm{ref}}^2\rangle} \frac{1}{S_i^2} \frac{\pi S_i}{D} \tag{A-21}$$

or

$$L_{eq} = 10 \log \frac{D_o^2 \pi}{DT} \sum_{i=1}^{N} \frac{\langle P_o^2\rangle_i}{\langle P_{\mathrm{ref}}^2\rangle} \frac{1}{S_i}. \tag{A-22}$$

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

$$L_{eq} = 10 \log \frac{D_o^2 \pi}{DT} \frac{N}{S} \frac{\langle P_o^2\rangle}{\langle P_{\mathrm{ref}}^2\rangle} \tag{A-23}$$

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) illustrates the distance relationship among the three vehicles as a function of time. Figure A-6(b) illustrates the individual and combined sound level envelopes.

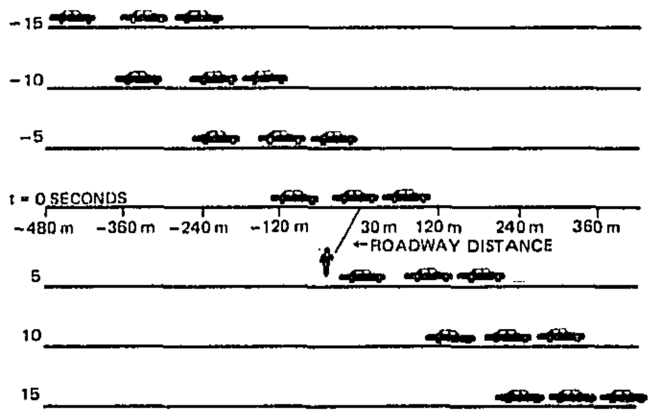


Figure A-6(a). Illustration of the Approximate Time-Distance Relationship of the Vehicles in Example Problem 4

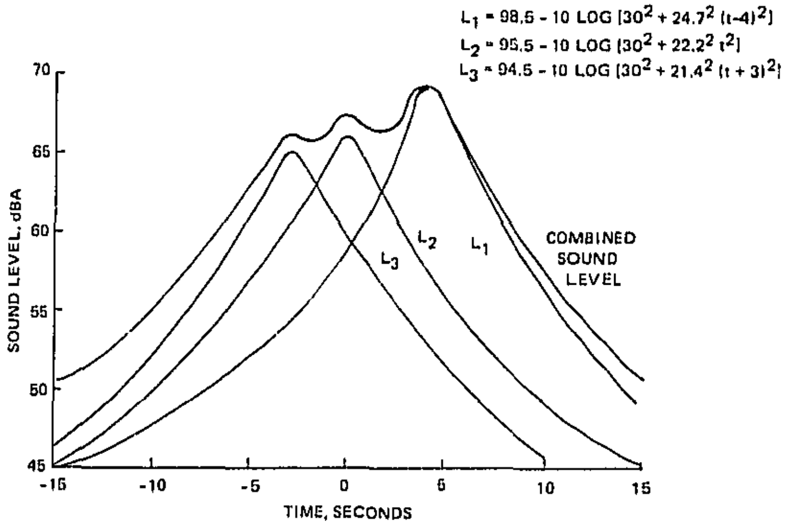


Figure A-6(b). Sound Level Time History of Three Passing Vehicles which upon expansion gives

$$\boxed{L_{eq} = L_o + 10\log\frac{N\pi D_o}{TS} + 10\log\left(\frac{D_o}{D}\right).} \qquad \text{(A-24)}$$

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 $\overline{L}_o$ 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.

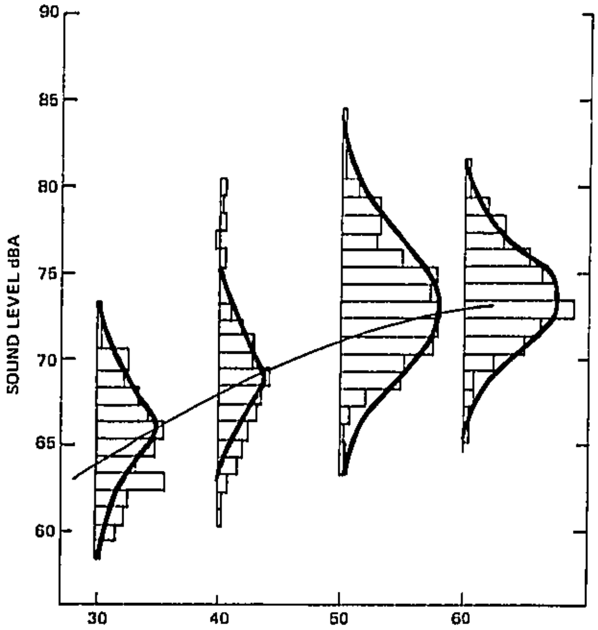


Figure A-7. Example Noise Emission Levels as a Function of Speed

Returning to Equation (A-22), assume that all N vehicles within this class are traveling at the same average speed, therefore,

$$L_{eq} = 10 \log \frac{\pi D_o^2}{TDS} \sum_{i=1}^{N} \frac{\langle P_o^2 \rangle_i}{\langle P_{\mathrm{ref}}^2 \rangle}. \qquad \text{(A-26)}$$

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 $\Sigma\,[\langle P_o^2 \rangle_i / \langle P_{\mathrm{ref}} \rangle]$. 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

$$E \left\{ \sum_{i=1}^{N} \frac{\langle P_o^2 \rangle_i}{\langle P_{\mathrm{ref}}^2 \rangle} \right\} = ?$$

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,

$$L_o = 10 \log \frac{\langle P_o^2 \rangle}{\langle P_{\text{ref}}^2 \rangle}$$

and

$$10^{\frac{L_o}{10}} = \frac{\langle P_o^2 \rangle}{\langle P_{\text{ref}}^2 \rangle}$$

so that the mean square pressure sum may be written in terms of levels,

$$E\left\{ \sum_{i=1}^{N} \frac{\langle P_o^2 \rangle_i}{\langle P_{\text{ref}}^2 \rangle} \right\} = E\left\{ \sum_{i=1}^{N} 10^{\left(\frac{L_o}{10}\right)_i} \right\}. \tag{A-29}$$

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

$$e^{\left(\frac{\ln 10}{10}\right)L_o}\, e^{-\frac{(L_o-\bar{L}_o)^2}{2\sigma_o^2}} = e^{\left(\frac{\ln 10}{10}\right)L_o}\, e^{-\frac{(L_o^2+\bar{L}_o^2-2\bar{L}_oL_o)}{2\sigma_o^2}} \tag{A-33a}$$

$$= e^{-\left[\frac{L_o^2}{2\sigma_o^2}-\left(\frac{\bar{L}_o}{\sigma_o^2}+\frac{\ln 10}{10}\right)L_o+\frac{\bar{L}_o^2}{2\sigma_o^2}\right]}. \tag{A-33b}$$

Thus, it is necessary to now evaluate the integral

$$\frac{N}{\sigma_o\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{-\left[\frac{L_o^2}{2\sigma_o^2}-\left(\frac{\bar{L}_o}{\sigma_o^2}+\frac{\ln 10}{10}\right)L_o+\frac{\bar{L}_o^2}{2\sigma_o^2}\right]}\, dL_o = ? \tag{A-34}$$

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

$$x = L_o, \quad a = \frac{1}{2\sigma_o^2}, \quad b = -\left(\frac{\bar{L}_o}{\sigma_o^2}+\frac{\ln 10}{10}\right), \quad c = \frac{\bar{L}_o^2}{2\sigma_o^2}, \tag{A-35}$$

Then the integral is

$$\text{integral} = \sqrt{\frac{\pi}{\frac{1}{2\sigma_o^2}}}\exp\left[\frac{\left(\frac{\bar{L}_o}{\sigma_o^2}+\frac{\ln 10}{10}\right)^2 - 4\left(\frac{1}{2\sigma_o^2}\right)\frac{\bar{L}_o^2}{2\sigma_o^2}}{4\left(\frac{1}{2\sigma_o^2}\right)}\right]$$

$$= \sigma_o\sqrt{2\pi}\exp\left\{\left[\frac{\bar{L}_o^2}{\sigma_o^4}+\left(\frac{\ln 10^2}{10}\right)+2\,\frac{\bar{L}_o}{\sigma_o^2}\left(\frac{\ln 10}{10}\right)-\frac{\bar{L}_o^2}{\sigma_o^4}\right]\frac{\sigma_o^2}{2}\right\}$$

$$= \sigma_o\sqrt{2\pi}\exp\left[\frac{1}{2}\left(\frac{\ln 10^2}{10}\right)\sigma_o^2+\left(\frac{\ln 10}{10}\right)\bar{L}_o\right]$$

$$= \sigma_o\sqrt{2\pi}\, e^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2\sigma_o^2}\, e^{\left(\frac{\ln 10}{10}\right)\bar{L}_o}. \tag{A-36}$$

Recalling the multiplicative constants indicated in Equation (A-34) which had been momentarily dropped,

$$NE\left\{10^{\frac{L_o}{10}}\right\} = \frac{N}{\sigma_o\sqrt{2\pi}}\,\sigma_o\sqrt{2\pi}\, e^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2\sigma_o^2}\, e^{\left(\frac{\ln 10}{10}\right)\bar{L}_o}. \tag{A-37}$$

This result can now be substituted in (A-26)

$$L_{eq} = 10 \log \frac{1}{T} \left(\frac{\pi D}{S}\right) \left(\frac{D_o}{D}\right)^2 \sum_{i=1}^{N} \frac{\langle P_o^2 \rangle_i}{\langle P_{ref}^2 \rangle}$$

$$= 10 \log \frac{1}{T} \left(\frac{\pi D}{S}\right) \left(\frac{D_o}{D}\right)^2 N e^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2 \sigma_o^2} e^{\left(\frac{\ln 10}{10}\right)\bar{L}_o} \qquad \text{(A-38)}$$

with a little rearranging and recognizing that

$$10 \log e^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2 \sigma_o^2} = 0.115\sigma_o^2 \qquad \text{(A-39)}$$

and that

$$10 \log e^{\left(\frac{\ln 10}{10}\right)\bar{L}_o} = \bar{L}_o$$

Equation (A-38) will reduce to

$$\boxed{L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N\pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right).} \qquad \text{(A-40)}$$

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

$$L_{eq_{TOT}} = 10 \log \left[10^{\left(\frac{L_{eq}}{10}\right)_{cars}} + 10^{\left(\frac{L_{eq}}{10}\right)_{\text{med. trucks}}} + 10^{\left(\frac{L_{eq}}{10}\right)_{\text{heavy trucks}}} \right]. \qquad \text{(A-41)}$$

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)

$$t_1 < 0 < t_2 \quad \text{and} \quad \left|\frac{tS}{D}\right|_{t_1, t_2} >> 1$$

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

$$L_{eq} = 10\log\left[\frac{1}{T}\sum_{i=1}^{N}\int_{t_1+t_i}^{t_2+t_i}\frac{\langle P_o^2\rangle_i}{\langle P_{ref}^2\rangle}\,\frac{D_o^2}{D^2+S^2(t-t_i)^2}\,dt\right]. \tag{A-42}$$

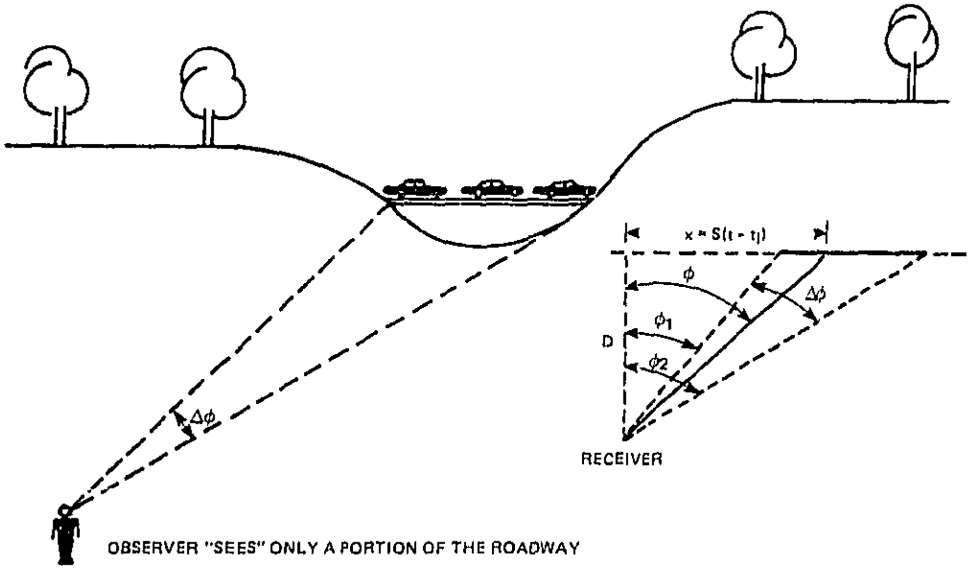


Figure A-8. Finite Roadway (Segment)

In (A-42), the limits of integration are arranged so that each vehicle passes through the segment, i.e.,

$$S(t-t_i)\big|_{t=t_2+t_i} = St_2$$

and

$$S(t-t_i)\big|_{t=t_1+t_i} = St_1\,.$$

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 $\tan^2\phi + 1 = \sec^2\phi$

$$\frac{D}{S}\int_{\phi_1}^{\phi_2}\frac{\sec^2\phi}{D^2(1+\tan^2\phi)}\,d\phi = \frac{1}{DS}\int_{\phi_1}^{\phi_2}\frac{\sec^2\phi}{\sec^2\phi}\,d\phi \qquad \text{(A-45)}$$

and after cancelling

$$\frac{1}{DS}\int_{\phi_1}^{\phi_2} d\phi = \frac{\phi_2 - \phi_1}{DS} = \frac{\Delta\phi}{DS}. \qquad \text{(A-46)}$$

Returning to Equation (A-42)

$$L_{eq} = 10\log\left[\frac{1}{T}\,\frac{D_o^2\Delta\phi}{DS}\sum_{i=1}^{N}\frac{\langle P_o^2\rangle_i}{\langle P_{ref}^2\rangle}\right]. \qquad \text{(A-47)}$$

Implementing the previous statistical treatment for the summation (i.e., Equations (A-29), A-38))

$$L_{eq} = 10\log\left[\frac{1}{T}\,\frac{D_o^2\Delta\phi}{DS}\,N e^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2\sigma_o^2}\,10^{\frac{\bar{L}_o}{10}}\right] \qquad \text{(A-48)}$$

and with a little arranging

$$L_{eq} = 10\log\left[10^{\frac{\bar{L}_o}{10}}\,e^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2\sigma_o^2}\,\frac{N\pi D}{S}\left(\frac{D_o}{D}\right)^2\frac{1}{T}\,\frac{\Delta\phi}{\pi}\right]. \qquad \text{(A-49)}$$

so that

$$\boxed{L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10\log\frac{N\pi D_o}{TS} + 10\log\left(\frac{D_o}{D}\right) + 10\log\frac{\Delta\phi}{\pi}.} \qquad \text{(A-50)}$$

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

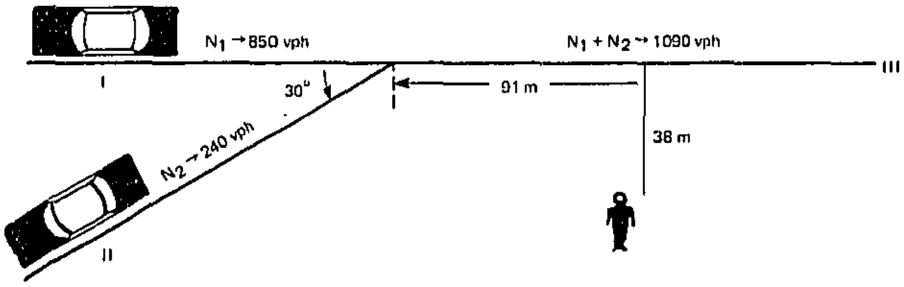
$$10\log\frac{\Delta\phi}{\pi} \simeq 0$$

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.

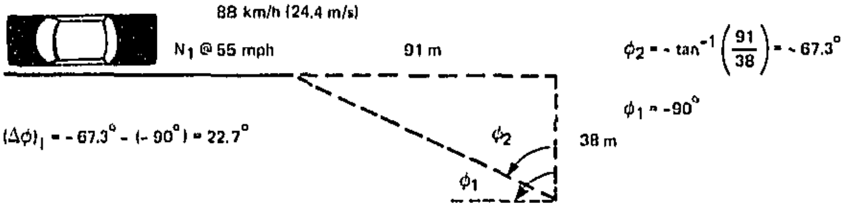


Suppose for automobiles,

$$\bar{L}_o + 0.115\,\sigma_o^2 = 32 + 30 \log S$$

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,



$\phi_2 = -\tan^{-1}\left(\frac{91}{38}\right) = -67.3°$

$\phi_1 = -90°$

$(\Delta\phi)_I = -67.3° - (-90°) = 22.7°$

Using Equation (A-50)

$$L_{eq} = L_o + 115\,\sigma_o^2 + 10 \log \frac{N\pi D_o}{TS} + 10 \log\left(\frac{D_o}{D}\right) + 10 \log \frac{\Delta\phi}{\pi}$$

$$L_{eq} = 32 + 30 \log S_1 + 10 \log \frac{N_1 \pi D_o}{TS_1} + 10 \log\left(\frac{D_o}{D_1}\right) + 10 \log \frac{\Delta\phi_1}{\pi}$$

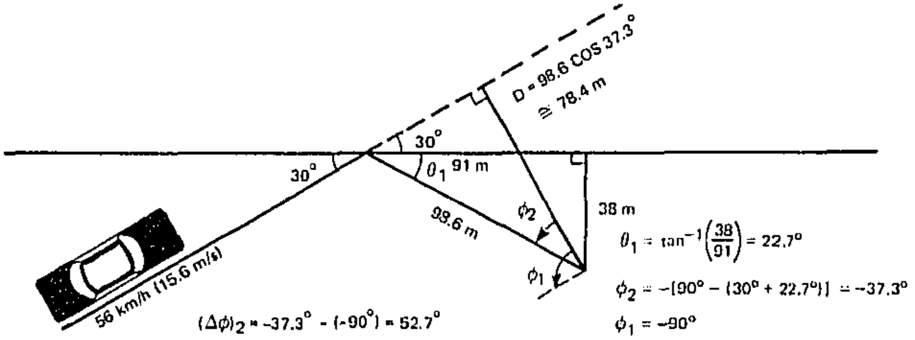
$$L_{eq} = 32 + 30 \log (24.4) + 10 \log \frac{N_1 \pi \times 15}{3600(24.4)} + 10 \log\left(\frac{15}{38}\right) + 10 \log \frac{22.7°}{180°}$$

$$L_{eq} = 27.9 + 10 \log N_1 .$$

(Continued)

EXAMPLE PROBLEM NUMBER 7 (Continued)

For Segment II

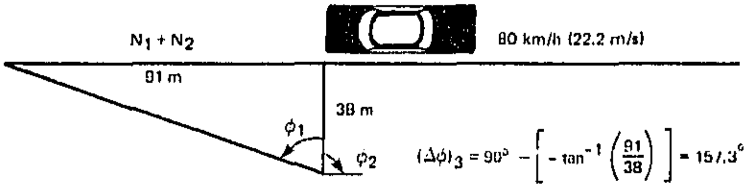


$$L_{eq} = 32 + 30 \log S_2 + 10 \log \frac{N_2 \pi D_o}{TS_2} + 10 \log \left(\frac{D_o}{D_2}\right) + 10 \log \frac{\Delta\phi_2}{\pi}$$

$$L_{eq} = 32 + 30 \log (15.6) + 10 \log \frac{N_2 \pi \times 15}{(3600)15.6} + 10 \log \left(\frac{15}{78.4}\right) + 10 \log \frac{52.7}{180^\circ}$$

$$L_{eq} = 24.5 + 10 \log N_2 .$$

For Segment III



$$L_{eq} = 32 + 30 \log S_3 + 10 \log \frac{N_3 \pi D_o}{TS_3} + 10 \log \left(\frac{D_o}{D_3}\right) + 10 \log \frac{\Delta\phi_3}{\pi}$$

$$L_{eq} = 32 + 30 \log (22.2) + 10 \log \frac{(N_1 + N_2)\pi \times 15}{3600(22.2)} + 10 \log \frac{15}{38}$$

$$+10 \log \frac{157.3^\circ}{180^\circ}$$

$$L_{eq} = 35.5 + 10 \log (N_1 + N_2) .$$

(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,

$$L_\alpha = 10 \log \frac{\langle P^2 \rangle_\alpha}{\langle P_{ref}^2 \rangle} = 10 \log \frac{\langle P_o^2 \rangle}{\langle P_{ref}^2 \rangle} \frac{D_o^2}{R^2} \left(\frac{D_o}{R}\right)^\alpha . \tag{A-54}$$

Expanding,

$$L_\alpha = 10 \log \frac{\langle P_o^2 \rangle}{\langle P_{\mathrm{ref}}^2 \rangle} + 10 \log \left(\frac{D_o}{R}\right)^2 + 10 \log \left(\frac{D_o}{R}\right)^\alpha . \tag{A-55}$$

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.

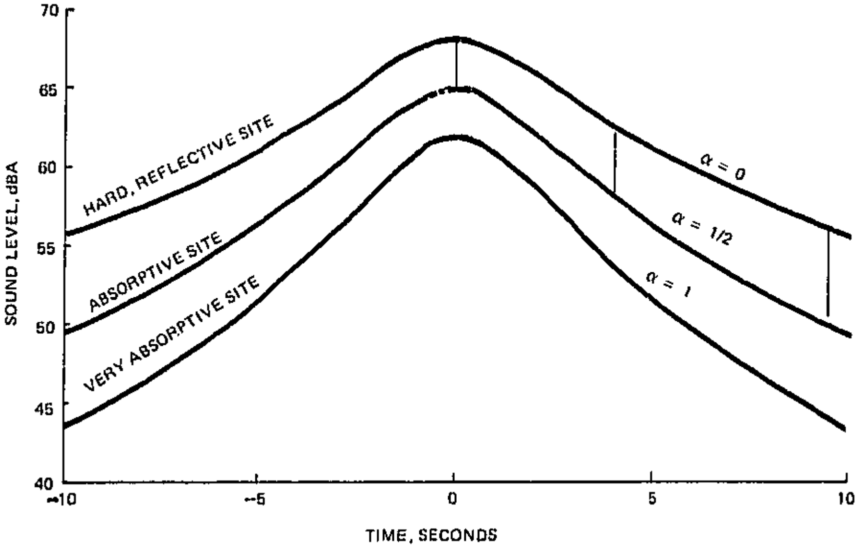


Figure A-9. Sound Level Recorded by an Observer 60 m from the Roadway for Three Different Site Types—Hard Site, Absorptive Site, and Very Absorptive Site

Equation (A-42) can be modified to account for the excess attenuation,

$$L_{eq} = 10 \log \left[\frac{1}{T} N e^{\frac{1}{2}\left(\frac{\ln 10}{10}\right)^2 \sigma_o^2} \; 10^{\frac{\bar{L}_o}{10}} \int_{t_1}^{t_2} \left(\frac{D_o}{R}\right)^{\alpha+2} dt \right] \tag{A-57}$$

and since $R = \sqrt{D^2 + (St)^2}$, the above becomes, after expanding,

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N}{T} + 10 \log \int_{t_1}^{t_2} \frac{D_o^{\alpha+2}}{(D^2 + S^2 t^2)^{\frac{\alpha+2}{2}}} \, dt \,. \tag{A-58}$$

(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 $S\,dt = D \sec^2 \phi \, d\phi$

$$\int_{t_1}^{t_2} \frac{D_o^{\alpha+2}}{(D^2 + S^2 t^2)^{\frac{\alpha+2}{2}}} \, dt = D_o^{\alpha+2} \int_{\phi_1}^{\phi_2} \frac{\frac{D}{S} \sec^2 \phi \, d\phi}{(D^2 + D^2 \tan^2 \phi)^{\frac{\alpha+2}{2}}} \, d\phi \,. \tag{A-59}$$

Since $D^2 + D^2 \tan^2 \phi = D^2 \sec^2 \phi$, the right side of (A-59) becomes

$$D_o^{\alpha+2} \frac{D}{S} \int_{\phi_1}^{\phi_2} \frac{\sec^2 \phi \, d\phi}{(D^2 \sec^2 \phi)^{\frac{\alpha+2}{2}}} = \frac{D_o^{\alpha+2}}{SD^{\alpha+1}} \int_{\phi_1}^{\phi_2} \frac{d\phi}{(\sec \phi)^{\alpha}} \tag{A-60}$$

and since $\sec \phi = (\cos \phi)^{-1}$

$$\int_{t_1}^{t_2} \frac{D_o^{\alpha+2}}{(D^2 + S^2 t^2)^{\frac{\alpha+2}{2}}} \, dt = \frac{D_o^{\alpha+2}}{SD^{\alpha+1}} \, \psi_\alpha(\phi_1, \phi_2) \tag{A-61}$$

where

$$\psi_\alpha(\phi_1, \phi_2) \triangleq \int_{\phi_1}^{\phi_2} (\cos \phi)^{\alpha} \, d\phi \,. \tag{A-61a}$$

Substitution (A-61) in (A-58)

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N}{T} + 10 \log \frac{D_o^{\alpha+2}}{SD^{\alpha+1}} \, \psi_\alpha(\phi_1, \phi_2) \tag{A-62}$$

and with a little rearranging

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N\pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right)$$

$$+ 10 \log \left(\frac{D_o}{D}\right)^{\alpha} + 10 \log \frac{\psi_\alpha(\phi_1, \phi_2)}{\pi} \,. \tag{A-63}$$

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,

$$\frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi} = \frac{1}{\pi} \int_{\phi_1}^{\phi_2} \sqrt{\cos \phi} \; d\phi. \tag{A-64}$$

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

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N\pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right)$$
$$+10 \log \left(\frac{D_o}{D}\right)^{1/2} + 10 \log \frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi}. \tag{A-65}$$

If similar terms are combined,

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N\pi D_o}{TS} + 15 \log \left(\frac{D_o}{D}\right)$$
$$+10 \log \frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi} \text{ dB} \tag{A-66}$$

for the absorptive site. When $\alpha = 0$, the equivalent sound level is given by

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10 \log \frac{N\pi D_o}{TS} + 10 \log \left(\frac{D_o}{D}\right)$$
$$+10 \log \frac{\Delta\phi}{\pi} \text{ dB} \tag{A-67}$$

for the nonattenuated site which is the same as Equation (A-50).

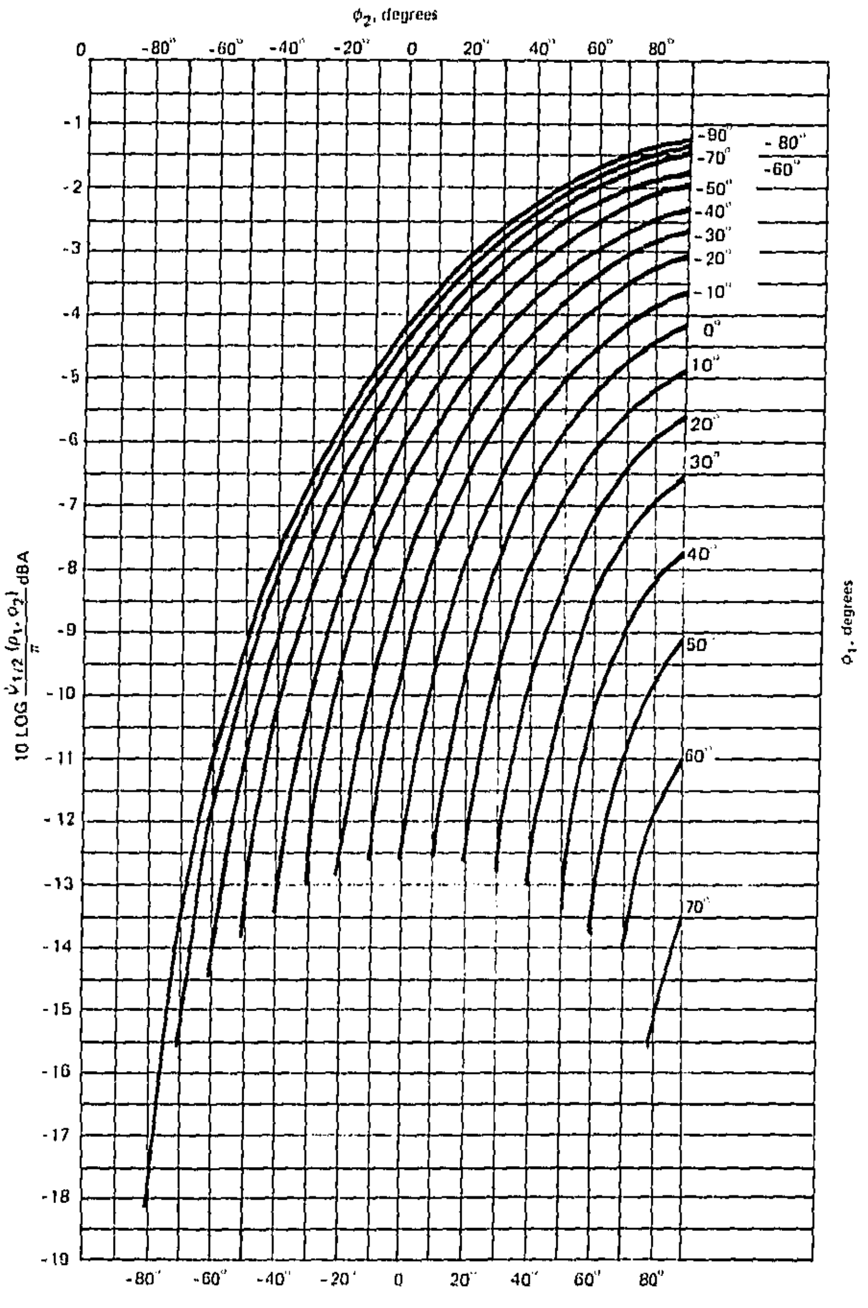


Figure A-10. Adjustment Factor for Finite Length Roadways for Absorbing Sites

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

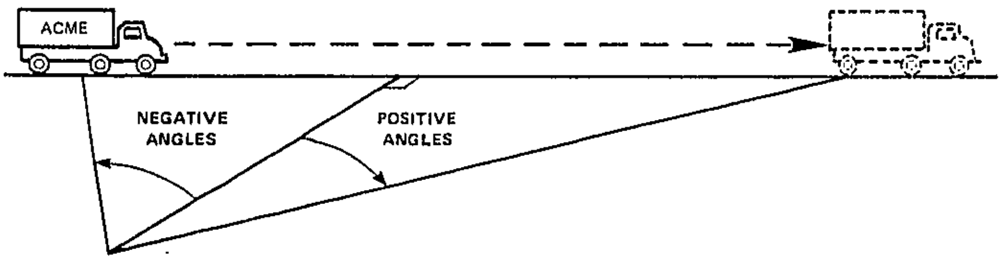
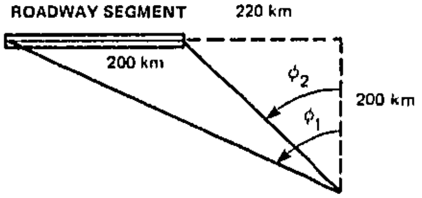


Figure A-11. Proper Angle Identification of Roadway Segments

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

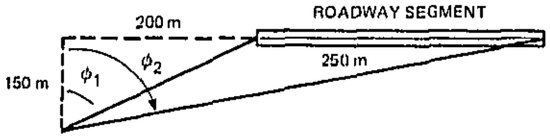
$$10 \log \frac{\psi_{1/2}(\phi_1, \phi_2)}{\pi} = 10 \log \frac{\psi_{1/2}(-64.5^\circ, -47.7^\circ)}{\pi} = -11.6 \text{ dB}$$

for an absorptive site.

(Continued)

EXAMPLE PROBLEM NUMBER 9 (Continued)

2. Completely positive segment



$$\phi_1 = +\tan^{-1}\left(\frac{200}{150}\right) = 53.1°$$

$$\phi_2 = +\tan^{-1}\left(\frac{200 + 250}{150}\right) = 71.6°$$

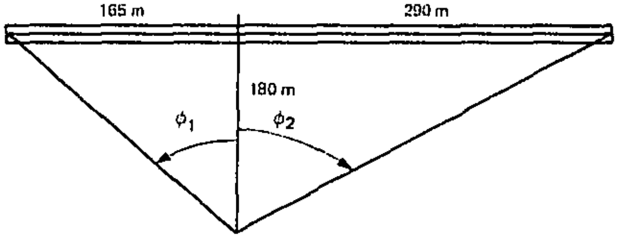
reflective site

$$10 \log \left(\frac{\Delta\phi}{\pi}\right) = 10 \log \frac{71.6° - 53.1°}{180°} = 10 \log \left(\frac{18.5°}{180°}\right) = -9.9 \text{ dB}$$

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,

$$L_{eq} = 65.9 - 10 \log \frac{\Delta\phi_3}{\pi} + 5 \log \frac{D_o}{D_3} + 10 \log \frac{\psi_{1/2}(-90°, 67.3°)}{\pi}$$

$$L_{eq} = 65.9 + 0.6 - 2.0 - 1.5 = 63.0 \text{ dBA}.$$

$$L_{eq_{TOT}} = 10 \log \left[10^{5.13} + 10^{4.26} + 10^{6.3}\right] = 63.3 \text{ dBA}.$$

(Continued)

EXAMPLE PROBLEM NUMBER 10 (Continued)

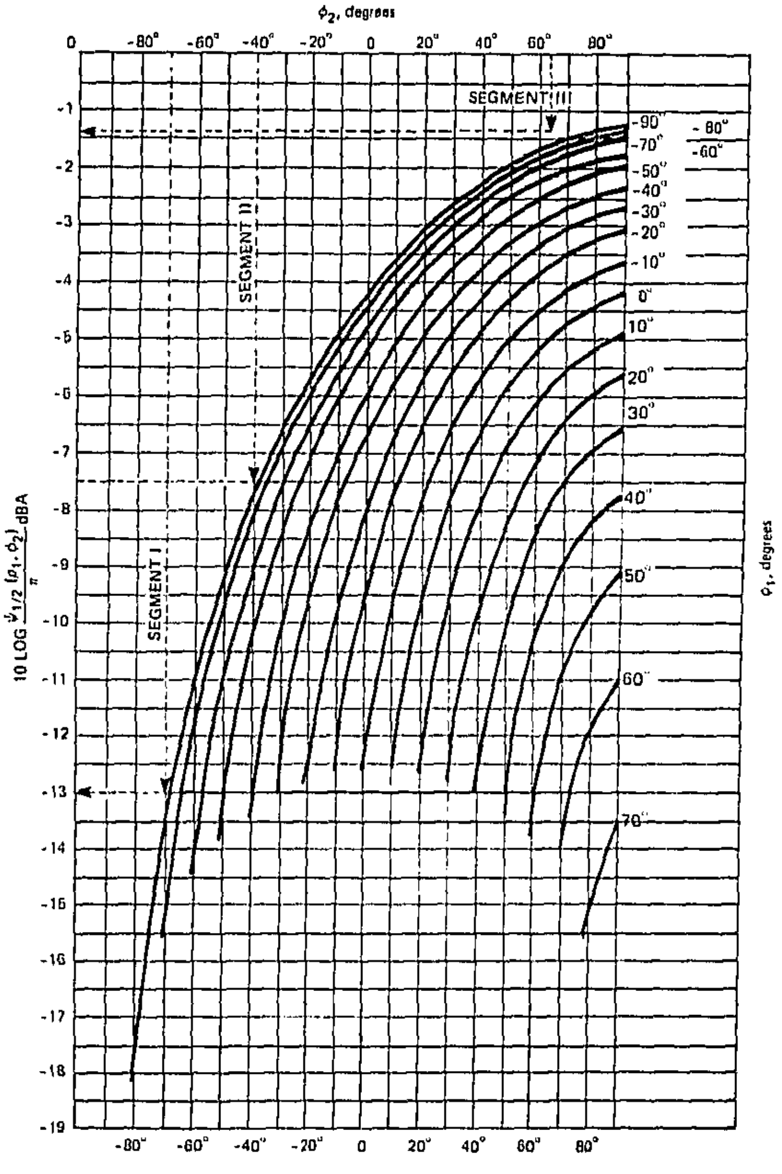


Figure A-12. Adjustment Factor for Finite Length Roadways for Absorbing Sites – Example Problem 10

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, $D << |Sl|$, 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.

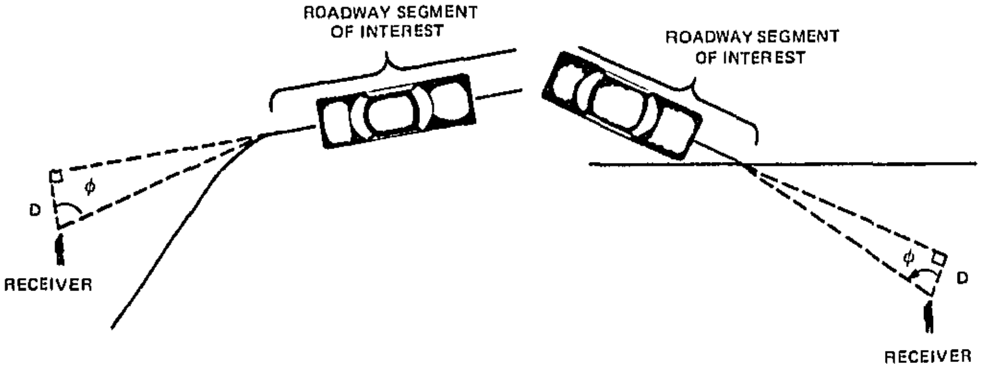


Figure A-13. Case 1: Two Situations in Which a Receiver is Very Close to an Extended Portion of a Roadway Segment

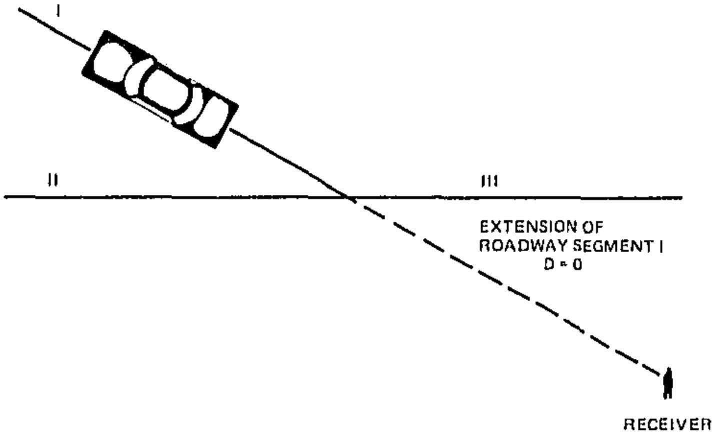


Figure A-14. Case 2: Example of Situation in Which the Receiver is on the Extension of a Roadway Segment

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

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10\log\frac{ND_o}{ST} + 10\log\frac{1}{1+\alpha}\left[\left(\frac{D_o}{St_1}\right)^{1+\alpha} - \left(\frac{D_o}{St_2}\right)^{1+\alpha}\right]. \qquad \text{(A-69)}$$

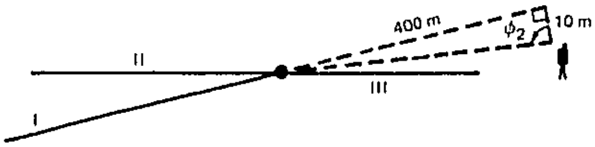
By defining St_1 as the distance, R_n, between the receiver and the near end of the roadway segment, and St_2 as the distance, R_f, between the receiver and the far end of the roadway segment, (A-69) becomes

$$L_{eq} = \bar{L}_o + 0.115\sigma_o^2 + 10\log\frac{ND_o}{ST} + 10\log\frac{1}{1+\alpha}\left[\left(\frac{D_o}{R_n}\right)^{1+\alpha} - \left(\frac{D_o}{R_f}\right)^{1+\alpha}\right] \qquad \text{(A-70)}$$

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

$$L_{eq}(h) = (\bar{L}_o)_E + 10\log\frac{ND_o}{S} + \begin{cases} 10\log\frac{2}{3}\left[\left(\frac{D_o}{R_n}\right)^{3/2} - \left(\frac{D_o}{R_f}\right)^{3/2}\right] \\ 10\log\left[\left(\frac{D_o}{R_n}\right) - \left(\frac{D_o}{R_f}\right)\right] \end{cases} - 30\text{ dBA} \quad \text{(A-72)}$$

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:

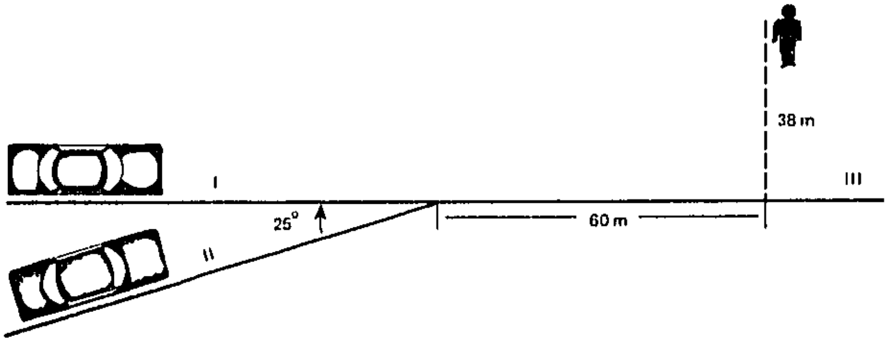
(a) the site is reflective, $\alpha = 0$

(b) the site is absorptive, $\alpha = 1/2$

Assume the vehicle speeds on Segment III are the same as on Segment I.

(Continued)

EXAMPLE PROBLEM NUMBER 12 (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

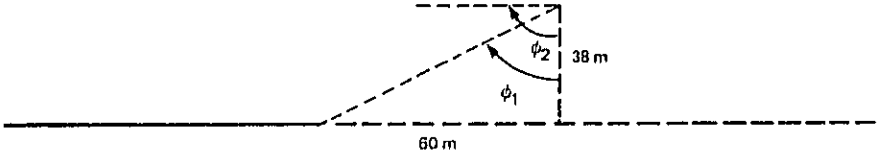
On Segment II the flow and reference energy mean emission levels are:

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)

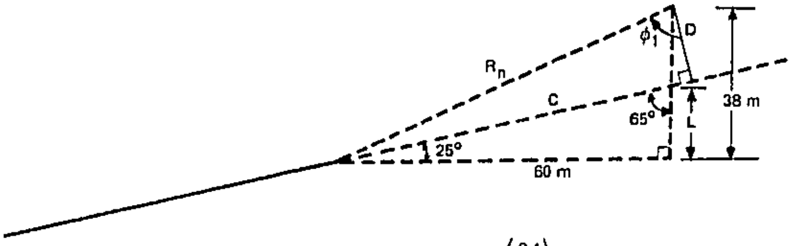
EXAMPLE PROBLEM NUMBER 12 (Continued)

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

$$L_{eq}(h)_{\mathrm{I}} = 60.9 \text{ dBA}$$

Segment II:



$L = 60 \tan 25° = 28.0 \text{ m}$

$D = (38 - 28) \sin 65° = 9.1 \text{ m}$

$R_n = \sqrt{60^2 + 38^2} = 71.0$

$R_f = \infty$

$\phi_1 = \cos^{-1}\left(\frac{9.1}{71}\right) = 82.6°$

$\phi_2 = 90°$

$C = \sqrt{71^2 - 9.1^2} = 70.4 \text{ m}$

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

$$L_{eq}(h)_{\text{II}} = 56.0 \text{ dBA}$$

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

$$L_{eq}(h)_{\text{III}} = 68.9 \text{ dBA}$$

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
$10 \log \dfrac{\psi_{1/2}(58,90)}{\pi}$	−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

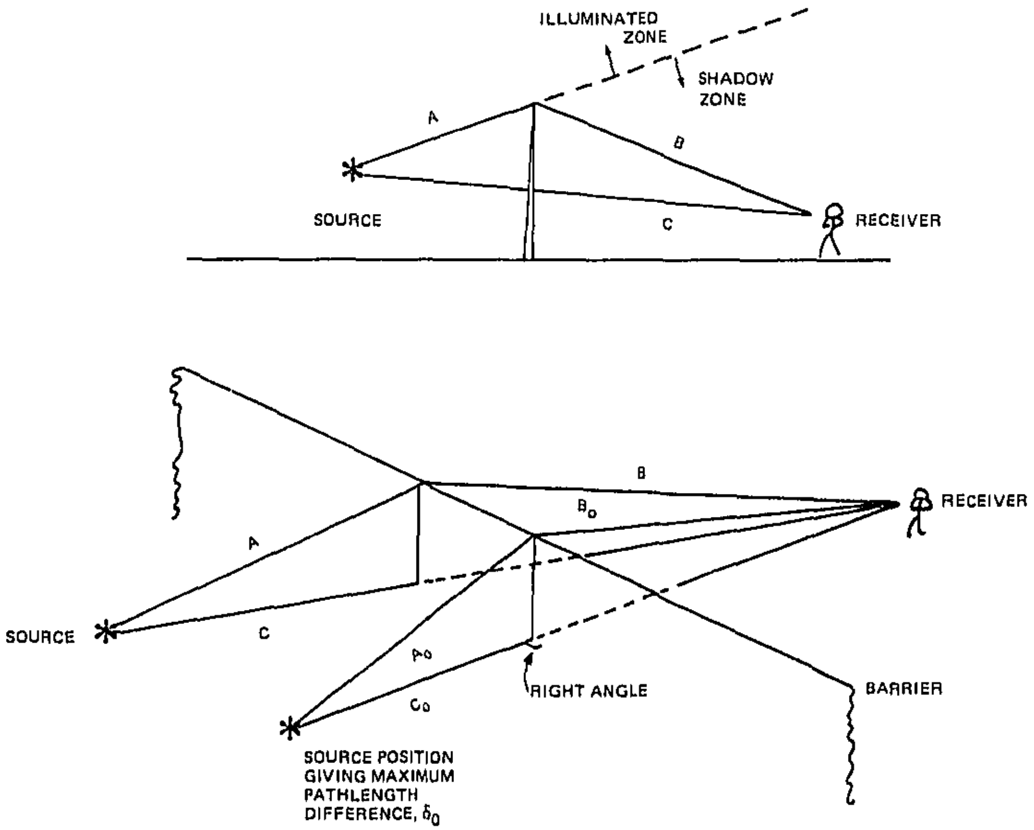
In the context of this report the term barrier is considered to include walls and berms. Barriers affect sound by interrupting its propagation and creating an *acoustic shadow zone.* (See Figure B-1.) The sound level in the shadow zone is lower than the respective free field sound level. In the illuminated 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

$$N \triangleq 2\,\frac{\delta}{\lambda} = 2\,\frac{f\delta}{c} \tag{B-1}$$

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

$$\Delta = \begin{cases} 0 & N \leqslant -0.1916 - 0.0635\epsilon \\ 5(1 + 0.6\epsilon) + 20\log\dfrac{\sqrt{2\pi|N|}}{\tan\sqrt{2\pi|N|}} & (-0.1916 - 0.0635\epsilon) \leqslant N \leqslant 0 \\ 5(1 + 0.6\epsilon) + 20\log\dfrac{\sqrt{2\pi N}}{\tanh\sqrt{2\pi N}} & 0 \leqslant N \leqslant 5.03 \\ 20(1 + 0.15\epsilon) & N \geqslant 5.03 \end{cases} \tag{B-2}$$



δ = PATHLENGTH DIFFERENCE
$\delta = \pm(A + B - C)$
δ_0 = MAXIMUM PATHLENGTH DIFFERENCE
$\delta_0 = \pm(A_0 + B_0 - C_0)$

+ FOR RECEIVERS IN SHADOW ZONE
− FOR RECEIVERS IN ILLUMINATED ZONE

Figure B-1. General Source/Receiver/Barrier Geometry

where

$\epsilon = 0$ for a wall

$\epsilon = 1$ 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

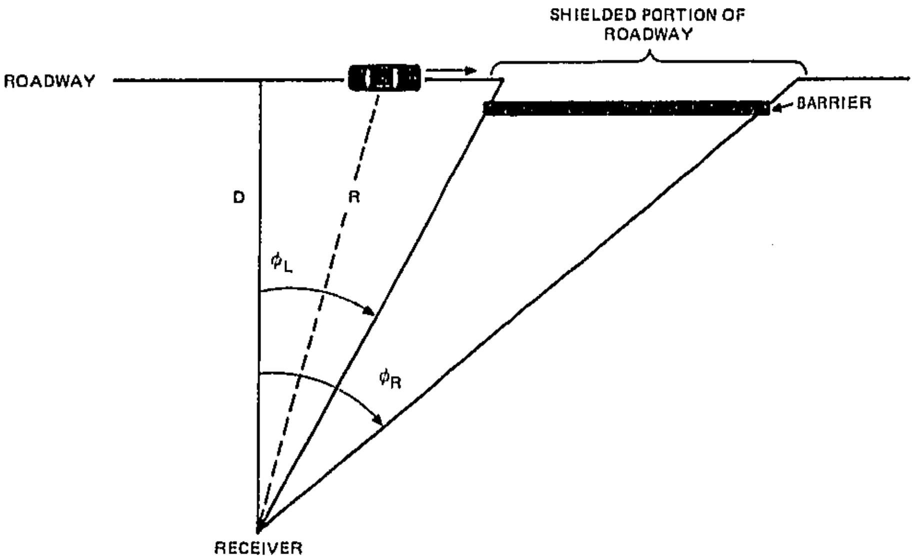


Figure B-2. Source/Receiver/Barrier Geometry Used for the Determination of Barrier Attenuation

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.

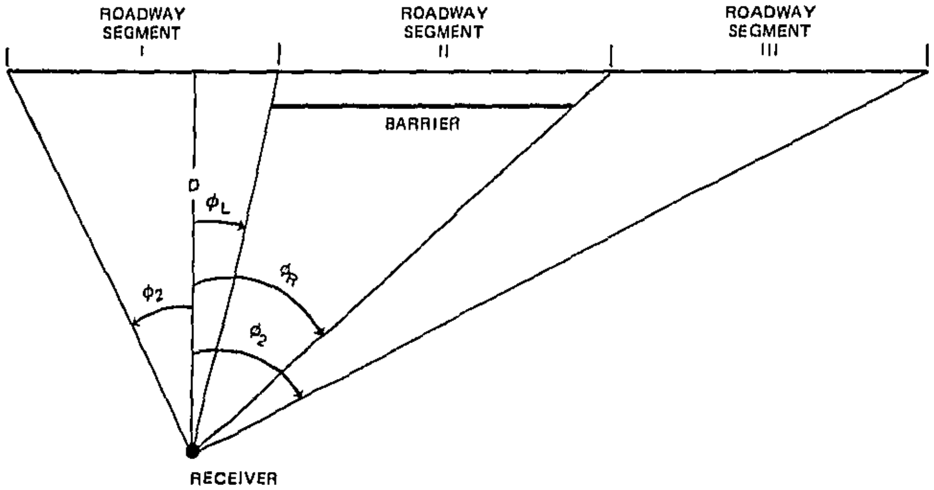


Figure B-3. Finite Roadway/Finite Barrier Geometry for Insertion Loss Calculations

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

$$3\epsilon \;=\; 10\log\left(10^{0.3\epsilon}\right)$$

$$5\,(1+0.6\epsilon) \;=\; 10\log\;10^{\frac{5+3\epsilon}{10}} \;=\; 10\log\left(\sqrt{10}\;\,10^{0.3\epsilon}\right)$$

$$20\,(1+0.15\epsilon) \;=\; 10\log\;10^{\frac{20+3\epsilon}{10}} \;=\; 10\log\left(100\times 10^{0.3\epsilon}\right)$$

which when combined with the log terms in (B-12) gives

$$\Delta_i = \begin{cases} 20\log(1) & N_i \leqslant -0.1916 - 0.0635\epsilon \\[2ex] 10\log\left[\dfrac{\sqrt{10}\;\,10^{0.3\epsilon}\;\,2\pi|N_o|_i\cos\phi}{\tan^2\sqrt{2\pi|N_o|_i\cos\phi}}\right] & (-0.1916-0.0635\epsilon) \leqslant N_i \leqslant 0 \\[2ex] 10\log\left[\dfrac{\sqrt{10}\;\,10^{0.3\epsilon}\;\,2\pi(N_o)_i\cos\phi}{\tanh^2\sqrt{2\pi(N_o)_i\cos\phi}}\right] & 0 \leqslant N_i \leqslant 5.03 \\[2ex] 10\log\left[100\times 10^{0.3\epsilon}\right] & N_i \geqslant 5.03. \end{cases} \qquad \text{(B-13)}$$

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)

$$B_i = 10\log\frac{1}{\phi_R-\phi_L}\int_{\phi_L}^{\phi_R}\left\{\begin{array}{ll} 1 & N_i \leqslant -0.1916-0.0635\epsilon \\[2ex] \left[\dfrac{10^{-0.3\epsilon}\;\tan^2\sqrt{2\pi|N_o|_i\cos\phi}}{\sqrt{10}\;\,2\pi|N_o|_i\cos\phi}\right] & \begin{array}{r}(-0.1916-0.0635\epsilon)\\ \leqslant N_i \leqslant 0\end{array} \\[2ex] \left[\dfrac{10^{-0.3\epsilon}\;\tanh^2\sqrt{2\pi(N_o)_i\cos\phi}}{\sqrt{10}\;\,2\pi(N_o)_i\cos\phi}\right] & \begin{array}{l} d\phi \\ 0 \leqslant N_i \leqslant 5.03\end{array} \\[2ex] \dfrac{10^{-0.3\epsilon}}{10^0} & N_i \geqslant 5.03. \end{array}\right\}$$

(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,

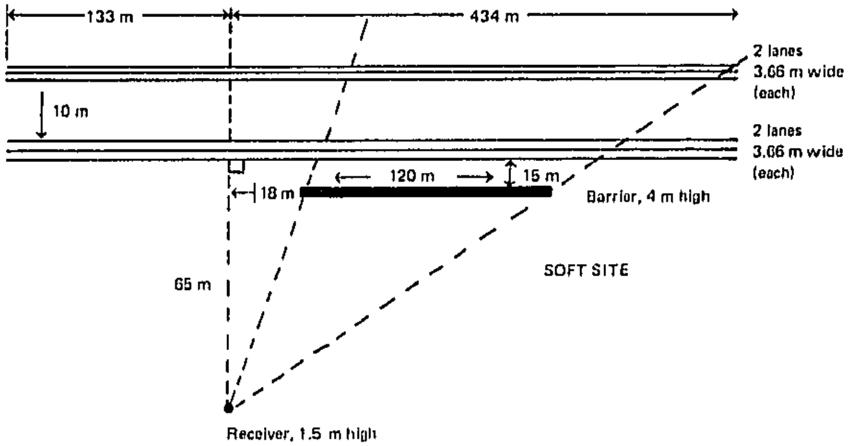
$$IL = \begin{pmatrix}\text{Sound level before}\\ \text{barrier construction}\end{pmatrix} - \begin{pmatrix}\text{Sound level after}\\ \text{barrier construction}\end{pmatrix}. \qquad \text{(B-14)}$$

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

$$D_E = [(\text{Receiver}-\text{near lane } {\rm C\!\!\!L} \text{ distance}) \times (\text{Receiver}-\text{far lane } {\rm C\!\!\!L} \text{ distance})]^{1/2}$$

$$D_E = \left[\left(65 + \frac{3.66}{2}\right)\left(65 + 3.66 + 3.66 + 10 + 3.66 + \frac{3.66}{2}\right)\right]^{1/2}$$

$$D_E = 76.61 \text{ m.}$$

(Continued)

EXAMPLE PROBLEM NUMBER 1 (Continued)

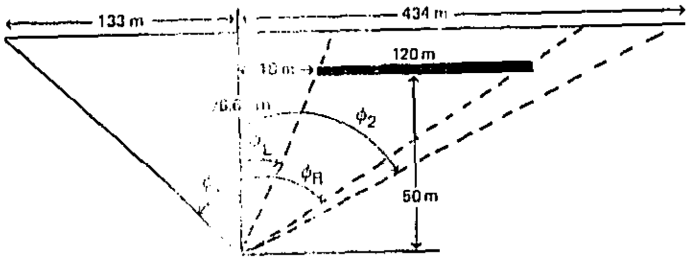
2. With Barrier

D_E = Receiver-barrier distance (perpendicular) + [(Barrier—near lane ℄ distance) × (Barrier—far lane ℄ distance)]$^{1/2}$

$$D_E = 50 + \left[\left(15 + \frac{3.66}{2}\right)\left(15 + 3.66 + 10 + 3.66 + \frac{3.66}{2}\right)\right]^{1/2}$$

$$D_E = 75.23 \text{ m.}$$

Calculation of Roadway Segment Angles



$$\phi_1 = -\tan^{-1}\left(\frac{133}{76.61}\right) \simeq -60°$$

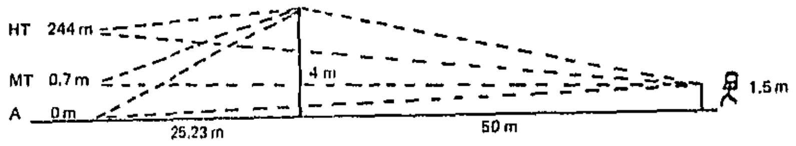
$$\phi_L = \tan^{-1}\left(\frac{18}{50}\right) \simeq 20°$$

$$\phi_R = \tan^{-1}\left(\frac{18 + 120}{50}\right) \simeq 70°$$

$$\phi_2 = \tan^{-1}\left(\frac{434}{76.61}\right) \simeq 80°$$

Calculation of δ_o, N_o

Redrawing the barrier in a cross-section



A $\delta_o = \sqrt{25.23^2 + 4^2} + \sqrt{(4-1.5)^2 + 50^2} - \sqrt{1.5^2 + 75.23^2} = 0.36 \text{ m}$

MT $\delta_o = \sqrt{25.23^2 + (4-0.7)^2} + \sqrt{25^2 + 50^2} - \sqrt{(1.5-0.7)^2 + 75.23^2} = 0.27 \text{ m}$

HT $\delta_o = \sqrt{25.23^2 + (4-2.44)^2} + \sqrt{2.5^2 + 50^2} - \sqrt{(2.44-1.5)^2 + 75.23^2} = 0.10 \text{ m}$

(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

$$\boxed{L_{eq}^{a}(h) = 65.5\,\mathrm{dBA}}$$

$$I.L. = L_{eq}^{b}(h) - L_{eq}^{a}(h) = 66.7 - 65.5$$

$$\boxed{I.L. = 1.2\,\mathrm{dBA}}$$

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	100	2450	195	100	2450	195	100	2450	195	100						
4.	S(km/h)		88	84	82	88	84	82	88	84	82	88	84	82						
5.	D(m)		–	76.81	–	–	76.81	–	–	76.23	–	–	76.81	–						
6.	ϕ_1 (degrees)	Fig. 5	-60			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_iD_o/S_i) (dB)	Fig. 3	26.2	15.4	14.7	26.2	15.4	14.7	26.2	15.4	14.7	20.2	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 $(\psi_o(\phi_1,\phi_2)/\pi)$ (dBA)	Fig. 6							-6.6	-6.6	-6.6									
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	56.6	58.9	18.8	46.9	56.1	47.6	46.8	50.1						
19.	$L_{eq}(h)$ (dBA)		64.6			62.0			56.8			53.7								
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	–	−6.0	−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

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	–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

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	−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

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	−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	50	60	70	80	90
−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.[illegible]	−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	60	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

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	−3.2	−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

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	−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

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	−5.1	−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_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	−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	–	–	–	−5.6	−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

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	−5.3	−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	−6.0	−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

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	−5.7	−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	−9.6	−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

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	−5.8	−6.6	−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	−6.6
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	−11.6	−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	−11.6	−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

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	−6.2	−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	−16.0	−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	−19.6	−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	−19.6	−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	−19.5
−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^o_R

LEFTMOST BARRIER ANGLE, ϕ^o_L

	−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

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	−16.4	−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

LEFTMOST ROADWAY ANGLE, ϕ_1^o

	−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	−7.6	−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

LEFTMOST ROADWAY ANGLE, ϕ_1^o	RIGHTMOST ROADWAY ANGLE, ϕ_2^o																	
	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 handled 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)

$$10 \log (N_i \pi D_o / T S_i) . \tag{F-1}$$

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

$$10 \log \left[\frac{\left(N_{(\mathrm{AADT})_i}\right)(\pi)(D_o \text{ metres})}{(S_i \text{ km/h})\ (24 \text{ hours})} \right] . \tag{F-2}$$

This reduces to

$$10 \log \left[\frac{\left(N_{(\mathrm{AADT})_i}\right)(D_o)}{S_i} \right] - 38.8 . \tag{F-3}$$

Substitution of Equation (F-3) into the Equation (1) will give $L_{eq}(24)$.

$$L_{eq}(24)_i = (\bar{L}_o)_{E_i} + 10 \log \left(\frac{N_{(\mathrm{AADT})_i} D_o}{S_i} \right) + 10 \log \left(\frac{D_o}{D} \right)^{1+\alpha}$$

$$+10 \log \left[\frac{\psi_\alpha(\phi_1, \phi_2)}{\pi} \right] - 38.8 . \tag{F-4}$$

$$L_{dn} = 10 \log \left\{ \frac{1}{24} \left[15 \left(10^{\frac{L_d}{10}} \right) + 9 \left(10^{\frac{L_n + 10}{10}} \right) \right] \right\} \tag{F-5}$$

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.

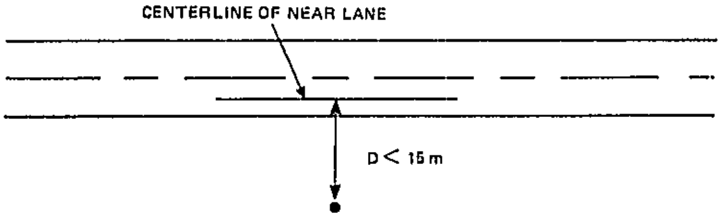


Figure G-1. Situations Where *D* is Less than 15 Metres

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.

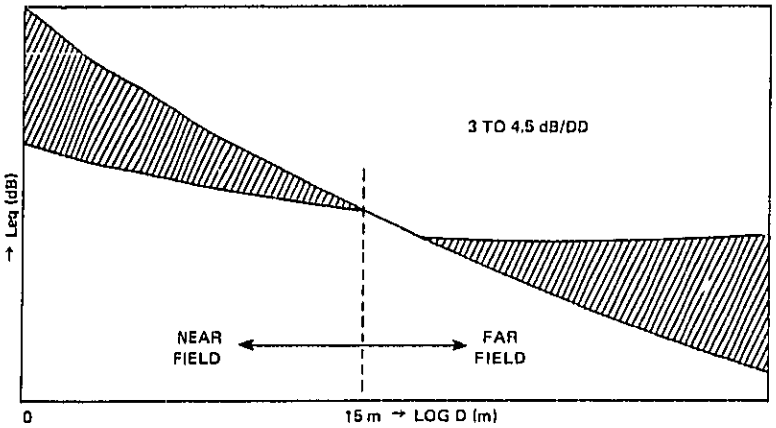


Figure G-2. Noise Levels Versus Distance

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)
⩽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,

$$L_{eq} = 10 \log \frac{1}{T} \int_{t_1}^{t_2} \frac{\langle P^2(t) \rangle}{\langle P_{\text{ref}}^2 \rangle}\, dt = 10 \log \frac{1}{T} \int_{\phi_1}^{\phi_2} \frac{\langle P^2(\phi) \rangle}{\langle P_{\text{ref}}^2 \rangle} \frac{D}{S} \sec^2 \phi \, d\phi \qquad \text{(J-2)}$$

where $P_{\text{ref}} = 2 \times 10^{-5}$ 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

$$\langle P^2 \rangle_{R_1} = \langle P_o^2 \rangle \left(\frac{D_o}{R_1}\right)^{2+\alpha_1} . \qquad \text{(J-3)}$$

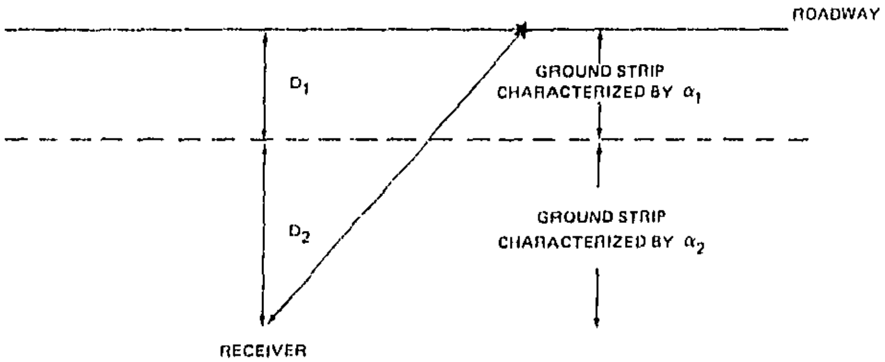
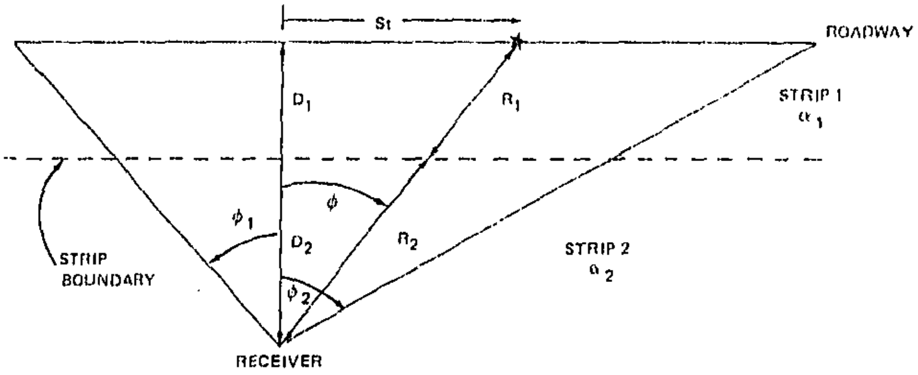


Figure J-1. Highway Site Consisting of Two Absorptive Ground Strips Parallel to the Roadway



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.

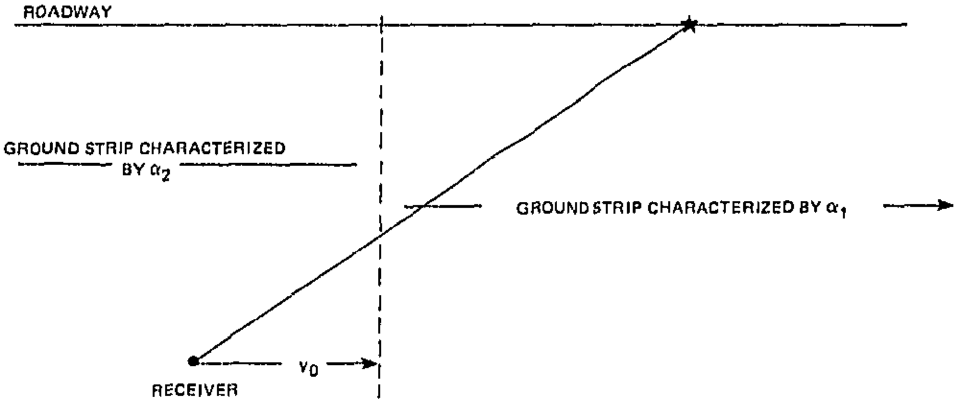


Figure J-3. Highway Site Consisting of Two Absorptive Ground Strips Normal to the Roadway

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

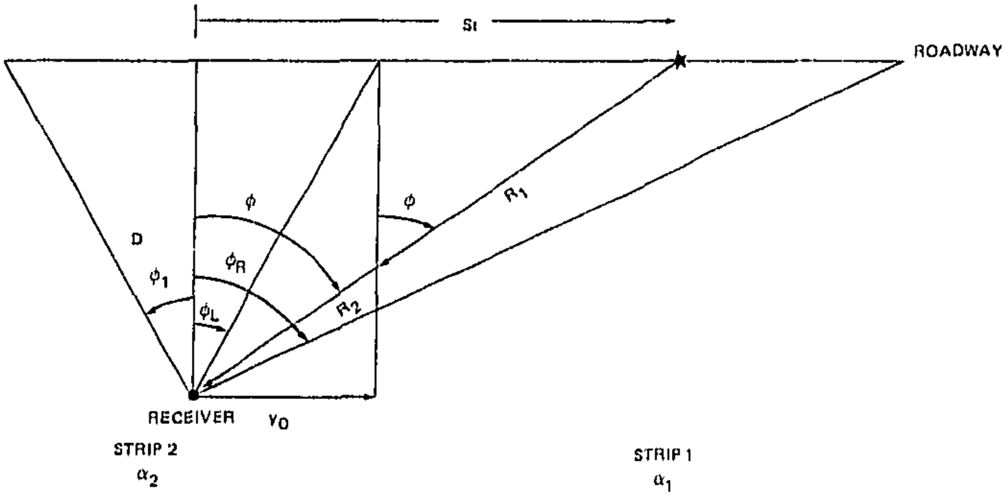
$$R = \frac{D}{\cos\phi} \quad \text{and} \quad R_1 = R\left(1 - \frac{y_o}{D}\cot\phi\right)$$

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

$$L_{eq} = 10 \log \left[\frac{1}{T} \int_{\phi_L}^{\phi_R} \frac{\langle P_o^2 \rangle}{\langle P_{\mathrm{ref}}^2 \rangle} \left(\frac{D_o}{D} \cos \phi \right)^2 \left(\frac{D_o}{D} \cos \phi \right)^{\alpha_1} \left(1 - \frac{y_o}{D} \cot \phi \right)^{\alpha_2 - \alpha_1} \frac{D}{S} \sec^2 \phi \, d\phi \right]. \tag{J-19}$$

Bringing the constants outside the integral and combining similar terms, (J-19) becomes

$$L_{eq} = 10 \log \left[\frac{\langle P_o^2 \rangle}{\langle P_{\mathrm{ref}}^2 \rangle} \frac{D_o}{ST} \left(\frac{D_o}{D} \right)^{1+\alpha_1} \int_{\phi_L}^{\phi_R} (\cos \phi)^{\alpha_1} \left(1 - \frac{y_o}{D} \cot \phi \right)^{\alpha_2 - \alpha_1} d\phi \right]. \tag{J-20}$$

Expanding (J-20), the single vehicle equivalent sound level is

$$\begin{aligned} L_{eq} &= L_o + 10 \log \frac{D_o}{ST} + 10 \log \left(\frac{D_o}{D} \right)^{1+\alpha_1} \\ &\quad + 10 \log \frac{1}{\pi} \int_{\phi_L}^{\phi_R} (\cos \phi)^{\alpha_1} \left(1 - \frac{y_o}{D} \cot \phi \right)^{\alpha_2 - \alpha_1} d\phi + 5 . \end{aligned} \tag{J-21}$$

For a class of vehicles, (J-22) is modified to give the following result

$$\begin{aligned} L_{eq} &= (\bar{L}_o)_E + 10 \log \frac{ND_o}{ST} + 10 \log \left(\frac{D_o}{D} \right)^{1+\alpha_1} \\ &\quad + 10 \log \frac{1}{\pi} \int_{\phi_L}^{\phi_R} (\cos \phi)^{\alpha_1} \left(1 - \frac{y_o}{D} \cot \phi \right)^{\alpha_2 - \alpha_1} d\phi + 5 . \end{aligned} \tag{J-22}$$

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

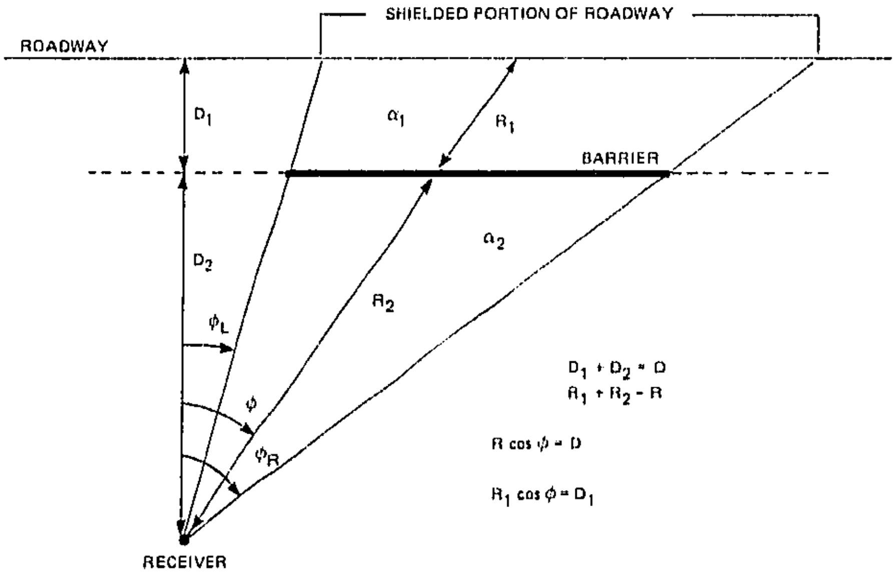


Figure J-5. Roadway-Barrier-Receiver Geometry for a Finite Barrier in the Presence of Absorptive Ground Strips Parallel to the Roadway

$$\langle P^2\rangle_i = \langle P_o^2\rangle_i \left(\frac{D_o}{R_1}\right)^{2+\alpha_1} 10^{-\Delta_i/10} \left(\frac{R_1}{R}\right)^{2+\alpha_2} \tag{J-23}$$

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,

$$L_{eq_i} = 10 \log \frac{1}{T} \int_{\phi_L}^{\phi_R} \frac{\langle P^2(\phi)\rangle_i}{\langle P_{\mathrm{ref}}^2\rangle} \frac{D}{S_i} \sec^2\phi \, d\phi ,$$

so that

$$L_{eq_i} = 10 \log \left[\frac{1}{T} \int_{\phi_L}^{\phi_R} \frac{\langle P_o^2\rangle_i}{\langle P_{\mathrm{ref}}^2\rangle} \left(\frac{D_o}{D_1} \cos\phi\right)^{2+\alpha_1} \left(\frac{D_1}{D}\right)^{2+\alpha_2} 10^{-\Delta_i/10} \frac{D}{S_i} \sec^2\phi \, d\phi \right]. \tag{J-25}$$

Taking the constant terms outside the integral and combining similar terms in (J-25) results in

$$L_{eq_i} = 10 \log \left[\frac{\langle P_o^2\rangle_i}{\langle P_{\mathrm{ref}}^2\rangle} \frac{D_o}{S_i T} \left(\frac{D_o}{D}\right) \left(\frac{D_o}{D_1}\right)^{\alpha_1} \left(\frac{D_1}{D}\right)^{\alpha_2} \int_{\phi_L}^{\phi_R} (\cos\phi)^{\alpha_1} \, 10^{-\Delta_i/10} \, d\phi \right]. \tag{J-26}$$

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

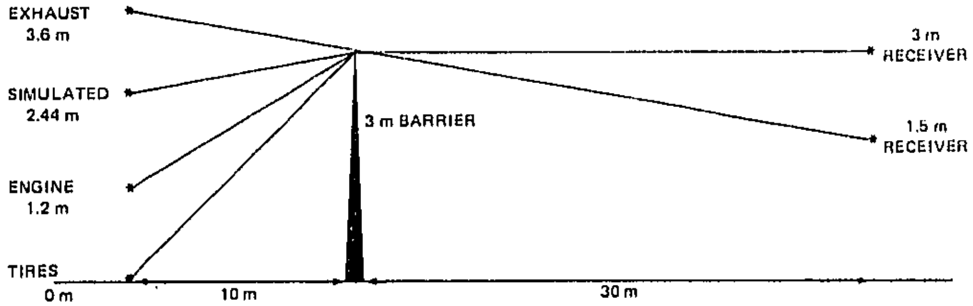


Figure K-1. Source-Barrier-Receiver Geometry Used to Examine the Effects of Source Height on Barrier Attenuation

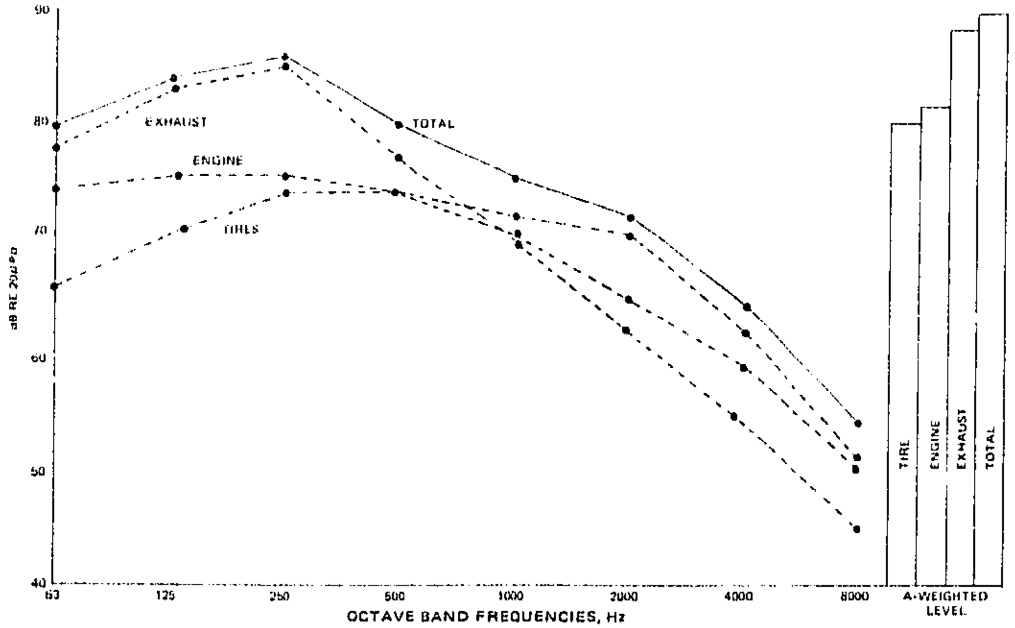


Figure K-2. Individual and Total Heavy Truck Noise Spectra Used in Example Calculations (Source Fundamentals and Abatement of Highway Traffic Noise," FHWA-HHI-HEV-73-7976-1)

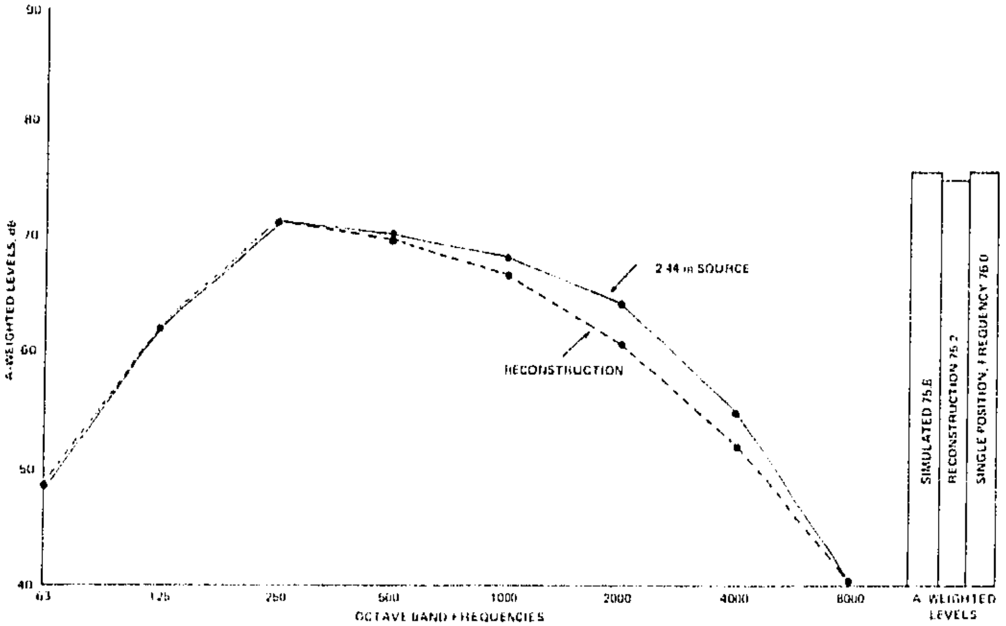


Figure K-3. Octave Band and A-Weighted Sound Levels Behind the Barrier at the 1.5 m Receiver logarithmically combined to produce the reconstructed A-weighted octave band levels at the receiver. The A-weighted levels at the receiver were then combined to give the A-weighted level at the receiver.

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.

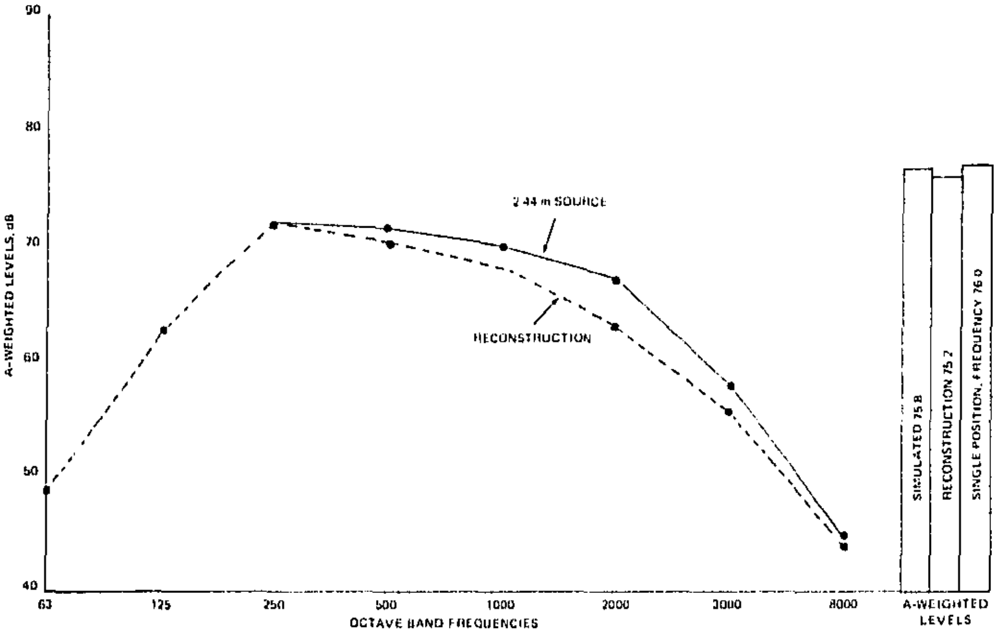
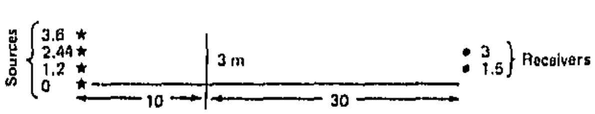
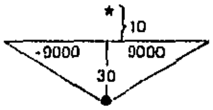


Figure K-4. Octave Band and A-Weighted Sound Levels Behind the Barrier at the 3 m Receiver

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

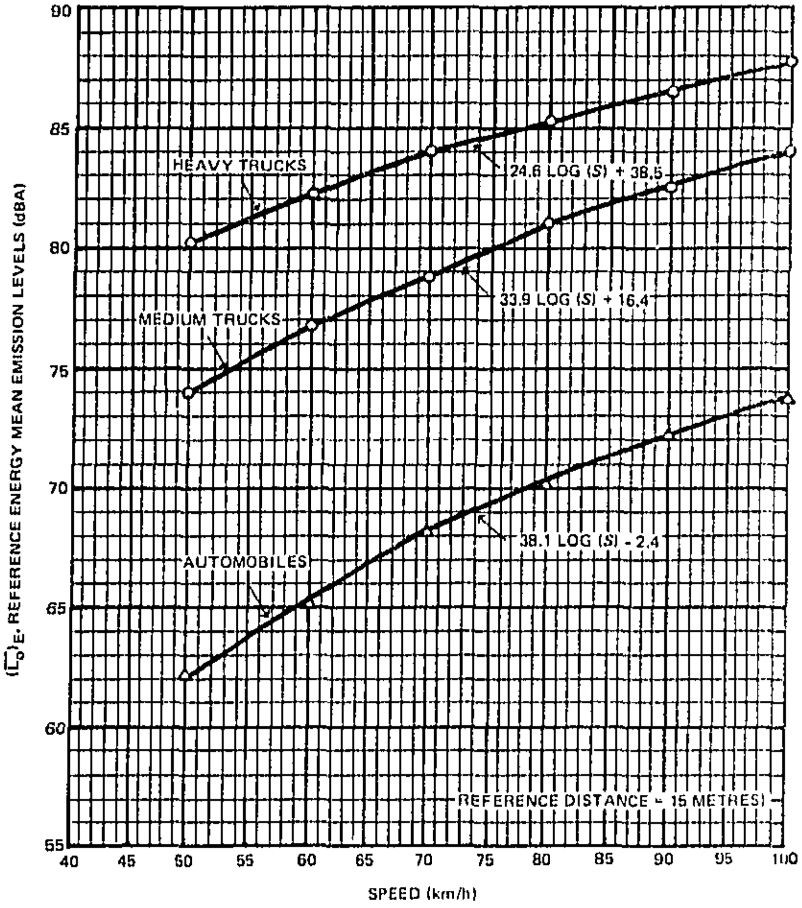
This appendix contains all of the tables, figures and nomographs needed to predict a noise level from highway traffic using the FHWA model.

NAME ______________________________ 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_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_H (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

Δ 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

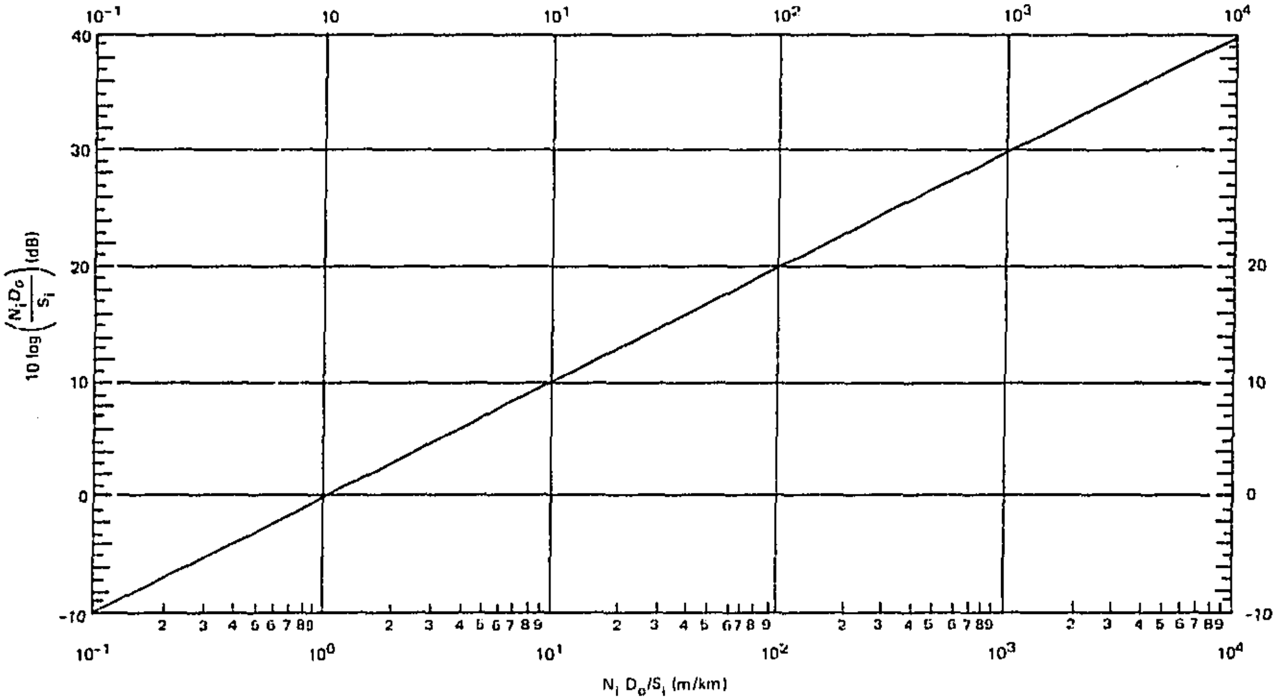


Figure 3. Adjustment for Real Traffic Flows

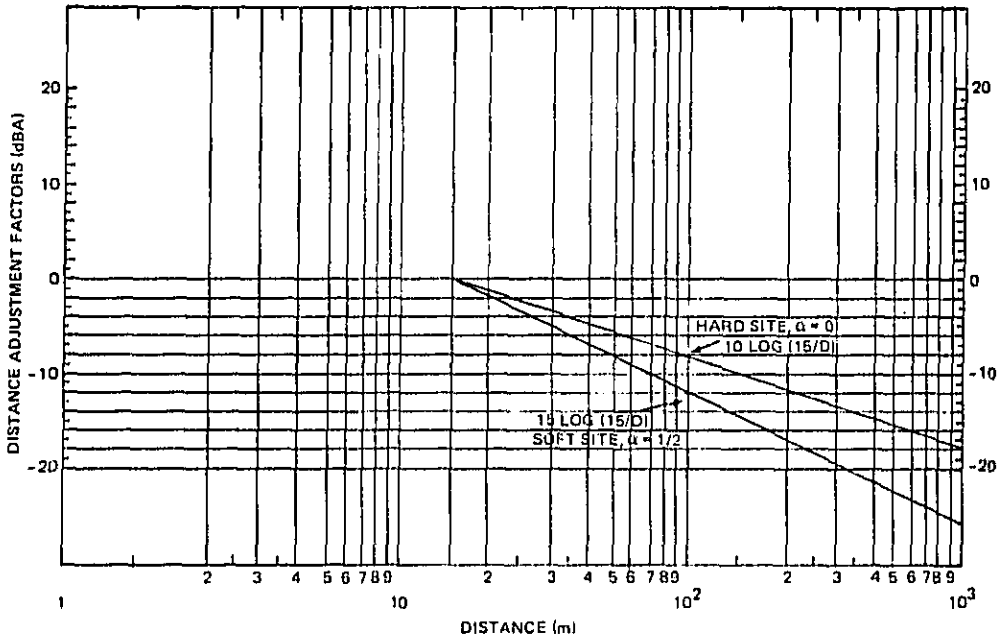


Figure 4. Adjustments for Distances Other Than 15 Metres

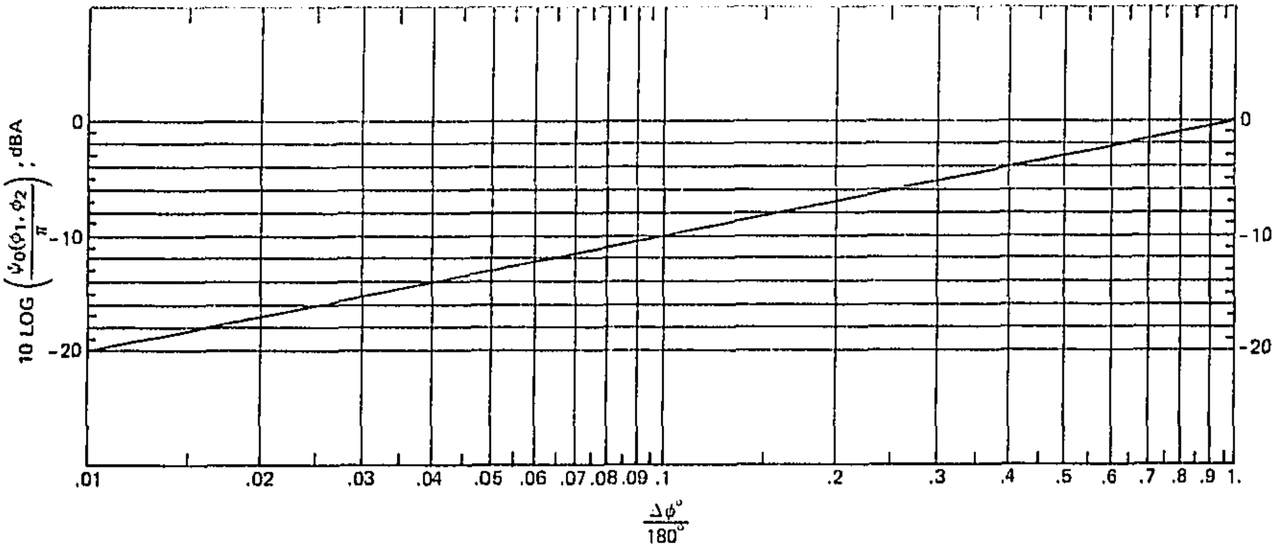


Figure 6. Adjustment Factor for Finite Length Roadways for Hard Site (α = 0)

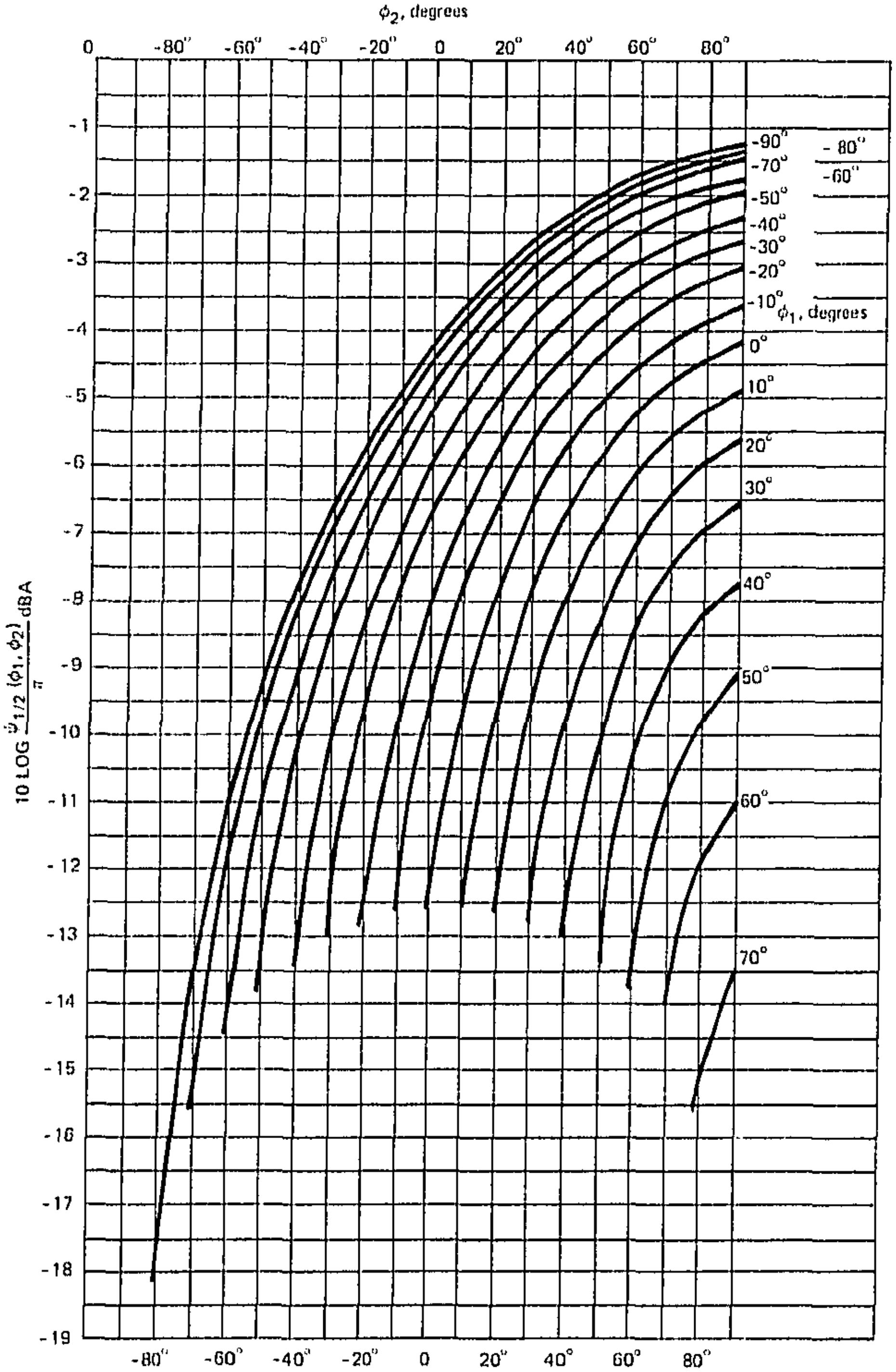
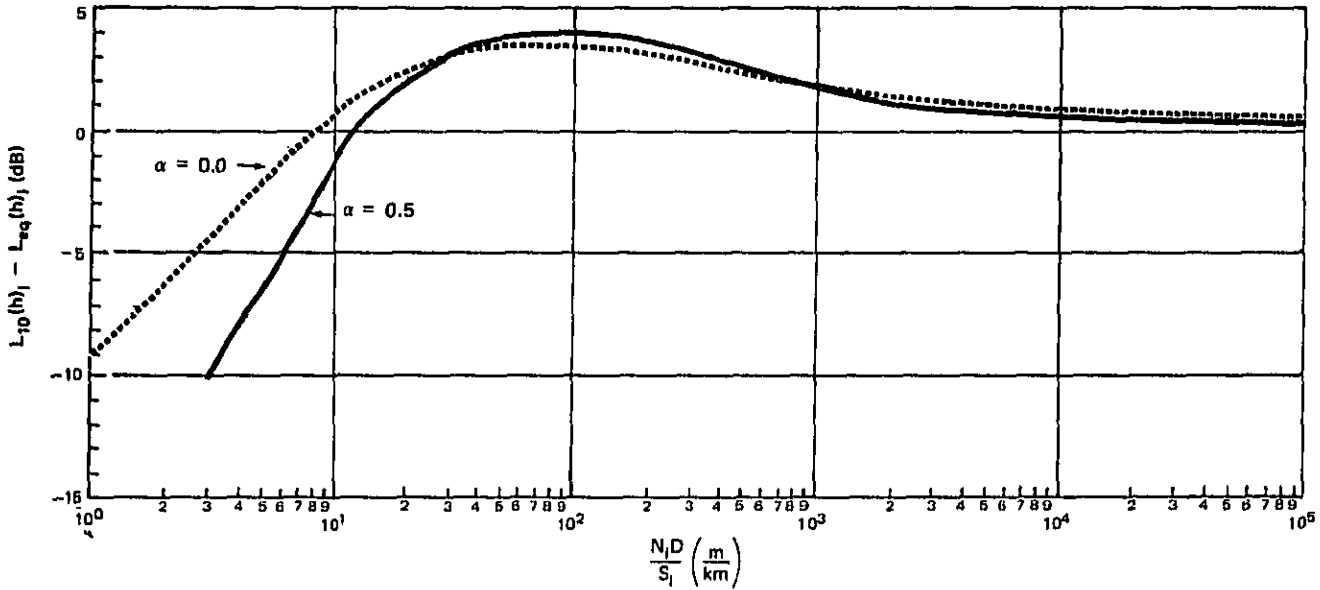


Figure 7. Adjustment Factor for Finite Length Roadways for Absorbing Sites ($\alpha = 1/2$)



(SOURCE: NCHRP REPORT NO. 173)

Figure 15. Adjustment Factor for Converting $L_{eq}(h)_i$ to $L_{10}(h)_i$

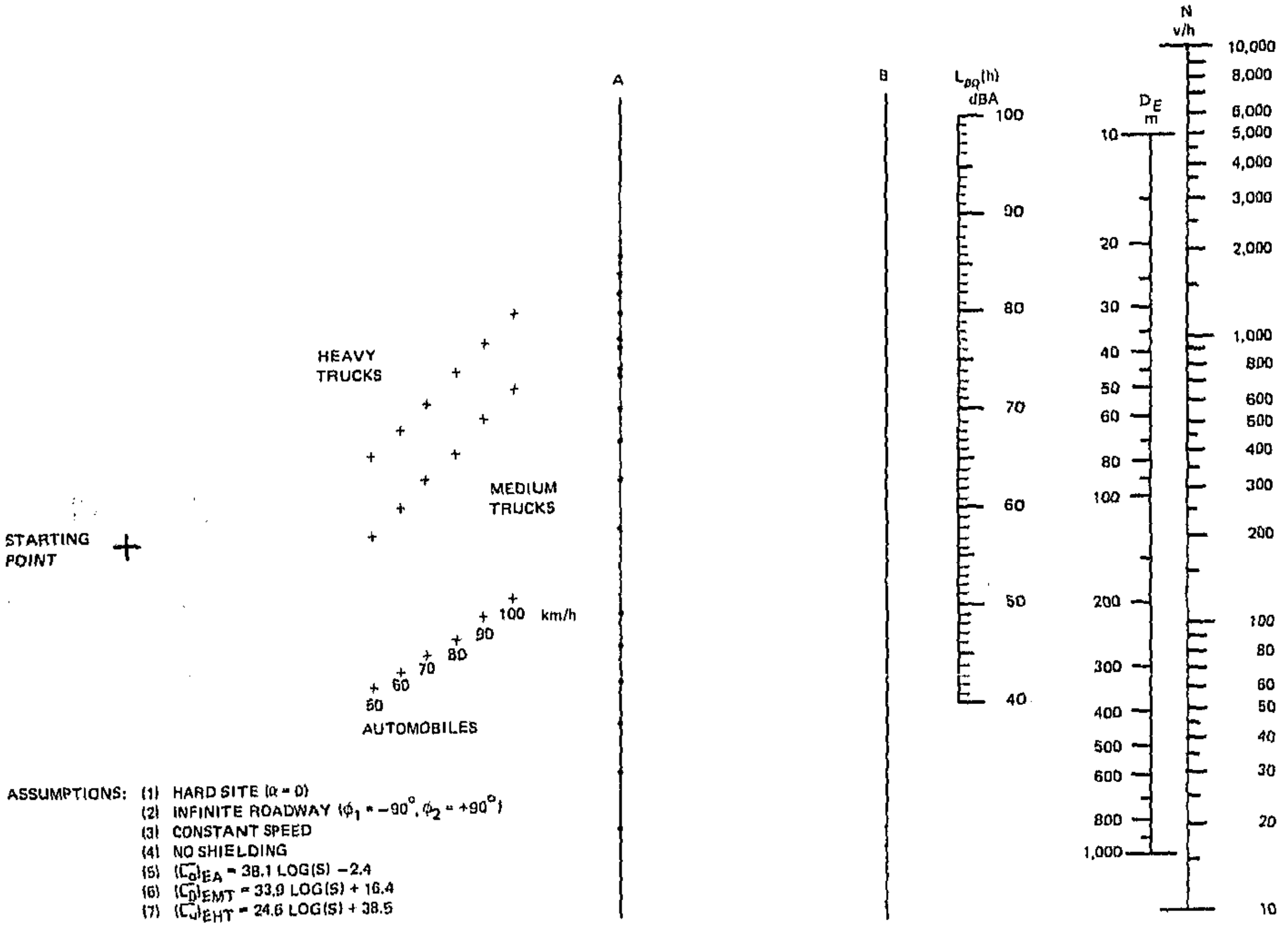
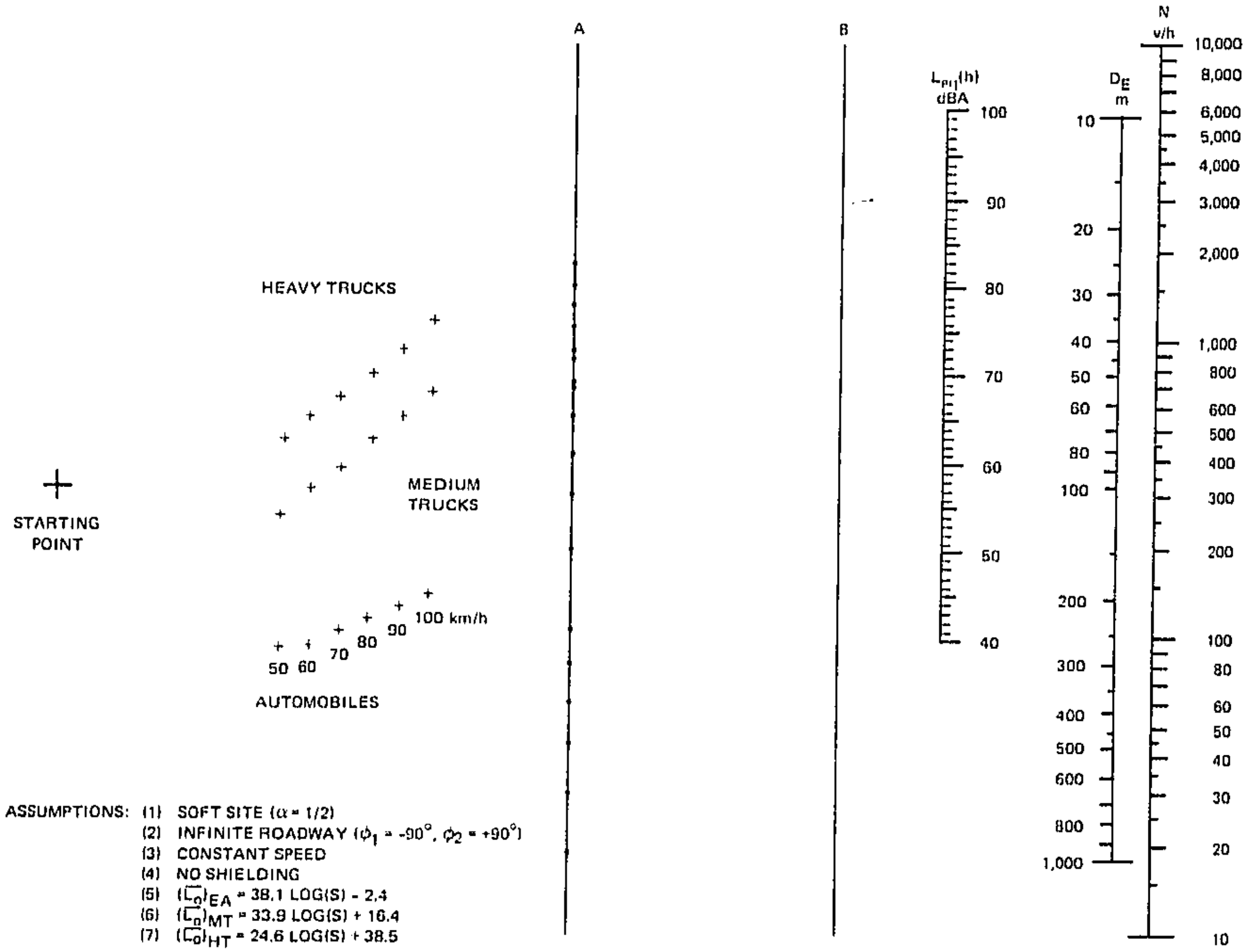


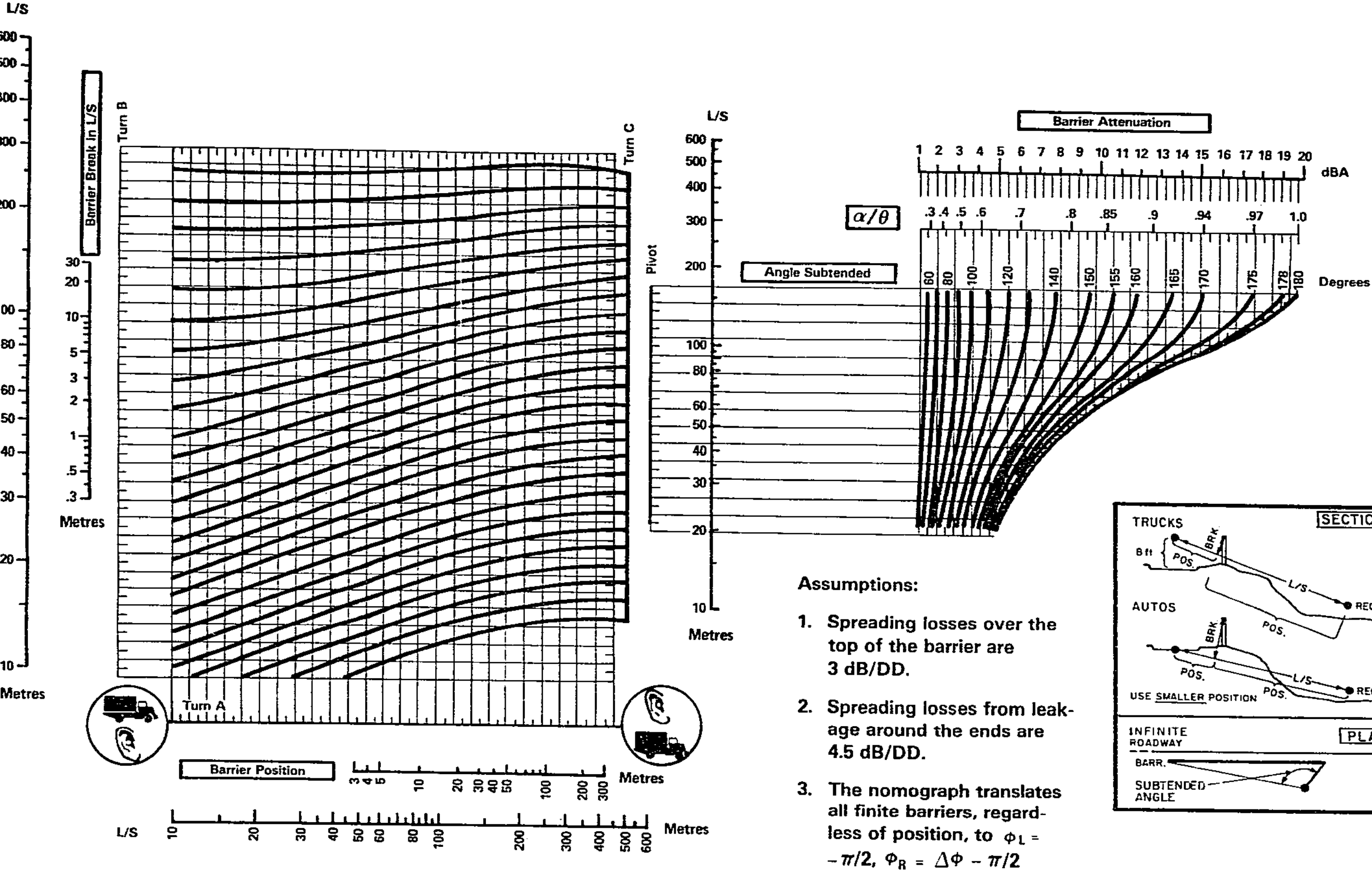
Figure 19. FHWA Highway Traffic Noise Prediction Nomograph (Hard Site)



ASSUMPTIONS: (1) SOFT SITE ($\alpha = 1/2$)
(2) INFINITE ROADWAY ($\phi_1 = -90°$, $\phi_2 = +90°$)
(3) CONSTANT SPEED
(4) NO SHIELDING
(5) $(\overline{L}_0)_{EA} = 38.1 \text{ LOG(S)} - 2.4$
(6) $(\overline{L}_0)_{MT} = 33.9 \text{ LOG(S)} + 16.4$
(7) $(\overline{L}_0)_{HT} = 24.6 \text{ LOG(S)} + 38.5$

Figure 20. FHWA Highway Traffic Noise Prediction Nomograph (Soft Site)

*U.S. GOVERNMENT PRINTING OFFICE : 1979 0-292-548/[illegible]



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

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 $15 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.