NBSIR 86-3311 (DoT)

Guidelines for the Prevention of Traffic Noise Problems

Fred F. Rudder, Jr.
Simone L. Yaniv

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
Building Physics Division
Gaithersburg, MD 20899

April 1985

Issued January 1986

Prepared for:

U.S. Department of Transportation
Federal Highway Administration
ce of Implementation, HRT-10
er-Fairbank Research Center
) Georgetown Pike
ean, Virginia 22101

NBSIR 86-3311 (DoT)

GUIDELINES FOR THE PREVENTION OF TRAFFIC NOISE PROBLEMS

Fred F. Rudder, Jr.
Simone L. Yaniv

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
Building Physics Division
Gaithersburg, MD 20899

April 1985

Issued January 1986

Prepared for:
U.S. Department of Transportation
Federal Highway Administration
Office of Implementation, HRT-10
Turner-Fairbank Research Center
6300 Georgetown Pike
McLean, Virginia 22101

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

EXECUTIVE SUMMARY

The purpose of these guidelines is to assist local authorities in the identification of potential traffic noise problems and the noise-compatible development of property adjacent to highways. The noise generated by highway traffic is the most generally pervasive environmental noise source within a a community. However, noise-compatible land development must recognize environmental noise sources other than highway traffic noise to ensure compatibility between the total noise environment and the expected land use. These guidelines, therefore, also include the noise generated by railway operations and aircraft noise in the assessment process.

The guidelines are quantitative rather than qualitative in scope. Calculations are required to conduct an assessment of a specific site. The calculations are not difficult and may be performed with a pocket calculator. The guidelines are intended to be a complete document in that all the necessary information is included along with step-by-step instructions and examples illustrating the methods. Specialized training is not required to utilize these guidelines.

The guideline format is based upon the application of local data to evaluate present and future conditions for a proposed land development. These data are used to predict the noise environment at a site and to estimate the effectiveness of possible noise mitigation measures. Since the guidelines are intended only to identify possible noise problems, the methods used are approximate. However, these approximations are consistent with accepted engineering practices, and the resulting estimates identify potential problems and their severity. Once this identification has been accomplished, the developer or local authority may perform additional estimates using more refined methods to justify the proposed action. References to these more refined methods are included in the guidelines, as appropriate.

Finally, these guidelines are not intended to be a refined design tool for evaluating alternatives, although one may use the methods for preliminary design evaluation. Following the steps included in the guidelines, the noise exposure of land may be estimated for the following sources and conditions:

- Multi-lane highway traffic for uniform traffic flow within 1500 ft of the pavement;

- Diesel-electric railway trains, including warning horns, within 1500 ft of the railway track;

- Aircraft operational noise as provided by the local airport authority; and

- The combination of the above noise sources with the existing noise environment at the site.

The guidelines present accepted noise criteria for evaluating the compatability of the proposed land development considering the noise exposure of the land. These criteria are used to assess both the outdoor land use compatibility and the indoor land use compatibility.

The mitigation of noise is also considered in the guidelines. The following mitigation techniques are included:

- Highway traffic noise barriers;
- Building location and orientation relative to the noise sources; and
- Building envelope noise isolation including composite constructions such as windows, walls, and doors.

It is recognized that local authorities may require guidance in the implementation of noise control measures to achieve noise-compatible land use. In this context, planning and zoning strategies are discussed, building noise control codes are reviewed and referenced.

1. OVERVIEW OF GUIDELINES

The guidelines are presented in three main sections: Outdoor Noise Environment, Mitigation Techniques, and Noise Compatible Development.

1.1 CHARACTERIZATION OF THE OUTDOOR NOISE ENVIRONMENT

Sound Levels

A quantitative description of the outdoor noise environment is the first step in the assessment of noise-compatible land use. These guidelines use the Day-Night Average Sound Level which is abbreviated DNL and is symbolized mathematically as L_{dn}. The DNL is an accepted measure of environmental noise that allows the noise from different sources to be combined so as to assess the total environmental noise at a building site (Ref. 1).

The basic component of L_{dn} is the equivalent sound level denoted by the symbol L_{eq}. The equivalent sound level, L_{eq}, is a time average of the A-weighted acoustic energy generated by a noise source (Ref. 2). The term "A-weighted" denotes a standardized frequency weighting applied to the noise (Ref. 3). The magnitude of the equivalent sound level is measured in A-weighted decibels denoted by dBA.* The A-weighting frequency characteristic approximates the frequency sensitivity of the human ear so that the L_{eq} value characterizes the environmental noise in a manner similar to that of human response to noise.

The value of L_{dn} at a site is determined by the noise exposure of the site during a "daytime" period from 7 a.m. to 10 p.m. and the noise exposure of the site during a "nighttime" period from 10 p.m. to 7 a.m. The noise levels at night, however, are considered to be 10 dB greater in magnitude than noise levels of similar magnitude occuring during the daytime period. This +10 dB nighttime weighting is intended to account for the increased sensitivity of people to noise that occurs during sleeping hours as a result of the drop in background noise levels at night.

The selection of the Day-Night Average Sound Level or DNL for use in these guidelines requires that local information or data to estimate the noise exposure be collected for both the daytime and the nighttime periods. These data must be averaged for a typical day of the year. The details of specific information required, such as traffic flow data, number of trains, etc., are described in Section 2.

Levels of outdoor noise that relate the noise exposure to land use compatibility have been established (Ref. 1). These levels are based upon several considerations. However, the primary consideration is that noise disrupts a

---

* All quantities used in these guidelines are A-weighted sound levels. The notation dBA and dB will be used interchangeably.

person's activity and, thereby, produces a generally adverse response, and a person's expected activity may be related to the intended land use. Additional considerations used to establish noise criteria are the degree to which the activity may be sensitive to outdoor noise and the feasibility of mitigation of the noise either outdoors or by the building envelope.

Table 1 has been extracted from Ref. 1 and presents suggested compatibility guidelines for residential land use. The application of such guidelines to local conditions is a local policy judgement. However, the purpose of presenting Table 1 is to illustrate the practical aspects of using these guidelines to assess noise-compatible land use.

First, if the outdoor DNL is less than 55 (L_{dn} <55 dB), residential land use is considered to be compatible with the outdoor environment without restriction. If the DNL is greater than 75 dB (L_{dn} >75 dB), residential land use is considered to be totally incompatible with the outdoor noise.* Hence, the 20 dB range between L_{dn} = 55 and L_{dn} = 75 is important. It is equally important to note that intervals of 5 dB are used to establish restrictions for compatible land use. The implication of this 5 dB interval is that a ±3 dB change in the estimated noise environment or noise mitigation alternatives may be significant to the final assessment of noise-compatible land use.

Notes On Sound Levels

- The equivalent sound level, L_{eq}, is a time average of the sound energy over a specific time interval, T. The DNL or L_{dn} is a time average over a 24-hour time period with a +10 dB weighting applied to the nighttime sound levels. Both L_{eq} and L_{dn} are measured in A-weighted decibels denoted as dBA.
- Instrumentation is availalble for the direct measurement of both L_{eq} and L_{dn} using standardized methods (Ref. 4).
- A 3 dB change or a 3 dB difference in sound level is generally considered to be unnoticeable by the average person (Ref. 5); however, a 3 dB difference is important in using these guidelines, as it represents either a doubling or halving in the amount of acoustic energy.
- A 10 dB change in sound level corresponds to a doubling of the perceived loudness (Ref. 5).
- People respond differently to sound of the same level. As a result, the average response of people to noise should be used to evaluate noise-compatible land use.

---

* Section 4.2 includes a discussion of a model building code for noise control. This model building code sets the upper limit at L_{dn} >80 dB for totally incompatible residential land use.

Table 1. SUGGESTED LAND USE COMPATABILITY GUIDELINES: RESIDENTIAL LAND USE (Ref. 1, Table 2, pp 6-11 and as noted)

Standard land use coding manual number	Residential Land Use	Day-Night Average Sound Level Range, L_{dn}, dB						
		Below 55	55 to 60	60 to 65 (1)	65 to 70 (2)	70 to 75 (3)	75 to 80 (4)	Above 80
11	Household units	yes	yes	20	25	30	No	No
11.11	Single units-detached	yes	yes	20	25	30	No	No
11.12	Single units-semidetached	yes	yes	20	25	30	No	No
11.13	Single units-attached row	yes	yes	20	25	30	No	No
11.21	Two units-side-by-side	yes	yes	20	25	30	No	No
11.22	Two units-one above the other	yes	yes	20	25	30	No	No
11.31	Apartments-walk up	yes	yes	20	25	30	No	No
11.32	Apartments-elevator	yes	yes	20	25	30	No	No
12	Group quarters	yes	yes	20	25	30	No	No
13	Residential hotels	yes	yes	20	25	30	No	No
14	Mobile home parks or courts	yes	yes	20	No	No	No	No
15	Transient lodgings	yes	yes	20	25	30	35	No
16	Other residential	yes	yes	20	25	30	No	No

Notes:

(1) Ref. 1 combines the DNL intervals 55 to 60 and 60 to 65 without specifying a value of the building envelope Noise Level Reduction (NLR).

(2) A value of 20 dB NLR for the building envelope can be achieved using normal construction and by keeping windows closed.

(3) Local conditions may require residential use. However, it should be discouraged in this DNL range. When residential use must be allowed, the building envelope Noise Level Reduction must be 25 dB.

(4) Local conditions may require residential use. However, it should be strongly discouraged in this DNL range. When residential use must be allowed, the building envelope Noise Level Reduction must be 30 dB.

Prediction and Propagation of Noise from the Source

Section 2 of these guidelines presents noise prediction methods for highway traffic and diesel-electric trains. The predictions incorporate details of the noise source. However, the predictions are limited to the land area within 1500 ft of either side of the highway pavement or railway track centerline.

The prediction methods assume that both the highway and the railway alignments are straight and continue indefinitely to the left and to the right from the receiver's location. The methods then predict the source sound level at a reference location adjacent to the highway or railway alignment. For highway traffic noise, the reference location is 50 ft from the pavement edge of the near lane. For railway noise, the reference location is 100 ft from the centerline of the railway track. The predicion methods do not apply to receiver locations closer to the source than the reference distance for the source.

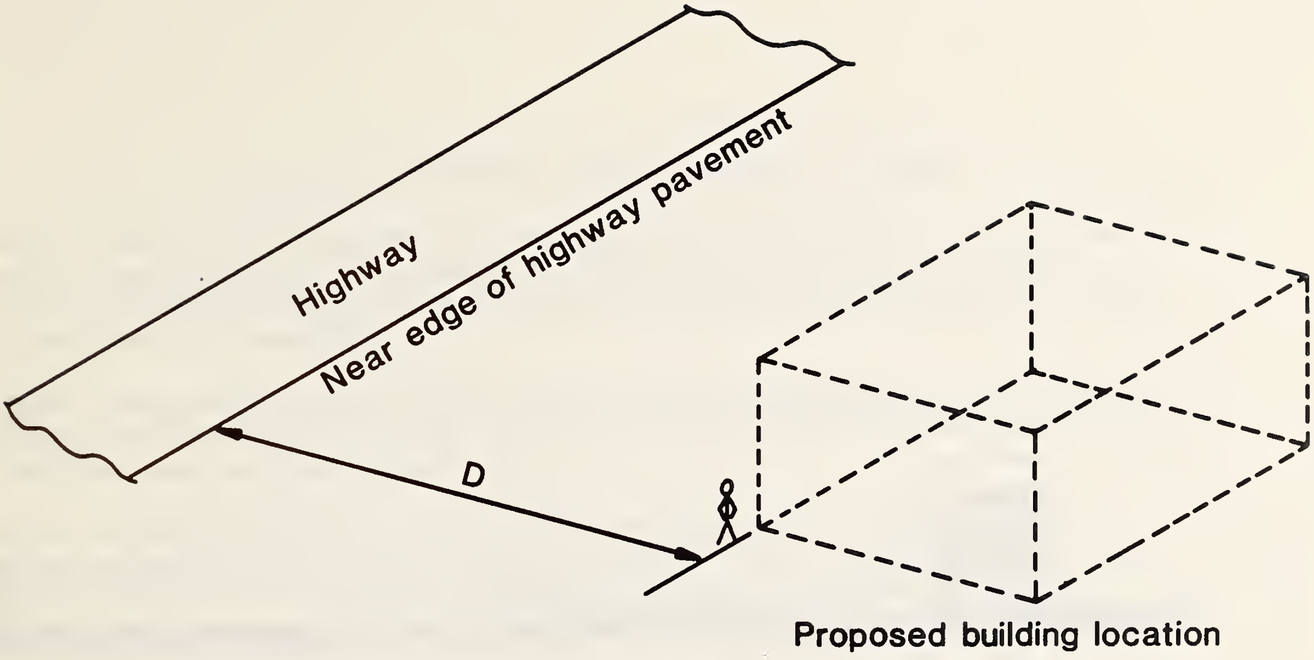
As noise propagates away from the highway or the railway, the sound level decreases. However, the rate at which the sound level decreases with distance depends upon both the source and the site characteristics. The method used to incorporate site characteristics into the propagation model assumes that the receiver location has an unobstructed view of either the highway or the railway.* Figure 1 illustrates typical source-receiver geometry considered by the method.

With the geometry shown in Figure 1, the propagation model allows the user to select either a "hard" site or a "soft" site. A "hard" site is an idealization of either gravel or sparse vegetation between the source and the receiver. A "soft" site is an idealization of a site covered with grass or vegetation within 1 ft of the ground. The choice of either a hard site or a soft site determines the sound level decrease from the source reference location to the receiver. Soft site propagation yields a larger sound level decrease with distance than the hard site propagation (Refs. 6, 7, and 8). Figure 2 illustrates typical site conditions for selecting either hard site or soft site characteristics for the noise propagation.

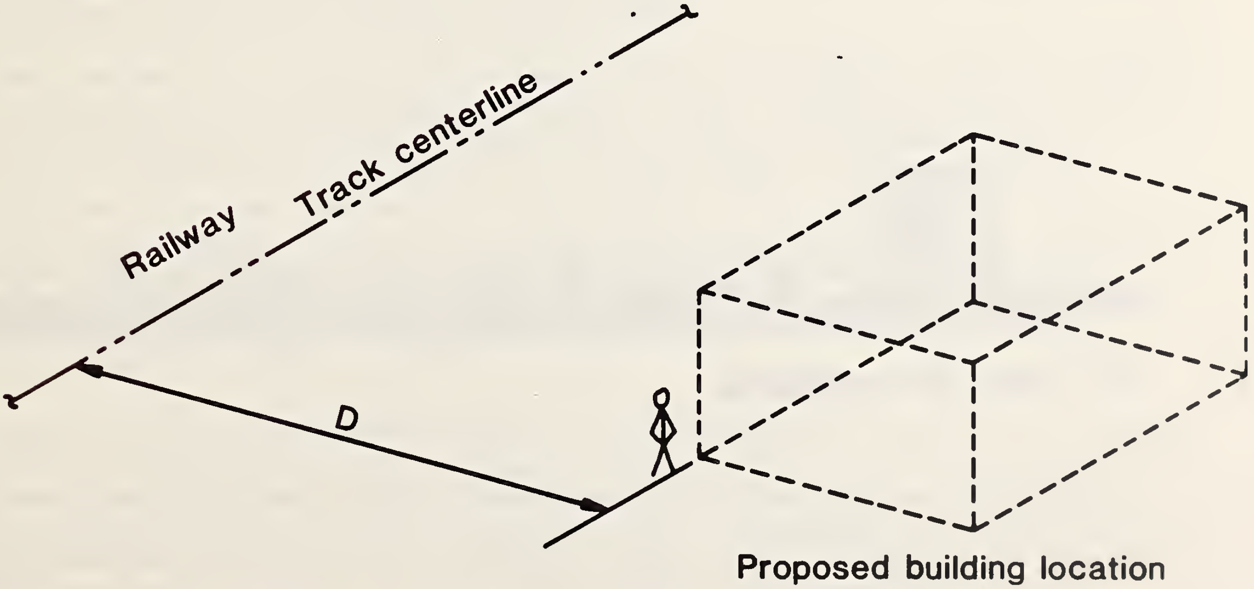
The prediction of the DNL due to aircraft noise is quite complicated (Ref. 9) as compared to highway and railway noise prediction. Due to this complexity, these guidelines do not attempt to include an airport/aircraft noise prediction method. However, these noise level predictions should be available from the local airport authority as part of their planning process (Refs. 10 and 11). The guidelines, however, do allow for the incorporation of aircraft noise into both the site noise exposure estimate and the building envelope noise isolation estimate.

---

* Simple site topographic features such as a depressed roadway or a berm may be incorporated in the model as described for barriers in the Section 3.



a) Source-receiver geometry for highway traffic noise



b) Source-receiver geometry for railway noise

Figure 1. Source-Receiver Geometry for the Present Guidelines

a) Hard-site conditions

b) Soft-site conditions

Figure 2. Typical Site Conditions for Highway Traffic Noise Prediction

Notes on Prediction and Propagation of Noise

- Source sound levels depend upon the source characteristics. Since the guidelines use L_{dn} as the measure of environmental noise, the estimation of the source characteristics for the time period from 10 p.m. to 7 a.m. is particularly important.

- These guidelines provide methods for predicting highway traffic noise and diesel-electric railway noise. Aircraft noise prediction must be obtained from the local airport authority.

- Noise propagation away from the source depends upon both the source characteristics and the site characteristics. For highway traffic noise either "hard" site or "soft" site noise propagation may be used. For railway noise propagation only the "hard" site conditions are considered.

1.2 CHARACTERIZATION OF THE INDOOR NOISE ENVIRONMENT

These guidelines consider only the indoor noise environment resulting from outdoor noise sources. The indoor noise environment is fixed in terms of a criterion level. The criterion level is based upon both the intended building use and the occupants daily activities within the building. This approach recognizes that outdoor noise may interfere with occupants activities, and that the degree of interference may be associated with both the intended use of a building and the interior building subdivisions.

People exposed to noise in their homes show a generalized adverse response which increases with increasing noise exposure level. This generalized adverse response is complex and involves a combination of factors including speech interference, sleep interference, and a frustrated desire for quiet and the ability to use telephone, radio, and T.V. satisfactorily. Among the activities interferred with, speech communication is the most often mentioned. A level of 100-percent sentence intelligibility is achieved if the noise level indoors is at or below 45 dB, dropping rapidly to 90 percent if the noise level increases to 65 dB. For this reason, a level of 45 dB indoors is considered to be an acceptable level for rooms sensitive to noise.

Since the outdoor noise environment is characterized by the DNL, the indoor noise criterion levels must also be characterized by the DNL. As used in these guidelines, the difference between the outdoor DNL value and the indoor DNL criterion level is the Noise Level Reduction, NLR, that must be provided by the building envelope. That is, if the outdoor DNL is $L_{dn} = 65$ dB and the indoor criteria level is $L_{dn} = 45$ dB, the required noise level reduction for the building envelope is 20 dB.

The main objective of these guidelines is to provide a method whereby the user may evaluate building construction on a site exposed to possibly several noise sources to determine the building noise level reduction.

Notes On Indoor Noise Characteristics

- For the purpose of these guidelines, only the contribution from outdoor noise to the indoor noise environment is considered.

- The indoor noise environment is establihsed in terms of a criterion level or a level expressed as an indoor DNL.

- The criterion level may be based upon either a noise criterion for noise sensitive room use within a building or as an average for the entire indoor space.

- Using normal construction, it is easy to achieve a building noise level reduction of 20 dB. Very unconventional building construction must be used to achieve a 40 dB building noise level reduction.

1.3 ESTIMATION OF FUTURE CONDITIONS

Noise-compatible land use requires the evaluation of both the existing and prospective noise environments at the building site. The reason for considering future conditions is that the noise environment may change, and the effect of the change must be evaluated. Normally, a 20-year period is used for planning purposes (Refs. 13 and 14). However, local considerations will establish this planning period and policy regarding noise compatibility.

For example, a proposed residential development adjacent to an existing right-of-way for a future major highway must be judged in terms of the expected future noise environment. Until the highway is opened, the houses may be overdesigned for noise. However, the result is avoiding potential future conflicts between the noise environment and the planned land use.

These guidelines allow the user to evaluate site noise exposure quickly. As a result, it is easy to estimate the future noise levels. The information required for this evaluation is the change in the noise source characteristics. The only difficulty is obtaining future estimates of the traffic flow for a highway or the characteristics of train operations for railway noise. For aircraft noise, the local airport authority must provide the predictions. Ref. 14 provides a more complete discussion of these considerations.

Notes on Future Conditions

- When evaluating the significance of future noise levels, a change in the noise source characteristics must result in a DNL change of 3 dB to be significant. As described in Section 2, if all traffic flow parameters such as speed, percentage mix of heavy trucks, and the fraction of heavy trucks operating at night remain constant but the total daily traffic count is allowed to vary, then the total count must double to cause a +3 dB change, or decrease by half to cause a -3 dB change in the DNL. Hence, an extremely accurate estimated future traffic count is not too important for evaluating <u>changes</u> in the traffic noise environment.

1.4 MITIGATION TECHNIQUES

The mitigation of environmental noise is an option for resolving conflicts between the noise source and the desired land use. Mitigation techniques may focus upon any one or all of the elements of the engineering discipline of noise control. These elements are:

1) Source noise control - decrease noise generated by trucks, trains, aircraft, etc.
2) Path noise control - alter the propagation of noise from the source to the receiver location.
3) Receiver noise control - alter the immediate environment at the receiver location.

These guidelines address only mitigation techniques related to path and receiver noise control. The noise generated by the traffic flow, or the railway operations, is established using current noise emission characteristics of automobiles, trucks, and diesel-electric trains, and does not include provisions for the alteration of these characteristics. However, the dependence of highway noise on traffic flow variables such as speed and vehicle mix may be evaluated.

The guidelines allow the user to evaluate the effectiveness of the following mitigation techniques:

- Variation of vehicle mix and traffic flow on highways;
- Decrease in sound level due to distance between the source and the receiver;
- Utilization of barriers or berms for highway traffic noise;
- Utilization of buildings and building components for partial mitigation of highway traffic and railway noise for outdoor receiver locations; and
- Utilization of the building envelope for mitigation of highway, railway, and aircraft noise for receivers located indoors.

These mitigation techniques may be used individually or in combination either to avoid or to resolve conflicts between the noise environment and the desired land use. The decision as to which technique or combination of techniques to use depends upon the specific conditions at the site. One objective is to achieve the most cost-effective mitigation. These guidelines only address the degree of mitigation effectiveness. The cost of alternative mitigation techniques is a local consideration.

Table 2 has been prepared to provide the reader with a feeling for the effectiveness of various mitigation techniques. The effectiveness is estimated in terms of the change in the outdoor DNL resulting from implementation of each mitigation technique. For the conditions listed in Table 2, it is evident that increasing the source-receiver distance by providing a buffer zone between the highway and receiver is not too effective, unless the highway noise levels at 50 ft are already low, and the cost of land is not a consideration. Similarly, changing the average speed of traffic is not as effective as prohibiting heavy trucks from the highway. However, based upon specific site conditions, it may be reasonable and prudent to use a combination of mitigation techniques to ensure noise-compatible land use.

It is the objective of these guidelines to provide the user with methods suitable to evaluate alternative noise mitigation techniques. Details are provided in the following sections.

Finally, for residential land use, two criteria should be simultaneously satisified to ensure noise compatibility: an outdoor criterion and an indoor criterion. The outdoor criterion recognizes that noise may intrude upon normal outdoor activities about a residence. The indoor criterion applies to normal indoor activities. Utilization of the building envelope construction to achieve the indoor criterion will do nothing to mitigate the effects of outdoor noise on outdoor activities around the residence. Table 3 illustrates the general nature of the problem of satisfying both an outdoor criterion and an indoor criterion to ensure noise-compatible land use. It is seen that above an outdoor DNL of 65 dB, it is difficult or impossible to achieve acceptable outdoor conditions, and that acoustical design considerations are required for the building envelope. It should also be emphasized that the term "windows closed" implies that mechanical ventilation or perhaps air conditioning is required in addition to the acoustical design consideration.

Notes On Noise Mitigation

- Mitigation of outdoor noise by 5 to 10 dB is easily achieved using site design techniques. Higher levels of noise mitigation are more difficult to either implement or achieve.

- For outdoor DNL between L_{dn} = 60 dB and L_{dn} = 65 dB and residential land use, both outdoor and indoor noise mitigation is required. Acceptable indoor conditions are usually achieved with normal construction by keeping windows closed.

- For outdoor DNL above L_{dn} = 65 dB, the outdoor environment becomes unacceptable for residential land use. Acoustical design of the building envelope is required and windows must be closed and sealed to achieve a compatible indoor environment.

Table 2. Ranges of L_{dn} Decrease for Various Mitigation Techniques as Estimated Using These Guidelines

Mitigation technique	Range of L_{dn} decrease,* dB	Applicable noise source	Qualifications for application
Change vehicle mix	10 to 12	Highways	Prohibition of heavy trucks from highways.
Lower traffic speed	5	Highways	From 55 mph to 30 mph with 10-percent heavy trucks.
Decrease traffic volume	3	Highways	50 percent decrease in 24-hour traffic flow.
Increase the source to receiver distance	20 to 23	Highways	At 1500 ft and relative to level at 50 ft.
	13 to 16	Railways	At 1500 ft and relative to level at 100 ft.
Locate a barrier or berm between source and receiver	5 to 18	Highway	Receiver is shielded by the barrier and is within 25 ft of the barrier.
Shielding by buildings or building components	3 to 15	Highway and railway	Building, courtyards, screened yards, and shielded balconies. Relative to level at building location.
Building envelope noise level reduction	15 to 40	Highway, railway, and aircraft	Varies from normal construction with open window to a tightly sealed envelope utilizing special acoustical design features. Relative to level at the building location.

* Decrease relative to level prior to the implementation of the noted mitigation technique.

Table 3. Mitigation Effectiveness for Outdoor and Indoor Criteria for Residential Land Use

Outdoor DNL L_{dn}, dB	Outdoor activities criterion, $L_{dn} = 55$	Indoor activities criterion, $L_{dn} = 45$	Building envelope noise level reduction, dBA
Less than 55	Compatible	Compatible	-
55 to 60	Acceptable	Compatible with normal construction and windows open	-
60 to 65	Acceptable with outdoor noise mitigation	Compatible with normal construction and windows closed	20
65 to 70	Marginally acceptable, outdoor noise mitigation difficult to implement	Discourage residential use and require windows closed with acoustical design of the building envelope.	25
70 to 75	Generally unacceptable	Strongly discourage residential use and require windows closed with acoustical design of the building envelope.	30
75 to 80	Unacceptable	Allow transient lodgings only and require windows closed with acoustical design of the building envelope.	35
Greater than 80	******** Prohibit residential land-use ********		

NOTE: The outdoor criterion of $L_{dn} = 55$ and the values of the building envelope noise level reduction are from Ref. 1. The indoor criterion level of $L_{dn} = 45$ is inferred from Ref. 1 and is a commonly accepted value (Refs. 13 and 14).

1.5 NOISE COMPATIBLE LAND USE DEVELOPMENT

With a quantitative description of the outdoor and indoor noise environment and the possibilities of implementation of noise mitigation techniques, the tools are available to assess both the feasibility and practicality of achieving noise-compatible land use development. Such considerations are, however, dependent upon local desires and policies concerning the ranking of environmental values among the socioeconomic and technical priorities of the community.

Land Use Control Techniques

The techniques available to communities for the implementation of noise-compatible land use are varied. It is difficult to identify any specific technique or combination of techniques that may be applied to all communities. Therefore, guidance can only be provided concerning general techniques that may apply to local conditions.

At the local level of government, land use control is limited by two factors:

(1) The enabling legislation of the state whereby the police powers of the state are delegated to local governments, and

(2) The level of sophistication of the local governments and their planning agencies.

Both regulatory and non-regulatory controls may be utilized to achieve noise-compatible land use. Regulatory controls may comprise land use zoning, subdivision regulations, building codes, health codes, and consumer protection ordinances. Non-regulatory controls may encompass public acquisition of land by either direct purchase or easement rights, and the application of financial considerations using taxation or capital investment incentives. These various techniques are discussed in Section 4.3 of these guidelines.

These guidelines provide methods for the technical evaluation of environmental noise, the mitigation of the effects of noise upon a community, and the quantitative comparison of noise control alternatives. The application of these methods to local conditions forms a basis for developing feasible controls to ensure compatible land use.

2. THE OUTDOOR NOISE ENVIRONMENT

This section describes the methods for estimating the outdoor noise environment at a site. These methods assume that the site is generally flat and is free of obstructions between the noise source and the location(s) for estimating the noise exposure. If the site provides natural shielding of the source from the receiver's location, the noise exposure estimates must be adjusted as described in the following section on mitigation. Figures 1 and 2 illustrate the source-receiver geometry.

The prediction methods place the receiver at a 5 ft elevation above the ground. This elevation correponds to the ear height of a standing person or the center of the ground floor of a building envelope. The horizontal distance between the noise source and the receiver is the primary site variable required for these calculations. A scale map of the site indicating the locations of the noise sources and the receivers is helpful. All horizontal distances are measured from the near edge of the highway pavement for traffic noise or the centerline of the railway track for train noise.

2.1 HIGHWAY TRAFFIC NOISE PREDICTION

Necessary Information

The following is required to estimate the noise generated by highway traffic:

- Number of lanes of traffic.
- Average cruise speed of traffic in miles per hour, mph.
- Annual average daily traffic, AADT, in vehicles per 24 hours.
- Percentage of AADT of each vehicle type in the traffic stream, including
  - percentage of automobiles and light trucks
  - percentage of medium trucks
  - percentage of heavy trucks.
- Fraction of each vehicle type operating on the highway during the nighttime period from 10 p.m. to 7 a.m.*

This list should not overwhelm the user. For an existing or a proposed highway, the first three items are generally available from State Highway Departments. It may be more difficult, however, to obtain information on the percentage vehicle mix and the fraction of each vehicle type operating at night. Representative data are provided in these guidelines for the annual average

---

* If a 1000 heavy trucks operate each 24 hours and 200 of these operate at night, the fraction of heavy trucks operating from 10 p.m. to 7 a.m. is 0.20.

daily traffic, percentage vehicle mix, and the fraction of each vehicle type operating at night. The user, however, should obtain if at all possible more representative estimates for the local conditions

As indicated above, the complete traffic flow is assumed to comprise three vehicle types. These vehicle types are defined as follows:

Type 1. Automobiles and Light Trucks - all vehicles with two axles and four wheels designed primarily for transportation of nine or fewer passengers or for the transportation of cargo. Generally, the vehicle weight is less than 10,000 lb.

Type 2. Medium Trucks - all vehicles having two axles and six wheels designed for transportation of cargo. Generally, the vehicle weight is greater than 10,000 lb but less than 26,000 lb.

Type 3. Heavy Trucks - all vehicles having three or more axles and designed for transportation of cargo. Generally, the vehicle weight is greater than 26,000 lb.

This vehicle classification and the noise emission characteristics used to develop the highway traffic noise prediction method for these guidelines are identical to more refined methods (Refs. 6, 7, and 8). For the purpose of noise prediction, a bus may be considered equivalent to a medium truck.

Noise Prediction Procedure

The highway traffic noise prediction method is performed in two stages. First, the DNL resulting from the traffic flow is obtained at a reference distance of 50 ft from the pavement edge of the near lane. This estimate is based upon traffic information described above and requires an adjustment for the site characteristics adjacent to the highway. The second stage of the prediction method is an adjustment for site conditions that affect the rate at which the traffic noise decreases with distance away from the highway. Either a soft site or a hard site condition may be selected for these two adjustments.

In order to organize the step-by-step procedure, a worksheet format is utilized in conjunction with lookup tables. The necessary worksheets and lookup tables are grouped together in Section 2.6. Example 1 below illustrates the use of worksheet number 1.

EXAMPLE 1. Predict the DNL at a location 300 ft from a four lane highway with the following traffic flow information:

- Average cruise speed is 50 mph.
- Annual average daily traffic is 20,000 vehicles/day.
- The percentage mix of vehicles is: automobiles, 92 percent; medium trucks, 2 percent; heavy trucks, 6 percent.

- The fraction of vehicles operating at night: automobiles and light trucks. 0.14; medium trucks, 0.10; and heavy trucks, 0.17.

Figure 3 is a completed worksheet for this example using the hard site noise propagation characteristics. Figure 4 is a completed worksheet using the soft site noise propagation characteristics. The estimated DNL values are 67 dB for the hard site and 61 dB for the soft site. Each of the entries in Figures 3 and 4 will now be described.

The necessary information is listed at the top of the worksheet for ease of reference. The percentage mix of vehicles and the fraction of vehicles of each type operating at night are obtained from averages of vehicle counts on similar highways located in similar land use areas. The data listed in the example problem would result from the following vehicle count:

Vehicle Type	24-hr count	10 p.m. to 7 a.m. count
Automobile and light trucks	18,400	2500
Medium trucks	400	40
Heavy trucks	1,200	205

The first step in the highway noise prediction method is to estimate the traffic flow reference noise level term. The value is obtained from Table 4 using the cruise speed and the percentage mix of vehicles in the traffic flow. Table 4 comprises 12 subtables with each subtable corresponding to the percentage of heavy trucks in the traffic stream. Within each subtable, the value is obtained using the percentage mix of medium trucks and the average cruise speed of the traffic. The range of values for percentage mix of vehicles and average cruise speed in Table 4 includes almost any possible traffic condition.

The 58 dB value entered in Figures 3 and 4 corresponds to the 6-percent heavy truck and 2.5-percent medium truck volumes and the 50 mph speed condition. Although the example indicated 2 percent medium trucks, the value for 2.5 percent is used for the example problem.

In using these guidelines, the following rule should be followed when interpolating values form the lookup tables: if the difference between two values in the table is 3 dB or less, use the higher value, and if the difference is greater than 3 dB, use the average of the two values.

WORKSHEET I. HIGHWAY TRAFFIC NOISE PREDICTION

PROJECT: EXAMPLE 1 PREDICTION FOR HARD SITE

Prepared by: F. RUDDER   Date: January 1984

TRAFFIC FLOW INFORMATION

Number of traffic lanes	Average cruise speed	Annual average daily traffic AADT
4	50 mph	20,000 Vehicle/Day

Vehicle type	Percent of AADT	Fraction operating at night
automobiles & light trucks	92	f_{n1} = 0.14
medium trucks	2	f_{n2} = 0.10
heavy trucks	6	f_{n3} = 0.17

HIGHWAY TRAFFIC NOISE PREDICTION

Step in the prediction method	Lookup Table	Value from lookup table
1. Traffic flow reference noise level	4	58 dB
2. Adjustment for AADT and nighttime traffic	5*	47 dB
3. Adjustment for site conditions (Use - 31dB for hard site; -34dB for soft site)	none	-31 dB
4. Day-night noise level at 50 ft (Add values in Steps 1,2, and 3)	none	74 dB
5. Adjustment for receiver at 300 ft	6(hard site) 7(soft site)	-6.6 dB
6. Day-night noise level at receiver (Add values in Steps 4 and 5)	none	67.4 dB

* If heavy trucks are present use the value of f_{n3} to enter Table 5.
If heavy trucks are not present use the value of f_{n2} to enter Table 5.
If only automobiles and light trucks are present use the value of f_{n1} to enter Table 5.

Figure 3. Completed worksheet for highway traffic noise prediction: hard site conditions

WORKSHEET I. HIGHWAY TRAFFIC NOISE PREDICTION

PROJECT: EXAMPLE 1 PREDICTION FOR SOFT SITE

Prepared by: F. RUDDER Date: January 1984

TRAFFIC FLOW INFORMATION

Number of traffic lanes	Average cruise speed	Annual average daily traffic AADT
4	50 mph	20,000 Vehicle/Day

Vehicle type	Percent of AADT	Fraction operating at night
automobiles & light trucks	92	f_{n1} = 0.14
medium trucks	2	f_{n2} = 0.10
heavy trucks	6	f_{n3} = 0.17

HIGHWAY TRAFFIC NOISE PREDICTION

Step in the prediction method	Lookup Table	Value from lookup table
1. Traffic flow reference noise level	4	58 dB
2. Adjustment for AADT and nighttime traffic	5*	47 dB
3. Adjustment for site conditions (Use - 31dB for hard site; -34dB for soft site)	none	-34 dB
4. Day-Night Noise Level at 50 ft (Add values in Steps 1,2, and 3)	none	71 dB
5. Adjustment for receiver at 300 ft	6(hard site) 7(soft site)	dB -9.6
6. Day-Night Noise Level at Receiver (Add values in Steps 4 and 5)	none	61.4 dB

* If heavy trucks are present use the value of f_{n3} to enter in Table 5. If heavy trucks are not present use the value of f_{n2} to enter Table 5. If only automobiles and light trucks are present use the value of f_{n1} to enter in Table 5.

Figure 4. Completed worksheet for highway traffic noise prediction: soft site conditions

Table 4. Traffic Flow Reference Noise Levels in dB

a) 0 Percent Heavy Trucks

S mph	Percentage med. trucks		
	0	2.5	5.0
30	47	48	49
35	49	50	51
40	51	52	53
45	52	53	54
50	53	54	55
55	54	55	56
60	55	56	57

b) 2 Percent Heavy Trucks

S mph	Percentage med. trucks		
	0	2.5	5.0
30	51	51	52
35	52	53	53
40	53	54	54
45	54	55	56
50	55	56	57
55	56	57	58
60	57	58	59

c) 4 Percent Heavy Trucks

S mph	Percentage med. trucks		
	0	2.5	5.0
30	53	53	53
35	54	54	55
40	55	55	56
45	56	56	57
50	57	57	58
55	58	58	59
60	58	59	59

d) 6 Percent Heavy Trucks

S mph	Percentage med. trucks		
	0	2.5	5.0
30	54	54	55
35	55	55	56
40	56	56	57
45	57	57	58
50	58	58	59
55	59	59	60
60	59	60	60

Table 4. Traffic Flow Reference Noise Level in dB (continued)

e) 8 Percent Heavy Trucks

S mph	Percentage med. trucks		
	0	2.5	5.0
30	55	55	55
35	56	56	57
40	57	57	58
45	58	58	59
50	59	59	59
55	60	60	60
60	60	61	61

f) 10 Percent Heavy Trucks

S mph	Percentage med. trucks		
	0	2.5	5.0
30	56	56	56
35	57	57	57
40	58	58	58
45	59	59	59
50	60	60	60
55	60	61	61
60	61	61	62

g) 12 Percent Heavy Trucks

S mph	Percentage med. trucks		
	0	2.5	5.0
30	56	57	57
35	58	58	58
40	58	59	59
45	59	60	60
50	60	60	61
55	61	61	61
60	61	62	62

h) 14 Percent Heavy Trucks

S mph	Percentage med. trucks		
	0	2.5	5.0
30	57	57	57
35	58	58	58
40	59	59	59
45	60	60	60
50	61	61	61
55	61	62	62
60	62	62	62

Table 4. Traffic Flow Reference Noise Levels in dB (continued)

i) 16 Percent Heavy Trucks

S mph	Percentage med. trucks		
	0	2.5	5.0
30	58	58	58
35	59	59	59
40	60	60	60
45	60	61	61
50	61	61	62
55	62	62	62
60	62	62	63

j) 18 Percent Heavy Trucks

S mph	Percentage med. trucks		
	0	2.5	5.0
30	58	58	58
35	59	59	59
40	60	60	60
45	61	61	61
50	62	62	63
55	62	62	63
60	63	63	63

k) 20 Percent Heavy Trucks

S mph	Percentage med. trucks		
	0	2.5	5.0
30	58	59	59
35	60	60	60
40	60	61	61
45	61	61	62
50	62	62	62
55	63	63	63
60	63	63	64

l) 22 Percent Heavy Trucks

S mph	Percentage med. trucks		
	0	2.5	5.0
30	59	59	59
35	60	60	60
40	61	61	61
45	62	62	62
50	62	62	63
55	63	63	63
60	64	64	64

The second step in the worksheet is an adjustment that accounts for the total traffic volume and the fraction of vehicles of a given type operating during the nighttime period from 10 p.m. to 7 a.m. The value of this adjustment is obtained from Table 5 using the AADT and the fraction of the loudest vehicle type operating at night (see the note at the bottom of the worksheet). For this example, heavy trucks are present in the traffic flow; so, the value of $f_{n3} = 0.17$ is used with the AADT = 20,000 to obtain the 47 dB adjustment.

The third step in the worksheet is an adjustment for site conditions as indicated in the worksheet. The value of the adjustment is -31 dB for a hard site and -34 for a soft site.

The fourth step in the worksheet is the simple addition of the first three numbers, remembering that the site adjustment is a negative number. For the hard site example in Figure 3 the addition is: $58 + 47 + (-31) = 105 - 31 = 74$. As indicated in the worksheet, this result is the DNL at a location 50 ft from the near edge of the pavement.

The DNL at the receiver location is obtained by adding the distance adjustment obtained from Table 6 for the hard site condition and Table 7 for the soft site condition in step 5 to the DNL value in step 4. This DNL value represents the noise exposure at the receiver for unobstructed source-receiver site conditions.

Comments on the Lookup Tables

The value listed in the lookup tables are presented as integer values in dB units. These values are the result of more involved calculations and have been rounded to the nearest integer value. The distance attenuation presented in Table 6 and 7 are similarly rounded to the nearest tenth of a dB. This is done to emphasize that the distance attenuation is a smooth function of distance and should not imply accuracy of the prediction.

For convenient reference, blank copies of the worksheets I, II and III are grouped together in Section 2.6.

Representative Traffic Flow Data

For reference, representative traffic flow data have been compiled or estimated to assist the user. These data are presented for AADT values, percentage vehicle mix, and fraction of each vehicle type operating during the nighttime period from 10 p.m. to 7 a.m.

For the annual average daily traffic, the value of the AADT was estimated in Ref. 16 in relation to a population place size and the functional roadway classification system used by FHWA (Ref. 17). The population place size is defined by census data and corresponds to the population living in a contiguous geographic area (Ref. 18). The representative values for AADT are presented in Table 8.

Table 5. Traffic Noise Adjustment for AADT and Nighttime Conditions in dB

AADT, veh/24 hr	f_n, fraction of vehicles travelling from 10 p.m. to 7 a.m.							
	0	0.03	0.06	0.11	0.17	0.24	0.33	0.375*
1,600	32	33	34	35	36	37	38	38.4
2,000	33	34	35	36	37	38	39	39.4
2,500	34	35	36	37	38	39	40	40.4
3,200	35	36	37	38	39	40	41	41.4
4,000	36	37	38	39	40	41	42	42.4
5,000	37	38	39	40	41	42	43	43.4
6,300	38	39	40	41	42	43	44	44.4
8,000	39	40	41	42	43	44	45	45.4
10,000	40	41	42	43	44	45	46	46.4
12,500	41	42	43	44	45	46	47	47.4
16,000	42	43	44	45	46	47	48	48.4
20,000	43	44	45	46	47	48	49	49.4
25,000	44	45	46	47	48	49	50	50.4
32,000	45	46	47	48	49	50	51	51.4
40,000	46	47	48	49	50	51	52	52.4
50,000	47	48	49	50	51	52	53	53.4
63,000	48	49	50	51	52	53	54	54.4
80,000	49	50	51	52	53	54	55	55.4

* Uniform 24 hour traffic flow.

Table 6. Traffic Noise Adjustment for Distance: Hard Sites in dB

D,	NUMBER OF TRAFFIC LANES					
ft	1	2	3	4	6	8
50	0	0	0	0	0	0
75	- 1.6	- 1.5	- 1.4	- 1.3	- 1.2	- 1.1
100	- 2.8	- 2.6	- 2.5	- 2.3	- 2.2	- 2.0
150	- 4.5	- 4.2	- 4.0	- 3.8	- 3.6	- 3.4
200	- 5.7	- 5.4	- 5.1	- 4.9	- 4.6	- 4.4
250	- 6.6	- 6.3	- 6.0	- 5.8	- 5.5	- 5.2
300	- 7.4	- 7.0	- 6.8	- 6.6	- 6.2	- 5.9
350	- 8.0	- 7.7	- 7.4	- 7.2	- 6.8	- 6.5
400	- 8.6	- 8.3	- 8.0	- 7.7	- 7.3	- 7.0
450	- 9.1	- 8.8	- 8.5	- 8.2	- 7.8	- 7.4
500	- 9.6	- 9.2	- 8.9	- 8.7	- 8.2	- 7.9
750	-11.3	-10.9	-10.6	-10.3	- 9.9	- 9.5
1000	-12.5	-12.2	-11.8	-11.6	-11.1	-10.7
1500	-14.3	-13.9	-13.6	-13.3	-12.8	-12.4

Table 7. Traffic Noise Adjustment for Distance: Hard Sites in dB

D, ft.	NUMBER OF TRAFFIC LANES					
	1	2	3	4	6	8
50	0	0	0	0	0	0
75	- 2.4	- 2.2	- 2.0	- 1.9	- 1.7	- 1.6
100	- 4.2	- 3.8	- 3.6	- 3.4	- 3.0	- 2.8
150	- 6.7	- 6.2	- 5.9	- 5.6	- 5.1	- 4.7
200	- 8.5	- 8.0	- 7.5	- 7.2	- 6.6	- 6.2
250	- 9.9	- 9.3	- 8.9	- 8.5	- 7.9	- 7.4
300	-11.1	-10.5	-10.0	- 9.6	- 8.9	- 8.4
350	-12.1	-11.4	-10.9	-10.5	- 9.8	- 9.2
400	-12.9	-12.3	-11.7	-11.3	-10.6	-10.0
450	-13.7	-13.0	-12.5	-12.0	-11.3	-10.7
500	-14.3	-13.7	-13.1	-12.7	-11.9	-11.3
750	-17.0	-16.3	-15.7	-15.2	-14.4	-13.7
1000	-18.2	-18.1	-17.5	-17.0	-16.2	-15.5
1500	-23.3	-22.6	-22.0	-21.4	-20.5	-19.8

Similarly, representative values of both the percentage vehicle mix and the fraction of vehicles operating during the nighttime were developed based upon available information (Ref. 19). These data are presented in Table 9 for urban and rural areas and the FHWA functional roadway classification.

2.2 RAILWAY NOISE PREDICTION

These guidelines allow the user to predict the railway noise exposure for trains powered by diesel-electric locomotives. The noise generated by electric powered trains or rapid-rail system operations are not included.

Necessary Information

The following information is required to estimate the noise generated by trains powered by diesel-electric locomotives and, as required, by the train warning horns at grade crossings:

- Average speed of the train in miles per hour.
- The average number of trains passing the site each 24 hours.
- The average number of trains passing the site for the nighttime period from 10 p.m. to 7 a.m.
- The characteristics of the "average train" as determined by the number of diesel-electric locomotives and the number of cars in the train. (Discussed below.)
- The distance(s), D, measured away from the track centerline and L, measured along the track from the site to each grade crossing requiring an approach warning by the train. (See Figure 5.)

Characteristics of The Average Train

To estimate the DNL for railway operations it is necessary to determine the noise exposure resulting from each passage of a train. Three considerations make this prediction more complicated than the prediction of the noise generated by highway traffic. First, the duration of the train noise must be considered. The duration depends upon the train length and the speed. Next, the noise from the locomotive must be considered in conjuction with the noise generated by the cars. (This is similar to the mix of heavy trucks and automobiles for highway traffic noise). Lastly, the distance attenuation of railway noise for a time-averaged sound level such as L_{eq} (the basis for the DNL value) depends on the length of the train, and to a lesser degree, upon the train speed. All of these details, if included directly in these guidelines, would result in a cumbersome methodology unsuited for the purpose of these guidelines.

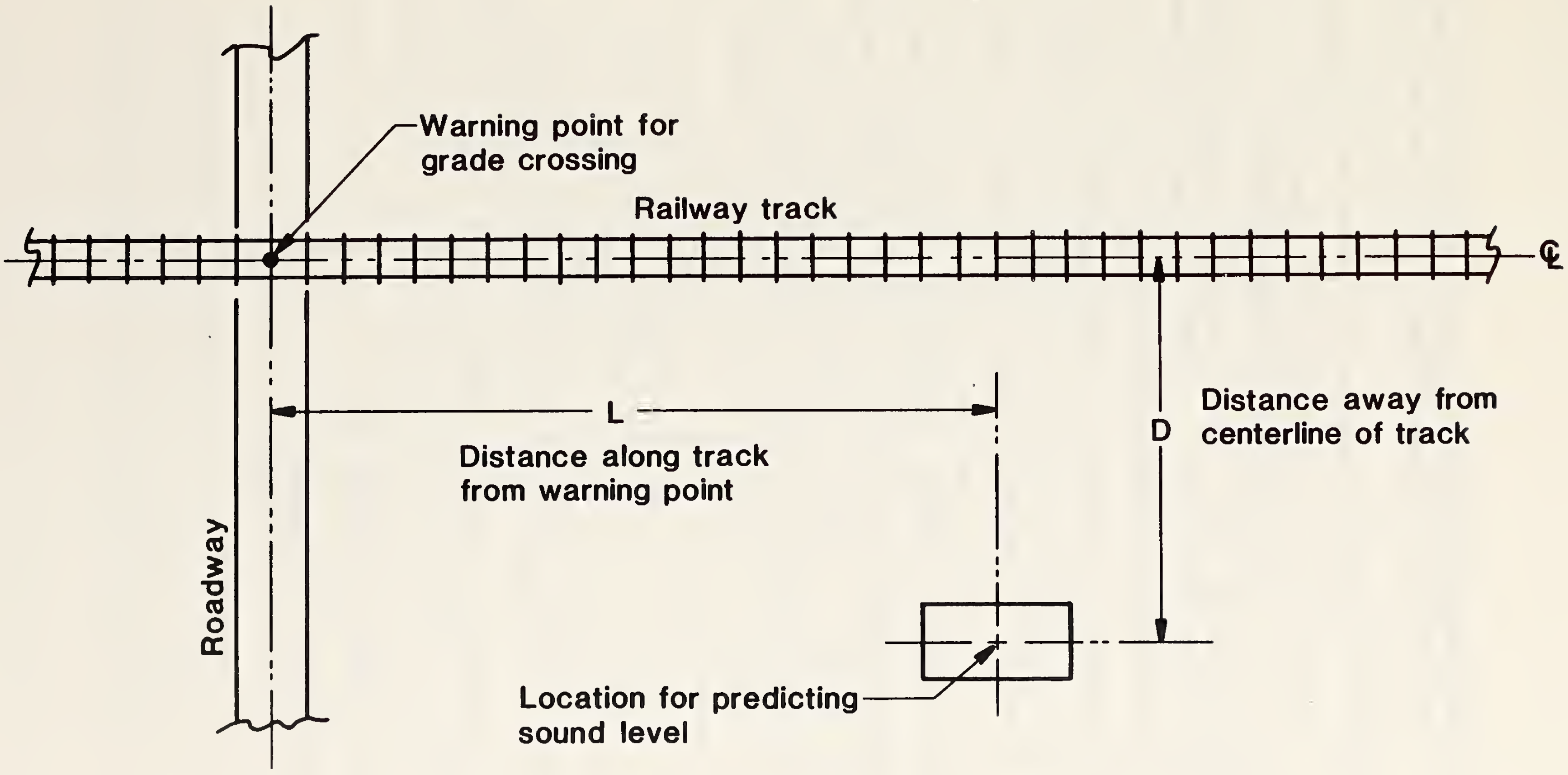


Figure 5. Plan View of Site Describing Distances Required to Predict Sound Levels Resulting From Railway Trains

Table 8. Representative Values of Annual Average Daily Traffic, AADT, Vehicles Per 24 Hours (1976)

Population Place Size*	Interstate	Other FWY and Expwy	Major Arterials	Minor Arterials	Collectors	Local Streets
>2M	75,000	66,000	19,000	9,500	4,000	1,100
1M to 2M	60,000	32,000	17,000	7,000	3,500	700
500k to 1M	47,000	34,000	16,000	8,000	3,800	700
200k to 500k	40,000	29,000	16,000	8,500	3,800	800
100k to 200k	32,000	23,000	15,000	7,300	3,300	650
50k to 100k	22,000	20,000	12,000	6,000	3,000	650
25k to 50k	23,000	17,000	11,000	5,500	2,500	600
5k to 25k	18,000	13,000	8,900	4,300	2,000	500
RURAL	14,000	4,600	2,500	900	400	100

* Place size is defined as in Ref. 18

M denotes population in millions
k denotes population in thousands

Table 9. Representative Values of f_n and F_i as Estimated from Ref. 19 Data

	URBAN AREAS							
Highway classification	Automobiles and light trucks (i=1)		Medium trucks (i=2)		Heavy trucks (i=3)		Motorcyles and buses (i=4)	
	f_{n1}	F_1	f_{n2}	F_2	f_{n3}	F_3	f_{n4}	F_4
Interstate, FWY and expwy	0.15	0.88	0.11	0.02	0.26	0.09	0.16	0.01
Other Principal arterials	0.14	0.93	0.10	0.02	0.20	0.04	0.14	0.01
Minor arterials	0.13	0.95	0.07	0.02	0.13	0.02	0.14	0.01
Collectors	0.13	0.94	0.06	0.02	0.12	0.02	0.11	0.01

	RURAL AREAS							
Highway classification	Automobiles and light trucks (i=1)		Medium trucks (i=2)		Heavy trucks (i=3)		Motorcyles and buses (i=4)	
	f_{n1}	F_1	f_{n2}	F_2	f_{n3}	F_3	f_{n4}	F_4
Interstate	0.13	0.78	0.13	0.03	0.28	0.18	0.16	0.01
Other Principal arterials	0.12	0.86	0.10	0.03	0.22	0.10	0.11	0.01
Minor arterials	0.12	0.90	0.08	0.03	0.14	0.06	0.09	0.01
Collectors	0.14	0.87	0.10	0.04	0.14	0.08	0.11	0.01

To simplify the guidelines without compromising the noise exposure estimate, an average train is defined in terms of all of the trains expected to pass the site. To this effect, it is assumed that both the daily total number and number of nighttime train pass-by events are equal for the "average trains" and the actual trains.

This approach is taken since individual trains along a given track may vary in the number of locomotives and the number of cars, and one really desires an average.

The average train is defined in terms of the average number of diesel-electric locomotives per train and the average number of cars per locomotive.

EXAMPLE 2. For the data listed below, determine the characteristics of the average train to use in these guidelines.

Estimate of Actual Operations

Train number	Number of locomotives	Number of railway cars	Scheduled passage time	Direction
1	2	60	2:00 a.m.	Eastbound
2	2	45	6:00 a.m.	Eastbound
3	3	80	9:30 a.m.	Eastbound
4	4	120	5:00 p.m.	Westbound
5	3	100	11:00 p.m.	Westbound
Total	14	405		

The total number of trains is five with three trains passing during the nighttime. The number of locomotives in the average train is 14/5 or 3 locomotives per train and 405/14 or 29 railway cars per locomotive. Hence, the average train comprises three diesel-electric locomotives and 87 railway cars.

Noise Prediction Procedure

A worksheet format is utilized to perform the railway noise prediction. A two-part sheet is used to list the necessary information required for the prediction. The first part is used to document the characteristics of the average train. The second part is used to document the site location relative to grade crossings requiring the trains to use warning horns.

Similarily, a two-part noise prediction worksheet is used: the first part to predict the pass-by noise and the second part to predict the noise exposure for warning horns. The noise exposures resulting from the train for pass-bys and from the warning horns are then combined to determine the total site railway noise exposure.

For convenient reference, blank copies of the data sheet and the noise prediction worksheets are presented in Section 2.6.

EXAMPLE 3. Using the train operational data given in EXAMPLE 2, determine the site noise exposure if the pass-by speed is 40 mph and the site is located 400 ft from the railway track centerline, and 600 ft from a grade crossing requiring a warning horn.

A completed data sheet for this example problem is presented in Figure 6. Note that the fractional values for both the average number of locomotives per train and the average number of railway cars per locomotive are rounded to the nearest interger.

A completed worksheet for predicting the pass-by noise resulting from the average daily railway operation is presented in Figure 7. The first step in the prediction is to determine the reference noise level for one train pass-by. This value is obtained from Table 10 using the average number of locomotives per train, the average number of railway cars per locomotive, and the train speed. Table 10 comprises four subtables each corresponding to a different average number of locomotives per train. For example problem 3, Table 10c is used since there are three locomotives per train.

The second step in the prediction is an adjustment for the total number of trains per 24 hours. This adjustment is obtained from Table 11. For example problem number 3 since there are five trains per day the value is -6.8 dB.

The third step in the prediction is another adjustment which accounts for nighttime train pass-by events. This adjustment is obtained from Table 12 using the fraction of trains that pass the site between 10 p.m. and 7 a.m. For this example, the fraction is 3/5 = 0.60, and the value of the adjustment is 8 dB.

Step 4 is the simple addition of the values of the reference noise level and the two adjustments to this reference level. For the example problem, the arithmetic is: 68 + (-6.8) + 8 = 69.2 dB. This value is the DNL at a location 100 ft along side the railway track centerline for the five average train operations.

For locations beyond 100 ft from the track centerline, the DNL value estimated in Step 4 must be adjusted to account for distance attenuation. Only hard site conditions are included in these guidelines for estimating the railway noise distance attenuation. For the example, the distance adjustment is obtained from Table 13 using the distance D = 400 ft (see Figure 5) and the average number of railway cars per locomotive, 29. The value of the distance adjustment for the example is -6.7 dB. This value is entered in step 5 of Part I of the worksheet.

WORKSHEET II. DIESEL-ELECTRIC RAILWAY NOISE PREDICTION DATA

Project: EXAMPLE PROBLEM 2

Prepared by: F. RUDDER Date January 1984

PART I DATA DESCRIBING THE AVERAGE TRAIN *

a) Train speed, mph: S = 40

b) Total number of trains per day: N_T = 5

c) Total number of trains operating at night: N_n = 3

d) Total number of locomotives per day: N_L = 14

e) Total number of railway cars per day: N_c = 405

(1) Calculate the average number of locomotives per train:

$N = N_L/N_T$ = 14/15 → 3

(2) Calculate the average number of railway cars per locomotive:

$\bar{n} = N_c/N_L$ = 405/14 → 29

(3) Calculate the fraction of railway operations occurring during the nighttime (10 p.m. to 7 a.m.)

$f_n = N_n/N_T = 3/5 = 0.6$

PART II DATA DESCRIBING THE SITE LOCATION (see Figure 5)

a) Distance from track to the site, ft: D = 400

b) If there is a warning point within 1/2 mi of the site, determine the distance along the track from the warning point, ft: L = 600

* The mathematical notation for the data follows the notation used in Appendix A which describes the railway noise prediction model.

Figure 6. Completed Data Sheet for Railway Noise Prediction: Example 2

WORKSHEET III. DIESEL-ELECTRIC RAILWAY NOISE PREDICTION: PASS-BY NOISE EXPOSURE

PART I DIESEL-ELECTRIC PASS-BY OPERATIONS

(1) From Table 10 and the data for the average train of Worksheet II

(N = 3 ; $\bar{n}$ = 29 ; and S = 40 mph)

Reference sound level for one pass-by = 68 dBA

(2) From Table 11 the sound level adjustment for N_T = 5 trains per day = -6.8 dB

(3) From Table 12 the sound level adjustment for f_n = 0.6 fraction of nighttime operations = +8.0 dB

(4) Adding (1), (2), and (3) above, the day-night sound level for railway pass-by noise at a location D_o = 100 ft away from the track = 69.2 dB

(5) From Table 13 the sound level adjustment for the distance D = 400 ft from the track centerline = -6.7 dB

(6) Adding (4) and (5) above, the day-night sound level for railway pass-by noise at a location D = 400 ft from the track centerline = 62.5 dB

IF THERE ARE NO WARNING POINTS WITHIN 1/2 MILE OF THE SITE, THE ABOVE RESULT, (6), IS THE DAY-NIGHT SOUND LEVEL AT THE SITE RESULTING FROM PASS-BY NOISE OF DIESEL-ELECTRIC TRAINS.

IF WARNING HORN NOISE OCCURS, PROCEED TO PARTS II AND III OF THIS WORKSHEET

Figure 7. Completed Worksheet for Railway Pass-by Noise Prediction: Example 3.

Table 10. Reference Sound Level for Railway Pass-By Operations in dB

a) One Diesel-electric Locomotive Per Train

Average number of railcars per locomotive	Train Speed, mph				
	20	30	40	50	60
fewer than 10	63	62	61	61	61
10 to 19	63	63	62	62	63
20 to 29	64	63	63	63	64
30 to 39	64	64	64	64	65
40 to 49	64	64	65	65	66
50 to 59	65	65	65	66	66

b) Two Diesel-Electric Locomotives per Train

Average number of railcars per locomotive	Train Speed, mph				
	20	30	40	50	60
fewer than 10	66	65	64	64	64
10 to 19	66	66	65	65	66
20 to 29	67	66	66	66	67
30 to 39	67	67	67	67	68
40 to 49	67	67	68	68	69
50 to 59	68	68	68	69	69

Table 10. Reference Sound Level for Railway Pass-By Operations in dB (concluded)

c) Three Diesel-electric Locomotive Per Train

Average number of railcars per locomotive	Train Speed, mph				
	20	30	40	50	60
fewer than 10	68	66	66	66	66
10 to 19	68	67	67	67	67
20 to 29	67	68	68	68	68
30 to 39	69	68	68	69	69
40 to 49	69	69	70	70	70
50 to 59	70	69	70	71	71

d) Four Diesel-Electric Locomotives Per Train

Average number of railcars per locomotive	Train Speed, mph				
	20	30	40	50	60
fewer than 10	69	68	67	67	67
10 to 19	69	69	68	68	69
20 to 29	70	69	69	69	70
30 to 39	70	70	70	70	71
40 to 49	70	70	71	71	72
50 to 59	71	71	71	72	72

Table 11. Sound Level Adjustment for Railway Pass-By Operations: Total Number of Trains Per Day

Number of trains per 24 hours	Adjustment, dB
1	-13.8
2	-10.8
3	- 9.0
4	- 7.8
5	- 6.8
6	- 6.0
7-8	- 5
9-11	- 4
12	- 3
13-17	- 2
18-21	- 1
22-27	0
28-33	+1
34-42	+2
43-53	+3
54-66	+4
67-84	+5
84-110	+6
111-132	+7
133-172	+8
173-210	+9
211-265	+10

Table 12. Sound Level Adjustment for Railway Noise: Fraction of Total Events During the Night

Fraction of trains operating at night	Adjustment dB
0 to 0.02	0
0.03 to 0.05	1
0.06 to 0.09	2
0.10 to 0.13	3
0.14 to 0.20	4
0.21 to 0.28	5
0.29 to 0.38	6
0.39 to 0.52	7
0.53 to 0.68	8
0.69 to 0.88	9
0.89 to 1.00	10

Table 13. Sound Level Adjustment for Railway Pass-By Noise: Distance Away from the Track Centerline

Distance away from track, ft	Average number of railway cars per locomotive					
	Fewer than 10	10 to 19	20 to 29	30 to 39	40 to 49	50 to 59
100	0.0	0.0	0.0	0.0	0.0	0.0
200	- 3.2	- 3.2	- 3.2	- 3.1	- 3.1	- 3.1
300	- 5.3	- 5.2	- 5.2	- 5.1	- 5.1	- 5.1
400	- 7.0	- 6.8	- 6.7	- 6.6	- 6.5	- 6.4
500	- 8.4	- 8.1	- 7.9	- 7.7	- 7.6	- 7.5
600	- 9.5	- 9.1	- 8.9	- 8.7	- 8.6	- 8.5
700	-10.6	-10.1	- 9.8	- 9.5	- 9.4	- 9.2
800	-11.5	-10.9	-10.6	-10.3	-10.1	- 9.9
900	-12.3	-11.6	-11.3	-10.9	-10.7	-10.5
1000	-13.0	-12.3	-11.9	-11.5	-11.3	-11.1
1100	-13.7	-12.9	-12.5	-12.0	-11.8	-11.6
1200	-14.3	-13.5	-13.0	-12.5	-12.2	-12.0
1300	-14.9	-14.0	-13.5	-12.8	-12.7	-12.4
1400	-15.5	-14.5	-13.9	-13.0	-13.1	-12.8
1500	-16.0	15.0	-14.4	-13.8	-13.5	-13.2

The sixth and final step in the pass-by noise perdiction is the addition of the distance adjustment of step 5 to the DNL value obtained in Step 4. The arithmetic for the example is 69.2 + (-6.7) = 69.2 - 6.7 = 62.5 or 63 dB. This is the DNL at the receiver location for the pass-by noise exposure.

Since problem example 3 includes warning horn noise exposure, we must proceed to Part II of Worksheet III. Figure 8 is the completed worksheet for warning horn noise prediction of the example problem. The prediction method requires the user to obtain a reference level and to adjust this reference level to obtain the DNL.

The first step in predicting warning horn noise exposure is to obtain the reference level _at the receiver location_. This reference level assumes that trains approach the warning point from either direction, and that the warning is initiated 1/4 mi along the track before the leading locomotive crosses the warning point. The reference level for warning horn noise is obtained from Table 14 using the receiver location as indicated in Figure 5. For the example problem with the receiver 400 ft away from the track centerline and 600 ft along the track away from the warning point, the reference level is 48 dB.

The second step is to adjust the reference level for the total number of events and for duration of each event. This adjustment is obtained from Table 15 and, for the example problem, is +8 dB.

The third step is to adjust the reference level for the fraction of nighttime occurences of warning horn noise. This adjustment is obtained from Table 12 and is +8 dB.

Step 4 is the simple addition of the reference level in step 1 and the adjustments in steps 2 and 3. For the example problem the arithmetic is: 48 + 8 + 8 = 64 dB. This is the DNL at the receiver location for warning horn noise.

One final calculation is required to complete the example. We have estimated the train pass-by DNL to be 63 dB and the train warning-horn DNL to be 64 dB. At this site, however, the pass-by and warning horn noise occur _simultaneously_ for each train moving along the track. We must now determine the _combination_ of these _simultaneous_ noise events. (The answer is NOT 63 + 64 = 127 dB!)

Part III of the railway noise prediction indicates the method for _combining_ two _simultaneous_ noises to obtain the total noise at a location. The data for the example problem are entered as indicated in Figure 8. The answer is obtained using Table 16 and, for the example problem, is 67 dB. This is the total DNL at the receiver due to railway noise at the site.

Combining Sound Levels

The last example illustrated the method for _combining_ two _simultaneous_ sound levels to determine the total sound level. The combination of these two

WORKSHEET III. DIESEL-ELECTRIC RAILWAY NOISE PREDICTION: PASS-BY NOISE EXPOSURE

PART II WARNING HORN NOISE PREDICTION

(1) From Table 14 or Figure 5 a the location L = 600 ft along the track from the warning point and D = 400 ft from the track,

Reference should level for one warning = 48 dBA

(2) From Table 15 the sound level adjustment for N_T = 5 trains per day passing the site at S = 40 mph is = + 8 dBA

(3) From Table 12 the sound level adjustment for f_n = 0.6 fraction of nighttime operations is = + 8 dBA

(4) Adding (1), (2), and (3) above, the day-night sound level for railway warning horn noise at the location L = 600 ft and D = 400 ft is = 64 dBA

PART III COMBINED PASS-BY AND WARNING HORN NOISE PREDICTION

The pass-by sound level and the warning sound level must be combined to obtain the total noise prediction at the location.

(1) From Part I; step (6) the Pass-By Day-Night Sound Level is = 63 dB

(2) From Part II; step (4) the Warning Horn Day-Night Sound Level is = 64 dB

(3) Using (1) and (2) above, the sound level difference is:
higher level - lower level = 64 - 63 = 1

(4) Using the sound level difference from step (3) and from Table 16, the combined Day-Night Sound Level is:
higher level + adjustment = 64 + 2.5 = 66.5 = 67 dB

THE RESULT (4) ABOVE IS THE COMBINED DAY-NIGHT SOUND LEVEL AT THE SITE FOR RAILWAY NOISE

Figure 8. Completed Worksheet for Railway Warning Horn Noise Prediction and Combined Railway Noise Prediction: Example 3

Table 14. Reference Sound Level: Railway Warning Horns is dB

(See Figure 5)

Distance away from track, ft	L, Distance along track mesured from the warning point, ft											
	0 to 400	600	800	1000	1200	1400	1600	1800	2000	2200	2400	2600
100	55	55	55	55	54	50	45	43	41	40	38	37
200	52	52	52	51	50	48	45	42	41	40	38	37
300	50	50	49	49	48	46	44	42	41	39	38	37
400	48	48	48	47	47	45	43	42	40	39	38	37
500	47	47	47	46	45	44	43	41	40	39	38	37
600	46	46	46	45	44	43	42	41	40	39	38	37
700	45	45	45	44	44	43	42	41	40	39	38	37
800	44	44	44	43	43	42	41	40	39	38	37	37
900	44	43	43	43	42	41	41	40	39	38	37	37
1000	43	43	42	42	41	41	40	39	39	38	37	36
1100	42	42	42	41	41	40	40	39	38	38	37	36
1200	42	41	41	41	40	40	39	39	38	37	37	36
1300	41	41	41	40	40	39	39	38	38	37	36	36
1400	41	40	40	40	39	39	38	38	37	37	36	36
1500	40	40	40	39	39	39	38	38	37	37	36	36

Table 15. Sound Level Adjustment for Railway Warning Horns in dB: Total Number of Trains and Train Speed

number of trains/ 24-hr	Train speed mph				
	20	30	40	50	60
1	4	2	1	0	-1
2	7	5	4	3	2
3	9	7	6	5	4
4	10	8	7	6	5
5	11	9	8	7	6
6	12	10	9	8	7
7-8	13	11	10	9	8
9-10	14	12	11	10	9
11-13	15	13	12	11	10
14-17	16	14	13	12	11
18-22	17	15	14	13	12
23-28	18	16	15	14	13
29-35	19	17	16	15	14
36-45	20	18	17	16	15
46-56	21	19	18	17	16
57-71	22	20	19	18	17
72-90	23	21	20	19	18
91-110	24	22	21	20	19
111-142	25	23	22	21	20
143-180	26	24	23	22	21
130-225	27	25	24	23	22

Table 16. Table for Combining Sound Levels

Combined Level = Higher Sound Level + Adjustment

Sound Level Difference = Higher Sound Level
- Lower Sound Level

Sound level difference, dB	Adjustment, dB
0	3.0
1	2.5
2	2.1
3	1.8
4	1.5
5	1.2
6	1.0
7	0.8
8	0.6
9	0.5
10	0.4
>10	0.0

Example: Determine the combined sound level for three sound levels of 65, 60, and 58 dB.

65 - 60 = 5: Combined level = 65 + 1.2 = 66.2 dB

66.2 - 58 = 8.2: combined level = 66.2 + 0.6 = 66.8 dB

Combined sound level is 66.8 or 67 dB.

sound levels is not the simple addition of the two sound levels as indicated by both the example and the values listed in Table 16. Indeed, the values in Table 16 indicate that the combined level of two sounds of equal level is a level that is 3 dB greater than the two equal levels. That is, the combination of two simultaneous sounds each at a level of 50 dB is 53 dB, or the combination of two levels, one of 60 dB and one of 50 dB is 60 dB (see Table 16).

Now, we return to our example problem of the train pass-by noise and the warning horn noise. The pass-by DNL was estimated to be 63 dB, and the warning horn noise was estimated to be 64 dB resulting in a total level of 67 dB. Nothing was said about noise from the roadway at the grade crossing. Suppose that the noise from the roadway at the grade crossing was estimated to be L_{dn} = 55 dB at the receiver. Then, the combination of the three sound levels is calculated according to the rules indicated in Table 16. Since the difference 67-55 = 12 dB, and is greater than 10, the adjustment for traffic noise is 0 dB. Thus, the combination yields 67 + 0 = 67 dB.

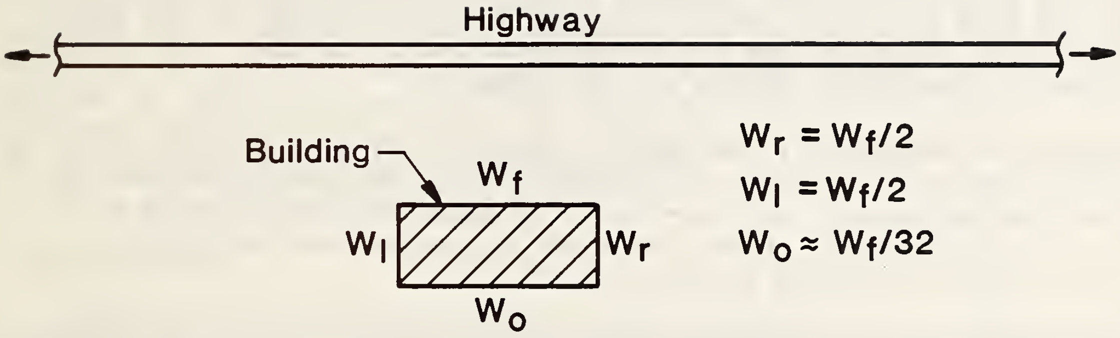
Since the present guidelines require the user to perform calculations, it is worthwhile explaining the physics that determine when the user should add two numbers using ordinary arithmetic and when the two numbers should be combined using Table 16. The key to this is the understanding of the combination of acoustic energy at a single location. When the receiver is exposed to two or more simultaneous noise sources, he receives a total amount of acoustic energy. This total or combined energy may be expressed as a level in dB units, just as the energy from each noise source may be expressed as a level in dB units. The acoustic energies from each source add together (in the sense of 2 + 2 = 4) and the combination are then expressed as a level in dB units. As a result, the adjustments given in Table 16 indicate that combining the energy from two identical noise sources doubles the total energy and increases the level by 3 dB. Similarly, if the energy output from a noise source was decreased by half, the level would decrease by 3 dB relative to the original level.

EXAMPLE 4. Consider a receiver exposed to noise generated by highway traffic at a site with a single building. The guidelines assume that the highway extends indefinitely in both directions from the building location. It is desired to estimate the total acoustic energy received at each exterior wall of the building. The geometry is as indicated in Figure 9a.

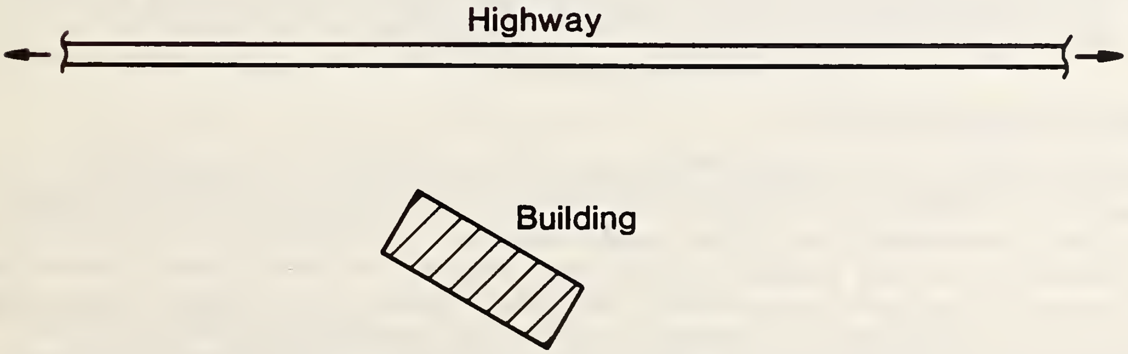
First, consider the wall facing the highway. The total acoustic energy received at this wall is the total predicted by the guidelines, since a person standing along this wall and facing the highway can see the entire highway.

Next, consider a person standing at either end of the building and facing the highway. At either location, the receiver can see only half of the highway. Hence, one could expect that these locations receive only half of the total energy or half of the energy received at the wall facing the highway.

Finally, for a person standing along the side of the building facing away from the highway, the building totally obstructs the person's view of the highway, and no acoustic energy is received.



a) Building with walls parallel and perpendicular to highway



b) Building with walls at oblique orientation relative to the highway

Figure 9. Source-Receiver Geometry for Estimating Total Acoustic Energy at the Exterior Surfaces of a Building

This is a simplified consideration, but it is surprisingly close to reality. In reality, sound waves diffract or bend around physical objects so that just because one cannot see a noise source visually, it does not mean that one will not receive any acoustic energy. As a result, denoting W_f as the total energy at the building facade facing the highway, one would estimate $W_r = W_\ell = W_f/2$ and $W_o = 0$ for ideal conditions or the more nearly correct results: $W_r = W_\ell = W_f/(\pi/2)$ and $W_o = W_f/32$ (Refs. 20 and 21). (The notations are as follows: W_f is the total energy incident upon the building facade facing the highway; W_r and W_ℓ is the total energy incident upon the facades at the right and left end of the building; and W_o is the total energy incident upon the building facade on the side opposite of the highway.)

Continuing the example, if the incident sound level at the location of the building facade facing the highway is denoted as L_f, then the sound level at either end of the building is $L_r = L_\ell = L_f - 3$ dB since the total energy is decreased by a factor of 1/2. Using the other approximations one would estimate: $L_r = L_\ell = L_f - 2$ dB and $L_o = L_f - 15$ dB.*

Finally, Figure 9(b) illustrates the effect of orientation of the building relative to the highway. In this case, each of the facades is exposed to a different view of the highway, and one cannot simply state that a definite relationship is apparent as it is for the geometry illustrated in Figure 9(a). To evaluate conditions such as illustrated in Figure 9(b), it is necessary to conduct additional analyses (Ref. 20).

The above example illustrates one form of noise mitigation at a site. That is, the presence of the building altered the sound field at the site relative to the sound field estimated for the flat site free of obstructions. However, before discussing mitigation of noise, we must incorporate of aircraft noise, if it is appropriate, and the existing noise levels at the site to determine the total site noise exposure.

2.3 AIRCRAFT NOISE PREDICTION

Aircraft noise is an extremely important consideration for developing noise-compatible land use both within the vicinity of the airport property and along corridors underneath the flight paths serving the airport. The reason for this importance is the extent of land area exposed to noise levels exceeding $L_{dn} = 65$ dB due to aircraft operations. Whereas highway and railway noise is a consideration for land parcels located within a few hundred feet adjacent to these sources, it is difficult to assign with confidence a comparable distance for aircraft noise. The difficulty arises from the many factors that influence noise generated by aircraft operations, and the noise exposure of the land area

---

* To do this one must calculate levels in decibel units. See appendix B for a discussion of this. Also, it is important to note the words "incident upon" since we are really interested in energy at a location in the physical absence of the building.

surrounding the airport. A land located 2,000 to 3,000 ft adjacent to a runway may be exposed to noise levels below L_{dn} = 65 dB, while another land parcel located 2 to 3 miles from the end of a runway but underneath a flight path may be exposed to noise levels exceeding L_{dn} = 65 dB. As compared to either highway or railway noise, the prediction of aircraft noise is a very complex process.

It is beyond the scope of the present guidelines to provide a noise prediction method for aircraft noise. However, a brief discussion of the complexities of the problem is worthwhile. The user should understand that both accepted noise prediction methods and criteria are available to estimate the nature of the problem (Refs. 9 and 10). The noise predictions are available in terms of the DNL values, and can be obtained either for specifc locations about the airport or as contours of constant L_{dn} values plotted to scale for the land area surrounding the airport.

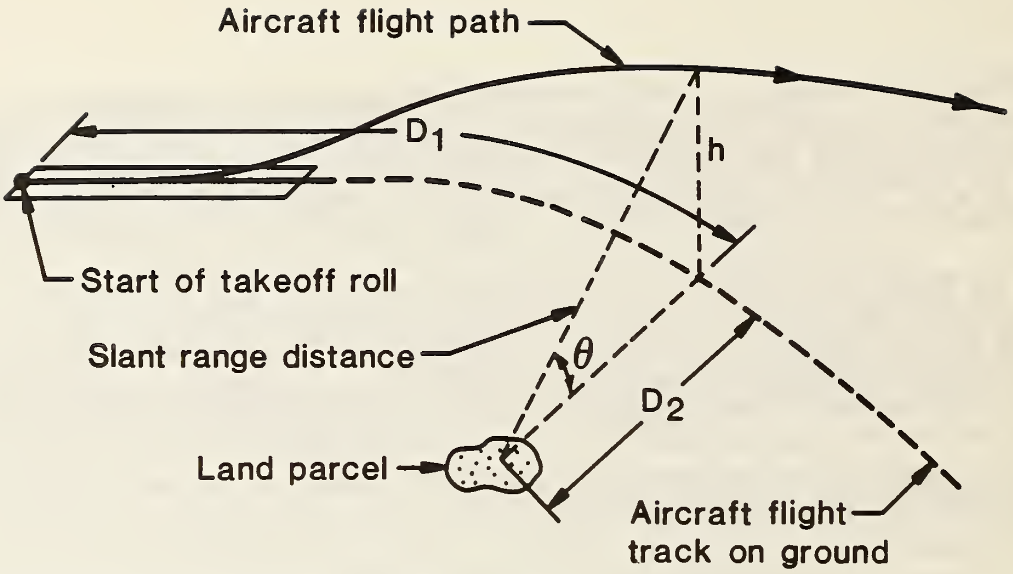
The Noise Source

Referring to the highway noise prediction method, it is sufficient to use three types of vehicles to describe the noise generated by highway traffic (see Table 4). For railway noise prediction, it is sufficient to consider only diesel-electric locomotive noise and railcar noise (see Table 10). However, prediction of aircraft noise involves many factors. The Integrated Noise Model (INM), developed by the Federal Aviation Administration (FAA), utilizes over 40 aircraft types. Moreover, computed noise exposures are related to the takeoff and landing conditions for each aircraft type. In particular, the takeoff noise emissions are determined by the thrust required or the aircraft takeoff weight. The takeoff weight will depend mainly upon the distance of the flight (fuel load variations). Further considerations include the average number of takeoff and landing operations in each direction for each runway (local prevailing wind conditions), and the anticipated incorporation of new technology in the design of commercial aircraft.

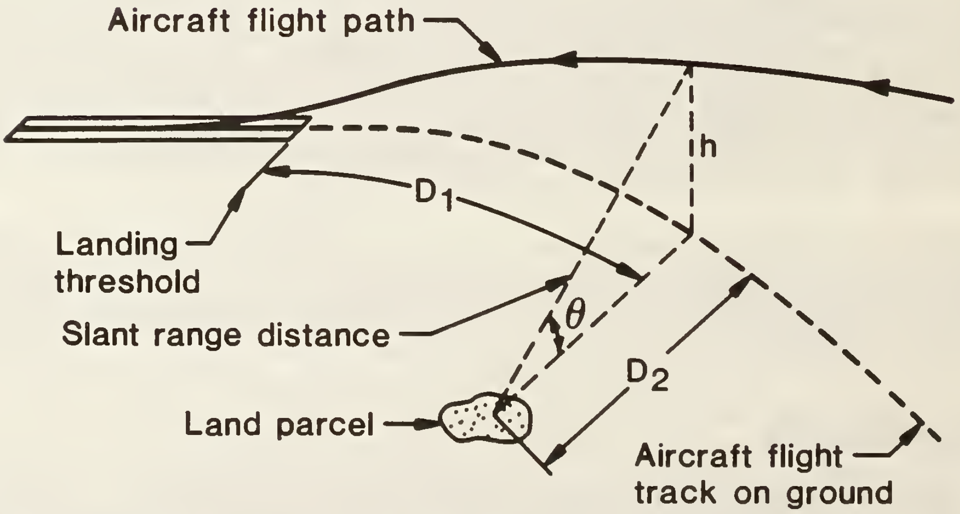
The picture is further complicated by the fact that not all aircraft types operate at all airports. Yet, it is necessary to incorporate all the details described above into an aircraft noise prediction model to estimate specific local conditions.

Source-Receiver Geometry

In the case of highway and railway noise, the source-receiver geometry is established by a single distance (see Figure 1) or by two distances in the case of the railway warning horns (see Figure 5). In both instances, a straight roadway or railway track alignment could be assumed and the results used for a majority of local conditions. This is not possible for aircraft noise prediction, since aircraft may takeoff and land using various flight paths relative to the end of a runway. Figure 10 illustrates one form of the source-receiver geometry for aircraft noise prediction (Ref. 22).



a) Aircraft takeoff operation



b) Aircraft landing operation

Figure 10. Basic Situations for the Calculation of DNL Due to Aircraft Operations (Ref. 22)

Figure 10 also indicates that the aircraft flight paths may vary depending upon whether the aircraft is taking-off or landing, and the air traffic control patterns established for each airport. For any particular runway and heading, multiple flight paths are possible. This means that for a fixed receiver location on the ground, the source-receiver distance is variable as is the noise emission of the source (aircraft type and operating conditions). These considerations complicate the prediction of aircraft noise exposure about airports.

Noise Propagation

Considering the source noise levels and the fact that the noise propagation path is relatively close to the ground, both highway traffic and railway noises attenuate rapidly with distance to sound levels below the outdoor criterion of L_{dn} = 55 dB.

However, due to the high noise levels associated with aircraft operations (especially takeoff) and the direct line-of-sight propagation path between the aircraft and the receiver, aircraft noise must propagate several thousand feet to attenuate to levels comparable to other environmental noise sources.

The high-frequency components of the noise attenuate more rapidly with distance than the low-frequency components. For a frequency-weighted noise measure (such as the A-weighted sound level) averaged over an exposure time (such as the equivalent sound level), the significant changes in the noise spectrum shape with distance introduce an additional level of detail that must be incorporated into the noise prediction method.

Ref. 22 is a manual method for estimating DNL values about an airport. In order to incorporate some of the above considerations into the noise prediction method, plots relating aircraft type, takeoff weight, and source-receiver distance to the noise emission of a single aircraft operation are presented. To cover all of the combinations, 271 plots are required!

Number of Operations

Perhaps the most easily understood aspect of noise prediction of airport operations is the number of operations per day. As discussed above, the total number of operations must be distributed among the various possible flight paths and among the types of operation (i.e., takeoff and landing) for each aircraft type. Further, for the DNL estimate, the operations must be accumulted for both daytime and nighttime periods. In particular, the DNL considers 1 nighttime aircraft operation to be equivalent to 10 daytime operations. This is identical to the adjustments applied to noise from traffic flow (Table 15) and to noise from railway operations (Table 12).

Noise Exposure of Land Areas

Given the many factors influencing the prediction of aircraft noise at a specific location, it is beyond the scope of these guidelines to describe a method. The above discussion is not intended to give the reader the impression that prediction of aircraft noise is too complicated a problem to be analyzed. On the contrary, the degree of complexity only means that the predictions must be based upon a computer model that can incorporate the necessary details. Approximate methods have been developed (Refs. 15 and 22). However, the user is advised to obtain predictions from the local airport authority as these are based upon accepted techniques (Ref. 9). The Integrated Noise Model (INM) developed by the Federal Aviation Administration provides the necessary prediction and presents the results in both tabular and plotted formats. The L_{dn} predictions may be obtained for a specific land parcel or for the entire land area exposed to specified levels of noise exposure. In the latter case, the prediction is in the form of a plot of noise contours enclosing the exposed land area. Additional information provided includes the total land area exposed to noise exceeding a specified level, and the cumulative exposure time above specified threshold A-weighted sound levels by time of day.

2.4 EXISTING NOISE SOURCES

The present guidelines focus upon the noise generated by highway, railway, and aircraft sources and the mitigation of this noise to evaluate noise-compatible land use. However, at any location, noise is always present and may not always be identifiable with a specific noise source. These noises are called "existing noise sources" and they establish the "existing noise levels" at the location. The existing noise levels are an important consideration for determining the effect of increasing the total noise environment when introducing an additional noise source.

Generally, it is necessary to establish the existing noise levels at a location by direct measurement (Ref. 4). However, analysis of existing noise levels from measurements at over 100 locations within urban areas of the United States has resulted in an approximate relationship between the existing DNL at a location and the population density of the area surrounding the location (Refs. 25 and 26). Before presenting these empirical results, it is worthwhile to describe the basis for assuming that such a relationship exists.

Transportation noise studies indicate that surface transportation noise is generally the greatest contributor to environmental noise. Highway traffic noise is the predominant component of surface transportation noise. However, traffic flow and conditions on a single local street may not independently represent a significant source of noise. Within an urban area, many local streets carry traffic serving the population residing within the area. The number of automobiles per person is a constant value as is the ratio of trucks to automobiles (see Tables 8 and 9). Although a single local street may not represent a significant noise source, the noise propagating to a location from several local streets combine to establish the total existing noise level. Since the total traffic flow is approximately related to the local population, it is reasonable to assume that the total existing noise level may be related to the local population or population density.

Table 17 presents empirical relationships between existing DNL at locations in an urban area and the population densities within the surrounding urban areas (Ref. 25). These results are based upon noise measurements conducted in residential urban locations not directly attributable to any major noise source such as major highways, railway, airports, or construction sites. In the absence of direct measurements, the results in Table 17 may be used to assess the existing noise levels at a site located away from major noise sources.

Table 17 also presents estimates of the equivalent sound level, L_{eq}, for three time periods during the 24-hour period. These time periods are:

- early morning (2 a.m. to 4 a.m.) (Ref. 26);
- nighttime (10 p.m. to 7 a.m.) (Ref. 26); and,
- daytime (7 a.m. to 10 p.m.).

The L_{eq} value for the daytime period is calculated using the DNL value and the nighttime L_{eq} value for each population density. It should be noted that the DNL value is 10 dB above the early morning L_{eq} value for each population density. This 10 dB difference emphasizes the 10 dB nighttime weighting utilized in the definition of DNL.

2.5 ESTIMATION OF FUTURE CONDITIONS

Noise-compatible land use decisions are based on the evaluation of the long-term noise impact that will result from the proposed action. Accordingly, both the future noise environment that would result from a proposed action and the future use of the noise exposed land areas must be evaluated. From year-to-year, the only factors that would normally remain constant are the noise criteria and the methods used to establish the compatibility between the noise environment and the expected land use.

The methods presented in Sections 2.1 through 2.4 provide a basis for estimating the future noise environment. For example, if it is anticipated that a highway will be expanded from two lanes to four lanes within the next few years, then it is appropriate to estimate the noise environment based upon both the existing conditions and the conditions that will prevail upon the completion of the highway expansion. This predition would require estimates of the future traffic flow characteristics and may require different distance attenuation adjustments than those indicated by Tables 6 or 7. Similarly, an airport expansion may result in altered flight paths and aircraft mix, with noise exposure changes for land areas surrounding the airport.

In conducting these future estimates, it may be assumed that the highway and railway noise source characteristics will not change significantly (see Tables 4 and 10) in the foreseeable future. However, due to the introduction of new aircraft types into the fleet, it may be appropriate to account for this

Table 17. Empirical Relationships Among Population Density, DNL, and Nighttime Measures of the Existing Noise Level (Refs. 25 and 26)

DNL L_{dn} dBA	Population density people/m_i^2	L_{eq} 2-4a.m. dBA	L_{eq} 10p.m-7a.m. dBA	L_{eq} 7a.m.-10p.m. dBA
51	1,000	41	46	-
52	1,250	42	46	42
53	1,600	43	47	43
54	2,000	44	48	44
55	2,500	45	49	45
56	3,150	46	49	52
57	4,000	47	50	53
58	5,000	48	51	54
59	6,300	49	52	55
60	8,000	50	53	56
61	10,000	51	53	59
62	12,500	52	54	60
63	16,000	53	55	61
64	20,000	54	56	62
65	25,000	55	56	64
66	31,500	56	57	65
67	40,000	57	58	66
68	50,000	58	59	67
69	63,000	59	60	68
70	80,000	60	60	70

NOTE: Two L_{eq} values for the nighttime periods are estimated from Ref. 26. The L_{eq} value for the daytime period is calculated using the DNL value and the L_{eq} value for the 10p.m.-7a.m. time period.

change when estimating aircraft noise exposure. As a result, the methods for estimating highway and railway noise exposures described in Sections 2.1 and 2.2 should remain valid for the foreseeable future.

The tabular format used for the highway and railway noise prediction methods is especially useful in estimating changes in the noise environment. For example, Table 4 can be used to estimate DNL changes related to both vehicle mix and traffic speed, Table 5 applies to changes in AADT and the nighttime traffic flow, and Tables 6 and 7 apply to the number of traffic lanes (consistent with the AADT estimate). Similar comments apply to the railway noise prediction method. As a result, the expected change in the noise environment may usually be evaluated simply by evaluating the change as indicated by a single table.

Depending upon the value of the future DNL, it remains a local policy judgement as to the steps necessary to ensure future noise-compatible land use. The noise exposure estimates may indicate present-day compatibility but a future conflict. If the conflict is to be avoided, then mitigation measures must be implemented. Since it cannot be assumed that the noise generated by automobiles, trucks, or diesel-electric trains will dramatically decrease in the future, mitigation techniques will generally be applied to the site adjacent to the source.

The particular mitigation techniques to utilize are site specific. The main considerations are the desirability to provide acceptable outdoor and indoor environments and the practicality of achieving the required degree of noise mitigation. The timing of the implementation, however, may well depend upon the choice of mitigation technique. If, for example, noise barriers are to be utilized as a mitigation technique, and the barriers are to be constructed with public funds on the right-of-way, then the noise barrier construction may be scheduled at the time at which the noise environment is expected to exceed the noise criterion. If, however, the migigation technique applies to private property and involves the building noise insulation, it may be necessary to implement zoning requirements and changes in the building code several years prior to an anticipated noise conflict. The remaining sections of these guidelines focus upon noise mitigation techniques and the noise-compatible development of land.

2.6 NOISE PREDICTION WORKSHEETS

Within this section, blank worksheets are grouped together for convenience. Worksheets are provided for predicting highway traffic and diesel-electric railway noise. The worksheets reference, at each step, the appropriate lookup table providing the required value or adjustment.

Highway Traffic Noise Prediction

Worksheet I is used to estimate the noise generated by traffic flow on highways. Tables 4 through 7 provide the necessary data for this prediction based upon the local traffic flow information. Tables 8 and 9 provide representative values for annual average daily traffic (AADT) and values for percent vehicle mix and nighttime vehicle operations.

Worksheet I is divided into three sections. The first section is simply a heading for inserting the project description, the person performing the calculations and the date. The second section lists the local traffic information required to conduct the noise prediction. The user should obtain this information from the State Highway Department. Data describing the distribution of the annual average daily traffic (AADT) and nighttime distribution of traffic by vehicle type may not be readily available. Representative values are presented in Tables 8 and 9 and may be used if local data are not available.

The third section of Worksheet I is for the actual noise prediction calculation. The first two entries are values from the indicated lookup tables using the traffic flow data in section two of the worksheet. The third entry is an adjustment constant for either hard site or soft site conditions (see Figure 2). The value entered in step 4 is the simple addition of the values in the first three steps, and represents the DNL at a location 50 ft from the edge of the near lane of the highway. This is the reference value of DNL for the highway traffic flow conditions.

Step 5 is the sound level adjustment added to the reference DNL value to obtain the DNL value at the receiver location. The entry in step 5 is obtained from Table 6 for hard sites and Table 7 for soft sites. The table selected must correspond to the site condition as entered in step 3 and the number of traffic lanes for the highway. The entry in step 6 is obtained by adding the adjustment value in step 5 to the reference DNL value in step 4. The DNL value obtained in step 6 is the DNL value at the receiver location adjacent to the highway. The receiver location is measured from the edge of the near lane of the highway (see Figure 1).

Section 2.1 presents examples illustrating the prediction of highway traffic noise. Figure 3 and 4 are examples of completed worksheets.

Diesel-Electric Railway Noise Prediction

Worksheets II and III are used to predict noise from diesel-electric trains. Worksheet II has two parts. The first part documents the basic data required to estimate the characteristics of the "average train" used for the noise prediction method. The second part documents the receiver location measured away from track centerline and, if there is a warning point within 1/2 mi of the receiver, the receiver location measured along the track from the warning point. These distances are illustrated in Figure 5.

Worksheet III is used to conduct the step-by-step calculations for the noise prediction. There are three parts to this worksheet. Part I is used to predict the DNL due to pass-by noise without warning horn. Part II is used to predict the DNL due to warning horn noise, and Part III is used to combine the pass-by DNL and the warning horn DNL to obtain the total DNL value due to railway noise. If warning horn noise is not a consideration, Parts II and III of this worksheet are not completed.

Tables 10 through 13 are used for the pass-by noise prediction and Tables 14 and 15 are used for the warning horn noise prediction. The data on Worksheet II are transferred to Worksheet III and are used to obtain the appropriate values from the lookup tables. Each step in Worksheet III indicates the lookup table used to obtain a value or an addition to obtain a result.

If warning horn noise is a consideration, the DNL value is estimated in Part II of Worksheet III. The pass-by noise and the warning horn noise must be combined to obtain the total DNL at the site due to railway noise. The required calculations are indicated in Part III and require the adjustments presented in Table 16.

If highway traffic noise and railway noise are combined at a site to obtain the total site exposure, the procedure is identical to that indicated in Part III of Worksheet III. Figures 6 through 8 illustrate a completed set of worksheets for the prediction of railway noise exposure at a site.

Existing Noise Levels

The determination of existing noise levels at a site should be based upon empirical data. However, if measurements are not appropriate, the existing noise levels may be estimated using the data presented in Table 17 if the population density at the site is known.

WORKSHEET I. HIGHWAY TRAFFIC NOISE PREDICTTION

PROJECT: ____

Prepared by: ________________________ Date: ____________

TRAFFIC FLOW INFORMATION

Number of traffic lanes	Average cruise speed	Annual average daily traffic AADT
________	________ mph	____________ vehicle/day

Vehicle type	Percent of AADT	Fraction operating at night
automobile & light trucks	________	f_{n1} ________
medium trucks	________	f_{n2} ________
heavy trucks	________	f_{n3} ________

HIGHWAY TRAFFIC NOISE PREDICTION

Step in the prediction method	Lookup Table	Value from lookup table
1. Traffic flow reference noise level	4	________ dB
2. Adjustment for AADT and nighttime traffic	5*	________ dB
3. Adjustment for site conditions (Use -31dB for hard site; -34dB for soft site)	none	________ dB ________
4. Day-night noise level at 50 ft (Add values in Steps 1,2, and 3)	none	________ dB
5. Adjustment for receiver at ________ ft	6(hard site) 7(soft site)	________ dB ________ dB
6. Day-night noise level at receiver (Add values in Steps 4 and 5)	none	________ dB

* If heavy trucks are present use f_{n3} in Table 5
If heavy trucks are not present use f_{n2} in Table 5.
If only automobiles and light trucks are present use f_{n1} in Table 5.

WORKSHEET II. DIESEL-ELECTRIC RAILWAY NOISE PREDICTION DATA

PROJECT: ____________________

Prepared by: ____________________ Date: ____________

PART I DATA DESCRIBING THE AVERAGE TRAIN *

a) Train speed, S = __________ mph

b) Total number of trains per day: N_T = __________

c) Total number of trains operating at night: N_n = __________

d) Total number of locomotives per day: N_L = __________

e) Total number of railway cars per day: N_c = __________

(1) Calculate the average number of locomotives per train:

$N = N_L/N_T$ = __________

(2) Calculate the average number of railway cars per locomotive:

$\bar{n} = N_c/N_L$ = __________

(3) Calculate the fraction of railway operations occurring during the nighttime (10 p.m. to 7 a.m.)

$f_n = N_n/N_T$ = __________

PART II DATA DESCRIBING THE SITE LOCATION (see Figure 5)

a) Distance from track to site: D = __________ ft

b) If there is a warning point within 1/2 mi of the site, determine the distance along the track from the warning point: L = __________ ft

---

* The mathematical notation for the data follows the notation used in Appendix A where the railway noise prediction model is described.

WORKSHEET III. DIESEL-ELECTRIC RAILWAY NOISE PREDICTION: PASS-BY NOISE EXPOSURE

PART I DIESEL-ELECTRIC PASS-BY OPERATIONS

(1) From Table 10 and the data for the average train on Worksheet II

(N = __________; $\bar{n}$ = ___________; and S = ________mph)

Reference sound level for one pass-by = __________ dBA

(2) From Table 11 the sound level adjustment for

N_T = _______ trains per day = __________ dB

(3) From Table 12 the sound level adjustment for

f_n = _________ fraction of nighttime operations = __________ dB

(4) Adding (1), (2), and (3) above, the day-night sound level for railway pass-by noise at a location D_o = 100 ft away from the track = __________ dB

(5) From Table 13 the sound level adjustment for the distance D = ________ ft away from the track centerline = __________ dB

(6) Adding (4) and (5) above, the day-night sound level for railway pass-by noise at a location D = ________ ft away from the track centerline = __________ dB

IF THERE ARE NO WARNING POINTS WITHIN 1/2 MILE OF THE SITE, THE ABOVE RESULT (6) IS THE DAY-NIGHT SOUND LEVEL AT THE SITE RESULTING FROM PASS-BY NOISE OF DIESEL-ELECTRIC TRAINS.

IF WARNING HORN NOISE OCCURS, PROCEED TO PARTS II AND III OF THIS WORKSHEET

WORKSHEET III. DIESEL-ELECTRIC RAILWAY NOISE PREDICTION: PASS-BY NOISE EXPOSURE

PART II WARNING HORN NOISE PREDICTION

(1) From Table 14 or Figure 5 at the location L = _____ ft along the track from the warning point and D = ____ ft from the track,

Reference sound level for one warning = __________ dBA

(2) From Table 15 the sound level adjustment for N_T = ________ trains per day passing the site at S = __________ mph is = __________ dB

(3) From Table 12 the sound level adjustment for f_n = __________ fraction of nighttime operations is = __________ dB

(4) Adding (1), (2), and (3) above, the day-night sound level for railway pass-by noise at a the location L = ___________ ft and D = ________ ft is = __________ dB

PART III COMBINED PASS-BY AND WARNING HORN NOISE PREDICTION

The pass-by sound level and the warning sound leave must be combined to obtain the total noise prediction at the location.

(1) From Part I; step (6) the pass-by day-nigth sound level is = __________ dB

(2) From Part II, step (4) the warning horn day-night sound level is = __________ dB

(3) Using (1) and (2) above, the sound level difference is: higher level - lower level = ____________________________

(4) Using the sound level difference from step (3) and from Table 16, the combined day-night sound level is: higher level + adjustment = ____________________________ = __________ dB

THE RESULT (4) ABOVE IS THE COMBINED DAY-NIGHT SOUND LEVEL AT THE SITE FOR RAILWAY NOISE

3. MITIGATION TECHNIQUES

By utilizing the methods described in Section 2, the total noise environment at a location may be estimated for the expected combination of noise sources. This combination always includes the existing noise level and one or more of the transportation noise sources. The next step in the evaluation is a comparison of the estimated noise levels with the noise compatibility criteria. The compatibility of the intended land use is then determined based upon the level of outdoor noise and indoor noise due to the outdoor noise. Since activities related to residential land use are generally the most noise-sensitive activities, the noise criteria for residential land use are the most restrictive criteria.

As indicated in Table 3, ideal criteria for residential land use are: outdoor DNL less than or equal to 55 dB and indoor DNL (due to outdoor noise) less than or equal to 45 dB. For outdoor DNL between 55 dB and 60 dB, residential land use is acceptable for outdoor activities and compatible for indoor activities with normal construction and window open. However, if the outdoor DNL exceeds 60 dB, additional steps or measures are required to achieve noise-compatible land use. The methods or techniques employed to achieve noise-compatible land use by controlling site conditions are called mitigation techniques and are discussed in this section. The mitigation techniques are classified in these guidelines according to their application to either outdoor conditions or indoor conditions. Generally, the mitigation of outdoor noise may result in a decrease in indoor noise levels. However, the reduction of indoor noise levels caused by outdoor noise sources will do nothing to improve the outdoor noise environment.

Before presenting the details of specific noise mitigation techniques, it is worthwhile to illustrate the significance of the problem, and to present a brief discussion of the physical principles that determine mitigation effectiveness.

Existing Noise Levels

Table 17 is an empirical relationship between existing noise levels and population density for residential urban areas. These results indicate that the outdoor DNL will exceed 55 dB for areas with a population density greater than 2,500 people/mi^2 and will exceed 60 dB for areas with a population density greater than 8,000 people/mi^2. Since these DNL values are associated with noise from unidentified sources, it is impossible to specify an appropriate mitigation technique for the outdoor environment. Fortunately, at these levels, noise exposure is not usually significant. However, mitigation of noise indoors due to the outdoor existing noise environment is possible. These mitigation techniques require that windows be closed and that the building envelope provide an adequate degree of noise isolation. As an indication of the significance of the existing noise levels and the possible need for mitigation, the Ref. 25 study estimated that in 1974, approximately 80 percent of the United States urban population resided in areas exposed to DNL exceeding 50 dB and 40 percent were exposed to DNL exceeding 60 dB.

Physical Aspects of Outdoor Noise Mitigation

These guidelines provide quantitative estimates of the effectiveness of various noise mitigation techniques. The effectiveness is stated in terms of a level reduction value expressed in A-weighted dB units. For example, if the outdoor DNL at a receiver location is estimated to be L_{dn} = 67 dB and the introduction of a noise barrier between the source and receiver provides a level reduction of 12 dB, then the DNL at the location of the receiver with the barrier in place is L_{dn} = 55 dB.

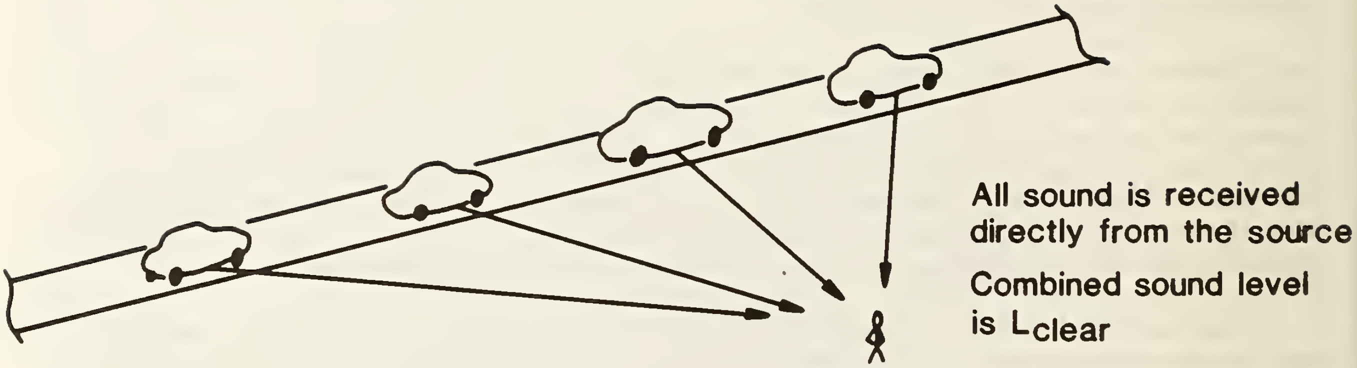
Figure 11 illustrates the concept of determining a level reduction for an outdoor location in the presence of several different source-receiver paths typical of a residential development. To estimate the A-weighted level reduction, one must use lengthy calculations based upon a knowledge of the frequency content of the source, the specific site geometry, the acoustic characteristics of reflecting surfaces, and average these effects over time. Such an approach, however, is too cumbersome for the purposes of these guidelines.

The approach used to estimate the A-weighted level reduction for various mitigation techniques is to provide lookup tables and empirical results that apply to typical source-receiver conditions. These results may then be applied to estimate the mitigation effectiveness. If the actual site conditions do not correspond to the typical source-receiver conditions, it then becomes necessary to employ more refined calculations if the situation warrants the effort. Technical appendices to the present guidelines are provided for this purpose.

Two physical aspects of outdoor noise mitigation are the diffraction or bending of sound waves around an object and the scattering or reflection of sound waves from an object. Figure 12 illustrates these two physical aspects of noise mitigation. In general, the diffraction of sound results in a positive degree of noise mitigation if the receiver is in the "shadow zone" behind a barrier. Scattering of sound may result in either a positive or negative degree of noise mitigation. If sound is scattered so that the total energy at the receiver decreases, the mitigation effectiveness is positive. If the sound is scattered or reflected toward the receiver so that the total energy reaching the receiver is increased, the mitigation effectiveness is negative. Except for extreme conditions, the effects of scattering or reflection may be ignored without introducing significant error in estimating the mitigation effectiveness. For the purpose of these guidelines, rules of thumb and examples of poor site design are presented to avoid problems related to reflections.

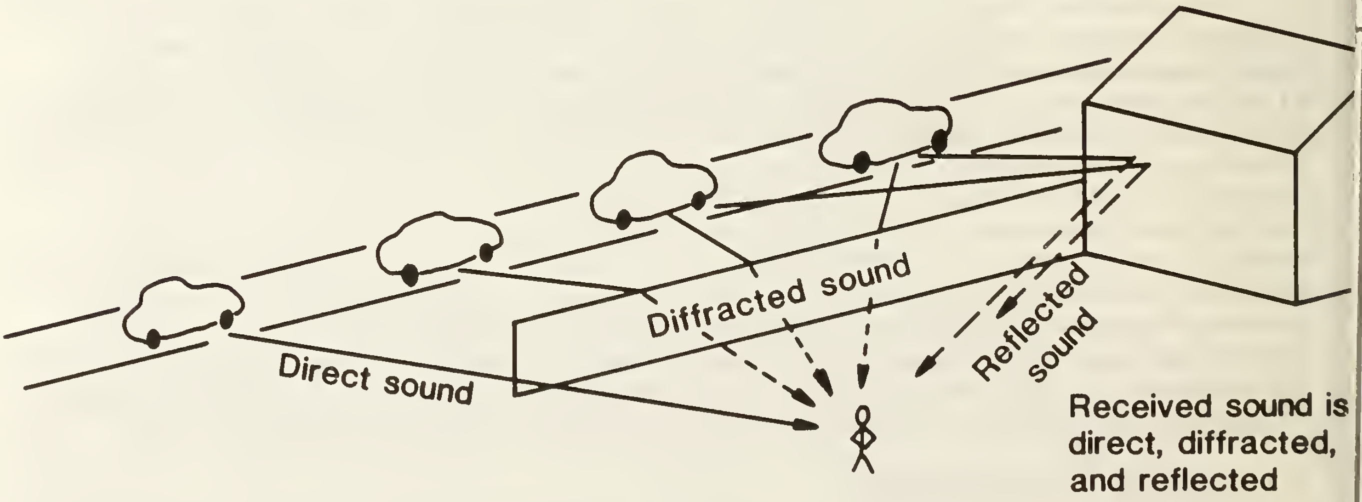
3.1 OUTDOOR NOISE MITIGATION

The mitigation of outdoor noise depends upon the noise sources causing the site noise exposure. The degree of mitigation effectiveness required to achieve a desired criterion depends upon the distance between the noise source and the receiver. Figure 13 presents the basic considerations using a rather extreme example of site noise exposure. Unless the aircraft noise exposure is below the criterion for total noise exposure, very little may be accomplished to achieve any degree of outdoor noise mitigation other than increasing the distance between the aircraft flight path and the receiver. For the railway



Combined sound level is L_{clear}

a) Clear site conditions

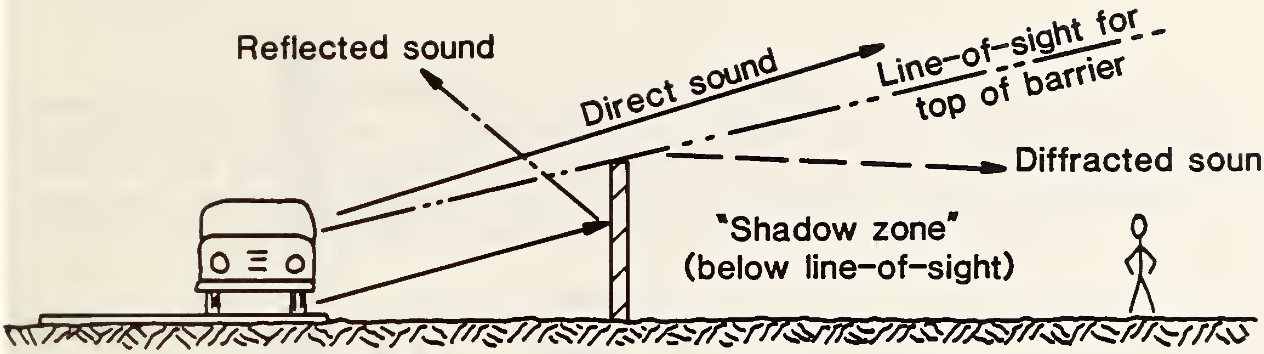


Combined sound level is $L_{built-up}$

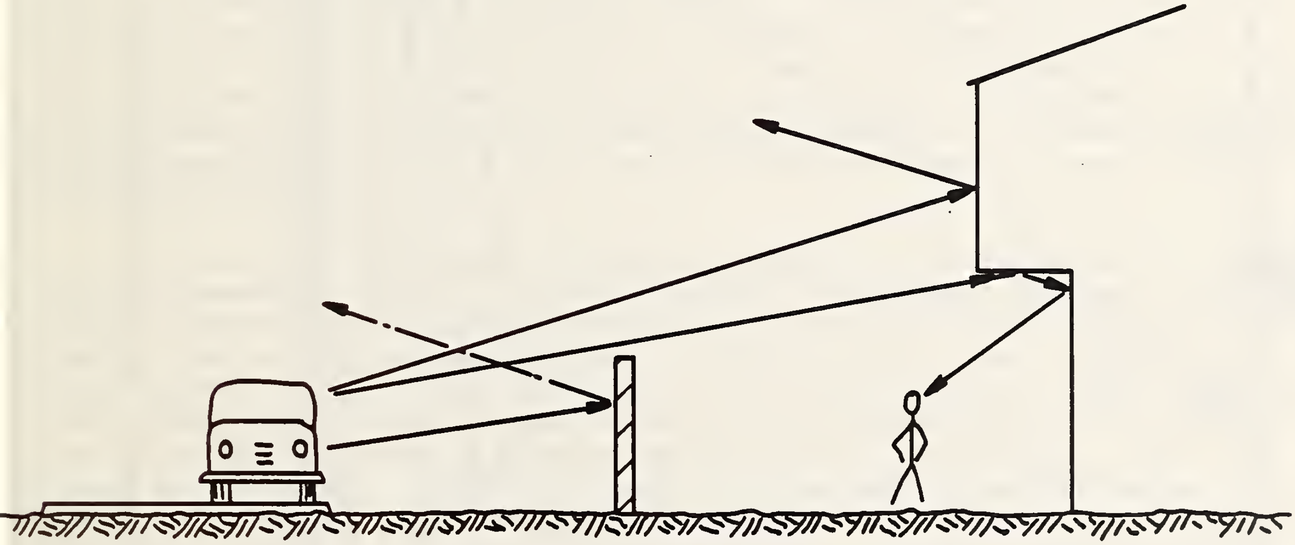
Receiver insertion loss = $L_{clear} - L_{built-up}$, dB

b) Built-up site conditions

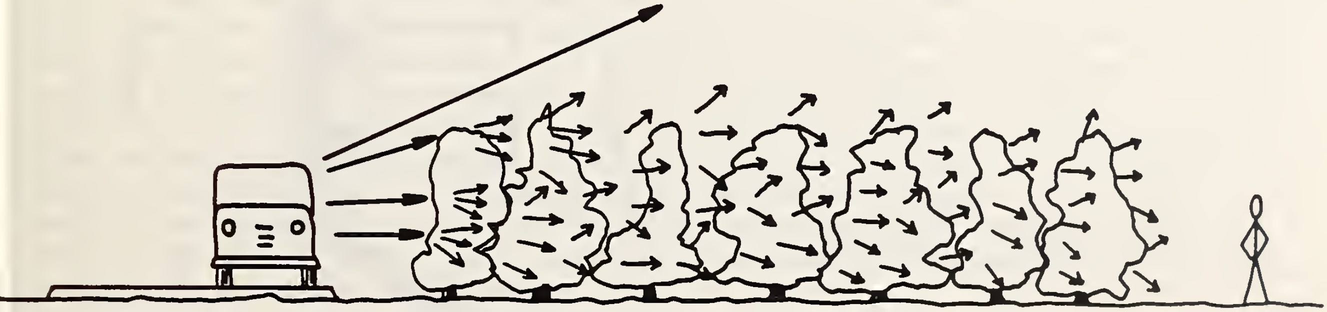
Figure 11. Propagation of Highway Noise to Receiver: Site Insertion Loss.



a) Direct, reflected, and diffracted sound for thin screen barrier



b) Reflected sound reaching receiver decreasing barrier effectiveness



c) Sound scattered by dense vegetation

Figure 12. Illustration of Diffraction, Reflection and Scattering of Sound by Objects next to Highway

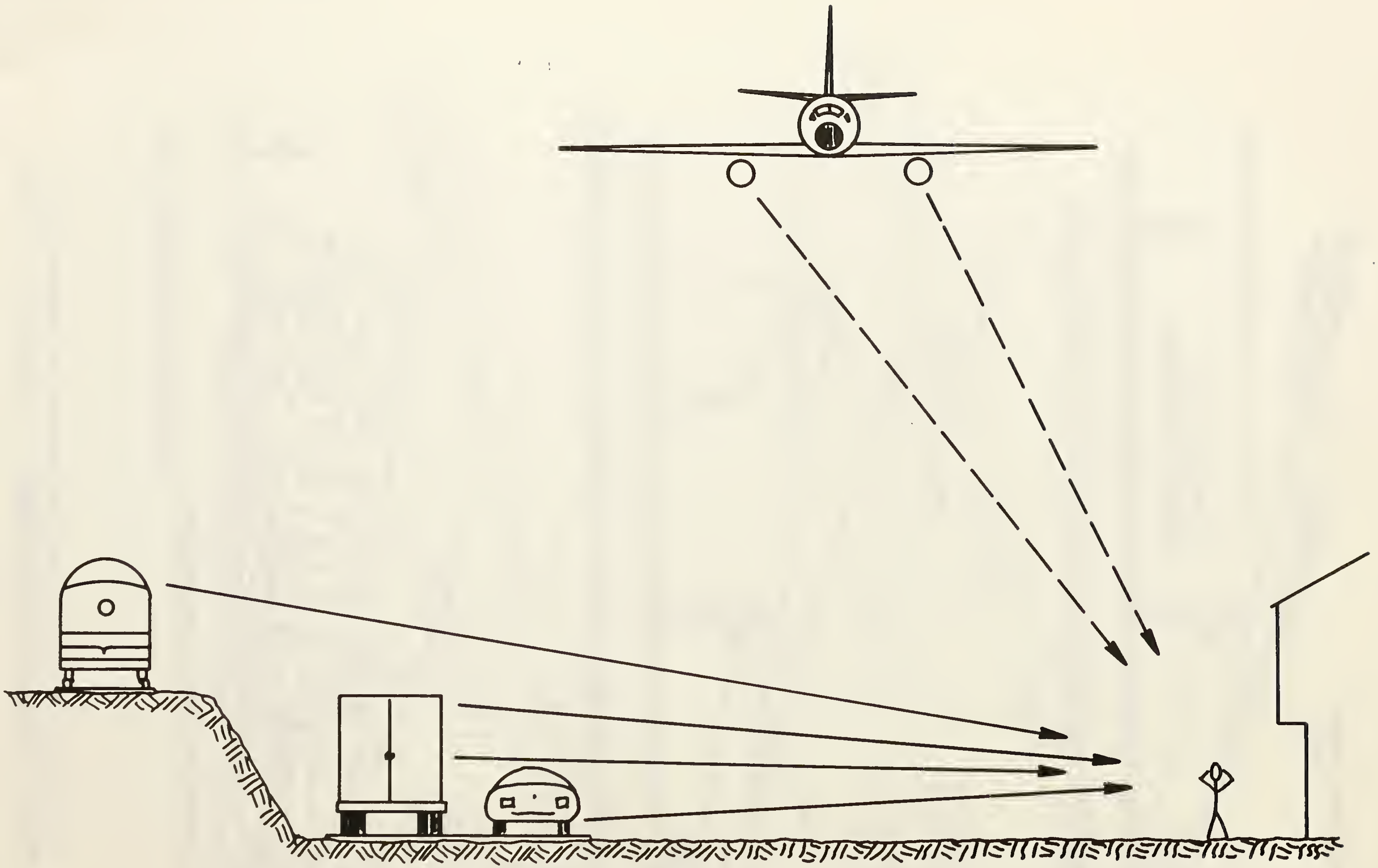


Figure 13. Site Noise Exposure for Combined Noise Sources

pass-by noise exposure and the highway traffic noise exposure, it may be practical to introduce a barrier between the receiver and these sources to achieve the desired degree of mitigation effectiveness. These guidelines describe the necessary considerations, and present a quantitative method for estimating highway noise mitigation effectiveness using barriers.

Highway Traffic Noise Barriers

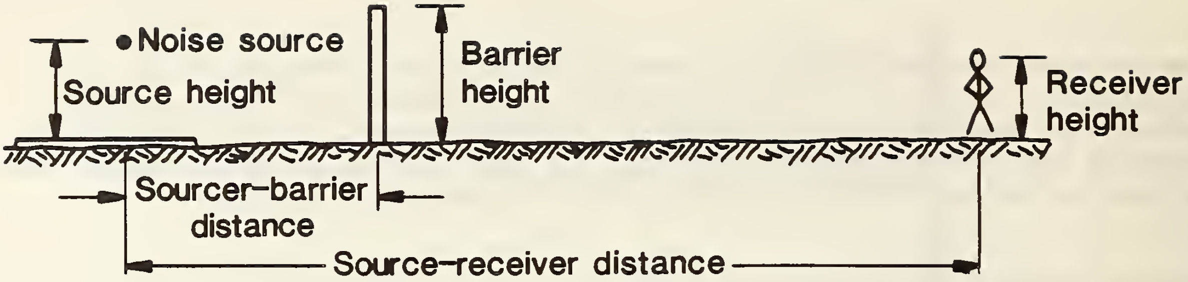
The mitigation effectiveness of highway traffic noise barriers is determined by the geometry relating the highway noise source location relative to both the top of the barrier and the receiver location. To be effective, the receiver location must be such that the receiver is totally shielded by the barrier (i.e., the barrier blocks the direct line of sight between the source and receiver). This shielding must consider all possible lines of sight between the source and receiver both in elevation and in the horizontal direction. Figure 14 illustrates the concepts of the relative source-receiver geometry and the degree of shielding provided by a barrier.

A specific barrier design considers alternative configurations of source-receiver geometry. First, the source height is established for the traffic flow. This is achieved by assigning a source height for each vehicle type in the traffic flow as follows: automobiles and light trucks, source height is 0 ft; for medium trucks, source height is 2.3 ft; and for heavy trucks, source height is 8 ft. These heights are measured relative to the pavement elevation and have been established from noise emission characteristics of vehicles. The above values for the source heights are accepted values used in barrier design (Refs. 6, 7, and 8). Since heavy trucks generate the highest noise levels and the source height is 8 ft above the pavement (i.e., exhaust noise dominates), the barrier height must generally be greater for a condition with trucks present in the traffic flow than for a condition without heavy trucks present.

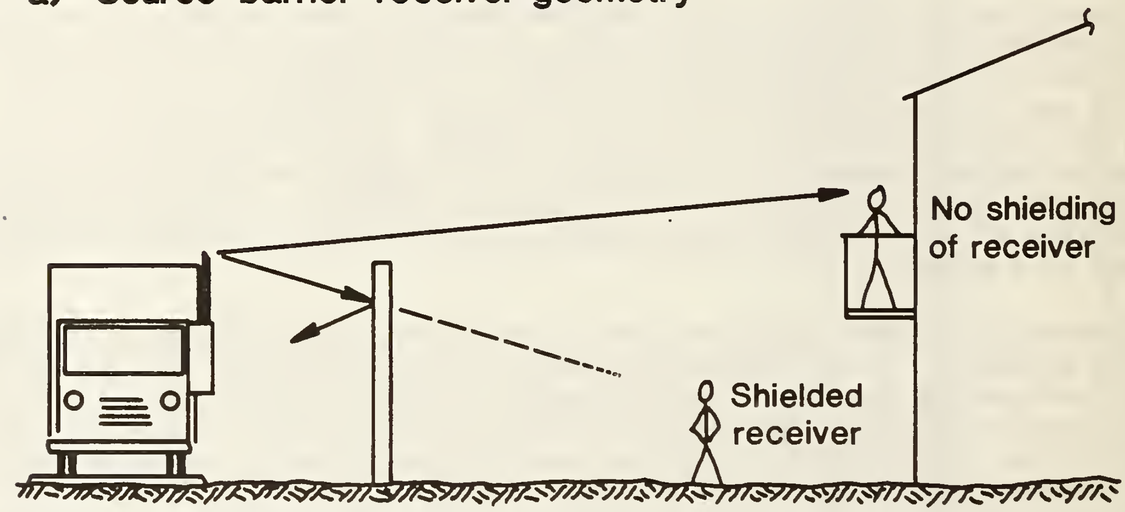
Next, the barrier length must be established so that the receivers are adequately shielded from noise generated by vehicles moving along the highway alignment. As indicated in Figure 14, the distances between the source and the barrier and the source and the receiver are also important geometric variables. This leads one to realize that for a barrier located at a fixed distance from the near edge of the pavement, the barrier effectiveness may depend upon the number of traffic lanes and will certainly depend upon the receiver locations away from the highway and each receiver elevation relative to the highway and the top of the barrier. Established methods are available to estimate the barrier effectiveness as a mitigation technique for highway noise (Refs. 6, 7 and 8) and to provide an optimized design considering all receiver locations behind the barrier (Ref. 27). However, these design-oriented methods are too combersome for these guidelines.

Estimation of Barrier Mitigation Effectiveness

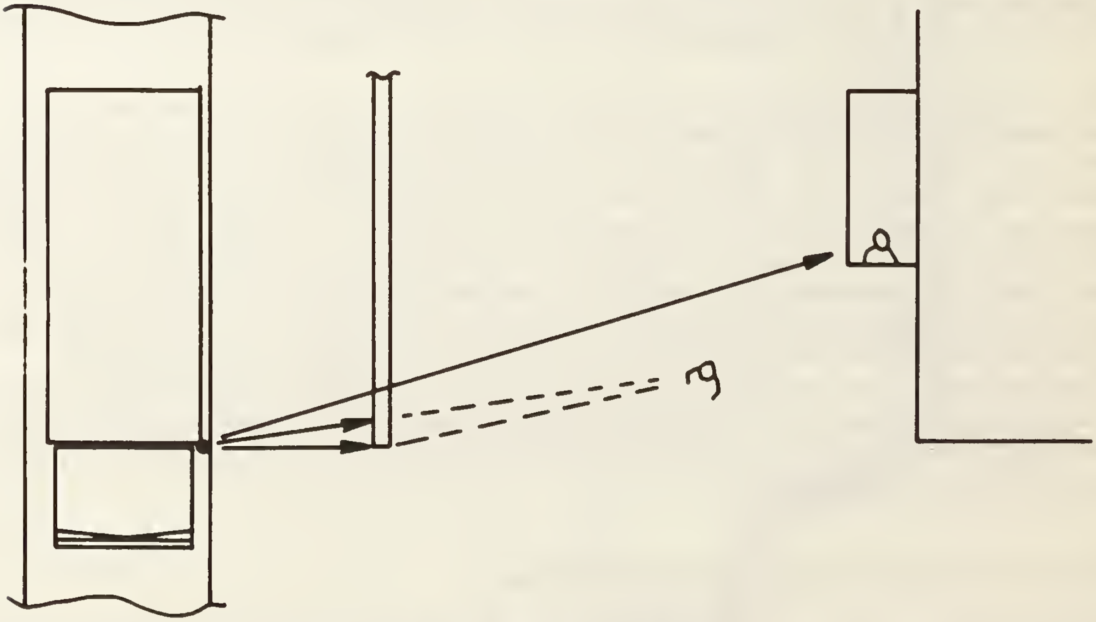
For the purpose of these guidelines, it is appropriate to utilize a somewhat restricted approach to estimating barrier effectiveness as a mitigation



a) Source-barrier-receiver geometry



b) Source-receiver relationship in elevation



c) Source-receiver relationship in plan

Figure 14. Source-Barrier-Receiver Relationship

technique for highway traffic noise. The restrictions generally apply to the geometry relating the source and receiver locations relative to the barrier.

Consistent with the highway traffic noise prediction method, it is assumed that the highway is comprised of several traffic lanes, has a straight alignment, and that the entire site is flat. The barrier is located at a fixed distance from the pavement edge next to the site. The barrier is of constant height and also extends indefinitely in both directions parallel to the highway. (The barrier may be considered to be of infinite length if it extends to either side of the receiver a distance equal to four times the receiver distance behind the barrier.) The receiver is located behind the barrier at various distances measured from the barrier. The receiver height is assumed to be 5 ft above ground elevation. (This is an average ear height for people standing.)

With these restrictions, Table 18 has been prepared for use in estimating the highway traffic noise mitigation that would result from building a barrier between the highway and various receiver locations. The values listed in Table 18 are "barrier insertion loss" values and represent the approximate A-weighted level reduction for traffic noise. Table 18 comprises three subtables with each subtable corresponding to different vehicle mixes in the traffic flow. This accounts for vehicle source height differences. For each subtable, the barrier geometry is defined in terms of barrier height and the distance from the edge of the pavement to the barrier. The receiver elevation is 5 ft above the ground elevation.

For a given barrier geometry and traffic flow, the barrier insetion loss is estimated from Table 18 as an average value and a positive or negative adjustment. This average value and the magnitude of the adjustment are based upon more extensive calculations incorporating both receiver location behind the barrier and from one to eight traffic lanes for the source locations. Since the near traffic lanes essentially establish the barrier insertion loss, the notes to Table 18 indicate that the value of the barrrier insertion loss are obtained only on the basis of the receiver location. The average value applies to receiver locations from 100 ft to 500 ft behind the barrier. If the receiver is within 100 ft of the barrier the insertion loss is the average value plus the adjustment. If the receiver is located beyond 500 ft behind the barrier, the insertion loss is estimated as the average value less the adjustment. An example will illustrate the use of Table 18.

EXAMPLE 5. We had previously estimated highway traffic noise at a site exposed to noise from all vehicle types for a receiver located 300 ft from the near edge of the pavement. The highway traffic noise was estimated to be L_{dn} = 67 dB for a hard site and 61 dB for a soft site.

We desire to estimate the L_{dn} at the receiver for a 10-ft high barrier located 25 ft from the edge of the pavement. Since the barrier is 25 ft from the pavement and the receiver is 300 ft from the pavement, the receiver is located 275 feet behind the barrier. From Table 18(c), with a barrier height of 10 ft and a barrier distance of 25 ft, the value listed is 7.5 ± 2.0 dB. Since the receiver is located between 100 ft and 500 ft behind the barrier, the estimated barrier insertion loss is 7.5 dB. Then, the estimated DNL value with

Table 18. AVERAGE BARRIER INSERTION LOSS ± ADJUSTMENT IN dB FOR HIGHWAY TRAFFIC NOISE SOURCE WITH RECEIVER HEIGHT AT 5 ft

Average value is for locations from 100 ft to 500 ft behind barrier; use a positive adjustment for locations within 100 ft and a negative adjustment beyond 500 ft

a) Automobiles and light trucks only

Barrier height, ft	Distance from edge of pavement to barrier, ft			
	25	50	75	100
8	11.0 ± 1.5	9.5 ± 0.5	8.5 ± 0.5	7.5 ± 0.5
10	14.0 ± 1.5	12.5 ± 1.5	11.0 ± 2.0	9.5 ± 0.5
12	15.5 ± 1.0	14.5 ± 1.5	13.5 ± 2.0	12.0 ± 2.0
16	17.5 ± 1.0	16.5 ± 1.0	16.0 ± 1.5	15.0 ± 1.5

b) Automobiles, light trucks, and medium trucks only

Barrier height, ft	Distance from edge of pavement to barrier, ft			
	25	50	75	100
8	9.0 ± 0.5	8.0 ± 0.5	7.5 ± 0.5	7.0 ± 0.5
10	12.5 ± 2.0	11.0 ± 2.0	10.0 ± 2.0	8.5 ± 1.0
12	14.5 ± 2.0	13.0 ± 2.0	12.0 ± 3.0	11.0 ± 2.0
16	17.0 ± 1.0	16.0 ± 2.0	15.0 ± 2.0	14.0 ± 2.0

c) Automobiles, light trucks, medium trucks, and heavy trucks

Barrier height, ft	Distance from edge of pavement to barrier, ft			
	25	50	75	100
8	6.0 ± 0.5	6.0 ± 1.0	6.5 ± 1.0	5.5 ± 0.5
10	7.5 ± 2.0	7.5 ± 2.0	7.5 ± 2.0	6.5 ± 1.5
12	10.5 ± 3.5	10.2 ± 3.5	10.0 ± 4.0	8.0 ± 2.0
16	14.5 ± 3.0	13.0 ± 4.0	12.5 ± 4.0	11.5 ± 3.5

the barrier is 67.0 - 7.5 = 59.5 ≈ 60 dB for a hard site and 61.0 - 7.5 = 53.5 ≈ 54 dB for a soft site.

Due to the nature of the approximation and averaging used to develop Table 18, the question arises as to how close the estimate is to the more detailed calculation. For the receiver location in the above example, the more detailed evaluation would estimate the barrier insertion loss to be 6 dB rather than 7.5 dB. As a result, the more detailed calculation would yield estimated DNL values of 61 dB for a hard site and 55 dB for a soft site. This 1 dB difference in DNL with the barrier in place is reasonable given the approximate nature of the barrier insertion loss values tabulated in Table 18.

When using the values presented in Table 18, the approximations used should be recognized. The differences between the tabulated values and the estimates obtained by the more detailed calculation procedure will be greatest for receiver locations within 100 ft of the barrier. The reason for this is that the barrier insertion loss decreases significantly from its highest values close to the barrier to a lower value at 100 ft from the barrier.

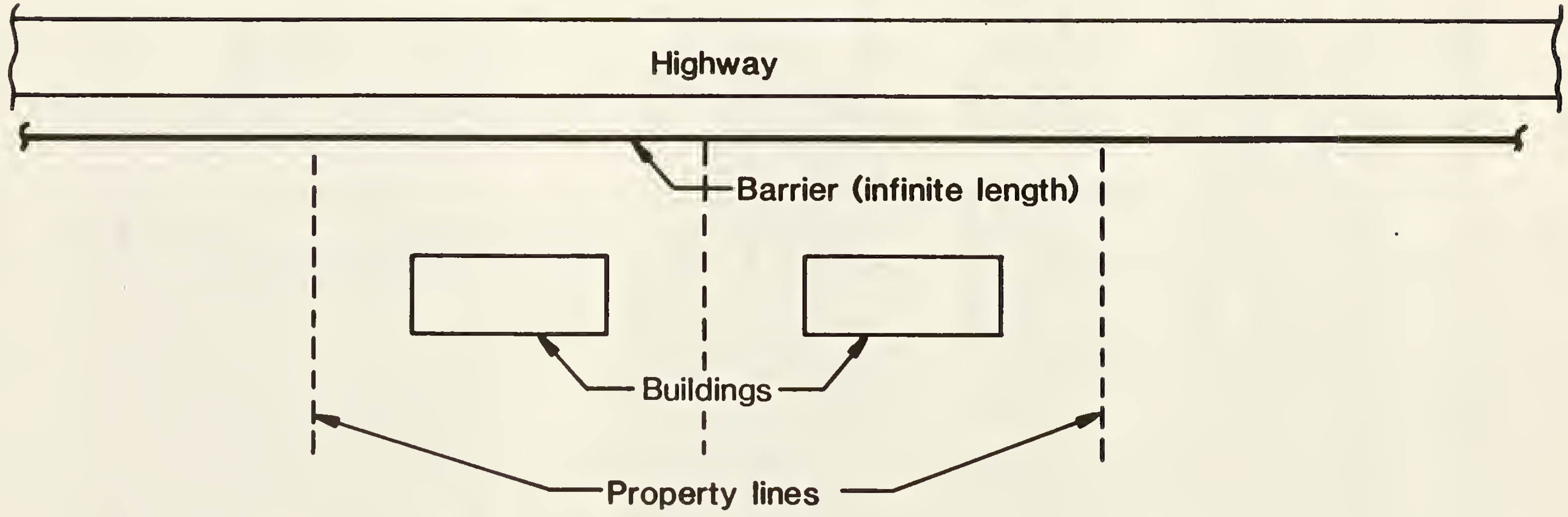
Finally, it must always be remembered that the values listed in Table 18 are for a barrier of constant height that extends along the entire highway alignment. In practice, barriers will not extend the entire length of the highway but will only shield a site from the highway directly adjacent to the site. Unless the barrier incorporates corner segments at its ends, sound will diffract or bend around the ends of the barrier as well as over its top, and the barrier performance may be decreased for the source-receiver location. Figure 15 illustrates an example of barrier design that may be used to increase the mitigation effectiveness to the levels indicated in Table 18.

Barrier Construction

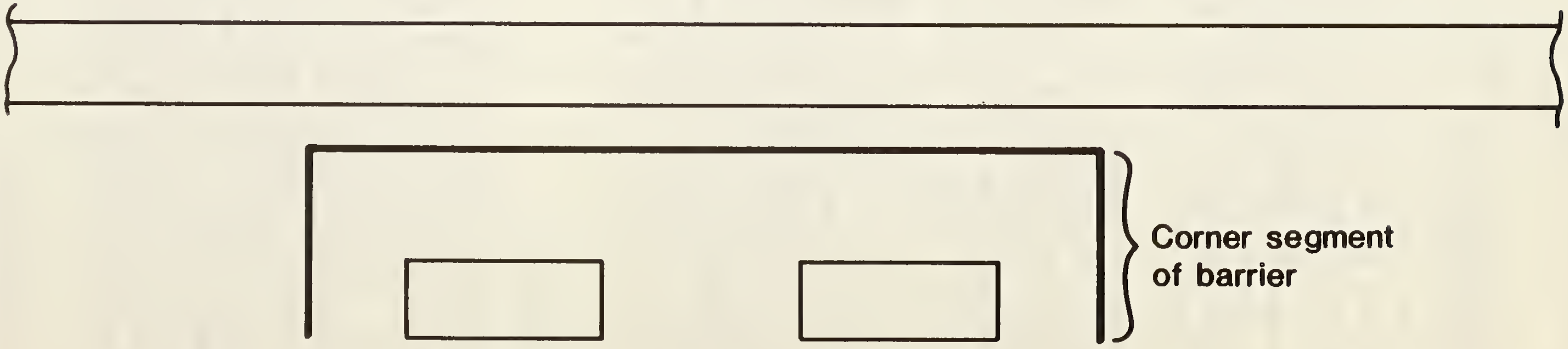
Highway traffic noise barriers may be constructed using various materials and techniques. The selection of materials or techniques is based upon local construction practices, cost, and aesthetics. As related to acoustic performance, however, the barrier material should exhibit sound transmission loss characteristics (this term will be described below in the subsection concerning the building envelope) sufficient to attenuate sound passing through the barrier, and the construction methods should ensure that no gaps or cracks are present that allow noise to pass through the barrier unattenuated. Specific considerations are design details beyond the scope of these guidelines (Refs. 28 and 29). As a general guide, the sound transmission loss of the barrier material should be at least 10 dB greater than the value for the barrier insertion loss. Table 19 is a partial listing of the A-weighted sound transmission loss values for materials that may be used for barrier construction (Ref. 28).

Natural Terrain and Berms

Often, natural terrain will obstruct the direct line of sight between the source and the receiver or berms will be constructed to block the line of



a) Site shielded by infinite length barrier



b) Site shielded by finite length barrier with corner segments to increase mitigation effectiveness

Figure 15. Plan View of Site Illustrating Shielding by Highway Noise Barriers

Table 19 Materials for Use in Barrier Construction (Ref. 28)

Material		Thickness, in	Transmission Loss, dBA	Coments
Wood	Fir	1/2	17	Tongue and groove boards for fir, pine, redwood, and cedar
		1	20	
		2	24	
	Pine	1/2	16	
		1	19	
		2	23	
	Redwood	1/2	16	Secure all joints to prevent cracks and gaps
		1	19	
		2	23	
	Cedar	1/2	15	
		1	18	
		2	22	
	Plywood	1/2	20	
		1	23	
Metal	Steel	24 ga 20 ga 16 ga		Anti-glare treatment required

Material	Thickness, in	Tranmission Loss, dBA	Comments
Concrete & Masonry			
light weight concrete	4	36	Grout may be required to seal gaps and cracks
	6	39	
Dense concrete	4	40	
Concrete Block	4	32	
	6	36	
Cinder block	6	28	
Brick	4	33	
Granite	4	40	

Notes: Ref. 28 provides a more complete listing.
A-weighted transmission loss values based upon truck noise spectrum.

sight as a noise-mitigation measure. The values in Table 18 may be used, with an adjustment, to evaluate the insertion loss for these conditions provided that the terrain or berm is generally parallel to the highway, and that it is at a constant elevation relative to the highway-receiver locations. The values of insertion loss for berms of this geometry are obtained by adding 3 dB to the insetion loss values determined by using Table 18 for a barrier of the same geometry (Ref. 6).

Vegetation

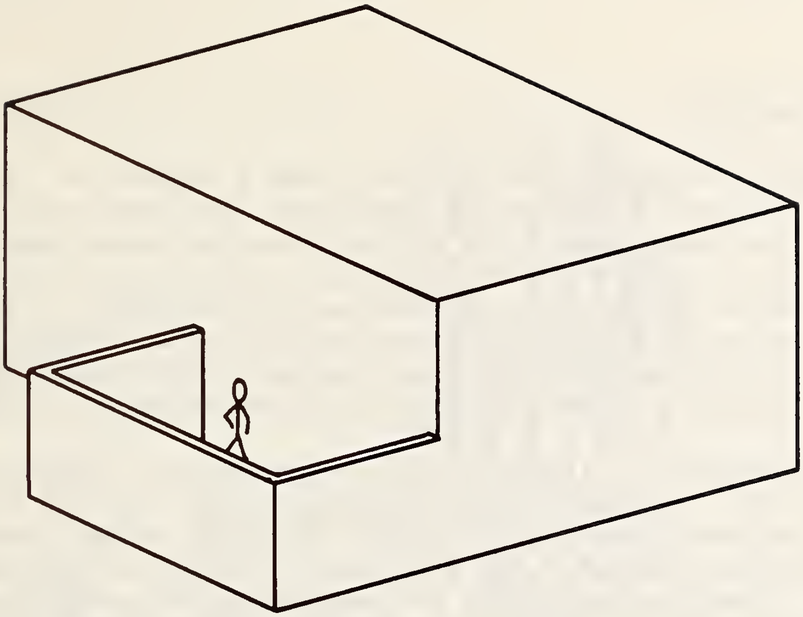
As indicated in Figure 12, vegetation can result in a scattering effect on highway traffic noise propagation with a resulting decrease in sound level in excess of the levels predicted for the clear site. However, the effect is significant only for very dense vegetation from ground level to heights exceeding 10 ft, and for a minimum distance of 100 ft between the source and the receiver. Furthermore, the foliage must remain on a year-round basis. As a guide, one may attribute excess attenuation due to vegetation on the basis of 5 dB per 100 ft of dense vegetation between the highway and the receiver (Ref. 8). However, it is good practice to assume that vegetation does not provide additional or excess noise attenuation unless site-specific field measurements are available. Indeed, planting trees on top of berms for aesthetic purposes may degrade the noise mitigation effectiveness of the berm due to the noise scattering effect of the foliage (Refs. 30 and 31).

Privacy Fences and Courtyards

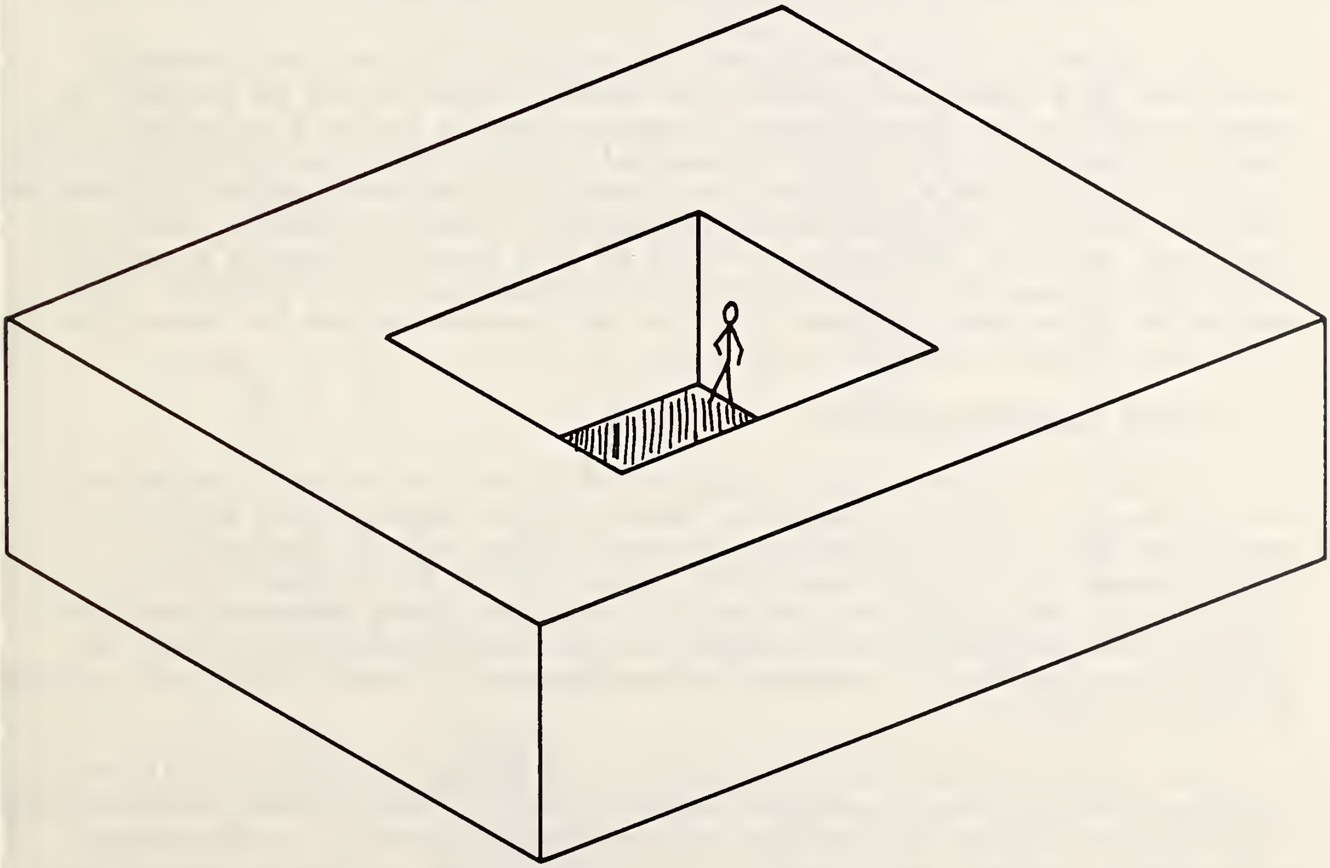
Figure 16 illustrates the concept of utilizing privacy fences and courtyards as an outdoor noise mitigation technique. Both the privacy fence and the courtyard are really just another form of noise barrier placed between the noise source and the outdoor receiver location. Their effectiveness as a noise mitigation technique depends upon the relative geometry of the source and the receiver. In contrast to the highway noise barrier, the sheilded area is rather small, and the fences or courtyards must be incorporated into the building design. Since the shielded area is adjacent to the building, the consideration of reflections from the building exterior surfaces must be incorporated into the estimate of the mitigation effectiveness (see Figure 12).

The available design methods for estimating the noise-mitigation effectiveness or insertion loss are limited to acoustic scale model measurements or field measurements (Refs. 32 and 36). These results, however, must be applied with careful judgement since the insertion loss estimates are expressed in terms of various noise descriptors not totally compatible with the L_{dn} descriptor used in these guidelines.

As a general guide, a privacy fence could provide an insertion loss of 3 dB and a courtyard a maximum of 6 to 10 dB in the L_{dn} value for the clear site if properly designed. These approximate values apply to the area enclosed by the fence or the courtyard and the building.



a) Privacy fence (solid wall, note fence height relative to receiver height)



b) Courtyard house

Figure 16. Conceptual Examples of Privacy Fences and Courtyards

Buildings as Noise Barriers

A house or building will provide shielding from a highway or railway source. As described above for privacy fences and courtyards, the land area shielded from the source and the magnitude of the mitigation effectivness are site specific. The geometric factors are the distance between the building and highway, the orientation of the building relative to the highway, the building length and width, the sound absorption characteristics of the building surfaces, and the proximity of other building surfaces that may reflect sound toward the shielded receiver location. Figure 17 illustrates the geometric concepts.

The degree of shielding or insertion loss provided by a building varies from point to point about the building. The calculations required to estimate the insertion loss are very complex in a strict technical sense. However, simplified approximations, suitable for preliminary estimates, are possible (Refs. 36 and 37). These approximations are based upon the concept of "geometric" or "ray acoustics" and do not incorporate diffraction of sound around the ends or over the top of buildings. Since the significant shielding occurs on the side of the building opposite the highway and rather close to the building surface, ignoring the sound diffraction over the top of the building is not a bad approximation even for single-story houses.

The estimation of the insertion loss provided by a building cannot be formulated in a convenient lookup table format. Appendix B.2 is provided in these guidelines for estimating the insertion loss of a single building in the absence of reflections of sound. These calculations allow the user to estimate the insertion loss on a point-by-point basis or to estimate contours of constant insertion loss for the area behind the building. The only general conclusion from these estimates is that the contour of 3 dB insertion loss is a semicirle with diameter equal to the building dimension parallel to the highway. This contour is illustrated in Figure 17. For any location within the semicirlce, the insertion loss is greater than 3 dB.

3.2 INDOOR NOISE MITIGATION

Section 3.1 addressed the mitigation of outdoor noise for locations on a site exposed to transportation noise sources. The outdoor noise mitigation techniques apply only to highway or railway sources and are limited in effectiveness to 15 dB or less. This section of the guidelines addresses the mitigation of noise received indoors due to outdoor noise sources. The term "indoor noise mitigation" applies only to the noise transmitted through the building envelope that is generated by the highway, railway, or aircraft sources described in Section 2.

The ability of the building envelope to attenuate outdoor noise is only one aspect of the overall envelope design criteria. Other design considerations focus upon the thermal performance, daylighting requirements, accessibility, and aesthetic values. As a result, the architect must develop an integrated envelope design that satisfies all criteria. These guidelines address the acoustic performance of the building envelope, and describe the implications of achieving the acoustic performance as related to other envelope design criteria.

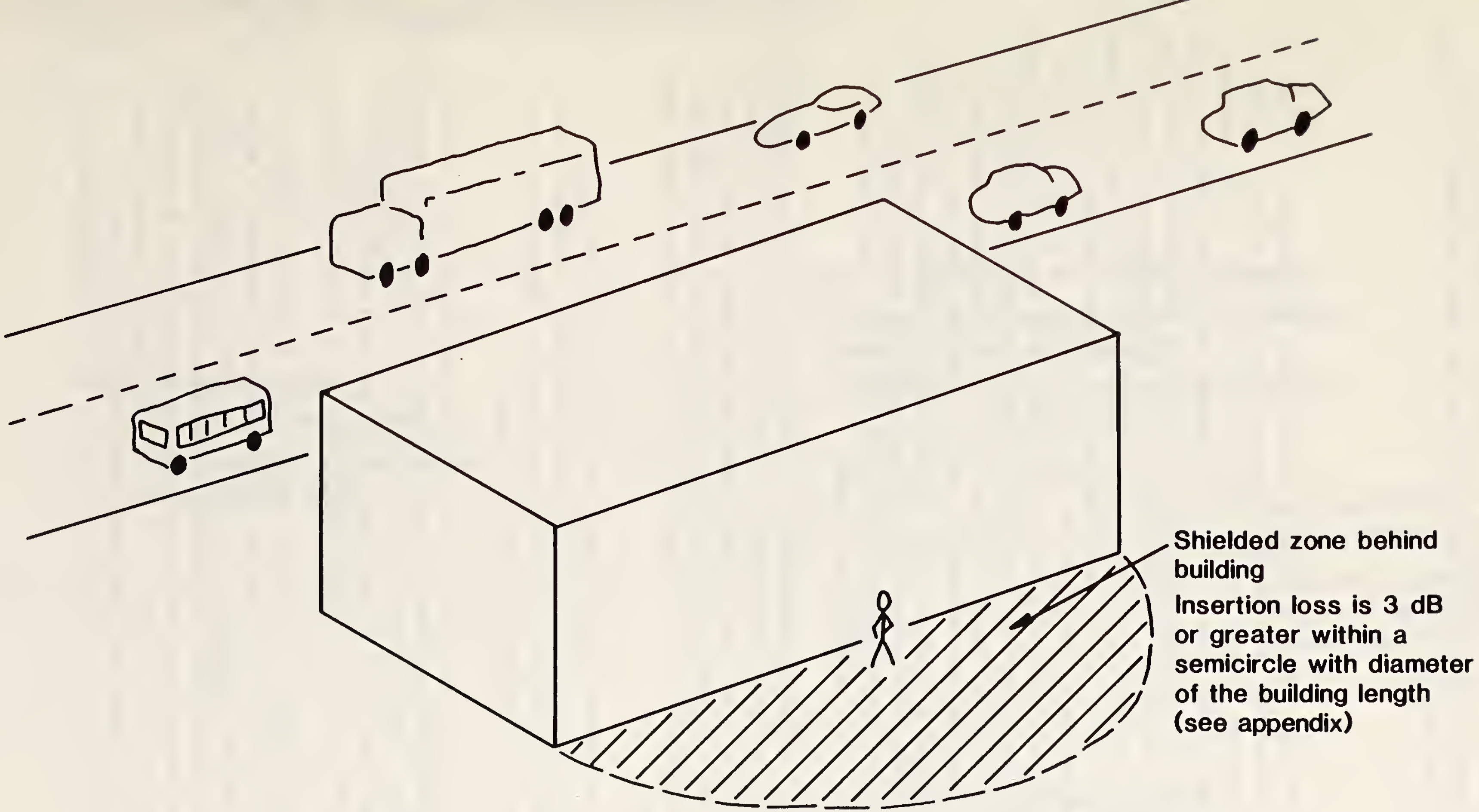


Figure 17. Buildings as Noise Barriers

Before describing the method for estimating the acoustic performance, it is necessary to introduce some terminology and to give the user an understanding of the physical aspects of the problem.

Terminology

These guidelines utilize the A-weighted sound level difference as the measure of the effectiveness of the indoor noise mitigation. If the outdoor noise level is 70 dBA and the indoor noise level in a room due to the outdoor noise is 50 dBA, the A-weighted sound level difference of 20 dBA characterizes the acoustic performance of the portions of the envelope surrounding the room. By using the A-weighted sound level difference, it is generally not possible to associate a single number with the acoustic performance of a dwelling and expect the single number to characterize all combinations of outdoor noise sources. For example, a field measurement program may establish that a given building exhibits a 23 dBA sound level difference for traffic noise and a 28 dBA sound level difference for aircraft noise. There is nothing wrong with the field measurements. The apparent discrepancy (which is a true characterization of the acoustic performance of the envelope) is mainly attributable to the difference in the spectral shapes between the two noise sources and source location relative to the building surface, rather than either a faulty field measurement or the physical characteristics of the building construction. Figure 18 summarizes some of the considerations.

The A-weighted sound level difference is an example of a noise isolation rating of the building. In fact, the noise isolation depends upon the noise source characteristics, the site conditions (such as building orientation relative to the noise source), the building envelope construction, and the sound absorptive characteristics of the room in which the indoor sound level is received or measured.

The building envelope construction does not uniquely define the A-weighted noise isolation provided by the building envelope. However, the construction details do play the most significant part in determining the A-weighted noise isolation performance of the envelope.

Obviously, to characterize uniquely the noise attenuation of a building envelope, one needs a description that is independent of all factors other than the construction details. Such a description is called a noise insulation rating. For these guidelines, the A-weighted sound transmission loss or A-weighted TL is utilized as a noise insulation rating as described below.

This terminology may appear, at first, to be just a play on words. However, it is very important to understand the difference between a noise isolation rating and a noise insulation rating. A noise isolation rating (such as the A-weighted sound level difference) incorporates all factors particular to the noise-source receiver relationship that effect a change in the acoustic environment at the receiver. A noise insulation rating incorporates only the details of the building envelope construction and is independent of all other factors. Knowing the noise source characteristics,

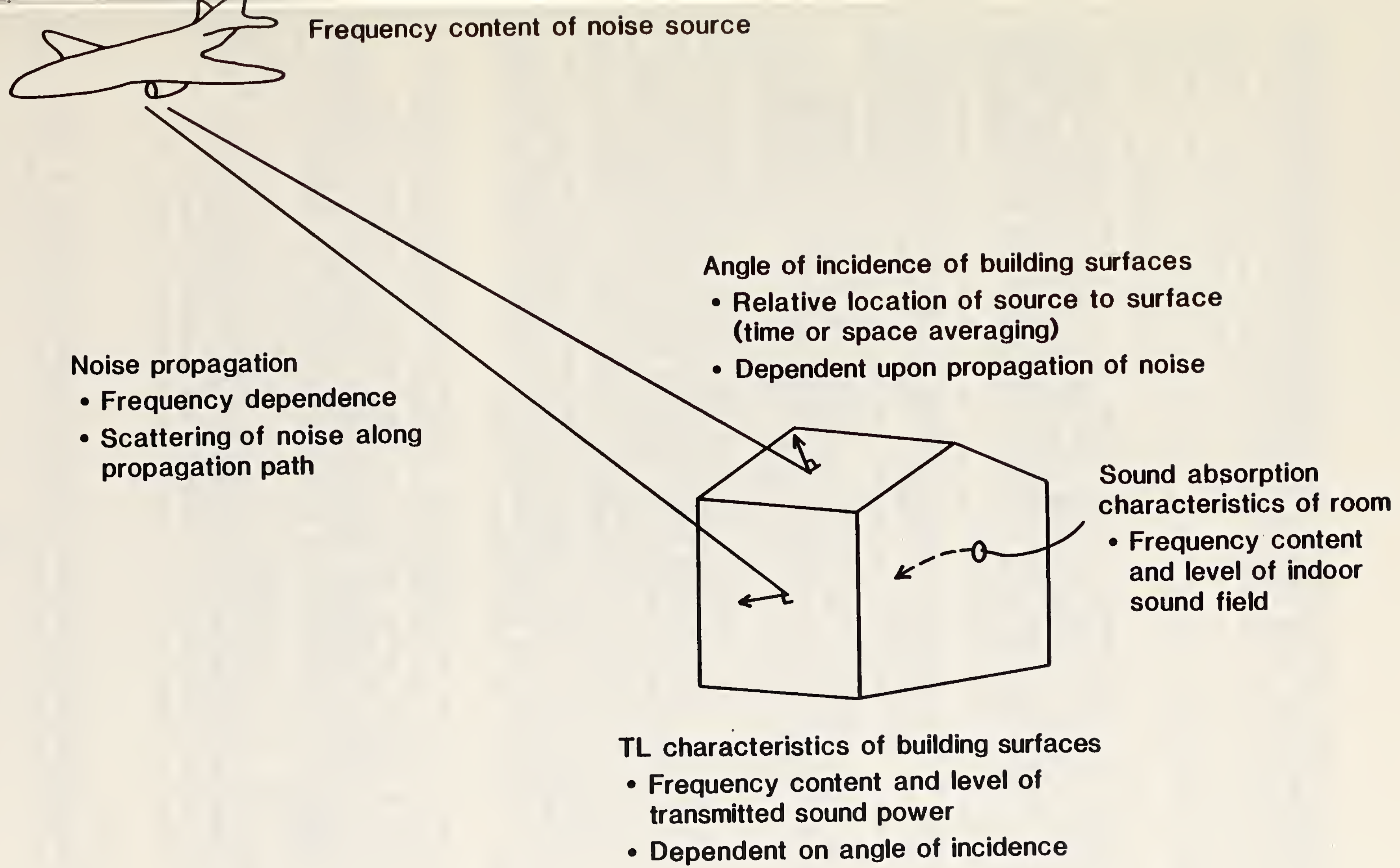


Figure 18. Factors Affecting the A-weighted Noise Level Reduction of the Building Envelope

the building site conditions, and the acoustic characteristics of the receiving room, the building envelope noise isolation may be estimated from the noise insulation characteristics of the envelope construction.

A-Weighted Sound Transmission Loss

The noise insulation of building construction* is determined using standardized laboratory measurements (Refs. 38 and 39). The laboratory measurements are conducted to ensure that the noise insulation data are independent of the acoustic conditions on each side of the construction. The resulting data are called sound transmission loss data and are determined for a wide range of test frequencies. These data may then be used to estimate the noise isolation performance of the building construction.

The procedure for relating the noise isolation in the built environment to the laboratory noise insulation performance of building construction is a complicated process. The complications arise from the complexity in describing the outdoor noise environment which strictly, should include the frequency-dependence of the noise sources, the noise propagation, and the scattering of the sound field at the exterior surfaces of the building. Such a procedure is totally unsuited for the purposes of these guidelines as it is too cumbersome.

In order to simplify the procedure for relating the noise insulation of building construction to the noise isolation performance of the building envelope, the first step is to develop an appropriate single number rating that accounts for the frequency dependence. Several rating schemes have been developed in the past just for this purpose (Refs. 40,41 and 42). Each of these ratings combine the frequency dependence of the outdoor noise source with the frequency dependence of the sound transmission loss characterisitcs of the construction to establish the single number rating. In each case, the objective of the rating is to estimate the indoor A-weighted sound level using the outdoor A-weighted sound level and the single number rating.

In developing these rating schemes, the frequency dependence or spectrum shape of the outdoor noise must be taken into account. This has been accomplished by utilizing outdoor noise spectra representative of transportation noise sources. The result is then an average rating representing an expected performance for each type of building construction. The effect of the outdoor noise spectrum shape in establishing the single number rating is embedded in the averaging process.

Based upon the above considerations, these guidelines also utilize a single number rating scheme for estimating the A-weighted sound level difference achieved by the building construction. However, the approach taken is to establish the rating by considering the outdoor noise spectrum shape and the

---

* The construction may be either a single component (such as a light frame wall) or a composite construction (such as a wall with windows and doors).

sound transmission loss characteristics of the construction to be independent. Details of the procedure are presented in Appendix C. The method characterizes the outdoor noise spectra using representative data for aircraft, railway, and highway traffic noise just as the previous methods (Refs. 40,41 and 42). The highway traffic noise spectra are based upon the vehicle noise emission characteristics of the FHWA STAMINA model (Ref. 8), and the aircraft and railway spectrum shape is taken as the average developed by the National Research Council of Canada (Ref. 42).

Accordingly, the rating scheme used in these guidelines comprises two numbers: one for highway traffic noise and another for aircraft and railway noise. Strictly speaking, these ratings are noise isolation ratings since they combine an average outdoor noise spectrum shape with the sound transmission loss characteristics of the construction. However, since the rating attempts to preserve the independence of the outdoor noise spectrum shape and the sound transmission loss characteristics of the construction, the ratings in these guidelines are called the A-weighted sound transmission loss values of the construction.

Tables 20 through 26 provide a listing of A-weighted sound transmission loss values of typical building construction. Each table corresponds to a specific component of the building envelope such as exterior walls, windows, doors, and roofs. For windows, single-glazed, double-glazed, and triple-glazed data are provided. In each table a description of the construction and two values for the A-weighted sound transmission loss is given. The value corresponding to the "composite transportation noise" applies to aircraft and railway noise and is based upon the reference spectrum shape developed by the National Research Council of Canada (Ref. 42). The value corresponding to the "traffic noise" is based upon the FHWA spectrum as described in the Appendix C.

The data contained in Table 20 through 26 are noise insulation data. The necessary steps to estimate the noise isolation of a building envelope are described below. The data in Tables 20 through 26 are used for this purpose.

Sound Transmission Loss of Building Construction

Before describing the method for estimating the building envelope noise isolation, it is worthwhile explaining the physical aspects of the problem. Since the discussion will touch on several different topics before they are all related, it must be remembered that the objective is to relate the sound transmission loss characteristics (noise insulation value) of the construction to the building envelope noise isolation characteristics. With this objective in mind, the first aspect to be considered is the definition of sound transmission loss.

Table 20. Average A-weighted Sound Transmission Loss of Exterior Walls*

Description	A-Weighted Transmission Loss	
	Composite transportation noise	Traffic noise
Metal and curtain walls with insulation between 2 sheets of galvanized steel; area weight less than 6 lbs/ft^2.	28	25
4 - 7 in masonry wall: either 4x8x16 concrete blocks or mortared bricks without finish.	36	35
4 - 7 in masonry wall: 4x8x13 3-cell concrete block; resilient channels 24 in o.c.; 1/2 in plaster board.	40	39
7/8 in stuccoed wall: No. 15 felt building paper and 1 in wire mesh; 2x4 wood studs 16 in o.c. with fiberglas building insulation; 1/2 in gypsum board screwed to channel.	43	40
8 in dense concrete wall: 3-cell concrete block; perimeter sealed.	41	40
8 in masonry wall: either bricks mortared together or 3-cell concrete blocks with block filler; 1/2 in plaster; finished with latex paint.	45	43
8 in masonry wall: 18x16x8 3-cell concrete blocks; resilient channels 24 in o.c.; 1/2 in gypsum board screwed to channels; painted both sides.	46	47
8 in double brick wall: 4-1/2 in each separated by 2 to 4 in cavity; wire ties; 1/2 in plaster on exposed sides.	48	47
Light frame wood wall with 2x4 wood studs 16 in o.c.; 2 to 3 in insulation; 1/2 in gypsum board.	31	29

* The data shown here were compiled from many sources and represent the average performance for the type of construction described.

Table 21. Average A-weighted Sound Transmission Loss of Exterior Walls with Windows*

Description	A-Weighted Transmission Loss	
	Composite transportation noise	Traffic noise
Light frame wall with wood siding: 2x4 wood studs with insulation; resilient channels 24 in o.c.; 1/2 in gypsum board; penetrated by 25 to 30-percent single-glazed sealed glass.	27	26
Light frame wall with wood siding: 2x4 wood studs with insulation; resilient channels 24 in o.c.; 1/2 in gypsum board; penetrated by 25 to 30-percent single-glazed sealed glass with storm sash.	30	28
Light frame wall with brick veneer or wood siding: 2x4 wood studs 16 in o.c. with fiberglas insulation; penetrated by 10 to 15-percent single-strength glazed sealed glass.	30	29
Light frame wall with wood siding or brick veneer: 2x4 studs with insulation; resilient channels 24 in o.c.; 1/2 in gypsum board; penetrated by 25 to 30-percent single-glazed sealed glass with storm sash.	31	29

* The data shown here were compiled from many sources and represent the average performance for the type of construction described.

Table 22. Average A-weighted Sound Transmission Loss of Single-Glazed Windows*

Description	A-Weighted Transmission Loss	
	Composite transportation noise	Traffic noise
3/32 to 7/16 in thick glass pane:		
o unsealed	18	17
o sealed	23	22
Single-strength pane with storm sash:		
o unsealed	24	22
o sealed	28	26

---

* The data shown here were compiled from many sources and represent the average performance for the type of construction described.

Table 23. Average A-weighted Sound Transmission Loss of Double-Glazed Windows*

Description	A-Weighted Transmission Loss	
	Composite transportation noise	Traffic noise
Parallel panes of same thickness (range: 3/32 to 1/8 in) mounted in 1 sash and sealed. Interpane spacing:		
° < 1/2 in	25	24
° > 1/2 in	26	25
Panes of different thickness (1/8 and 1/4 in) mounted in 1 sash and sealed:		
° in parallel with spacing of 1/2 to 3/4 in	28	27
° not in parallel with maximum spacing 3/4 in and minimum spacing 1/4 in	28	27
Parallel panes of same thickness (range: 5/32 to 1/4 in) mounted in 2 sash in parallel and sealed. Interpane spacing:		
° 2 1/2 - 4 in	35	31
° 3 - 6 in	36	32
° > 6 in	38	33
Panes of different thickness (1/8 and 1/4 in) mounted in parallel in 2 sash and sealed. Interpane spacing:		
° 1 to 1-1/2 in	30	29
° 1-1/2 to 2 in	33	30
° 2-1/2 to 6 in	37	33

* The data shown here were compiled from many sources and represent the average performance for the construction described.

Table 23. Average A-weighted Sound Transmission Loss of double-Glazed Windows* (Continued)

Description		A-Weighted Transmission Loss	
		Composite transportation noise	Traffic noise
Panes of different thickness (1/8 and 1/4 in) mounted in 2 sash not in parallel and sealed. Interpane spacing:			
Maximum, in	Minimum, in		
3	1	33	31
3	2	34	31
3	2	36	31
Panes of same thickness (1/8 or 1/32 in) mounted in 2 non parallel sash and sealed. Interpane spacing:			
Maximum, in	Minimum, in		
3	1	34	30
6	2	36	31

Table 24. Average A-weighted Sound Transmission Loss of Triple-Glazed Windows*

Description	A-Weighted Transmission Loss	
	Composite transportation noise	Traffic noise
1/8 in thick panes mounted in 1 wood sash with interpane spacings ranging from 1/8 to 13/32 in. Sealed.	25	24
2 panes 1/8 in thick mounted in 1 wood sash with an interpane spacing of 1/4 in and metal spacer. Third pane 1/8 in in separate wood pane 3/4 to 2 in apart. Sealed.	30	28
2 panes 1/8 in thick mounted in 1 sash with an interpane spacing of 1/4 in and metal spacer. Third pane either 1/8 or 1/4 in thick mounted in separate wood sash 3/4 - 2 in apart. Sealed.	32	30
2 panes 1/8 in thick mounted in 1 wood sash with interpane spacing of 1/4 in and metal spacer. Third pane 1/4 in separate wood sash 1 - 2 in apart. Sealed.	34	32
1/8 in panes mounted in 2 wood sash. First interpane spacing 1/4 in, second 4 in. Metal spacer. Sealed	37	33

---

* The data shown here were compiled from several sources and represent the average performance for the construction described.

Table 25. Average A-weighted Sound Transmission Loss of Doors*

Description	A-Weighted Transmission Loss	
	Composite transportation noise	Traffic noise
Hollow core wood door with weather stripping.	15	14
Solid core wood door with weather stripping.	21	20
Solid core wood door, weather stripped, and fully sealed.	25	24
Glass containing doors (French and sliding) weather stripped.	23	23
Metal door weather stripped.	23	23
Solid core wood door, weather stripped and with aluminum storm door fitted with single glazed window. Both sealed.	31	30
Acoustical doors.	43	42

---

* The data shown here were compiled from several sources and represent the average performance for the construction described.

Table 26. Average A-weighted Sound Transmission Loss of Domestic Roofs*

Description	A-Weighted Transmission Loss	
	Composite transportation noise	Traffic noise
Domestic roof: pitched wood frame sealed perimeter but without insulation or ceiling.	9	9
Domestic roofing: pitched wood frame insulation between roof joints; sealed perimeter but without ceiling.	23	20
Domestic roofing: pitched wood frame perimeter sealed; plaster ceiling but without insulation.	24	23
Domestic roofing: pitched wood frame insulation between roof joints; sealed perimeter; plaster ceiling.	34	31
Flat Domestic Roof: steel deck; plaster ceiling but without insulation.	25	23
Flat domestic roof: steel deck; plaster ceiling and 2 - 3 in insulation.	32	30

---

* The data shown here were averaged from several mostly foreign sources as data for construction typical of U.S. practice are scarce.

Sound transmission loss values are measured in decibels or dB units. The decibel or dB unit is the term used to identify 10 times the common logarithm of the ratio of two like quantities proportional to power or energy (Ref. 43).* The important part of the definition of the dB unit is that the quantities are proportional to power or energy. The sound transmission loss is defined in dB units using the ratio of the sound power on the noise source side of the construction to the power transmitted through the construction to the receiver side.

Sound power, like all forms of power, cannot be directly measured. However, sound power can be mathematically related to sound pressure and sound pressure can be directly measured using a microphone. The mathematical relationship between sound pressure and sound power depends upon both the noise source and the propagation characteristics of the sound field. These relationships are different for outdoor noise incident upon the building envelope and for sound fields within rooms. For either situation, however, a sound power to sound pressure relationship may be formulated, and the sound pressure (as measured by a microphone) can be expressed as a sound pressure level in dB units.

Since both the sound transmission loss and the sound pressure level are defined in terms of sound power, they are both measured in dB units and may be related mathematically. In this manner, the sound pressure level on the noise source side, the sound pressure level on the receiver side of the construction, and the sound transmission loss are related. Under laboratory conditions, a test specimen of building construction is built into a common wall between two special chambers or rooms. This type of facility is of special construction such that noise in the source chamber can only transmit through the specimen to the receiving chamber. Since both the source chamber and the receiving chamber are designed to possess well-defined acoustic characteristics, the mathematical relationship between sound power and sound pressure is also well-defined for these conditions. In this manner, laboratory measurement of the sound transmission loss based upon sound pressure level data is conducted using standard test methods (Refs. 38 and 39).

For the same building construction used as part of the building envelope, the noise exposure conditions for the construction are more complex than the laboratory conditions. However, using the same approach of mathematically relating sound power and sound pressure on either side of the construction, the sound pressure levels on either side of the construction and the sound transmission loss are also related. Since the noise exposure conditions are more complex for field conditions, other physical aspects of the problem must be incorporated into the sound power-sound pressure relationship (Ref. 20). Unfortunately, it is very difficult to mathematically incorporate all of these physical aspects, the result being a higher degree of uncertainty of the

---

* A logarithm is a mathematical operation on a number and it is not necessary to know how to use logarithms in order to use these guidelines.

sound power-sound pressure relationship as compared to the laboratory conditions. This uncertainty affects both the prediction and the measurement of sound transmission loss in the built environment.

It is now appropriate to discuss the other main physical aspects of relating noise insulation characteristics of the construction to the noise isolation characteristics of the building envelope.

Composite Envelope Construction

The building envelope is usually of mixed or composite construction such as masonry or frame walls containing windows and doors. Each component of the composite construction (masonry wall, frame wall, window, or door) exhibits different sound transmission loss characteristics. The question that now arises is how to estimate the sound transmission loss of the composite construction knowing the sound transmission loss characteristics of the components. To do this we also need to know the percentage distribution of the surface areas of each component. Rather than introducing the mathematics at this point, an example will be used to illustrate this physical aspect of the problem.*

Consider a wall with a total area of 100 ft^2 composed of 90 ft^2 of masonry wall and 10 ft^2 of glass windowpane. This construction is 90-percent masonry wall and 10-percent glass window. Now consider a wall built of the same materials but using 50 ft^2 of masonry wall and 50 ft^2 of glass windowpane. Since the masonry wall has a higher value of sound transmission loss than the glass window pane (see Tables 20 through 26), the construction with 90-percent masonry wall would be expected to exhibit a higher sound transmission loss than the construction composed of 50-percent masonry wall. The method of estimating the composite sound transmission loss will now be explained using the definition of sound transmission loss.

Since the sound transmission loss is defined in terms of the ratio of the outside or incident sound power to the transmitted sound power, we must determine this ratio. Further, since the composite wall has components of different areas, it is necessary to estimate the average outside sound power per unit area over the total wall area. (For the above example, this average value is $W_o/100$ where W_o is the total sound power on the outside.)≠ For the composite wall with 10-percent glass, the outside sound power for the masonry construction is $90W_o/100$ and for the glass is $10W_o/100$. For the composite wall with 50 percent glass, the outside sound power for the masonry construction is $50W_o/100$ and for the glass it is also $50W_o/100$.

---

* The mathematics are included in appendix C.

≠ Sound power per unit area has the dimensions of acoustic intensity, watts/m^2 and since intensity also incorporates the direction of sound propagation this approach is essential for defining outdoor-to-indoor sound transmission loss (Ref. 20).

For the masonry wall construction, suppose that the transmitted sound power per unit incident sound power is W_{TM} and for the glass is W_{TG} where the subscript T denotes transmitted sound power. (The numbers W_{TM} and W_{TG} are determined from the sound transmission loss of the masonry construction and the glass, respectively.) For the wall with 10-percent glass, the total transmitted sound power, denoted by $(W_{10})_T$, is the sum of the transmitted sound power values for the two components and is:

$$(W_{10})_T = (90W_o/100)W_{TM} + (10W_o/100)W_{TG}$$

and for the wall with 50-percent glass is given by:

$$(W_{50})_T = (50W_o/100)W_{TM} + (50W_o/100)W_{TG}.$$

The composite sound transmission loss is then determined by dividing each of the above values by the total outside sound power, W_o, and doing some arithmetic using logarithms. What is important, however, is the ratio $(W_{10})_T/W_o$ and $(W_{50})_T/W_o$.

For example we have:

$$(W_{10})_T/W_o = (90/100)W_{TM} + (10/100)W_{TG}$$

$$(W_{50})_T/W_o = (50/100)W_{TM} + (50/100)W_{TG}.$$

Since W_{TM} is a number less than W_{TG} (the masonry transmits less sound power than the glass), then we see that $(W_{10})_T$ is a number less than $(W_{50})_T$. That is, the wall with 10-percent glass transmits less sound power than the wall with 50-percent glass. This completes the example. The user should appreciate that the above procedure can be extended to any number of components of the composite wall.

So far, we have defined sound transmission loss and have indicated how this definition may be applied to estimating the sound transmission loss of a composite construction. We now consider how the details of the outdoor sound field may also be incorporated into the definition of sound transmission loss.

Outdoor Sound Field

The characterization of the outdoor sound field is an extremely difficult task. The many details that should be considered are the noise source characteristics, the noise propagation to the building envelope, source-receiver geometry, and time-varying sound levels. Due to the difficulty of incorporating all of these interrelated details, simplified models are used to develop design-oriented results (Ref. 20). These results indicate that the many variables may be incorporated (in an elementary fashion) as a single adjustment term for the incident outdoor sound power. This sort of adjustment may be called an "angle of incidence" adjustment. Although this terminology implies that source-receiver geometry is the main consideration, the adjustment also includes noise source characteristics, noise propagation, and time-varying characteristics. For a flat surface exposed to noise representative of highway, railway, and aircraft sources, an "angle of incidence" adjustment of -2 to -3.5 dB to the sound transmission loss appears appropriate for a wide range of angles (Ref. 20). (The angle of the incidence is measured normal to the plane of the building surface.)

For building surfaces that contain balconies or other projections, other adjustments must be applied. These adjustments are described later in these guidelines, and are based upon laboratory acoustic scale model measurements since the problem is too difficult to analyze mathematically.

We now turn to the consideration of the indoor sound field within the room and relate this physical aspect to the estimation of the noise isolation of the building envelope.

Indoor Sound Field

The outdoor sound power and the sound transmission loss of the exterior wall allow one to estimate only the average sound power transmitted at the inside surface of the wall. It now is required to determine how this transmitted sound power or acoustic energy is converted into the sound pressure field within the room. This is the topic of "room acoustics" where we are concerned with estimating an average indoor sound level that characterizes any point within the room volume.

First, the transmitted sound power or energy is partly dissipated and partly converted into acoustic pressure within the room volume. The energy dissipation results from the sound waves striking either the room boundaries and, if the room is furnished, the room contents. Carpets, sofas, draperies, people, and even sheetrock walls and ceilings all absorb a percentage of the sound (energy) striking their surfaces. As the sound waves propagate about the room (striking surfaces with part of the energy absorbed and part of the energy reflected), an indoor sound field is created. The occupant's ear is located in this sound field, and, if a microphone is placed within the sound field, a sound pressure level is measured. This sound pressure level is proportional only to the energy of the indoor sound field.

The total energy entering the room via the exterior wall equals the energy absorbed by the room contents and the energy of the sound field within the room. Since we are interested only with the indoor sound level, we must know the sound transmission loss characteristics of the exterior wall to determine the total energy entering the room and the total sound energy absorbed by the room contents. Then, the energy of the sound field is just the difference between the total energy and the absorbed energy.

In summary, the indoor sound field, as characterized by the indoor sound level, depends upon both the sound transmission loss of the exterior walls and the sound absorption characteristics of the room contents.

Sound Absorption of the Room

The total sound absorption of the room incorporates the effect of all the interior surface finishes and the room contents. For materials that are purchased or installed on the basis of area (such as sheetrock, carpet, or acoustical tiles), the sound absorption characteristics of the material are usually provided in terms of the sound absorption coefficient. In general, the sound absorption coefficient represents the fraction of the sound power absorbed by the material and is determined by laboratory measurement (Ref. 44). The sound absorption coefficient for any material varies with frequency, the manner in which the material is attached to the wall, ceiling, or floor, and also with the disposition of the material within the room. The total sound absorption provided by the material is the product of the absorption coefficient and the total area of the material. It also varies with frequency. The unit of total sound absorption is called the "sabin" (after a famous acoustical engineer) and the physical dimension for total sound absorption is area (ft^2 or m^2).

A physical object, such as a sofa, also absorbs sound. However, it is impossible to assign a definite surface area to the object. In this case, the total sound absorption may also be measured in the laboratory and is used to define the sound absorbing characteristics of the object. The total absorption of the object is measured in physical units of area and varies with frequency. Representative values for the total sound absorption of typical room contents are available (Ref. 44).

Since we are interested in knowing the sound absorption in terms of A-weighted frequency characteristics, the frequency dependence of the total sound absorption of the room must be considered. Fortunately, however, we can avoid complicated calculations. The above discussion on sound absorption was simply a method for establishing the basis for this approximation. The key to the physical understanding of this approximation is that the total sound absorption is expressed in units of area (ft^2 or m^2).

After many measurements and calculations for several different combinations of room surface finishes and typical room contents, acoustical engineers realized that the total sound absorption of a room is often proportional to the floor area of the room and essentially frequency independent (Refs. 40,41 and 42). The average value of this constant of proportionality appears to be 80-percent of the floor area of the room (Ref. 42).

Putting It All Together

Now, we can put all of the physics together to relate the building envelope noise isolation to site conditions, the noise insulation properties of the envelope construction, and the indoor conditions. The steps are as follows:

(1) Calculate the composite noise insulation of the building construction using the noise insulation properties and the surface areas of the components. The noise insulation properties may be estimated using the data contained in Tables 20 through 26 or as described in appendix C.

(2) Adjust the composite noise insulation for the total sound absorption of the room adjacent to the exterior walls and/or roof.

(3) Adjust the composite noise insulation for angle of incidence of the outside sound field.

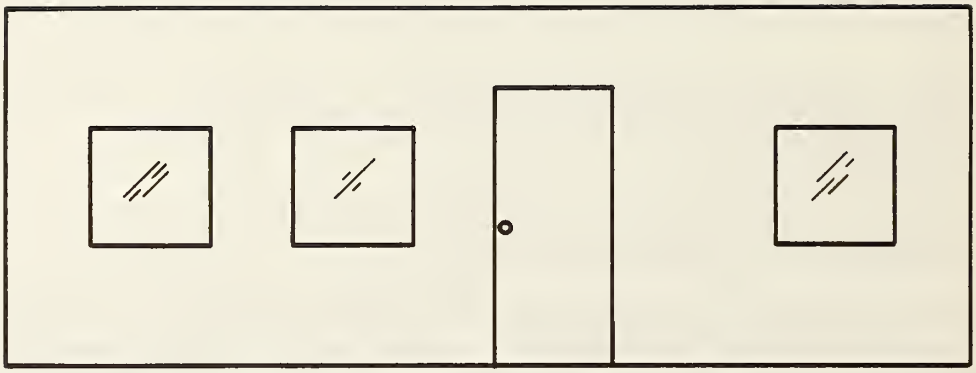
Actually, it is convenient to combine steps (1) and (2) above so that the required information is then a description of the building construction and the ratio of the area of each envelope component to the floor area of the room. (This is a result of approximating the total room absorption as a constant times the floor area.) The adjustment for angle of incidence may be obtained using the detailed procedure of Ref. 20 or simply as a constant ranging from -2.0 to -3.5 dB as judged best for the site conditions.

The main consideration is the estimate of the composite noise insulation of the building components. An example will illustrate the step-by-step calculation method.

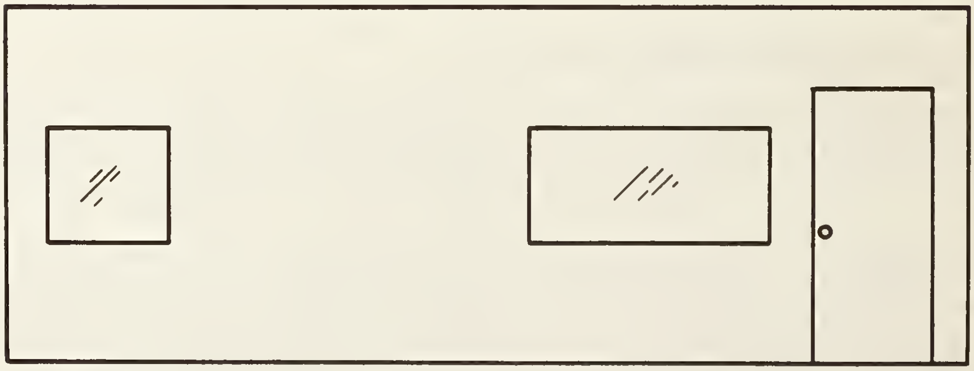
Estimation of the Envelope Noise Isolation

We now present the method for estimating the A-weighted noise isolation of the building envelope. First, a room or rooms with exterior walls are selected for analysis. Usually, a bedroom will be selected for residential construction, since sleep is a very noise-sensitive activity. Next, the outside walls of the room are designated, for the purpose of these guidelines, as "envelope members." An "envelope member" is characterized by two attributes: 1) it separates a room from the outside, and 2) the outdoor noise level is essentially uniform over the surface area of the member. For residential construction, the dimensions of the exterior walls of a room relative to the distance between the wall area and the source location are such that the second attribute is satisfied. Each envelope member, however, may be exposed to a different level of outdoor noise. As described below, the consideration of different levels of exterior noise on the envelope members is only a refinement needed for corner rooms exposed to highway traffic noise. Depending upon the room location within the building, it may be necessary to consider from one to five envelope members in order to estimate the noise isolation.

Each envelope member may comprise several individual components such as the basic wall construction, the windows, and doors. Each component is characterized by its A-weighted sound transmission loss value and its total surface area. Figure 19 illustrates two envelope members that are "acoustically



a) Envelope members: 3 windows with area S_1 each and TL_1, one door with area S_2 and TL_2, wall with area S_3 and TL_3



b) Envelope members: 2 windows of area $2S_1$ and S_1 and TL_1 each, one door with area S_2 and TL_2, wall with area S_3 and TL_3

Figure 19. Acoustically Identical Envelope Members (S denotes surface area and TL denotes sound transmission loss)

equivalent" since the component sound transmission loss values are identical and the total surface areas of the components are identical. The room sound absorption is characterized by the floor area of the room.

To estimate the composite noise isolation of the envelope member comprising two or more components, the following information is necessary:

- The A-weighted sound transmission loss of each component (see Tables 20 through 26 or appendix C).
- The total surface area of each component.
- The total floor area of the room.

The calculation is conducted utilizing a worksheet format similar to that described for the noise prediction models. A few examples will illustrate the use of the worksheets.

EXAMPLE 6. An exterior wall comprising the basic wall structure and some windows has the following characteristics:

Wall: area = 90 ft^2 TL = 34 dB*

Windows: area = 30 ft^2 TL = 22 dB*

The room dimensions are as follows: height, 8 ft; width, 15 ft; length 20 ft.

First, the values for the sound transmission loss must be adjusted for the component areas relative to the floor area of the room. Figure 20 illustrates a completed copy of Worksheet V indicating the necessary calculations. A blank copy of this worksheet is provided in Section 3.3 along with necessary lookup table. As indicated in Figure 20, one simply inserts the appropriate data and follows the step-by-step directions. The result is an adjusted value of the sound transmission loss for each component of the envelope member.

The user should note that the TL values must correspond to the noise source type as indicated in the worksheet and that the worksheet allows up to five components to be used in the next step of the calculation.

Figure 21 illustrates the next step utilizing worksheet VI. The adjusted TL values from Figure 20 are entered at the heading of Figure 21 as indicated. The step-by-step instructions are followed to obtain the composite TL of the envelope member. A blank copy of Worksheet VI is provided in Section 3.3. together with the necessary lookup table.

---

* These are A-weighted values. See Tables 20 through 26 for values representative of typical construction.

WORKSHEET V CALCULATION OF ADJUSTED TL VALUES FOR ENVELOPE MEMBER ELEMENT

Envelope member description: EXAMPLE 6. Window-Wall Combination

Noise source: Highway Traffic Room dimensions: Height 8 ; Width 15 ft; Length 20 ft

Total member area: 120 ft^3 Room floor area, $S_{f\ell}$: 300 ft^2

Envelop member element description	Element area, S_i ft^2	$S_i/S_{f\ell}$	Element TL*		Adjustment, Δ_s from Table 29		Adjusted Element TL TL+Δ_s
1. Wall	90	0.30	34	+	5.0	=	39
2. Window	30	0.10	22	+	10.0	=	32
3.				+		=	
4.				+		=	
5.				+		=	

* See Tables 20 through 26 for representative values.

Figure 20. Completed Worksheet for Calculating Adjusted TL Values of Elements: Example 6

WORKSHEET VI. CALCULATION OF COMPOSITE TL OF ENVELOPE MEMBER

Noise source: Highway traffic

Element Description Wall ____ Window ____ ____ ____ ____

____ ____ ____ ____ ____

Adjusted TL Value TL_1 = 39 : TL_2 = 32 : TL_3 = ____ : TL_4 = ____ : TL_5 = ____ :

TL difference: $TL_1 - TL_2 =$ 39-32 = +7

Adjustment Δ_c (from Table 30) = -7.8

Combined TL: $TL_{c2} = TL_1 + \Delta_c =$ 39-7.8=31.2

TL difference: $TL_{c2} - TL_3 =$ ____

Adjustment Δ_c (from Table 30) = ____

Combined TL: $TL_{c3} = TL_{c2} + \Delta_c =$ ____

TL difference: $TL_{c3} - TL_4 =$ ____

Adjustment Δ_c (from Table 30) = ____

Combined TL: $TL_{c4} = TL_{c3} + \Delta_c =$ ____

TL difference: $TL_{c4} - TL_5 =$ ____

Adjustment Δ_c (from Table 30) = ____

Combined TL: $TL_{c5} = TL_{c4} + \Delta_c =$ ____

Figure 21. Completed Worksheet for Calculating Composite TL of Envelope Member: Example 6.

As indicated in Figure 21, the composite TL of the example envelope member is 31 dBA.

Another example will illustrate a slightly more complicated problem.

EXAMPLE 7. We now estimate the effect of an open window upon the composite TL value. To do this, we use the same data as in the previous example. However, in this case the "window" is considered as two components: a "closed area" and an "open area." Assume that the windows are double hung so that, when they are open, 50% of the total glazed area is covered and 50% is open. We further assume that the covered portion of the window exhibits the TL value of the closed window and that the open portion transmits all of the energy incident upon its area directly into the room.* That is, the A-weighted sound transmission loss of the open portion is assumed to be 0 dB.

Figures 22 and 23 are the completed worksheets for this example. In Figure 23, it is seen that the composite A-weighted sound transmission loss for the windows fully open is 13 dBA as compared with 31 dBA for the windows closed. Admittedly, this is a dramatic example. However, the purpose is to emphasize the importance of keeping the envelope sealed to preserve the noise isolation performance.

Worksheets V and VI allow one to estimate the composite sound transmission loss of an envelope member comprising up to five components. It now remains to combine the sound transmission loss values of each envelope member to estimate the noise isolation of the room. To do this, we must now consider the outdoor sound levels over each envelope member, and possibly an angle of incidence correction.

Figure 24 and 25 illustrates building locations relative to the types of noise sources considered in these guidelines. For highway and railway noise sources, it is assumed that the building is generally rectangular in plan shape and that the envelope surfaces are either parallel (front and rear surfaces) or perpendicular (side surfaces) to the highway alignment. As indicated in Figure 24, adjustments to the outdoor DNL are listed for each of the building surfaces. The outdoor DNL adjustments are expressed in terms of dB relative to the outdoor DNL <u>for the clear site at the location of the envelope member</u>. (A corner room will have a member on the front envelope surface and a member on the side envelope surface.) The angle of incidence adjustments are listed in Figure 25 and are based upon the results of Ref. 20.

Unless the dimension of the side surface is equal to or greater than the setback distance, D, as indicated in Figure 25a, it is not necessary to estimate the outdoor DNL at each surface. A single estimate for the geometric center of

---

* We assume the covered portion of the window to exhibit the same TL value as the closed window since the "double pane" configuration will result in gaps and cracks around its perimeter. Whatever value of TL one desires to assume does not alter the final answer since the open area is so large.

WORKSHEET V. CALCULATION OF ADJUSTED TL VALUES FOR ENVELOPE MEMBER ELEMENT

Envelope member description: EXAMPLE 6. Wall-Open Window Combination

Noise source: Highway Traffic Room dimensions: Height 8 ; Width 15 ft; Length 20 ft

Total member area: 120 ft^3 Room floor area, $S_{f\ell}$: 300 ft^2

Envelop member element description	Element area, S_i ft^2	$S_i/S_{f\ell}$	Element TL*		Adjustment, Δ_s from Table 29		Adjusted Element TL $TL+\Delta_s$
1. Wall	90	0.30	34	+	5.0	=	39
2. Window (Covered)	15	0.05	22	+	13.0	=	35
3. Window (Open)	15	0.05	0	+	13.0	=	13
4.				+		=	
5.				+		=	

* See Tables 20 through 26 for representative values.

Figure 22. Completed Worksheet for Calculating Adjusted TL Values of Elements: Example 7

WORKSHEET VI. CALCULATION OF COMPOSITE TL OF ENVELOPE MEMBER

Noise source: Highway traffic

Element Description	Wall	Window	Window		
		Closed Portion	Open Portion		
Adjusted TL Value	TL_1 = 39 :	TL_2 = 35 :	TL_3 = 13 :	TL_4 = ____ :	TL_5 = ____ :

TL difference: $TL_1 - TL_2$ = 39-35 = +4

Adjustment Δ_c (from Table 30) = -5.5

Combined TL: $TL_{c2} = TL_1 + \Delta_c$ = 39-5.5=33.5

TL difference: $TL_{c2} - TL_3$ = 33.5-13=20.5

Adjustment Δ_c (from Table 30) = -20.5

Combined TL: $TL_{c3} = TL_{c2} + \Delta_c$ = 33.5-20.5=13

TL difference: $TL_{c3} - TL_4$ = ____

Adjustment Δ_c (from Table 30) = ____

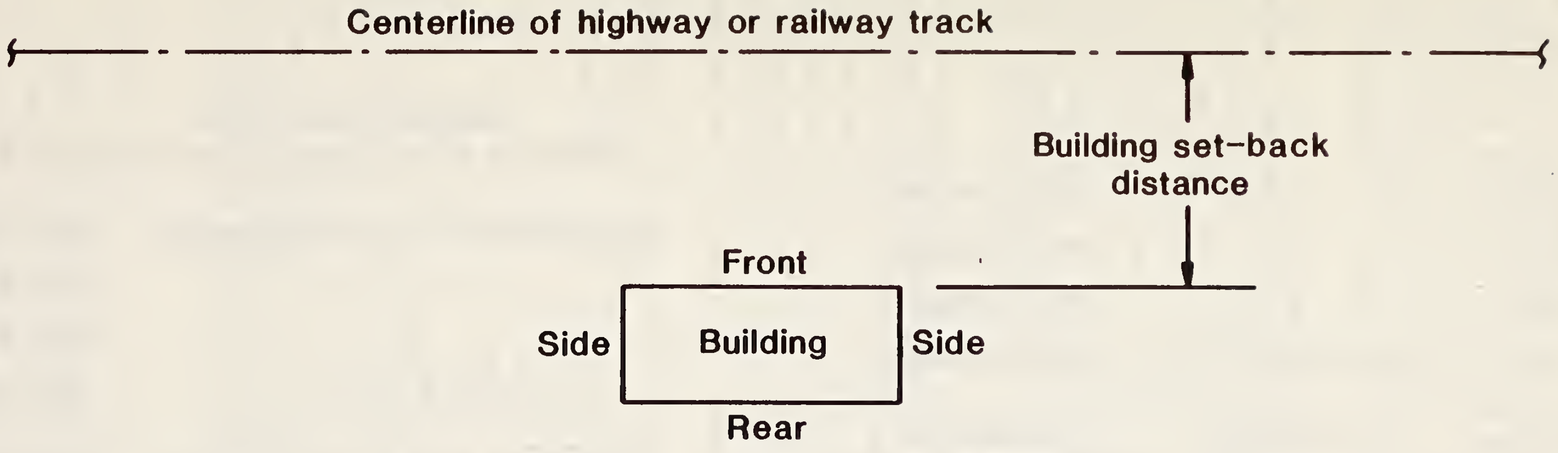
Combined TL: $TL_{c4} = TL_{c3} + \Delta_c$ = ____

TL difference: $TL_{c4} - TL_5$ = ____

Adjustment Δ_c (from Table 30) = ____

Combined TL: $TL_{c5} = TL_{c4} + \Delta_c$ = ____

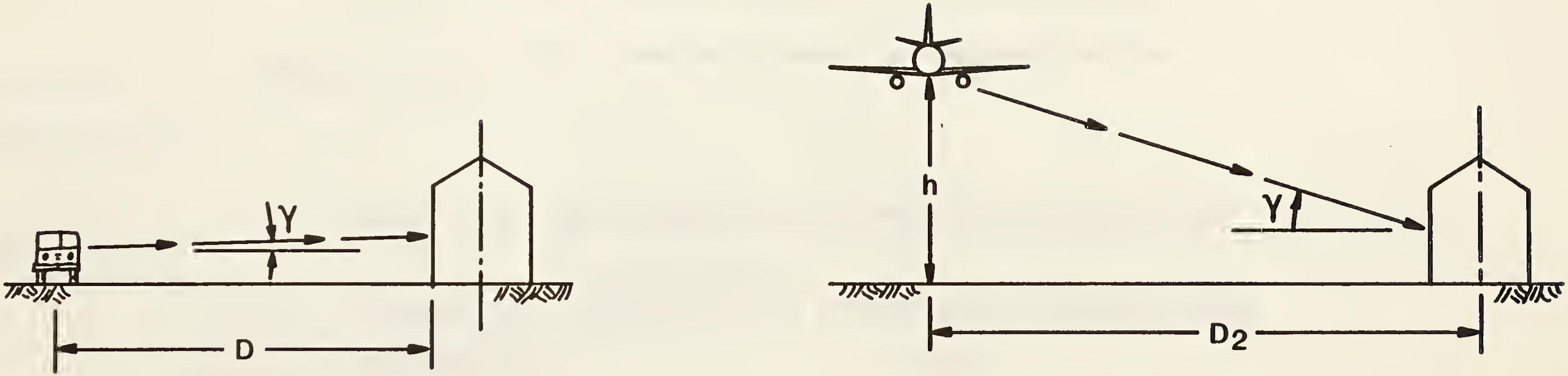
Figure 23. Completed Worksheet for Calculating Composite TL of Envelope Member: Example 7.



Envelope Member Location	DNL Adjustment for Worksheet VII dB (re. clear site condition)
Building front	0 dB
Building side	−3 dB
Building rear	−15 dB
Building roof – Generally not a consideration for highway and railway noise	

Note: Use 0 dB adjustment for all surfaces for aircraft noise

Figure 24. Noise Source Exposure Adjustment for Building Envelope



a) Highway and railway noise sources

b) Aircraft noise sources (see Fig. 10)

Envelope Member Location (see Fig. 24)	Angle of Incidence Adjustment for Worksheet VII dB (re. clear site condition)
Building front	10 log (cos γ) −2
Building side	−2
Building rear	0
Building roof	Generally not a consideration

10 log (cos γ) ≈ 0 for D ≥ 50 ft and buildings of fewer than 4 stories

Envelope Member Location	Angle of Incidence Adjustment for Worksheet VII dB (re. clear site condition)	
	$h/D_2 < 0.6$	$h/D_2 > 0.6$
Building front	10 log(cos γ)−2	−3.5
Building side	−2	−3.5
Building rear	0	−3.5
Building roof	−3	−3.5

Figure 25. Angle of Incidence Adjustments for Worksheet VII

the building is sufficient to characterize the outdoor noise. However, the DNL adjustments listed in Figure 24 must still be used. For highway noise, with the highway at ground elevation, it is usually not necessary to consider the roof surface for rooms located on the top floor of the building. Also, if the set-back distance, D, is greater than 50 ft and the total building height is less than 4 stories (50 ft or less), then the angle of incidence correction for the front surface is constant at -2 dB.

Figure 25b illustrates the aircraft-building relationship. In this case, the outdoor DNL and angle of incidence adjustments depend upon the average lateral distance, D_2, between the building location and the ground track (see Figure 10) and the aircraft altitude, h. If the relative location of the aircraft is such that it appears close to the horizon to an observer at the building location, then the angle of incidence adjustments used for highway noise apply.* If the aircraft location is such that it appears high above the horizon or overhead, a -3.5 dB angle of incidence adjustment should be used. In either case, no adjustment to the outdoor DNL for shielding of aircraft noise by the building is used.

Two examples will now be presented to illustrate the steps required to estimate the indoor sound level in buildings. In the first example, the building site is exposed to both highway noise and aircraft noise. For the second example, the building is exposed to noise from two intersecting highways. The examples are constructed to illustrate the method for calculating the envelope noise isolation for differing source-receiver locations. Since it would be impossible to cover all conditions that may arise, the examples are discussed to emphasize the calculation procedures.

EXAMPLE 8. A multi-unit three-story apartment building is to be located at a site exposed to noise from one highway and noise from aircraft operations. Using the method of Section 2, the highway traffic noise exposure is estimated to be L_{dn} = 63 dB, and the estimate of the aircraft noise exposure is L_{dn} = 65 dB. The combined outdoor DNL is obtained using Table 16 and found to be L_{dn} = 67 dB. From Table 3, it is seen that the site is marginally acceptable based upon the outdoor noise criterion of L_{dn} = 55 dB and, to achieve the indoor criterion of L_{dn} = 45 dB, windows must be assumed to be closed, and the building envelope noise level reduction should be 25 dB. Figure 26 illustrates the proposed building location relative to the highway along with the highway DNL values at the front and rear surfaces of the building. The average DNL value of 63 dB for the highway noise will be used for this example. These DNL values are for the clear site without the building present. We now estimate the envelope noise level reduction.

---

* This does not imply that aircraft noise and highway noise are similar in this case. The adjustment for aircraft noise is based upon time averaging for a single flyover. The adjustment for highway noise is based solely upon geometry. However, the magnitudes of the adjustments are approximately the same for the aircraft relative location as described.

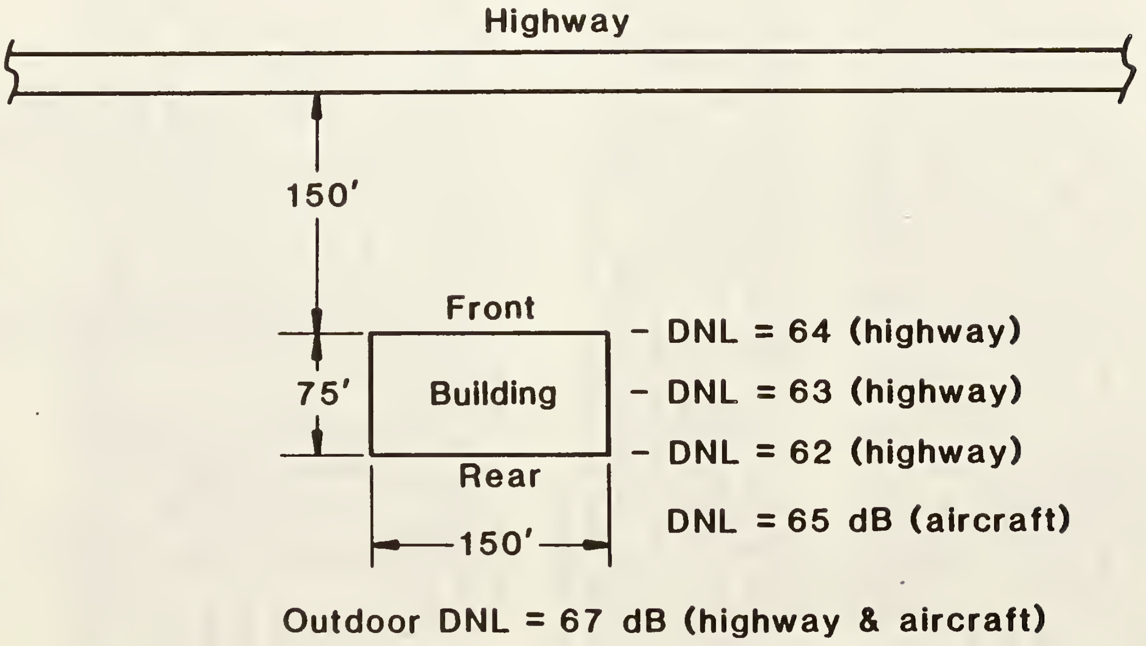


Figure 26. Building Location for Example Problem Illustrating Calculation of Building Envelope Noise Isolation

The first step is to identify the envelope members for each typical room in the apartment unit. The ground floor and first floor rooms will have only one exterior wall if they are located in the building center, and two exterior walls if they are corner rooms. The top floor units will also have the roof as an envelope member. For the present example, we shall concentrate on the top floor corner rooms, since these room represent the more complicated source-receiver geometry. Two conditions then arise: a front corner room with a wall facing the highway and a rear corner room with a wall facing away from the highway.

The next step is to estimate the composite TL for each envelope member for each room. Assume, for this example, that the exterior walls on the front and rear of the building are identical for each room (similar apartment units) and comprise windows, a wall, etc. We shall call these walls the entrance walls to distinguish them from the side walls. Also, assume that the side walls are identical for each room, but different from the entrance walls (perhaps the window area varies). Whatever the details, the envelope member TL values are obtained using Worksheets V and VI based upon the architectural features and the specific construction.

For this example, the following envelope member TL values are given for windows closed as:

	Envelope Member Composite TL		
Room and Noise Source	Entrance	Side	Roof
Front highway noise	31	34	--
Front aircraft noise	34	37	30
Rear highway noise	31	34	--
Rear aircraft noise	34	37	30

At this point, it must be emphasized that the above values are A-weighted transmission loss values and <u>not</u> noise isolation values.

It is now necessary to estimate the envelope noise isolation. Since the envelope member noise isolation and even the important envelope members to include* both depend upon the noise source, the envelope noise isolation must be estimated separately for each source and then the combined performance determined. Once again, a worksheet format is utilized to perform the calculations. Worksheet VII is used to calculate the adjusted TL for each envelope member. The adjustments incorporated in using Worksheet VII are angle of incidence of the outdoor noise and the room sound absorption adjustment.

---

* The roof may be excluded for highway traffic noise if the highway is located at the ground floor elevation of the building.

(Once these adjustments have been incorporated, the envelope TL value is, strictly speaking, transformed into a noise isolation type of value. That is, the term "adjusted TL" used in Worksheet VII is more properly called a noise isolation value. However, before the complete noise isolation value can be determined, we must incorporate a third adjustment for the exposure of the envelope member to the noise source).

Worksheet VIII is used to adjust the outdoor noise level at the envelope member and to compute the indoor noise level contribution due to noise propagating through the envelope member. Both the outdoor noise level at the envelope member and the adjusted TL values from Worksheet VII are entered in Worksheet VIII.

Figure 27 illustrates the steps required to calculate the adjusted TL values for the envelope members exposed to highway traffic noise. The composite TL values indicated in Figure 27 are the values listed above for this example. Figure 28 is the corresponding calculation for the aircraft noise. In both cases, the room absorption has been assumed to be "average" and the -1 dB adjustment used. For the angle of incidence adjustment, the values indicated in Figure 25a are used for highway noise, and the -3.5 dB average for aircraft noise is assumed, for this example, as suggested in Figure 26b.

The next step is to complete Worksheet VIII. The necessary information is the outdoor DNL, and adjustment for the envelope member exposure to the noise source, and the adjusted envelope member TL values from the Worksheet VII. Figure 29 illustrates the completed worksheet for the highway traffic noise, and Figure 30 illustrates the complete worksheet for the aircraft noise. The adjustments for the envelope member noise source exposure are from Figure 24 and are now discussed.

For highway traffic noise, the building will block or screen a portion of the roadway from an observer location behind the building. Similarly, a building surface will be exposed to only one portion of the highway-generated noise once the building is constructed. The "exposure adjustment" incorporates this consideration into the analysis, and constitutes a separate consideration from the angle of incidence adjustment. The use of the member TL values requires the incident sound power on the envelope members. For an envelope member exposed to only a portion of the highway, the outdoor DNL value must be adjusted to account for this partial noise exposure to estimate the indoor DNL contribution. For the building front, parallel to the highway, the adjustment is 0 dB since this surface is exposed to all of the acoustic energy generated by the highway. For the building sides, perpendicular to the highway, the adjustment is -3 dB since the building shields the side surface from half the incident energy generated by the highway. For the rear surface of the building, the adjustment is -15 dB due to the building shielding the entire roadway. These adjustments apply to the building orientation as indicated in Figures 25 and 26, an infinitely long highway as used for the noise prediction method of Section 2, and ignore reflections from other buildings. (See Example 4.)

We are now in a position to estimate the outdoor-to-indoor noise isolation due to the highway noise, the aircraft noise, and the total noise environment.

WORKSHEET VII. CALCULATION OF ADJUSTED TL VALUES FOR EACH ENVELOPE MEMBER

Noise source: Highway Traffic

	Envelope member description	Composite TL of envelope member from Worksheet VI		Adjustment for angle of incidence from Fig. 25		Room sound absorption adjustment*		Adjusted TL for the envelope member - enter value in Worksheet VIII
1.	Front room entrance wall:	31	+	-2	+	-1	=	28 dB
2.	Front room side wall:	34	+	-2	+	-1	=	31 dB
3.	Rear room side wall:	34	+	-2	+	-1	=	31 dB
4.	Rear room entrance wall:	31	+	0	+	-1	=	30 dB
5.	:		+		+		=	dB

* Room sound absorption adjustments, dB. Enter the same value for all members:

sparsely furnished or hard room use -4.0

average furnished room use -1.0

densely furnished or soft room use +2.0

Figure 27. Completed Worksheet for Calculating Adjusted TL Values for Each Envelope Member: Example 8, Highway Noise

WORKSHEET VII. CALCULATION OF ADJUSTED TL VALUES FOR EACH ENVLOPE MEMBER

Noise source: Aircraft Noise

	Envelope member description	Composite TL of envelope member from Worksheet VI		Adjustment for angle of incidence from Fig. 25		Room sound absorption adjustment*		Adjusted TL for the envelope member - enter value in Worksheet VIII
1.	Front & rear room entrance wall :	34	+	-3.5	+	-1	=	29.5 dB
2.	Front & rear room side wall :	37	+	-3.5	+	-1	=	32.5 dB
3.	Front & rear room roof (top floor) :	30	+	-3.5	+	-1	=	25.5 dB
4.	:		+		+		=	dB
5.	:		+		+		=	dB

* Room sound absorption adjustments, dB. Enter the same value for all members

sparsely furnished or hard room use -4.0

average furnished room use -1.0

densely furnished or soft room use +2.0

Figure 28. Completed Worksheet for Calculating Adjusted TL Values for Each Envelope Member: Example 8, Aircraft Noise

WORKSHEET VIII. CALCULATION OF INDOOR SOUND LEVEL CONTRIBUTION FROM EACH ENVELOPE MEMBER

Noise source: Highway Traffic

	Envelope member		Outdoor DNL, dBA		DNL adjustment for member source exposure Figure 24		Adjusted DNL, dBA		Adjusted TL from Worksheet VII (See Fig. 27)		Indoor sound level contribution of envelope member
1.	Front room entrance wall	:	63	+	0	=	63	-	28	=	35
2.	Front room side wall	:	63	+	- 3	=	60	-	31	=	29
3.	Rear room side wall	:	63	+	- 3	=	60	-	31	=	29
4.	Rear room entrance wall	:	63	+	-15	=	48	-	30	=	18
5.		:		+		=		-		=	

THE TOTAL INDOOR DNL IS OBTAINED BY COMBINING THE DNL CONTRIBUTIONS OF THE ENVELOPE MEMBERS USING TABLE 16.

Figure 29. Completed Worksheet for Calculating Indoor Sound Level Contribution from Each Envelope Member: Example 8, Highway Traffic Noise

WORKSHEET VIII. CALCULATION OF INDOOR SOUND LEVEL CONTRIBUTION FROM EACH ENVELOPE MEMBER

Noise source: Aircraft Noise

	Envelope member		Outdoor DNL, dBA		DNL adjustment for member source exposure Figure 24		Adjusted DNL, dBA		Adjusted TL from Worksheet VII (See Fig. 28)		Indoor sound level contribution of envelope member
1.	Front & rear room entrance wall	:	65	+	0	=	65	-	29.5	=	35.5
2.	Front & rear room side wall	:	65	+	0	=	65	-	32.5	=	32.5
3.	Front & rear room Roof (Top: floor only)	:	65	+	0	=	65	-	25.5	=	39.5
4.		:		+		=		-		=	
5.		:		+		=		-		=	

THE TOTAL INDOOR DNL IS OBTAINED BY COMBINING THE DNL CONTRIBUTIONS OF THE ENVELOPE MEMBERS USING TABLE 16.

Figure 30. Completed Worksheet for Calculating Indoor Sound Level Contribution for Each Envelope Member: Example 8, Aircraft Noise

The numbers in the right-hand column of Figures 29 and 30 represent the indoor DNL contribution due to each noise source-envelope member combination. It only remains to combine these levels to determine the total indoor level. To do this, we use Table 16 and the results in Figures 29 ad 30 as follows:

Front corner room/highway: Combine 35 and 29 to obtain 36 dBA indoor DNL

Rear corner room/highway: Combine 29 and 18 to obtain 29 dBA indoor DNL

Front corner room top floor/aircraft: Combine 35.5, 32.5, and 39.5 to obtain 42 dBA indoor DNL

Rear corner room top floor/aircraft: Combine 35.5, 32.5, and 39.5 to obtain 42 dBA indoor DNL

Front corner room top floor/highway and aircraft: Combine 36 and 42 to obtain 43 dBA indoor DNL

Rear corner room top floor/highway and aircraft: Combine 29 and 42 to obtain 42 dBA indoor DNL

From the combination of the indoor DNL contributions, it is seen that the total indoor DNL is estimated to be 42 to 43 dBA and would be considered, therefore, acceptable using the criterion indicated in Table 3. This estimate may be expected to vary by ± 3 dB due to the assumed room sound absorption (see note to Worksheet VII). It is obvious that aircraft noise dominates the indoor environment, in this example.

Before completing the example, we estimate the building envelope noise isolation expressed in terms of the outdoor-to-indoor DNL difference. For the combined highway and aircraft environment, the outdoor DNL is 67 dB and the indoor DNL is 43 dB for the front corner room on the top floor. The envelope noise isolation for this case is 67 - 43 = 24 dB. For the same room considering highway traffic noise only, the noise isolation is 63 - 36 = 27 dB and, for aircraft noise only, the noise isolation is 65 - 42 = 23 dB. For the rear corner room, the noise isolation is 25 dB for the combined highway and aircraft noise only. Hence, when the noise isolation of the building envelope is specified, it is necessary to incorporate all considerations of the source and the room location relative to the source if the noise isolation value is to have meaning. The reader may also appreciate that by considering a few typical combinations of envelope members and noise sources, the analysis may be used to evaluate an entire development utilizing similar construction without completely repeating the calculations for each and every room of every building.

EXAMPLE 9. We now consider a building site exposed to noise from two intersectng highways. The site geometry and the noise levels of each highway are illustrated in Figure 31. To simplify the presentation of the example, assume that the building dimensions relative to the setback distances from each highway allow one to consider the clear site sound levels to be essentially uniform over the building surfaces. Further, assume that the composite TL of

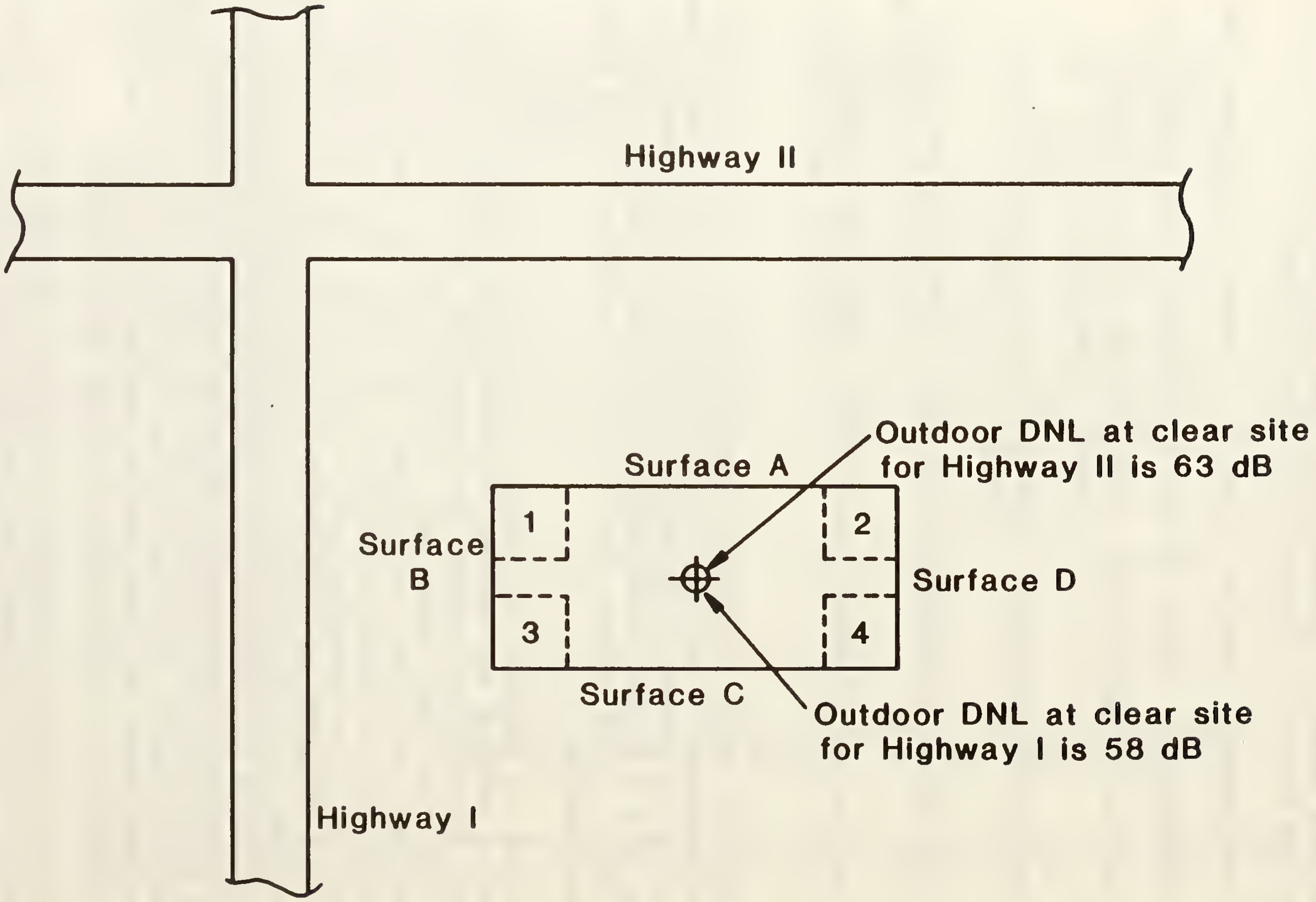


Figure 31. Building Location Relative to Two Intersecting Highways: EXAMPLE 9

all building surfaces is constant at 22 dB for highway traffic noise.* This example will emphasize the significance of the various adjustments when estimating the envelope noise isolation. The four corner rooms are used, with each room exhibiting a different exposure level from the noise sources.

The calculations are performed for each room using Worksheets VII and VIII for each combination of envelope member and highway. Worksheet VII is used to obtain the adjusted TL values of each envelope member and highway. Worksheet VIII is used to adjust the outdoor levels for each envelope member and highway. Table 27 summarizes the calculations, and illustrates the relative significance of each of the adjustment terms. For each room, the combined indoor DNL is also indicated. It is seen that although each envelope member has the same A-weighted noise insulation value (TL = 22 dB), each of the four rooms is estimated to exhibit a different A-weighted noise isolation value. Since the total outdoor noise level is 64 dB, the A-weighted noise isolation values for each room are:

Room 1: 64 - 47 = 17 dBA

Room 2: 64 - 46 = 18 dBA

Room 3: 64 - 44 = 20 dBA

Room 4: 64 - 42 = 22 dBA

These noise isolation values are relative to the clear site condition.

The above examples were presented to illustrate the steps required to determine the building envelope noise isolation. Table 28 provides a summary of the worksheets utilized to conduct this step-by-step calculation procedure with a brief description of the purpose of each worksheet. Tables 29 and 30 are presented in Section 3.3 together with worksheets VII and VIII for ease of reference.

Degradation of Noise Isolation Performance

The calculation of the envelope noise isolation requires the use of A-weighted values of the sound transmission loss for each component of an envelope member. The description of components listed in Tables 20 through 26 contain the words "sealed" and "unsealed" to denote that possible gaps and cracks may exist in the construction. These gaps or cracks result in degradation of the sound transmission loss performance of the construction since the noise will propagate through the gaps with very little loss of acoustic energy. The

---

* This is done to simplify the example. In practice, it is necessary to base the envelope member TL upon its construction details and never use an average value for the entire envelope.

Table 27. SUMMARY TABULATION OF CALCULATIONS FOR EXAMPLE PROBLEM NUMBER 9

Envelope/Source Description			Calculations Using Worksheet VII								Calculations Using Worksheet VIII								
Room	Envelope member	Highway source	Envelope member TL	+	Angle of incidence	+	Room Absorption	=	Adjusted TL	:	Outdoor noise	+	Noise Source exposure	=	Adjusted outdoor noise	−	Adjusted TL	=	Indoor noise
1	Surface A	I	22		-2		-1	=	19	:	58		- 3	=	55		19	=	36
1	Surface A	II	22		-2		-1	=	19	:	63		0	=	63		19	=	44
1	Surface B	I	22		-2		-1	=	19	:	58		0	=	58		19	=	39
1	Surface B	II	22		-2		-1	=	19	:	63		- 3	=	60		19	=	41
															Combined indoor level			=	47
2	Surface A	I	22		-2		-1	=	19	:	58		- 3	=	55		19	=	36
2	Surface A	II	22		-2		-1	=	19	:	63		0	=	63		19	=	44
2	Surface D	I	22		0		-1	=	21	:	58		-15	=	43		21	=	22
2	Surface D	II	22		-2		-1	=	19	:	63		- 3	=	60		19	=	41
															Combined indoor level			=	46
3	Surface B	I	22		-2		-1	=	19	:	58		0	=	58		19	=	39
3	Surface B	II	22		-2		-1	=	19	:	63		- 3	=	60		19	=	41
3	Surface C	I	22		-2		-1	=	19	:	58		- 3	=	55		19	=	36
3	Surface C	II	22		0		-1	=	21	:	63		-15	=	48		21	=	27
															Combined indoor level			=	44
4	Surface C	I	22		-2		-1	=	19	:	58		- 3	=	55		19	=	36
4	Surface C	II	22		0		-1	=	21	:	63		-15	=	48		21	=	27
4	Surface D	I	22		0		-1	=	21	:	58		-15	=	43		21	=	22
4	Surface D	II	22		-2		-1	=	19	:	63		- 3	=	60		19	=	41
															Combined indoor level			=	42

Table 28. Summary of Steps for Calculating the Building Envelope Noise Level Reduction

	Purpose	Data Input	Result Obtained
Worksheet V	Adjusted component TL values for surface area in calculating composite TL for an envelope member	Component TL and area and floor area of room	Adjusted TL value enter in Worksheet VI
Worksheet VI	Combination of envelope component TL values to obtain the composite TL of the envelope member	Adjusted TL values for each component from Worksheet V	Composite TL value of envelope member enter in Worksheet VII
Worksheet VII	Adjust envelope member TL for angle of incidence and room sound absorption	Envelope member TL and angle of incidence adjustment from Fig. 25	Enter value in Worksheet VIII
Worksheet VIII	Adjust outdoor DNL for member noise exposure and compute indoor DNL contribution	Outdoor DNL from prediction and envelope member TL values from Worksheet VII	Contribution to indoor DNL for envelope member
Table 29	TL adjustment values for surface area of components	Surface area of component and floor area of room	Enter value in Worksheet VI
Table 30	TL adjustment values for combining TL values	TL difference for two components	Enter value in Worksheet VI
Table 16	Combination of sound levels to determine total sound level	Outdoor DNL values or indoor DNL contributions for each envelope member	Combined outdoor DNL or combined indoor DNL values

details of the physics describing noise propagation through gaps and cracks is extremely complicated and beyond the scope of these guidelines. However, it is important to recognize the degree of degradation that may result if gaps or cracks exist in an otherwise adequate design. Reviewing the data presented in Tables 20 through 26, it is seen that differences of 3 to 5 dB between sealed and unsealed conditions are possible. Due to the complexities of the problem, the degradation associated with any specific gap or crack geometry must be determined by laboratory testing (Ref. 45). However, approximations to the theory do provide an indication of the degradation.

As a guide to estimating the degradation of the sound transmission loss due to gaps and cracks, Table 31 was prepared based on data presented in Ref. 41. The gap or crack, characterized in Table 31, are based upon air leakage tests and are expressed in terms of "air openings" in units of in^2 of opening/100 ft^2 of the envelope member. As seen in Table 31, if only 1/10 of 1 percent (12 in^2 of opening/100 ft^2) of the envelope member area is open, the TL value of the member may be drastically reduced. Below Table 31, a range of "air opening" values is indicated for several different types of construction with the range corresponding to "good workmanship" or "average workmanship." This range of values is suggested by Ref. 41 and should be suitable for prediction purposes.

Table 31 should be used for guidance only. Detailed calculations should be based upon laboratory data such as provided by Tables 20 through 26. That is, if an estimate of the effect of using sealed rather than unsealed windows is desired, use should be made of the corresponding data in Table 22.

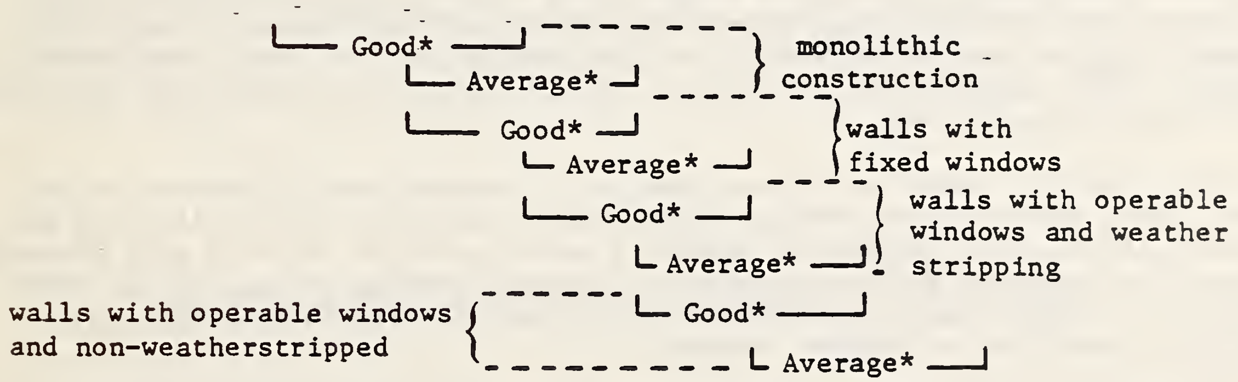
Table 31 is provided for general guidance only in that it indicates the importance of "sealing" the structure, especially if higher TL values are important to the design. It should be noted that for a given opening, the degradation is less important for the lower values of the envelope member sound transmission loss. What this means in practice is that well designed construction will perform poorly if the inplace construction results in a "leaky" structure. Further, a "leaky" structure may be realized if less than one percent of its surface area is open. To achieve noise isolation in practice, quality control during construction is an absolute necessity.

Open Window Conditions

The previous sections have dealt with procedures for estimating the envelope noise isolation under various conditions. Example 7 included the details of estimating the envelope member sound transmission loss for an open window. In that example, it was determined that the sound transmission loss changed 31 dBA for the closed condition to 13 dBA for the open condition. This change represents an 18 dBA degradation of the sound transmission loss for closed or sealed construction. As a rule of thumb, an envelope noise isolation value in the range of 10 to 15 dBA for open windows representing 10 to 20 percent of the total wall area may be used irrespective of the noise isolation value of the construction with the windows closed (Refs. 2, 14, and 46).

Table 31. Change in the envelope Member TL Due to Cracks and Gaps in the Construction (summarized from Ref. 41)

Envelope member TL Design value	Air Leakage Openings in^2/100 ft^2								
	<0.5	0.75	1.5	3.0	4.5	6.0	7.5	9.0	12.0
50 to 55	-6	-10	-12	-15	-17	-18	-19	-20	-21
45 to 50	-3	- 5	- 8	-10	-12	-13	-14	-15	-16
40 to 45	-2	- 3	- 4	- 6	- 8	- 9	-10	-10	-11
35 to 40	-1	- 1	- 2	- 3	- 4	- 5	- 5	- 6	- 7
30 to 35	0	0	- 1	- 1	- 2	- 2	- 3	- 3	- 4
25 to 30	0	0	0	0	- 1	- 1	- 1	- 1	- 1



---

* Indicates range of air leakage corresponding to either good workmanship or average workmanship.

Since closing windows impiles a requirement for either mechanical ventilation or air conditioning during warmer months, noise isolation requirements become directly related to both energy consumption and building operating costs. These considerations become significant for areas of the United States where climatic conditions do not require extended periods of heating or closed window conditions during the year.

The question then arises as to the time average of the envelope noise isolation if the envelope is assumed to be closed during part of the year and open during the remainder of the year. It must be remembered that the noise predictions used to estimate the outdoor DNL are annual averages. To be consistent, it is necessary to use an annual average value for the envelope noise isolation to estimate the annual average indoor DNL. Table 32 has been prepared to provide guidance for estimating an annual average value of the envelope noise isolation.

As an example, suppose that local climatic conditions indicate the following average number of days per year to provide indoor heating or cooling:

average days for heating = 180

average days for cooling = 65

average days heating/cooling not required = 120

For these conditions, it would be assumed that windows could be open 120 days per year and still achieve an adequate indoor thermal environment. Hence, the windows could be open 33 percent of the time during the year based upon thermal conmfort. The question now is: How does this affect the average noise isolation of the building envelope?

From Table 32 under the column heading of "windows open 30 percent of the time," it is seen that the average annual noise isolation would be 14 to 18 dB. If the building were designed to achieve a noise isolation of 30 dB with windows closed, the occupants would realize only an annual average value of 18 dB noise isolation if they opened their windows during periods when neither heating or cooling is required for thermal comfort.

Tables 31 and 32 convey the same basic message: to achieve the design noise isolation, gaps and cracks must be sealed and windows must remain closed on essentially an annual basis. If an economic penalty is to be assigned to requiring windows closed, the penalty is the cost of mechanical ventilation (not necessarily air conditioning) during the time period for which windows could be open to achieve indoor thermal comfort.

Screen Balconies and Courtyards

The open-window conditions described in the previous section apply to conventional windows that occupy from 10 to 20 percent of the area of an

Table 32. Average values of Building Envelope Noise Isolation for Combined Open/Closed Window Conditions

Closed Windows Noise Isolation, dB	Percentage of time windows are open									Open Windows Noise Isolation,* dB
	10	20	30	40	50	60	70	80	90	
15	15	15	14	14	14	14	14	13	13	13
20	19	17	17	16	15	15	14	14	13	13
25	21	19	18	17	16	15	14	14	13	13
30	22	20	18	17	16	15	15	14	13	13
35	23	20	18	17	16	15	15	14	14	13
40	23	20	18	17	16	15	15	14	14	13
45	23	20	18	17	16	15	15	14	14	13

* The open window noise isolation is assumed to be 13 dBA.

envelope member. Often, it is desired to provide sliding glass doors opening on to a balcony or courtyard as a design feature of the building. When closed, single pane sliding glass doors may exhibit an 18 to 23 dBA value of sound transmission loss (see Table 22). When open, however, the noise isolation of the envelope member is very low due to the large open area typical of sliding glass doors.

In order to provide some degree of noise isolation with either windows or sliding glass doors open, the use of screens or partially enclosed balconies has been recommended (Refs. 32-35). These referenced studies provide design-oriented methods for estimating the indoor noise level for a screened balcony or courtyard. These methods are based upon acoustic scale model studies and require detailed source-receiver geometric data to estimate the noise isolation achieved. Further, the noise measures used to develop these empirical results are not consistent with the L_{dn} measure used in the present guidelines.

However, the reader should be aware of these techniques which may be applied to specific building design features. As an approximation, a 3 to 6 dB outdoor-to-indoor noise isolation may be attributed to using screened balconies or courtyards with windows open in the absence of a more detailed acoustical analysis of the specific conditions.

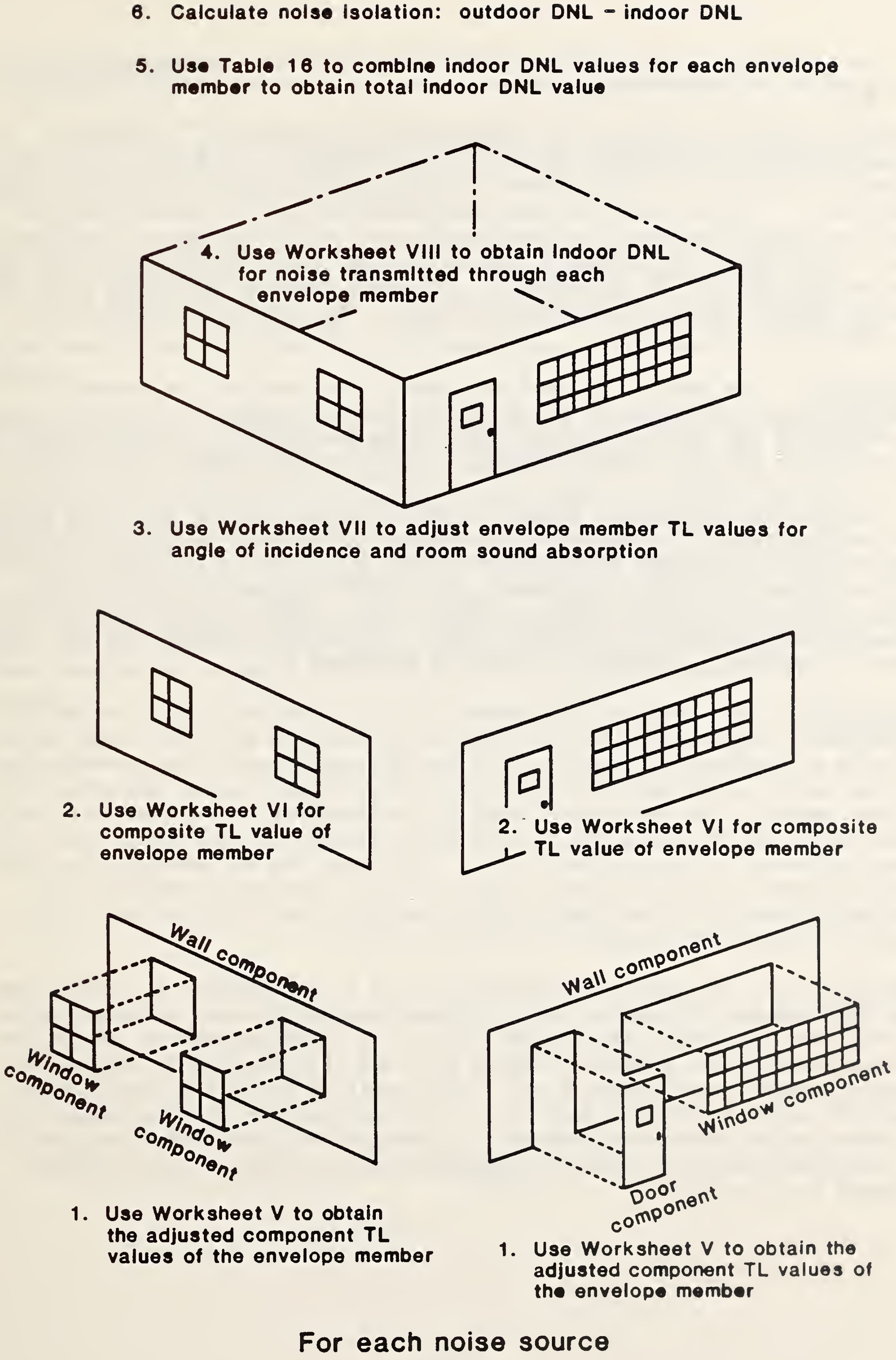
3.3 INDOOR NOISE MITIGATION WORKSHEETS

This section provides an overview of the calculation procedure, and the necessary worksheets and look up tables for estimating the building envelope noise isolation. This information is assembled within this section for ease of future use. If the user desires, the examples presented in Section 3.2 may be reviewed. However, each worksheet indicates the necessary step-by-step calculation procedure and, as required, the appropriate lookup table.

Use of Worksheets

The calculation procedure utilizes four worksheets to estimate the envelope noise isolation for each noise source. As used in these guidelines, a noise source is each highway, each railway track, and each aircraft flight path. For highway noise, each highway may comprise several lanes; but, for intersecting highways, the worksheets must be completed for each highway with the final indoor sound level obtained by combining the indoor sound level attributable to each source (see Example 9, Figure 31, and Table 27).

The four worksheets are distinct steps in the calculation procedure. Figure 32 illustrates these steps and indicates the purpose of each worksheet. Table 28, which was presented in the previous subsection, summarized the purpose of each worksheet and the result of the calculations of each worksheet. It is important to note that the heading "Noise Source: __________ " appears at the top of each worksheet. The purpose of this heading is to emphasize that each noise source must be considered individually when estimating the envelope noise isolation.



6. Calculate noise isolation: outdoor DNL − indoor DNL

5. Use Table 16 to combine indoor DNL values for each envelope member to obtain total indoor DNL value

4. Use Worksheet VIII to obtain indoor DNL for noise transmitted through each envelope member

3. Use Worksheet VII to adjust envelope member TL values for angle of incidence and room sound absorption

2. Use Worksheet VI for composite TL value of envelope member

2. Use Worksheet VI for composite TL value of envelope member

1. Use Worksheet V to obtain the adjusted component TL values of the envelope member

1. Use Worksheet V to obtain the adjusted component TL values of the envelope member

For each noise source

Figure 32. Purpose of Worksheets for Calculating Building Envelope Noise Isolation

The numbering of the worksheets is consecutive with the numbering of the noise prediction worksheets described in Section 2 of the present guidelines.

Worksheet V: The purpose of this worksheet is to obtain an "adjusted TL" value for each element or component of each envelope member (see Figure 32.) The "adjustment" accounts for the element surface area relative to the floor area of the room. The data required for this worksheet are the element surface areas, the room floor area (or room dimensions), and the element A-weighted TL values. The element A-weighted TL values may be obtained from Tables 20 through 26 or as described in the Appendix C. The adjustment is determined from Table 29. These TL values depend upon the noise source. The results are entered in Worksheet VI.

Worksheet VI: The purpose of this worksheet is to combine the element TL values to estimate the A-weighted TL values of the envelope member. The data input to this worksheet are the adjusted TL values from Worksheet V. These values are entered across the top of the worksheet along with the element description.

The adjusted element TL values are combined in sequence until all elements have been combined. The method for combining values is indicated in the worksheet with the adjustment obtained from Table 30. Figures 21 and 23 illustrate completed examples of this worksheet. The final combined TL value is the A-weighted TL value of the envelope member. This worksheet must be completed for each envelope member and noise soruce. The values obtained for the envelope members surrounding a room are entered on Worksheet VII.

Worksheet VII: The purpose of Worksheet VII is to adjust the TL values for each envelope member for angle of incidence correction and room sound absorption. The angle of incidence correction is obtained from Figure 25 and depends upon both the noise source and the orientation of the noise source relative to the envelope member. The room sound absorption adjustment is estimated as indicated at the bottom of the worksheet. The same adjustment is applied to each envelope member enclosing the room. The -1.0 dB adjustment for an "average" furnished room correponds to the assumption that the total room sound absorption is numerically equal to 80 percent of the room floor area (see Section 3.2). The adjusted TL values are entered in Worksheet VIII.

Worksheet VIII. The purpose of Worksheet VIII is to estimate the indoor DNL value attributable to outdoor noise transmitted through each envelope member. The input data are the total outdoor DNL value, an adjustment to the DNL for envelope member noise exposure (Figure 24), and the adjusted TL values for the envelope members from Worksheet VII. The result of the calculation is the indoor DNL value for the outdoor noise incident upon the envelope member for the noise source under consideration. To obtain the total indoor DNL value, the individual contributions are combined using the calculation procedure indicated in Table 16.

Several Noise Sources

If the building envelope is exposed to noise from several sources, Worksheets V through VIII must be completed to obtain the total indoor DNL for each source. These total source DNL values are then combined to obtain the grand total indoor DNL values using Table 16.

The outdoor DNL is also composed of contributions from each noise source with the total DNL combined using Table 16. Knowing both the outdoor and indoor DNL for each noise source and the total outdoor and total indoor DNL, one is now in a position to estimate the envelope noise isolation either for each noise source, any combination of noise sources, or for the total noise environment.

Usually, one is interested only in the building envelope noise isolation for the total noise environment. However, the consideration of the envelope noise isolation on a source-by-source basis may be important especially when evaluating alternative mitigation measures. For example, a highway noise barrier may result in a lower indoor DNL when used in conjunction with the envelope noise isolation for highway noise. However, if the site is also exposed to aircraft noise, the highway noise barrier will provide no indoor DNL change due to the aircraft noise. The worksheet format utilized in these guidelines allows the user to evaluate these important considerations if required. One has only to follow the step-by-step procedures for each noise source and combine and compare the final results to evaluate the various alternatives.

WORKSHEET V CALCULATION OF ADJUSTED TL VALUES FOR ENVELOPE MEMBER ELEMENT

Envelope member description: ________________________________

Noise source: ____________ Room dimensions: Height _____ft; Width ____ft;
Length _____ft

Total member area: _________ft^2 Room floor area, $S_{f\ell}$: ________ ft^2

Envelope member element Description	Element area, S_i ft^2	$S_i/S_{f\ell}$	Element TL*		Adjustment, Δ_s from Table 29		Adjusted element TL $TL+\Delta_s$
1.				+		=	
2.				+		=	
3.				+		=	
4.				+		=	
5.				+		=	

* See Tables 20 through 26 for representative values

Table 29. Values of the Adjustment Δ_s, dB, for Worksheet V

S_i is the surface area of the i^{th} member element
$S_{f\ell}$ is the floor area of the room

$S_i/S_{f\ell}$* PCT	Δ_s, dB
.5	+23.0
.63	+22.0
.8	+21.0
1.0	+20.0
1.25	+19.0
1.6	+18.0
2.0	+17.0
2.5	+16.0
3.2	+15.0
4	+14.0
5	+13.0
6.3	+12.0
8	+11.0
10	+10.0
12.5	+ 9.0
16	+ 8.0
20	+ 7.0
25	+ 6.0
32	+5.0
40	+4.0
50	+3.0
63	+2.0
80	+1.0
100	0.0
125	-1.0
160	-2.0
200	-3.0

* These values are included to cover the range appropriate to open windows and vents.

WORKSHEET VI. CALCULATION OF COMPOSITE TL OF ENVELOPE MEMBER

Noise source: ____

Element description ____________ ____________ ____________ ____________ ____________

____________ ____________ ____________ ____________ ____________

Adjusted TL value TL_1 = ________: TL_2 = ________: TL_3 = ________: TL_4 = ________: TL_5 = ________:

TL difference: $TL_1 - TL_2$ = ____________

Adjustment Δ_c (from Table 30) = ____________

Combined TL: $TL_{c2} = TL_1 + \Delta_c$ = ____________

TL difference: $TL_{c2} - TL_3$ = ____________

Adjustment Δ_c (from Table 30) = ____________

Combined TL: $TL_{c3} = TL_{c2} + \Delta_c$ = ____________

TL difference: $TL_{c3} - TL_4$ = ____________

Adjustment Δ_c (from Table 30) = ____________

Combined TL: $TL_{c4} = TL_{c3} + \Delta_c$ = ____________

TL difference: $TL_{c4} - TL_5$ = ____________

Adjustment Δ_c (from Table 30) = ____________

Combined TL: $TL_{c5} = TL_{c4} + \Delta_c$ = ____________

Table 30. Values of the Adjustment Δ_c, dB, for Worksheet VI

TL Difference dB	Δ_c, dB	TL Difference dB	Δ_c, dB
-9.0	-0.5	+ 1.0	- 3.5
-8.0	-0.6	+ 2.0	- 4.1
-7.0	-0.8	+ 3.0	- 4.8
-6.0	-1.0	+ 4.0	- 5.5
-5.0	-1.2	+ 5.0	- 6.2
-4.0	-1.5	+ 6.0	- 7.0
-3.0	-1.8	+ 7.0	- 7.8
-2.0	-2.1	+ 8.0	- 8.6
-1.0	-2.5	+ 9.0	- 9.5
0.0	-3.0	+10.0	-10.4

For TL Difference < - 9.0 $\Delta_c = 0$

For TL Difference > +10.0 $\Delta_c = -$ TL Difference

WORKSHEET VII. CALCULATION OF ADJUSTED TL VALUES FOR EACH ENVELOPE MEMBER

Noise source: ____________________

	Envelope member description	Composite TL of envelope member from Worksheet VI		Adjustment for angle of incidence from Fig. 25		Room sound absorption adjustment*		Adjusted TL for the envelope member - enter value in Worksheet VIII	
1.	__________:	__________	+	__________	+	__________	=	__________	dB
2.	__________:	__________	+	__________	+	__________	=	__________	dB
3.	__________:	__________	+	__________	+	__________	=	__________	dB
4.	__________:	__________	+	__________	+	__________	=	__________	dB
5.	__________:	__________	+	__________	+	__________	=	__________	dB

* Room sound absorption adjustment, dB. Enter the same value for all members

- sparsely furnished or hard room use -4.0
- average furnished room use -1.0
- densely furnished or soft room use +2.0

WORKSHEET VIII. CALCULATION OF ADJUSTED TL VALUES FOR EACH ENVELOPE MEMBER

Noise source: ______________________________

	Envelope member		Outdoor DNL dBA		DNL adjustment for member source exposure Figure 24a		Adjusted DNL dBA		Adjusted TL from Worksheet VII		Indoor sound level contribution of envelope member
1.	________	:	________	+	________	=	________	-	________	=	________
2.	________	:	________	+	________	=	________	-	________	=	________
3.	________	:	________	+	________	=	________	-	________	=	________
4.	________	:	________	+	________	=	________	-	________	=	________
5.	________	:	________	+	________	=	________	-	________	=	________

THE TOTAL INDOOR DNL IS OBTAINED BY COMBINING THE DNL CONTRIBUTIONS OF THE ENVELOPE MEMBERS USING TABLE 16.

4. NOISE COMPATIBLE DEVLOPMENT

4.1 ENVIRONMENT NOISE LEVELS COMPATIBLE WITH VARIOUS LAND USES

Planning with respect to environmental noise involves the separation of noise sensitive land uses from exposure to high noise levels, and in cases where this is not possible, the develoment of provisions for noise mitigation. These measures are taken because of the adverse effects of noise on people. The cumulative evidence from research indicates that exposure to day-night average sound levels in excess of 75 dB over prolonged periods of time may result in noise-induced hearing loss (Ref. 2). A number of investigations combining social surveys and physical noise measurements have revealed that people exposed to noise in their homes show a generalized adverse response which increases with increasing noise exposure level. This generalized adverse response is complex and involves a combination of factors including speech interference, sleep interference and a frustrated desire for quiet and the ability to use telephone, radio, and television satisfactorily (Refs. 2, 47, 48, 49, 51 and 52).

In the aggregate, the average adverse response of groups of people has been found to be stable and related to the cumulative noise exposure as expressed in a measure such as the DNL. Moreover, if the human response is stated in terms of the percentage of people who express a high degree of annoyance due to the activity interference produced by the noise, the relationship between noise exposure and the adverse response is accurately described by the function shown in Figure 33 (Refs. 48, 49 and 51).

Inspection of Figure 33 indicates that, for noise exposure at levels below 55 dB the percent of people highly annoyed by noise is insignificant, rising very slowly from less than 1 percent to 4 percent over the range of 45 to 55 dB. When the noise exposure level reaches 75 dB (the level where noise constitutes a potential hearing hazard), the number of people highly annoyed rises to about 40 percent. Above this exposure level, further increases in the noise exposure level give rise to sharp increases in the number of people highly annoyed. Within the 55 to 75 dB range, the relationship between the number of highly annoyed people and the exposure level can be approximated by a linear relationship (Ref. 48). Data on the overt community reaction to noise reveal that, on the average, the expected community reaction to an identifiable source of intruding noise changes from none to vigorous when the DNL increases from 55 to 75 dB (Refs. 2 and 49).

As mentioned previously, noise-induced annoyance arises from the activity interference produced by the noise exposure. Among the activities interferred with, speech interference is the most often mentioned (Ref. 2). The extent to which noise affects speech communication is dependent upon whether the speaker and listener are located indoors or outdoors and the vocal effort of the speaker.

For many indoor situations, if the speaker and the listener are separated by a distance greater than 3 ft (one meter), the speech level is more or less constant throughout the room because the speech sounds are reflected from the walls and other room boundaries. In such cases, for a normal voice communication

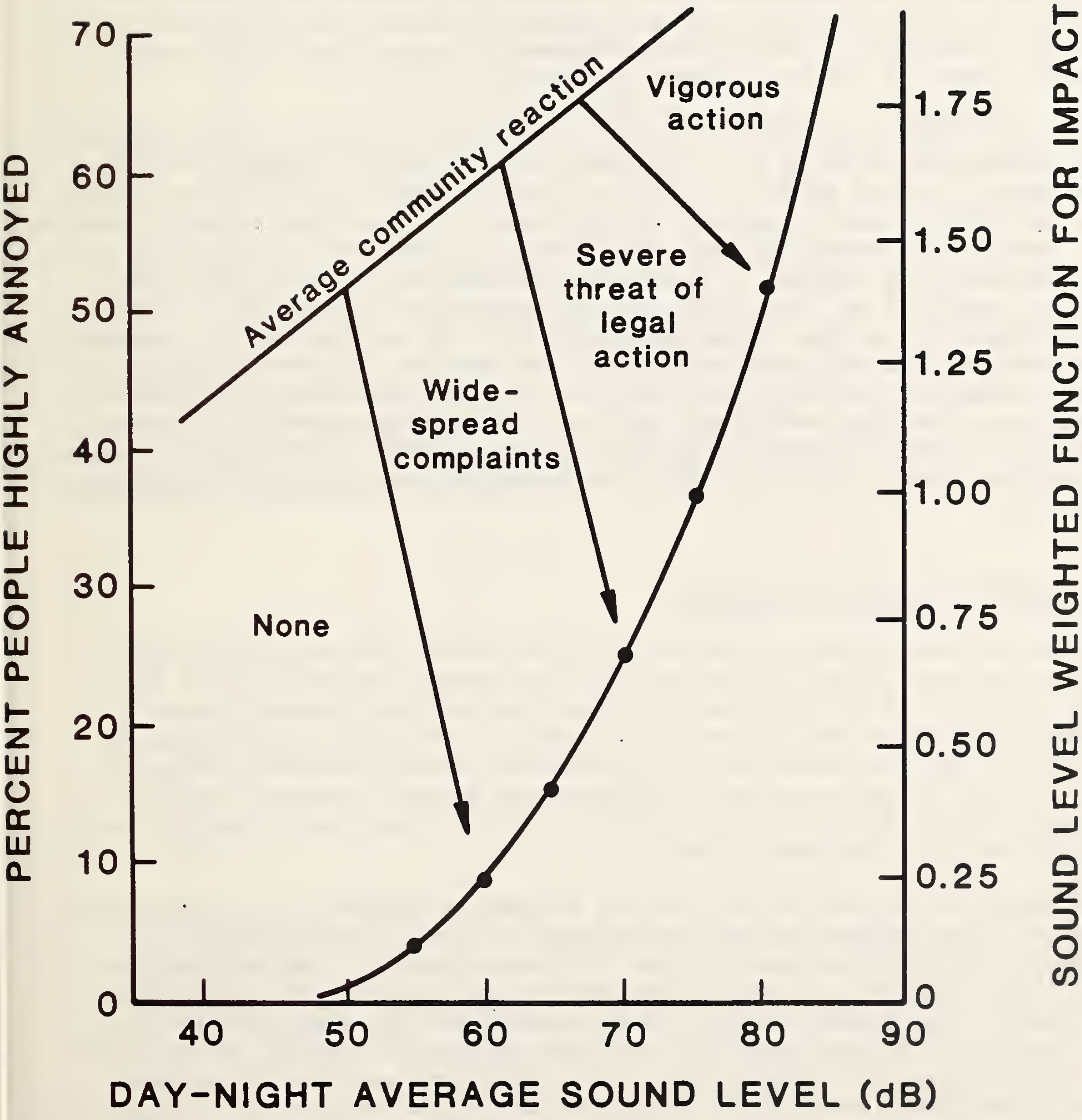


Figure 33. Summary of the Effects of Community Noise on People as a Function of Day-Night Average Sound Level.

level, a 100 percent sentence intelligibility is achieved if the indoor noise level is at or below 45 dB. The sentence intelligibility drops to 90 percent if the noise level raises to 65 dB and to 50 percent at 72 dB (Ref. 2).

Outdoors, the speech level at the receiver drops with increasing distance between the speaker and the listener because of the lack of reverberance resulting from the absence of reflecting walls. Thus, outdoors, the interference produced by noise depends upon the distance between the speaker and the listener. The noise levels for a 95 percent sentence intelligibility outdoors as a function of the distance between the speaker and the listener are shown in Table 33 for both normal and raised voice.

The major effects of noise on people for various levels of noise exposure are also summarized in Table 33. This table shows that, if the outdoor noise exposure level is below 55 dB, no serious adverse effects are likely to result, whereas, at 75 dB or above, serious effects occur, including a potential hearing damage. Based upon these findings, environmental noise levels compatible with various land uses are derived. These relationships are shown in Table 34. (Table 3 of section 1 of the report presents a specialized version of Table 34.) In assessing the data presented in Table 34, it is important to remember that the levels shown are based only upon consideration of human response to noise and do not include any considerations of either economics or feasibility. Thus, when decisions are made about land use, other factors such as economics and feasibility must be balanced against the levels shown in Table 34 as these levels provide a basis only for evaluating community response to noise (Refs. 1, 2, 10 and 48).

4.2 TECHNIOUES FOR LAND USE CONTROL

As the history of airport noise litigation shows, serious noise impact problems arise when either a noise source is introduced or modified in such a way as to result in a noise impact or when the land use pattern around a noise source changes in such a way as to result in excessive noise exposure levels for the new land uses, and its associated human activities (Refs. 61 and 62). In the latter case, the noise does not become a problem until the land around the noise source shifts from one type of land use to another (e.g., from agricultural to residential use).

The objective of a noise control and mitigation program is to prevent or decrease the noise impact on the land adjacent to a major noise source. Typically, such a program would include provisions both for controlling the noise at the source and or controlling land use patterns in the neighborhood of the source. The present section is concerned with the tools available to local authorities for the control of land use patterns. However, before these tools are discussed, it is important to note that land use control is often achieved at the local level where it is limited by two factors: 1) the existing enabling legislation of the state whereby the police powers of the state are delegated to the local governments; and, 2) the level of sophistication of the local government and the planning agency (Refs. 10 and 63). A summary of the major tools available for land use control is given in Table 35.

Table 33. Effects of Noise on People

DNL Outdoors, dB	Physilogical effects	Maximum Distance for percent sentence intelligibility outdoors		Percent of population highly annoyed	Community reaction
		ft	(m)		
55	none	1.5	(3.5)	4	none
60	none	6.5	(2.0)	9	minimal
65	none	5.0	(1.5)	15	moderate
70	unlikely	3.0	(0.9)	25	signficant
75	potential for noise induced hearing loss	1.5	(0.5)	37	severe

Table 34. Environment Noise Levels Compatible with Various Land Uses

DNL outdoors, dB	Noise exposure	Land uses	Noise control mesures
55 or less	not significant	residential, public recreational, and cultural	none
55-65	minimal	residential, public, recreational, and cultural	site and building planning to reduce noise levels in noise sensitive spaces
65-70	moderate	recreational, other than music shells and amphitheaters, commercial and public	site planning and outdoor-to-indoor noise level reduction of 25 dB required to insure adequate noise levels in noise sensitive spaces, mechanical ventilation and closed windows year round
70-75	significant	limited public uses, commercial, manufacturing and industrial	outdoor to indoor noise level reduction of 30 dB required to insure adequate noise levels in noise sensitive spaces, mechanical ventialation and closed windows year round
75 and above	severe	manufacturing and industrial	portions of building may require special noise control treatment

Table 35. Techniques for Local of Land Use Control

Regulatory Controls	Public Acquisition	Financial Incentives
Zoning: •to require exclusion of noncompatible land use •to require path discontinuity •to require outdoor-to-indoor noise isolation	Municipal land acquisition: •to create buffer zones •to prevent incompatible land use •to maintain present land use	Tax incentives: •to prevent incompatible land use development •to provide increased noise control
Subdivision regulations: •to require noise reduction in site design	•to develop compatible land uses for resale •to hold for future: - land banking	Capital improvements: •restrict municipal developments to quiet areas
Building codes: •to require noise isolation in new construction and/or in rehabilitation	Partial municipal land acquisition: •easement to allow limited land uses	
Health codes: •to define noise as health hazard •to require noise isolation in construction		
Disclosure of noise levels: •to inform purchaser of renter of noise problem		

Regulatory Controls of Land Use.

Zoning is one of the most powerful tools used to direct land use in accordance with a comprehensive master plan for the orderly growth of a whole community. It is the means by which many factors of concern are controlled including health, safety, pollution, density, lot size, building height, ratio of open space to developed land, and others. The zoning ordinance usually consists of a text and a map (or a series of maps). The text gives the substance of the standards applicable to each zoning district, and the procedure governing proposals for change of either the text or the map. The map allows residents and other interested parties to identify where various districts are, and what section of the ordinance applies to a given land area. Since the regulations governing each zoning district differ from each other, there exists a potential for preferential treatment of some districts. Accordingly, states often take special care to limit the local legislative power so as to insure fair and reasonable treatment for all.

While the preparation and administration of zoning ordinances vary from municipality to municipality, usually several bodies are involved, each with its own responsibilities. For example, a zoning commission may be responsible for preparing the original zoning ordinance; a board of appeals may be charged with granting variances in hardship cases and may hear appeals in cases involving disputes over the interpretation of the ordinance; the local legislature may enact amendments to either the text or the map in accordance with the recommendations it may receiver from a planning commission which itself may need to proceed only after holding public hearings on the matter under consideration (Ref. 64).

Traditionally, enforcement of zoning provisions are accomplished through the granting of approval to proceed with a proposed project prior to its construction. However, since some problems may not be anticipated until after the fact, many municipalities are now issuing occupancy permits. In the case of noise, this enforcement procedure is particularly useful since noise isolation of the building envelope cannot be measured until the building is completed.

To control noise at a site, zoning may be used in several ways. Land within a noise impacted area can be zoned for noise compatible uses such as commercial, industrial, or agricultural. However, this technique works successfully only if the community has a noncumulative type of zoning law which prohibits, for example, residences from being built in industrial zones. Under cumulative zoning, zones are ranked in some low to high use sequence such as heavy industrial, light industrial, commercial, multi-family residential, and single family residential. Any use permitted in a high use zone, such as single family residential zone, is also allowed in lower use zones such as commercial, light industrial or heavy industrial; however, the reverse is not true (Ref. 63).

The exclusion of certain land uses in noise impacted areas must be done with caution since overexclusion can result in certain areas being underutilized, with the attendant loss of revenues. In addition, overexclusion can interfere with the orderly development of surrounding districts, and/or the region as a whole.

Zoning regulations may require specific site design details or construction practices in designated areas where the noise levels exceed a specific DNL. These noise provisions may involve the construction of noise barriers, for example along a highway adjacent to a residential area, or specification of additional noise attenuation provisions beyond those specified in a building code.

While zoning is one of the most often used tool in land use control, its effectiveness is limited by the facts that: 1) it is not permanent, so the current legislative body is not bound by prior zoning actions which can be changed; 2) it is not retroactive so it may not be possible to prohibit a particular land use in noise impacted areas if the use already exists on the land; and, 3) it applies to the land within the boundaries of a particular jurisdiction; however, noise problems often span more than one jurisdiction, each with its own regulations. This is why in addition to zoning local authorities will often rely on more than one control technque.

The severity of the noise impact on the building occupants can be controlled to some extent through the local building codes. Unlike zoning ordinances, the building codes do not restrict land use but rather insure that specified criteria and conditions inside buildings are met. The key to the effectiveness of a building code is the issuance of occupancy permits since these can be made contingent upon the builder meeting well-defined criteria upon completion of the project. If the zoning ordinance and the building code are well coordinated so that, for example, the zoning ordinance specifies the areas where particular sections of the building code requirements must be met, the effectiveness of both can be greatly enhanced.

Most of the acoustical provisions contained in building codes are presented in the form of fixed acoustical performance requiremens as, for example, in the Appendix of the Uniform Building Code (Ref. 65). These requirements may be expressed in terms of: 1) specific construction techniques such as double-glazed windows or double-studded walls; 2) in terms of mandatory noise attenuation characteristics, such as a specified sound transmission class*; or 3) in terms of a defined sound level in a type of space, such as the maximum A-weighted sound level in a bedroom at night (Ref. 13).

Recently, a Model Noise Control Code (Ref. 13) was developed under the sponsorship of the U.S. Environmental Protection Agency which, in contrast to present practices, specifies variable performance requirements for residential and educational buildings based upon the prevailing day-night average sound level, DNL, on a site. The outdoor-to-indoor noise isolation requirements of this proposed code are shown in Table 36. The techniques for predicting and implementing the sound attenuation through the building envelope were given in Section 3 of the present guidelines.

---

* The Sound Transmission Class, or STC rating, is a single number rating used for partitions separating indoors rooms. The STC rating should never be used to rate the outdoor-to-indoor noise isolation of building construction.

Table 36. Outdoor-to-Indoor Noise Isolation Requirements Contained in the EPA Model Noise Control Code Specification (Ref. 13)

Outdoor day-night average sound level, in dB	Outdoor-to-indoor A-weighted level difference, dB
50 - 55	none
55 - 60	none
60 - 65	20
65 - 70	25
70 - 75	30
75 - 80	35
> 80	construction prohibited

Subdivision control ordinances represent another type of regulatory action that can be effectively used in land use planning. It is very closely related to zoning. However, while zoning usually applies to individual lots, subdivision regulations apply to larger units. Subdivision ordinances can be effectively used to create buffer zones between noise sources and noise sensitive areas.

In communities that neither have nor wish to use zoning or subdivision control laws, an alternatie may be to include noise as a health hazard in health codes. If the noise provisions of the health codes are quantitatively expressed, the developer may have to include noise control measures to obtain an occupancy permit for buildings located in noise-impacted lands. An alternative approach for controlling noise through land use control may consist of requiring that local real estate agents inform prospective buyers of all noise impacted areas or, that noise contours be drawn on a deed or on municipal maps, subdivision plats, or zoning and land use maps. In and of itself, disclosure of noise exposure levels will not prevent inappropriate land use, but through disclosure the forces of the market place may keep noise-impacted areas from being inappropriately developed (Ref. 68).

Non-Regulatory Controls

The most effective way to prevent incompatible land use development in the vicinity of major noise sources is the direct acquisition of the land surrounding the noise source. Once the land has been acquired, the community may keep the land as it is, develop it for noise compatible uses, or sell it with restrictions on the deed to insure that only compatible uses will be developed by the new owner.

An alternative approach may be restrictive easement. An easement is a right held by one person to make use for compensation of the land of another for a limited purpose. Thus, an easement does not involve a change in ownership, but, rather, the right for noise to intrude on a tract of land for price and the impositions of restrictions on the land use options available to the owner. Unlike zoning, once an easement has been obtained it is final. Moreover, since noise easements do not involve an outright acquisition of land, the easements usually can be obtained at a fraction of the total value of the land. Since the tract does not change hands, the land remains part of the community tax base. In fact, with compatible noise development, the tax assessment may even increase relative to the value prior to the easement. Accordingly, noise easements are usually considered to be less expensive than full purchase alternatives.

In undeveloped areas, another approach to the control of noise through land use can involve the purchasing of large tracts of undeveloped lands by the local authorities prior to any development on that land. The land can then be held in trust for future use in accordance with a comprehensive plan and with local land policies. This technique, known as land banking, can be inexpensive since the land is bought prior to its being needed; however, clearly it is practical only in scarcely developed areas (Ref. 67).

Land use controls can be enhanced through financial incentives. These can take many forms. If the area around a major noise source is used as agricultural land it may be taxed as such, rather than as future developable land. This may create an incentive to keep the land as it is. Alternatively, the owner might be given a tax credit if, and only if, the land is developed into a noise-compatible use. Financial incentives designed to keep noise impacted lands from incompatible development must be carefully implemented since there can be debate over the fairness of applying preferential tax assessment or credits to some lands and not to others. Further, lowering the assessed value of property may mean a narrowing of the tax base. Another financial approach may consist of selective extension of municipal services. For example, water and sewer lines may be extended to quiet areas but not to noise impacted lands since, in general, developers are likely to locate new developments where capital improvements are located as it saves them both time and money.

5. REFERENCES

1. Guidelines for Considering Noise in Land Use Planning and Control, Federal Interagency Committee on Urban Noise, U.S. Government Printing Office: 1981-337-006/8077, June 1980

2. Information on Levels of Environmental Noise Requisite to Protect the Public Health and Welfare with an Adequate Margin of Safety, Report 550/9-74-004, U.S. Environmental Protection Agency, Office of Noise Abatement and Control, 1974.

3. American National Standard Specifications for Sound Level Meters, ANSI S1.4-1971 (R1976) American National Standards Institute, 1430 Broadway New York, NY 10018, 1976.

4. Bishop, D. E., Noise Surveys - Community Noise; Chapter 35 in Handbook of Noise Control, C. M. Harris (Ed.), Second Edition, McGraw-Hill Book Co., 1979.

5. Stevens, S. S., On the Validity of the Loudness Scale, J. Acous. Soc. of Am., 31, (7), pp. 995-1003, July 1959.

6. Barry, T. M. and Reagan, J. A., FHWA Highway Traffic Noise Prediction Model, U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-RD-77-108, July 1978.

7. Rudder, F. F., Jr. and Lam, D. F., User's Manual - FHWA Highway Traffic Noise Prediction Model - STAMINA 1.0, U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-RD-78-139, January 1979.

8. Rudder, F. F., Jr., Lam, D. F., and Chueng, P., User's Manual: FHWA Level Highway Traffic Noise Prediction Model - STAMINA 1.0, U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-RD-78-138, May 1979.

9. Connor, Thomas, et al, INM, Integrated Noise Model Version 2 - User's Guide, U.S. Department of Transportation, Federal Aviation Administration, Report FAA-EE-79-09, September 1979.

10. Noise Control and Compatibility Planning for Airports, U.S. Department of Transportation, Federal Aviation Administration Advisory, Circular 150/5020-1, FAA Office of Environment and Energy, 1983.

11. Model Community Noise Control Ordiance, U.S. Environmental Protection Agency, Office of Noise Abatement and Control, September 1975.

12. Planning in the Noise Environment, U.S. Department of Defense, Air Force Manual 19-10, TM-5-803-2 (Army), and NAVFAC P-970 (Navy), 15 June 1978.

13. Miller, N. P. and Schultz, T. J., Noise Control for Building Codes: Model Noise Control Provisions, Bolt, Beranek, and Newman Report No. 3759, prepared for U.S. Environmental Protection Agency, Office of Noise Abatement and Control, 1978.

14. Rudder, F. F., Jr., Method for Assessing Benefits of Airborne Noise Isolation Requirements in Residential and Educational Buildings, U.S. Department of Commerce, National Bureau of Standards, Report No. NBSIR 83-2680, April 1983.

15. Galloway, W. J. and Schultz, T. J., Interim Noise Assessment Guidelines, U.S. Department of Housing and Urban Development, Office of Policy Development and Research, Report HUD-CPD-586 (2), December 1980.

16. Rudder, F. F., Ronk, L. and Hutcheson, B., National Roadway Traffic Noise Exposure Model, prepared for U.S. Environmental Protection Agency, Office of Noise Abatement and Control, November 1979.

17. National Highway Inventory and Performance Study Manual, 1976, U.S. Department of Transportation, Federal Highway Administration, June 1977.

18. 1970 Census of Population, Number of Inhabitants, United States Summary: Table 20, U.S. Department of Commerce, Bureau of Census, December 1971.

19. MacTavish, D. and Newmann, D. L., Vehicle Classification Case Study for the Highway Performance Monitoring System, U.S. Department of Transportation, Federal Highway Administration, August 1982.

20. Rudder, F. F. Jr., Line Source and Site Characterization for Defining the Sound Transmission Loss of Building Facades, J. of Sound and Vibration, 91, (3), pp. 403-424, 1983.

21. Road and Rail Noise: Effects on Housing, Central Mortgage and Housing Corporation (Canada), Report HNA 5156 12/77.

22. Bishop, D. E. et al, Calculation of Day-Night Levels (L_{dn}) Resulting from Civil Aircraft Operations, U.S. Environmental Protection Agency, Office of Noise Abatement and Control, Report No. EPA 550/9-77-450, January 1977.

23. Swing, J. W. and Pies, D. B., Development of Community Noise Ratings for Railroad Operations, paper presented at the 86th meeting of the Acoustical Society of America, Wyle Research Laboratory, 128 Maryland Street, El Segundo, CA 90245, 1974.

24. Fundamentals and Abatement of Highway Traffic Noise: Textbook and Training Course - Section 4 Non-Highway Noise Sources, U.S. Department of Transportation, Federal Highway Administration, September 1980.

25. Galloway, W. J., Eldred K. McK., and Simpson, M. A., Population Distribution of the United States as a Function of Outdoor Noise Level, U.S. Environmental Protection Agency, Office of Noise Abatement and Control, Report No. EPA-550/9-74-009-A, June 1974.

26. Fidell, S., Horonjeff, R., and Green, D. M., Statistical Analysis of Urban Noise, Noise Control Engineering, 16, (2), pp. 75-80, March-April 1981.

27. Bolbey, W., Higgins, J., and Reagan, J., Noise Barrier Cost Reduction Procedure STAMINA 2.0/OPTIMA: User's Manual, U.S. Department of Transportation, Federal Highway Administration, Report FHWA-DP-58-1, April 1982.

28. Simpson, M. A., Noise Barrier Design Handbook, U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-RD-76-58, February 1976.

29. May, D. N., The Optimum Weight of Highway Noise Barriers, J. of Sound and Vibration, 68, (1), p. 113, 1980.

30. Allen, W. A. and Dickinson, P., The Tree Lined Barrier, Proceedings of Internoise 77, pp. B 587-592, 1977.

31. Schuller, W. M. and deZeeu, J. H., Acoustic Effect of Trees on Barriers, Proceedings of Inter-noise 81, pp. 253-256, 1981.

32. Ettourey, S. M. and Fricke, F. R., Courtyard Acoustics; Applied Acoustics, 6, pp. 119-132, 1973.

33. Mohsen, E. A. and Oldham, D. J., Traffic Noise Reduction Due to the Screening Effect of Balconies on a Building Facade, Applied Acoustics, 10, pp. 243-257, 1977.

34. Oldham, D. J. and Mohsen, E. A., A Technique for Predicting the Performance of Self-Protecting Buildings with Respect to Traffic Noise, Noise Control Engineering, 15, (1), pp. 11-19, 1980.

35. Hammad, R. N. S. and Gibbs, B. M., The Acoustic Performance of Building Facades in Hot Climates: Part I - Courtyard and Part 2 - Closed Balconies, Applied Acoustics, 16, pp. 121-137 and pp. 441-454, 1983.

36. Lawrence, A. and Burgess, M., Measurement of Traffic Noise Shielding Provided by Buildings, Applied Acoustics, 13, pp. 211-225, 1980.

37. Whitter, K., A Practical Prediction Model for Shielding of Traffic Noise by Roadside Buildings, Proceedings of Inter-noise 81, pp. 293-296, 1981.

38. Acoustics - Measurement of Sound Insulation in Buildings and of Building Elements - Part III: Laboratory Measurements of Airborne Sound Insulation of Building Elements, ISO 140/III-1978 (E), International Organization for Standardization, 1, Rue de Varembe, Geneva, Switzerland.

39. Standard Test Method for Measurement of Airborne Sound Insulation in Buildings, ANSI/ASTM E336-77, American Society for Testing and Materials, 1916 Race Street Philadelphia, PA 19103.

40. Mange, G. E., Skale, S. R., and Sutherland, L. C., Background Report on Outdoor-Indoor Noise Reduction Calculation Procedures Employing the Exterior Wall Noise Rating (EWNR) Method, U.S. Department of Transportation, Federal Highway Administration, Report FHWA-TS-77-220, March 1978.

41. Pallett, D. S., Wehrli, R., Kilmer, R. D., and Quindry, T. L., Design Guide for Reducing Transportation Noise In and Around Buildings, U.S. Department of Commerce, National Bureau of Standards, Report BBS 84, April 1978.

42. Quirt, J. D., Acoustic Insulation Factor: A Rating for the Insulation of Buildings Against Outdoor Noise: Building Research Note No. 148, National Research Council of Canada, Division of Building Research, Ottawa, Canada, June 1979.

43. Standard Definitions of Terms Relating to Environmental Acoustics; ANSI/ASTM C634-792, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

44. Sabine, H. J. and Moulder, R., Sound Absorptive Materials: Chapter 21 in Handbook of Noise Control, C. M. Harris (Ed.), Second Edition, McGraw-Hill Book Co., 1979.

45. Sabine, M. J., Lacher, M. B., Flynn, D. R., and Quindry, T. L., Acoustical and Thermal Performance of Exterior Walls, Doors and Windows U.S. Department of Commerce, National Bureau of Standards, Report BSS-77, November, 1975.

46. Sutherland, L. C., Indoor Noise Environments Due to Outdoor Noise Sources, Noise Control Engineering, 11, (3), November-December 1978.

47. Von Gierke, H. E., Yaniv, S. L., Blackwood, L. B., Environmental Impact Statements, Chapter 45 in Handbook of Noise Control, C. H. Harris (Ed.), Second Edition, McGraw-Hill Book Co., 1979.

48. Guidelines for Preparing Environmental Impact Statement on Noise, Report of Working Group 69 on Evaluation of Environmental Impact of Noise, Committee on Hearing, Bioacoustics and Biomechanics, National Academy of Sciences, National Research Council, Washington, D.C., 1977.

49. Schultz, T. J., Community Noise Rating, Second Edition, Applied Science Publishers, 1982.

50. Galloway, W. V., and Schultz, T. J., Interim Noise Assessment Guidelines, U.S. Department of Housing and Urban Development, Office of Policy Development and Research, Report HUD-CPD-586 (2), December 1980.

51. Schultz, T. J., Synthesis of Social Surveys on Noise Annoyance, J. Acoust. Soc. Am., 64, pp. 377-405, 1978.

52. Alexandre, A., Decision Criteria Based on Spatio-Temporal Comparisons of Surveys on Aircraft Noise in Proceedings of the International Congress on Noise as a Public Health Problem, Dubrovnik, Yugoslavia, U.S. Environmental Protection Agency, Office of Noise Abatement and Control, Report 550/9-73-008 pp. 619-626, 1973.

53. Stevens, K. N., Rosenblith, W. A., and Bolt, R. H., A Community's Reaction to Noise: Can it be Forecast?, Noise Control, 1, pp. 63-71, 1955.

54. Galloway, W. J., and Bishop, D. E., Noise Exposure Forecasts: Evolution, Evaluation, Extensions and Land Use Interpretations, U.S. Department of Transportation, Federal Aviation Administration, Report No. 70-9, 1970.

55. Airport - Land Use Compatibility Planning, Advisory Circular 150/5050-6, U.S. Department of Transportation, Federal Aviation Administration, December 1977.

56. Bishop, D. E. and Horonjeff, R. D., Noise Exposure Forecast Contours for Aircraft Noise Tradeoff Studies at Three Major Airports, U.S. Department of Transportation, Federal Aviation Administration, Report No. 70-7, 1980.

57. California Department of Aeronautics, Noise Standards, California Administrative Code, Register 70, No. 48, 28 Chapter 9, Title 4, November 1970.

58. Policy and Procedure Memorandum 90-2, U.S. Department of Transportation, Federal Highway Administration, Volume 7, Chapter 7, Section 3, 1973, (revised in 1976 as Federal Aid Highway Program Manual).

59. Noise Abatement and Control: Department Policy, Implementation Responsibilities and Standards, U.S. Department of Housing and Urban Development Circular 1390.2, August 1971.

60. Guidelines for Noise Impact Analysis, U.S. Environmental Protection Agency Office of Noise Abatement and Control, Report PB82-219205, April 1982.

61. Caudra, E. D., Aircraft/Airport Noise and the Courts, Chapter 38 in Handbook of Noise Control, C. M. Harris (Ed.), Second Edition, McGraw-Hill Book Co., 1979.

62. Rosenthal, A. J., Noise and the Law, Chapter 37 in Handbook of Noise Control, C. M. Harris (Ed.), Second Edition, McGraw-Hill Book Co., 1979.

63. The Audible Lanscape: A Manual for Highway Noise and Land Use, U.S. Department of Transportation, Federal Highway Administration, Office of Research and Development, November 1974, reprinted August 1976.

64. So, F. S., Stollman, I., Barl, F., and Arnold, D. S., The Practice of Local Government Planning, International City Management Association, 1979.

65. Internal Conference of Building Officials, Uniform Building Code, Whittier, Ca. 1979, Appendix, Chapter 35, Sound Transmission Control.

66. Schultz, T. J., Miller, N. P., and Miller, R. L., Interim Report Task 1: Development of Noise Control Requirements for Model Building Code, Bolt, Beranek and Newman Report 3547, prepared for the U.S. Environmental Protection Agency, 1977.

67. Strong, A., Land Banking: European Reality, American Prospect, Johns Hopkin's University Press, 1979.

68. Taylor, S. M., Breston, B. E., and Hall, F. L, The Effect of Road Traffic Noise on House Prices, J. of Sound and Vibration, <u>30</u>, (4), pp. 523-541, 1982.

Appendix A. NOISE PREDICTION MODELS

This appendix presents the details of the noise prediction models described in Section 2 of the main text. Using these results, the tabulated values presented in the various lookup tables may be calculated directly.

A.1 Highway Traffic Noise Prediction Model

The basis for the highway traffic noise prediction model is the formulation presented in Appendix J of Ref. 6. The site geometry is illustrated in Figure 34. The highway pavement comprises several adjacent lanes and is considered to be acoustically hard. The land between the near pavement edge and the receiver is flat and free of obstructions. This land area may be either acoustically hard or soft.

Using the nomenclature of Ref. 6 and the distances illustrated in Figure 34, the equivalent sound level at the receiver for the i^{th} vehicle type on the r^{th} lane is given by:

$$\begin{aligned}(L_{eq})_{ir} = (\overline{L}_o)_{Eir} &+ 10 \log (\pi N_{ir} D_o / S_{ir}) \\ &+ 10 \log (D_o/D_r) \\ &+ 10 \log (D_o/D_{1r})^{\alpha_1} \\ &+ 10 \log (D_{1r}/D_r)^{\alpha_2} \\ &+ 10 \log [\Psi_{\alpha_1} (\phi_1, \phi_2)/\pi] \qquad \text{(A-1)}\end{aligned}$$

where

N_{ir} is the number of vehicles of the i^{th} type on the r^{th} lane

D_o is the reference distance for the vehicle emission level $(\overline{L}_o)_{Eir}$

S_{ir} is the speed of the i^{th} vehicle type on the r^{th} lane

$D_r = D_2 + D_{1r}$, total distance between the r^{th} lane and the receiver

$$\Psi_{\alpha_1} (\phi_1, \phi_2) = \frac{1}{\pi} \int_{\phi_1}^{\phi_2} [\cos \phi]^{\alpha_1} \, d\phi.$$

For an acoustically hard pavement, $\alpha_1 = 0$, and for a straight infinite-length roadway, the above expression may be simplified to obtain

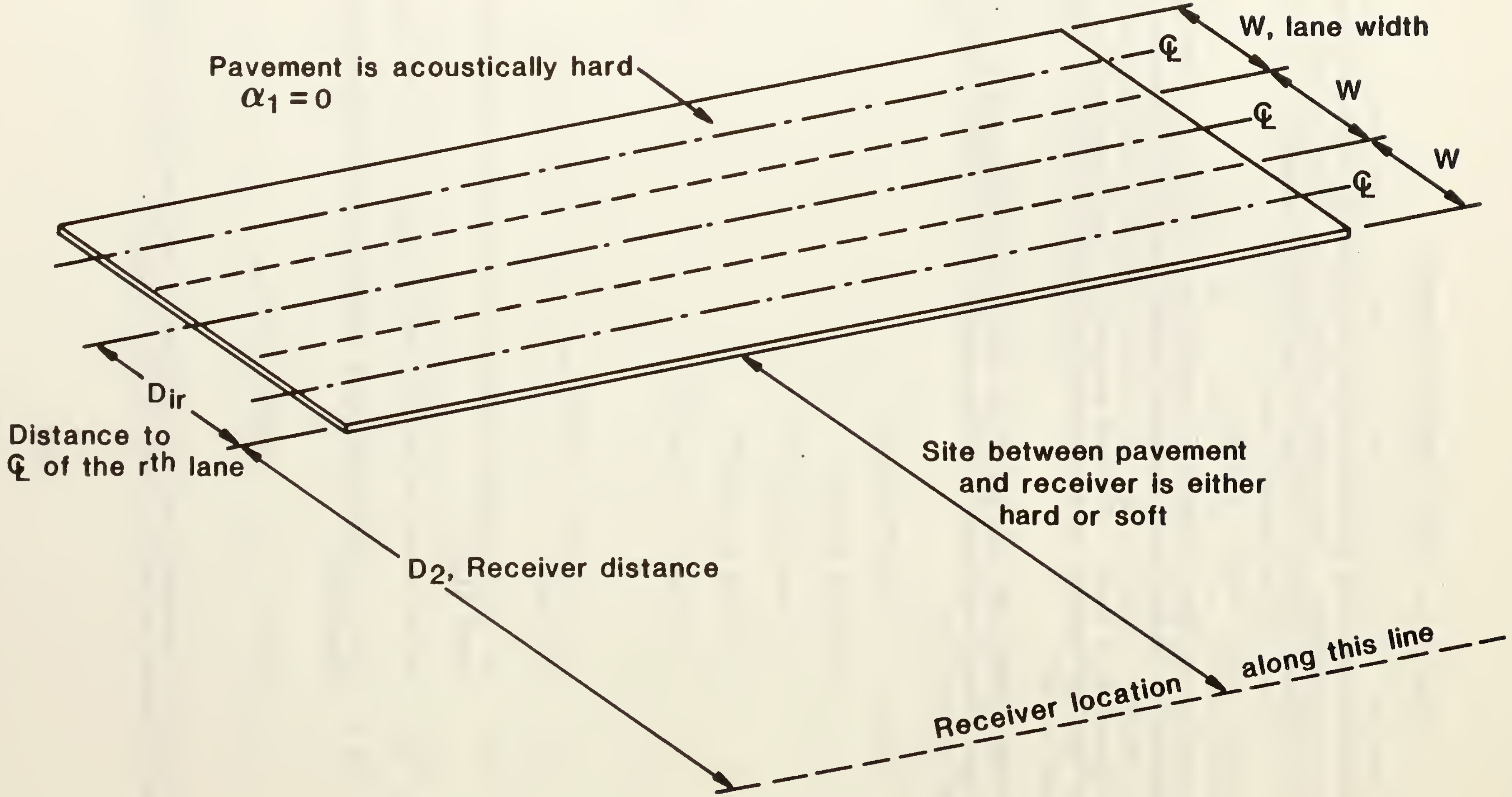


Figure 34 Pavement - Receiver Geometry for Highway Traffic Noise Prediction

$$(L_{eq})_{ir} = (\bar{L}_o)_{Eir} + 10 \log (N_{ir}/S_{ir}) + 10 \log (\pi D_o^2/K)$$

$$- 10 \log (D_2) + 10 \log [P_r^{\alpha_2}/(1+P_r)^{1+\alpha_2}] \qquad \text{(A-2)}$$

where $P_r \equiv (W/D_2)\ (r-1/2)$

K is a constant for maintaining consistent units among the several variables.

For multi-lane traffic flows, the eqivalent sound level is simply the summation of Equation (A-2) over all lanes and vehicle types on each lane. The next simplification results from assuming that the traffic flow is uniformly distributed over all lanes and, that the average cruise speed is constant for all vehicles on all lanes. With these assumptions the expression for the equivalent sound level of the traffic flow becomes:

$$\bar{L}_{eq} = 10 \log \left\{ \sum_{i=1}^{3} (N_i/N)\ 10^{(\bar{L}_o)_{Ei}/10}/S \right\} + 10 \log (N)$$

$$- 10 \log (D_2) + 10 \log (\pi D_o^2/K)$$

$$+ 10 \log \left\{ \frac{1}{n} \sum_{r=1}^{n} P_r^{\alpha_2}/(1 + P_r)^{1+\alpha_2} \right\} \qquad \text{(A-3)}$$

where N is the total vehicle count for the highway

S is the average cruise speed

n is the number of traffic lanes

subscript i denotes vehicle type

subscipt r denotes lane.

This result represents the equivalent sound level for the time period during which N vehicles pass by the receiver.

The expression for the day-night sound level is obtained by summing, on an energy basis, the expression given by Equation (A-3) for each hour of the day and introducing a + 10 dB weighting for the nighttime period from 10 p.m. to 7 a.m. and dividing the summation by 24-hr. However, data for traffic flows will not typically be available on an hourly basis. Therefore, it is assumed that only the total count during the daytime and the nighttime are available.

Further, it is asumed that during an average day the traffic speed does not vary, and remains constant for each hour.

With these assumptions, the expression for the day-night sound level at the receiver location may be expressed as:

$$
\begin{aligned}
L_{dn} = {} & 10 \log \left\{ \sum_{i=1}^{3} (f_{di} + 10\, f_{ni}) F_i \cdot 10^{(L_o)_{Ei}/10} / \overline{S} \right\} + 10 \log (\overline{N}) \\
& - 10 \log (D_2) + 10 \log (\pi D_o^2 / 24K) \\
& + 10 \log \left\{ \frac{1}{n} \sum_{r=1}^{n} P_r^{\frac{\alpha}{2}} / (1 + P_r)^{\frac{1+\alpha}{2}} \right\}
\end{aligned}
\qquad \text{(A-4)}
$$

where N is the AADT of the traffic flow, vehicles/24-hr

$\overline{S}$ is the average 24-hr cruise speed

$f_{di} = N_{di}/\overline{N}$, fraction of i^{th} vehicle type in the traffic flow during the day

$f_{ni} = N_{ni}/\overline{N}$, fraction of i^{th} vehicle type in the traffic flow during the night

$F_i = \overline{N_i}/\overline{N}$, fraction of the i^{th} vehicle type in the 24-hr traffic flow.

The relationships between the various vehicle count parameters are as follows:

$$
N_{di} = \sum_{day} N_i; \quad N_{ni} = \sum_{night} N_i; \quad \overline{N_i} = N_{di} + N_{ni}\ ; \quad \overline{N} = \sum_{i=1}^{3} \overline{N_i}
$$

where $\sum_{day}$ is a summation over the 15-hr period from 7 a.m. to 10 p.m.

$\sum_{night}$ is a summation over the 9-hr period from 10 a.m. to 7 a.m.

In the above development, three vehicle types have been assumed. The speed-dependent A-weighted noise emission levels for the vehicle types are obtained from Ref. 6 as:

$$
\begin{aligned}
&\text{Automobiles;} && (\bar{L}_o)_{E1} = 5.5 + 38.1 \log(S) \quad \text{dBA} \\
&\text{Medium Trucks;} && (\bar{L}_o)_{E2} = 23.4 + 33.9 \log(S) \quad \text{dBA} \qquad \text{(A-4)} \\
&\text{Heavy Trucks;} && (\bar{L}_o)_{E3} = 43.6 + 24.6 \log(S) \quad \text{dBA}
\end{aligned}
$$

where S is the cruise speed in mph.

Equation (A-4) may be used to calculate the day-night sound level. However, the formulation is inconvenient for a simplified lookup table format. Accordingly, the following approximation is used.

$$\sum_{i=1}^{3} (f_{di} + 10\, f_{ni}) F_i\, 10^{(\bar{L}_o)_{Ei}/10} \approx (1+9f_{nMAX}) \sum_{i=1}^{3} F_i\, 10^{(\bar{L}_o)_{Ei}/10} \qquad \text{(A-5)}$$

where f_{nMAX} is the fraction of nighttime traffic flow corresponding to the vehicle type with the highest sound level.

For example, if all vehicle types are present in the traffic flow, then $f_{nMAX} = f_{n3}$ since heavy trucks represent the vehicle type generating the highest sound level. If medium trucks and automobiles are present in the traffic flow, then $f_{nMAX} = f_{n2}$. If only one vehicle type is present in the traffic flow, the above result is exact.

We now define a reference distance, D_{ref}, for the highway system measured from the near edge of the pavement and away from the highway. This reference location is used to define the L_{dn} value for the highway system. The day-night sound level at this location is denoted as $(L_{dn})_{ref}$. The expression is obtained by substituting $D_2 = D_{ref}$ and Equation (A-5) into Equation (A-3). This result is formally subtracted from Equation (A-3) to obtain the normalized expression for the day-night sound level for receiver locations $D \geq D_{ref}$. The result may be expressed as:

$$L_{dn}(D) = (L_{dn})_{ref} + \Delta(D) \quad \text{for } D \geq D_{ref} \qquad \text{(A-6)}$$

where $(L_{dn})_{ref} = L_{dn}(D_{ref})$, Eqn (A-3) with (A-5)

$\Delta(D)$ is the distance attenuation function.

The expression for $L_{dn}(D_{ref})$ is:

$$
\begin{aligned}
L_{dn}(D_{ref}) = {} & 10 \log \left\{ \sum_{i=1}^{3} F_i\, 10^{(\tilde{L}_o)_{Ei}/10} / S \right\} \\
& + 10 \log \left\{ (1+9f_{nMAX}) \cdot N \right\} \\
& + \Delta_{ref} \qquad \text{(A-7)}
\end{aligned}
$$

The first term in this expression is used to obtain the traffic flow reference noise levels presented in Table 4. The second term in the expression is used to obtain the adjustment presented in Table 5. The last term is the hard site/soft site adjustment entered in step number 3 of the highway traffic noise prediction worksheet.

The complete expression for Δ_{ref} is:

$$\Delta_{ref} = 10 \log \left\{ \frac{\pi D_o^2}{24K\, D_{ref}} \right\} + 10 \log \left\{ \frac{1}{n} \sum_{r=1}^{n} [P_r^{\alpha}/(1+P_r)^{1+\alpha}]_{D=D_{ref}} \right\} \quad \text{(A-8)}$$

where the notation in the last term implies P_r is evaluated at $D = D_{ref}$ and α is the hard/soft site parameter for the land adjacent to the highway.

The value for the constant K depends upon the units used to measure distance, traffic flow speed and time. For the present development, distance is expressed in ft, speed in mph and time in hr; so, the value of K is 5280 ft/mph. For metric units utilizing m, km/hr and hr, K = 1000 m/km/hr.

The distance attenuation function, $\Delta(D)$, is given by the expression:

$$\Delta(D) = 10 \log (D_{ref}/D_2) + 10 \log (G(D_2)/G(D_{ref})), \quad \text{(A-9)}$$

where $G(D) = \sum_{r=1}^{n} [P_r^{\alpha}/(1+P_r)^{1+\alpha}]_D$

$p_r = (W/D)(r-1/2)$

W is the lane width

r is the lane number (r=1 denotes the near lane).

Equation (A-9) is used to obtain the distance adjustment values presented in Table 6 for hard sites (α=0) and in Table 7 for soft sites (α=0.5).

The explicit numerical values given in Tables 4 through 9 were obtained using the constants:

$D_o = 50$ ft

$D_{ref} = 50$ ft

$K = 5280$ ft/mph

$W = 12$ ft

The numerical evaluation of any of the above expressions is straightforward. The only required comment concerns the expression for Δ_{ref} given by Equation (A-8). As seen in Equation (A-8), the second term depends upon both the site condition (as characterized by α) and the number of traffic lanes. Numerically, the difference between $\alpha=0$ and $\alpha=0.5$ results in a 3 dB difference in the value of Δ_{ref}. The numerical result of incorporating the number of traffic lanes represents a difference of less than 0.5 dB for either $\alpha=0$ or $\alpha=0.5$. Hence, the Δ_{ref} term is incorporated as a "site constant" based upon $\alpha=0$ or $\alpha=0.5$, and the ±0.5 dB variation corresponding to the number of traffic lanes is ignored.

A.2 Railway Noise Prediction Model

The prediction of the day-night sound level resulting from railway operations incorporates two distinct types of events: warning horn noise and locomotive pass-by noise. For either type of event, the following procedure is used:

- Define the equivalent sound level for a single event with the duration of the noise corresponding to the 20 dB down points of the noise time history.

- Calculate the day-night sound level by summing the contribution of each single event equivalent sound level and by weighting the nighttime events by + 10 dB.

Denoting the single event level by L_{SEL}, the expression for the day-night sound level is:

$$L_{dn} = L_{SEL} + 10 \log (N/24) + 10 \log (1+9f_n) \qquad \text{(A-10)}$$

where $L_{SEL} = L_{eq} + 10 \log (T_o)$

L_{eq} is the equivalent sound level for the single event of duration T_o

N is the number of events per day

f_n is the fraction of the daily events that occur between 10 p.m. and 7 a.m.

Equation (A-10) is the basic relationship used to predict the value of L_{dn} for railway-operations. Hence, we may concentrate upon obtaining the expressions for L_{SEL} for warning horn noise and for pass-by noise. The reader may also note that Equation (A-10) also applies to aircraft noise prediction where L_{SEL} corresponds to an aircraft noise event (see Ref. 22).

Warning Horn Noise

For warning horn noise, the site geometry is illustarted in Figure 35. To simplify the analysis, it is assumed that any two single warning horn noise events may be combined into one event comprising the train pass-by with the warning horn operating continuously between the two horn initiation points indicated in Figure 35. This assumption is equivalent to assuming that, on an average day, an equal number of trains approach the warning point from either direction.

For the purpose of developing a tabulation format for computing the noise exposure, it is convenient to define a reference distance, D_{ref}, and a reference speed for the train, S_{ref}. Then, considering the warning horn to be a continuous point source generating a maximum sound level L_{horn} at a distance D_{ref}, and, assuming "hard site" noise propagation (i.e., geometrical spreading), the expression for the single event level is:

$$L_{SEL} = (L_{SEL})_{ref} + \Delta L_{SEL}(L,D) \qquad \text{(A-11)}$$

where

$$(L_{SEL})_{ref} = L_{horn} + 10 \log (\bar{L}/KS) + 10 \log [H(0,\bar{\ell}_{ref})/\bar{\ell}_{ref}]$$

$$\Delta L_{SEL}(L,D) = 10 \log [(D_{ref}/D)\, H(\bar{\ell},\bar{\ell})/H(0,\bar{\ell}_{ref})]$$

$$H(x,y) = \tan^{-1} [(x+y)] - \tan^{-1} [(x-y)]$$

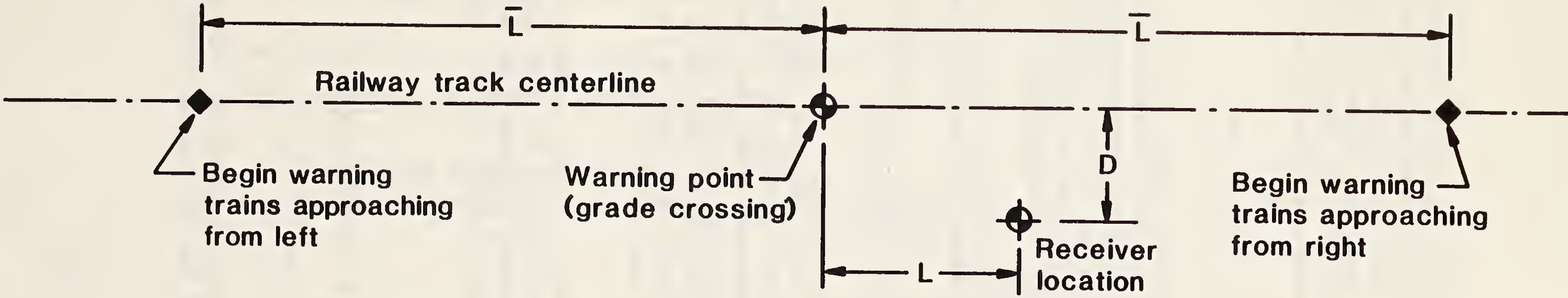
$$\ell = L/D;\ \bar{\ell} = \bar{L}/D;\ \bar{\ell}_{ref} = \bar{L}/_{Dref}.$$

Remembering that L_{SEL} as defined by Equation (A-11) comprises two "actual" events, we substitute Equation (A-11) into Equation (A-10) to obtain the expression for the day-night sound level for warning horns. The result is

$$L_{dn} = L_{horn} + 10 \log [(D_{ref}/S_{ref}) \tan^{-1} (\bar{L}/D_{ref})/24K] + \Delta L_{SEL}(L,D)$$

$$+ 10 \log [S_{ref}N/S] + 10 \log (1+9f_n). \qquad \text{(A-12)}$$

By defining the values for the nine parameters (L_{horn}, L, D, S, N, f_n, L, D_{ref}, and S_{ref}) numerical results are obtained. The numerical values in Table 12 were obtained using the last term of Equation (A-12). The numerical values in Table 14 were obtained using the first three terms of Equation (A-12) with the numerical values: L_{horn} = 101 dBA, D_{ref} = 100 ft, S_{ref} = 50 mph (K = 5280 ft/mph) and $\bar{L}$ = 1/4 mi = 1320 ft. The numerical values in Table 15 were obtained using the next-to-last term of Equation (A-12).



Single event comprises the lead locomotive initiating the warning at a distance $\bar{L}$ away from the warning point and stopping the warning when the lead locomotive reaches the warning point. For a train moving at speed S, the duration of the single event is $T_o = \bar{L}/S$.

Figure 35. Source-Receiver Geometry and Single Event Definition for Predicting Railway Warning Horn Noise Exposure.

The value of L_{horn} = 101 dBA at 100 ft from the track centerline is an approximation. This level is selected to be 10 dB higher than the reference diesel-electric locomotive noise level described below. Since the L_{dn} value is directly proportional to the value of L_{horn}, the values in Table 14 may be corrected for variations in L_{horn} as desired. For example, if local data indicate that L_{horn} was 105 dBA at 100 ft, the values in Table 14 would all be increased by 4 dB.

Diesel-Electric Pass-By Noise

The prediction of the pass-by noise day-night sound level for a diesel-electric locomotive and a number of railway cars is more complicated than either the prediction of highway traffic or the warning horn noise exposures described previously. The complication arises from the details of the noise emission characteristics of the locomotive, the cars, and the train. Otherwise, the prediction models are similar in that the following method is used:

1) Define the single event level for an average event in terms of a level at a reference distance and a distance attenuation function; and,

2) Define the day-night sound level in terms of the single event level and the day-night distribution of the noise events.

Figure 36 illustrates the train as a finite length line source moving at constant speed along a straight railway track. The locomotive noise is assumed to be characterized as a point noise source whose sound power output is independent of the train speed. The railway cars generate noise that varies linearly with the logarithm of the train speed and exhibits a dipole directivity with the dipole axis perpendicular to the track alignment. The sound power distribution of the cars is assumed to be constant along the length of the cars. These noise emission characteristics are representative of diesel-electric locomotives and railway rolling stock (Ref. 23).

Since we are concerned with the total energy at the receiver, we can calculate the energy received from each locomotive and from the line source of railway cars for an average train pass-by comprising N locomotives and n railway cars. With this approach, the total train length is denoted by ℓ and is expressed as:

$$\ell = N\ell_{loco} + n\ell_{car} \tag{A-13}$$

where ℓ_{loco} is the average length of a locomotive = 70 ft

ℓ_{car} is the average length of a car = 70 ft.

The single event levels are obtained by integrating the time-dependent sound level at the reference distance between the 20 dB down points measured from the maximum pass-by level.

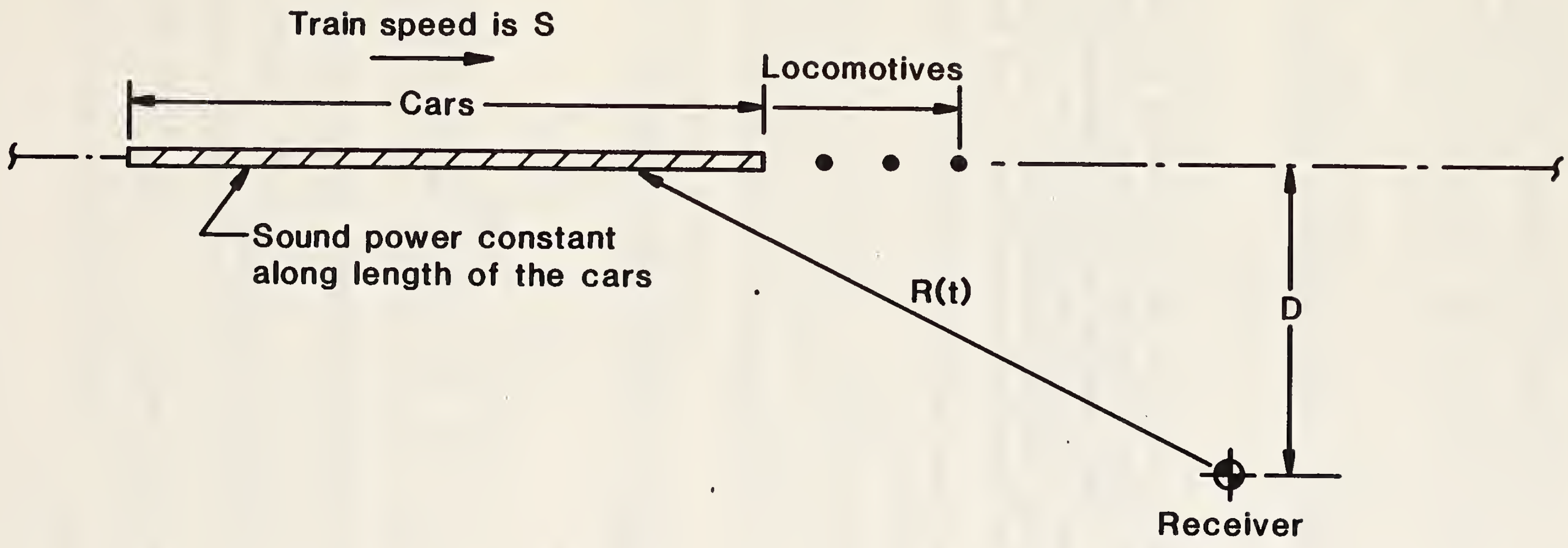


Figure 36. Source–Receiver Geometry for Diesel-Electric Railway Pass-by Noise Prediction.

Denoting the maximum locomotive pass-by level by L_1, referenced to the distance D_{ref}, the single event level for a locomotive pass-by is expressed as

$$(L_{SEL})_1 = L_1 + 10 \log (D_{ref}/3S) + 10 \log [g_1(3x) + g_2(3x)] \qquad \text{(A-14)}$$

where S is the pass-by speed

$x = D_{ref}/D$ and $6D_{ref}/S$ is the duration of the event

$g_1(Z) = Z \tan^{-1}(Z)$; $g_2(Z) = Z^2/(1+Z^2)$

Denoting the maximum pass-by level of the railway cars by L_2, referenced to the distance D_{ref}, the single event level for the line source of length ℓ is obtained by a double integration. The first integration is over the length of the line source for a fixed instant of time, and the second integration is over the time interval between the 20 dB down points of the pass-by time history. (It should be noted that by considering the cars to be distributed over the total train length, the wheel noise of the locomotive is included in the analysis.)

Performing the details of the integration, the single event level for the railway car pass-by is obtained as:

$$(L_{SEL})_2 = L_2 + 10 \log\left\{\bar{\ell}[g_1((2\bar{\ell}+3)x) - g_1(3x)]/[g_1(\bar{\ell}) + g_2(\bar{\ell})]\right\} \qquad \text{(A-15)}$$

where $\bar{\ell} = \ell/2\, D_{ref}$, and $2(\bar{\ell}+3)D_{ref}/S$ is the duration of the event.

Based upon the data of Ref. 23, the following noise emission characteristics for D_{ref} = 100 ft are introduced:

Locomotive: $L_1 = 91$ dBA

L_{cars} $L_2 = 84.5 + 20 \log (S/55)$; S, mph.

If there are N locomotives per train, the train length is then given by the expression:

$$\ell = (N\ell_{loco} + n\ell_{cars}) = N\,(\ell_{loco} + \bar{n}\ell_{cars})$$

where $\bar{n}$ is the number of cars per locomotive.

Introducing the dimensionless train length:

$$\tilde{\ell} = (\ell_{loco} + \bar{n}\ell_{cars})/2D_{ref}$$

the expression for the total equivalent sound level at the receiver is obtained by adding, on an energy basis, N times the contribution of a single locomotive, Equation (A-14) and the contribution of the railway cars, Equation (A-15). The resulting expression is substituted into Equation (A-10) to obtain the relationship for predicting the day-night sound level.

In order to develop a format suitable for tabulation, the resulting L_{dn} expression is normalized to the reference distance, D_{ref}. The result is the estimated L_{dn} at the reference distance and a distance attenuation term. The detailed expression is:

$$L_{dn} = (L_{dn})_{ref} + \Delta L_{train} \qquad \text{(A-16)}$$

where

$$(L_{dn})_{ref} = (L_{train})_{ref} + 10 \log (N_{train}/24) + 10 \log (1+9f_n)$$

$$(L_{train})_{ref} = L_1 + 10 \log (N\, D_{ref}/S) + 10 \log [G(1,\, s,\, \overline{n},\, N)]$$

$$\Delta L_{train} = 10 \log [G(x,\, S,\, \overline{n},\, N)/G(1,\, S,\, \overline{n},\, N)]$$

$$G(x,\, S,\, \overline{n},\, N) = [g_1(x) + g_2(x)]/3 + \frac{\tilde{\ell}(S/55c)^2\, [g_1((2N\tilde{\ell}+3)x) - g_1(3x)]}{[g_1(N\tilde{\ell}) + g_2\,(N\tilde{\ell})]}$$

N_{train} is the total number of trains per day

f_n is the fraction of trains operating at night

N is the average number of locomotives per train

$\overline{n}$ is the average number of cars per locomotive

S is the train speed in mph

$c = 10^{(L_1 - 84.5)/20}$ and,

all other terms are as defined previously.

The numerical values in Table 10 were obtained using the above expression for $(L_{train})_{ref}$. The adjustment in Table 11 were evaluated using the second term in the above expression for $(L_{dn})_{ref}$ and the values in Table 12 were obtained using the last term. The values for the distance attenuation listed in Table 13 were based upon the above expression for ΔL_{train}.

In order to develop a similar model for soft site noise propagation, the procedure must be evaluated numerically rather than using the simple lookup table format possible for the hard site condition.

Combining Sound Levels

For a site exposed to railway noise generated by warning horns, diesel-electric locomotives and by railway cars, during a single event it is necessary to combine the two sound levels to determine the total noise exposure. Similarly, if a site is exposed to both highway and railway noise, it is necessary to combine the two simultaneous noise events to determine the total noise exposure. Indeed, if any two sound levels are simultaneously received, their combined level may be obtained using the following expression:

$$L_{combined} = L_1 + 10 \log [1 + 10^{-(L_1-L_2)/10}] \tag{A-17}$$

where L_1 and L_2 are the two sound levels.

If L_1 is always taken as the higher of the two sound levels, Equation (A-17) may be easily tabulated since the second term will be between 0 and 3 dB. This result is the basis for the procedure given in Table 16 for combining the sound levels.

Appendix B. OUTDOOR NOISE MITIGATION

This appendix presents the technical background necessary to document to procedures used to obtain the barrier insertion loss values listed in Table 18. It also contains an approximate method for determining the insertion loss values for locations about buildings exposed to highway traffic noise.

B.1. Highway Traffic Noise Barriers

The insertion loss of a barrier depends upon the relative geometry of the noise source location, the top edge of the barrier, and the receiver location. The geometric nonclature for the barrier insertion loss prediction is illustrated in Figures 37, 38, and 39. The methodology utilized is based upon the development presented in Appendix B of ref. 6. However, two important differences are introduced for the purposes of the present guidelines. First, the present results are developed for the special case of an infinite-length barrier parallel to the highway. Second, the small angle approximation used in Ref. 6 to relate the maximum path length difference of a point on the line source is replaced by the exact expression. Except for these two differences the present methodology is identical to that contained in the Ref. 6.

Clear Site Conditions

For the clear site in the absence of the barrier, the expression for the equivalent sound level at the receiver for the ith vehicle type on the jth lane of the roadway is given by:

$$(L_{eq})_i = (\overline{L}_o)_{Ei} + 10 \log \left(\frac{\pi D_o^2 N_i}{K\, D_r S_i}\right) + 10 \log \left\{ \frac{1}{n} \sum_{j=1}^{n} \frac{P_j^{\alpha}}{(1+P_j)^{1+\alpha}} \right\} \qquad \text{(B-1)}$$

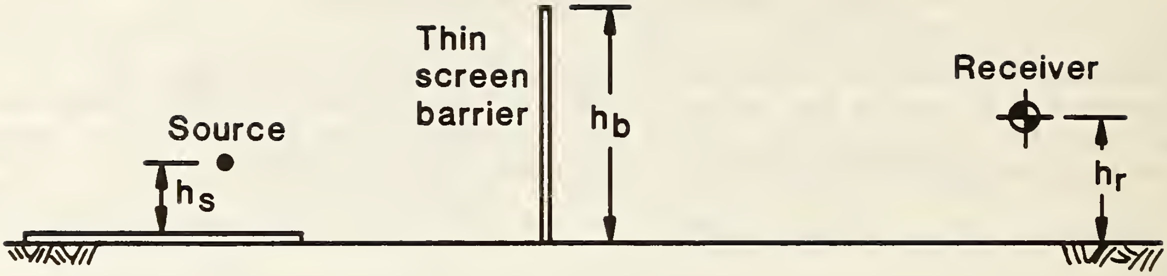
where $P_r = (W/D_r)(j - 1/2)$; $D_r = D_2 + D_{1j}$

K is a constant for maintaining consistent units among the several variables.

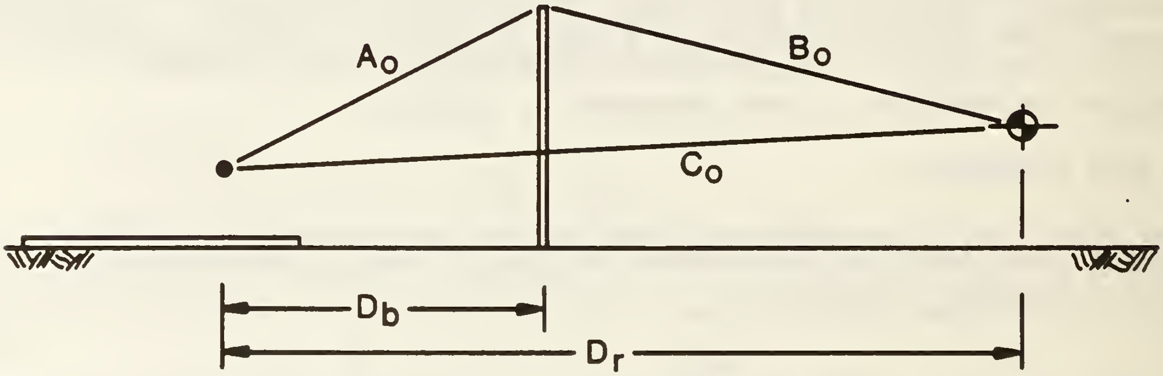
The result is identical to Equation (A-2).

Site Conditions with Barrier Installed

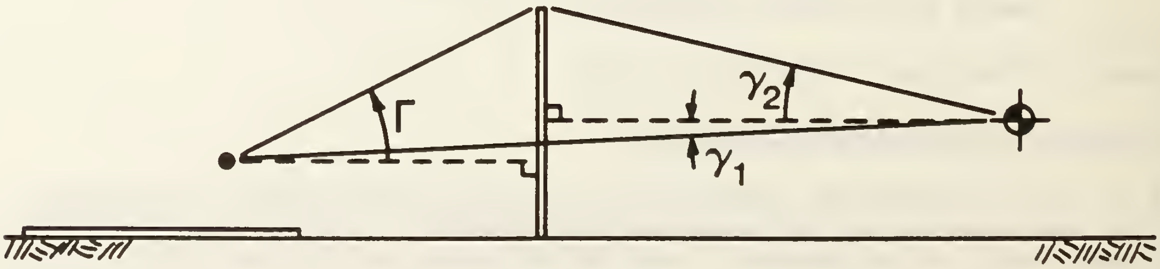
When a barrier is installed between the source and the receiver, the acoustic energy at the location of the receiver is decreased if the receiver is within the "shadow zone" of the barrier. The net attentuation provided by the barrier is called the barrier insertion loss and is defined as the equivalent sound level at the receiver location before the barrier is installed less the equivalent sound level after the barrier is installed. Equation (B-1) represents the "before" conditions.



a) Definition of source, barrier, and receiver heights



b) Definition of distances relating source, top of barrier, and receiver



c) Definition of angles relating source, top of barrier, and receiver

Figure 37. Geometric Nomenclature for Thin Screen Barrier: Section Through Site Perpendicular to Highway and Containing the Receiver Location.

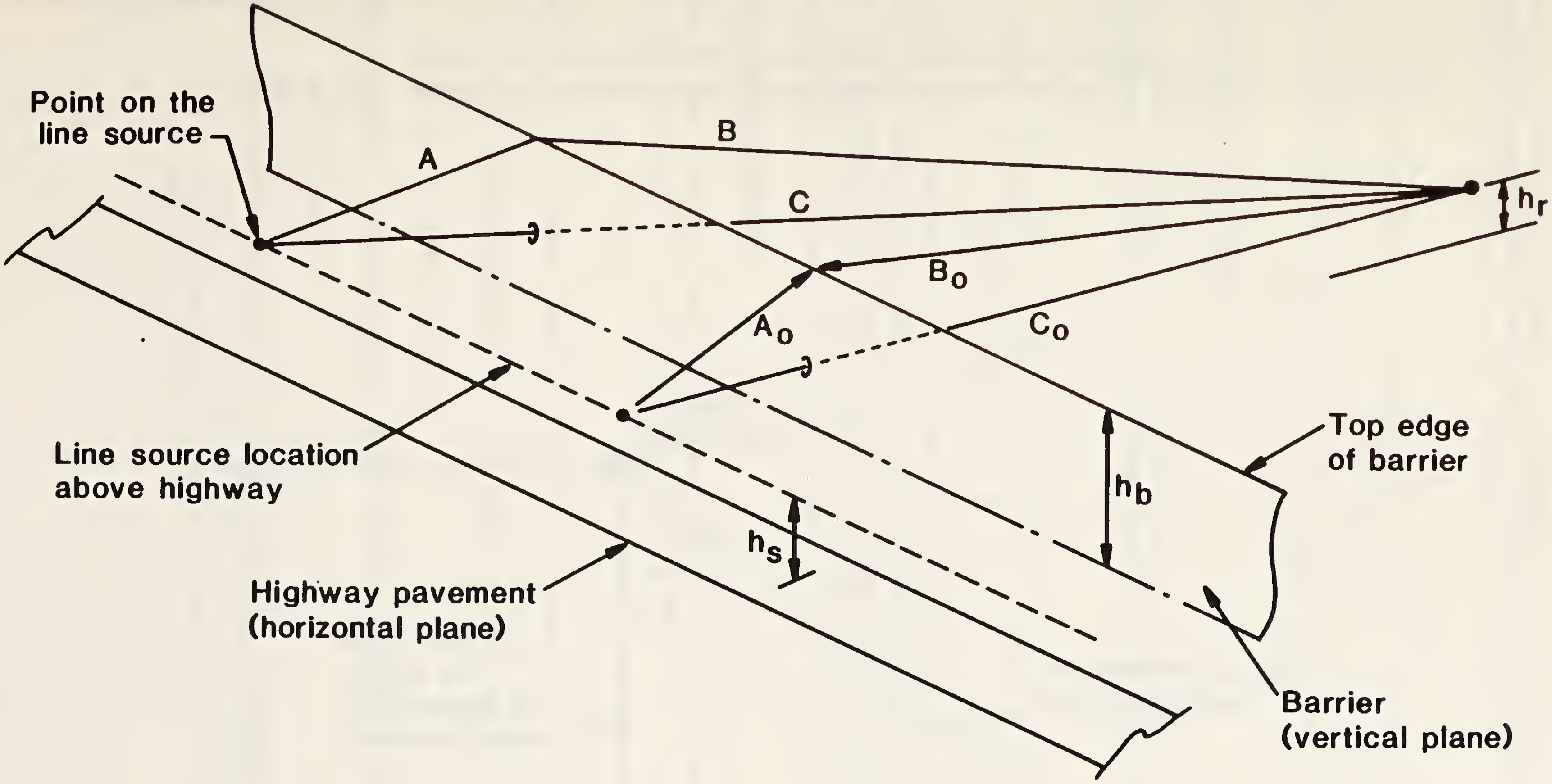


Figure 38. Geometric Nomenclature Relating Noise Source Location to the Reference Plane Perpendicular to the Highway and Containing the Receiver Location (See Figure 37)

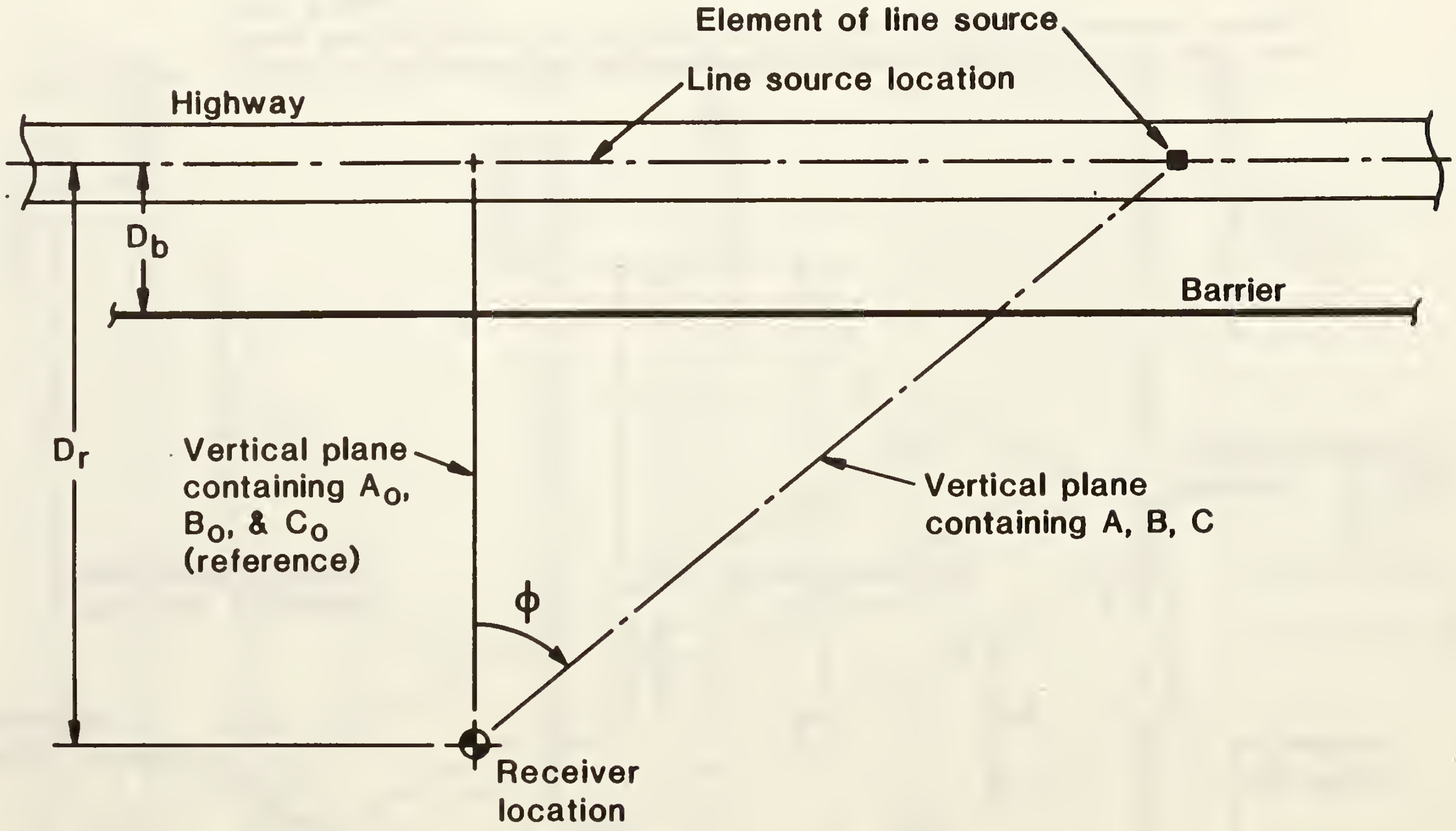


Figure 39. Geometric Nomenclature Relating the Location of an Element of the Line Source to the Receiver Plane (See Figures 37 and 38)

Following the same argument as presented in Ref. 6 and assumptions used to develop Equation (A-2) and (B-1), the equivalent sound level after the barrier is installed is given by the expression:

$$(L_{eq})_i = (\overline{L}_o)_{Ei} + 10 \log \left\{ \left(\frac{\pi D_o^2 N_i}{K D_r S_i} \right) \right\} + 10 \log \left\{ \frac{1}{n} \sum_{j=1}^{n} \frac{10^{\overline{\Delta}_{ij}/10}}{(1+P_j)} \right\} ,\text{dB} \qquad \text{(B-2)}$$

where $\overline{\Delta}_{ij}$ defines the barrier noise attenuation for the i^{th} vehicle type of the j^{th} lane of the highway.

Barrier Insertion Loss

The expression for the barrier insertion loss for the i^{th} vehicle type on the highway is obtained by subtracting Equation (B-2) from Equation (B-1). The result is:

$$(IL)_i = 10 \log \left\{ \sum_{j=1}^{n} \frac{P_j^{\alpha_2}}{(1+P_j)^{1+\alpha_2}} \right\} - 10 \log \left\{ \sum_{j=1}^{n} \frac{10^{\overline{\Delta}_{ij}/10}}{(1+P_j)} \right\} ,\text{dB} \qquad \text{(B-3)}$$

This result asssumes that the vehicle distribution is uniform over all lanes and that the travel speed is constant. The parameters that determine the value of the barrier insertion loss are the geometric variables illustrated in Figures 37 through 39 and the site constant $\underline{\alpha}$. The only remaining problem is establishing the functional form of $\overline{\Delta}_{ij}$.

Barrier Diffraction

The attenuation provided by the barrier is characterized by the Fresnel Number, N, and is defined by the relationship:

$$N = 2\delta/\lambda = 2f\delta/c \qquad \text{(B-4)}$$

where λ is the wave length of the sound wave

f is the frequency of the sound

c is the speed of sound

The parameter δ is called the path length difference and is defined as:

$$\delta = \pm (A+B-C) \qquad \text{(B-5)}$$

where the + sign is used if the receiver is in the shadow zone and

the - sign is used if the receiver has a direct line of sight to the noise source.

With this background, the function $\overline{\Delta}_{ij}$ is defined as:

$$10^{\overline{\Delta}_{ij}/10} \equiv \frac{2}{\pi} \int_{o}^{\pi/2} 10^{-\Delta_{ij}/10} \, d\phi \tag{B-6}$$

where ϕ is the angle illustrated in Figure 39 and the integration limits are established by the assumption that the highway and the barrier are both of infinite length.

The only complication is that the integral in Equation (B-6) must be numerically evaluated since Δ_{ij} is a complicated function of the angle ϕ.

The Attenuation Function $\Delta_{ij}(\phi)$

Using the diffraction theory of Ref. 6, the attenuation function is given by the relationships:

$$10^{-\Delta_{ij}/10} = \begin{cases} 1 & \text{for} \quad N_{ij} \leq -0.1916 - 0.0635\varepsilon \\ 10^{-(1+0.6\varepsilon)/2} \tan^2 \sqrt{2\pi |N_{ij}|} & \text{for} \quad -0.1916-0.0635\varepsilon \leq N_{ij} \leq 0 \\ 10^{-(1+0.6\varepsilon)/3} \tanh^2 \sqrt{2\pi N_{ij}} & \text{for} \quad 0 \leq N_{ij} \leq 5.03 \\ 10^{-2(1+0.15\varepsilon)} & \text{for} \quad N_{ij} \geq 5.03 \end{cases} \tag{B-7}$$

where $\quad N_{ij}(\phi) = (2f/c)\delta_{ij}(\phi)$

Again, following Ref. 6, the amount of numerical effort is vastly reduced by assuming a frequency of 550 Hz rather than conducting the calculations for a specific source spectrum. With this approximation, the expression for the Fresnel Number is:

$$N_{ij}(\phi) = \begin{cases} 3.21 \ \delta_{ij}(\phi) & \text{with distance measured in m} \\ 0.982 \ \delta_{ij}(\phi) & \text{with distance measured in ft.} \end{cases}$$

Referring to Figure 38, it now remains to determine the functional relationship between the site geometry as described in Figure 37 for the reference plane and Figure 39 for an element of the line source located by the angular coordinate ϕ.

We now introduce the following notation:

$$\delta_o = \delta(\phi{=}0) = \pm(A_o + B_o - C_o) \qquad \text{(B-8)}$$

$$\delta(\phi) = \pm(A(\phi) + B(\phi) - C(\phi))$$

With the geometry as defined in Figures 37 through 39, the following functional relationships are obtained:

$$A(\phi) = A_oF(\Gamma,\phi)$$

$$B(\phi) = B_oF(\gamma_2,\phi) \qquad \text{(B-9)}$$

$$C(\phi) = C_oF(\gamma_1,\phi)$$

where $F(\theta,\phi) = (1+\cos^2\theta \tan^2\phi)^{-1/2}$.

For small values of θ, $F(\theta,\phi) \approx \cos\theta$, and the relationships (B-8) and (B-9) result in the approximation:

$$\delta(\phi) \approx \delta_o \cos\phi.$$

In many practical barrier design problems this approximation connot be used, and the more complicated functions obtained by substituting Equations (B-8) and (B-9) into (B-7) and, by integrating according to Equation (B-6), are required. To simplify the notation, the subscripts i and j have been dropped in Equations (B-8) and (B-9).

Barrier Attenuation Tables

In order to develop numerical values suitable for the present guidelines, an extensive tabulation of barrier insertion loss values was developed. Figure 40 is a self-explanatory example of one of these tabulations. The values in Figure 40 may be compared to the value of 6.0 dB ± 1.0 dB given in Table 18c) for an 8 ft high barrier located 25 ft from the pavement. The distance D given in Figure 40 is the distance from the near edge of the pavement to the receiver.

B.2 Shielding Provided by Buildings

Figure 17 of the main text is a qualitative illustration of the noise shielding provided by buildings. The topic of sheilding provided by "barriers" of the form of buildings is complicated and perhaps still a research topic. However, using the approach described by Wittner in Ref. 37, an approximate result may be obtained. This approximation ignores sound diffraction completely and assumes that geometric or "ray" acoustics describes the physics of the problem. From a practical standpoint, these assumptions mean that the building should be high, wide and deep. The insertion loss values that are predicted can be expected to be slightly higher than what one might measure under field

MAXIMUM BARRIER INSERTION LOSS, dB

BARRIER HEIGHT: 8.0 ft
DISTANCE FROM PAVEMENT TO BARRIER 25 ft
RECEIVER HEIGHT: 5.0 ft
HEAVY TRUCKS

D	Number of Traffic Lanes					
ft	1	2	3	4	6	8
50	6.3	6.4	6.4	6.5	6.6	6.6
75	5.5	5.5	5.6	5.6	5.7	5.7
100	5.3	5.3	5.3	5.3	5.4	5.4
150	5.1	5.1	5.1	5.1	5.2	5.2
200	5.1	5.1	5.1	5.1	5.1	5.1
250	5.0	5.0	5.0	5.1	5.1	5.1
300	5.0	5.0	5.0	5.0	5.1	5.1
350	5.0	5.0	5.0	5.0	5.0	5.0
400	5.0	5.0	5.0	5.0	5.0	5.0
450	5.0	5.0	5.0	5.0	5.0	5.0
500	5.0	5.0	5.0	5.0	5.0	5.0
750	5.0	5.0	5.0	5.0	5.0	5.0
1000	5.0	5.0	5.0	5.0	5.0	5.0
1500	5.0	5.0	5.0	5.0	5.0	5.0

Figure 40. Example of Barrier Insertion Loss Tabulation

conditions. To simplify the analysis, it is further assumed that no other building is located near by and that no sound is reflected toward the receiver. Figure 41 illustrates the site geometry for estimating the shielding provided by buildings. In terms of the dimensionless coordinates (ξ,η) illustrated in Figure 41, the insertion loss is given by the expression:

$$IL(\xi,\eta) = -10 \log (\Phi(\xi,\eta)/\pi),\ \text{dB} \quad \text{for } \eta > o \text{ and } -a \leq \xi \leq +a. \tag{B-10}$$

The function $\Phi(\xi,\eta)$ is given by the expression

$$\Phi(\xi,\eta) = \pi - [\phi_1(\xi,\eta) + \phi_2(\xi,\eta)] \tag{B-11}$$

where $\phi_1(\xi,\eta) = \tan^{-1}[(1+\xi)/\eta)]$

$\phi_2(\xi,\eta) = \tan^{-1}[(1-\xi)/\eta)]$

$\xi = x/a;\ \eta = [y-(D+b)]/a.$

Since the highway is of infinite length, the y-axis is a center line of symmety for the insertion loss value. It may be shown that the contour of IL = 3 dB is a circle of radius a (half the building width) centered at $(\xi,\eta) = (0,0)$. Similarily for IL > 3 dB, the contours are elliptical in shape with the major axis centered at $\eta = 0$ (i.e., the rear face of the building). The expression for a contour of constant insertion loss is given by the equation:

$$\eta = -k + \sqrt{k^2 + 1 - \xi^2} \tag{B-12}$$

where $k = 1/\tan \beta$

$\beta = \pi \cdot 10^{-IL/10}$ for $IL \geq 3$ dB.

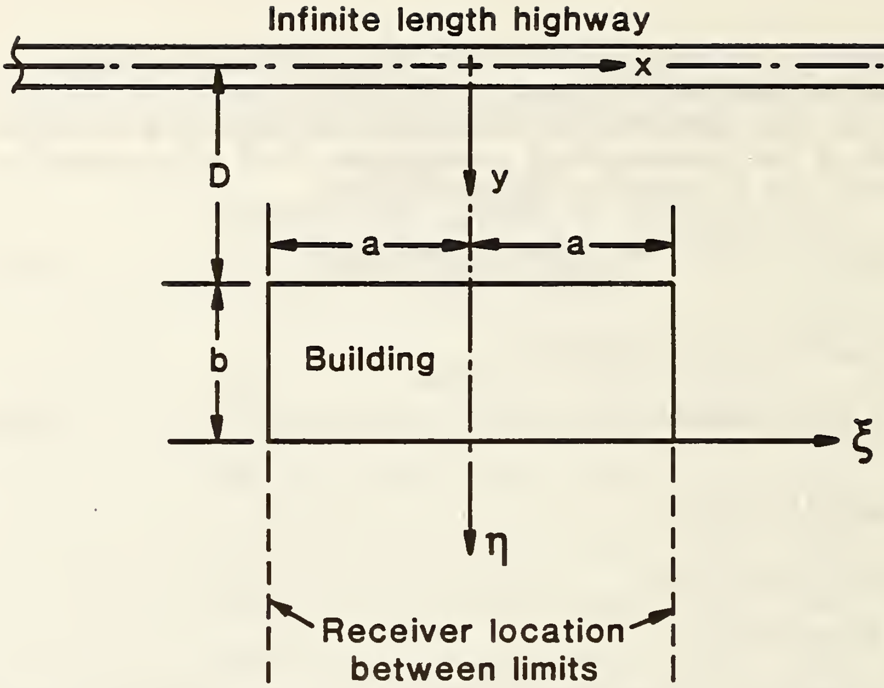
By setting $\xi = 0$ in Equation (B-12), one obtains an estimate of the distance away from the rear surface of the building to the contour of constant insertion loss. Further, Equation (B-12) may be integrated to obtain the area enclosed between the contour insertion loss and the rear surface of the building. The resulting expression for the area is:

$$A = a^2\ [\beta - \sin\beta\ \cos\beta]/\sin^2\beta \tag{B-13}$$

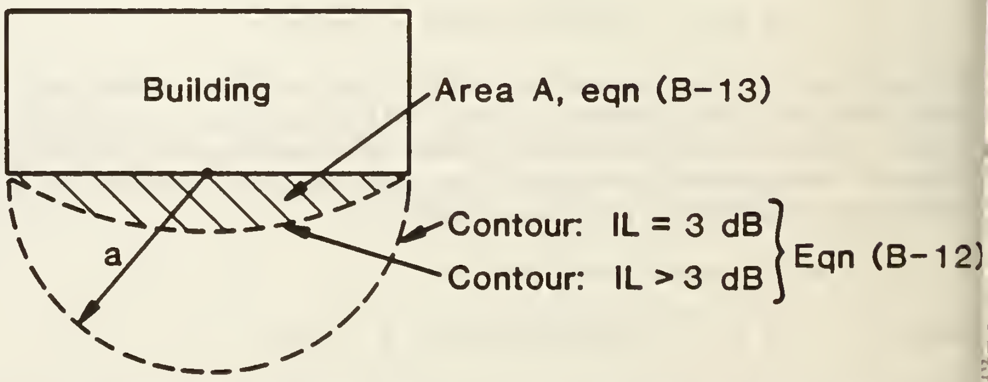
where $\beta = \pi \cdot 10^{-IL/10}$ for $IL \geq 3$ dB.

The above results may be useful in estimating the maximum values of insertion loss provided by buildings.

For rows of buildings and the inclusion of reflections, the user should consult the following paper: Yeow, K.W., Popplewell, N., and Mackay, J.F.W., Shielding of noise from statistically stationary traffic flows by simple obstacles, Journal of Sound and Vibration, Vol. 57 No. 2, 22 March 1978.



a) Geometric nomenclature



b) Nomenclature for contours of constant insertion loss

Figure 41. Nomenclature for Insertion Loss Estimate Provided by Buildings

Appendix C. A-WEIGHTED NOISE ISOLATION OF BUILDINGS

This appendix describes the details of the calculations required to estimate the A-weighted sound transmission loss values described in Section 3.2 of the main report, and the noise isolation of building envelopes.

C.1 Normalized Noise Spectra

The first step in estimating the A-weighted sound transmission loss is the determination of the normalized noise spectrum characterizing the outdoor noise. Two normalized spectra are described in this appendix: a highway traffic noise spectrum and a "composite" spectrum. The method used to normalize the data, however, may be applied to any other spectrum shape desired.

The noise spectrum is defined by a set of values for the band center frequencies, f_r, and the corresponding band pressure levels, L_r. It is assumed that the data comprise a total of N values: $\{f_r, L_r\}$ $r=1,\ldots,N$. The spectrum is then defined between the band center frequency limits f_1 and f_N.

The band center frequencies, f_r, are related to the index r by the expression:

$$f_r = 2^{c(r-q)} \cdot 10^3, \text{ Hz} \tag{C-1}$$

where $c = 1$ for octave band data

$c = 1/3$ for one third-octave band data

$q = 1 + [3 - \log (f_1)]/c \log (2).$

It is assumed that the spectrum may be approximated as a continuous function of frequency as:

$$L(f) = L_A + \Delta L (f), \text{ dB} \tag{C-2}$$

where L_A is the overall A-weighted sound level

$\Delta L(f) = A - \frac{m}{\log(2)} \log (f/f_{ref})$

$f_{ref} = 1000$ Hz.

Substituting Equation (C-1) into Equation (C-2), the approximation for the band pressure level at the r^th center frequency is:

$$L_r = L_A + \Delta L_r, \quad \text{dB} \tag{C-3}$$

where $\Delta L_r = A - c(r-q)m$

$r = 1,\ldots,N$ ·

Denoting the actual band pressure levels as L_r, the overall A-weighted sound leve is expressed as:

$$L_A = 10 \log \left\{ \sum_{r=1}^{N} 10^{[L_r+W_r]/10} \right\} ,\text{dB} \qquad \text{(C-4)}$$

where W_r is the A-weighted relative response value for the r^{th} center frequency.

We can now define a normalized spectrum by the set of sound levels:

$$\tilde{L}_r \equiv L_r - L_A, \text{ dB} \qquad \text{(C-5)}$$

$r = 1,\ldots,N$ ·

In Equations (C-2) and (C-3), the constants A and m are determined by a least-square data fit by considering the error between the normalized data, $\tilde{L}_r$, and the approximation, ΔL_r. The total mean-square error is then expressed as:

$$\varepsilon_T^2 = \sum_{r=1}^{N} (\tilde{L} - \Delta L_r)^2 \cdot \qquad \text{(C-6)}$$

The values of A and m are determined by minimizing the total mean-square error.

The resulting expressions are:

$$A = 6 \left\{(N+1) \; [(2N+1)/3 - q] \; \Sigma \, \tilde{L}_r + [2q - (N+1)] \; \Sigma r \cdot \tilde{L}_r\right\}/N(N^2-1) \qquad \text{(C-7a)}$$

$$m = (6/c) \left\{(N+1) \; \Sigma \, \tilde{L}_r - 2 \; \Sigma r \cdot \tilde{L}_r\right\}/N(N^2-1) \qquad \text{(C-7b)}$$

where the summations are over r = 1, ...,N.

Table 37 presents the normalized one-third-octave band data used in the present guidelines. The traffic noise spectrum is based upon the FHWA STAMINA 1.0 model (Ref. 8) and the "composite" spectrum is based upon the spectrum used to develop the AIF rating (Ref. 21).

For the data in Table 37, the least square procedure described above yields the following results:

TABLE 37. Normalized A-weighted Spectra

f_c, Hz	Composite spectrum $\tilde{L}_r$, dB(re L_A)	Traffic Noise spectrum $\tilde{L}_r$, dB(re L_A)
50	-28.1	-
63	-23.1	-3.3
80	-17.8	-4.0
100	-14.2	-4.2
125	-11.2	-4.6
160	- 8.9	-6.1
200	- 8.4	-7.2
250	- 8.7	-8.5
315	- 8.7	-8.3
400	- 8.5	-8.1
500	- 9.1	-8.0
630	- 9.4	-8.2
800	- 9.5	- 8.4
1000	-10.3	- 8.8
1250	-10.9	-10.2
1600	-11.3	-11.4
2000	-11.5	-12.8
2500	-11.6	-14.9
3150	-12.5	-17.0
4000	-13.3	-18.7
5000	-14.8	-21.2
6300	-16.2	-23.2
8000	-20.2	-25.9
10000	-25.8	-

composite spectrum: $N = 24;\ A = -13.5;\ m = 0.05$ (C-8a)

traffic noise spectrum: $N = 22;\ A = -12.4;\ m = 2.8$ (C-8b)

The above values of A and m may be substituted into Equation (C-2) to obtain the explicit functional form for $\Delta L(f)$. Figure 42 is a plot of both $\tilde{L}_r$ and $\Delta(f)$ for the composite noise spectrum. Figure 43 is the corresponding result for the highway traffic noise spectrum. The slope, m, given by Equation (C-7b) is used to characterize the outdoor noise used in calculating the A-weighted sound transmission loss of a structure.

C.2 Normalized Sound Transmission Loss

The normalized sound transmission loss is defined in an identical manner as described above for the noise spectrum. The sound transmission data defined by the set of values $\{f_r, TL_r\}$ are used to estimate an expression for the sound transmission loss as follows:

$$TL(f) = TL_{ref} + \frac{n}{\log(2)} \log (f/f_{ref}) \tag{C-9}$$

where $TL_{ref} = TL(f_{ref})$

$f_{ref} = 1000$ Hz.

For the band center frequencies given by Equation (C-1) and using the least square error procedure described in Section C.1, the estimates of TL_{ref} and n are given by the expressions:

$$\begin{aligned} TL_{ref} = 6 \{&(N+1) [(2N+1)/3 - q] \Sigma\, TL_r \\ &+ [2q - (N+1)] \Sigma r \cdot TL_r\}/N(N^2-1) \end{aligned} \tag{C-10a}$$

$$n = (6/c) \{2\, \Sigma r \cdot TL_r - (N+1)\, \Sigma\, TL_r\}/N(N^2-1). \tag{C-10b}$$

The summations denoted by Σ are over the band center frequency index $r = 1,\dots,N$ (see Equation (C-1)). Equation (C-10) may be compared with Equation (C-7). It is also mentioned that m is the average slope of the outdoor noise spectrum in dB/octave and n is the average slope of the sound transmission loss data. As defined by Equations (C-2) and (C-9), the m is positive if the outdoor noise spectrum decreases with increasing frequency, and, n is positive if the TL data exhibit a trend of increasing with increasing frequency.

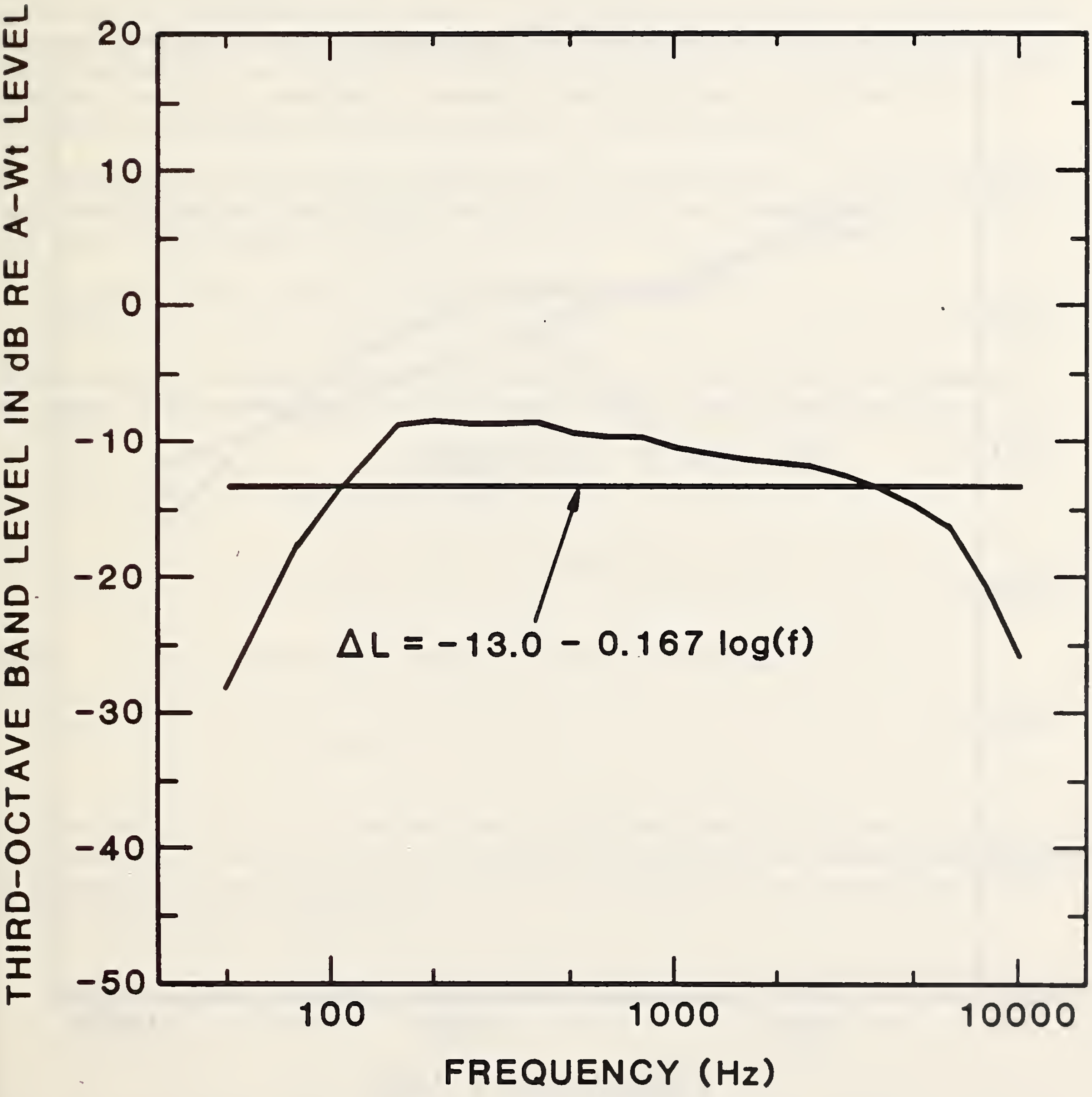


Figure 42. Normalized Spectrum for Composite Noise

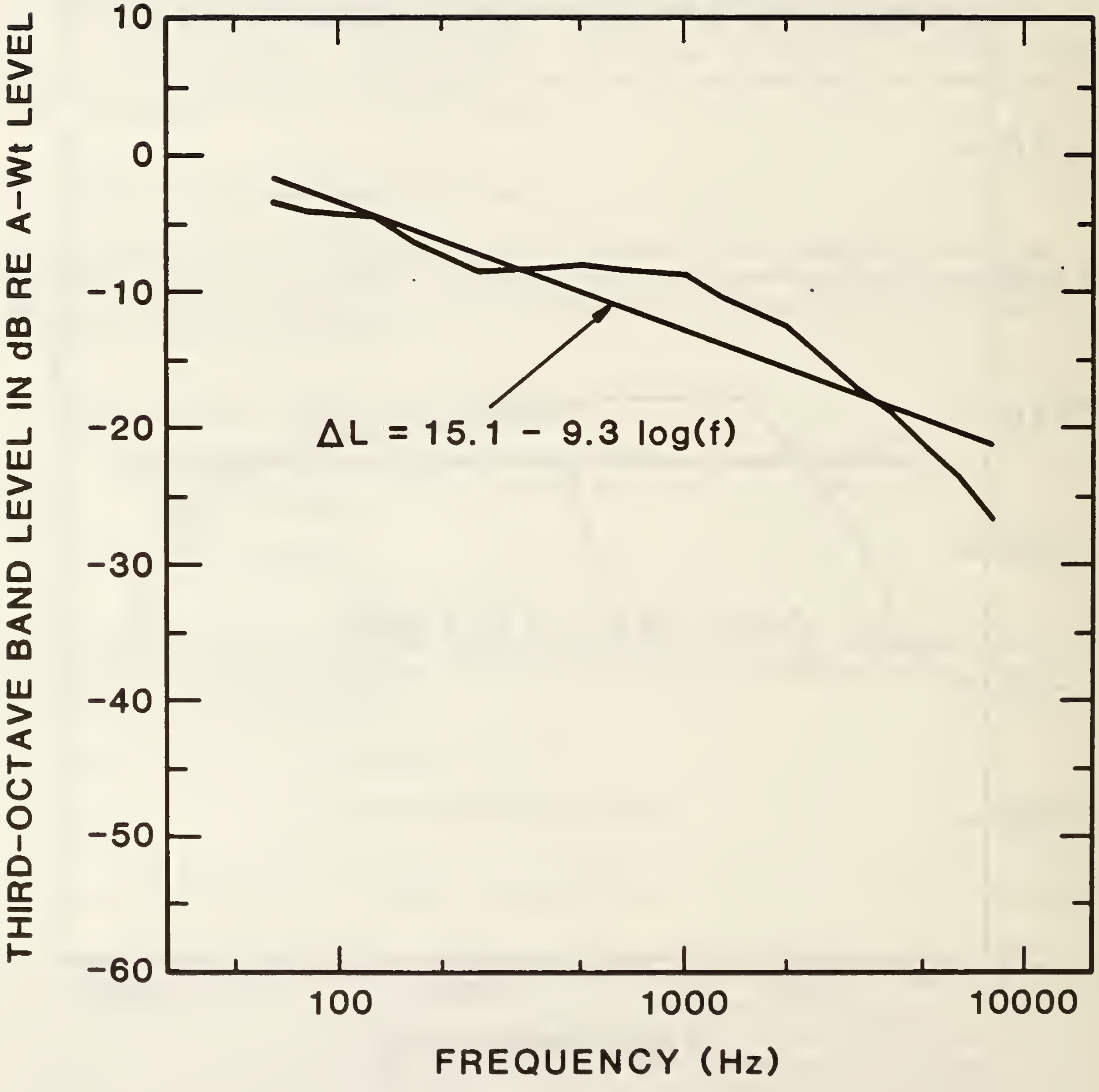


Figure 43. Normalized Spectrum for Highway Traffic Noise

C.3 A-Weighted Sound Transmission Loss

This section defines the A-weighted sound transmission loss untilizing the above approximations for the outdoor noise spectrum and the sound transmision loss of the structure. Properly, the terminology should be "A-weighted noise isolation" as described in the main text. However, it will be seen that the method, in fact, results in a characterization of the noise insulation of the construction that is adjusted to incorporate the effect of the outdoor noise spectrum shape in a systematic manner. The objective, of course, is to estimate the A-weighted noise isolation of the construction.

For outdoor-to-indoor sound transmission, the relationship between the indoor band sound pressure level, L_{Ir}, and the outdoor band sound pressure level, L_r, for the r^{th} band center frequency is:

$$L_{Ir} = L_r - TL_r + 10 \log [(S_w/A) \overline{\cos\theta}]_r + 6, \text{ dB} \tag{C-11}$$

Introducing the A-weighted relative response for the r^{th} band and summing over all bands, the expression for the overall indoor A-weighted sound level is:

$$\begin{aligned} L_{Ir} &= L_A + 10 \log [(S_w/A) \overline{\cos\theta}] + 6 \\ &+ 10 \log \{ \sum_{r=1}^{N} 10^{[\tilde{L}_r + W_r - TL_r]/10} \} \text{ ,dB} \end{aligned} \tag{C-12}$$

where L_A is the outdoor overall A-weighted sound level:

$\tilde{L}_r = L_r - L_A$ (see Eqn. (C-5)).

In Equation (C-12), it is assumed that the normalization for the receiving room sound adsorption and the angle-of-incidence correction is essentially independent of frequency. Considering this term to be a constant, the A-weighted sound transmission loss is defined as:

$$TL_A = - 10 \log \{ \sum_{r=1}^{N} 10^{[\tilde{L}_r + W_r - TL_r]/10} \} \tag{C-13}$$

For each band center frequency, f_r, the normalized outdoor level, $\tilde{L}_r$, and the sound transmission loss, TL_r, may be approximated using Equations (C-1), (C-3), and (C-9). The results are:

$$\tilde{L}_r \approx \Delta L_r = A - c(r-q)m \tag{C-14a}$$

$$TL_r \approx TL_{ref} - c(q-r)n \qquad \text{(C-14b)}$$

Substituting these values into Equation (C-13), the A-weighted sound transmission loss is approximated by the expression:

$$TL_A = TL_{ref} - A - c(m+n)q - 10 \log \left\{ \sum_{r=1}^{N} 10^{[W_r - c(m+n)r]/10} \right\} \qquad \text{(C-15)}$$

Similarily, the A-weighted noise reduction, denoted by $\widehat{NR}_A$, may be estimated by noting that the outdoor sound level is approximated by the expression:

$$\hat{L}_A = L_A + A + mcq + 10 \log \left\{ \sum_{r=1}^{N} 10^{[W_r - cmr]/10} \right\} \qquad \text{(C-16)}$$

to obtain:

$$\widehat{NR}_A = TL_{ref} - 10 \log [(S_W/A)\, \overline{\cos\theta}] - 6 + C_{mn} \qquad \text{(C-17)}$$

where $C_{mn} = -cnq + B_m - B_{(n+m)}$

$$B_M \equiv 10 \log \left\{ \sum_{r=1}^{N} 10^{[W_r - cMr]/10} \right\} .$$

The importance of these results is that the approximations to the A-weighted sound transmission loss and the A-weighted noise reduction indicate relationships whereby the outdoor noise spectrum shape and the sound transmission loss of the construction may be characterized independently of each other. This may be seen by realizing that the summations appearing in Equations (C-15) through (C-17) may be calculated independently of either the specific noise spectrum or the sound transmission loss data.

Since one is mainly interested in estimating the A-weighted noise reduction (i.e., the difference between the outdoor and indoor A-weighted sound levels), the values of C_{mn} required for Equation (C-17) are presented in Figure 44. Since the products cm and cn are independent of the bandwidth, the value of C_{mn} is also independent of bandwidth. This means that the above results apply equally to both octave band and one-third-octave band data.

C.4 Evaluation of the Procedure

A numerical evaluation of the above procedure was conducted to estimate the error between using the direct calculation indicated by Equation (C-12) and the approximate calculation indicated by Equation (C-17). Since the normalization terms for sound absorption and angle of incidence are the same in both expressions,

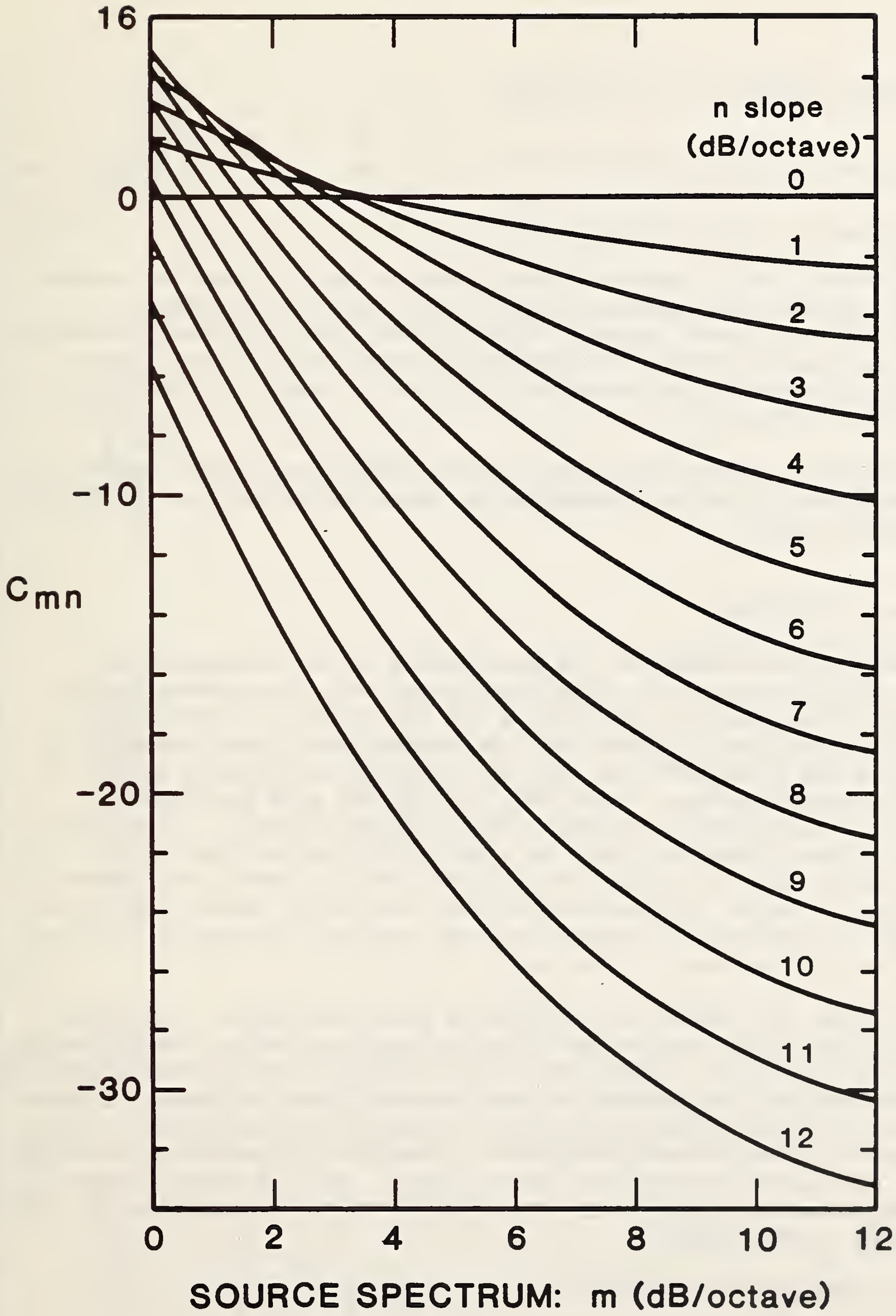


Figure 44. Values of the Term C_{mn}

the comparison was based upon the following:

$$(NR_A)_{direct} = -10 \log \left\{ \sum 10^{[\tilde{L}_r + W_r - TL]/10} \right\} - 6 \quad , dB \qquad \text{(C-18a)}$$

$$(NR_A)_{approximate} = TL_{ref} + C_{mn} - 6 \ , \ dB \ . \qquad \text{(C-18b)}$$

Using the A-weighted traffic noise spectrum given in Table 37 and the average slope m = 2.8 dB/octave (see Equation (C-8b)), the results indicated in Table 38 were obtained. These results indicate that, the approximate technique underpredicts the A-weighted noise reduction by approximately 2 dB, with a sample standard deviation of approximately 1 dB over a range of noise reduction values between 25 and 35 dBA.

The values presented in Tables 20 through 26 of the main text, were based upon the direct calculation of the A-weighted noise reduction rather than predicted values as described above.

C.5 Open Window Conditions

This section presents the basis for the calculation of the average annual envelope noise level reduction for conditions requiring open windows during part of the year. The main text emphasizes the importance of maintaining a completely sealed envelope to insure that the design noise level reduction is achieved. During the cold months of the year, windows will remain closed to maintain indoor thermal comfort. Similarly, during the warm months air conditioning may be utilized to maintain indoor thermal comfort. Depending upon the local climate, however, there is a period during the year when windows could remain open to achieve the desired indoor thermal environment. The question then arises as to the estimation of the annual average value of the envelope noise isolation if windows are open during a portion of the year and closed during the remainder of the year.

We begin by defining two values of the envelope noise isolation: one value corresponding to the closed window condition and the other value corresponding to the open window condition. These two values represent the extreme conditions, and we are concerned with calculating a value between these extremes. Example 6 in the main text illustrates how one estimates the envelope A-weighted noise level reduction for closed window conditions. Example 7 illustrates the steps for estimating the noise isolation for open windows. Both of these values depend upon the percentage of glazing area of the envelope surrounding the room and the open area of the window.

We define the closed and open envelope noise isolation as follows:

$(\Delta L_A)_{closed}$	is the A-weighted noise isolation with windows closed
$(\Delta L_A)_{open}$	is the A-weighted noise isolation with the window open

Table 38. Comparison Between Direct and Approximate Calculation of A-Weighted Noise Reduction: Highway Traffic Noise Spectrum

Construction category	Sample size	Mean difference direct - approximate, dBA	Sample standard deviation, dBA	Range of NR_A values, dBA
Glazing	178	+ 2.4	1.0	10 to 46
Walls	131	+ 1.8	1.0	20 to 54
Doors	43	+ 2.4	0.9	10 to 45
Roofs	37	+ 3.0	1.0	10 to 35

The average annual outdoor L_{dn} value is denoted as L_{dnO}.

With these definitions, we then obtain the average indoor day-night sound levels:

$$(L_{dnI})_{open} = L_{dnO} - (\Delta L_A)_{open} \quad \text{for windows open } \underline{\text{all day}} \tag{C-19a}$$

$$(L_{dnI})_{closed} = L_{dnO} - (\Delta L_A)_{closed} \quad \text{for windows closed } \underline{\text{all day}} \tag{C-19b}$$

From the definition of the equivalent sound level, the average annual indoor sound level for the windows open and the windows closed is expressed as:

$$L_{dnI} = 10 \log \left\{ (T_{open}/T_{year}) \cdot 10^{(L_{dnI})_{open}/10} + (T_{closed}/T_{year}) \cdot 10^{(L_{dnI})_{closed}/10} \right\} ,\text{dB} \tag{C-20}$$

where T_{open} and T_{closed} represent the average number of days that the windows are open or closed per year, respectively, and

$$T_{year} = 365 \text{ day per yar} = T_{open} + T_{closed} .$$

We now define the percentage of time that the windows are open as:

$$P_{open} = 100 \; (T_{open}/T_{year})$$

and note that

$$P_{closed} = 100 - P_{open}$$

Substituting these definitions into Equation (C-20), we obtain the expression for the average annual envelope noise isolation as:

$$L_{dnO} - L_{dnI} = - 10 \log \left\{ (P_{open}/100) \cdot 10^{-(\Delta L_A)_{open}/10} + ((1-P_{open})/100 \cdot 10^{-(\Delta L_A)_{closed}/10} \right\} ,\text{dB} \tag{C-21}$$

This result was used to calculate the values shown in Table 32 using $(\Delta L_A)_{open}$ = 13 dBA and the range of values for $(\Delta L_A)_{closed}$ and P_{open}.

C.6 Formulation or Worksheets

This section describes the mathematical basis for the worksheets and lookup tables used to calculate the noise reduction of the building envelope. Figure 32 illustrates the physical aspects of each worksheet and the nomenclature utilized in the present guidelines. Table 28 of the main text lists the purpose of each worksheet. The present discussion focuses upon the formulation of each worksheet, and is provided because the steps utilized may not appear "a priori" to correspond to the steps one might use in a direct calculation.

Worksheets V through VIII are used to calculate the indoor DNL contribution for each envelope member and each outdoor noise source. The results obtained in Worksheet VIII must be combined using Table 16 for each outdoor noise source. The indoor DNL values for all noise sources must then be combined using Table 16 to determine the total indoor DNL at the site. Since the worksheets are used to calculate the indoor DNL contribution for each envelope member, the discussion will assume that the outdoor noise source is fixed and the corresponding outdoor DNL is used to estimate the indoor DNL.

The envelope member is composed of several elements, with each element exhibiting an A-weighted TL value corresponding to the noise source being considered. The noise reduction provided by the envelope member is denoted by NR and depends upon the following:

TL - the composite A-weighted sound transmission loss of the envelope member,

S_w - the total surface area of the envelope member,

A - the total room sound absorption,

6 - the constant difference between the non-diffuse outdoor sound field and the diffuse indoor sound field, and

$\overline{\cos\theta}$ - the angle of incidence correction (site condition).

The mathematical relationship is (see Equation (C-17)):

$$NR = TL - 10 \log [(S_w/A)\overline{\cos\theta}]-6 \text{ , dB.} \quad \text{(C-22)}$$

We now proceed to rearrange this relationship into a form convenient for presentation in a worksheet format. Since we want to estimate the indoor DNL, denoted by $(L_{dn})_I$, we must relate NR to the outdoor DNL and the indoor DNL. Further, we remember that the TL value is based upon the outdoor sound field incident upon the envelope member. Our relationship is then of the form:

$$NR = (L_{dn})_O + \Delta_I - (L_{dn})_I \quad \text{(C-23)}$$

where Δ_I is an adjustment to the outdoor DNL value for the noise source to account for the sound energy incident upon the element.

Denoting the right hand side of Equation (C-22) as $TL_{adjusted}$, we substitute equation (C-23) into equation (C-22) and solve for $(L_{dn})_I$. The result is:

$$(L_{dn})_I = (L_{dn})_O + \Delta_I - TL_{adjusted} \text{ , dB} \qquad \text{(C-24)}$$

and is the basis for the calculations contained in Worksheet VIII. Note that in Worksheet VIII, Δ_I is the DNL adjustment for the exposure of the member to the noise source and is obtained as indicated in Figure 24. The value of $TL_{adjusted}$ is obtained from Worksheet VII.

With the above steps, the expression for $TL_{adjusted}$ is:

$$TL_{adjusted} = TL - 10 \log [(S_w/A)\overline{\cos\theta}] -6 \text{ , dB .} \qquad \text{(C-25)}$$

Worksheet V through VII are used to calculate this expression. However, the explicit relationship for obtaining the value of the TL from the values of TL_i for the various <u>elements</u> of the envelope member must now be incorporated. Doing this we obtain:

$$TL_{adjusted} = - 10 \log[\sum_{i=1}^{n} (S_i/S_w)10^{-TL_i/10}] - 10 \log[(S_w/A)\overline{\cos\theta}] -6 \qquad \text{(C-26)}$$

where TL_i is the A-weighted sound transmission loss value of the i^{th} member element

S_i is the surface area of the i^{th} member element.

Equation (C-26), however, is not in a form convenient for a worksheet format. We now proceed to cast our expression in an appropriate format. To do this we wish to separate terms into simple expressions that may be added together in dB units. Further, we approximate the room sound adsorption, A, using the relationship $A=cS_{f\ell}$, where c is a constant and $S_{f\ell}$ is the floor area of the room. The average value of c is 0.80 as explained in the main text. Doing this, we obtain the result

$$TL_{adjusted} = TL_c - 10 \log[\overline{\cos\theta}] + 10 \log(c) \qquad \text{(C-27)}$$

where

$$TL_c = 10 \log [\sum_{i=1}^{n} (S_i/S_{f\ell})10^{-TL_i/10}] -6$$

The calculations <u>indic</u>ated by Equation (C-27) are conducted using Worksheet VII. The term $- 10 \log[\overline{\cos\theta}]$ is the angle of incidence correction from Figure 25 appropriate to the noise source, and the room sound absorption adjustment, $- 10 \log(c)$, is obtained as described by the footnote to Worksheet VII ($^-10 \log(0.8) = - 1.0$ dB).

It is now necessary to calculate the value of the composite sound transmission loss, TL_c. This is accomplished by using Worksheets V and VI. First, however, it is best, once again, to rearrange the expression for TL_c into a form convenient for a worksheet format. This is done by defining the following two quantities:

$$\Delta_{si} \equiv -10 \log (S_i/S_{f\ell}), \qquad \text{(C-28a)}$$

$$\overline{TL_i} \equiv TL_i - 6 \cdot \qquad \text{(C-28b)}$$

With these definitions, the expression for TL_c becomes:

$$TL_c = -10 \log[\sum_{i=1}^{n} 10^{-(\overline{TL_i} + \Delta_{si})/10}] \text{ , dB} \cdot \qquad \text{(C-29)}$$

The calculation indicated by Equation (C-29) is performed using Worksheet VI and will be explained momentarily.

First, we consider the calculations for Worksheet V which evaluates the quantity $\overline{TL_i} + \Delta_{si}$. The value $\overline{TL_i}$ is obtained from Tables 20 through 26 or as described in section C.3 of this appendix (see equation (C-17)). As described in Section C.3, $TL_i = TL_{ref} + C_{mn}$. The adjustment, Δ_{si}, is defined by Equation (C-28a) and is given in Table 29. We now focus upon the calculations in Worksheet VI.

To explain the calculation procedure we express Equation (C-29) as follows:

$$TL_c = -10 \log[\sum_{i=1}^{n} 10^{-t_i/10}] \qquad \text{(C-30)}$$

where $t_i = \overline{TL_i} + \Delta_{si}$ and is obtained from Worksheet V.

Now, we use examples to illustrate the calculations for Worksheet VI. Consider an envelope member with two elements. We can then obtain values of t_1 and t_2 using Worksheet V and we need to evaluate

$$TL_c = -10 \log[10^{-t_1/10} + 10^{-t_2/10}] \qquad \text{(C-31)}$$

without directly calculating either $10^{-t_1/10}$, $10^{-t_2/10}$ or using logarithms.

We now express Equation (C-31) as follows:

$$TL_c = t_1 + \Delta_c \qquad \text{(C-32)}$$

where $\Delta_c \equiv -10 \cdot \log(1 + 10^{(t_1 - t_2)/10}) \cdot$

We note that Δ_c depends only upon the difference between the two values t_1 and t_2. For large positive values of this difference (i.e., $(t_1 - t_2) \geq 10$), $\Delta_c \approx t_2 - t_1$ and $TL_c \approx t_2$ (i.e, the combined TL value is close to the TL value of the "weaker" component). For large negative values of this difference (i.e., $t_1 << t_2$) then $\Delta_c \approx 0$ and $TL_c \approx t_1$ (i.e., the combined TL value is approximately equal to the value of the "weaker" component). Further, we note that the value of TL_c does not depend upon which element is assigned the value t_1 or t_2. Values for Δ_c are presented in Table 30 of the main text.

Consider now a three-element wall where:

$$TL_c = - 10 \log[10^{-t_1/10} + 10^{-t_2/10} + 10^{-t_3/10}] \text{ ,dB} . \qquad \text{(C-33)}$$

We combine the first two elements as described above to obtain $TL_{c2} = t_1 + \Delta_c$ which yields the result

$$10^{-TL_{c2}/10} = 10^{-(t_1+\Delta_c)/10} = 10^{-t_1/10} + 10^{-t_2/10}$$

Then, the expression for TL_c of the three-element wall becomes:

$$TL_c = - 10 \log[10^{-TL_{c2}/10} + 10^{-t_3/10}] \quad \text{, dB} \qquad \text{(C-34a)}$$

or

$$TL_{c3} = TL_{c2} + \Delta_c \quad \text{, dB} \qquad \text{(C-34b)}$$

where $\Delta_c = - 10 \log[1 + 10^{(TL_{c2} - t_3)/10}]$.

The calculations indicated by Equation (C-34a) are identical to the calculations for the two-element wall, except that we use TL_{c2} and t_3 to evaluate Δ_c. One may repeat the above argument for an envelope member with four or more elements and realize that we combine the t_i values using two "elements" at each stage. After the first combination, however, one of the elements is the combination resulting from the previous step. Worksheet VI is formatted to accomodate up to five elements; however, the same format could be used for any number of elements.

D. ENVIRONMENTAL NOISE DESCRIPTORS FOR NOISE-COMPATIBLE LAND USE PLANNING

Obtaining environmental noise information that is meaningful for land use planning efforts is predicated upon the choice of a noise measure (or measures) which accurately describes the noise environment in terms that are relevant to human response to noise.

The accumulated evidence of research on human response to sound indicates that the magnitude of sound as a function of time and frequency is the major basic indicator of human response. The dominant characteristic of community noise is that it is not steady -- at any particular location the noise fluctuates considerably from quiet at one instant to loud the next. Over the last few years, two very closely related noise measures that capture both the characteristics of environmental noise and human response have emerged as particularly useful for land use planning. These measures are the equivalent sound level (L_{eq}) and the yearly day night sound level (L_{dn}, DNL) in decibels. [Refs. 1,2,10,47,48,49 and 50]

The equivalent sound level (L_{eq}) is used primarily to describe and assess the noise environment, present or prospective, at those sites where the concern is for the effects of noise over a short period of time (e.g. 1-hr., 8-hr.), rather than over the entire 24-hour period as, for example, in commerical and industrial areas. The equivalent sound level is the A-weighted sound level of the steady-state noise which has the same energy content, in a specified period of time, as the time-varying noise. Thus, two sounds, one of which contains twice as much energy as the other but lasts only half as long as the other, would be characterized by the same equivalent level. The mathematical definition of L_{eq} is:

$$L_{eq} = 10 \log \left\{ \frac{1}{T} \int_{o}^{T} 10^{L(t)/10} \, dt \right\}, \text{ dB.} \qquad \text{(D-1)}$$

The yearly day night sound level (L_{dn} or DNL) is used to describe the average noise environment, present or prospective, at those sites where the concern is for the effects of noise over the entire 24-hour period, such as in residential areas and hospital zones where a primary consideration is the needs of residents for rest and quiet. The DNL is the average A-weighted equivalent sound level for the entire 24-hour period with a nighttime penalty of 10 dB added to the L_{eq} between 10 p.m. and 7 a.m. The penalty is intended to account for the increased sensitivity of people to noises that occur during sleeping hours relative to waking hours. During the night, interior background noise levels in most residential areas generally drop far below their daytime levels. Moreover, the activities of most households at night also decrease during sleeping hours thereby lowering internally generated noise levels. Thus, noise events occurring at night are more intrusive since the increase in the noise level of the noise event over the background is greater at night than it is during the day.

Mathematical definition of DNL is:

$$L_{dn} \equiv 10 \log \left\{ \frac{1}{24} \int_{\text{day}} 10^{L(t)/10}\, dt + \frac{10}{24} \int_{\text{night}} 10^{L(t)/10}\, dt \right\} \qquad \text{(D-2a)}$$

or, if L(t) is based upon average conditions so that it is characterized by an average hourly value, is:

$$L_{dn} \equiv 10 \log \left\{ \frac{15}{24}\, 10^{L_{\text{day}}/10} + \frac{90}{24}\, 10^{L_{\text{night}}/10} \right\} \qquad \text{(D-2b)}$$

where $$L_{\text{day}} = 10 \log \left\{ \int_{\substack{\text{average}\\ \text{daytime}\\ \text{hour}}} 10^{L(t)/10} dt \right\}$$

where $$L_{\text{night}} = 10 \log \left\{ \int_{\substack{\text{average}\\ \text{nighttime}\\ \text{hour}}} 10^{L(t)/10} dt \right\}$$

While the yearly day night sound level and the equivalent sound level have emerged as the most useful and widely used noise measures for land use planning efforts other schemes are still encountered. These include the community noise rating (CNR), the noise exposure forecast (NEF), the community noise equivalent level (CNEL), and the statistical descriptors, in particular the level exceeded 10 percent of the time (L_{10}). For this reason a brief description of these noise measures and of their relationships follow.

Both CNR and NEF were primarily developed for evaluating noise-compatible land use around airports. CNR was the direct outcome of the experience gained by consultants in their practice and their interpretation of the limited research data that was available in the 50's when CNR was proposed [Ref. 53]. Originally, CNR was merely a scheme for interpreting community reactions to noise exposure in a number of case studies involving different noise sources.

The orginal CNR specified that the noise was to be measured and plotted as octave-band levels. The resulting graph was then to be compared to a set of other curves which resembled the loudness contours. The curves were plotted at 5 dB intervals in the mid-frequency region. On the basis of these comparisons, a noise rank level was assigned to the noise, corresponding to the highest rating curve into which a measured spectrum intruded. The values obtained were then adjusted by a series of noise corrections based on noise spectra, ambient levels in the community, the "intrusiveness" of the noise, and whether or not it had an impulsive character and was repetitious. A correction was also applied to account for the previous experience of the community with the particular type of noise exposure being evaluated. In addition, adjustments were provided for the time of day and the period of the year during which the noise occurred. Each adjustment factor had the effect of either raising or lowering the rank level originally obtained. A range of discrete community responses as a function of CNR was provided to assist in the interpretation of the data. These community responses included no reaction, sporadic complaints, widespread complaints, threat of legal action, and vigorous community reaction.

Since its proposal in 1955, CNR has undergone changes. One of the major changes was the substitution of the preceived noise level as a means of determining the noise level rank, thus shifting the emphasis from consideration of loudness to consideration of annoyance as a major attribute of community response to noise [Ref. 54). As more research data became available more refinements were incorporated into the noise measure. For example, adjustments for the duration of individual aircraft flyovers and for the presence of discrete frequency components were developed as these were found to influence human response. Finally, a computational scheme for assessing the cumulative effects at various points around airports of the noise produced by different aircraft types flying along different flight paths was proposed. The procedure eventually evolved into the noise exposure forecast (NEF) which allowed NEF to be plotted on a map of the neighborhood surrounding an airport. Thus, areas experiencing similar noise exposures could be enclosed in contours drawn on a map of the land around an airport.

The NEF methodology was adopted by the Federal Administration (FAA) in its efforts to assess land uses around civilian airports and for determining the effects of changes in aircraft operating procedures, the introduction of new types of aircraft in the fleet, or changes in the aircraft mix at a particular airport [Refs. 54 and 55]. It was also used by the department of Housing and Urban Development (HUD) until recently to assess the eligibility for assistance for construction of residential developments around airports.

When used for land use planning purposes, the NEF values were interpreted as follows. In areas located in zones where the NEF values were equal or less than 20 no complaints were expected from the community; accordingly, such areas were considered suitable for residential development. In areas where the NEF values ranged from 20 to 30 some activities, expecially those involving speech communication, might be interferred with; thus, noise consideration was called for when the area was proposed for residential development. Areas where the NEF values were between 30 and 40 were usually considered to be suitable for commercial development and for office buildings, provided these latter buildings included some form of soundproofing if speech communication was an important consideration. Residential and school development by and large were not found compatible for these areas as the noise exposure levels were severe enough to elict complaints and possibly group action. Finally, in areas where NEF values were equal or greater than 40, activities demanding of speech communication were found undesirable, and all buildings were considered to require soundproofing treatment to protect occupants from undue noise exposure.

The community noise equivalent level (CNEL), used primarily in California to monitor land use planning around airports [Ref. 57], is an A-weighted energy average level for the 24-hr period with 5 dB weighting factor for the noise levels occurring in the evening between 7 a.m. and 10 p.m. increased to 10 dB for night events occurring between 10 p.m. and 7 a.m. CNEL is essentially identical to DNL except for the evening penalty. For most distributions of noise levels around airports, the numerical difference between DNL and CNEL is insignificant in most instances, amounting to less than 1 dB.

There does not exist a fixed relationship between DNL, CNEL, CNR and NEF because not all of these schemes handle frequency weighting in the same manner, nor consider the duration of individual events or the presence of discrete frequency components, nor apply the night penalty in an identical fashion. For example, DNL and CNEL account for the differential sensitivity of people to various frequencies by means of the A-weighting while CNR and NEF use the perceived noise level. Similarly, while CNEL, DNL, CNR and NEF all penalize noise events occurring between 10 p.m. and 7 a.m. by 10 dB, the details concerning the manner in which the penalty is applied differ. In the case of CNR and NEF, it is the nighttime exposure that is weighted, where as in the case of DNL, the penalty is applied to the level directly rather than to the exposure. Nevertheless, one may translate one noise measure into another by using the following relationship, which for most instances, yield approximations that are valid within a ±3 dB tolerance.

$$\mathrm{LDN} \cong \mathrm{CNEL} \cong \mathrm{NEF} + 35 \cong \mathrm{CNR} - 35 \tag{D.3}$$

Until several years ago the Federal Highway Administration (FHWA) specified the upper limit of acceptable highway traffic noise for different types of land uses around highways in terms of the A-weighted sound level exceeded 10 percent of the time (L_{10}) [Ref. 58]. Since assitance from the FHWA in the form of highway construction or reconstruction grants is contingent upon the assessment of traffic noise impacts and consideration of noise abatement measures, many state highway departments throughout the country performed noise analyses in terms of L_{10}.

Most free-flowing traffic gives rises to a normal (i.e., Gaussian) distribution of noise levels. In such cases the relationship between L_{eq} and L_{10} is given by:

$$L_{eq} = L_{10} - 1.28\ s + 0.115\ s^2,\ \mathrm{dB} \tag{D.4}$$

where s is the standard deviation of the noise level distribution. For values of s ranging from 1 to 10 dB, the relationship between L_{eq} and L_{10} may be approximated by:

$$L_{eq} \cong L_{10} - 2,\ \mathrm{dB}. \tag{D.5}$$

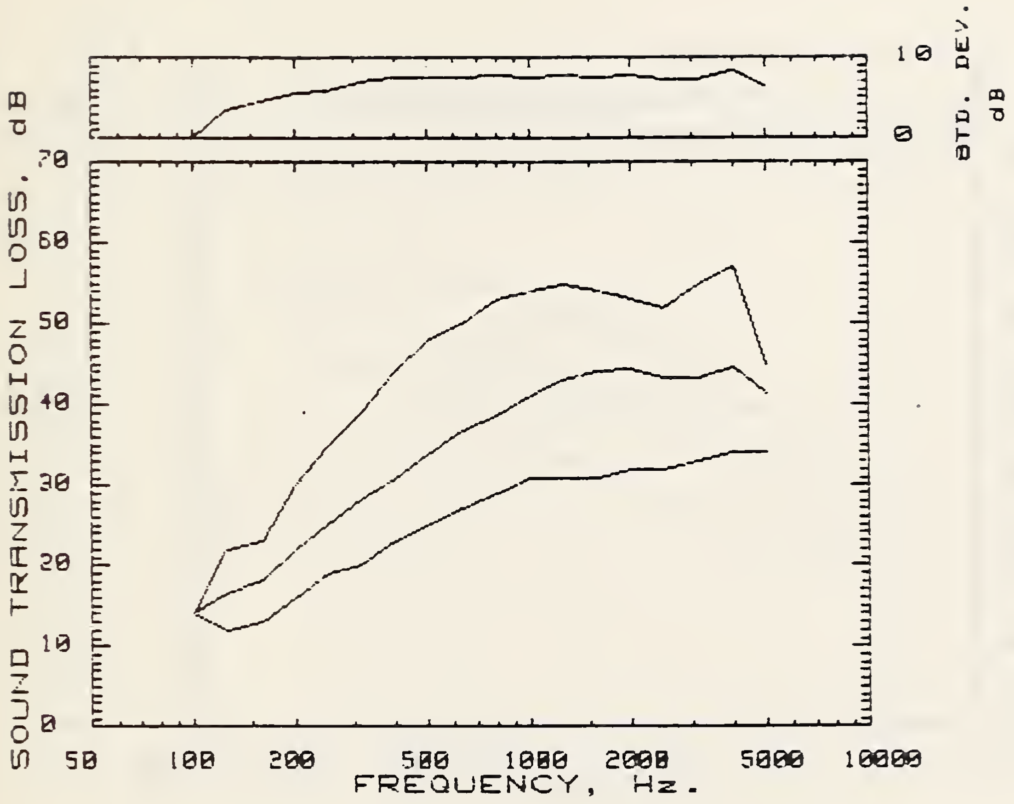
For most highways the standard deviation is on the order of 2 to 5 dB. In such cases Equation (D.5) above is correct to within ±1 dB.

The Department of Housing and Urban Development (HUD) provides minimum national standards designed to protect residents from excessive noise exposure in their homes and communities through assistance for new construction and/or rehabilitation of older buildings. Until 1979, HUD noise standards for all environments other than those of airports were expressed in terms of the amount of time in a 24-hr period during which the A-weighted sound levels could not exceed defined values. Four categories of land uses -- unacceptable, normally unacceptable, normally acceptable, and acceptable were defined as a function of noise levels. For example, areas impacted for 10 minutes out of the 24-hr period by A-weighted noise levels of 80 dB or exceeding 7-5 dB for 8 hr were considered totally "unacceptable" for residential use, while areas where the A-weighted sound levels did not exceed 65 dB for more than 8 hr per 24-hr were considered to be "normally acceptable."

There does not exist a well-defined relationship between these former HUD noise standards and other noise measures. For example, values of L_{eq} up to 95 dB could be in compliance with the former HUD standards depending upon the time distribution of the noise levels considered. However, as mentioned previously, HUD has revised its interim noise standard which are now expressed in terms of the day-night average sound level. [Ref. 50].

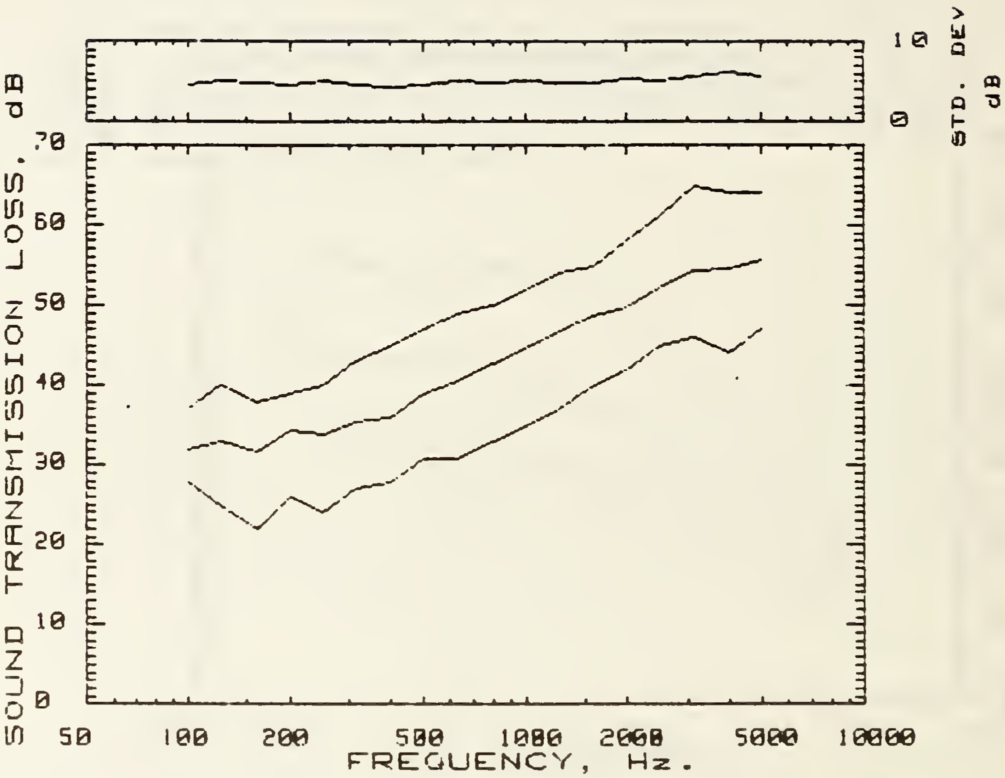
APPENDIX E. AVERAGE SOUND TRANSMISSION LOSS OF EXTERIOR BUILDING ELEMENTS

In this appendix the average sound transmission loss values of each type of building element described in Tables 20-26 of Section 3.2 of the main report are presented. These values were obtained by averaging, at each 1/3-octave band, the sound transmission loss data compiled from many sources. Also included in this appendix are plots of these average sound transmission loss values, the minimum and maximum values observed for each construction type, and the standard deviation of these data.



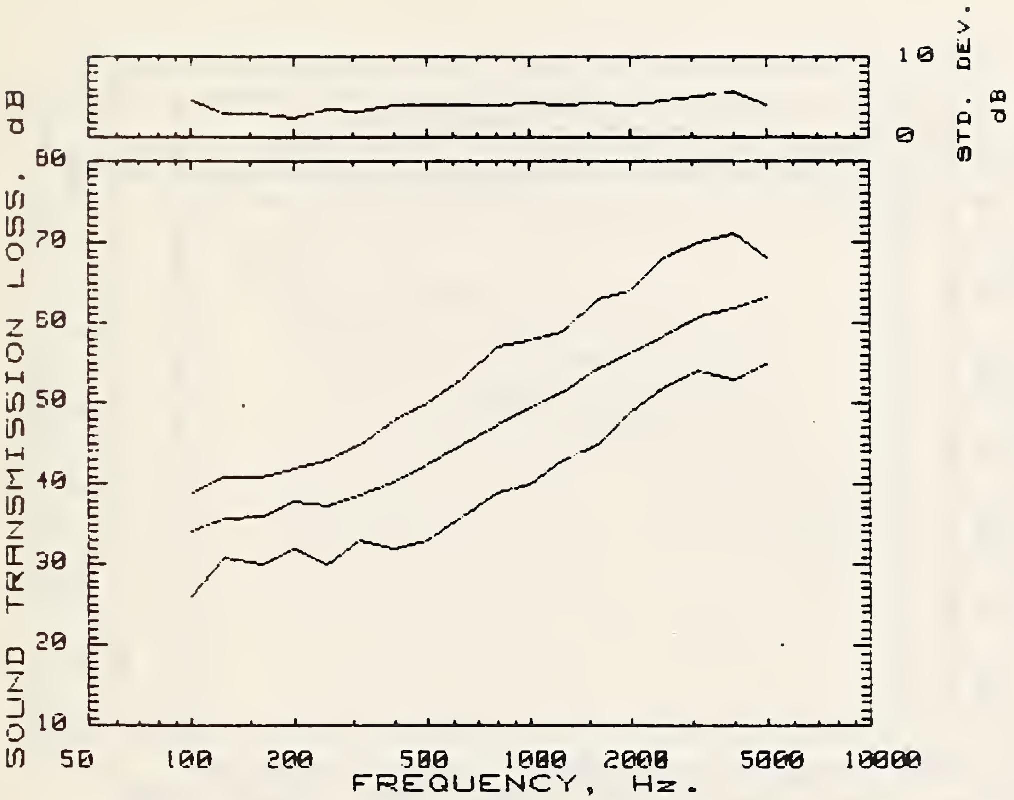
Hz	dB	Hz	dB
125	16	800	39
160	18	1000	41
200	22	1250	43
250	25	1600	44
315	28	2000	45
400	31	2500	43
500	34	3150	43
630	37	4000	45

Figure 45. Average and range of sound transmission loss of metal and curtain walls consisting of 2 sheets of galvanized steel with insulation and having an area weight of less than 6 lbs/ft^2.



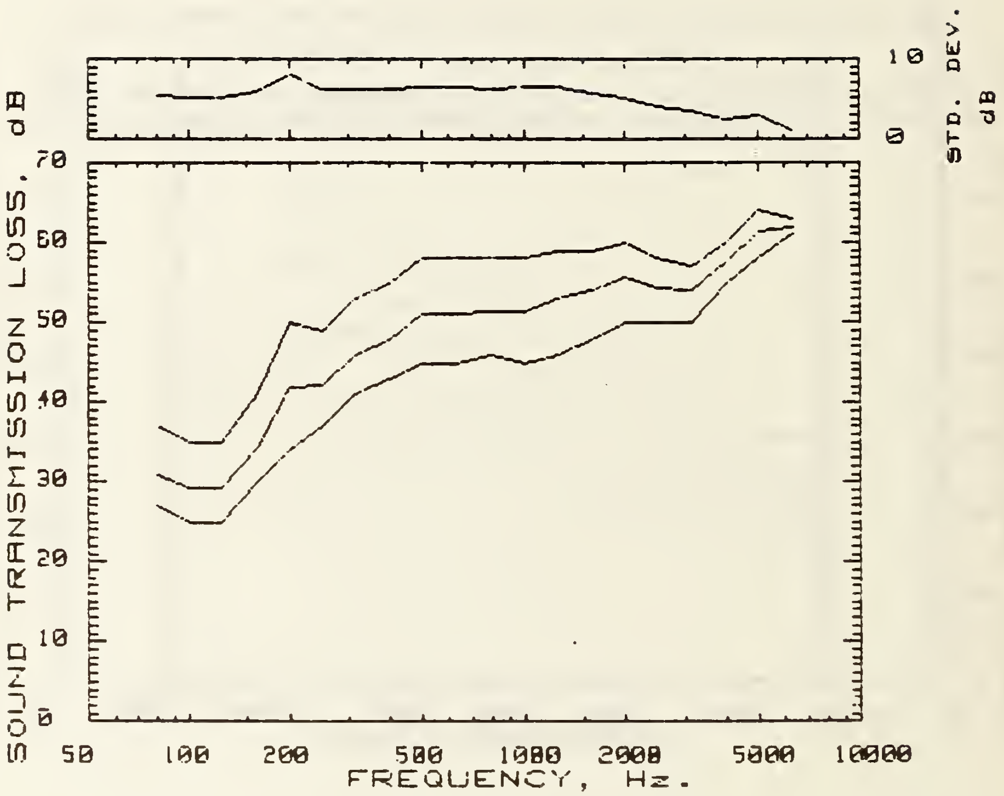
Hz	dB	Hz	dB
125	33	800	43
160	32	1000	45
200	34	1250	47
250	34	1600	49
315	35	2000	50
400	36	2500	52
500	39	3150	54
630	41	4000	55

Figure 46. Average and range of sound transmission loss of 4-7-in masonry walls consisting of either 4x8x16 concrete blocks or mortared bricks without finish.



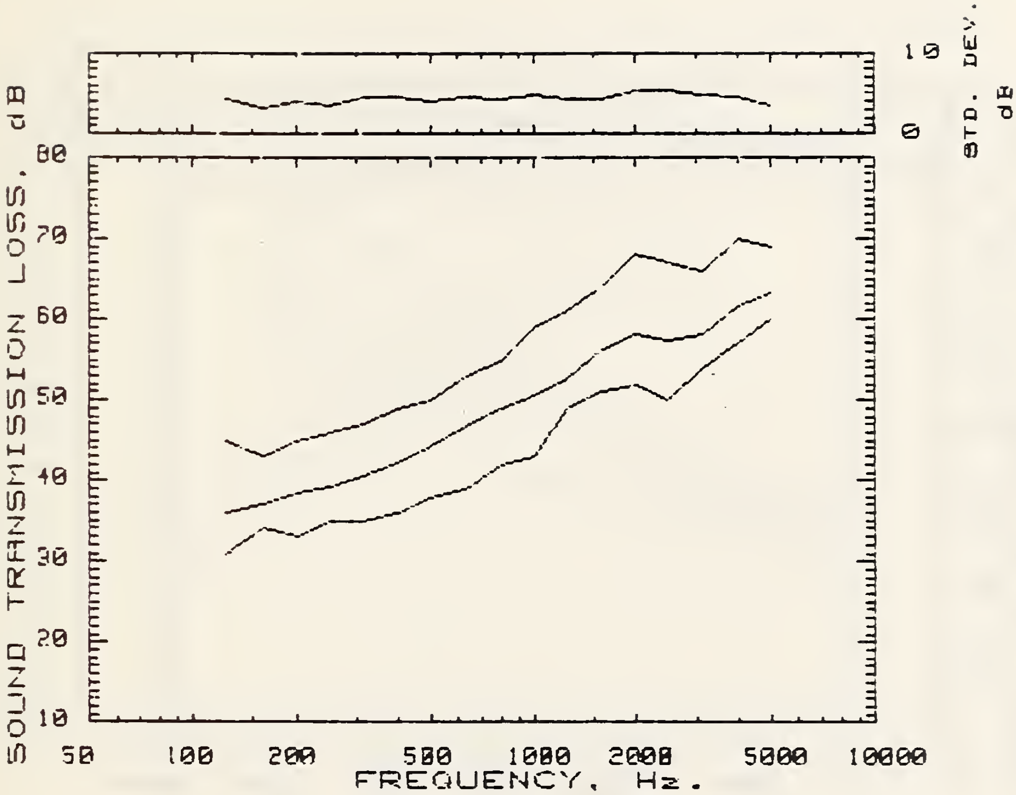
Hz	dB	Hz	dB
125	34	800	54
160	35	1000	55
200	37	1250	57
250	37	1600	58
315	39	2000	60
400	40	2500	60
500	45	3150	58
630	50	4000	61

Figure 47. Average and range of transmission loss of 4-7-in masonry walls consisting of 4x8x13 3-cell concrete blocks with resilient channels 24-in o.c. and 1/2-in plaster board.



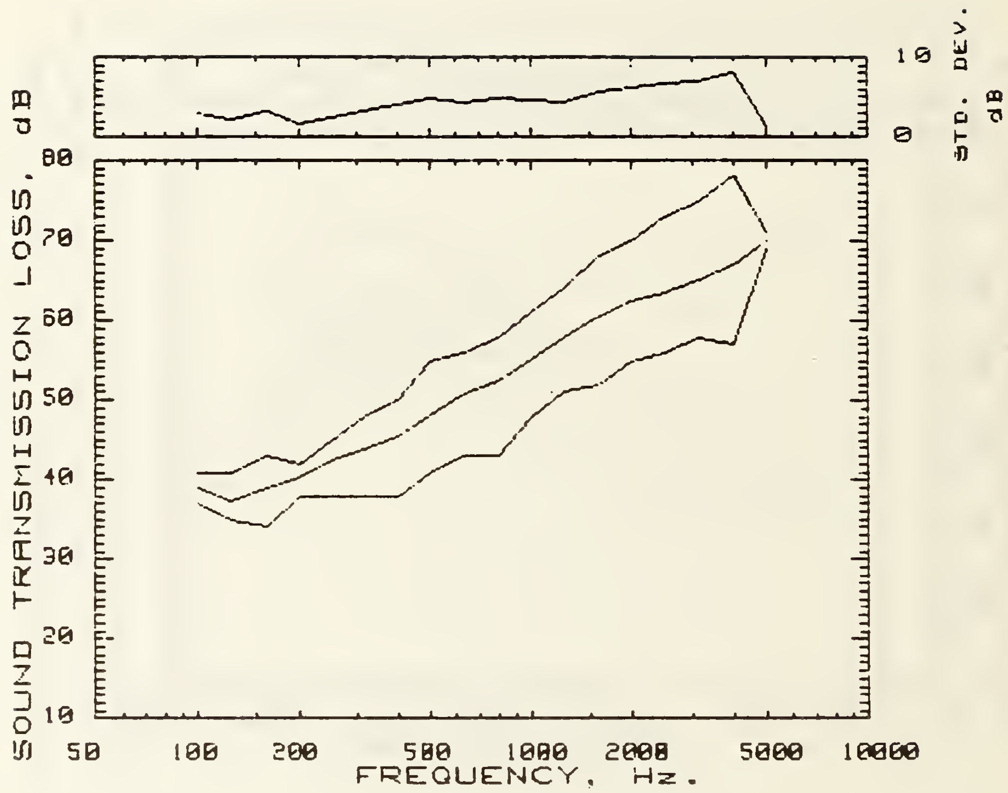
Hz	dB	Hz	dB
125	29	800	51
160	34	1000	51
200	42	1250	53
250	42	1600	54
315	46	2000	56
400	48	2500	54
500	51	3150	54
630	51	4000	58

Figure 48. Average and range of sound transmission loss of 7/8-in stuccoed wall with No. 15 felt building paper and 1-in wire mesh with 2x4 wood studs 16-in o.c. with fiberglas building insulation and 1/2-in gypsum board screwed to channel.



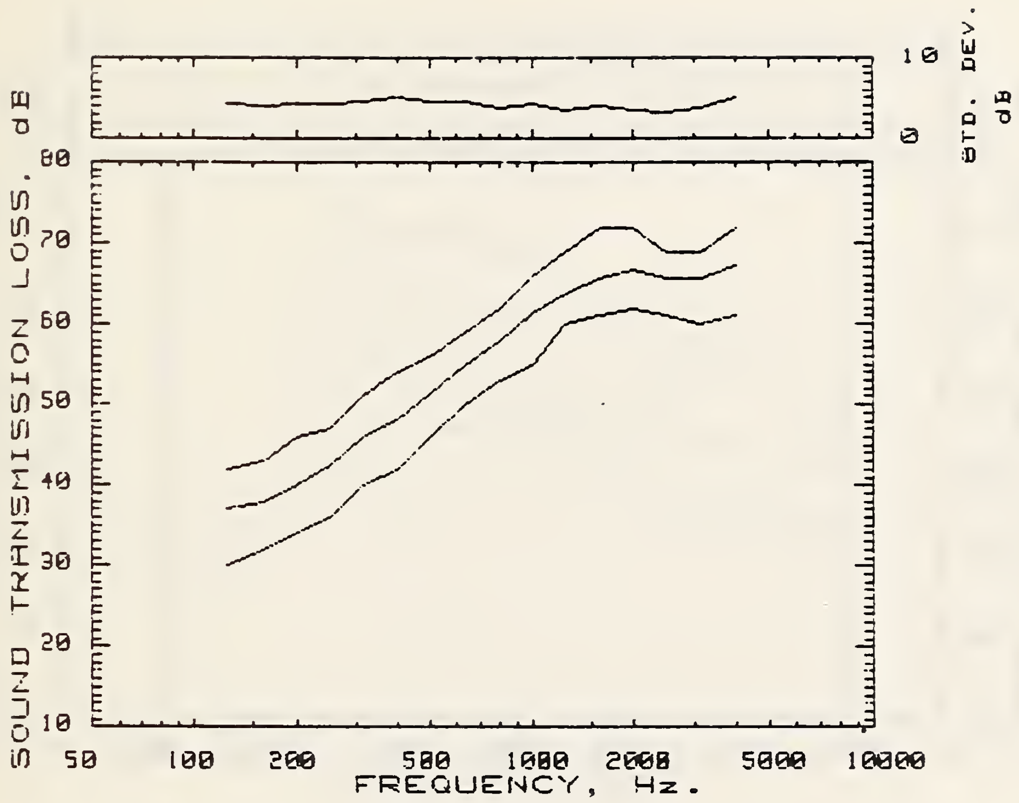
Hz	dB	Hz	dB
125	36	800	49
160	37	1000	51
200	39	1250	53
250	39	1600	56
315	41	2000	58
400	42	2500	57
500	44	3150	58
630	47	4000	62

Figure 49. Average and range of sound transmission loss of dense concrete walls 8-in thick consisting of 3-cell blocks with perimeter sealed.



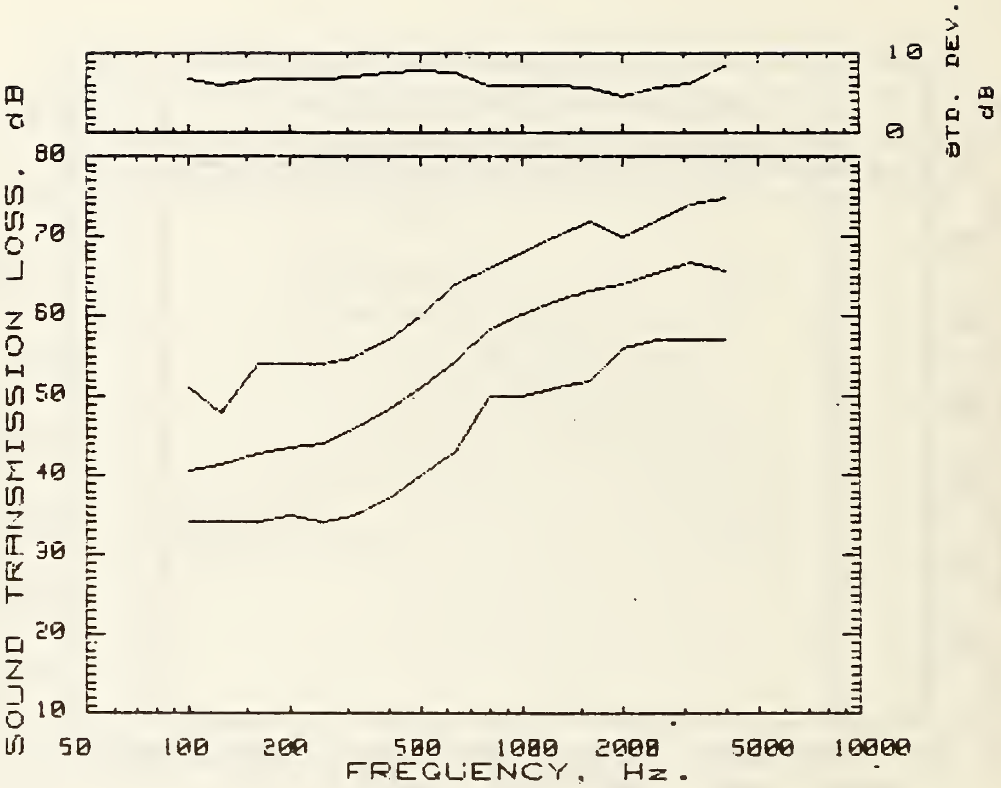
Hz	dB	Hz	dB
125	37	800	53
160	39	1000	55
200	40	1250	58
250	43	1600	61
315	44	2000	63
400	46	2500	64
500	48	3150	65
630	51	4000	67

Figure 50. Average and range of sound transmission loss of 8-in thick masonry walls consisting of either bricks mortared together or 3-cell concrete blocks with block filler with 1/2-in plaster and finished with latex paint.



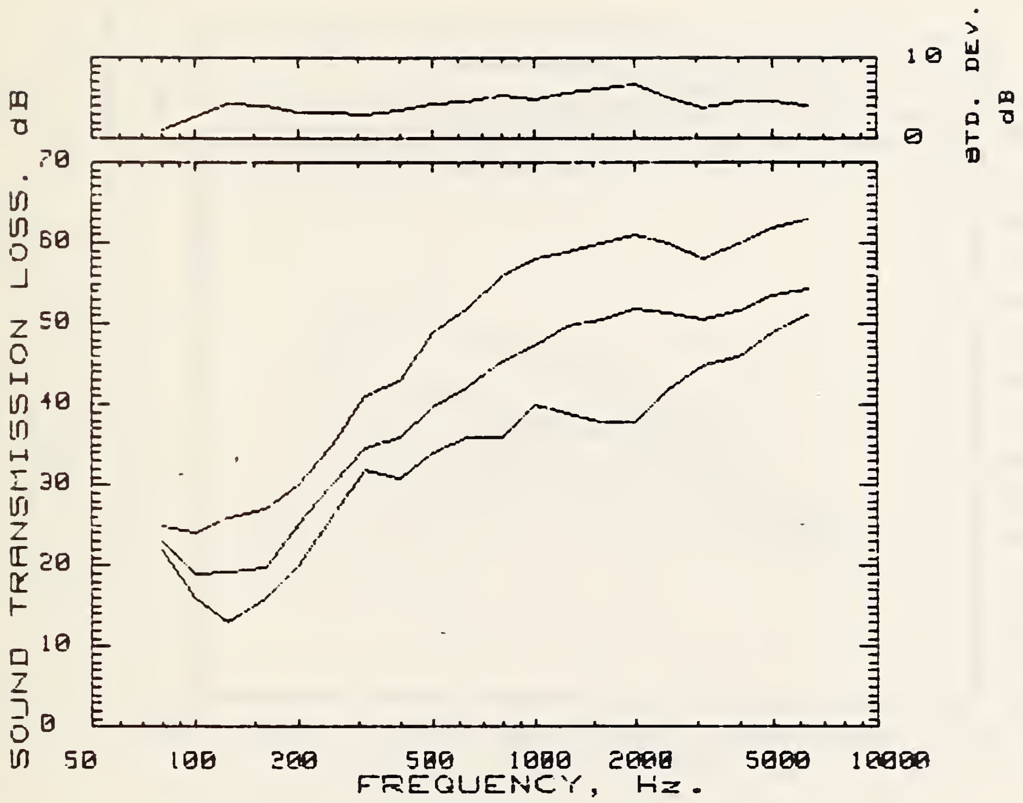
Hz	dB	Hz	dB
125	37	800	58
160	38	1000	61
200	40	1250	64
250	43	1600	66
315	46	2000	67
400	48	2500	66
500	51	3150	66
630	55	4000	67

Figure 51. Average and range of sound transmission loss of masonry walls 8-in thick consisting of 18x16x8 3-cell concrete blocks with resilient channels 24-in o.c. with 1/2-in plaster board and painted on both sides.



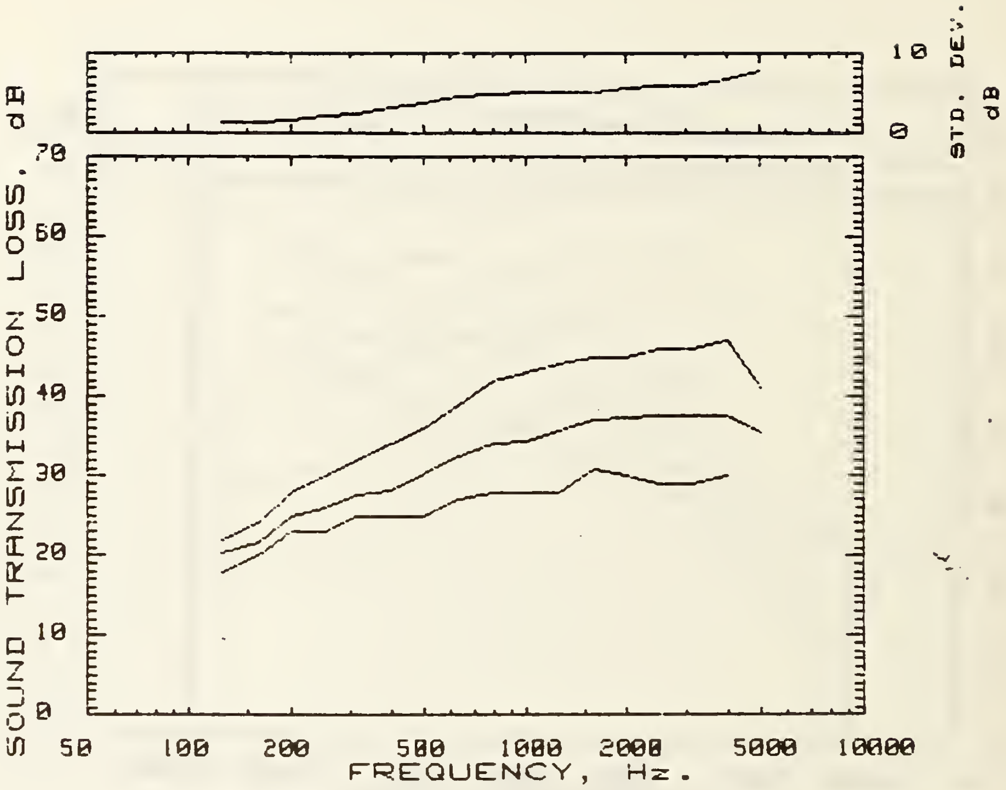
Hz	dB	Hz	dB
125	41	800	59
160	43	1000	60
200	44	1250	62
250	44	1600	63
315	46	2000	64
400	48	2500	65
500	51	3150	67
630	55	4000	66

Figure 52. Average and range of sound transmission loss of double brick walls consisting of 4-1/2-in walls separated by 2-4-in cavity with wire ties and 1/2-in plasterboard on both sides.



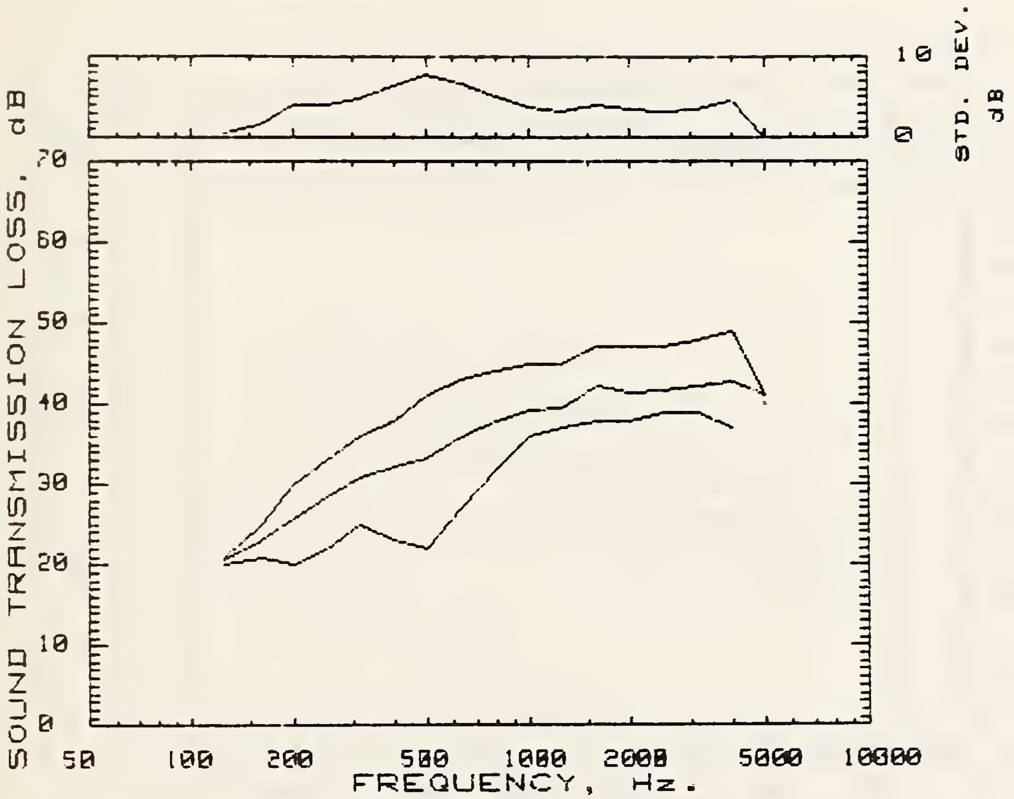
Hz	dB	Hz	dB
125		800	
160		1000	
200		1250	
250		1600	
315		2000	
400		2500	
500		3150	
630		4000	

Figure 53. Average and range of sound transmission loss of light frame wood wall with 2x4 wood studs 16-in o.c., 2-3-in insulation and finished with 1/2-in gypsum board.



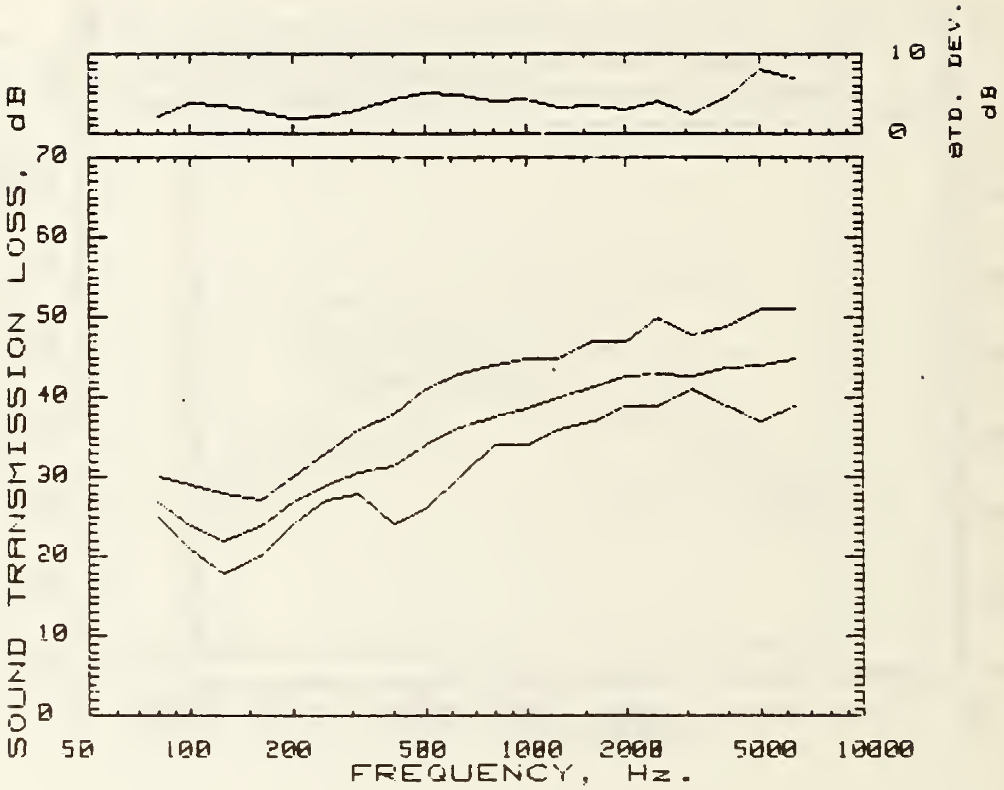
Hz	dB	Hz	dB
125	20	800	34
160	22	1000	35
200	25	1250	36
250	26	1600	37
315	28	2000	37
400	28	2500	38
500	30	3150	38
630	33	4000	38

Figure 54. Average and range of sound transmission loss of light frame walls with wood siding, 2x4 wood studs with insulation, resilient channels 24-in o.c., finished with 1/2-in gypsum board and penetrated by 25-30 percent glass.



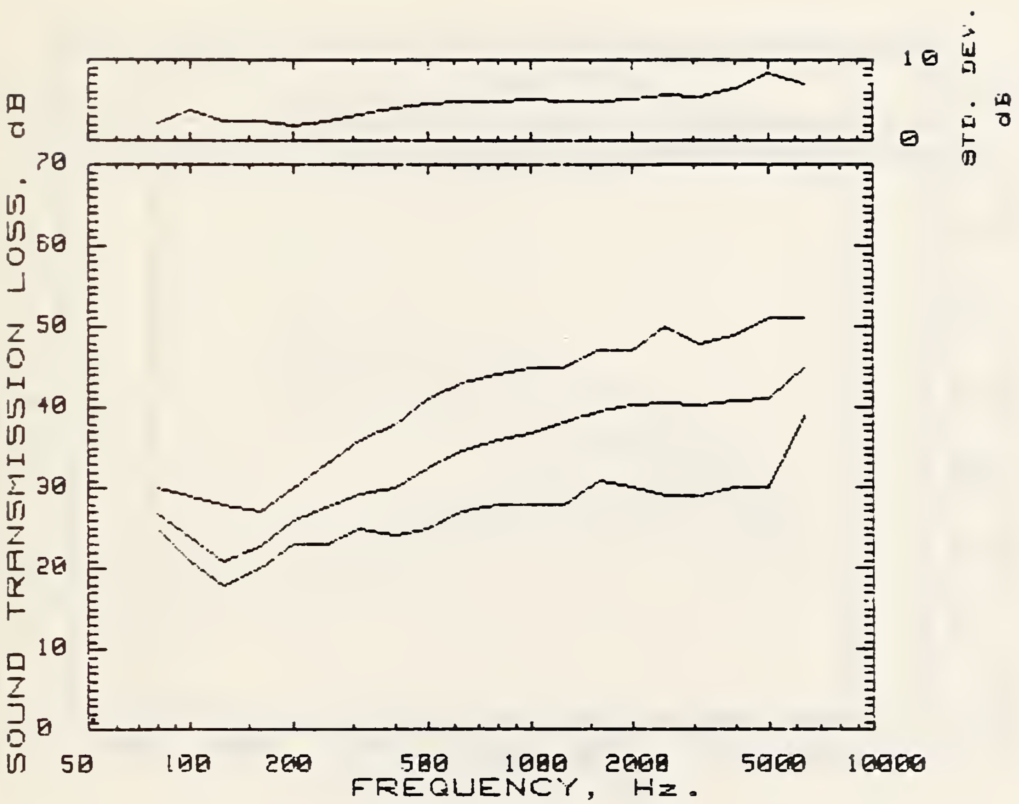
Hz	dB	Hz	dB
125	21	800	38
160	23	1000	39
200	26	1250	40
250	28	1600	42
315	31	2000	41
400	32	2500	42
500	33	3150	42
630	36	4000	43

Figure 55. Average and range of sound transmission loss of light frame walls with wood siding, 2x4 wood studs 16-in o.c. with insulation, resilient channels 24-in o.c., finished with 1/2-in gypsum board and penetrated by 25 to 30 percent single glazed sealed glass with storm sash.



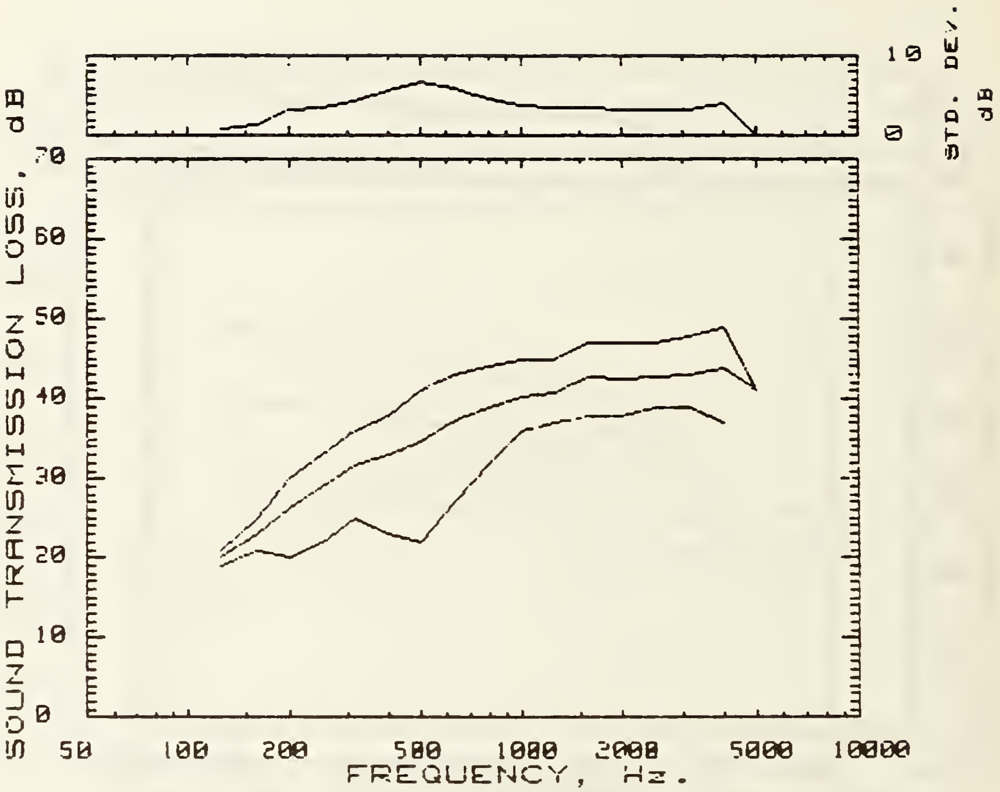
Hz	dB	Hz	dB
125	22	800	38
160	24	1000	39
200	27	1250	40
250	29	1600	41
315	31	2000	43
400	31	2500	43
500	34	3150	43
630	36	4000	44

Figure 56. Average and range of sound transmission loss of light frame walls with either brick veneer or wood siding, 2x4 wood studs 16-in o.c. with fiberglass insulation and penetrated by a 10-15 percent single strength glazed sealed window.



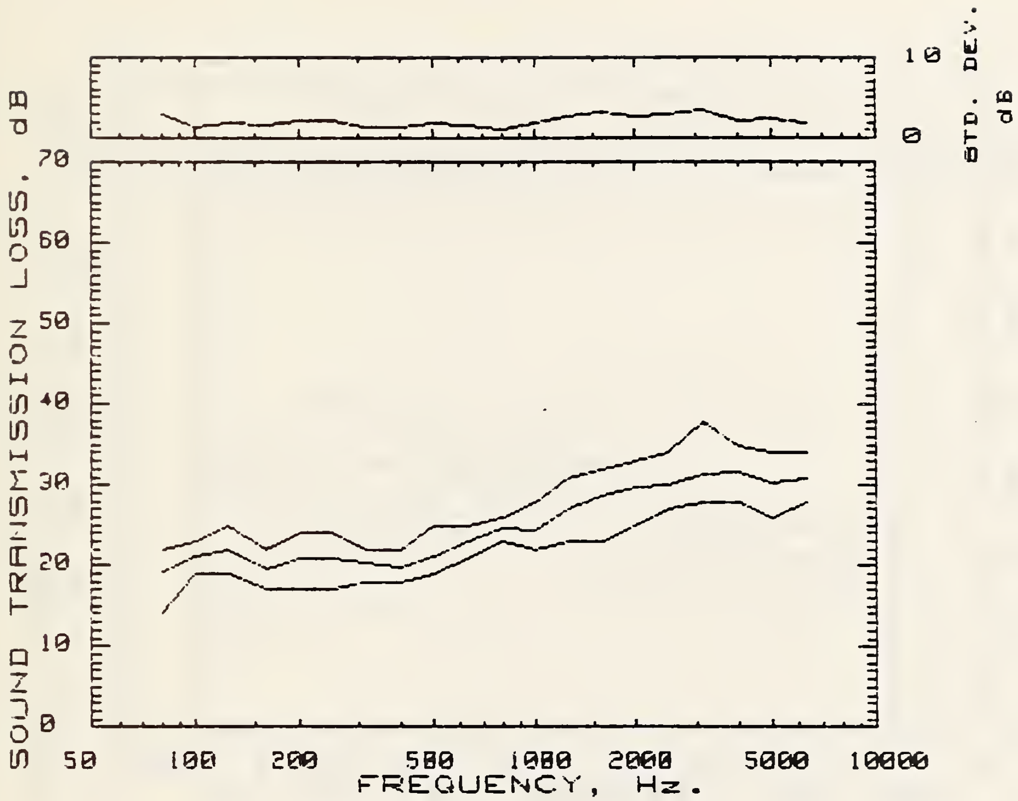
Hz	dB	Hz	dB
125	21	800	36
160	23	1000	37
200	26	1250	38
250	28	1600	39
315	29	2000	40
400	30	2500	41
500	32	3150	40
630	35	4000	41

Figure 57. Average and range of sound transmission loss of light frame walls with either wood siding or brick veneer, 2x4 wood studs, resilient channels 24-in o.c. and 1/2-in gypsum board but no insulation and penetrated by 25-30 percent single glazed sealed glass.



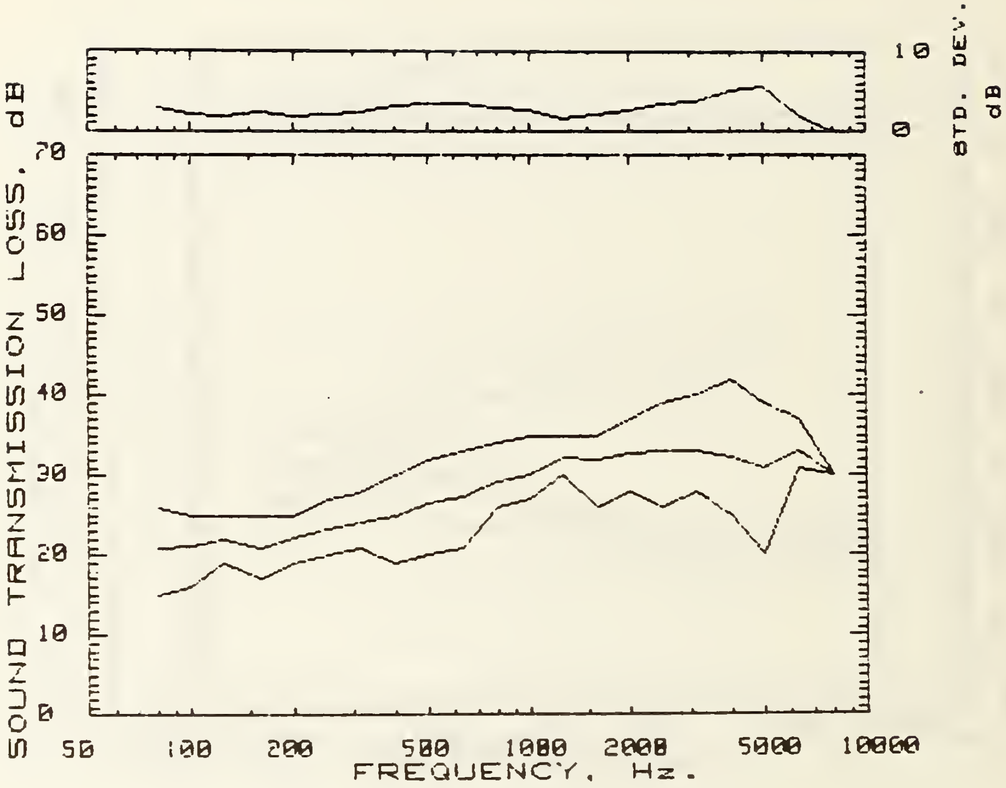
Hz	dB	Hz	dB
125	20	800	39
160	23	1000	40
200	26	1250	41
250	29	1600	43
315	32	2000	42
400	33	2500	43
500	35	3150	43
630	37	4000	44

Figure 58. Average and range of sound transmission loss of light frame walls with either wood siding or brick veneer, 2x4 studs with insulation, resilient channels 24-in o.c., 1/2-in gypsum board and penetrated by 25-30 percent single glazed sealed glass with storm sash.



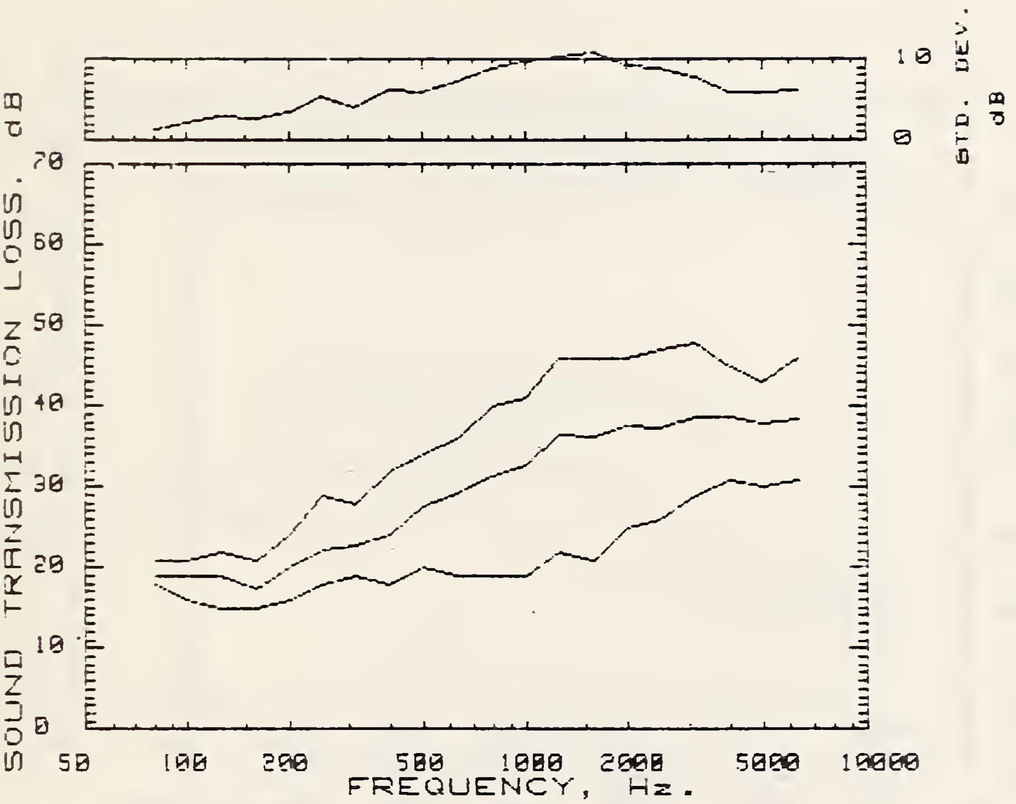
Hz	dB	Hz	dB
125	22	800	29
160	21	1000	30
200	22	1250	32
250	23	1600	32
315	24	2000	33
400	25	2500	33
500	26	3150	33
630	27	4000	33

Figure 59. Average and range of sound transmission loss of 3/82-7/16-in thick single glazed sealed windows.



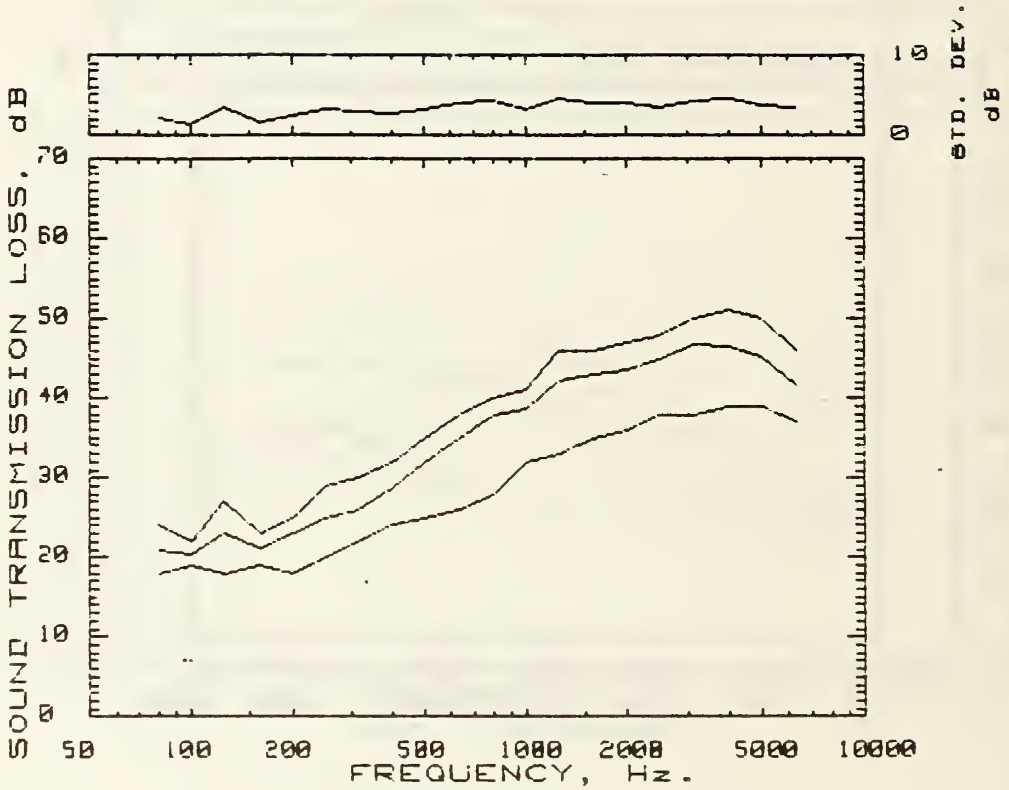
Hz	dB	Hz	dB
125	22	800	23
160	20	1000	25
200	21	1250	24
250	21	1600	27
315	20	2000	29
400	20	2500	30
500	20	3150	30
630	21	4000	31

Figure 60. Average and range of sound transmission loss of 3/32-7/16-in thick single glazed unsealed windows.



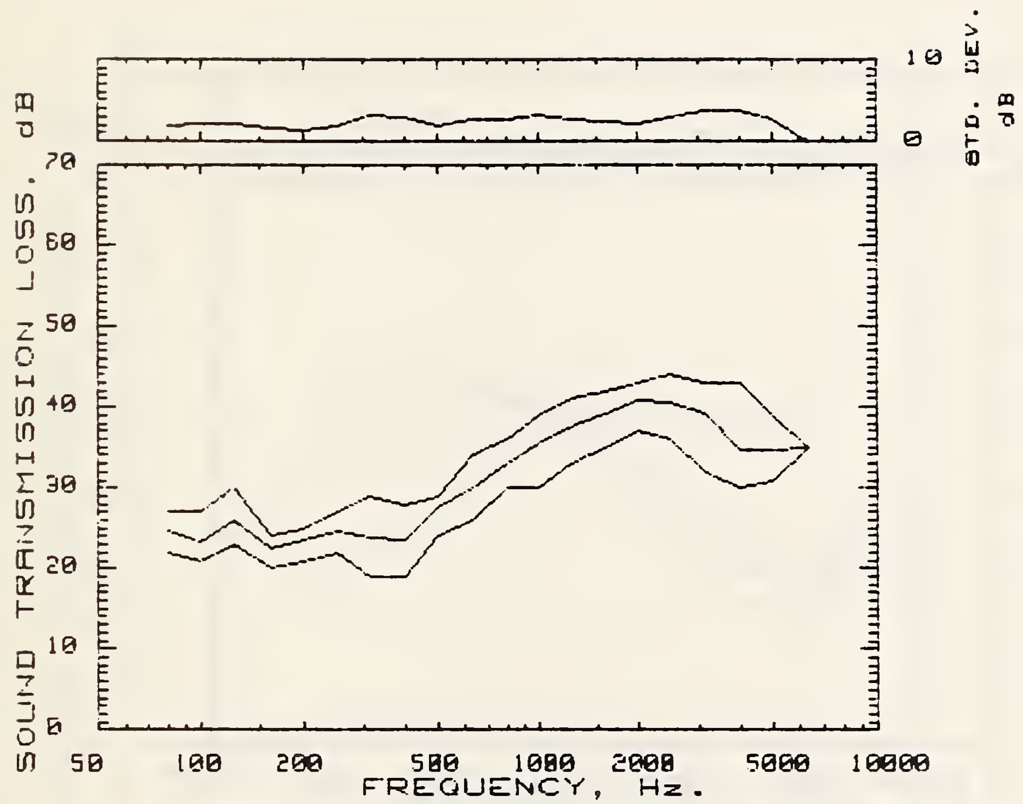
Hz	dB	Hz	dB
125	19	800	32
160	17	1000	33
200	20	1250	37
250	22	1600	36
315	23	2000	38
400	24	2500	37
500	28	3150	39
630	29	4000	39

Figure 61. Average and range of sound transmission loss of single strength panes with storm sashes unsealed.



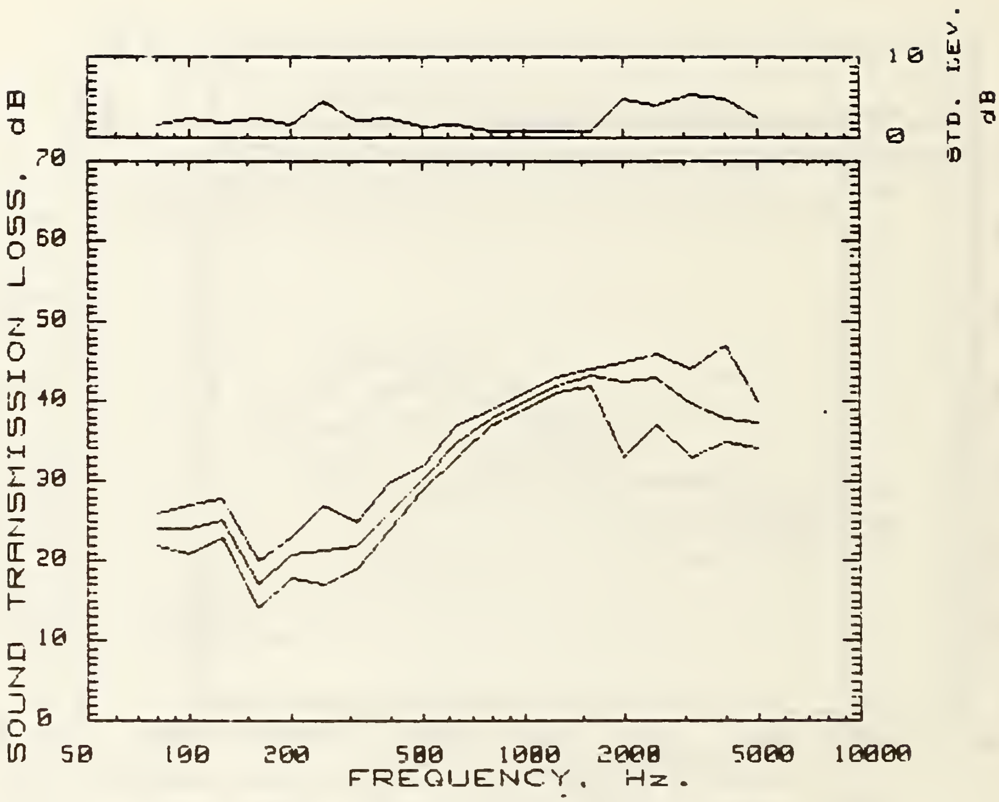
Hz	dB	Hz	dB
125	23	800	38
160	21	1000	39
200	23	1250	42
250	25	1600	43
315	26	2000	44
400	29	2500	45
500	32	3150	47
630		4000	46

Figure 62. Average and range of sound transmission loss of single strength sealed windows with storm sashes.



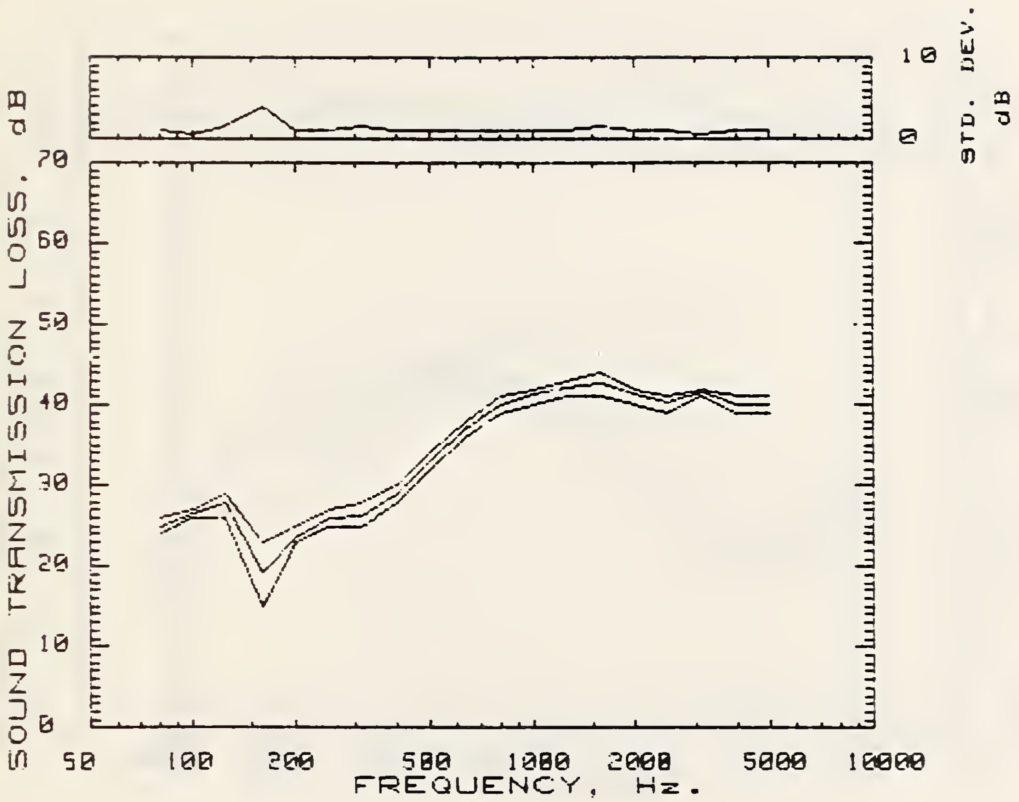
Hz	dB	Hz	dB
125	26	800	33
160	22	1000	36
200	23	1250	38
250	25	1600	39
315	24	2000	41
400	24	2500	41
500	28	3150	39
630	30	4000	35

Figure 63. Average and range of sound transmission loss of double glazed sealed windows consisting of parallel panes of the same thickness contained within a range of 3/32-3/8-in, mounted in one sash with an interpane spacing of less than 1/2-in.



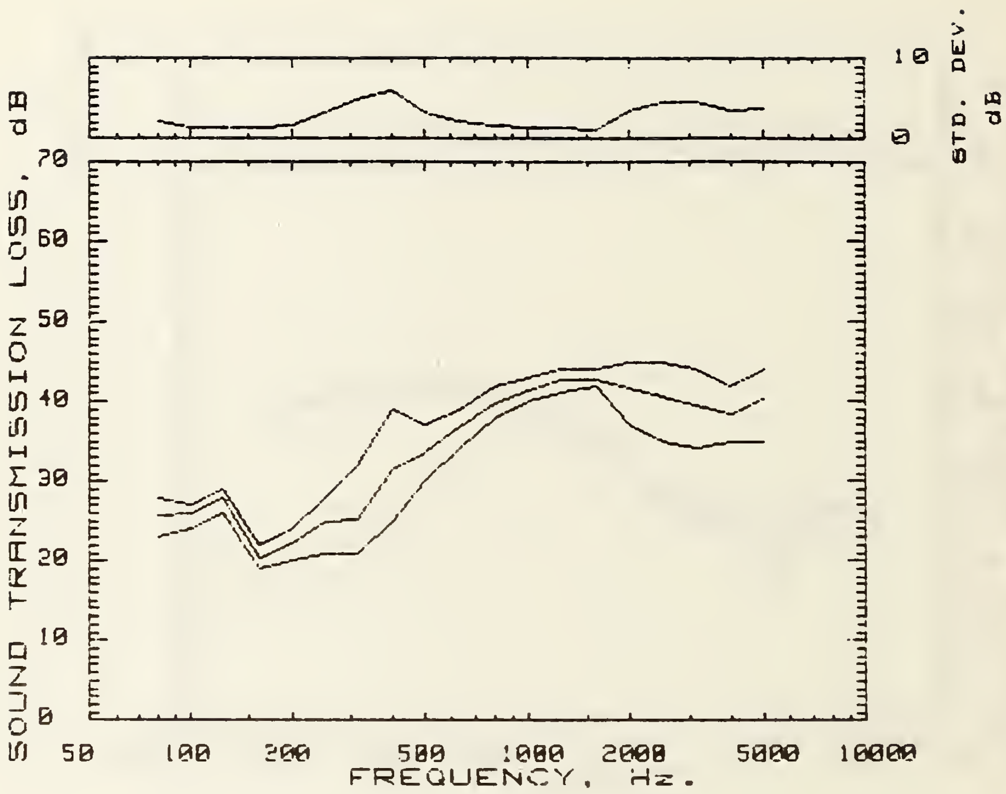
Hz	dB	Hz	dB
125	25	800	40
160	17	1000	42
200	21	1250	43
250	22	1600	43
315	26	2000	43
400	30	2500	43
500	35	3150	40
630	38	4000	38

Figure 64. Average and range of sound transmission loss of double glazed sealed windows consisting of two panes of the same thickness contained within a range of 3/32-1/8-in mounted in parallel in one sash with an interpane spacing greater than 1/2 in.



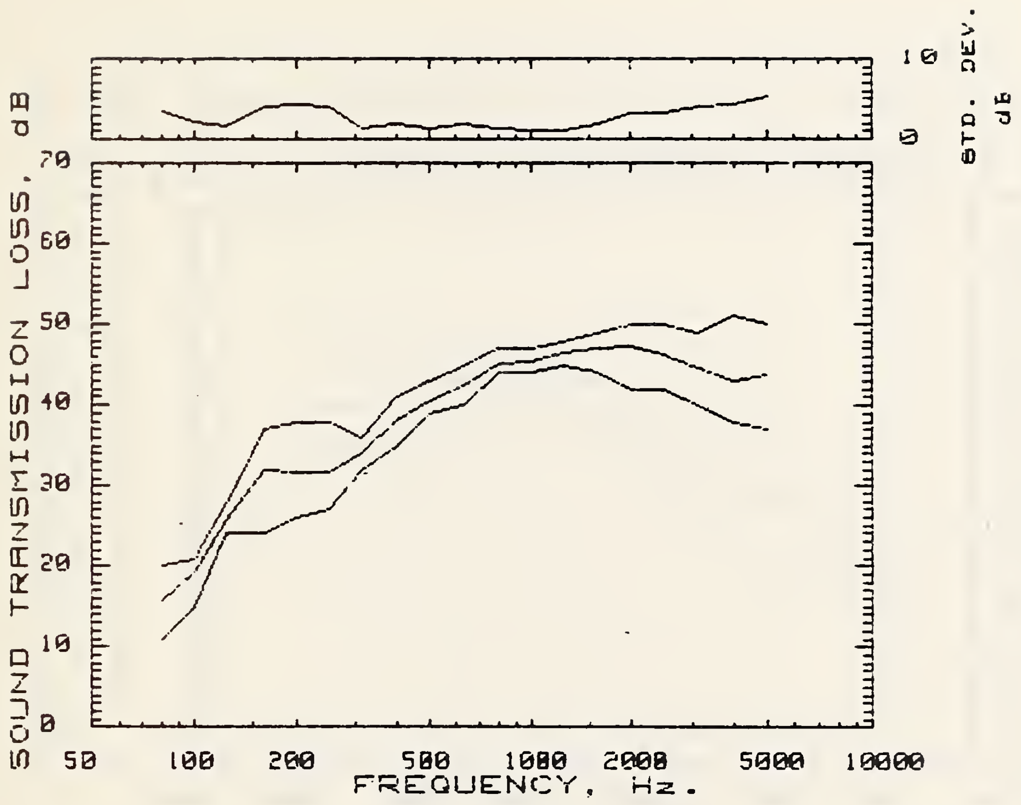
Hz	dB	Hz	dB
125	28	800	40
160	19	1000	41
200	24	1250	42
250	26	1600	43
315	26	2000	41
400	29	2500	40
500	33	3150	42
630	37	4000	40

Figure 65. Average and range of sound transmission loss of double glazed sealed windows consisting of panes of different thicknesses, 1/8 and 1/4-in mounted in one sash in parallel with an interpane spacing of 1/2-3/4-in.



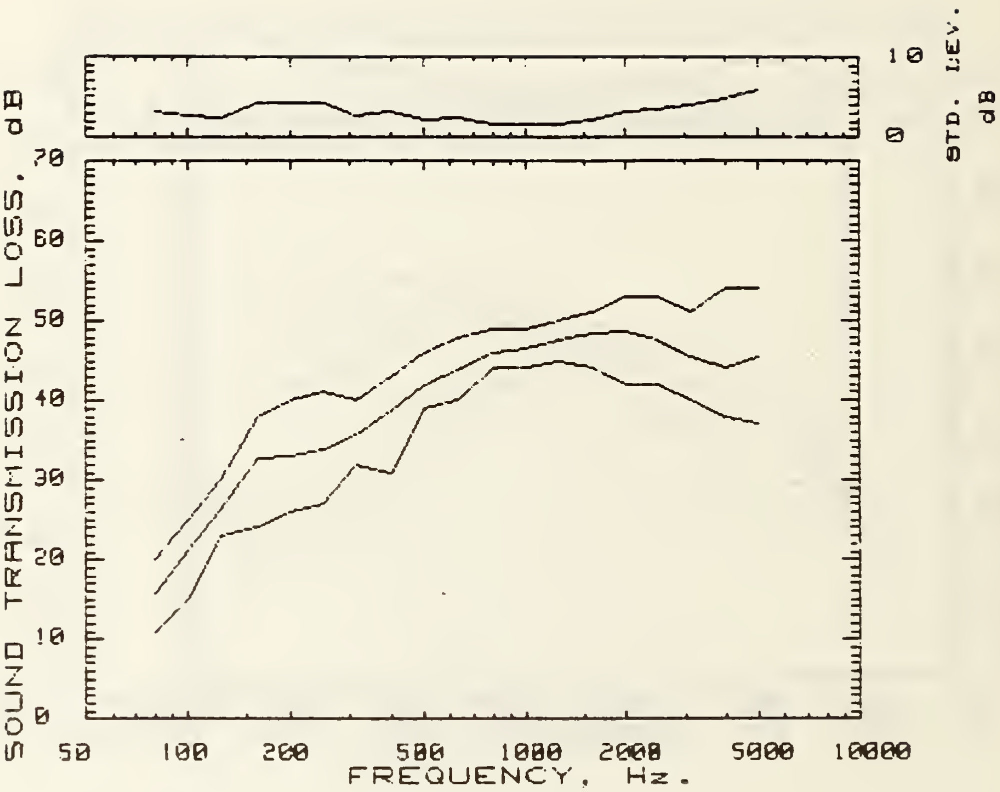
Hz	dB	Hz	dB
125	28	800	40
160	20	1000	42
200	22	1250	43
250	25	1600	43
315	25	2000	42
400	32	2500	41
500	34	3150	39
630	37	4000	38

Figure 66. Average and range of sound transmission loss of double glazed sealed windows consisting of panes of different thicknesses, 1/8 and 1/4-in mounted in one sash not in parallel with maximum interpane spacing of 3/4-in and minimum interpane spacing of 1/4-in.



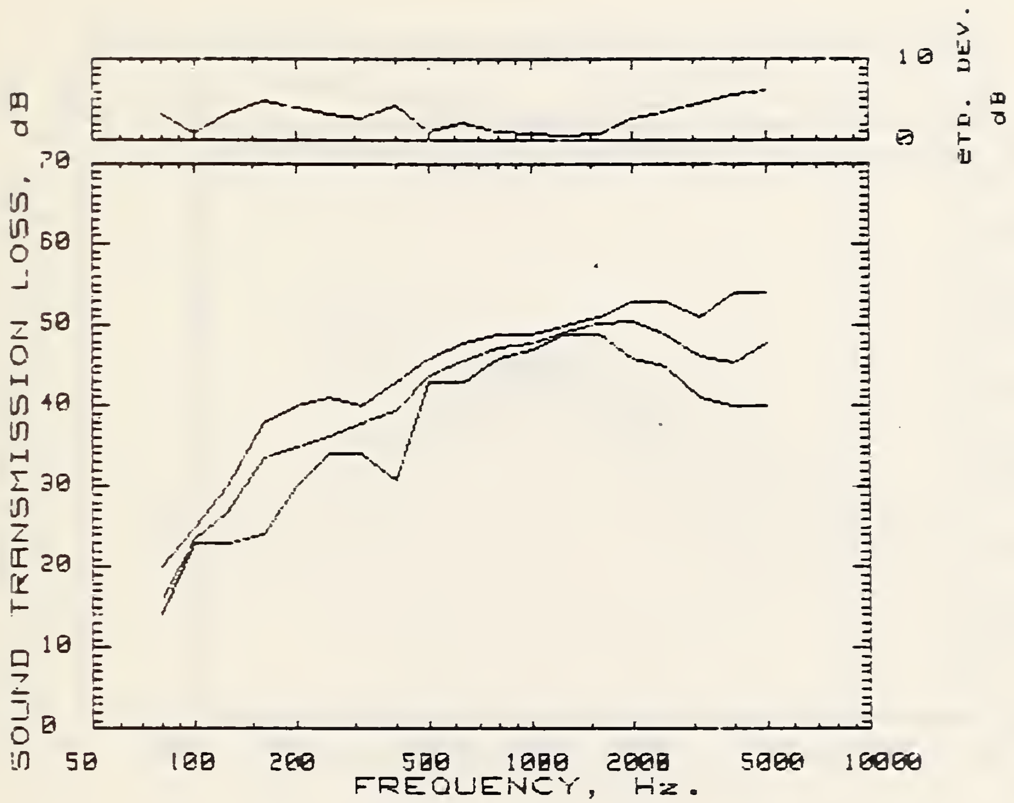
Hz	dB	Hz	dB
125	26	800	45
160	32	1000	45
200	32	1250	47
250	32	1600	47
315	34	2000	47
400	38	2500	46
500	41	3150	45
630	43	4000	43

Figure 67. Average and range of sound transmission loss of double glazed sealed windows consisting of panes of the same thickness, contained within a range of 5/32-1/4-in mounted in parallel in 2 sashes with an interpane spacing of 2-1/2 to 4-in.



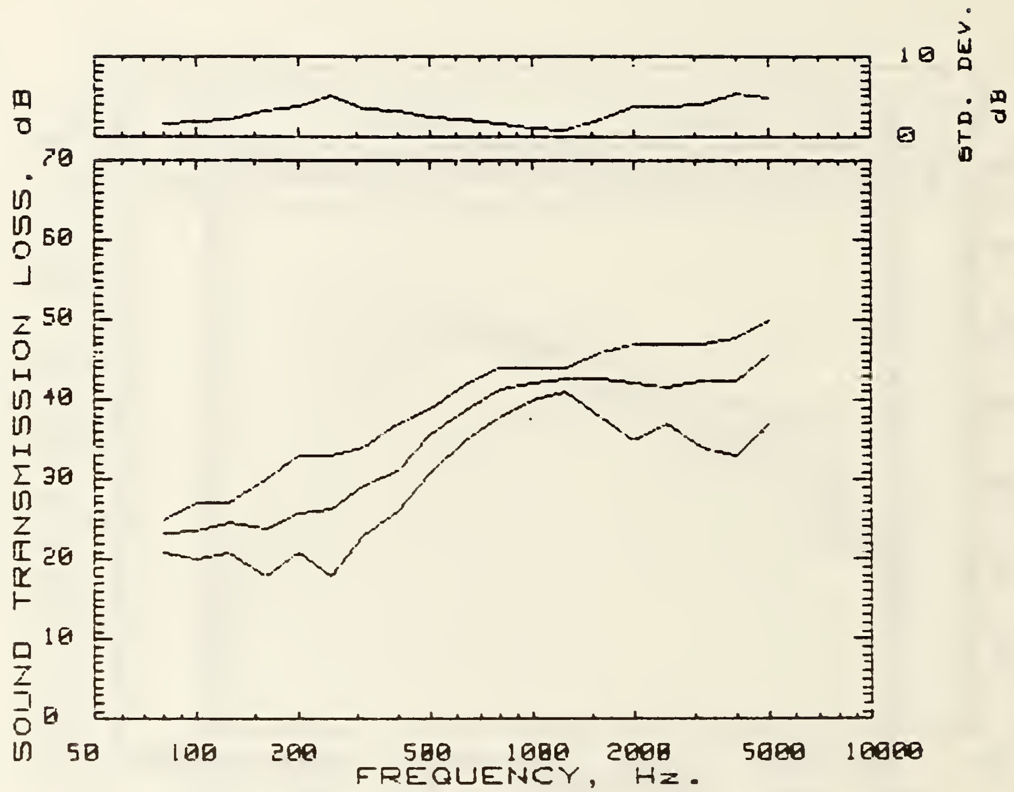
Hz	dB	Hz	dB
125	26	800	46
160	33	1000	46
200	33	1250	48
250	34	1600	49
315	36	2000	49
400	39	2500	48
500	42	3150	45
630	44	4000	44

Figure 68. Average and range of sound transmission loss of double glazed sealed windows consisting of panes of the same thickness, contained within a range of 5/32-1/4 in mounted in parallel in 2 sashes with an interpane spacing of 3-6-in.



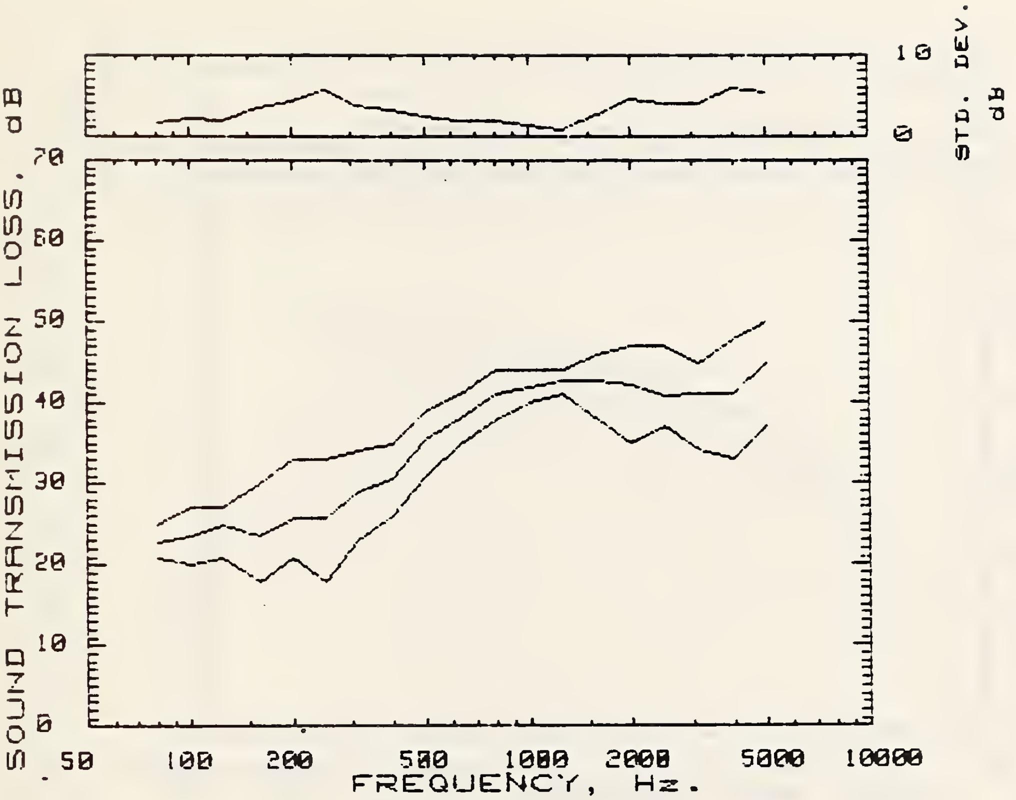
Hz	dB	Hz	dB
125	27	800	47
160	34	1000	48
200	35	1250	49
250	36	1600	50
315	38	2000	51
400	40	2500	49
500	44	3150	46
630	46	4000	46

Figure 69. Average and range of sound transmission loss of double glazed sealed windows consisting of parallel panes of the same thickness contained within a range of 5/32-1/4-in mounted in 2 sashes in parallel with a interpane spacing greater than 6-in.



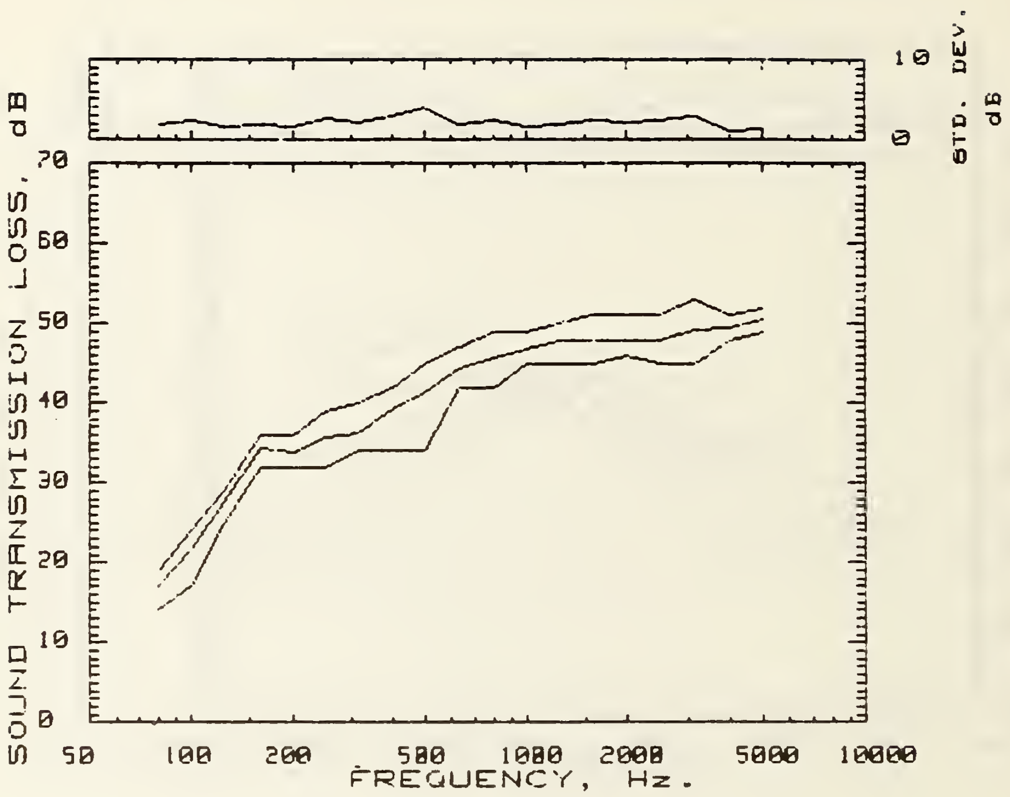
Hz	dB	Hz	dB
125	25	800	41
160	24	1000	42
200	26	1250	43
250	26	1600	43
315	29	2000	42
400	31	2500	42
500	36	3150	43
630	39	4000	43

Figure 70. Average and range of sound transmission loss of double glazed sealed windows consisting of panes of different thicknesses each 1/8 and 1/4-in mounted in parallel in two sashes with an interpane spacing between 1 and 1-1/2-in.



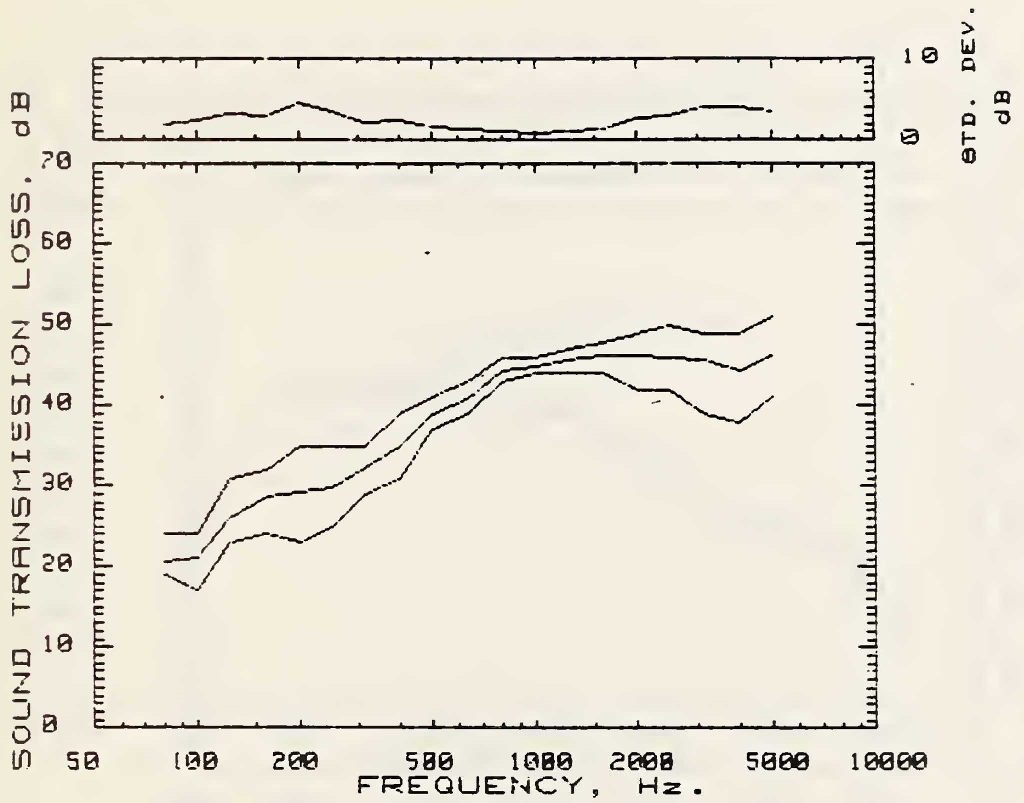
Hz	dB	Hz	dB
125	28	800	43
160	29	1000	44
200	29	1250	45
250	30	1600	45
315	32	2000	45
400	34	2500	44
500	39	3150	43
630	41	4000	44

Figure 71. Average and range of sound transmission loss of double glazed sealed windows consisting of panes of different thicknesses, each 1/8 and 1/4-in, mounted in parallel in 2 sashes with an interpane spacing between 1-1/2 and 2-in.



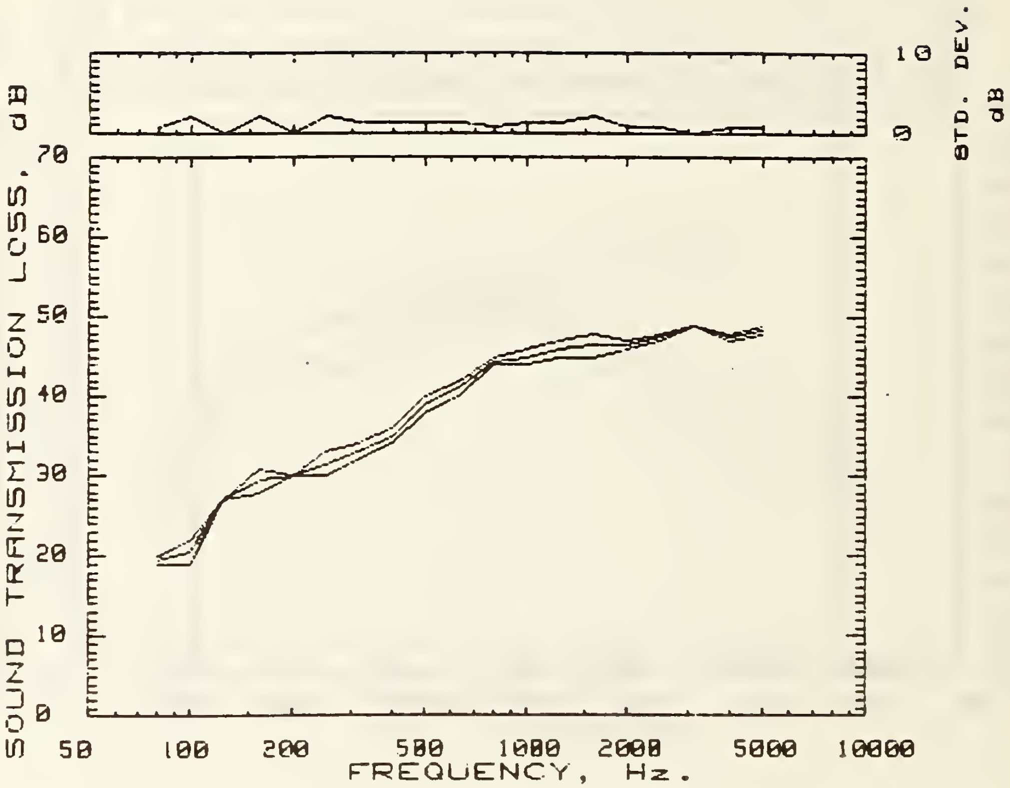
Hz	dB	Hz	dB
125	28	800	46
160	34	1000	47
200	34	1250	48
250	36	1600	48
315	36	2000	48
400	39	2500	48
500	42	3150	49
630	44	4000	50

Figure 72. Average and range of sound transmission loss of double glazed sealed windows consisting of panes of different thicknesses, each 1/8 and 1/4-in, mounted in parallel in 2 sashes with an interpane spacing between 2-1/2 and 6-in.



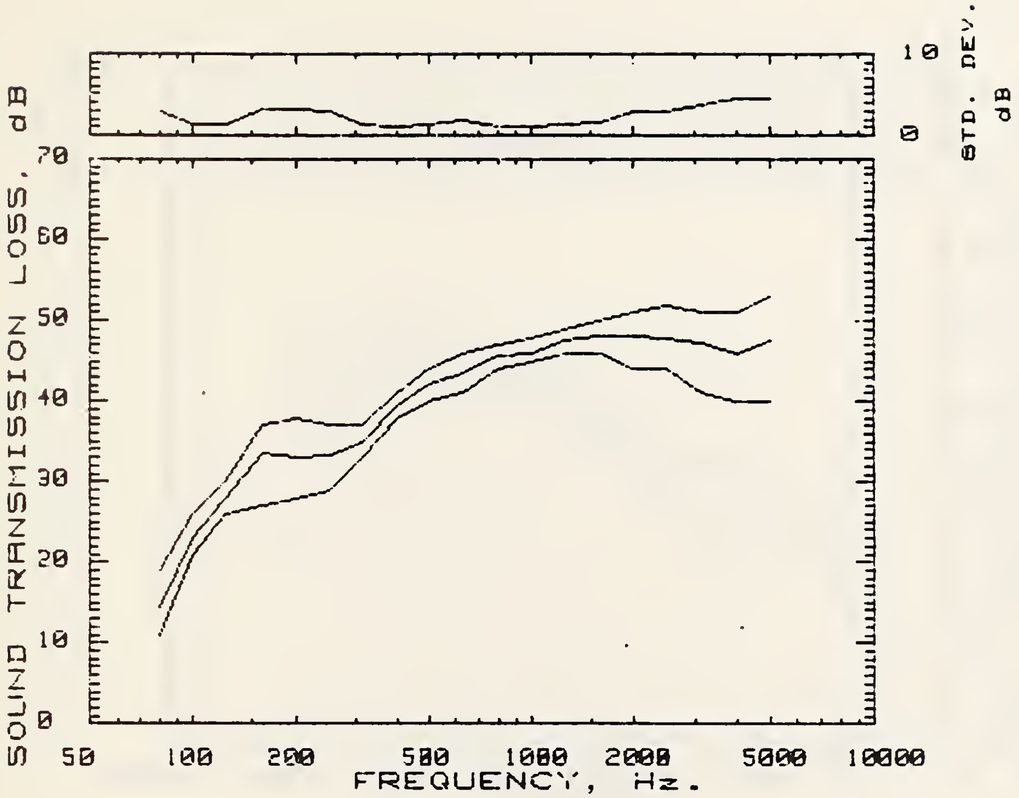
Hz	dB	Hz	dB
125	26	800	44
160	29	1000	45
200	29	1250	46
250	30	1600	46
315	32	2000	46
400	35	2500	46
500	39	3150	46
630	41	4000	44

Figure 73. Average and range of sound transmission loss of double glazed sealed windows consisting of panes of different thicknesses each 1/8 and 1/4-in mounted in 2 sashes not in parallel with a maximum interpane spacing of 3-in and a minimum interpane spacing of 1-in.



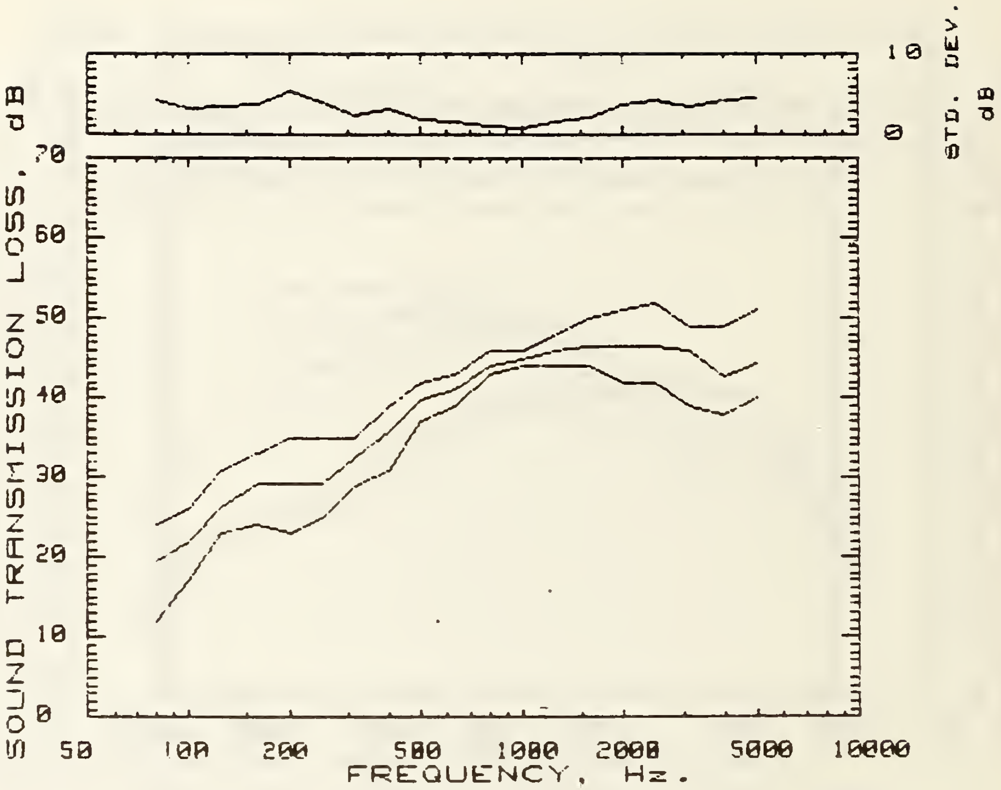
Hz	dB	Hz	dB
125	27	800	45
160	30	1000	45
200	30	1250	46
250	32	1600	47
315	33	2000	47
400	35	2500	48
500	39	3150	49
630	41	4000	48

Figure 74. Average and range of sound transmission loss of double glazed sealed windows consisting of panes of different thicknesses each 1/8 and 1/4-in, mounted in 2 sashes not in parallel with a maximum interpane spacing of 3-in and a minimum interpane spacing of 2-in.



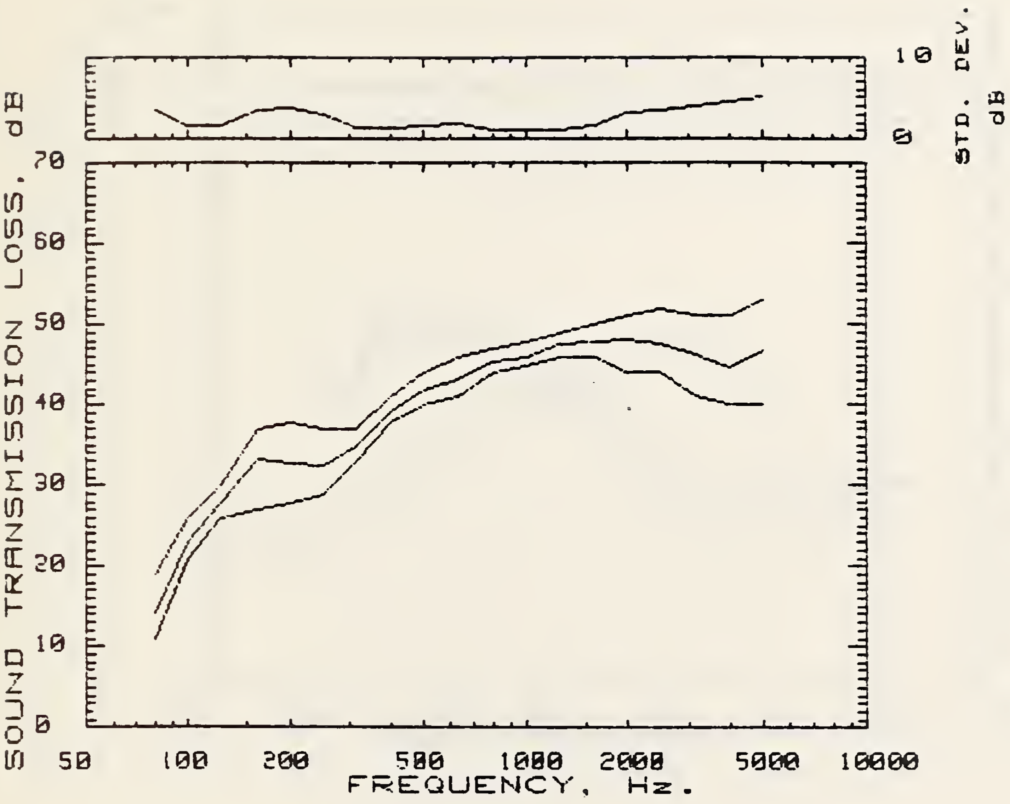
Hz	dB	Hz	dB
125	28	800	46
160	34	1000	46
200	33	1250	48
250	33	1600	48
315	35	2000	48
400	39	2500	48
500	42	3150	47
630	44	4000	46

Figure 75. Average and range of sound transmission loss of double glazed sealed windows consisting of panes of different thicknesses each 1/8 and 1/4-in, mounted in 2 sashes not in parallel with interpane spacing of 6-in and minimum interpane spacing of 2-in.



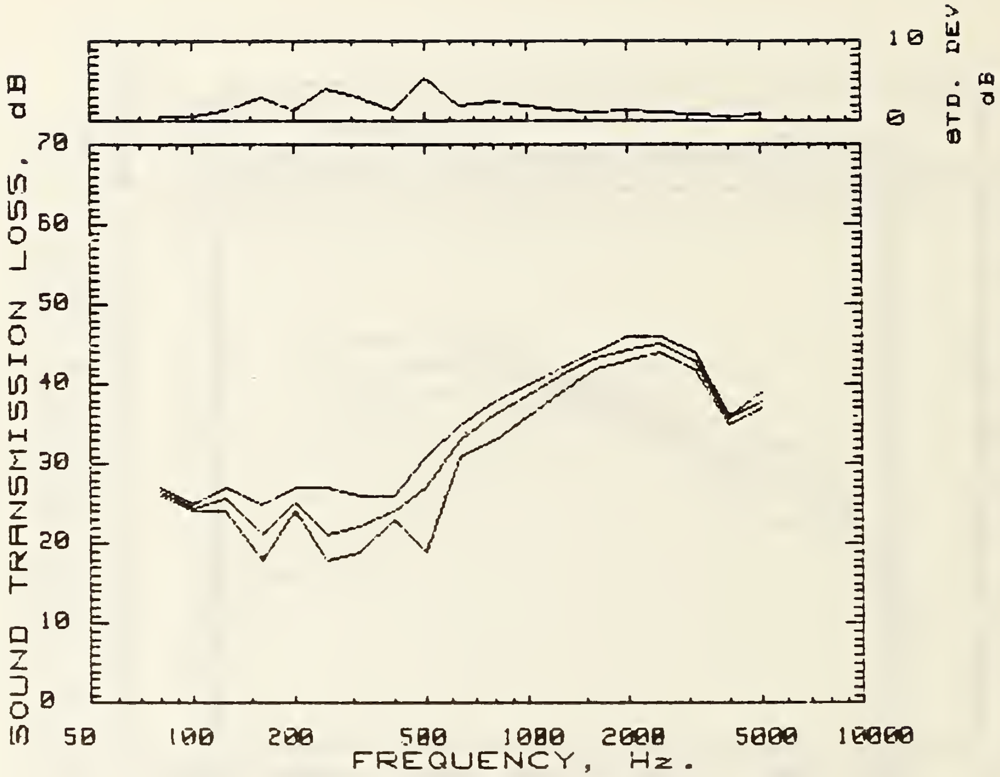
Hz	dB	Hz	dB
125	26	800	44
160	29	1000	45
200	29	1250	46
250	29	1600	47
315	33	2000	47
400	36	2500	47
500	40	3150	46
630	41	4000	43

Figure 76. Average and range of sound transmission loss of double glazed sealed windows consisting of panes of the same thickness contained within a range of 1/32-1/8-in, mounted in 2 sashes not in parallel with a maximum interpane spacing of 3-in and minimum interpane spacing of 1-in.



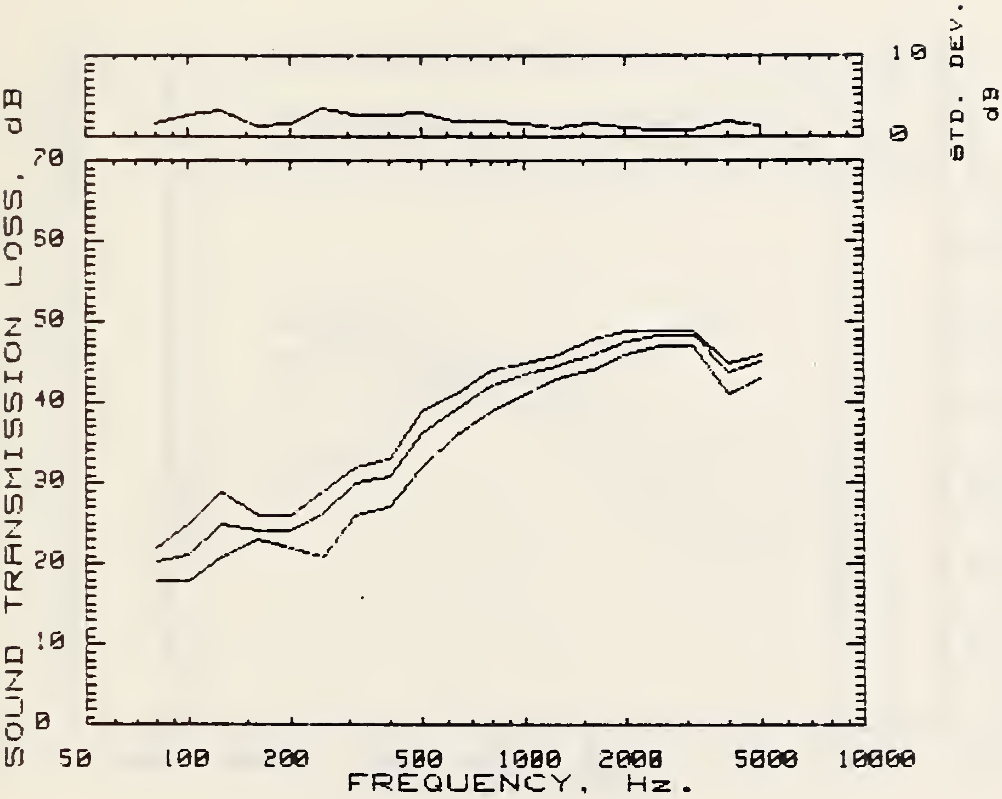
Hz	dB	Hz	dB
125	28	800	46
160	33	1000	46
200	33	1250	48
250	33	1600	48
315	35	2000	48
400	39	2500	48
500	42	3150	46
630	43	4000	45

Figure 77. Average and range of sound transmission loss of double glazed sealed windows consisting of panes of the same thickness contained within a range of 1/8-1/3-in, mounted in 2 sashes not in parallel with a maximum interpane spacing of 6-in and a minimum interpane spacing of 2-in.



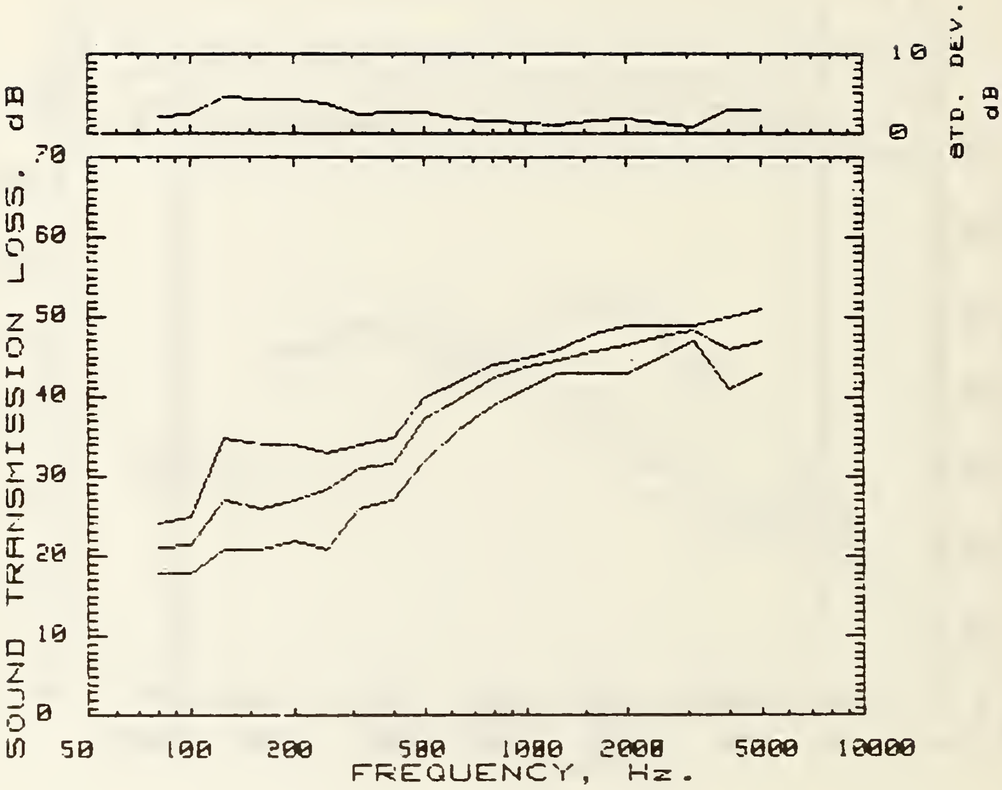
Hz	dB	Hz	dB
125	26	800	36
160	21	1000	39
200	25	1250	41
250	21	1600	43
315	22	2000	45
400	24	2500	45
500	27	3150	43
630	33	4000	36

Figure 78. Average and range of sound transmission loss of triple glazed sealed windows consisting of 1/8-in panes mounted in 1 wood sash with interpane spacing ranging from 1/8-13/32-in.



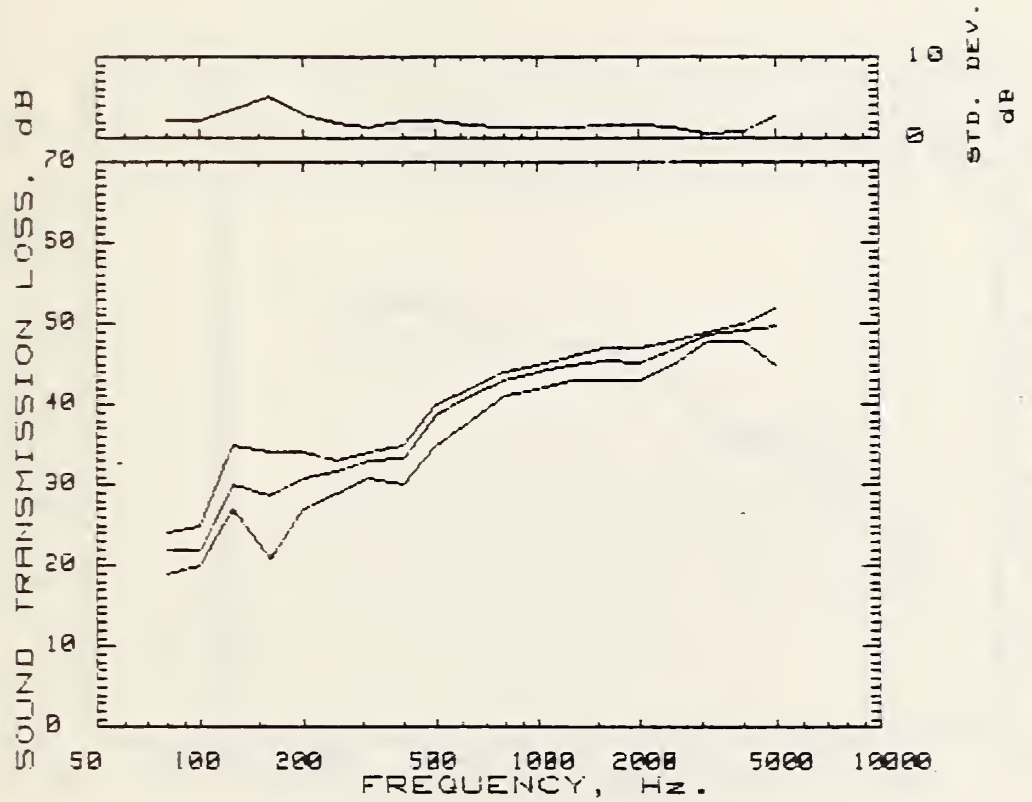
Hz	dB	Hz	dB
125	25	800	42
160	24	1000	44
200	24	1250	45
250	26	1600	46
315	30	2000	48
400	31	2500	48
500	36	3150	48
630	39	4000	48

Figure 79. Average and range of sound transmission loss of triple glazed sealed windows consisting of 2 panes 1/8-in thick mounted in 1 wood sash with an interpane spacing of 1/4-in and a metal spacer and with a third pane 1/8-in thick mounted in a separate sash with a 3/4-2-in space.



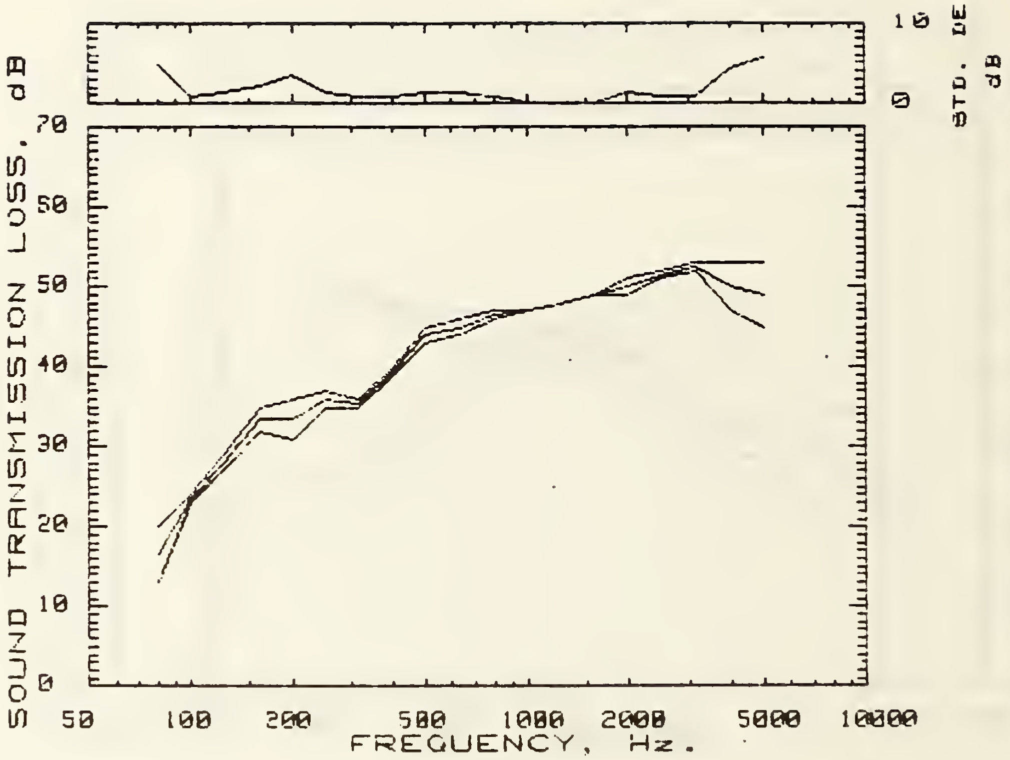
Hz	dB	Hz	dB
125	27	800	42
160	26	1000	44
200	27	1250	45
250	29	1600	46
315	31	2000	46
400	32	2500	48
500	37	3150	48
630	40	4000	46

Figure 80. Average and range of sound transmission loss of triple glazed sealed windows consisting of 2 panes 1/8-in thick mounted in 1 wood sash with an interpane space of 1/4-in and a metal spacer and with the third pane consisting of either a 1/8 or 1/4-in thick glass mounted in a separate sash 3/4-2-in away.



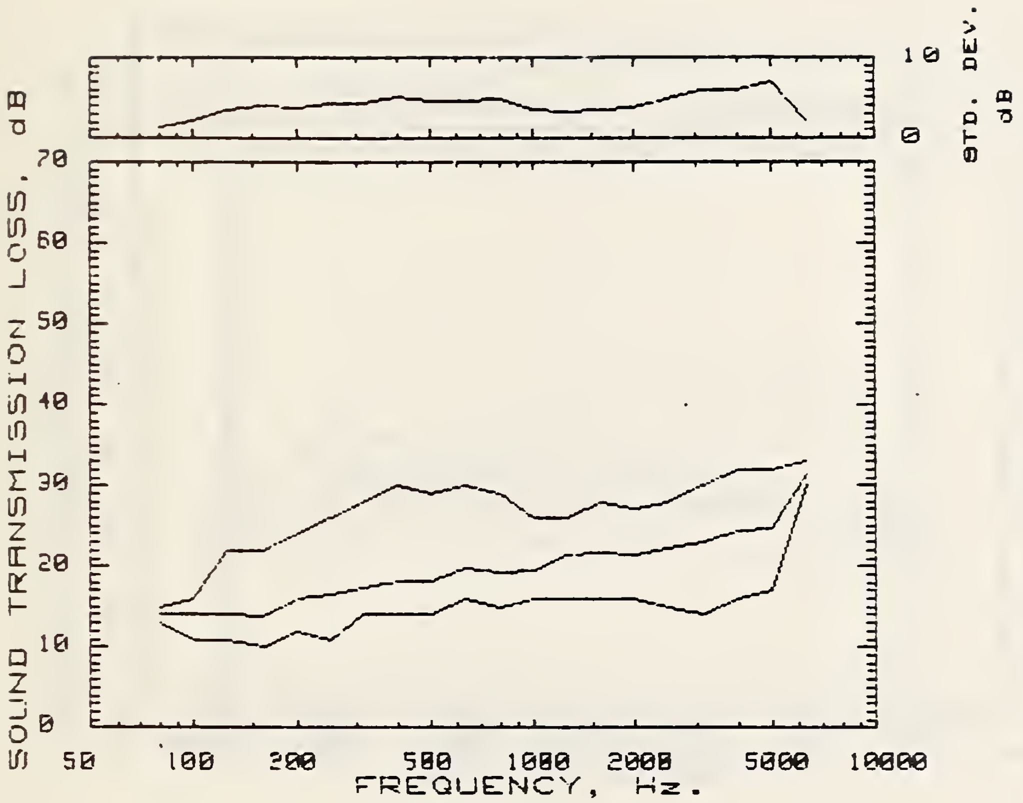
Hz	dB	Hz	dB
125	30	800	43
160	29	1000	44
200	31	1250	45
250	32	1600	45
315	33	2000	45
400	33	2500	47
500	39	3150	49
630	41	4000	49

Figure 81. Average and range of sound transmission loss of triple glazed sealed windows consisting of 2 panes 1/8-in thick mounted in 1 sash with an interpane spacing of 1/4-in and a metal spacer and with the third pane consisting of 1/4-in glass mounted 1-2-in away in a separate sash.



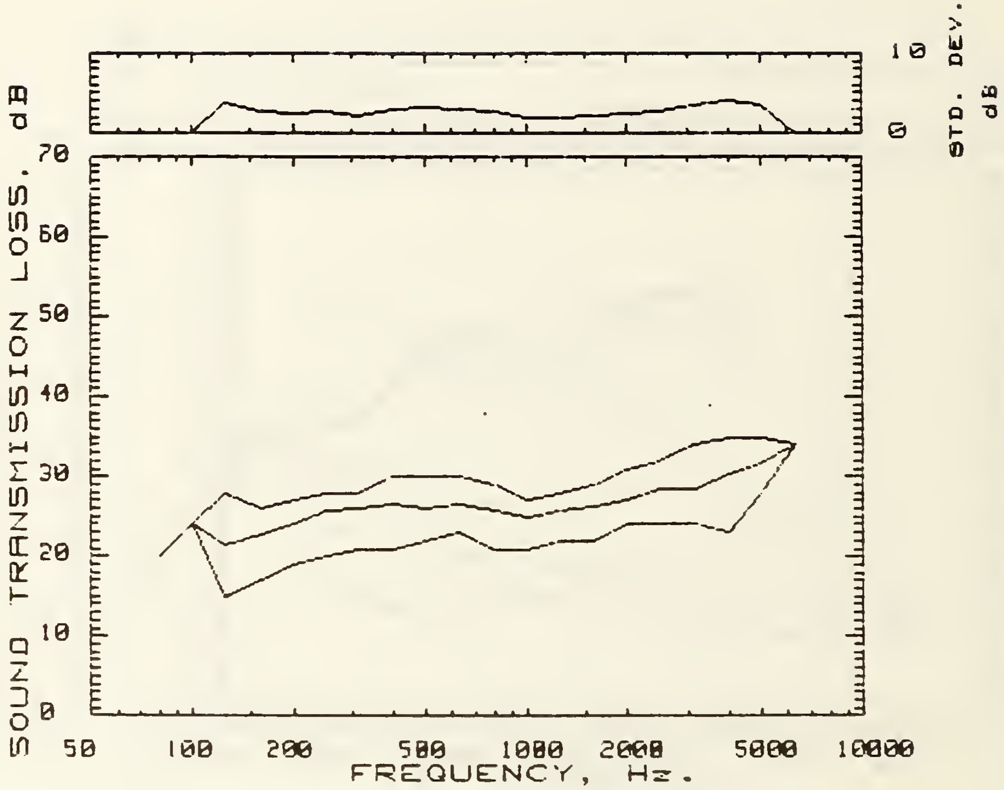
Hz	dB	Hz	dB
125	28	800	47
160	34	1000	47
200	34	1250	48
250	36	1600	49
315	36	2000	50
400	40	2500	52
500	44	3150	52
630	45	4000	50

Figure 82. Average and range of sound transmission loss of triple glazed sealed windows consisting of 1/8-in thick panes mounted in 2 wood sashes with a first interpane spacing of 1/4-in and a second interpane spacing of 4-in.



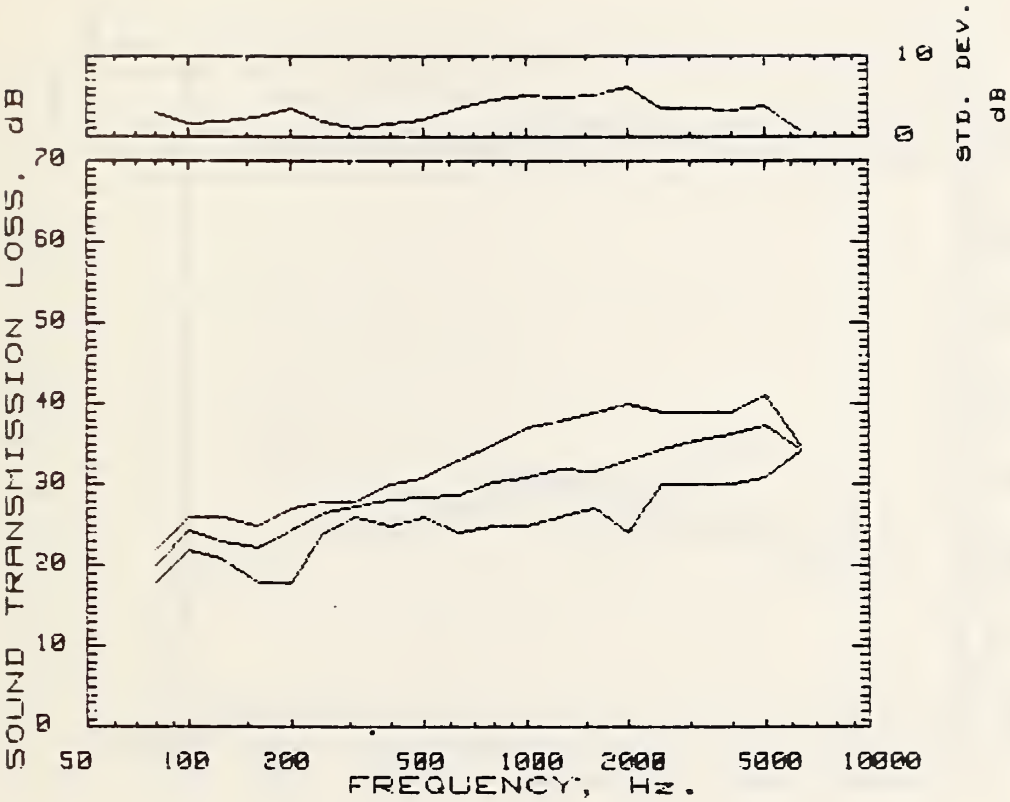
Hz	dB	Hz	dB
125	14	800	19
160	14	1000	20
200	16	1250	22
250	17	1600	22
315	18	2000	22
400	18	2500	22
500	18	3150	23
630	20	4000	24

Figure 83. Average and range of sound transmission loss of hollow core wood doors with weather stripping.



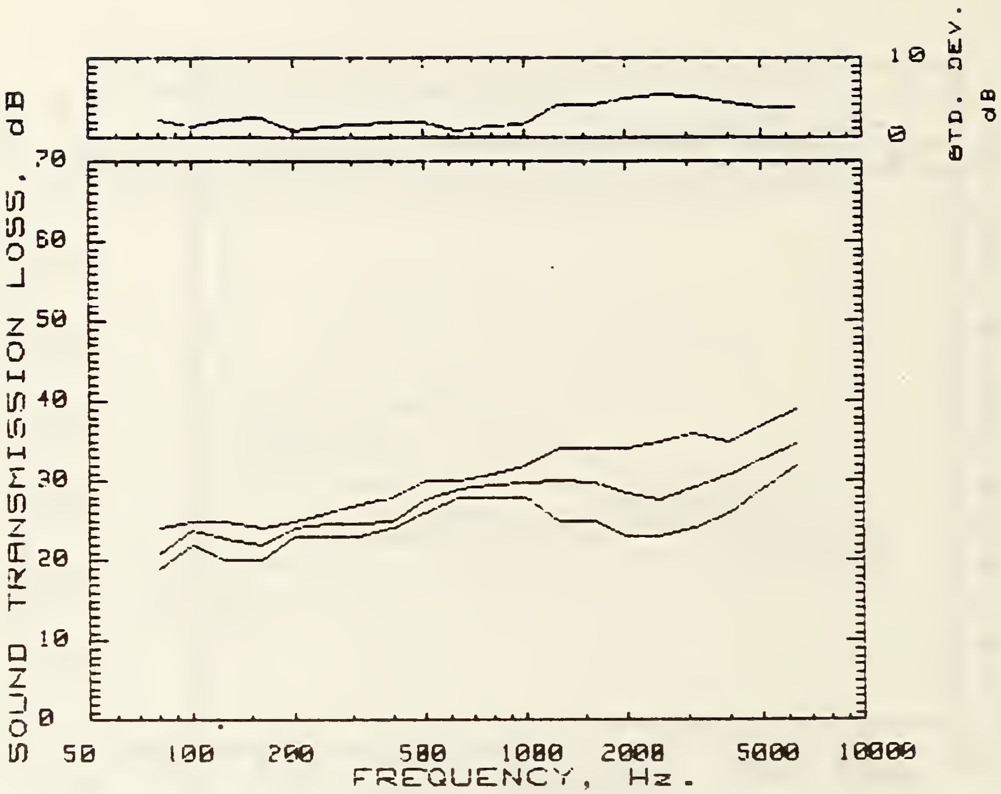
Hz	dB	Hz	dB
125	21	800	26
160	23	1000	25
200	24	1250	26
250	26	1600	26
315	26	2000	27
400	27	2500	28
500	26	3150	28
630	27	4000	30

Figure 84. Average and range of sound transmission loss of solid core wood doors with weather stripping.



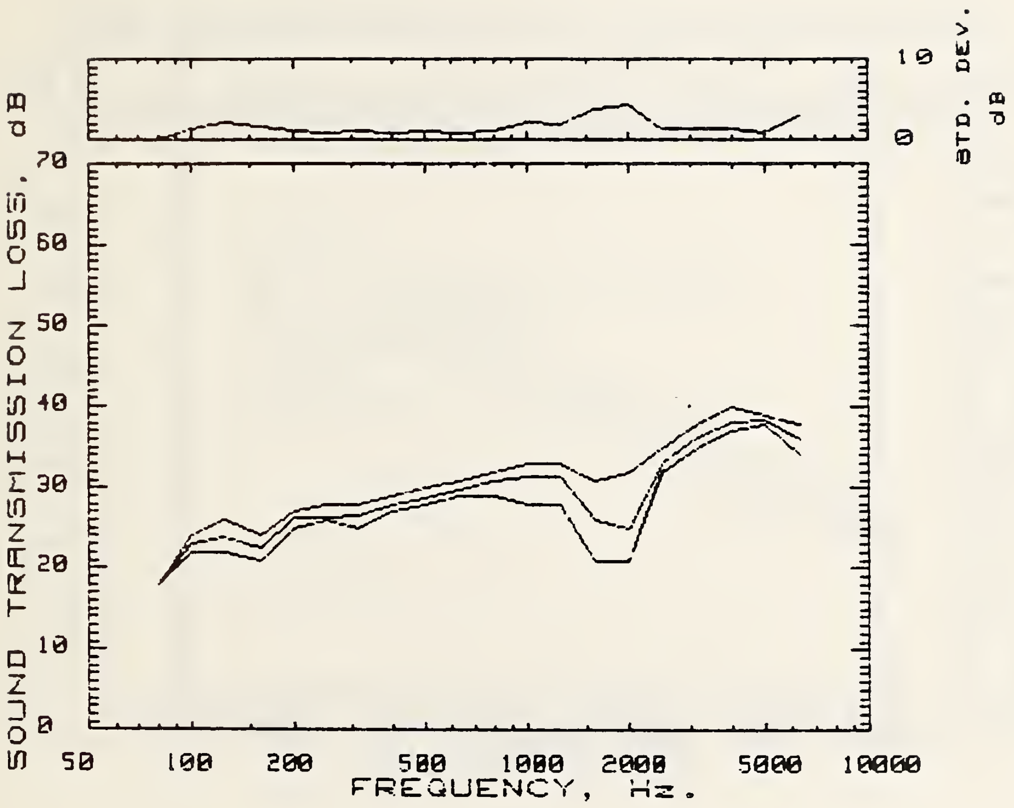
Hz	dB	Hz	dB
125	23	800	30
160	22	1000	31
200	25	1250	32
250	26	1600	32
315	27	2000	33
400	28	2500	35
500	28	3150	35
630	29	4000	36

Figure 85. Average and range of sound transmission loss of weather stripped and sealed solid core wood doors.



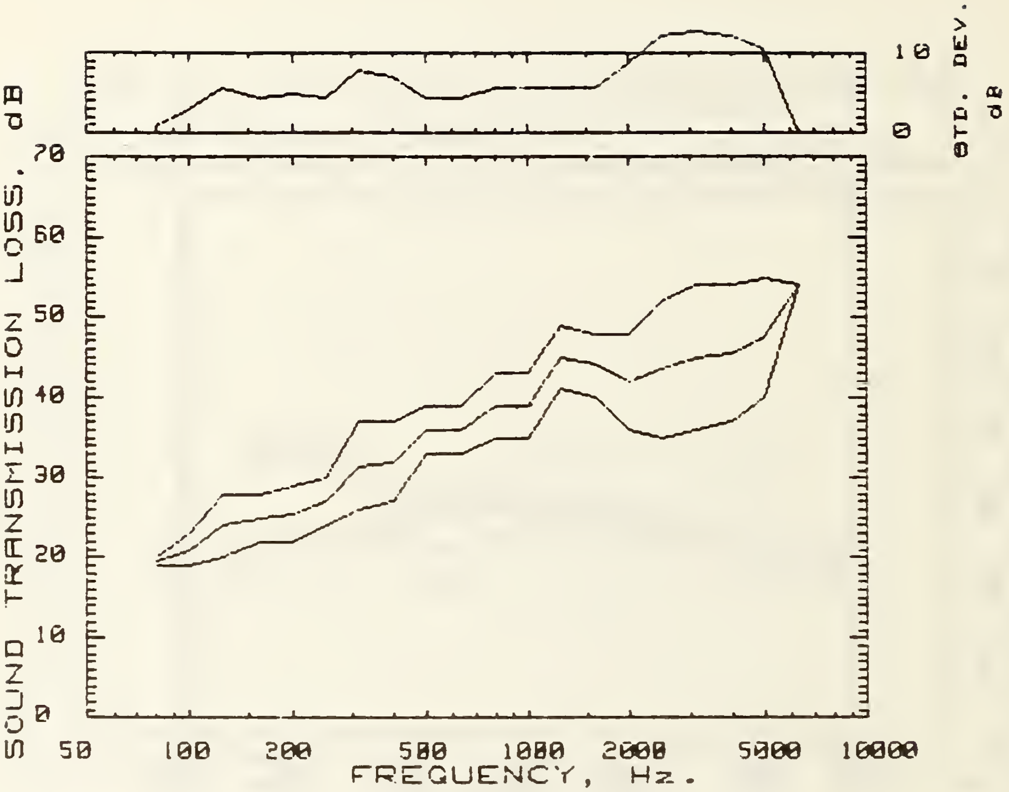
Hz	dB	Hz	dB
125	23	800	30
160	22	1000	30
200	24	1250	30
250	25	1600	30
315	25	2000	29
400	25	2500	28
500	28	3150	30
630	29	4000	31

Figure 86. Average and range of sound transmission loss of weather stripped glass containing doors.



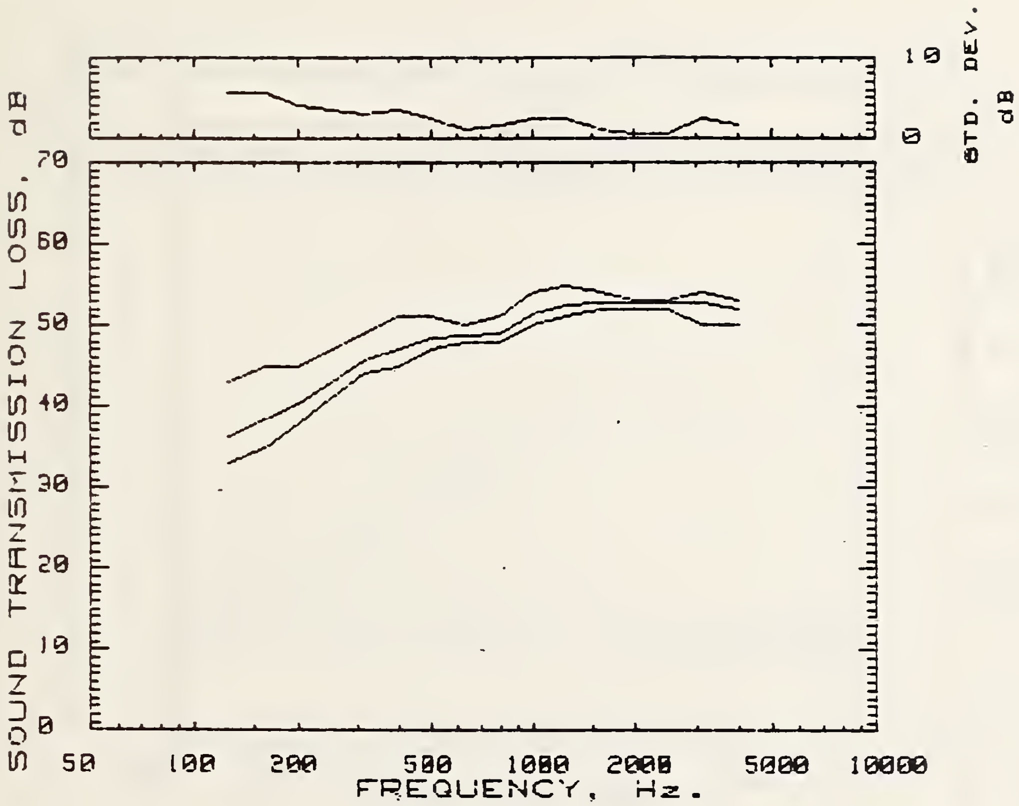
Hz	dB	Hz	dB
125	24	800	31
160	22	1000	31
200	26	1250	31
250	26	1600	26
315	27	2000	25
400	28	2500	33
500	29	3150	36
630	30	4000	38

Figure 87. Average and range of sound transmission loss of weather stripped metal doors.



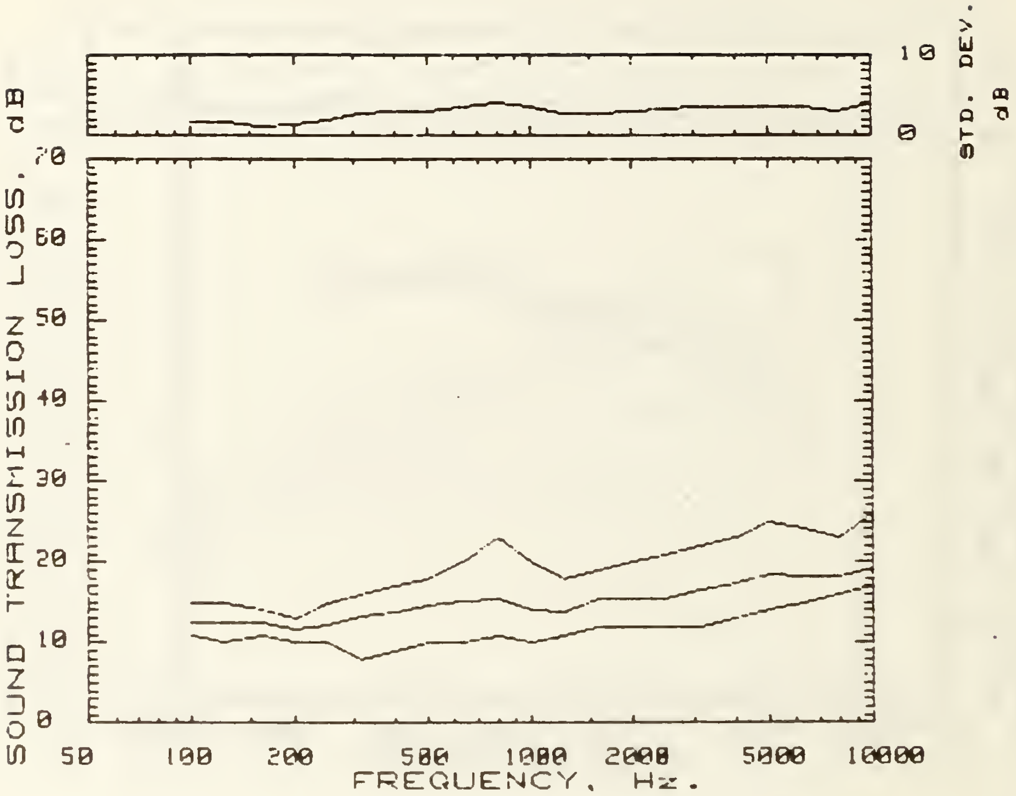
Hz	dB	Hz	dB
125	22	800	27
160	23	1000	26
200	24	1250	27
250	26	1600	28
315	26	2000	29
400	27	2500	30
500	26	3150	30
630	27	4000	32

Figure 88. Average and range of sound transmission loss of weather stripped and sealed solid core wood doors with aluminum sealed storm door fitted with a single glazed window.



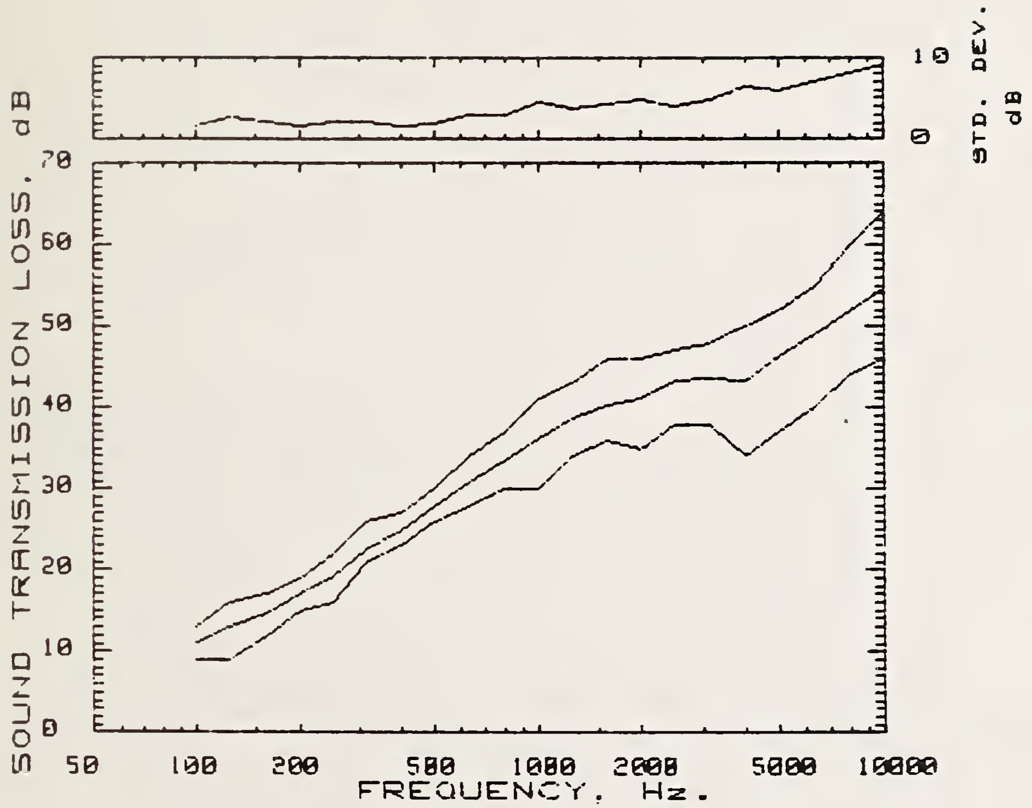
Hz	dB	Hz	dB
125	36	800	49
160	38	1000	51
200	40	1250	52
250	43	1600	53
315	46	2000	53
400	47	2500	53
500	48	3150	52
630	49	4000	52

Figure 89. Average and range of sound transmission loss of acoustical doors.



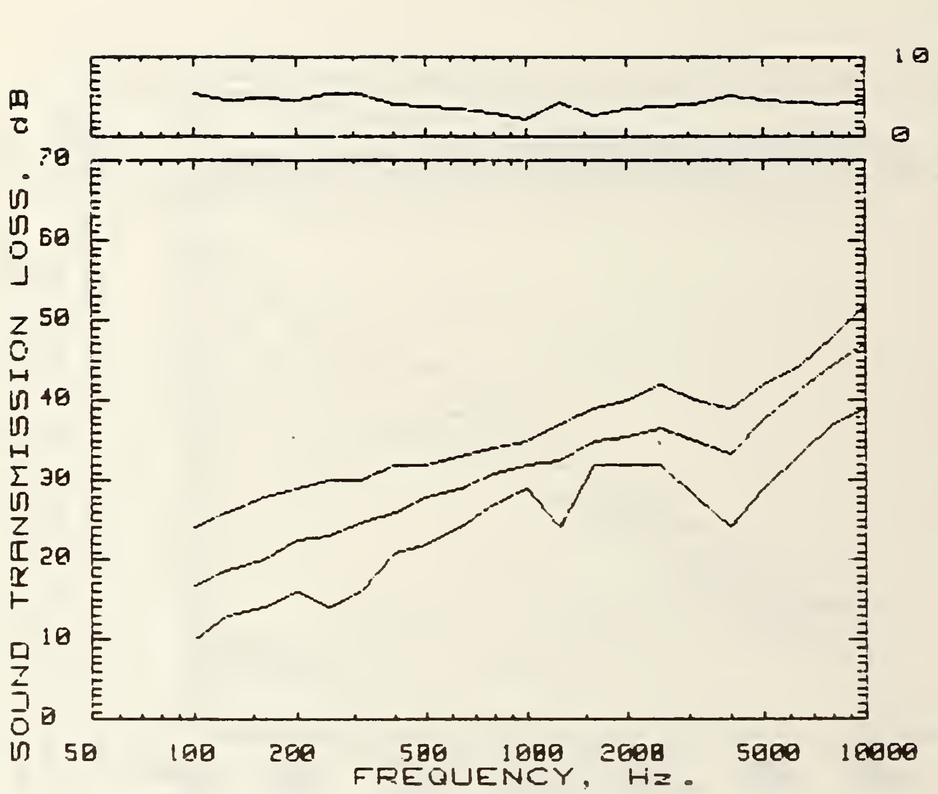
Hz	dB	Hz	dB
125	13	800	16
160	13	1000	14
200	12	1250	14
250	12	1600	15
315	13	2000	15
400	14	2500	16
500	15	3150	17
630	15	4000	17

Figure 90. Average and range of sound transmission loss of pitched wood frame domestic roof with sealed perimeter but without insulation or ceiling.



Hz	dB	Hz	dB
125	13	800	34
160	15	1000	36
200	17	1250	39
250	19	1600	40
315	22	2000	41
400	25	2500	43
500	28	3150	44
630	31	4000	43

Figure 91. Average and range of sound transmission loss of pitched wood frame domestic roof with sealed perimeter and insulation between roof joists but without ceiling.



Hz	dB	Hz	dB
125	19	800	31
160	20	1000	32
200	22	1250	32
250	23	1600	35
315	25	2000	35
400	26	2500	37
500	28	3150	35
630	29	4000	33

Figure 92. Average and range of sound transmission loss of pitched wood frame domestic roof with sealed perimeter and plaster ceiling but without insulation.