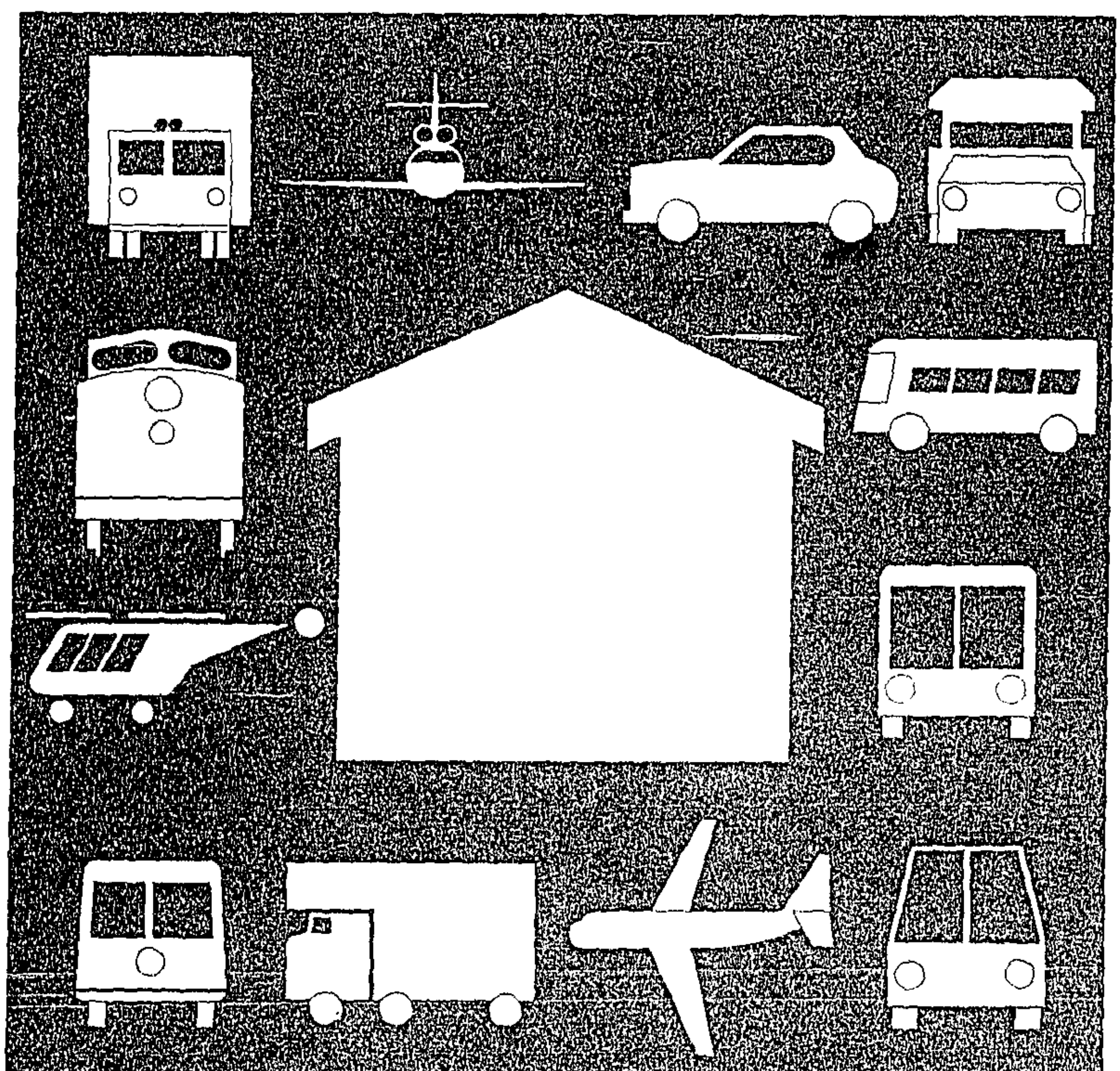
Building Science Series 84

DESIGN GUIDE

for Reducing Transportation Noise in and Around Buildings

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards



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Conversion Table to SI Units

This publication uses customary English units for the convenience of engineers and others who use them habitually. The table below is for the reader interested in conversion to SI units. For additional information see:
(1) NBS LC1078, Dec., 1976, "The Metric System of Measurement".
(2) Z210.1-1976, "ASTM/IEEE Standard Metric Practice".

Quantity	To convert from	To	Multiply by
Length	inch	m (meter)	2.540×10^{-2}
	foot	m	3.048×10^{-1}
	mile	m	1.609×10^{3}
Area	in^2	m^2	6.452×10^{-4}
	ft^2	m^2	9.290×10^{-2}
Volume	in^3	m^3	1.639×10^{-5}
	ft^3	m^3	2.832×10^{-2}
	gallon	m^3	3.785×10^{-3}
Temperature	°F	°C	$t_{°C} = (t_{°F} - 32)/1.8$
T. difference	$\Delta t_{°F}$	K	$\Delta T_K = \Delta t_{°F}/1.8$
Mass	pound	kg	4.536×10^{-1}
	ounce	kg	2.835×10^{-2}
Pressure	psi	Pa	6.895×10^{3}
	in H_2O	Pa	2.488×10^{2}
	in Hg	Pa	3.386×10^{3}
	mmHg	Pa	1.333×10^{2}
Energy	Btu	J	1.055×10^{3}
	MBtu	J	1.055×10^{9}
	kWh	J	3.600×10^{6}
	ft • lbf	J	1.356×10^{0}
	kilocalorie	J	4.187×10^{3}
Power	Btu/h	W	2.931×10^{-1}
	hp	W	7.457×10^{2}
Flow	gal/min	m^3/s	6.309×10^{-5}
	ft^3/min	m^3/s	4.719×10^{-4}
Density	lb/ft^3	kg/m^3	1.602×10^{1}
	lb/gal	kg/m^3	1.198×10^{2}
Heat Capacity	Btu/(lb • °F)	J/(kg • K)	4.187×10^{3}
	$Btu/(ft^3 \cdot °F)$	$J/(m^3 \cdot K)$	6.707×10^{4}

ABSTRACT

This design guide presents a unified procedure for the selection of noise criteria in and around buildings, for the prediction of exterior and interior noise levels arising as a consequence of transportation systems operations, and for the evaluation of the adequacy of building designs with regard to environmental noise. Noise criterion levels are suggested in terms of equivalent sound levels (Leq). Simplified predictive methods enable the estimation of noise levels arising as a consequence of highway, railway, and aircraft operations. The sound isolation provided by the building shell is estimated by means of a new single-figure rating system. Finally, design manipulations which may make possible the improvement of the acoustic conditions in and around buildings are suggested.

Key words: Acoustics; architectural acoustics; building acoustics; environmental noise; noise; noise control; sound; transportation system noise.

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Chapter 1
How to Use This Design Guide

Sound surrounds us everywhere—the song of a meadowlark, the laughter of children, and the rustle of autumn leaves. Unfortunately, the march of technology and the trend toward higher living densities have meant that these desired sounds of birds, children, and nature are often masked by the roar of automobiles, trucks, locomotives, and airplanes. The purpose of this design guide is to quantitatively estimate the magnitude of noise, or unwanted sound, at a building site in order to choose the most appropriate building occupancy for that site, or to design features into new or existing buildings that will reduce or control noise.

In the design of new buildings, architects, builders, designers, developers, and engineers make decisions which affect future acoustic conditions in and around the buildings. When the decisions are wrong, acoustic comfort may be lost causing building occupants annoyance and stress. Such discomfort can often be averted by changes in the building's location or orientation or in its construction materials and workmanship.

In dealing with noise problems, the material in this guide can be used . . . to solve simple problems due to noise from highways, railways, and aircraft, and . . . to cast up a warning flag when a serious noise problem is encountered. Seeing such a red flag, the designer should seek the professional consultation of expert acousticians.

This noise design guide was written by acousticians, architects, and psychologists at the National Bureau of Standards working to a strict timetable. It was agreed at the outset of the project that the guide's methods of calculation and the data supporting them would have to be drawn from state-of-the-art materials. This has had the disadvantage of a loss of potential detail and precision, but the advantage of simplification, which the user of this guide will no doubt appreciate.

The guide has one salient advantage over most other guides in that it is quantitative, offering you a method of calculating not just *how* transportation noise affects your building, but *how much*. Furthermore, the guide is arranged in a sequence of chapters which parallel your design sequence. The guide is meant to accompany you as a drafting board companion in a design voyage as you depart from first concepts that are vague and tentative until you arrive at a finished building scheme that is robust, rich in detail, and well-reasoned—especially insofar as the analysis of transportation system noise is concerned.

The design guide aims to get right to the point in attacking your urgent noise problems in building or site design. Hence, it aims neither to nag you about fundamentals of acoustics nor overburden you with esoteric details. If you need fundamentals, you can get them from one of the many excellent textbooks available (the references at the end of this chapter [1-22] include references to the literature on general acoustics [1-5], noise and vibration control [6-10], basic acoustical measurements [11, 12], and acoustics and architectual design [13-22]); if you want to penetrate the relevant details on acoustics (and we hope you will) specific references are listed at the end of each chapter.

What type of person should use this design guide? We think it can be anyone who has a technical background and a fundamental knowledge of building design and construction. We refer to the guide's user as a *designer*, but we think of this designer as any architect, builder, building designer, contractor, developer, engineer, landscape architect, or student who is faced with a noise problem in building or site design. If this shoe fits, welcome! You're the designer we're seeking to help.

Of course, as a designer you have a responsibility, too, that of creating a scheme. A building scheme is essential since this design guide is based on analysis; and it cannot work without a scheme to analyze.

In designing your building or site scheme, you will be juggling a myriad of design variables: building codes, available financing, and costs; structural, enclosure, mechanical, electrical, and communications systems; color, texture, massing, shape, size, and arrangement; and not just acoustics, but also aesthetics, comfort, health, privacy, safety, and security. Many of these other design variables relate to or interface with acoustics, but some will be in conflict. As a designer you must use judgment to make tradeoffs in achieving a happy blend of needed features in your scheme. We, of course, assist you only in noise prediction and control. We think you will welcome this assistance.

Managing all these design variables is like herding frogs. Just as you approach one, it leaps away in an unexpected direction. Still, this guide is meant to do what it says—give you guidance about acoustics as you design. To do so, the guide makes a number of assumptions about design, which will now be discussed in conjunction with the contents of the guide.

As it progresses, design is expressed as a set of pictures describing a scheme. The scheme is the conversation piece; that is, the focal point and basis of all communications about the building project. The designer, consulting engineer—all of these get their heads together over the scheme to assess it, evaluate it, revise it, or discard it and start afresh. This design guide, too, requires a scheme against which you are to examine noise conditions.

The scheme is customarily drawn to scale in plan, elevation, section, perspective—as many two-dimensional drawings as are needed to visually explain the scheme as it will eventually be when built in three dimensions. The acoustics design guide analyses may require small scale drawings in plan (maps and site plans), and for some projects drawings in section to illustrate, in a vertical plane, the path of the sound as it moves from its source across the terrain (including barriers) to a building or other "receiver." The design guide analysis will require large scale drawings to show the general layout and details of the proposed building sufficient for its calculations and evaluations.

Before the scheme is started, design communications do not exist as pictures, but mostly as words—the *conversations* of owner and designer, and the *narrative* of an architectural program. This may be just a few notes on a restaurant placemat or a lengthy, formal exposition of the objectives, scope, criteria, desired spaces, features, and functions of the proposed project. An ideal architectural program would contain the full set of explicit constraints which apply to the project. By constraint is meant anything which limits the degrees of freedom in the design. Constraints are not necessarily bad, only facts of life for a designer. In truth, constraints are desirable because they impose some limit, some restriction on the number of possible schemes. Since this number is infinite, the constraints can be a blessing, setting a boundary on unfettered, hence intolerable, design freedom.

Very few architectural programs approach the ideal in containing all constraints—instead most constraints are implicitly held in the designer's mind rather than explicitly printed in the program.

Some constraints are physical; for example, the configuration of the site and its surrounding environment, the characteristics of sound, the changes of weather. For purposes of this design guide, physical constraints critical for acoustic calculations develop from information which is to be obtained as directed in the first part of the next chapter (Chapter 2).

Other constraints are man-made, or "artificial", and are referred to here as rules. Rules include the provisions of building codes, as well as standards, requirements, and design criteria. Like other types of constraints, rules limit the number of possibilities in design; but rules also serve as objectives, as a way of measuring a scheme and evaluating it. If the rules are truly predictive of satisfactory buildings, then a scheme on paper which complies with the rules should describe a future building that will turn out to be satisfactory.

This design guide employs a noise criterion as the type of rule which is to govern your acoustic design and evaluation. The term "noise criterion" is used to denote a noise (sound pressure) level to be used as a design goal for your building project. Chapter 3 tells you how to select noise criteria appropriate for your building and its outdoor activity areas. The set of noise criteria you select then serves as a target to achieve for your building scheme. We hope that you will not only be able to achieve the design goal specified by the criteria you select, but even lower sound levels.

Earlier we mentioned physical constraints, the constraints arising from the physical nature of the site and from the physics of acoustic and other natural phenomena. As a designer, you cannot deal, or interact, with these physical constraints directly, just as you do not initially deal with a real building, only the scheme for a future building. Hence, you must have a method for modeling, for representing the site and acoustic phenomena in the same language of words, numbers, and pictures as you use for your scheme. Chapter 5 explains this concept, showing how you can quantitatively estimate the magnitude of sound coming from such transportation sources as highways, railways and aircraft, as it reaches your site or building.

Physical constraints and rules have been discussed. There is still a third, and final, type of constraint, namely the scheme constraint, which is simply a constraint arising from a decision that has been made about your scheme. If you decide that your building is to be a school, you have constrained it against becoming a home, a hospital, or an office building. If you decide it is to be built of brick, then you have constrained it against being built of concrete or cinder block. As more and more design decisions are made, the range of possibilities for your scheme is constantly narrowed. The most general of these scheme constraints are usually made quite early in the design process, and are uppermost in the architectural program, or problem statement. Such general scheme constraints are the type of building occupancy (commercial, industrial, institutional, or residential, etc.), the overall capital budget and in turn the general size of the building, the general level of quality for the building, the type of fire construction, etc. Since these general constraints are important to acoustical design, they must be stated (as set forth in Chapter 2) in advance of design.

As building design proceeds, decisions descend from the general to the particular, and constrain more and more the eventual outcome. In fact, design may be thought of as a process of scheme constraint setting—a process which moves from diagrammatic drawings to detailed drawings; and from abstractions like safety and security to concrete representations of walls, floors, and roofs. As it moves along, design relies upon a variety of plan, section, elevation, and perspective drawings to represent the scheme in a way that it can be studied. Through the visualization of the scheme, the designer educates himself about the future building, and is able, even if imperfectly, to imagine what the building will be like and how it will operate when occupied.

A good deal of the designer's attention is drawn to the building shell, that skin of walls and openings, roofs, and exposed floors which will separate the building from its outdoor environment. Design may proceed from the inside out, considering first the occupants, their needs and activities; then the rooms and spaces suitable for these activities; then the building shell to contain the rooms and spaces; and, finally, the relationship of this shell to the site. Or alternatively, design may proceed from the outside in, thinking first about the outdoor environment, the forces of climate, and relationships to neighboring buildings; then concentrating upon the building shell; and finally upon the building's rooms, occupants, and functions.

To be realistic, the designer must surely follow both routes, from the inside-out, and from the outside-in. This two-way approach is certainly needed for acoustical design, and is a concept embodied in this design guide. Inside-out design commences with the selection of an indoor noise criterion in Chapter 3, and then aims at the selection of representative rooms for acoustic analysis in Chapter 6. Outside-in design commences with the gathering of physical site data in Chapter 2, and the estimation of site noise from separate sources in Chapter 5. The sound from these various sources can be summed, and is that which is expected to impinge upon the rooms for which noise is to be predicted in Chapter 6.

Of course, inside-out design decisions are entangled with outside-in decisions. For example, in Chapter 6, you will probably want to limit your analyses, since they are time-consuming, to a small number of rooms, including only those critical rooms which are fairly susceptible to noise *and* which are exposed to the loudest sound conditions. But here you will be caught up in conflict—for if you design from the inside-out and identify your critical rooms early on, you will no doubt begin immediately to revise your scheme to fortify these rooms rendering them no longer critical; likewise, if you design from the outside-in, you will tend to sum transportation sounds at some arbitrary point, or points, on your site where you anticipate a critical room to appear in your scheme, but having identified the potentially noisy points on the site, you will want to begin immediately to ameliorate the noise level at those points. For example, you might choose to let the proposed building itself serve as a barrier, turning its back to the sources of sound, and locate rooms having special needs for quiet on the protected side of the building. In this fashion, progress in both inside-out and outside-in design is constantly interrupted by revisions in your scheme, and by the tendency to reverse your design direction.

Designers manage such mutually entangled decision chains through iterations of a scheme simply by working first from the outside-in and then from the inside-out.

Moreover, designers can generate alternative schemes which appear promising, and then compare the various schemes. By providing a method of analysis applicable for nearly any scheme, this design guide aids in such comparisons. Time spent in scheme generation, analysis, and comparisons will be rewarded with increasing insight into your building's noise conditions and their solution. Chapter 7 contains some explicit and much implicit advice to aid you in generating design alternatives.

Designing either from the inside out or from the outside in, you arrive inevitably at the building shell, your main line of defense against transportation noise. The room-by-room calculations of Chapter 6 are essentially calculations of the sound isolation afforded such rooms by that portion of the shell which constitutes the exterior faces of the rooms. To make these calculations, you will rely upon single-figure ratings for various types of exterior walls and wall openings, roofs, and exposed floors. A special single-figure shell isolation rating (SIR) system was devised for this purpose, and Chapter 6 describes the procedures for implementing this system. Appendix A presents SIRs for a variety of building shell materials and constructions.

In summary, this design guide is intended to aid you in making acoustic decisions for a building problem which confronts you. The guide's chapters are arranged in a sequence compatible with the overall design process for buildings. If you are using the guide for the first time or need to refresh your memory on its use, you will want to study the general discussion which is contained in this chapter. Then you will collect background information about your project site and make the early decisions about your building scheme called for in Chapter 2. Then, formulate noise criteria for the types of building occupancies or room functions you have in mind as described in Chapter 3. Then using the strategies described in Chapter 4, you will select a point or points on your site for estimating sound levels. Chapter 5 will then assist you in estimating the sound coming to your site from highway, railway and aircraft sources. For the first two sources, Chapter 5 will also show you how to estimate the attenuation of sound as it crosses various types of barriers. If your site or building is exposed to more than one source of sound, the contributions of these various sources can be summed as described early in Chapter 6.

By this time, it is presumed, you will have completed a schematic design for your building which can be analyzed for its noise transmission properties and interior noise levels by means of the strategies and methods of Chapter 6. The analysis is made on a room-by-room basis.

If the room sound levels are greater than the noise criteria you formulated in Chapter 3, you will want to revise your scheme. If the noise criteria are not met in just a few rooms, you may wish to make detailed scheme adjustments for only those rooms affected. If your scheme's noise troubles are more general, however, you will look for more extensive changes in your scheme. In either case, you will be helped by the suggestions in Chapter 7.

In this guide, interior noise sources are not estimated. Because of the great diversity of sources, including heating, cooling, and ventilating systems; office equipment; conversation; etc., such estimates would be cumbersome. Instead, interior sources are accounted for by assuming they contribute to the sound coming from exterior transportation sources. If you want more precise estimates, you should refer to the public texts on noise and vibration control, and on acoustics and architectural design listed at the end of this chapter, (also reference [22]); or you should obtain the services of an acoustical consultant.

This design guide has its main emphasis upon problems of transportation noise in the design of new buildings, since this is a common noise problem. It is also a complicated problem because there are many unknowns in building schemes during their formative stages. The design problem can be stated thus: *given an architectural program and a scheme for a proposed build-*

ing, predict acoustical conditions in the rooms of the building, or in the outdoor activity areas of the building, and bring all spaces to pre-established noise criterion levels.

The guide can be helpful in other types of problems as well; problems like those listed below:

Site Selection: *given a desired building occupancy, such as a school or apartment building, select a site which will have acoustic conditions within specified noise criteria.*

Analysis of a Building Site: *given a site, analyze its acoustic conditions, or the conditions to be expected in a proposed building of a selected type of occupancy.*

Environmental Impact Statements: *given a proposed building scheme, predict the impact of transportation noise upon the rooms of the building.*

Building Re-design: *given a completed building, improve the acoustic conditions of its rooms or outdoor activity areas to satisfy noise criteria.*

In using the guide to address such additional problems as the ones listed above, you will select among the offerings of its various chapters. This should be easy to do once you have familiarized yourself with the guide in connection with problems of building design.

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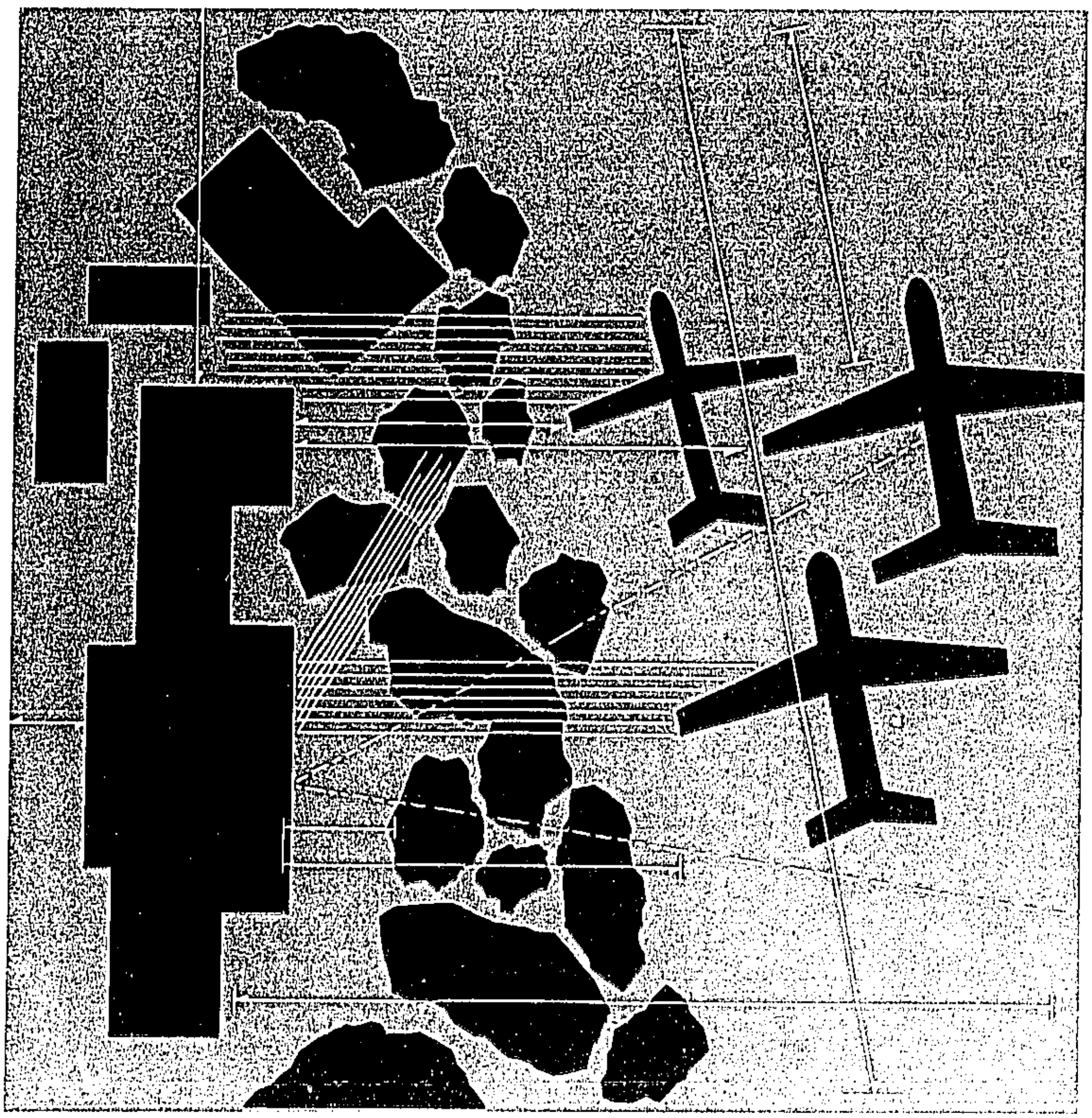

Chapter 2
What You Need to Know Before You Begin to Design

Chapter 1 described the general philosophy and structure of this design guide and how it can be used to solve building design problems resulting from transportation system noise. Here in Chapter 2, we will specify the information you will need to address these problems. Much of the information you gather for transportation system noise analysis will also be essential for other design purposes.

In addition to data collection, Chapter 2 has a second goal; namely, to identify the procedure to estimate the severity of the noise problem at your site and proposed building. If you have a dire problem beyond the reach of this guide, you should get assistance from an expert acoustician. If it appears that you have no potential problem, desist . . . your time will be better spent in other spheres. But, if your problem lies within these two extremes, carry on, this design guide can be of help to you.

Direct measurements of noise and the equipment for making these measurements are expensive. This guide calls for making estimates of the sound level of transportation noise from statistics such as counts of aircraft flyovers, highway traffic, and railway passbys, and does not require or rely upon direct measurements of noise levels. If a designer has the required measurement equipment and the expertise to operate the equipment, he is also likely to have access to good ways of quantitatively estimating and predicting acoustic conditions, and perhaps these ways are more detailed than those found in this guide.

You should realize that the scope of this design guide has been deliberately restricted to exclude some potentially serious noise problems. Your attention is principally directed toward consideration of highway, railway (including rail rapid transit) and aircraft noise. However, it is not possible to include detailed consideration of complicated highway intersections (including such factors as stoplights or severe grades), railroad yard operations, or airport operation noise problems due to airports located closer to your site than the distances listed in Table 2–1.* These problems are too complex to be solved by this design guide.

** In order to make the results more immediately useful to American architects and designers, customary engineering units are used rather than the (metric) International System of Units (SI) normally used in NBS publications.*

Table 2–1. Minimum Distances between Airports and Building Sites [1,2].*

International Airport **		Commercial or Military Airport		General Aviation Airport	
Distance to Side of Runway	Distance to End of Runway	Distance to Side of Runway	Distance to End of Runway	Distance to Side of Runway	Distance to End of Runway
3000 feet	4 miles	2000 feet	2½ miles	1000 feet	1 mile

** If your building or site is within the distances of Table 2–1, you will have noise problems beyond the scope of this design guide, and you should secure the services of an expert acoustician.*

*** Airports are classified as International, Commercial or Military, and General Aviation according to the effective number of jet aircraft operations (takeoffs and landings) daily (NJeff). To account for the extra annoyance of nighttime operations, their number is multiplied by seventeen when added to the number of daytime operations. Hence, NJeff = 17 NJnight + NJday.*

For International Airports, NJeff is greater than 1300.

For Commercial or Military Airports, NJeff is between 501 and 1300.

For General Aviation Airports, NJeff is less than 500.

Similarly, consideration of noise problems due to fixed or temporary noise sources such as noisy industrial plants, or highway or building construction is beyond the scope of this design guide because of the diverse range of potential problems.

Two classes of information will be needed: (1) information about the building site and the surrounding area and information about the operational characteristics of the various transportation systems (information which we have referred to as physical constraints); and (2) information about the proposed building (information we have called scheme constraints).

Building site data consist of geographical and topographical information about the site and the lands adjacent to the site. The information should be sufficient to prepare a noise source map of the area to scale, and to cut vertical sections through this map in order to show transportation noise sources in relationship to the surrounding terrain (including any man-made structures) and your proposed building. Of special interest are any barriers (natural or man-made), intervening rows of buildings, or extensive growths of vegetation which might divert, reflect, or absorb a portion of the sound before it reaches your site and building.

Usually, the noise source map can be drawn from city, county, highway and other maps which are inexpensive and easy to obtain. The third (vertical) dimension is lacking in many of these maps but can be determined from topographical maps issued by the Coast and Geodetic Survey. If these maps do not provide the information needed, you may have to run surveys with a hand level or a transit. But before you perform these surveys be sure to exhaust all avenues of existing information such as: city, county, and regional planning commissions; public utility companies for electric power, natural gas, sewer and water, or telephone services; city, county, and state departments of streets, roads and highways; irrigation and weed and pest control districts; port authorities; departments of building regulation; city, county, or state engineers or surveyors; and, the Bureau of Reclamation, National Park Service, or Army Corps of Engineers. These agencies may not have the information you need, or may not be able to release it; but if they do have it and can release it, your job will be lessened.

The main purposes of the noise source map are to identify the locations of all potential transportation system noise sources, and to determine which areas on your site have the lowest noise levels resulting from these transportation systems. Ideally, the noise source map might contain sound contours of equal noise level covering the entire site. This could aid in the identification and selection of a preferred building location. But the development of such a contour map is difficult and is likely to be beyond your resources. Another factor is that this technique of selecting a preferred building location requires that your site be large enough to permit relocating the building. This is not always possible and, thus, special design strategies, as outlined in this guide, are needed.

In addition to the geographical and topographical information discussed above, there is also a need for information about the transportation system operational characteristics. The specific information that is needed depends on the type of transportation system being analyzed. The complete list of required data are given in Chapter 5, which should be reviewed thoroughly before you attempt to acquire the necessary information. The possible sources of this information are discussed below.

For information on highways, you should contact the city or county director of traffic; city, county or state department of streets, roads and highways (or department of transportation); or the city, county, or state engineer. Federal agencies such as the Department of Transportation, Federal Highway Administration, or Highway Research Board may also be able to provide the needed information.

For information on railways you should contact the supervisor of customer relations for the railway. The city, county, or state department of transportation may also be of some help, as well as the city, county or state engineer. The Association of American Railroads may be able to put you in touch with the relevant offices or agencies.

Information on airports can be obtained from the Federal Aviation Administration (FAA) area office for commercial airports, or from the Military Agency in charge for military airports. You might also contact the FAA District Office, (or airport operator), or the airport manager to get the required information.

Keep in mind that transportation systems can change dramatically with time. Also, land use patterns are not fixed, but vary over the years. For example, the future abandonment of a nearby airport or railway line could erase a presently crucial noise problem. Likewise, highway noise could be alleviated by the development of quieter tires or more silent engines. On the other hand, noise conditions could eventually worsen because of increased traffic on existing freeways or the construction of new highways. Naturally, you should try to anticipate future changes. In making your predictions, you can consult the data; review the plans and projections; and seek the assistance of departments of streets and roads, highway departments, planning agencies, railway companies, and the like.

We have thus delineated some of the required physical data on the site and neighboring land, and sources of information on transportation system operational characteristics. Now let us review the second main class of needed information; information about your proposed building which is necessary for interior noise level calculations. We have referred to this type of information as scheme constraints, and have indicated that only the most general scheme constraints must be spelled out here.

Scheme constraints needed are: the type of building occupancy—be it commercial, educational, industrial, institutional, or residential, etc.; the building size in terms of floor area, or in terms of beds for general hospitals, classrooms for schools, etc.; the overall building budget, which together with the proposed building size, will yield some notion about building quality; the general type of construction, whether heavily fire-resistant or not, and the general type of construction material, whether heavy or lightweight. Knowing these scheme constraints is essential for anticipating the typical room size, amount of exterior shell exposure, and typical room furnishings, whether sound absorptive or not, for the room-by-room calculations of Chapter 6. Knowing the general degree of building quality and workmanship is also needed for estimates of room sound levels. Finally, the type of occupancy for the building as a whole and the functions of special rooms within the building are scheme constraints needed for selecting noise criteria in Chapter 3. The decision about these noise criteria is especially critical to the people who will occupy the building, people whom you will want to satisfy in terms of acoustic comfort.

As you come face to face with the problem of satisfying these future occupants, keep in mind that in recent times their peace and comfort have been increasingly intruded upon by loud noises. They are constantly bombarded by noise from all kinds of sources — namely, automobiles, trucks, trains, airplanes, but also construction machinery and industrial equipment, to name just a few. Regretably, the only refuge they may have from these disruptive noises is inside their homes and offices. Thus, it is no wonder that people become upset and dissatisfied when they are disturbed even there.

Of course, the best answer would be to reduce noise at its source. But this option is frequently not one over which the designer has control. Therefore, the designer must concentrate upon minimizing the effect of noise at the "receiver", namely inside homes, offices, churches, schools, etc. To effectively isolate people from these noises the designer needs to know beforehand the characteristics of the noise source. For many types of sources this information is either not available or would be too voluminous, therefore difficult and expensive to gather.

Construction noise and industrial noise are two such cases. Estimation and prediction of the noise from these sources is difficult because there are many different equipment types and functions to be described. That these sources operate intermittently on a variable time schedule only further complicates the problem, and requires elaborate measurements of the sound produced.

This is not the case for highway, railway and aircraft noise. Although there obviously are different types of autos, trucks, trains, and airplanes, in general, many of these vehicles operate in the same manner, performing the same function. This allows certain assumptions to be made about how the noise is generated, which in turn makes it possible for you to predict the noise levels produced by each type of vehicle. This is the basis for the predictive methods described in Chapter 5.

We may be able to spare you the trouble of performing these complete calculations. We mentioned earlier in this chapter that two situations would make these calculations unnecessary or inappropriate. The first situation is a building site having severe noise problems, which would direct you toward the services of an expert noise control engineer or acoustical consultant; the second situation, the one to be discussed next, is a building site which probably has no severe noise problem whatever. Let's examine this possibility now.

Table 2-2 provides a list of minimum distances which you can use as rules of thumb for eliminating transportation system sound sources as matters of concern. The values in Table 2-2 are the distances necessary for the noise generated by "typical" highway and railway operations to decrease to an A-weighted day-night sound level of 55 dB (these units are explained more fully in Chapter 3) at the exterior of the building under consideration. As is indicated in Chapter 3, this corresponds to the noise level in a typical suburban neighborhood, and is not generally regarded as excessive noise. In Table 2-2, the decrease of sound level with distance is assumed to be a function only of geometrical spreading, or divergence, and does not include decreases due to barriers or other forms of shielding which would further reduce the sound levels and render Table 2-2 values more conservative.

The values in Table 2-2 for airports are the distances required for the noise generated by "typical" aircraft operations to decrease to a sound level that is "clearly acceptable." This is based on the information given in reference [1], which evaluates a building site as "clearly acceptable" if the "noise exposure is such that both the indoor and outdoor environments are pleasant."

If your site or building is located at distances greater than those shown in Table 2-2, the probability is low that noise would exceed an A-weighted day-night sound level of 55 dB. Thus, there would be no need to perform the predictive computations of this design guide. This, of course, is contingent upon whether or not your situation is truly "typical." For example, these reference distances would not apply where there are extremely high vehicular traffic volumes —more than 10,000 automobiles per hour, or more than 300 trucks per hour.

On the other hand, if your building site is closer than the distances specified in Table 2-2 to one or more of the three transportation systems noise sources, the noise levels for your building should be determined by the predictive methods of Chapter 5.

The use of Table 2-2 is an informal procedure, which may not be adequate for your needs. Thus, a more formal procedure for the preliminary elimination of non-intrusive noise sources from further consideration is outlined in the following steps. Complete these steps using the Preliminary Source Evaluation Worksheet shown in Figure 2-1.

Instructions for the Use of the Preliminary Source Evaluation Worksheet

STEP 1 INPUT DATA

You must first determine the distances from all major highways, railway lines, and airports to the building site or proposed building location. For aid in selecting the most appropriate building location on your site, refer to Chapter 4. Distances can be obtained from area maps. For highways and railways, the distance should be measured along the shortest perpendicular line from the centerline of

Table 2-2. Distance Criteria for Elimination of Non-intrusive Transportation System Noise Sources [1].

Noise Source	There is a possibility of excessive noise due to this source if the building site is:					
Highway	within 1000 feet of any major roadway *					
Railroad	within 3000 feet of any railway line					
Aircraft	within the distances given below:					
	1. International Airport **		2. Commercial or Military Airport**		3. General Aviation Airport**	
	Distance to Side of Runway	Distance to End of Runway	Distance to Side of Runway	Distance to End of Runway	Distance to Side of Runway	Distance to End of Runway
	3½ miles	16 miles	2½ miles	9½ miles	1 mile	5 miles

* *A major roadway is one with traffic of more than 50 autos per hour or more than 5 trucks per hour.*
** *See the footnotes of Table 2-1 for definitions for the three types of airports.*

PRELIMINARY SOURCE EVALUATION WORKSHEET

Noise Source		1 Building-Source Distance	2 Might there be excessive noise? (yes or no) [See Table 2-2]	3 If the answer is no in all cases, for highways, railways, or airports *	4 If the answer is yes for one or more of the sources,
Highway	#1	feet		Omit Section 2 of Chapter 5	Obtain the data and perform the computations outlined in Sec. 2 of Chapter 5 for each highway with a *yes* answer.
	#2	feet			
	#3	feet			
	#4	feet			
Railway	#1	feet		Omit Section 3 of Chapter 5	Obtain the data and perform the computations outlined in Sec. 3 of Chapter 5 for each railway with a *yes* answer.
	#2	feet			
	#3	feet			
	#4	feet			
Airport	#1	miles		Omit Section 4 of Chapter 5	Obtain the data and perform the computations outlined in Sec. 4 of Chapter 5 for each airport with a *yes* answer.
	#2	miles			
	#3	miles			
	#4	miles			

* *If the answer is no for all three types of transportation system noise source, this design guide evaluation is not necessary.*

Figure 2-1. Preliminary Source Evaluation Worksheet.

the highway or railway to the building or site; and, for airports from the nearest runway. Also to accurately estimate the noise generated by aircraft, you should determine if the building is to be near the side of a runway or in line with the end of a runway. Moreover, you should classify the airport in one of three categories [2]:

1. International Airport or airport serving a greater metropolitan area
2. Airport serving commercial carriers or military airport
3. General Aviation—propeller aircraft

Record this information on the worksheet which provides spaces for as many as four highways, four railways, and four airports for your building site. Distances should be in feet except for airport data, which should be in miles.

STEP 2 NOISE SOURCE EVALUATION

Now you can evaluate each of the sources listed in Column 1 of the worksheet. Using the distances of Table 2-2 as references, determine if any of the sources may possibly generate excessive noise at the building site. To determine the appropriate distance to use as a reference for the airport noise estimation, look in Table 2-2 under the airport category and then choose the distance corresponding to the building location, to the side of the runway or in line with the end of the runway. Record the results in Column 2 as either *yes* or *no* answers. Then, depending upon the answer in Column 2, proceed to either Column 3 (a *no* answer) or Column 4 (a *yes* answer). If any highway (or other type of source) has a *yes* answer, the noise prediction computations should be performed for each such source.

A word of warning should be given here. All of the reference distances listed in Table 2-2 are approximate. You must exercise some judgment in deciding which potential noise sources can be neglected and which ones can't. Unfortunately, this will be difficult until you gain some experience in making these decisions. In general, it is always a good idea to analyze any source about which you are uncertain. That way there will be little chance of omitting a source which could generate excessive noise at the building site.

Clearly, there are many noise problems that require the expert advice of an acoustical consultant or noise control engineer. Although this guide equips you to make quantitative estimates of noise levels, and suggests design alternatives to ameliorate difficult design problems, you would be wise to obtain the services of a consultant in the following circumstances:

(a) If your building occupancy is one that requires unusually low noise criteria (for example, a recording studio or library), and the anticipated site noise levels are expected to be high due to the immediate proximity of an airport, industrial plant, etc. Here, your building's construction will have to be unusual, incorporating special noise control provisions.

(b) If the procedures of this design guide yield estimates of interior noise well in excess (15–20 dB) of the noise criteria, your building design should be changed. It may be best to do this with the assistance of a consultant.

(c) If your building site falls into the "clearly unacceptable" category as defined by Schultz and McMahon in "Noise Assessment Guidelines" [1], you should obtain the services of a consultant to consider the advisibility of construction on or rejection of the site, or of the special adaptations which may be required. Schultz and McMahon define "clearly unacceptable" as . . . a noise exposure at the site so severe that the construction costs to make the indoor environment acceptable would be prohibitive and the outdoor environment would still be intolerable.

References: Chapter 2 Information Collection

[1] Schultz, T. J., and McMahon, N. M., Noise Assessment Guidelines, U.S. Department of Housing and Urban Development Report No. TE/NA 171 (Bolt Beranek and Newman, Inc., Cambridge, Massachusetts, August 1971).

[2] Jensen, P., and Sweitzer, G., How You Can Soundproof Your Home, (Lexington Publishing Co., Lexington, Massachusetts, 1974).

Chapter 3
How to Select Noise Criteria

From reading Chapter 2, you have determined whether or not your site or building noise problem is one which can be analyzed by using this design guide. This chapter tells how to select *noise criteria,** maximum acceptable sound levels appropriate for your site and building occupancy, when the origin of the sound is due to external transportation systems.

Once you have selected noise criteria . . . your design goals . . . you can proceed to estimate the amount of sound coming to your site from highway, railway, and aircraft sources; reduce this estimate of the amount of sound to account for the effects of dense vegetation or other barriers (see Chapter 5), and then make an initial noise analysis for your building's interior and its outdoor activity areas. If the sound levels you estimate (in Chapter 6) are greater than the noise criteria you have selected, you will probably want to pursue implementation of suggested design alternatives (in Chapter 7) to bring estimated sound levels to within selected noise criterion levels.

This chapter will offer two approaches to selecting noise criteria . . . an approach using the simplified Table 3-1, or an approach using the more comprehensive Table 3-2. Before selecting the criteria, however, you should study and understand the following principles of sound, how it is measured, and how noise criteria can be based upon sound measurements.

The response of your future building's occupants to noise depends upon the physical characteristics of the noise, the acoustic properties of the building, the activity in which occupants are engaged, and their sensitivity to noise along with a complex set of other psychological, physiological, social, and cultural factors. Obviously, it is essential that you, the building designer, make a number of simplifying assumptions about noise and the human perception of noise, in order to deal with acoustic phenomena quantitatively. Using this guide, you will be able to predict the sound conditions in and around your proposed building, and you will have some idea of the degree to which your building's occupants will be satisfied with its acoustic environment.

Experts generally agree upon the definition of noise as unwanted sound; and sound, for our purposes, is a propagating pressure disturbance in air. Many properties of this pressure disturbance can be described quantitatively, but the most important properties are the magnitude, or amplitude, of the pressure changes about atmospheric pressure; the time-variation of the pressure changes (frequency); and the distribution of sound energy across bands of frequency. People can hear sound within the range of pressure amplitudes extending from approximately 20 μPa (Micropascals) at the threshold of audibility to 20,000,000 μPa at the threshold of feeling. The lift-off noise of a Saturn rocket is about 20,000,000,000 μPa, an even greater pressure amplitude, well above the threshold of feeling. Because this is an enormous range of magnitudes, and because acousticians need to observe the effects of small changes at both extremes, they have eschewed a linear scale and adopted a logarithmic scale (to the base ten). This scale compresses a range of one to a billion to a range of 0 to 9.

The numbers 0 to 9 represent relative quantities, and the quantity measured on such a scale is referred to as a level. Scientists and engineers usually work with energy quantities that would be proportional to the square of the sound pressure rather than to the sound pressure itself. This presents no difficulty, since the logarithm of a squared number is two times the logarithm

* *In this design guide, the word criterion denotes a noise (sound pressure) level which you, the designer, will select as a design target, or goal for your building project. The Environmental Protection Agency uses criteria in a different sense; namely as standards reflecting available knowledge as to the health and welfare effects of such environmental pollutants as noise.*

of the original number; therefore, instead of a range of levels from 0 to 9, the range runs from 0 to 18 for sound pressure squared. The unit on this scale is called a bel. The bel has been divided into 10 smaller units known as decibels, so that the range of sound pressures, from the approximate threshold of hearing to Saturn rocket noise, runs from 0 to 180 decibels.

Decibel scales thus provide a convenient way to describe the large range of sound pressures to which your building occupants will be exposed. The sound pressure level (SPL) is defined as:

$$SPL = 20 \log_{10} \frac{p}{p_{ref}},$$

where p is the magnitude of the amplitude of the sound pressure (measured over some appropriate averaging time), and p_{ref} is a reference pressure, taken as 20 μPa. The units of SPL are decibels, abbreviated dB. The level near the threshold of audibility is 0 dB, and at the threshold of feeling is approximately 120 dB.

The logarithmic decibel scale is extremely useful; however, it can be puzzling. On a linear scale, the total sound pressure due to two identical noise sources would be twice that of one of the sources operating alone. However on a logarithmic scale, the total sound pressure level resulting from two identical noise sources is 3 dB higher than the level produced by either source alone. (If you double a number, its logarithm will always increase by 0.3; hence, 0.3 bels, or 3 decibels). Also, if two sound sources whose levels differ by more than 10 dB are added together, the resultant level will be less than 0.5 dB higher than the level produced by the greater source operating alone.

The above paragraphs have concentrated upon sound magnitude, or amplitude; but as mentioned earlier, subjective responses to noise are also based upon frequency. The frequency range of hearing extends from approximately 20 hertz to 20,000 hertz. The unit hertz, abbreviated Hz, has been adopted to avoid possible confusion between the previously used term "cycles per second" and other "cycles" of machinery or natural phenomena. The 20 to 20,000 Hz range is referred to as the audio region as distinguished from the infrasonic range (20 Hz and below) and the ultrasonic range (20,000 Hz and above).

The perceived loudness of a sound depends primarily upon sound pressure, but is also influenced by frequency. Likewise, one's subjective response of pitch is highly dependent upon frequency, but is also somewhat affected by sound pressure. Moreover, sounds subjectively characterized as "low pitched" have energy content principally in the low frequency range, and vice versa.

People are most sensitive to sounds in the mid-band or high frequencies. People are less annoyed or distracted by sound frequencies in the lower frequency ranges. To compensate for this, sound levels to be used for noise criteria are customarily *weighted*, as shown in Figure 3–1, to de-emphasize the importance of low frequency sound while emphasizing mid-band and high frequency sound.

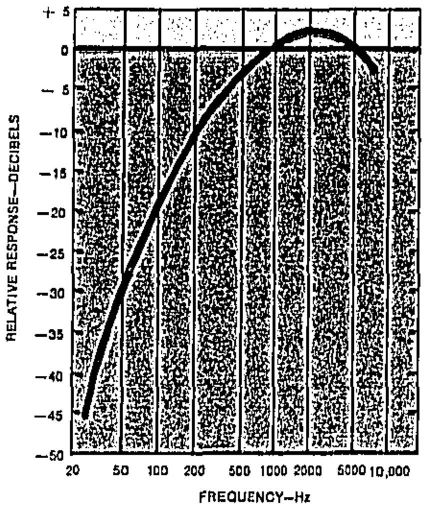

Figure 3–1. Frequency Response Curve for A-weighting [1, 2, 3].

There are various weightings or "scales," but in this design guide, we will consider only the one termed the "A-weighting" scale (to distinguish it from others, e.g., B, C, D, etc.). It has the advantage of standardization both nationally [1] and internationally [2, 3] and is the most commonly accepted weighting scale. Special filters are built into sound level meters so that they measure and indicate A-weighted sound levels.

Figure 3-2 illustrates the A-weighted levels of sounds encountered in daily life [4]. The range of A-weighted SPLs found in building spaces varies from approximately 20 dB for studios for sound recording to 90 dB for boiler rooms. Clearly, these two types of building room occupancies are highly specialized, and the range of SPLs for ordinary occupancies extends from approximately 35 to 60 dB.

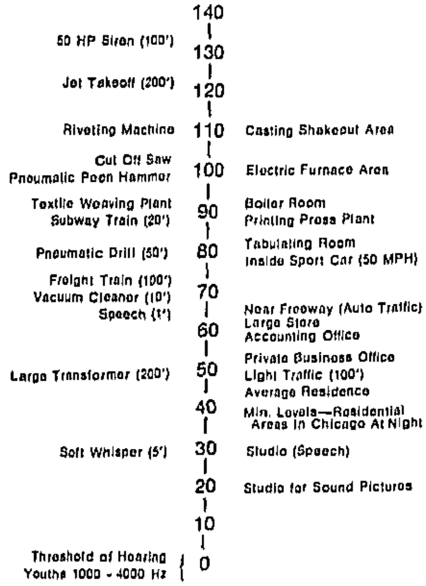

Figure 3–2. Typical A-weighted Sound Pressure Levels [4].

Sounds vary over time. As an example of the variation of noise level with time, consider a train—its sound will increase as the train approaches and then subside as the train moves away. The maximum sound pressure level as the train rushes by would be much greater than the sound pressure level measured as the train disappears in the distance. However, the variation in the train's sound level can be accounted for by averaging the sound energy over the time of the train's passage, and thereby determining an "equivalent" steady sound level.

Moreover, since transportation sounds vary from hour to hour as traffic ebbs and flows, another type of long term time averaging is needed. It is based upon time periods related to the intended time of building occupancy, or use . . . 1, 8, or 24 hours. During such a long time period, a great many trains could pass, and the sound level meter indication would typically have varied over an extremely wide range. This can be accounted for by obtaining measurements in terms of (A-weighted) equivalent sound pressure levels. Such equivalent A-weighted sound pressure levels, then, are constant sound levels which, in a given situation and over a given time period, convey the same sound energy as the actual, measured sound.

The nature of the averaging of sounds in equivalent sound levels is such that two sounds, one of which contains twice as much energy but lasts only half as long as the second, is characterized by the same equivalent level; so is a third sound with four times as much energy but lasting only one fourth as long. Thus, equivalent sound levels tend to average out sounds of very high level but short duration. For example, an equivalent sound level of 60 dB over a twenty-four hour day would permit sound pressure levels of 110 dB, but these would be limited to a total duration of less than one second in the course of the twenty-four hour period [4].

The concept of equivalent sound level was used in United States Air Force studies of noise from aircraft as early as 1957 [4, 5], and was introduced in Germany in 1965 to evaluate the impact of aircraft noise upon the neighbors of airports [6]. It was soon recognized in Austria as appropriate for evaluating the impact of street traffic noise in dwellings and schoolrooms [7, 8]. It is now the rating used in both East Germany and West Germany standard guidelines for city planning [9, 10], and it has been widely accepted in Sweden for use in traffic noise surveys [11, 12].

Our use of the equivalent A-weighted sound level conforms to the policy of the Environmental Protection Agency which selected it as the one consistent measurement scale "based upon existing scientific and practiced experience and methodology" which satisfies the following guidelines:

"1. The measure should be applicable to the evaluation of pervasive long-term noise in various defined areas and under various conditions over long periods of time.

2. The measure should correlate well with known effects of the noise environment on the individual and the public.

3. The measure should be simple, practical and accurate. In principle, it should be useful for planning as well as for enforcement or monitoring purposes.

4. The required measurement equipment, with standardized characteristics, should be commercially available.
5. The measure should be closely related to existing methods currently in use.
6. The single measure of noise at a given location should be predictable, within an acceptable tolerance, from knowledge of the physical events producing the noise.
7. The measure should lend itself to small, simple monitors which can be left unattended in public areas for long periods of time." [4]

Of course, the equivalent A-weighted sound level is not without its deficiencies. Still, these deficiencies do not preclude the use of this measurement scale based upon present knowledge until more is known about the frequency-weighting and time-averaging of acoustical data.

Four types of equivalent A-weighted sound levels are suggested in this design guide as noise criteria for various building types:

- Leq(1),* the "one-hour" Leq for short-term occupancies such as churches and theatres,
- Leq(8), the "eight-hour" Leq for offices and commercial buildings used during an 8-hour working day,
- Leq(24), the "twenty-four hour" Leq for educational occupancies,* and,
- Ldn, the day-night equivalent A-weighted sound level, for residential occupancies.** Ldn, like the Leq(24), has a 24-hour averaging period, but in addition has a built-in penalty for night-time noise.

Examples of outdoor day-night equivalent sound levels in various locations are shown in Figure 3-3. Note in particular that a level of Ldn = 55 dB is characteristic of suburban locations, and that levels in excess of this are characteristic of urban, noisy urban, or city (major metropolis) noise levels.

There are several, general ways in which your building's occupants could be adversely affected by noise . . . it could cause a loss of hearing, activity interference or annoyance, and possible consequent stress. In this design guide, noise criteria are related solely to annoyance or activity interference. Hearing impairment is not considered herein since it only tends to occur in factories and similar locations where very loud noise is experienced over long periods of time. Stress *per se* is not considered herein since its causes are often multifaceted and its effects difficult to diagnose. In selecting noise criteria, then, you are aiming at noise levels that will not be so high as to create annoyance, or to interfere with activities, particularly those requiring verbal communication.

The total noise environment within a building originates from two principal sources . . . indoor and outdoor. The procedures of this design guide provide quantitative estimates only for that portion of the total interior noise due to transportation-system-related external sources. The procedures do not include detailed calculations for the possibly larger contribution of use-related internal sources such as mechanical systems and occupant activities, or to non-transportation system related exterior sounds. However, the guide permits you to account for noise generated indoors by an adjustment to your selected noise criteria. The explanation which follows provides the underlying basis for such an adjustment.

When all interior sources have been totally silenced, such as when the HVAC (heating, ventilating, and air-conditioning) system has been shut down, and when building occupants are quiet or asleep, total indoor noise environment may approach the levels due to the external sources. Under these circumstances, the interior and exterior sound pressure levels will differ by a constant amount; and if the exterior noise increases due to some change such as increased traffic volume, then the interior noise level will increase accordingly. The exact amount of difference between interior and exterior noise levels would be related to the building shell's noise isolation properties, the types of interior furnishings, the nature of the energy-frequency distribution (or "spectrum") of the exterior noise, and the degree to which windows are open or closed. Such factors as these are dealt with in Chapter 6 of this design guide.

Activity within the building presents a complication, however, since use-related and mechanical equipment noise can vary widely. Hence, there are no general rules

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* Leq is pronounced in accordance with its three letters "L"-"e"-"q"; and Leq(1) is called the "one-hour"-"L"-"e"-"q".

** The use of Leq (24) for educational occupancies, as suggested by reference [3], was adopted in this design guide because it was felt that this was the most appropriate metric for this type of building occupancy. Since schools are often used in the early evening hours, Leq(8) would not be appropriate because it would exclude the noise exposure during those hours. On the other hand, Ldn would not be appropriate either, because imposing a nighttime penalty would be unnecessarily severe. Ideally, a measure based on fourteen to sixteen hours would be best suited for education occupancy. But since such a measure is not customary, Leq(24) was chosen.

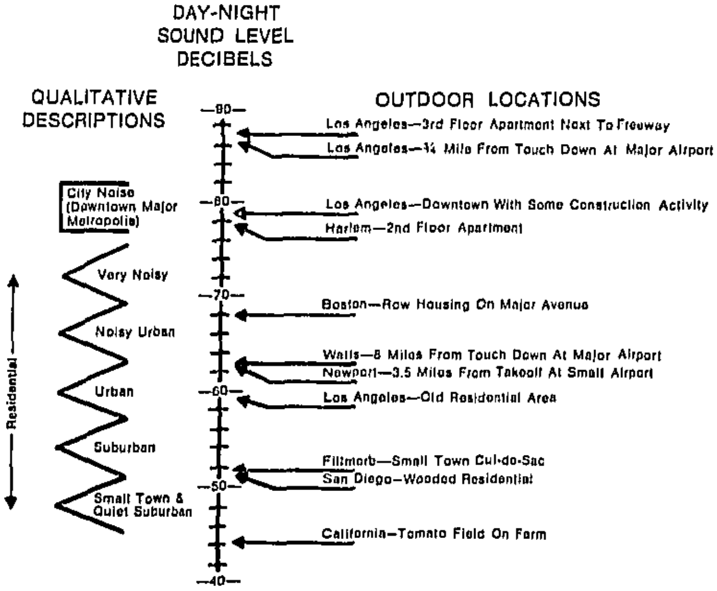

Figure 3–3. Examples of Outdoor Day-Night Equivalent Sound Levels Measured at Various Locations [4].

for estimating indoor, use-related noises. Rather, if precise calculations are needed, they ought to be performed by the mechanical systems engineer responsible for HVAC systems or by acousticians knowledgeable about potentially noisy equipment such as office machinery or data processing equipment.

When indoor-generated sound levels are known, the rules for logarithmic addition are applicable for combining interior use-related noise and interior transportation-system related noise (of exterior origin). For example, these rules are such that when two equal components are combined, the level corresponding to the total is 3 dB larger than either individual component.

A number of recent publications issued by the U.S. Environmental Protection Agency summarize current knowledge regarding human response to noise. Several of these discuss equivalent sound levels in some detail.

In the document "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare With an Adequate Margin of Safety" (the "levels document") levels are identified to protect public health in a large number of situations [4]. Some of these levels are specifically suggested with the understanding that "health and welfare" includes personal comfort and well-being as well as the absence of noise-related mental anguish and annoyance, or activity interference. In particular, speech interference was one important basis upon which some of these levels were identified. The levels identified in the "levels document" for interior spaces correspond to *overall* equivalent sound levels in the building, regardless of whether the noise is due to interior or exterior sources. Some means is therefore needed to adjust the EPA recommended levels to allow for interior noise sources.

In addition to complications introduced by the variable acoustical properties of the building shell and furnishings and by the variability of internal use-related noise sources, there is very little knowledge available concerning the most satisfactory balance between noises of interior and exterior origin for specific building occupancies. Under some circumstances, and particularly when there is an adverse psychological reaction to noise of external origin, building occupants may prefer that any noise of external origin be dominated and heavily masked by internal noises, even at the cost of a significantly increased overall noise level. Under other circumstances, when the noises of external origin are approximately comparable to the use-related interior noises, there can be a subjective response indicating a satisfactory balance. An acoustical consultant may be able to advise you about systems which provide helpful masking sounds.

There are no data to justify a generally applicable statement of preference.

Lacking quantitative knowledge concerning people's preference for any specific imbalance between two components of an overall noise level, we therefore postulate that the two components are equal. This postulate implies that each of the two components individually be 3 dB less than the overall level. In reference [4], a noise criterion of 45 dB was suggested as the maximum total level above which activity interference and resultant annoyance would be at risk. If this noise criterion is adjusted downward by 3 dB to account for indoor-generated noise, it takes the value 42 dB. An additional margin of conservatism would result in a level of 40 dB.

This value, Leq = 40 dB, is suggested as the noise criterion for interior noise of exterior origin. The value of 40 dB is the value which appears in Table 3–1.

Indoor-generated noises may be individually as much as 3 dB higher than noises of outdoor origin with the outdoor noise at the upper limiting level for the external contribution. For example, if your indoor noise criterion is 45 dB, it will be satisfied if the interior noise level due to external sources is no greater than 40 dB, and the noises of internal origin are no greater than 43 dB. The 3 dB difference reflects a barely perceptible difference in subjective loudness to the two contributions.

There are numerous ways of satisfying any suggested criterion level (such as 45 dB) with differing combinations of indoor and outdoor generated noise. For example, if the indoor component is essentially at the limiting level, then the external origin component must be at least 10 dB less than the limiting value.

If you anticipate especially adverse exterior noise conditions, or building occupants who are especially sensitive to noise, you may wish to mask, or dominate, external noise by internal noises even at the cost of a substantially increased overall noise level. In other cases, you may wish to bring internal noise to a level just equal to external noise, with the expectation that your building's occupants will perceive this as a satisfactory balance. However, such design decisions as these are probably best left to acoustical experts whom you should consult.

Some recent laboratory studies have dealt with identification of the levels at which various highway traffic noises start to interfere with the ability to relax and enjoy listening to the spoken word [13]. In one particular study the recommended indoor noise level for intruding traffic noise for subjects listening to the spoken word was comparable to the value of 40 dB suggested in this design guide. Whereas the aforementioned study gives tentative support to this recommendation, additional research will be needed for confirmation.

Based upon the above explanations, it is then recommended that you select noise criteria from the simplified Table 3–1 whenever it is applicable.

Table 3–1. Noise Criteria for Simplified Selection.

Area	*Level*
Indoor Rooms	
Residential areas, including hospitals	Ldn ≤ 40 dB
Areas with activities such as schools, offices, conference rooms, etc.	Leq(24) ≤ 40 dB
Outdoor Activity Areas	
Residential areas for which quiet is a basis for use, etc.	Ldn ≤ 55 dB
Areas in which people spend limited amounts of time such as school yards, playgrounds, etc.	Leq(24) ≤ 55 dB

If your building project is to house a highly specialized occupancy, or if outdoor activity areas are to be an important element in your design, however, you may select your noise criteria from Table 3–2 (which is a comprehensive listing of recommendations of other authors [14–31]) or from a consideration of the maximum distances over which

Table 3-2. Comprehensive List of Noise Criteria for Buildings [4].

	Knudsen, Harris 1950	Beranek 1953	Beranek 1957	Lawrence 1962	Kosten, Van Os 1962	ASHRAE 1967	Denisov 1970	Kryter 1970	Tokyo 1971	USSR 1971	Beranek 1971	Doelle 1972	Wood 1972	Rettinger 1973	Sweden 1971	Switzerland 1970	Czechoslovakia 1967	West Germany 1965
RESIDENTIAL	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]	[24]	[25]	[26]	[27]	[28]	[29]	[30]	[31]
Home																		
Bedroom	35–45	35	35–45	25	30	25–35		40		35	34–47	35–45	35	34–42	25	35–45	40	
Living Room	35–45	35		40	35	30–40		40		35	38–47		40		25	35–45	40	
Apartment	35–45		35–40	30		35–45		38			34–47			38–42		35–50	40	
Hotel	35–45		35–40	35–40		35–45		38		35	34–47	35–54	30–40	42		35–50	40	
COMMERCIAL																		
Restaurant	50–55	55	55	40–60	50	40–55		55		55	42–52	45–60	45–50	50		40–50	65	
Private Office	40–45	50	30–45	35–45	30–45	25–45	40–45	35			38–47	30–45	40–45	48	40			
General Office	45–55		40–55	40–60	60	35–65	50–60	35–40		50	42–52	45–55	45–55	50				
Transport.						35–55				60								
INDUSTRIAL																		
Workshop																		
Light		50		40–60							52–61		55–65			45–55		
Heavy		75		60–80	70		85				66–80		60–75	70		50–60		
EDUCATIONAL																		
Classroom	35–40	35	35	30–40	30	35–45		35		40	38–47	35	35–45	38	35	35–45		
Laboratory				40–50		40–50	40–50				47–48		45–50	42				
Library	40–45	40	42–45	35–45	35	35–45		40			38–47	40–45	40–45	42			40	
HEALTH																		
Hospital	35–40	40	42	20–35	35	30–45		40		25	34–47	40	40–45	38	25–35	25–35	35–40	
RECREATIONAL																		
Swimpool						45–60							50–60	50				
Sports (ampl.)		60	30			35–45						60		40			60	
Gymnasium					55	40–50						55–60	45–55	48				
AUDITORIA																		
Assembly Hall	35–40	35	35–40	40–45		30–40		38			30–42	35–45	35–45					
Church	35–40	40	40	35–40	35	25–35		40		35	30–42	35–40	35–40	38–42				
Concert Hall	30–35	30–35	25–35	25–35	30	25–35		28–35			21–30	25–35	30–35	34				
Court Room	40–45	40	40–45	40–45	35			40			42	35–40	35–40					
Record Studio	25–30	30	25–30	20–30	20	25–35		28			21–34	25–30	30	30				
TV Studio	25–30	30	30	25–35	30	25–35		28			21–34	30–35	35	34–38				
Mot. Pict. Studio	25–30	30	25–30		25–35			28			21–34	35	25					
Mot. Pict. Theater	35–40	40	40		35	35–45		40		40		40	35–40	38				
Loc. Theater	30–35	35	30–35		25	30–40		33			30–34	30–35		34			35	
OUTSIDE																		
Rural									35–45	35								35–45
Suburb									40–50	45								38–50
Urban									50–60									40–55
Industrial									50–60									50–65
Res. Areas Near Schools Hospitals															55			

conversation is satisfactorily intelligible. Many of the Table 3–2 recommended levels are A-weighted, but few are equivalent sound pressure levels; however, the provisions presented here allow you to account approximately for this difference. Moreover, Table 3–2 levels are not accompanied by any recommendations as to the acceptable component of interior noise which may be due to exterior sources.

If you do select from Table 3–2, be aware of these four provisos:

(1) For most occupancies, a range of levels, rather than a single number, is suggested in Table 3–2. This reflects the variability in the needs of building clients and occupants, as well as the fact that these levels pertain to data conventionally measured with sound level meters averaging over, at most, several seconds. Since the typical time period over which the Leq measures are averaged is appreciably longer . . . 1 to 24 hours . . . the levels obtained from a sound level meter will naturally fall in a range of values.

(2) The noise criteria you select should fall within the recommended ranges of Table 3–2. For buildings like theatres and churches which have short-term occupancies, Leq(1) is suggested as the measure. For offices and commercial buildings having an eight-hour workday occupancy, the Leq(8) is suggested; for other nonresidential buildings, the Leq(24) is suggested; and, for all residential buildings, the Ldn is suggested.

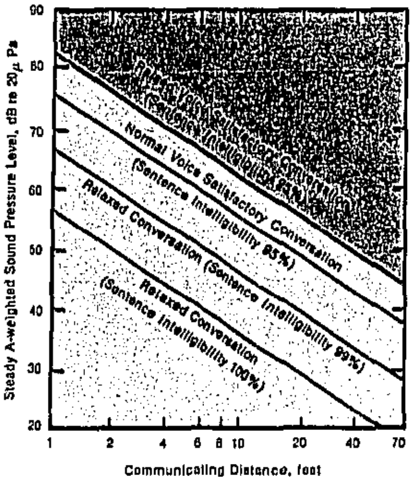

Figure 3–4. Maximum Distances Outdoors Over Which Conversation is Considered to be Satisfactorily Intelligible in Steady Noise [4].

(3) All of the suggested criteria for acceptable interior sound levels should be decreased by approximately 5 dB to account for sound generated inside the building.

(4) Perhaps most importantly, the designer must exercise judgment to account for the special needs of the building client, occupants, and occupancy with regard to the relevant noise sources and noise criteria.

Obviously, Table 3–1 is simpler than Table 3–2, but circumstances may dictate that Table 3–2 be used. In order to develop the ability to judge which option is appropriate, you may wish to consider whether the two approaches actually lead to widely disparate values. Note that a value of 45 dB for indoor rooms, as suggested by the EPA, falls within the suggested range for many building occupancies; and, that interior A-weighted noise levels due to external sources in the range 40–42 dB will usually be acceptable.

For example, a mid-range total noise level of 40 dB for assembly halls is consistent with the suggestions of Table 3–2. Therefore, 35 dB is the corresponding suggested noise criterion level for indoor noises of external origin. Consistent with (2) above, the appropriate metric for assembly halls is Leq(1). This suggested noise criterion (Leq(1) $\lesssim$ 35 dB) should next be adjusted to the client's special requirements if they appear to be unusual. Finally, most of the Table 3–2 noise criteria for assembly halls recommend a range of approximately 10 dB. Thus, your Leq(1) noise criterion level should be chosen from the range 30 dB to 40 dB, depending upon your judgment and the client's special requirements.

In selecting design criteria for outdoor areas, the information in Figure 3–4 is a useful supplement to Table 3–1. This figure indicates that the recommended value of 55 dB will permit a relaxed conversation, with 99% sentence intelligibility, at a distance of up to about four feet.

This figure can be used to develop other criteria for outdoor activity areas. For example, if you believe that relaxed conversations with 99% sentence intelligibility must be possible at distances up to 20 feet, then the appropriate criterion would be an equivalent level of 30 dB, clearly an unusual and stringent criterion for outdoor activity areas.

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Chapter 3—
Noise Criteria

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Chapter 4
How to Select a Point on Your Site for Estimating Transportation System Noise

In Chapter 3 you selected one or more noise criterion levels for your proposed building occupancy. In Chapter 5, you will calculate the sound level at your site due to highway, railway, and aircraft noise sources. It is these sound levels that will be used in Chapter 6 to determine the total exterior sound level in your outdoor activity areas, and the interior sound level in your building's rooms. Also in Chapter 6, you will compare the predicted sound levels to the noise criterion levels that you selected, to determine whether or not your outdoor activity areas and building's rooms will be too noisy.

Since sound is attenuated as it propagates away from its source, the sound levels will vary from one geographical point to another over your site; and, indeed, each of the computations in Chapter 5 is for the sound level at one particular point. Since each of these computations takes time, you will want some strategy for keeping the number of calculations at a minimum. Such strategies are elusive since the construction of your proposed building and its site development may change the acoustical conditions on the site. Moreover, there are a large number of variables which will affect your selection of a site location for estimating transportation system generated sound levels. Thus, we can offer no one specific algorithm for keeping the number of Chapter 5 calculations at a minimum. However, we will in this chapter give you some crude strategies which should be of assistance in keeping the number of calculations reasonable.

To take advantage of these strategies for limiting the number of required calculations, you should already be somewhat familiar with the contents of Chapters 5 and 6. For example, you should know that there are three major stages in predicting the noise from transportation system sources for each activity area or room in your proposed building. In Chapter 5 you will complete the *first stage* by determining the sound level at some selected point due to a *single* transportation system noise source, be it a highway, railway or airport. This sound level is estimated by performing the calculations necessary to fill out one or at most two worksheets for each source.

The result of completion of each worksheet is the sound level at one particular point on your site due to a single transportation system noise source.

If there is more than one transportation system noise source affecting your site, you must proceed to the *second stage*, and fill out the additional worksheet(s) as required. If for example, your site is affected by three highways (one of which has a sound barrier), a railway, and an airport, you would end up with seven completed worksheets when you finish the instructions of Chapter 5. Again, it is emphasized that the sound levels predicted using these worksheets will be for one particular point on the site.

In the *third stage*, the sound level at a single site location for any combination of the different types of transportation system noise cited above will be determined. Henceforth, we will use the terms "site point" and "receiver" to refer to the location on your site for which design guide calculations are to be made. This site point could be an arbitrary location you have selected, or it could be a proposed outdoor activity area as explained in the first part of Chapter 6, or the interior of some selected room in your building as explained later on in Chapter 6.

Note that Chapter 6 also offers some strategies; namely, strategies for selecting representative rooms so as to minimize the number of Chapter 6 room-by-room calculations. The gist of these strategies is, whenever possible, to select trial rooms which have potentially troublesome, or critical, sound conditions. These are strategies which, ideally, should dovetail with strategies for selecting a point or points on your site for Chapter 5 computations.

Given the complexities involved, you can now see that the selection of trial site locations for Chapter 5 calculations will be based upon both (a) an early familiarity with your site so as to anticipate where critically high or low sound levels will likely occur, and (b) an advanced understanding of your proposed building so as to anticipate which of its rooms require quiet acoustic conditions, and which are less sensitive to noise . . . you could then plan to locate noise-sensitive rooms at quiet site locations, and rooms that are less sensitive to noise at noisy site locations.

To explore the matter further, let's discuss two typical building design problems. First, let's consider the design of an eight-room dwelling on a relatively small site, say a residential lot 75 ft wide and 120 ft deep, subjected to noise from a railway 500 ft from the lot's rear property line (see Figure 4–1). On such a site there is little choice in the dwelling's location, especially if building setback distances are required for the lot. However, even if setbacks are not required and the dwelling could be aligned with the front lot line to keep it as far away from the railway as possible, little benefit would be achieved; because the sound level at the front of the lot would be only one or two decibels lower than at the rear. This is in accordance with the rule of thumb that the equivalent sound level decreases by approximately 4 to 6 decibels for every doubling of distance from a source. What does this mean? It means that as you get farther and farther from the railway, small changes in distance do not change the sound level appreciably. If the sound level has been determined at the rear property line 500 ft from the railway, the sound level at 1,000 ft from the railway is approximately 4 to 6 decibels less. To realize an additional attenuation of 4 to 6 decibels, the distance must be increased to 2,000 ft; then 4,000 ft, 8,000 ft, and 16,000 ft, etc., for each additional 4 to 6 decibels of attenuation.

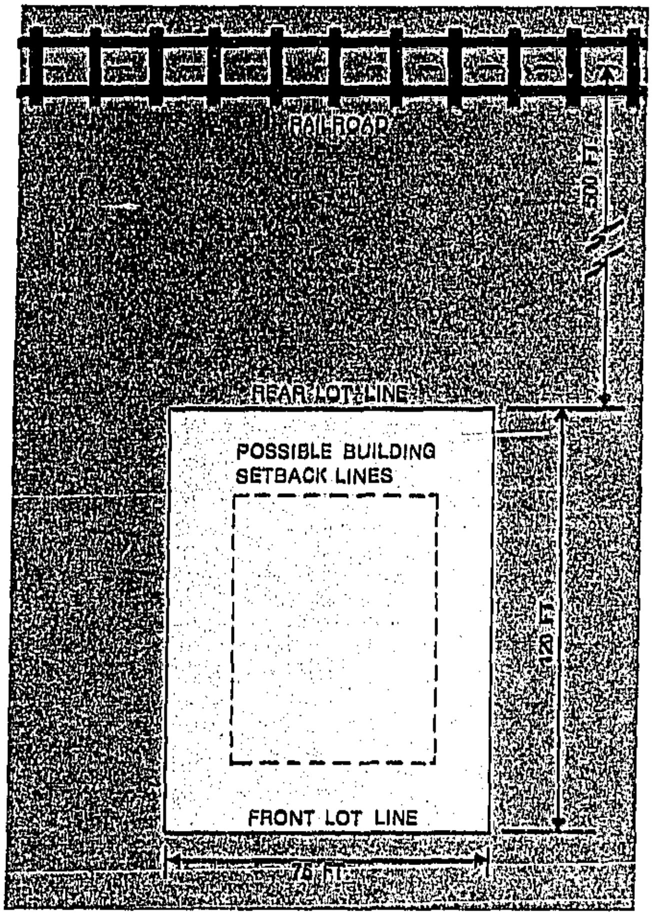


Figure 4–1. Dwelling Design Problem Site.

For this design problem, the best strategy is simply to calculate the sound level at the centroid of the area bounded by setback lines; or, if there are no setback requirements, at the centroid of the site itself. Then you may assume that this sound level is approximately correct for any outdoor activity areas on your site, or for any of the exterior rooms in your proposed building.

A good approximation of the noise levels throughout a site, based on the distance from the noise source, can be estimated by calculations for just a few locations. If the distances from the source to the chosen location are selected so that they vary by less than ±15 percent, then generally the calculations already performed for one distance will suffice. Within these limits, the sound level will not vary by more than ±1 decibel among locations. For example, if your chosen location is 500 ft from the noise source and a sound level of 60 decibels has been determined at that location for a given source, a location 435 ft from the source will have a sound level of approximately 61 decibels and a location 575 ft from the source will have a sound level of approximately 59 decibels. Barriers, of course, will alter these sound levels in the manner discussed in Chapter 5, so this part of the calculation must still be made. Unless the noise source is very close to the

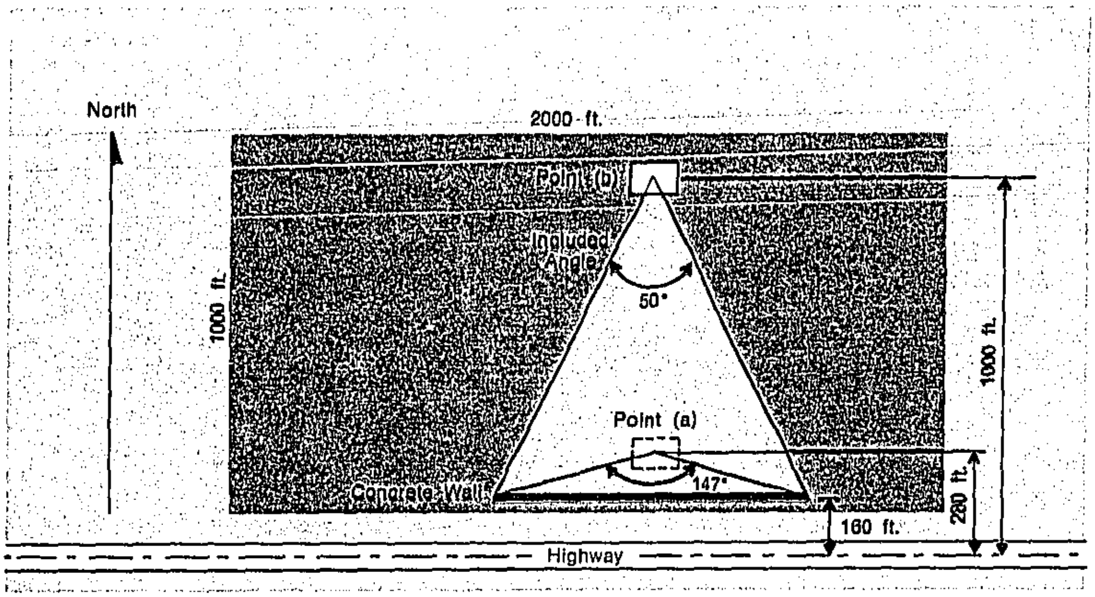


Figure 4–2. Elementary School Site Plan.

site, or unless the site is very large compared to its distance from the source, quite possibly only a single sound level estimation will be necessary—one corresponding to the center of the site.

Now, let's consider a more complex problem involving the design of an eight-room elementary school for a large, level site near a major roadway as in Figure 4–2.

The roadway is partially shielded from the site by a 10 ft-high and 800 ft-long, concrete wall that is located 160 ft from the centerline of the highway. This wall acts as a sound barrier and reduces the noise from the highway to varying degrees at different locations on the site. The site is large enough (2,000 ft long by 1,000 ft wide) to allow some freedom in the location of the school.

The school is to be a one-story building containing eight classrooms, each of which is 30 ft wide by 30 ft long by 9 ft high. For simplification, we will assume that these are to be the only rooms, aside from corridors, in the school. The building scheme, shown in Figure 4–2, provides four rooms on each side of a double-loaded corridor. Since this, or any other probable building scheme, is small in floor area relative to the site area, there are many alternatives for locating the school on the site.

What strategy should be used to choose one or more points on the site for trial calculations? The northern portion of the site, farthest from the highway, will probably be a quiet area of the site. Still, part of the southern portion of the site is shielded by the concrete wall, which could effectively shield a one-story building from the automobile and truck noise on this highway. Thus, let's consider two points . . . point (a) near the concrete wall and point (b) near the northern boundary of the site, as shown in Figure 4–2.

The sound level at point (a), close to the concrete wall, depends on the distance between this point and the centerline of the highway, and on the amount of noise reduction provided by the concrete wall. If we neglect the effect of the concrete wall, the sound level at point (a), call it L, would be affected by the distance attenuation of the sound as it propagates from the highway to this point 280 ft away. But the sound level at point (a) is less than L because of the shielding effect provided by the wall. The amount of noise reduction is a function of the wall's effective height relative to the highway and the school, and also a function of the length of the wall relative to the length of the roadway, hence relative to the "included angle," as shown in Figure 4–2. The effect of these factors, which are discussed in detail in Chapter 5, can be most simply stated as . . . the higher the wall and the larger the included angle (long wall), the more noise reduction provided. Thus, point (a) was chosen as near to the wall as possible (to maximize the effective wall height), and midway along the wall's length (to maximize the included angle). For the geometry shown in Figure 4–2, a noise reduction due to the shielding effect of about 5 decibels could be expected. The sound level at point (a) is thus (L — 5) decibels.

The sound level at point (b), close to the northern boundary of the site, also depends on the distance between this point and the centerline of the highway, and on the amount of noise reduction provided by the concrete wall. Point (b) is chosen midway along the wall (to maximize the included angle) and at a distance of 1000 ft from the centerline of the highway. Again neglecting the effect of the concrete wall, the sound level at point (b) is equal to the sound level at point (a) (L for no concrete wall) minus a correction to account for the additional distance attenuation between points (a) and (b). This additional distance attenuation, which follows the rule of thumb that the equivalent sound level decreases by approximately 4 to 6 decibles for every doubling of distance away from the source, amounts to about 8 decibels for this case. Thus, the sound level at point (b), neglecting the effect of the concrete wall, is approximately (L — 8) decibels.

The shielding effect of the wall at point (b) is less pronounced than at point (a) because both the effective wall height and the included angle are decreased. For the geometry shown in Figure 4–2, a noise reduction due to the shielding effect of only 1 decibel could be expected. The sound level at point (b) is thus (L — 8 — 1), or (L — 9) decibels, which is approximately 4 decibels less than the sound level at point (a). Hence, point (b) should be chosen as the quietest point to locate the school and to estimate the transportation system noise. Actually, since most of the reduction in sound level at point (b) is due to distance attenuation (8 decibels), any point along the northern boundary of the site (1000 ft from the centerline of the highway) has a sound level of approximately (L — 8) decibels. Since the calculated noise reduction of 1 decibel provided by the concrete wall at point (b) is insignificant you may choose any point along the northern boundary.

Either of these two building design problems could be further complicated by the presence of two, three, or more transportation system noise sources. In this case, the selection of a point for estimating the site noise level can be very difficult. The best strategy, for such a case with several noise sources, is to pick a point as far away from the noisiest source as possible; but if this is not possible or if you suspect aircraft noise to be a problem, select the centroid of the site for initial calculations.

You may want to consider other alternative building locations using intuition in the selection of points for estimating sound levels. Until you develop this intuition, you can use the following simple site-related guidelines.

Site-Related Guidelines

No siting options . . .
Choose the centroid of the building if the noise sources are far away; but if the noise sources are close-by choose points where critical building rooms are to be located.

Siting options available:

Single source (no barrier) . . .
Choose a point as far away as possible from the source if it will result in a decrease in sound level; i.e., the distance between the source and your proposed building is at least doubled by moving farther away. If the source is far away from your site, or if aircraft is the noise source, the choice of a site point is noncritical.

Single source (with barrier) . . .
If possible, choose a point which satisfies the guidelines above for a single source with no barrier and is located as close as possible to the barrier and midway along its length. This point benefits from both distance attenuation and barrier noise reduction. If the selection of such a point is not feasible, choose an intermediate point for which a trade-off between distance attenuation and barrier noise reduction may be made.

Multiple Sources . . .
Choose a point as far away as possible from the noisiest source, if it will result in a decrease in sound level, i.e., the distance between the source and your proposed building is at least doubled by moving farther away. If you can't guess which source is noisiest or if all sources are equally noisy, choose the centroid of your site as the point for estimating the transportation system noise.

Now that we have discussed site-related guidelines, let us now turn to building-related guidelines. Those guidelines refer to positioning the building at a point on your site that you have chosen. If we refer to the previous example of the construction of a school, the overall dimensions of the building scheme are small relative to the size of the site, and in comparison with the probable distance between the building and the highway. It is doubtful that the sound levels will vary much from one end of the building to the other; and thus, there is no need to calculate the sound levels for various points along the building.

Now let's consider the case of a large building located close to a highway as in Figure 4-3. The distance from the highway to the far end of the building is twice as long as the distance to the near end of the building (200 ft as compared to 100 ft). Thus, you can expect the sound level to vary by 4 to 6 decibels from one end of the building to the other. The best strategy for such a case is to calculate the sound level for each point of interest, be it an outdoor activity area or one of the rooms of the building.

Again, as with site-related guidelines, you must use intuition in selecting the number of points for estimating the sound level. Until you develop this intuition, you can use the following simple building-related guidelines.

Building-Related Guidelines

Building is small and is located far from the source . . .

Choose a point *corresponding to the centroid of the building and follow the appropriate site-related guidelines listed previously. Using only one point for your calculations is valid if the two ends of the building are within ±15 percent of the distance from the source to the building . . .*

Building is large and is located close to the source . . .

Choose several points *corresponding to the location of outdoor activity areas and rooms of interest. You can limit the total number of points using the rule of thumb that the sound level will only vary by ±1 decibel for locations within ±15 percent of the distance from the source to the point of calculation . . .*

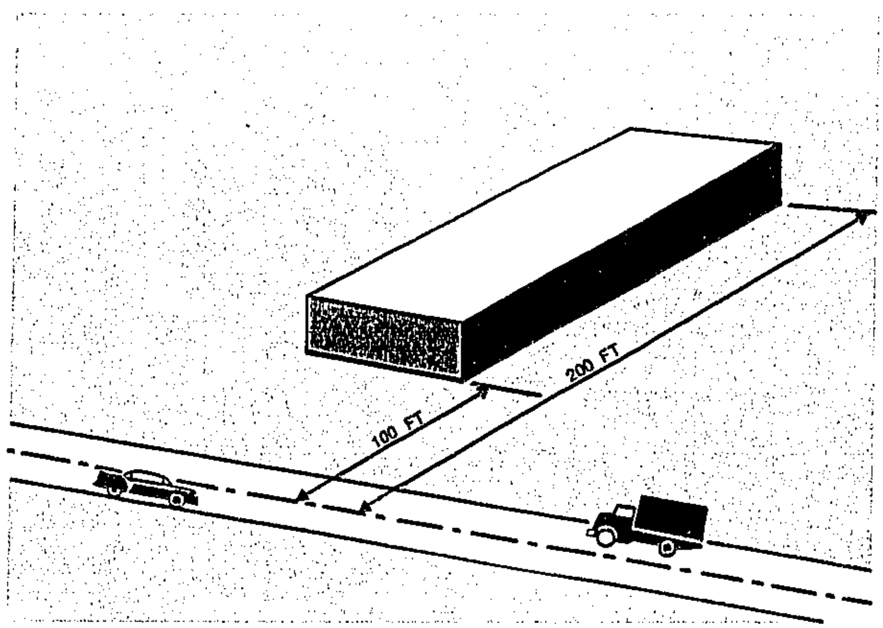
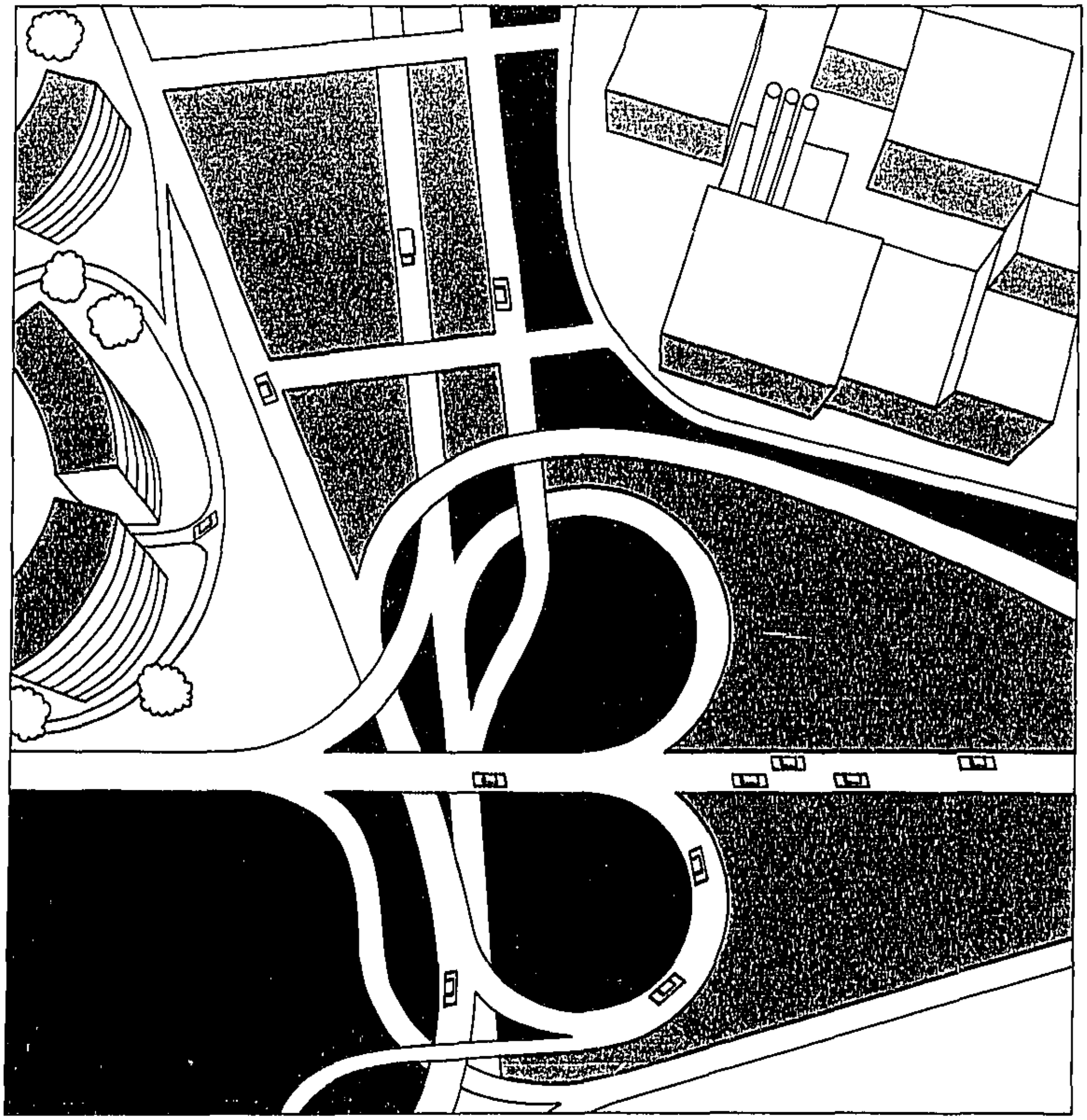


Figure 4-3. Building Located Close to a Highway.



Chapter 5 How to Estimate Building Site Noise

Section 1 Sound Propagation and Barriers

When dealing with sound and its effects on the occupants of your proposed building, three components need to be considered: the source of the sound, the path along which the sound travels, and the receiver or individual who hears the sound. Various effects of sound on the receiver have been discussed in Chapter 3. In this section the sources of sound and how sound propagates from the source to the receiver are described.

Sound can be generated by the vibration of a solid body in contact with the air; forces acting directly on the air, such as a fan; or by the violent motion of the air itself as from a jet. Consider for example, what happens when the sheet metal panels of a truck hood are set into vibration by the truck's engine. The vibrating panels move in and out. As they move outward, they push against the air nearest them; as they move inward they produce a partial vacuum, or rarefaction, in the nearby air. The alternate compression and expansion of the air adjacent to the panels results in small local fluctuations in the atmospheric pressure. These fluctuations in turn cause a portion of the air farther away from the panel also to fluctuate in pressure. This local disturbance is thus propagated through the air as sound waves that reach our ears. The same general principles apply to other mechanisms of sound generation in that small local fluctuations in the atmospheric pressure are created and propagated through the air as sound waves.

The sound waves that are generated by these two mechanisms are known as elastic waves, which are characterized by the fact that a disturbance initiated at one point is propagated to other points in a predictable manner determined by the physical properties of the medium of propagation. The sound heard by a receiver depends upon the type of sound wave, the medium (usually air), the type of wave divergence taking place, and the excess attenuation.

Two common types of sound waves are spherical sound waves and cylindrical sound waves. Spherical sound waves are usually generated by a source whose overall dimensions are small compared with the wavelength of the sound produced. This type of sound source is called a *point source*. In contrast, cylindrical sound waves are generated by a source whose radial dimensions are small compared to the wavelength of the sound produced, but axial dimensions are infinite or extremely large. This type of sound source is called a *line source**.

Wave divergence refers to the spreading out of the sound wave from a source into the surrounding atmosphere. The effect of this spreading is to decrease the sound level at the receiver as he moves farther away from the source. Wave divergence is different for point and line sources—for an *idealized point source*, the sound level decreases by 6 dB for each doubling of distance away from the source; for an *idealized line source*, the sound level decreases by 3 dB for each doubling of distance away from the source. These values of wave divergence are for ideal sources which radiate sound uniformly into a homogeneous loss-free atmosphere, free of barriers.

Excess attenuation is the added decrease of sound level beyond that caused by simple

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* *It should be pointed out that since this design guide uses the Leq metric, which is based on averaging the variations of the sound level over some specified time period to obtain an equivalent sound level, to make a distinction between point and line sources is not quite accurate. If a point source such as an auto or truck moves past a stationary receiver, the instantaneous sound level will first increase as the source approaches, reach a maximum, and then decrease as the source moves away. In using the Leq metric, this time varying sound level is averaged to give constant equivalent sound level of equal energy. Thus, the net effect is to approximate the moving point source as a stationary, infinite line source generating a sound level equal to Leq at the receiver. This fact is mentioned only for the sake of technical accuracy. It has no effect on how you will perform the calculations in later sections because it has been implicitly incorporated into the transportation system noise models.*

wave divergence, and includes attenuation by absorption in the air; attenuation by environmental conditions (rain, sleet, snow or fog); attenuation by grass, shrubbery and trees; attenuation and fluctuation due to wind and temperature gradients, atmospheric turbulence and the characteristics of the ground; and, attenuation due to barriers or other types of shielding [1]. Thus, by including excess attenuation you can correct the ideal, loss-free case to account for atmospheric and environmental elements that reduce sound levels.

In this design guide, the sound level generated by each type of transportation system noise source will be predicted assuming "typical" values of attenuation due to wave divergence and environmental conditions. Then account will be taken for additional attenuation effects of any barriers, rows of intervening buildings or heavy vegetation.

The remainder of this section contains a general discussion of sound barriers and how to predict the attenuation they provide. Also, the barrier effect of buildings and the attenuation due to vegetation are discussed. These shielding effects are essential for predicting highway and railway noise in Sections 5.2 and 5.3 of this chapter.

Barriers

A sound barrier can be any obstruction which shields, or partially shields, the sound source from the receiver. The effect of this shielding is to reduce the level of the sound heard by a receiver by an amount dependent upon, among other things, the location and configuration of the obstruction. Based on this definition, walls, earth berms, the sides of depressed highways or railways, the edges of elevated highways and railways, and any other obstruction of sufficient size can act as sound barriers. Examples of these types of shielding are shown in Figures 5.1-1 through 5.1-4.

The attenuation provided by a barrier depends upon how much of the total sound energy is blocked from the receiver. Obviously, if some of the sound energy can pass by the barrier, its effectiveness is lessened. There are basically four paths which sound can follow from the source, past (or through) the barrier, to the receiver [2]. These paths, discussed in the next few paragraphs, are shown in Figure 5.1-5.

The direct path refers to the sound that passes over or around the barrier without being affected i.e., there is no diffraction.

Figure 5.1-1. Shielding by a Wall.

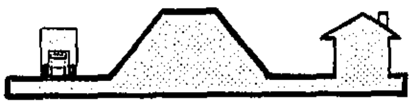


Figure 5.1-2. Shielding by an Earth Berm.

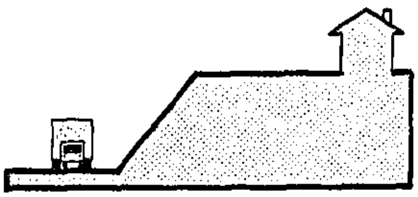


Figure 5.1-3. Shielding by a Depressed Highway or Railway.

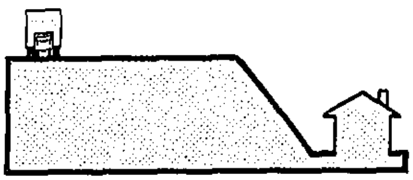


Figure 5.1-4. Shielding by an Elevated Highway or Railway.

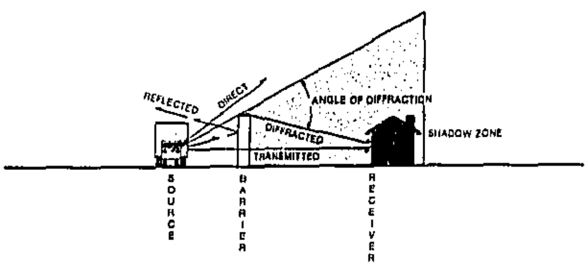


Figure 5.1-5. Paths along which sound energy can travel from the source to the receiver [2]. Also shown is the shadow zone and the angle of diffraction associated with the source-barrier-receiver geometry.

For this path, the barrier does not block the line-of-sight between the source and receiver and therefore provides little or no attenuation. The direct path can be affected only by increasing the height of the barrier so that the line-of-sight between the source and receiver is blocked.

Sound energy that passes just over the top edge of the barrier is bent down into the apparent shadow zone, which is the area visually shielded from the source as shown in Figure 5.1–5. This path is the diffracted path, analogous to the optical diffraction of light. The sound waves that are diffracted are attenuated, and the larger the angle of diffraction (defined in Figure 5.1–5), the more the sound wave is attenuated in this shadow zone. The amount of sound energy reaching the receiver via the diffraction path is dependent upon the barrier height and the location of the source and receiver relative to the barrier. If either the source or receiver is placed close to the barrier, the angle of diffraction and hence the attenuation is increased. The amount of attenuation due to diffraction of the sound wave is dependent on the shape of the barrier. In general, most theories of diffraction that have been developed for predicting barrier attenuation treat only infinitely long walls with a thickness much less then the wavelength of the diffracted sound (rigid-screen barriers). Theoretical and experimental investigations [3] have shown that the attenuation by wedge-shaped or wide barriers is somewhat different from that predicted by rigid-screen theories. However, predicting the attenuation by these other barrier shapes is difficult and only a small improvement in the accuracy can be achieved. Hence, this design guide applies the theory developed for an infinitely long rigid-screen for all barrier shapes and sizes.

Another path is one directly through the barrier. Sound traveling this path is reduced by an amount related to the so-called transmission loss of the barrier, a measure of the reduction in level of the sound that passes through the barrier. The transmission loss depends most importantly upon the weight per unit area of the barrier—the heavier the barrier the less sound transmitted. As a general rule, if the surface weight density, which is the weight density (lb/ft^3) multiplied by the barrier thickness (ft), is greater than 4 lb/ft^2, the transmission of sound through the barrier will be negligible relative to the sound energy diffracted over or around the barrier [4].

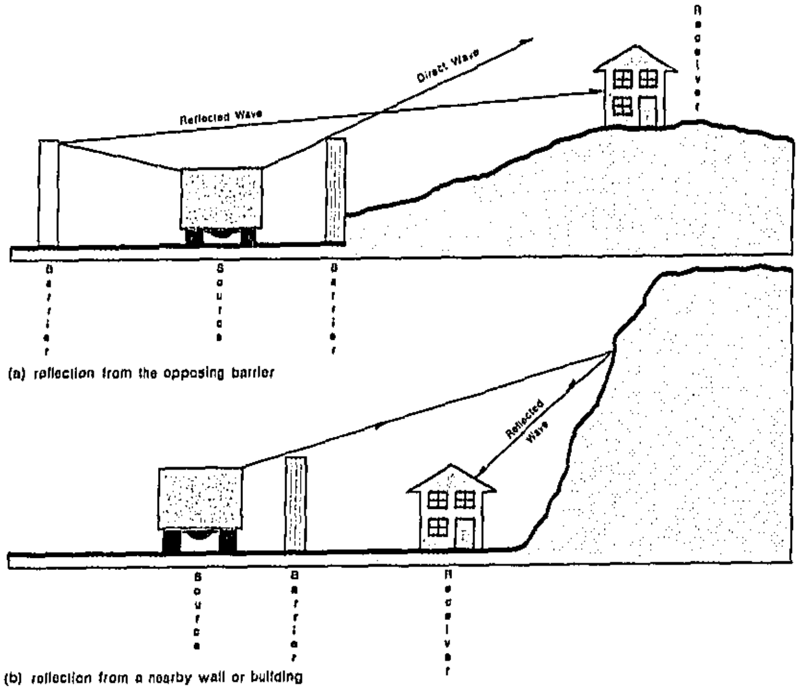


Figure 5.1–6. Two cases where reflected waves effectively reduce barrier attenuation.

The last path shown in Figure 5.1–5 is the reflected path. Reflected sound is usually of concern only to a receiver on the same side of the barrier as the sound source. Two special cases where reflected sound waves may be important are shown in Figure 5.1–6. In both cases, part of the sound energy radiated by the source is reflected from a nearby surface and then propagated to the receiver. Depending upon the location of the reflecting surface and barrier relative to the source and receiver, the barrier attenuation may effectively be reduced to zero (i.e., the sound level at the receiver is the same with or without the barrier). It should be noted that in most practical cases, the reflected noise does not play an important role in the treatment of barriers [5]. If you encounter a serious situation of reflected noise, you may need the services of an acoustical consultant.

If the barrier provides a substantial amount of attenuation, the sound diffracted over or around the barrier into the shadow zone usually represents the most important path between the source and receiver. Hence, estimating the amount of attenuation due to diffraction is the primary calculation involved in determining barrier attenuation in Sections 5.2 and 5.3. However, there are two other considerations in determining barrier attenuation. These are the overall length of the barrier relative to the source length, and the presence of holes or openings in the barrier. A short barrier permits sound to propagate around its ends, and a barrier with holes permits sound to be transmitted directly through the barrier.

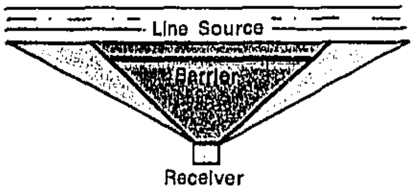


Figure 5.1–7. Paths for Sound Energy to Travel Around the Ends of a Barrier.

For sources, such as highways and railways, which are conceptually represented as line sources, the length of the barrier is particularly important. For example in Figure 5.1–7, the noise diffracted over the top of the barrier is reduced; however, the sound propagating from the part of the roadway extending beyond the ends of the barrier is not affected by the barrier. As a result, the actual reduction of sound due to the barrier is less than that predicted for the diffraction of the sound wave. To be effective, barriers must not only break the line-of-sight between the receiver and the nearest section of roadway, but also between the receiver and sections far up and down the roadway. To decide when predicted barrier attenuation must be adjusted to account for sound coming around its ends, refer to the barrier "included angle," denoted "a", and defined in Figure 5.1–8. If the included angle, "a", is greater than 170°, the barrier can be considered infinitely long. This means that the attenuation depends only upon sound diffraction across the top of the barrier. But if the included angle, "a", is 170° or less, the barrier length is considered finite, and adjustments must be made to account for sound coming around the ends of the barrier. These adjustments are included in the predictive procedures of Sections 5.2 and 5.3.

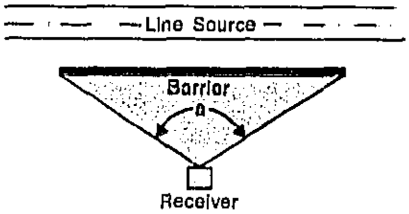


Figure 5.1–8. Barrier Geometry Showing the Included Angle, a.

Holes or openings substantially increase the sound transmission of a barrier, thus reducing its effectiveness. This is best illustrated by the data shown in Table 5.1–1. If, for example, a barrier has openings which amount to ten percent of its total area, its overall attenuation would not be greater than an A-weighted sound level difference of 4 dB, considering attenuation due to both transmission and diffraction. For a barrier with openings greater than ten percent of its area, the attenuation will probably be negligible.

Percent of Barrier Area that is Open	Maximum Transmission Loss Possible, dB
50%	0
10%	4
5%	7
1%	14
0.5%	17
0.1%	24

Table 5.1–1. Transmission Loss for Barriers with Holes [2].

Before continuing this discussion, let's review a few general principles of barrier attenuation; specifically, the relationship between sound attenuation expressed in decibels and in energy terms as shown in Table 5.1-2. The meaning of these numbers can be explained by considering, as an example, a barrier which attenuates the noise from a highway by an A-weighted sound level difference of 10 dB. Referring to Table 5.1-2, it can be seen that this attenuation of 10 dB is equivalent to eliminating 90 percent of the energy initially propagated towards the receiver. This drastic reduction in energy relative to the sound level attenuation can be understood in view of the logarithmic nature of the measure. Table 5.1-3 provides general rules for the feasibility of obtaining various levels of attenuation from barriers [5].

Table 5.1-2. Attenuation in Terms of Decibels and Energy [2].

Attenuation __dB Reduction	Remove __% of Energy
3	50%
6	75%
10	90%
20	99%
30	99.9%
40	99.99%

Table 5.1-3. Feasibility of Obtaining Attenuation from Barriers [5].

Barrier Attenuation*	Feasibility
5 dB	Simple
10 dB	Attainable
15 dB	Very Difficult
20 dB	Nearly Impossible

A-weighted sound level attenuation in decibels

The method used in this design guide for calculating the attenuation provided by a barrier is based on the work of Kugler and Piersol [6]. Their model, which assumes that highway traffic can be treated as a line source parallel to an infinitely long screen barrier, relates the attenuation to the path length difference, L. Given the source-barrier-receiver geometry shown in Figure 5.1-9, the path length difference is defined as,

$$L = A + B - C.$$

The distance (A + B) is the shortest path over the barrier's edge from the source to the receiver; C is the direct path distance from the source to the receiver through the barrier.

The relationship between the path length difference and the attenuation provided by a barrier is a function of the frequency spectrum of the sound source. Kugler and Piersol found that the reduction of highway noise by a barrier could be estimated with sufficient accuracy by assuming a frequency of 500 Hz [6]. The dashed curve of Figure 5.1-10 shows the relationship between path length difference and the attenuation provided by an infinitely long barrier screening a line source radiating sound at a frequency of 500 Hz. As a more conservative estimate of the noise reduction, Kugler and Piersol proposed a simplified linear curve shown dotted in Figure 5.1-10. However, this design guide employs the solid curve shown in this figure, which is even more conservative because the attenuation for small values of L goes to zero instead of asymptotically approaching a value of 5 dB as for the general line source model; and because the maximum attenuation is limited to an A-weighted sound level difference of 12 dB for large values of L due to environmental effects.

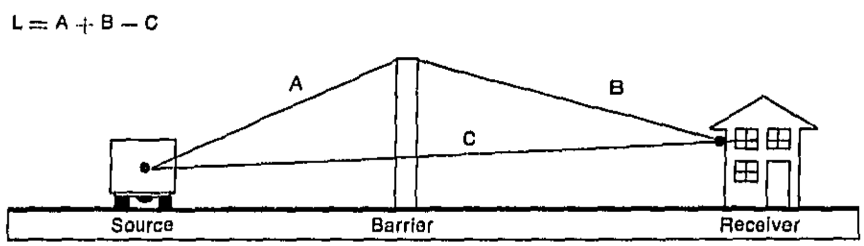


Figure 5.1-9. Barrier Path Length Difference.

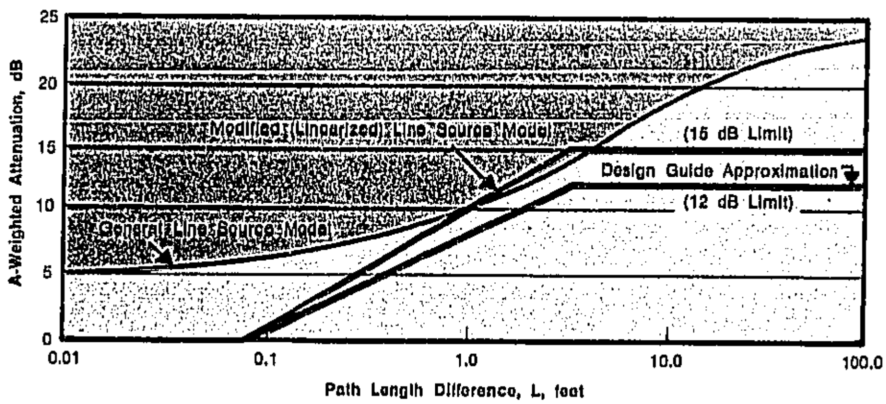


Figure 5.1–10. The A-weighted attenuation provided by an infinitely long barrier versus path length difference for various models [6]. The assumed frequency of the source is 500 Hz.

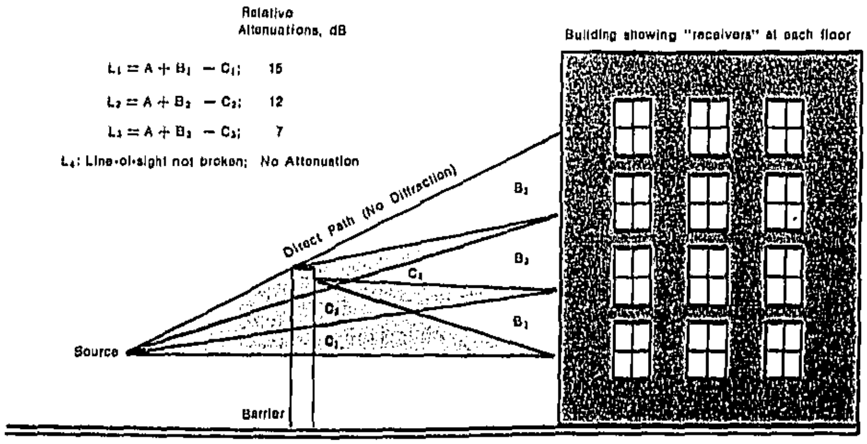
When sound is attenuated by a barrier, it is not uniformly reduced in level across its entire frequency range. Instead, its high frequencies are reduced more than its low frequencies. The result is a change in the spectrum shape of the sound at the building site. This is of little or no consequence in calculating the sound level in outdoor activity areas, but it is important in estimating the sound level inside a room since the spectrum shape of the sound can be critical in determining the sound isolation properties of the building shell. Low frequency sound energy passing over the barrier is easily transmitted through the external shell of the building. Based on a detailed study of this problem, discussed in Appendix B, it was found that the building shell isolation rating must be degraded by about 3 dB for exterior noise dominated by sound propagating over a barrier. Alternatively, the estimates of barrier attenuation can be reduced by a corresponding amount. This correction in incorporated in the solid curve of Figure 5.1–10.

To predict the attenuation of a barrier you must determine the path length difference—L. You can do this graphically by an accurately scaled section cutting through the terrain between the transportation system sound source and your proposed building. Such a drawing will show the height of the source and receiver relative to the top edge of the barrier. Since any real transportation system sound source is composed of several subsources (e.g., heavy truck noise is a combination of sounds radiated from the engine, fan, intake, exhaust, and tires), an effective source height based upon all the subsources must be used. The effective source height is dependent upon the type of transportation system sound source—it is assumed to be located at the roadway surface for automobiles; at track level for railway cars; at eight feet above the surface for heavy trucks; and fifteen feet above the surface for diesel-electric locomotives (more will be said about effective source height in Sections 5.2 and 5.3).

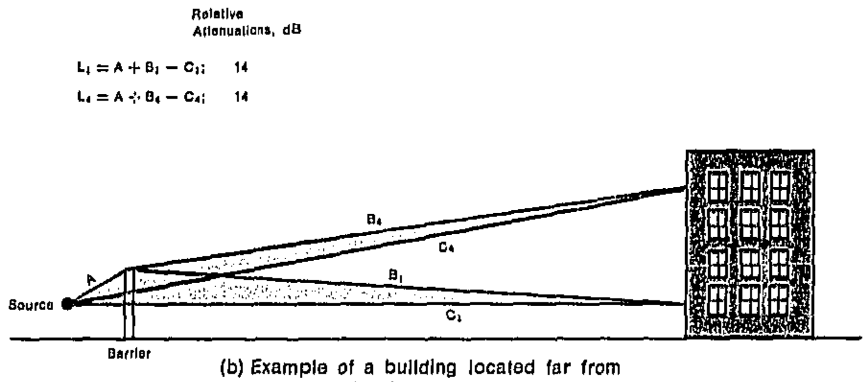
The receiver location will be in some outdoor activity area on your site or some room in your building. The following examples discuss the effect of receiver location on the resulting attenuation.

1. Rules for calculating L

If the building you are designing is to be many stories high, the attenuation provided by a barrier can vary substantially between the ground and upper floors. This variation is dependent upon the height and location of the barrier and sound source relative to your building. The way to check this is to calculate the value of L for several representative story heights, and then using these values, determine the barrier attenuation from Figure 5.1–10. Two examples are shown in Figures 5.1–11a and 5.1–11b.



(a) Example of a building located close to a barrier, showing the change in attenuation for receiver locations at each floor.



(b) Example of a building located far from a barrier, showing that the effect of receiver height on the attenuation is minimal.

Figure 5.1–11. Examples of Determining the Path Length Difference for Various Receiver Locations.

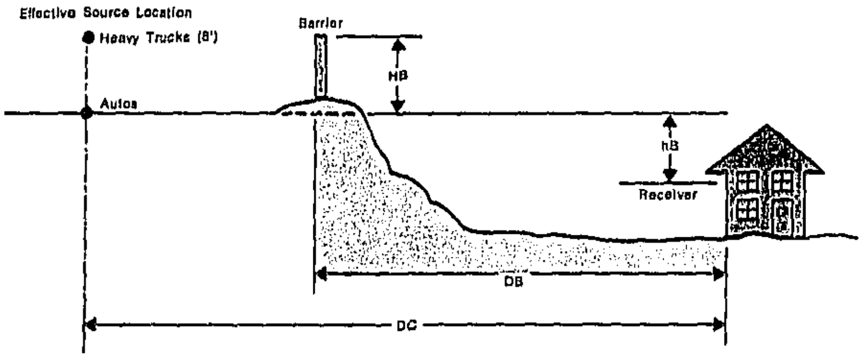
In Figure 5.1–11a, the building is close to the barrier, and the attenuation varies between two extremes. For the ground floor the attenuation is high, but it continuously decreases so that for the upper floors there is no barrier attenuation at all because the line-of-sight with the source is not blocked.

The second example, shown in Figure 5.1–11-b, does not have these extremes of attenuation. Since the building is farther away from the barrier than in Figure 5.1–11a, the value of L does not vary much between the top and bottom floors.

Selections of representative building rooms for noise prediction are discussed in Chapter 6. Essentially, the selection is left to you, the user of this design guide. When in doubt, you should estimate the barrier attenuation at each outdoor activity area and room that you analyze in Chapter 6.

An alternative to graphically measuring the dimensions of A, B and C from a drawing is to calculate A, B and C from vertical dimensions of the source, barrier, and receiver. This method, shown in Figure 5.1–12, has the advantage that the effective source height is included in the equations for A, B and C. This method, discussed in Sections 5.2 and 5.3, is preferred for determining the path length difference. Horizontal and vertical dimensions should be measured as precisely as possible so that an accurate estimate of the attenuation can be calculated.

For most barriers, determining the attenuation is relatively simple. To deal with special cases, however, you should be familiar with the general rules discussed below.



Automobiles

$$A = \sqrt{HB^2 + (DC - DB)^2}$$
$$B = \sqrt{(HB + hB)^2 + DB^2}$$
$$C = \sqrt{hB^2 + DC^2}$$

Heavy Trucks 8' Effective Source Height

$$A = \sqrt{(HB - 8)^2 + (DC - DB)^2}$$
$$B = \sqrt{(HB + hB)^2 + DB^2}$$
$$C = \sqrt{(hB + 8)^2 + DC^2}$$

Figure 5.1–12. Example Showing Horizontal and Vertical Dimensions of Source, Barrier, and Receiver Geometry and Equations for A, B and C.

2. Barriers in series

There may be sites having more than one barrier between the source and receiver, as shown in Figure 5.1–13. Whereas, both barriers attenuate noise, and might be considered "in series", such an additional complication is not worth the slight improvement in accuracy; instead, only the "dominant" barrier—the one which provides the most attenuation—should be considered. To determine which barrier is "dominant", calculate the path length difference for both, and choose the barrier with the larger value of L. This, of course, presumes that both barriers are long enough to block all of the source; if not, you must also consider the length of each barrier.

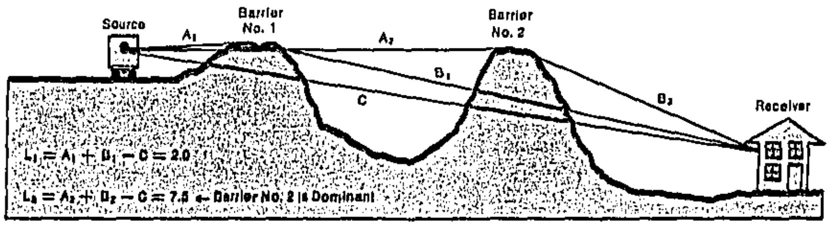


Figure 5.1–13. Example of Two Barriers in Series, Showing How to Determine Which Barrier is Dominant.

3. Receiver located beyond the end of the barrier

When a receiver is located just at the end of the barrier, the receiver is not shielded from one end of the line source. For this case, the maximum attenuation is an A-weighted sound level difference of 3 dB. For receivers beyond the end of the barrier, as in Figure 5.1–14, the attenuation is negligible.

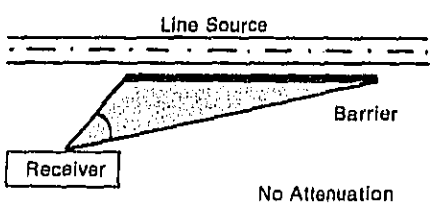


Figure 5.1–14. Receiver Located Beyond the End of a Barrier.

4. Elevated and depressed highways and railways

Some general comments can be made concerning the attenuation of depressed and elevated highways and railways as a function of receiver location. As shown in Figure 5.1–15, as the receiver position is progressively moved farther away from a sound source located on an elevated configuration, the path length difference (hence the attenuation) decreases. Conversely, for a sound source located in a depressed configuration (Figure 5.1–16), the path length difference (hence the attenuation) increases for more remote receiver locations. Thus, to obtain optimal attenuation for a given elevation or depression the receiver should be located close to the elevated highway or railway, but as far away as possible from a depressed highway or railway.

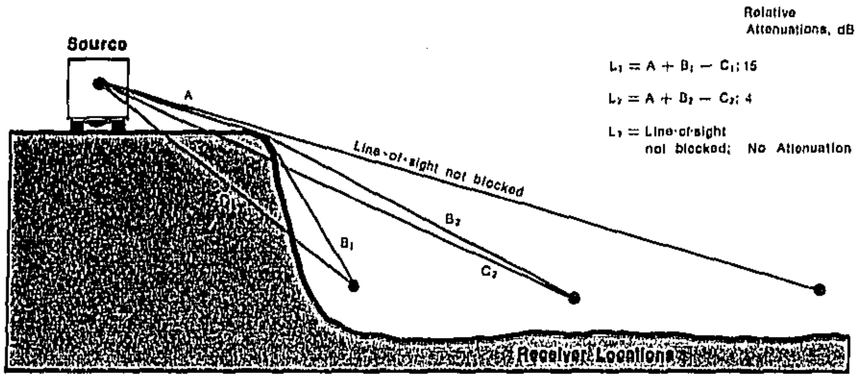


Figure 5.1–15. Example Showing How Attenuation Decreases as the Receiver Location is Moved Farther from an Elevated Highway or Railway.

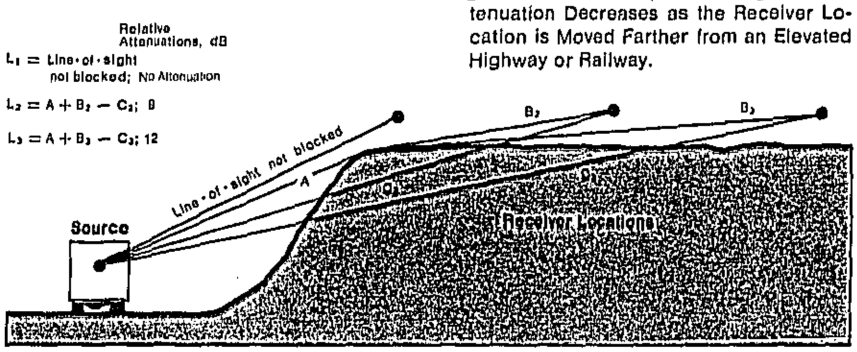
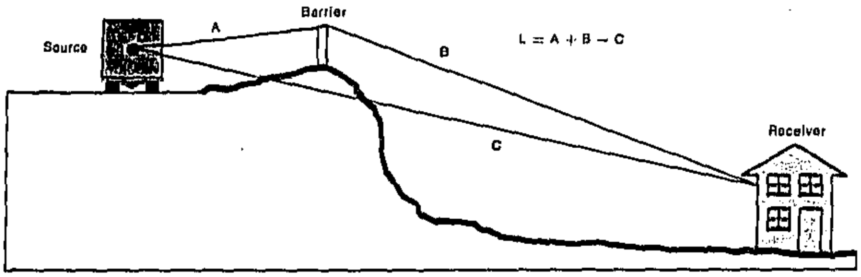


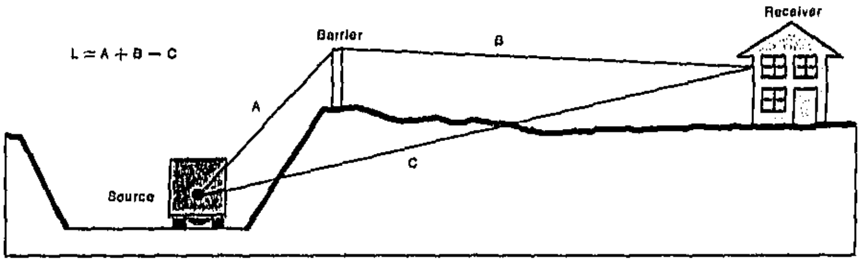
Figure 5.1–16. Example Showing How Attenuation Increases as the Receiver Location Is Moved Farther from a Depressed Highway or Railway.

5. Combination of elevated or depressed configurations plus a barrier

For a barrier combined with an elevated or depressed configuration, the path length difference is determined as shown in Figures 5.1–17a and 5.1–17b, respectively. For these and other similar combinations, the important thing is the barrier height relative to the source and receiver, which is measured in terms of path length difference.



(a) Elevated highway or railway and barrier.

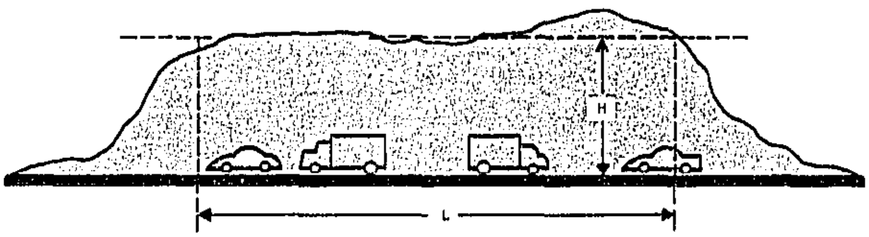


(b) Depressed highway or railway and barrier.

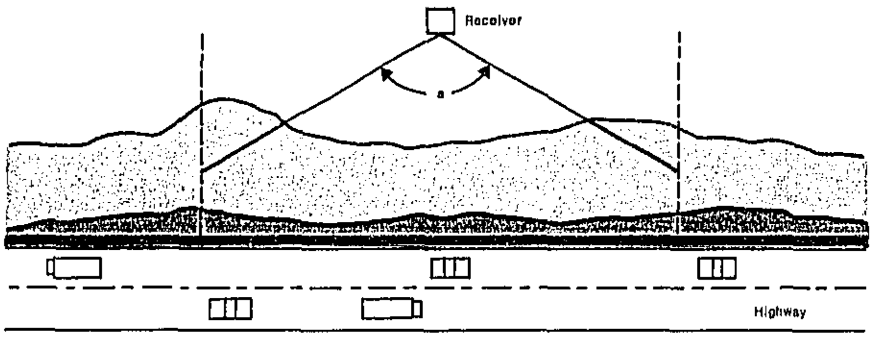
Figure 5.1–17. Method of Determining the Path Length Difference for Combinations of Different Types of Shielding.

6. **Path length distance for elevated and depressed configurations and earth berms**

Determining the distances necessary to calculate the path length difference for elevated and depressed configurations and earth berms can be difficult since they are likely to be irregular in height or width. Figures 5.1–18a and 5.1–18b show how to estimate roughly the height and length for one example of an earth berm. The same general method should be used for elevated and depressed configurations. Since, such methods provide only approximate distances, they should be applied conservatively. Moreover, if any of these configurations are questionable because they are either short in length or not very high, their attenuation should be disregarded.



(a) Section through earth berm showing assumed height, H, and length, L.

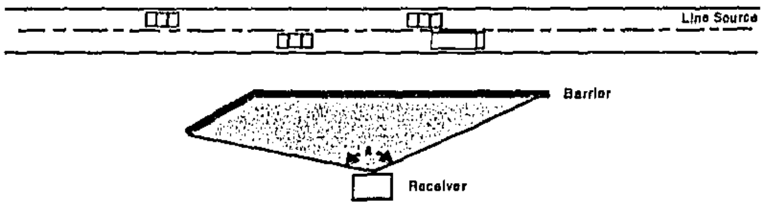


(b) Top view of berm showing the assumed included angle, a.

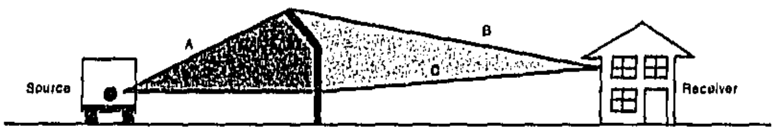
Figure 5.1–18. Technique for Estimating Dimensions of an Earth Berm.

7. Barrier turned at the end or top

If a barrier is not straight but angled, either at the end or at the top, the path length difference is still determined by how much of the source is blocked from the sight of the receiver as shown in Figures 5.1–19a and 5.1–19b. Note that this angling of a barrier is one way to increase its performance without making it excessively long or high.



(a) Plan view of barrier turned at the end



(b) Plan view of barrier turned at the top

Figure 5.1–19. Included Angle and Path Length Difference for Barriers With Turns.

8. Summary

In summary, the following can be said about noise barriers.

1. If a barrier does not block the line-of-sight between the source and receiver, the barrier will provide little or no attenuation.
2. If a barrier is constructed of a material with a surface weight density greater than 4 lb/ft^2 and there are no openings through the barrier, transmitted sound will usually be negligible.
3. If there are openings over 10 percent or more of the barrier area, barrier attenuation will be negligible.
4. Diffracted sound is usually the most

important aspect in estimating barrier attenuation.

5. Reflected sound can be important for receivers on the source side of a barrier, but it normally is not a factor for receivers on the side opposite from the source. Hence reflected sound is usually not important to your building and site.
6. Transmission of sound around the ends of the barrier can be critical if the barrier included angle is less than 170°.
7. Barrier attenuations greater than an A-weighted sound level difference of 10 dB are difficult to obtain.
8. For two or more barriers "in series", consider only the "dominant" barrier.
9. Assume no attenuation for a receiver located beyond the end of a barrier.

9. Buildings as Barriers

Let us now discuss the shielding provided by rows of buildings located between a sound source and your building site. The excess attenuation of such buildings acting as barriers can be as high as 10 dB, but special procedures are needed to predict the attenuation based on the size, shape and spacing of the intervening buildings.

One way of handling such shielding would be to deal with each building acting as a barrier. A simpler but more approximate method is that given in reference [6]. This technique, the one used in this design guide, assigns a value of 4.5 dB attenuation for the first row of buildings and an additional 1.5 dB for every subsequent row, up to a maximum of 10 dB. (For example, four rows of buildings between the source and building site would provide a total attenuation of 9 dB.) To obtain these values of attenuation the following conditions must exist:

1. The open area between the buildings must be less than 40 percent of the total open area, so that the buildings form an effective visual barrier between the source and your building or site.
2. The average height of the first row of buildings should equal or exceed the average height of your proposed building. (For example, a row of one-story buildings on a level terrain, may provide little or no attenuation for the second floor of a building located behind the row of one-story buildings.)
3. The row of buildings acting as a barrier should visually block most of the length of the source from your building or site.

For buildings acting as barriers that are less densely packed than 60 percent a lower noise attenuation could be estimated. If the buildings acting as a barrier occupy only 10 to 20 percent of the area paralleling the source, each building might produce a small localized amount of shielding, but the combined effect of such sparsely spaced buildings would be negligible. On the other hand, a long, continuous, solid building occupying most of the area along a source can be treated as a barrier, and its attenuation estimated by methods previously discussed using path length difference and included angle. In general, however, judgments concerning the barrier effects of buildings should be made conservatively.

10. Vegetation as a Barrier

Let us now describe a last form of excess attenuation due to vegetation. To provide significant attenuation, the vegetation should consist of large belts of trees or shrubs more than 50 feet in depth, more than 10 feet in height and dense enough to visually block the source from the receiver. The excess attenuation due to such belts can be as high as 5 to 10 dB, but its accurate estimation is difficult. Research has shown that diffusion or scattering of the sound waves off the leaves, stems and trunks, rather than absorption, is the principal mechanism for attenuating the sound [7, 8, 9]. The amount of diffusion, hence attenuation, is dependent upon the height, width and overall density of the belt. The density depends upon the species of vegetation, planting patterns, and the foliage distribution from the ground to the top of the tree or shrub. (Obviously, deciduous trees provide little attenuation when dormant.) Prediction of excess attenuation based on these factors is not practical for this design guide; instead, you should simply allow an A-weighted attenuation of 5 dB per 100 foot depth of woods up to a 10 dB maximum [10]. For these values of attenuation, the following conditions must exist:

1. The woods must be of sufficient density to block all visual paths between the source and receiver.
2. The underbrush or ground cover should also be of sufficient density and height to block all visual paths between the source and receiver.
3. The woods should extend at least 15 feet above any line-of-sight between the source and all portions of your building or site.
4. The woods should be long enough to visually block most of the length of the source from the receiver.
5. To be effective year-around there should be a reasonable mixture of both deciduous and evergreen trees, or all should be evergreen.

For low density growth a token amount of attenuation such as 2 or 3 dB per 100 feet, up to a 10 dB maximum, might be permissible [10]. It is also pointed out that the reason for the 10 dB maximum is that the effectiveness of the vegetation belt can be compromised when sound propagating over the tops of the trees is bent down to earth beyond the growth by various mixtures of wind and temperature gradients. Thus, the 10 dB limitation is imposed so that the excess attenuation is not overestimated.

Another aspect of vegetation shielding is that although a single tree or even a few widely scattered trees do not appreciably reduce the noise, they do have aesthetic and psychological value by visually screening the source from the receiver. Thus, during construction of your building an effort should be made to preserve any existing trees, hedges or other shrubbery. Or, new landscaping could be planned, to help shield the source from the building. Cook and Van Haverbeke [7], give the following recommendations concerning planting and types of vegetation:

1. "To reduce noise from high-speed car and truck traffic in rural areas, plant 65- to 100-foot wide belts of trees and shrubs, with the edge of the belt within 50 to 80 feet of the center of the nearest

Table 5.1–4. Evergreen Trees and Shrubs That Should Be Suitable for Year-Round Noise Screening and That Have a Relatively Wide Range of Adaptability [7].

Common name	Regions of best adaptability
Tall	
Fir	
white	Nationwide
Veitch's silver, Nikko	East
balsam	Midwest, North, Northeast
corkbark	Midwest, Southwest, Southeast
Fraser	East, Southeast
California red	West
Spanish	West Coast
Cedar	
atlas	West Coast
deodar, Cedar of Lebanon	West Coast, South, Gulf Coast
Port-Orford cedar	West Coast, South, Southeast
Arizona cypress	Southwest, South, Southeast
Spruce	
Norway, white Serbian,	Nationwide (best in north)
Oriental, blue	Nationwide (best in north)
Pine	
western white	West
ponderosa	West, Midwest
Scotch	Nationwide (best in north)
red	East, North
Austrian, eastern white	Midwest, East
Monterey	California Coast
Douglas fir	Nationwide (except South)
Giant sequoia, Redwood	West Coast
Western redcedar	West
Hemlock	
eastern	East, Southeast
Carolina	East Coast, Southeast, South
western	West Coast
Medium	
Juniper (upright)	
eastern redcedar and varieties	East of Rocky Mountains
Rocky Mountain and varieties	West of Rocky Mountains, Midwest
Chinese and varieties	Nationwide
Grecian	Nationwide
Irish	Nationwide (best in north)
Swedish	Nationwide (best in north)
Yew	
Japanese and varieties	Nationwide
English	Nationwide (best in east)
Arborvitae	
American and varieties	Nationwide (best in north, northeast)
Oriental and varieties	South
Short	
Juniper	
Chinese (Pfitzer) and others	Nationwide
Mugo pine	Nationwide
Arborvitae	
American and varieties	Nationwide
Oriental and varieties	Nationwide
Yew	
Japanese and varieties	Nationwide
Some Broad-leaved Evergreens	
Pyracantha	Nationwide (best in south half)
Euonymus	Nationwide
Privet	South

traffic lane. Center tree rows should be at least 45 feet tall (See Table 5.1–4 for species recommendations). Where right-of-way width is large, as on certain sections of Interstate highways, several rows of trees and shrubs may be planted, to reduce noise levels at adjacent property.

2. "To reduce noise from moderate-speed car traffic in urban areas, when tire-roadway interaction is the principal cause of noise, plant 20- to 50-foot-wide belts of trees and shrubs, with the edge of the belt from 20 to 50 feet from the center of the nearest traffic lane. Use shrubs 6 to 8 feet tall next to the traffic lane, with backup rows of trees 15 to 30 feet tall (see Table 5.1–4 for species recommendations).
3. "Trees and shrubs should be planted close to the noise source, as opposed to close to the protected area, for optimum results.
4. "Where possible, use taller varieties of trees which have dense foliage and relatively uniform vertical foliage distribution (or combinations of shorter shrubs and taller trees to give this effect). Where the use of tall trees is restricted, use combinations of shorter shrubs and tall grass, or similar soft ground cover, as opposed to paving, crushed rock or gravel surfaces.
5. "Trees and shrubs should be planted as close together as practical, to form a continuous, dense barrier. The spacing should conform to established local practices for each species.
6. "Where year-round noise screening is desired, evergreens, or deciduous varieties which retain their leaves throughout most of the year, are recommended.
7. "The belt should be approximately twice as long as the distance from the noise source to the receiver and when used as a noise screen parallel to a roadway, should extend equal distances along the roadway on both sides of the protected area."

This concludes the discussion of sound propagation and barriers. The remaining sections of this chapter deal with the three major noise sources: highways, railways and aircraft. Proceed to these sections as directed in Chapter 2.

References Chapter 5 Section 1 Sound Propagation and Barriers

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Chapter 5
Section 2
How to Estimate Highway Noise

Highway traffic, probably the most common and widespread source of noise, is extremely variable—different vehicles traveling at different speeds through continuously changing highway configuraions and surrounding terrains. Obviously, to estimate highway noise, many simplifying assumptions must be made concerning how the noise is generated and how it propagates from the highway to the building site. Even after these assumptions have been applied, the problem of predicting highway noise is still complex.

Researchers have developed predictive models of complex highway traffic systems, but the models are either long and detailed, or rely upon computers for numerical results [1, 2, 3]. For our purposes we would like a method of estimating highway noise that is as simple as possible to use. One of the simplest tools for estimating highway noise is a nomogram developed by Bolt Beranek and Newman, Inc.* [3], which is easy to use and gives results that are conservative (i.e., the predicted levels are higher than would actually occur) in all but a few

* *This work, which was undertaken by Bolt Beranek and Newman, Inc., was sponsored by the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration, and was conducted by the National Cooperative Highway Research Program which is administered by the Transportation Research Board of the National Academy of Sciences-National Research Council.*

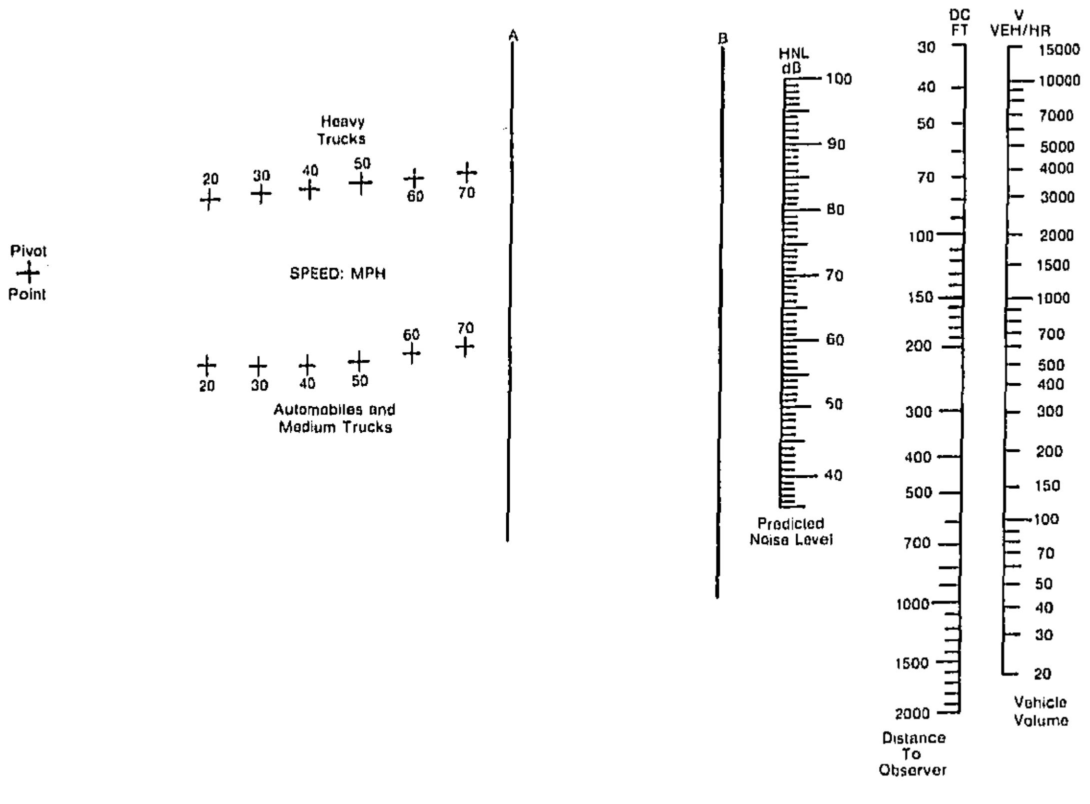


Figure 5.2-1. Highway Noise Prediction Nomogram [3].

very special cases. A nomogram is simply a graph containing three or more scales graduated for different variables so that when a straight line connects the values on any two scales, the related value may be read directly from the third scale at the point intersected by the line (See Figure 5.2–1). The graphical procedures for using this nomogram are given later in this chapter in STEPS H3 to H5.

The analytical model upon which the highway nomogram is based is highly idealized. For example, the model assumes that the different vehicle types can be categorized in three groups based upon the vehicles' noise generating characteristics. The groups —automobiles, medium trucks and heavy trucks [3]—have basic differences both physical and acoustical.

Automobiles are vehicles with two axles and four wheels. This group includes, in addition to passenger cars, light pick-up and panel trucks. Under normal operating conditions, automobile noise is composed primarily of engine-exhaust noise and tire-roadway interaction noise, which are both concentrated near the pavement surface. Hence, the effective source height is taken at this surface.

Medium trucks refer generally to gasoline-powered two-axle, six-wheel vehicles such as local delivery or short-haul trucks. One distinction between this group and heavy trucks, other than just physical size, is that medium trucks do not have a vertical exhaust stack. Like automobiles, medium truck noise is primarily engine-exhaust and tire noise, which again are concentrated near the pavement surface; and although the exhaust outlet may be slightly higher for medium trucks than for automobiles, the effective source location is still assumed to be at the pavement surface [3]. In general, the sound levels generated by medium trucks are similar, but are higher than automobiles for the same operating conditions.

Approximately 80 percent of heavy trucks are diesel-powered vehicles with three or more axles. Long-haul tractor-trailer vehicles constitute the majority of this group which also includes dump trucks, cement mixers, etc. Heavy truck noise is a combination of engine, fan, intake, exhaust, and tire noises. However, extensive measurements of actual traffic conditions have shown that heavy truck noise can be adequately simulated using only the exhaust noise source and neglecting other sources [3]. Based on this, the effective source location is assumed to be 8 feet above the pavement surface.* Thus, the major differences between the sound generated by automobiles and medium trucks, and the sound generated by heavy trucks are the magnitude and spatial location of the sound source.

Geographically, the model assumes that the real highway configuration can be approximated by a single "equivalent" lane that is straight and infinitely long. It also assumes that this equivalent lane lies at grade on a level trerrain, which means that there is no shielding. The vehicles in each group (automobiles, medium trucks and heavy trucks) are considered to be traveling at a constant speed characteristic of the vehicle group. The model further assumes that the noise generated by each of the vehicle groups can be characterized by the traffic volume flow (vehicles/hour) and the average speed (miles/hour) for that group. Analysis of this idealized model shows that the noise of automobiles and medium trucks increases with traffic volume and average speed; and that the noise of heavy trucks under the same conditions (for both the tire and exhaust sources) increases with traffic volume, but decreases slightly with an increase in average speed.

As far as propagation of the noise is concerned, the model assumes that the equivalent lane is an infinitely long line source radiating uniformly into a half-plane (actually as many as three infinitely long, line sources, corresponding to automobiles, medium trucks and heavy trucks). The equivalent level of the noise propagated from the highway decreases by an A-weighted sound level of 4.5 dB for every doubling of distance from the roadway [3]. This value of attenuation has been determined empirically, and includes losses due to air absorption and excess ground attenuation, in addition to the usual cylindrical divergence associated with a line source.

As was previously mentioned, the predicted sound levels are conservatively high in all but a few special cases, such as when the ground plane is very reflective and no shielding is present, or when the highway is highly curved as shown in Figure 5.2–2. In this latter case, the highway differs considerably from the model's assumption of an infinitely long straight highway, and could be treated as two separate highways. Assuming

* *Exhaust stacks for heavy duty trucks are typically about thirteen feet above the roadway. It is presumed that the authors of reference [3], in assuming an eight-foot height for the noise source of heavy trucks, were attempting to account for both tire noise (source near the roadway surface) and exhaust noise (source approximately thirteen feet above the roadway).*

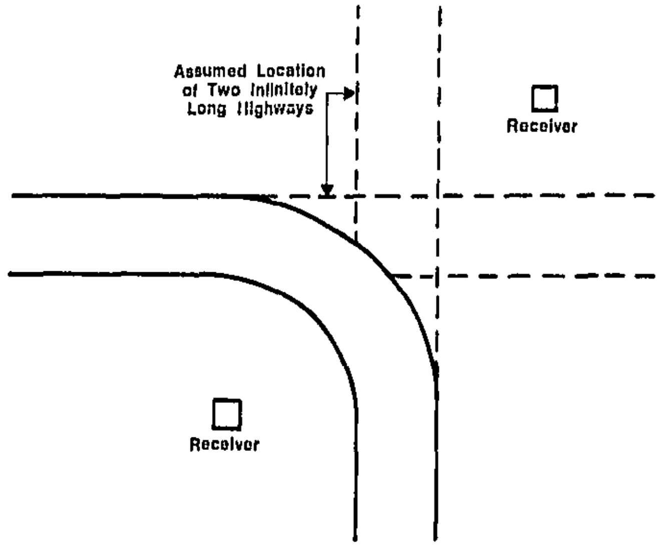


Figure 5.2-2. Example of a Highly Curved Highway.

the traffic volumes and average speeds are the same for both portions of this highway, the sound level at a receiver located inside the curve would be at most 3 dB higher than that predicted by the model. Hence, you can conservatively estimate the sound level at the building site by adding 3 dB to the nomogram value for a single highway. For a receiver located outside the curved position of the highway, the model would overestimate the sound level by an amount dependent on the degree of curvature and the location of the receiver.

For cases other than the special case just discussed, the nomogram will over-predict the actual sound level by a few decibels depending upon the complexity of the real highway and the surrounding terrain relative to the model's assumptions. Over-prediction may be excessive when there is a vertical translation of the roadway to an elevated or depressed position with respect to the surrounding terrain. The effect of this translation, as discussed in Section 1 of this chapter, is to shield the highway from the building site in the same manner as a barrier. Such effects are accounted for by subtracting the attenuation due to the shielding from the predicted level. These shielding adjustments are made in STEPS H9, H10 and H11 of the highway noise prediction method which follows.

Before proceeding, you should briefly study the flow diagram of Figure 5.2-3 which outlines the steps necessary to estimate highway noise. Starting at the top of the chart and moving downward, you first obtain the required traffic, highway and roadway shielding input data (STEPS H1 and H2).

Then using these data, calculate the sound levels of automobiles, medium trucks, and heavy trucks (STEPS H3 to H8); and the corrections for any barriers (STEPS H9 to H13). Following this, determine the total noise level due to this one highway by combining the contributions from the three vehicle groups (STEP H14). If there is more than one highway near your site, repeat the previous steps for each of these highways (STEPS H1 to H14). Finally, combine the sound level contributions from all of the highways to get the total highway noise level at your chosen building location (STEP H15). All steps should be recorded on Highway Worksheets 1 and 2 shown in Figures 5.2-4 and 5.2-5. A detailed example showing these step-by-step calculations is given in Section 5.5.

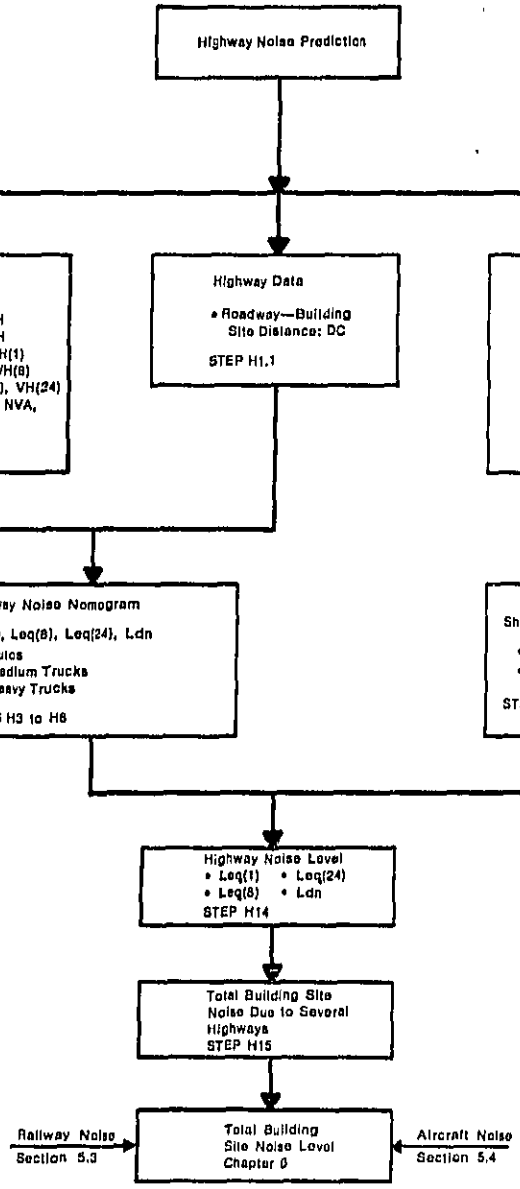


Figure 5.2-3. Highway Noise Prediction Flow Diagram.

Highway Worksheet 1

Building Project ______________________ Highway Number ______________________

Location ______________________ Site point or building room for which sound pressure levels are being estimated ______________

Owner ______________ Designer ______________ Date ______________ Revised ______________

Roadway—Building Site Distance: DC (Feet)

		Autos		Medium Trucks		Heavy Trucks	
Average Vehicle Speed, mph		SA		SM		SH	
Total Number of Vehicles							
a) Leq(1)		VA(1)		VM(1)		VH(1)	
b) Leq(8)		VA(8)		VM(8)		VH(8)	
c) Leq(24)		VA(24)		VM(24)		VH(24)	
d) Ldn		DVA	NVA	DVM	NVM	DVH	NVH
Average Vehicle Volume (veh/hr)		VA		VM	VMC	VH	
Predicted Noise Levels							
a) Leq(1)	Leq(1) No Shielding						
	Total Shielding Correction (Highway Worksheet 2)						
	Leq(1) Corrected for Shielding						
b) Leq(8)	Leq(8) No Shielding						
	Total Shielding Correction (Highway Worksheet 2)						
	Leq(8) Corrected for Shielding						
c) Leq(24)	Leq(24) No Shielding						
	Total Shielding Correction (Highway Worksheet 2)						
	Leq(24) Corrected for Shielding						
d) Ldn	HNL						
	RDN						
	CDN						
	Ldn No Shielding						
	Total Shielding Correction (Highway Worksheet 2)						
	Ldn Corrected for Shielding						
Total Highway Noise							
Building Site Noise Due To Several Highways							

Figure 5.2–4. Highway Worksheet 1.

Highway Worksheet 2

Building Project ______________________

Location ______________________

Owner ______________________

Highway Number ______________________

Site point or building room for which sound pressure levels are being estimated ______________________

Designer ______________________

Date ____________ Revised ____________

Roadway—Building Site Distance: DC (Feet)

Shielding Geometry	Barrier				Elevated Roadway			Depressed Roadway			
	DB	HB	hB	a	DE	HE	a	DD	HD	hD	a

Path Length Difference					
	Autos And Medium Trucks	$A_{a/m}$	$B_{a/m}$	$C_{a/m}$	$L_{a/m}$
	Heavy Trucks	A_h	B_h	C_h	L_h

Correction For "Infinite" Shielding Element	Auto	Medium Truck	Heavy Truck
	CSA/M	CSA/M	CSH

Correction For "Finite" Shielding Element			
	Included Angle Ratio, RA		
	Auto	Medium Truck	Heavy Truck
	CSA/M	CSA/M	CSH

Building Barrier	nr		CSB	
Vegetation	dw		CSV	

Total Shielding Correction	Auto	Medium Truck	Heavy Truck
	CSA/M + CSB + CSV	CSA/M + CSB + CSV	CSH + CSB + CSV

Figure 5.2–5. Highway Worksheet 2.

STEP H1 PHYSICAL SITE DATA

The information that is required on the highway geometry and the building site location can be obtained from local maps as indicated in Chapter 2. The data should be determined for each highway that you have listed on the Preliminary Source Evaluation Worksheet with a *yes* answer in Column 2. The required data are:

1. Nearest perpendicular distance between the center of the roadway and the selected location on the building site, DC, in feet.

   See Figure 5.2-6 for an example of how DC is determined. Record this value on Highway Worksheet 1.

2. Location and geometry of any obstruction that visually shields the highway from the building, in feet.

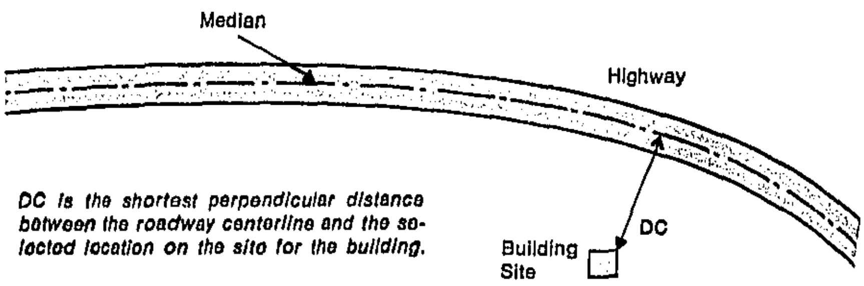
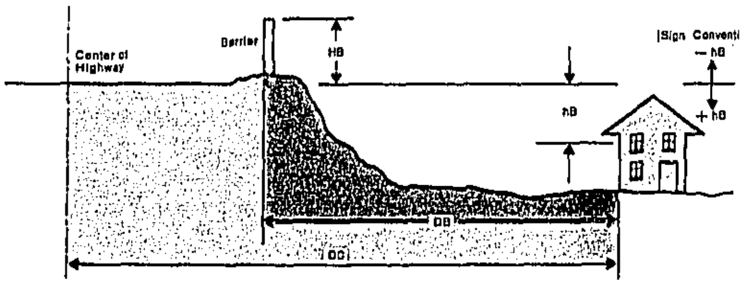
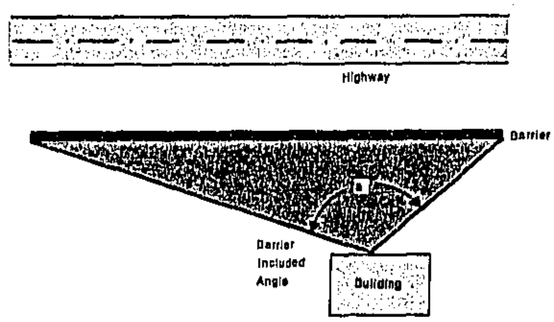


Figure 5.2-6. Determination of Roadway—Building Site Distance, DC.

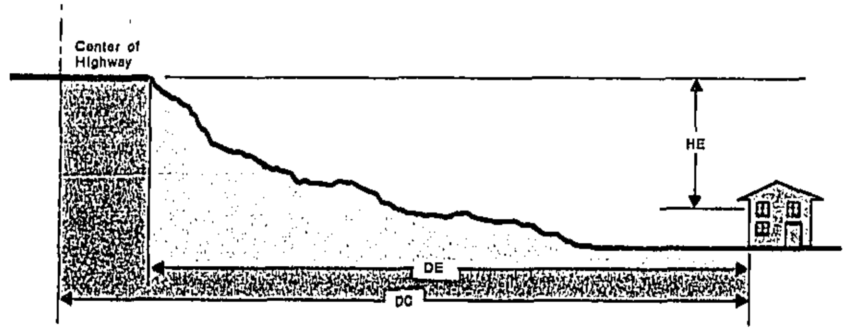


(a) Barrier linear dimensions.
Be sure to note the sign convention for hB; positive below the plane of the roadway and neagtive above.

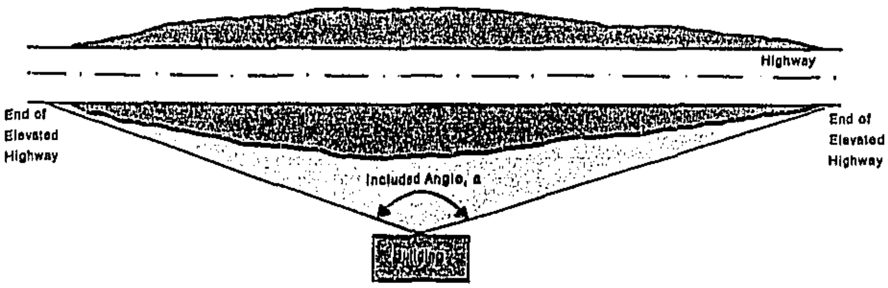


(b) Barrier included angle.

Figure 5.2-7. Highway Barrier Dimensions.

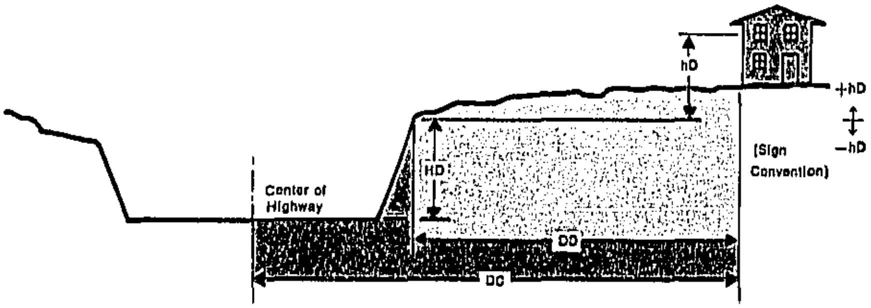


(a) Elevated highway linear dimensions.

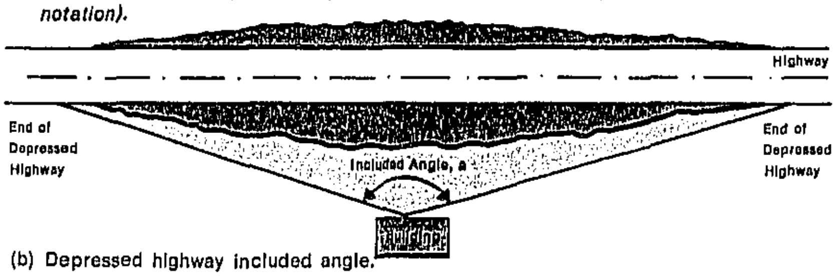


(b) Elevated highway included angle

Figure 5.2-8. Elevated Highway Dimensions.



(a) Depressed highway linear dimensions. *Be sure to note the sign convention for hD; negative below the top of the depression and positive above (different from barrier notation).*



(b) Depressed highway included angle.

Figure 5.2-9. Depressed Highway Dimensions.

Determine if any barriers, elevated roadways and depressed roadways are present and then obtain the appropriate distances as shown in Figures 5.2–7, 5.2–8 and 5.2–9, and listed below. Distances should be determined as accurately as possible. If there is no shielding, omit this part of STEP H3 and all of STEPS H9, H10, and H11.

Barrier: DC, DB, HB, hB, a
Elevated Roadway: DC, DE, HE, a
Depressed Roadway: DC, DD, HD, hD, a

Note that the distances hB and hD can be positive or negative; be sure to record the appropriate sign on Highway Worksheet 2.

3. Presence of any rows of buildings or belts of vegetation that shield the building site from the roadway.

   Refer to the discussion of Section 1 of this chapter to determine if there is any significant shielding due to buildings or belts of vegetation. If there is, gather the appropriate data listed below.

   a) Buildings as Barriers: nr—number of rows of buildings

   b) Vegetation: dw—depth of woods

   Record the value on Highway Worksheet 2.

STEP H2 HIGHWAY TRAFFIC DATA

The information that is required on highway vehicle traffic can be obtained from the agencies listed in Chapter 2. These data should be determined for each highway that you listed on the Preliminary Source Evaluation Worksheet with a *yes* answer in Column 2. The values should be the total for all lanes of the highway and should be based on typical operating conditions. Calculations are based upon existing traffic volumes; but if you anticipate changes, use future traffic volumes. If you are unable to obtain information on medium trucks, neglect them and consider only autos and heavy trucks. The required data to be recorded on Highway Worksheet 1 are:

1. Average vehicle speed in miles per hour: SA-auto; SM-medium truck; SH-heavy truck.

2. Average vehicle traffic volume in vehicles per hour: VA-auto; VM-medium truck; VH-heavy truck.

   The method of calculating the average vehicle traffic volume depends upon the noise criterion, or metric, being used for your proposed building be it Leq(1), Leq(8), Leq(24), or Ldn. Use the appropriate averaging method listed below and obtain any additional data necessary to make the calculations for the metric you are using.

- **Leq(1),** 1-hour energy equivalent sound level

  Determine the total number of vehicles in each group that passes by during the one selected hour of critical building use; VA(1), VM(1), VH(1). Since these values are already on an hourly basis, no averaging is needed. Merely use these traffic volumes directly in the nomogram prediction.

  $$VA=VA(1); \qquad VM=VM(1); \qquad VH=VH(1)$$

- **Leq(8),** 8-hour energy equivalent sound level

  Determine the total number of vehicles in each group that passes by during the eight hours of building use; VA(8), VM(8), VH(8). The average traffic volumes to be used for the nomogram predictions are calculated by dividing the number of passbys in eight hours by 8 to get the average number of vehicles per hour.

  $$VA=\frac{VA(8)}{8}; \qquad VM=\frac{VM(8)}{8}; \qquad VH=\frac{VH(8)}{8}$$

- **Leq(24),** 24-hour energy equivalent sound level

  Determine the total number of vehicles in each group that passes by on a typical day; VA(24), VM(24) VH(24). The average traffic volumes to be used for the nomogram predictions are calculated by dividing the total number of daily passbys by 24 to get the average number of vehicles per hour.

  $$VA=\frac{VA(24)}{24}; \qquad VM=\frac{VM(24)}{24}; \qquad VH=\frac{VH(24)}{24}$$

- **Ldn,** Day-night sound level

  Determine the total number of vehicles in each group that passes by during the "daytime" (7 A.M. to 10 P.M.) and the "nighttime"

(10 P.M. to 7 A.M.); DVA, DVM, DVH and NVA, NVM, NVH, respectively. The average traffic volumes to be used for the nomogram prediction are calculated by dividing the number of "daytime" passbys by 15 to get the average number of vehicles per hour.

$$VA = \frac{DVA}{15}; \quad VM = \frac{DVM}{15};$$

$$VH = \frac{DVH}{15}$$

* * * * *

Now you have the necessary input data for the prediction of highway noise. The complete graphical procedure for using the Highway Noise Nomogram (shown in Figure 5.2-1) is outlined in the following steps. The procedure must be performed three times, once for each vehicle group. Starting with automobiles, the necessary input parameters (for Highway Worksheet 1) are the vehicle speed (SA), vehicle volume (VA) and the roadway-building site distance (DC). Referring to Figure 5.2-1, the steps are:

STEP H3 NOMOGRAM PROCEDURE

Draw a straight line from the left pivot point through the point corresponding to the vehicle speed (the bottom scale for autos and medium trucks and the upper scale for heavy trucks). Extend this line until it intersects with line A.

STEP H4 NOMOGRAM PROCEDURE

Draw another straight line from this point of intersection on line A to the point on the far right scale corresponding to the vehicle traffic volume. This line intersects line B.

STEP H5 NOMOGRAM PROCEDURE

Draw a third straight line from the intersection on line B to the point on the DC scale corresponding to the distance from the selected location on the building site to the center of the roadway. This line intersects the scale marked HNL. The value of HNL at this point of intersection is the predicted noise level if the metric being used to evaluate the building is Leq(1), Leq(8) or Leq(24).

Leq(1) = HNL; Leq(8) = HNL;

Leq(24) = HNL

Record this value on Highway Worksheet 1 and continue the prediction procedures omitting STEP H6. But if the day-night sound level is being used, record HNL in the appropriate space on Highway Worksheet 1 and complete STEP H6.

STEP H6 DAY-NIGHT SOUND LEVEL

Compute the factor CDN, which is a correction for the relative number of "daytime" (7 A.M. to 10 P.M.) and "nighttime" (10 P.M. to 7 A.M.) vehicle passbys. It is determined from the ratio of the "daytime" vehicle traffic volume to the "nighttime" vehicle traffic volume, RDN. (Data on vehicle traffic volumes are from Highway Worksheet 1.)

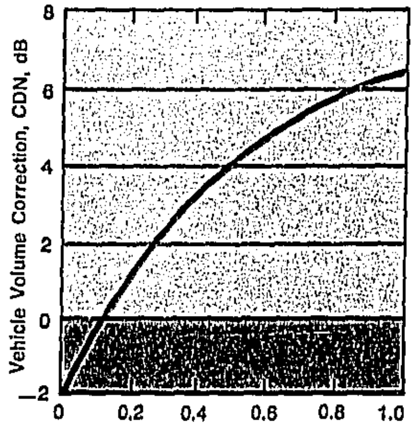


Figure 5.2-10. Vehicle Volume Correction Factor, CDN.

CDN is determined by locating on the horizontal axis of Figure 5.2-10 the value of RDN. Read up until intersecting the curve. The value of CDN can be read off the vertical axis directly left of the intersection. Using this value of CDN and the value of HNL from STEP H5, calculate Ldn from the following equation:

Ldn = HNL + CDN

Record this value on Highway Worksheet 1.

* * * * *

As mentioned previously, medium trucks are noisier than automobiles. If this difference in noise level is taken into account, the same scales that were used on the Highway Noise Nomogram for the automobile noise prediction can also be used to predict medium truck noise. A method of correcting for this difference in noise level is given in STEP H7. After completing STEP H7, proceed to STEP H8 and perform the heavy truck noise prediction.

STEP H7 MEDIUM TRUCKS

To account for the difference in noise level between automobiles and medium trucks, a corrected medium truck volume is used. This corrected vehicle traffic volume, VMC, is equal to the actual volume, VM, multiplied by ten.

$$VMC = 10VM$$

Record this value on Highway Worksheet 1. Now repeat STEPS H3, H4 and H5 (also STEP H6 if Ldn is the metric being used) using the values SM, VMC, and DC. In repeating the nomogram procedure remember to use the lower scale of vehicle speeds for medium trucks.

STEP H8 HEAVY TRUCKS

Heavy truck noise is determined by repeating STEPS H3, H4 and H5 (also STEP H6 if Ldn is the metric being used) using the values SH, VH and DC from Highway Worksheet 1. In repeating the nomogram procedure remember to use the upper scale of vehicle speeds for heavy trucks.

* * * * *

STEPS H1 through H8 assumed that there was no obstruction, or shielding, between the highway and the building site. If there is any shielding due to a barrier, elevated roadway, depressed roadway, rows of buildings or a belt of vegetation, it should be taken into account. This is done in STEPS H9 to H13.

The corrections for shielding due to barriers and elevated or depressed highways are related to the effective sound source heights for the three vehicle groups. The effective sources are assumed to be near the roadway surface for autos and medium trucks, and eight feet above the roadway surface for heavy trucks. Thus, there are two corrections; one for autos and medium trucks, CSA/M, and one for heavy trucks, CSH. These corrections are determined by calculating the path length differences from the equations listed in STEP H9 for the type of shielding that is present. Using these values of L, CSA/M and CSH are determined in STEP H10 for an "infinite" shielding element or in STEP H11 for a finite shielding element.

The shielding corrections for rows of buildings which act as barriers and for vegetation are related to the physical layout of the highway, the site, and building. The correction for the shielding due to rows of buildings which act as barriers, CSB, is computed in STEP H12. The correction for the shielding due to vegetation, CSV, is computed in STEP H13. Note that the attenuation due to rows of buildings which act as barriers, and to vegetation is added to any attenuation due to barriers and elevated or depressed highways. For example, if the A-weighted sound level attenuations of a barrier, two rows of buildings, and 100 feet of dense woods are 5, 6, and 5 dB, respectively, the total A-weighted sound level attenuation is 16 dB.

After these shielding corrections are applied, the individual component sound levels are calculated. Then, these are combined to get the total highway noise in STEP H14.

If there is no shielding present, the noise levels calculated in the previous steps are the values to be used to predict noise levels in your building and on the site. Omit STEPS H9 to H13 and proceed to STEP H14 to get the total noise due to the highway.

STEP H9 PATH LENGTH DIFFERENCE

Compute the path length difference for autos and medium trucks, La/m, and for heavy trucks, Lh, for the type of shielding present. Be sure the obstruction blocks the line-of-sight between the source and receiver, in particular for heavy trucks which have the source located eight feet above the road surface. If the line-of-sight is not blocked, the correction is zero.

1. Barrier:

$$Aa/m = \sqrt{HB^2 + (DC - DB)^2}$$
$$Ah = \sqrt{(HB - 8)^2 + (DC - DB)^2}$$
$$Ba/m = Bh = \sqrt{(HB + hB)^2 + DB^2}$$
$$Ca/m = \sqrt{hB^2 + DC^2}$$
$$Ch = \sqrt{(hB + 8)^2 + DC^2}$$

2. Elevated Highway:

$$Aa/m = [DC - DE]$$
$$Ah = \sqrt{64 + (DC - DE)^2}$$
$$Ba/m = Bh = \sqrt{HE^2 + DE^2}$$
$$Ca/m = \sqrt{HE^2 + DC^2}$$
$$Ch = \sqrt{(HE + 8)^2 + DC^2}$$

3. Depressed Highway:

$$Aa/m = \sqrt{HD^2 + (DC - DD)^2}$$
$$Ah = \sqrt{(HD - 8)^2 + (DC - DD)^2}$$
$$Ba/m = Bh = \sqrt{hD^2 + DD^2}$$
$$Ca/m = \sqrt{(HD + hD)^2 + DC^2}$$
$$Ch = \sqrt{(HD + hD - 8)^2 + DC^2}$$

From these values the path length differences are calculated from the following equations.

$$La/m = Aa/m + Ba/m - Ca/m$$
$$Lh = Ah + Bh - Ch$$

Record these values on Highway Worksheet 2 and proceed to the next step.

STEP H10 SHIELDING CORRECTION—"INFINITELY" LONG BARRIER

Compute the shielding corrections CSA/M and CSH. These values are determined from the path length differences calculated in the previous step [4]. If the path length difference is less than 0.1 ft or is negative, there is no significant shielding and the correction is zero. But if the path length difference is positive and greater than 0.1 ft, the shielding correction is determined by locating on the horizontal axis of Figure 5.2-11 the value of the path length difference. Read up until intersecting the curve. The value of the shielding correction can be read off the vertical axis directly left of the intersection. This procedure is followed using La/m to determine CSA/M and Lh to determine CSH. Record these values on Highway Worksheet 2. If the included angle, a, is less than 170° the shielding element is of "finite" length, and you must proceed to STEP H11. But if the included angle, a, is greater than 170°, no adjustment to the shielding corrections is needed. Omit STEP H11 and continue the design guide analysis.

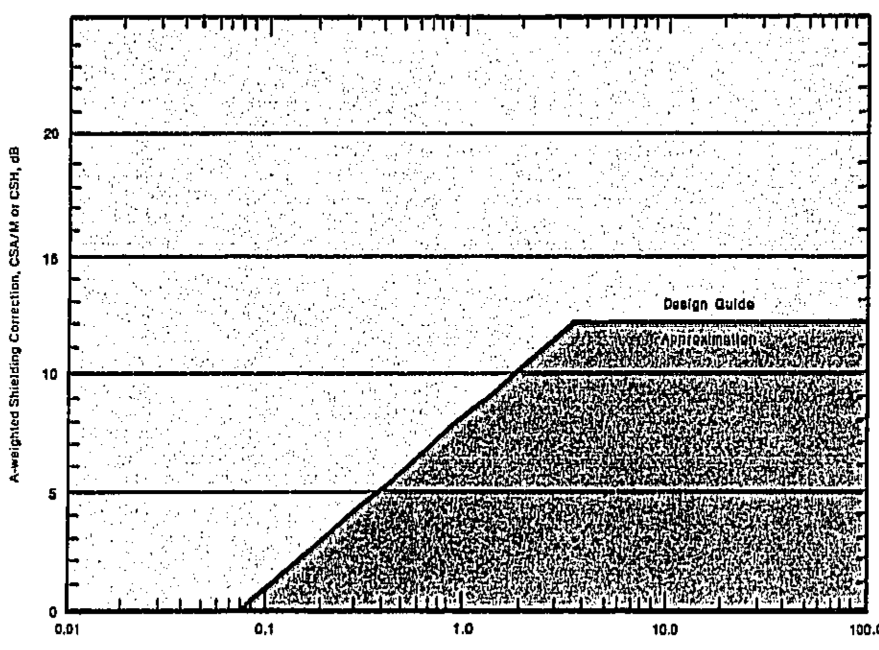


Figure 5.2-11. A-weighted Shielding Correction for Barriers.

STEP H11 SHIELDING CORRECTION— "FINITE" BARRIER

Compute the adjusted values of CSA/M and CSH to account for shielding elements of "finite" length. These adjusted shielding corrections are determined from the factor RA, which is calculated from the included angle, a (in degrees), using the following equation:

$$RA = \frac{a}{180^\circ}$$

Now go to Table 5.2-1 and enter the first column at the value of CSA/M and read across that row to the column corresponding to the value of RA. This is the adjusted value of CSA/M. Repeat this procedure using the value of CSH to get the finite shielding correction for heavy trucks. Record these adjusted shielding corrections on Highway Worksheet 2 and continue the design guide analysis.

Table 5.2-1. Shielding Corrections for a Finite Barrier.

"Infinite" Barrier Shielding Correction CSA/M or CSH	RA = a/180°										
	0	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
1	0	0	0	0	0	0	1	1	1	1	1
2	0	0	0	1	1	1	1	1	2	2	2
3	0	0	0	1	1	1	2	2	2	3	3
4	0	0	1	1	1	2	2	2	3	3	4
5	0	0	1	1	1	2	2	3	3	4	5
6	0	0	1	1	2	2	3	3	4	5	6
7	0	0	1	1	2	2	3	4	4	6	7
8	0	0	1	1	2	2	3	4	5	6	8
9	0	0	1	1	2	3	3	4	5	7	9
10	0	0	1	1	2	3	3	4	6	7	10
11	0	0	1	1	2	3	3	4	6	8	11
12	0	0	1	1	2	3	4	5	6	8	12

STEP H12 SHIELDING CORRECTION—BUILDINGS ACTING AS BARRIERS

Calculate the correction, CSB, for rows of buildings which shield the highway from your building site. This correction depends on the number of rows of intervening buildings, nr, and is determined from Table 5.2-2. Record this correction on Highway Worksheet 2 and continue the design guide analysis.

Table 5.2-2. Shielding Corrections for Buildings Acting as Barriers [4].

Number of Rows	Shielding Correction, CSB
1	4.5
2	6.0
3	7.5
4	9.0
5 or more	10.0

STEP H13 SHIELDING CORRECTION—VEGETATION

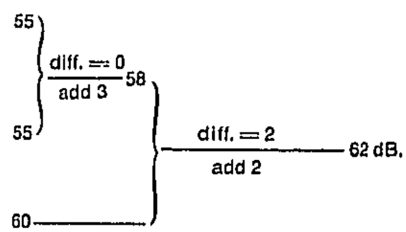
Calculate the correction, CSV, for a belt of vegetation of depth dw, which shields the highway from your building. This correction is simply an A-weighted sound level attenuation of 5 dB for the first 100 feet of woods and 10 dB for woods over 200 feet in depth. Interpolation between these values is left to your discretion. Record the correction on Highway Worksheet 2 and continue the design guide analysis.

STEP H14 TOTAL HIGHWAY NOISE

Compute the total noise at the building site due to the highway. First, sum the shielding corrections on highway Worksheet 2 for each vehicle group and record these values on Highway Worksheet 1. Subtract these total shielding corrections from the unshielded noise levels to get the individual components at the building site. Since these levels are logarithmic in nature, they cannot be simply added together or averaged to get the total noise level. Instead, they are combined, two values at a time, with the use of Table 5.2-3. Starting with the auto and medium truck noise levels, subtract one from the other to get the difference. With this value go to Table 5.2-3 and determine the level adjustment which is to be added to the larger of the two original noise levels. Now repeat this procedure with this adjusted level and the noise level for heavy trucks. The result of this combination is the total noise at the building site due to this (one) highway. For example, if the A-weighted sound levels for autos, medium trucks and heavy trucks are 55, 55, and 60 dB respectively, the total noise due to this highway is,

Table 5.2-3. Level Adjustment for Summing Noise Levels.

Difference Between Two Noise Levels, dB	Level Adjustment (To Be Added To The Larger of The Two Values)
10 or more	0
4-9	1
2-3	2
0-1	3



Record the total noise level on Highway Worksheet 1.

• • • • •

This completes the prediction of highway noise. These procedures should be repeated for each highway that is listed on the Preliminary Source Evaluation Worksheet with a *yes* answer in Column 2. The total noise at the building site due to all highways is the logarithmic summation of the noise contributions from each highway. This computation is performed in STEP H15.

STEP H15 TOTAL NOISE LEVEL DUE TO SEVERAL HIGHWAYS

The total noise level at the building site you have selected is determined by summing the components from all highways affecting your site. Summing is done two values at a time, by the same method as used in STEP H14. (Refer to this step for the procedure of summing noise levels.)

Record this value on Highway Worksheet 1.

* * * * *

Now proceed to Sections 5.3 and 5.4 to predict the noise levels due to railways and aircraft. If these two transportation system noise sources do not affect your building site, proceed directly to Chapter 6.

References Chapter 5 Section 2 Highway Noise

[1] Gordon, C. G., Galloway, W. J., Kugler, B. A., and Nelson, D. L., Highway noise—a design guide for highway engineers, NCHRP Report 117 (Bolt Beranek and Newman Inc., Los Angeles, California 1971). Available from the Highway Research Board, 2101 Constitution Ave., Washington, D.C. 20418.

[2] Wesler, J. W., Manual for highway noise prediction, U.S. Department of Transportation Report No. DOT-TSC-FHWA-72-1 (Department of Transportation, Transportation Systems Center, Cambridge, Mass., March 1972). Available from the National Technical Information Service, Springfield, Virginia, Accession Nos. PB 226-086, PB 226-087 and PB 226-088.

[3] Kugler, B. A., Commins, D. E., and Galloway, W. J., Establishment of standards for highway noise levels: Volume 1—Design guide for highway noise prediction and control, BBN Report No. 2739 (Bolt Beranek and Newman Inc., Los Angeles, California, February 1974).

[4] Kugler, B. A., and Piersol, A. G., Highway noise: a field evaluation of traffic noise reduction measures, NCHRP Report 144 (Bolt Beranek and Newman Inc., Canoga Park, California, 1973). Available from the Highway Research Board, 2101 Constitution Ave., Washington, D.C. 20418.

Chapter 5 Section 3 How to Estimate Railway Passby Noise

Railroad operations can be classified as either line operations or yard operations. Line operations are movements of trains of various types over main line and local track; yard operations are the various activities concentrated in a railway terminal. Railroad yard operations generate noise through the disassembling and recoupling of cars to form new trains, and the maintenance and repair of cars and locomotives. Although a limited amount of research has been devoted to the modeling of noise phenomena in railroad yards, the models are complex since there are so many different types of sound sources operating for various lengths of time on an intermittent basis [1, 2], thus making it very difficult to predict the noise that is generated. For this reason railroad yard noise will not be treated in this design guide.

Railway line operations are a much more common source of railroad noise than yard operations. The noise generated by train passbys is a function of the type of vehicle in use, how it is operated, and the configuration of the trackbed relative to the surrounding terrain. Although there has been a fair amount of research devoted to the modeling of railway line passbys [1–5], there is still much to be learned. Unlike highways, which have been the subject of a great deal more research than railways, no simple nomogram method for predicting passby noise has been developed.

The analytical model * which is used in this design guide for predicting railway noise considers four general types of vehicles as noise sources: locomotives, freight cars, passenger coaches, and rapid transit vehicles. These vehicles, either in combination with one of the other types or by themselves, form three general train categories. These are freight trains, conventional passenger trains, and rapid transit trains. A freight train consists of one or more locomotives, usually diesel-electric, pulling a combination of various types of freight cars. A conventional passenger train is similar to a freight train in that it consists of one or more locomotives pulling several coaches, but one important difference is that the loco-

** The railway noise model is based on work performed by Wyle Laboratories, El Segundo, California, under the sponsorship of the Association of American Railroads, Washington, D.C. [1]. The design guide's technique for predicting the generated noise levels is modified slightly to include more recently published data and to simplify the necessary calculations.*

motive may either be diesel-electric or all electric.* The third type, rapid transit trains, differs from the other two types in that there is not a centralized source of propulsion pulling a series of cars, but rather electric motors on the axles of each car. There is a wide variety of different types of vehicles which can be classified as rapid transit trains. As a result, some of the newer vehicles may be quieter than predicted by the methods of this design guide. Also, the prediction procedures are not applicable to underground subway operations or "classic" street cars.

A diesel-electric locomotive utilizes a diesel engine driving an electrical alternator or generator which in turn drives electric traction motors on the wheels. An all-electric locomotive, on the other hand, obtains its electrical power from an external source, normally an overhead line or third rail, to drive its traction motors. The vast majority of trains in the United States are hauled by diesel-electric locomotives—as of 1971, 99% of the 27,000 locomotives in service were diesel-electric, with most of the remainder being all-electric [6].

For noise propagation, the model assumes locomotive is a combination of sounds radiated from the exhaust outlet, the engine casing, the cooling fans, the transmission, the electrical equipment, and the interaction of the wheels and rails—the predominant source of noise is the exhaust outlet. Hence, all-electric locomotives, which have no diesel engine and thus no exhaust, are generally quieter than diesel-electric locomotives.

Having no propulsion system, freight cars and passenger coaches generate noise mainly by the rolling of the wheels on the rails. The magnitude of the noise depends heavily on the condition of the wheels and track, and on the type of vehicle suspension. Modern passenger coaches with auxiliary hydraulic suspension systems in addition to normal springs can be about 10 dB quieter than older passenger coaches or freight cars which have only springs.

The noise of rapid transit trains, even though there are electric motors on each axle that are sources of noise, is also predominantly generated by the interaction of the wheels upon the rails. In fact, because rapid transit vehicles are usually newer and have better suspension systems, they are generally quieter than freight cars or passenger coaches.

Geographically, the predictive model assumes that the real railway configuration can be approximated by a single "equivalent" track that is straight and infinitely long. It also assumes that this "equivalent" track lies at grade on a level terrain, which means that there is no shielding. The model further assumes that the trains that use this track can be grouped into one of the three general categories (freight, conventional passenger, or rapid transit) and that each of these categories can be characterized by an average speed, an average train length, and an average number of passbys for normal operating conditions.

Freight train noise is analyzed by considering two distinct sources: the diesel-electric locomotive and the freight cars; but conventional passenger trains and rapid transit trains are considered to generate noise primarily through wheel-rail interaction. This means that for conventional passenger trains the locomotive is assumed to be all-electric. Hence, if the conventional passenger train locomotives are diesel-electric a locomotive noise component must be added.

For noise propagation, the model assumes that diesel-electric locomotive equivalent sound level decreases by an A-weighted value of 5.3 dB for every doubling of distance from the railway. The equivalent sound level from freight cars, passenger coaches, and rapid transit vehicles is assumed to decrease by an A-weighted sound level difference of 6.2 dB for every doubling of distance from the railway. These two values of attenuation are applicable only for distances greater than 150 feet from the railway, but it is not anticipated that your building or site would be 150 feet or closer to a railway. The values were determined empirically and include corrections for attenuation due to spreading of the sound waves (divergence), increased duration of the noise at points farther away from the railway, air absorption, and excess ground attenuation [1].

As mentioned previously, the model assumes that the railway lies at grade on a level terrain. If the railway is either elevated or depressed relative to the surrounding terrain, the effect may be to shield the railway from the building site in the same manner as a barrier. Such effects are taken into account by substracting the attenuation due to the shielding from the predicted level. These shielding adjustments are made in STEPS R11, R12 and R13.

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* *There are also gas turbine locomotives, but these are few in number and will not be considered herein.*

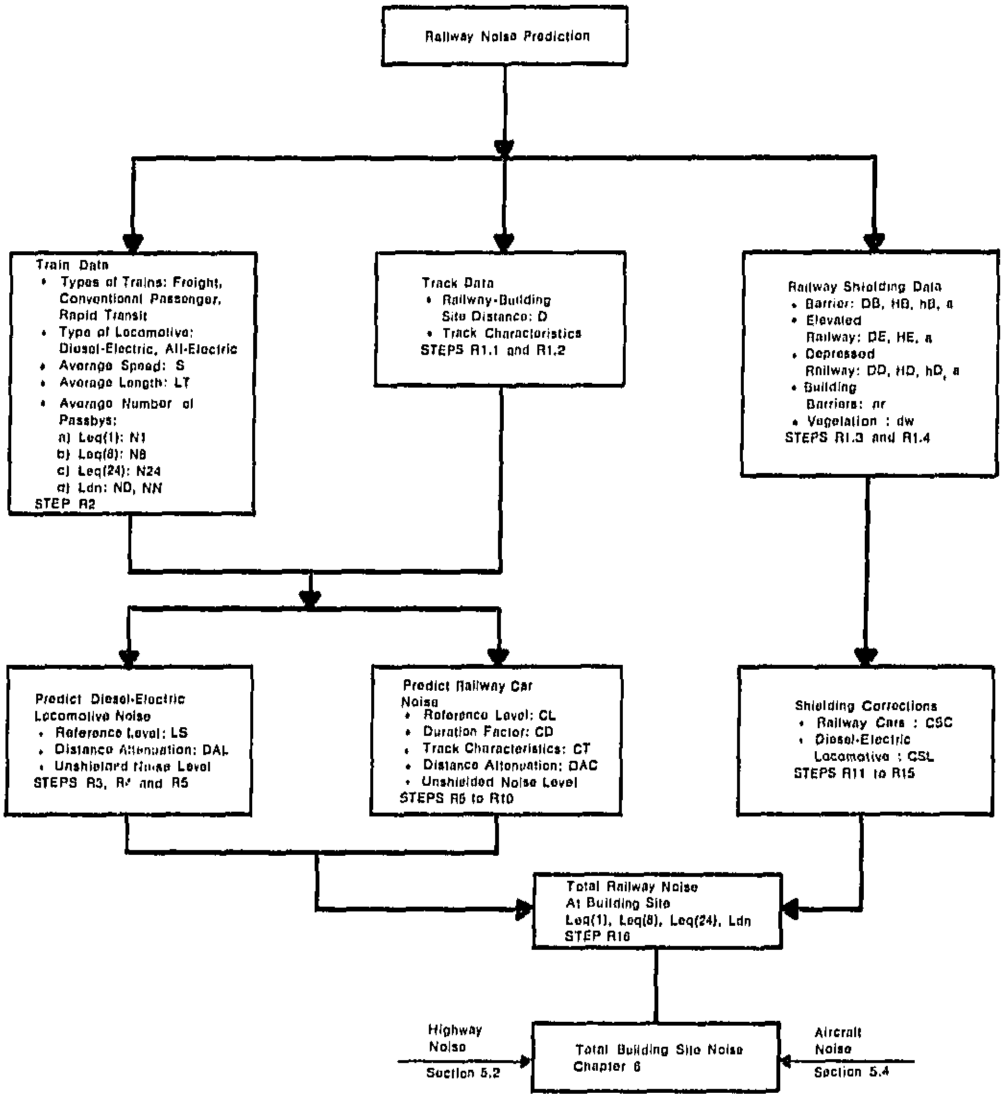


Figure 5.3-1. Railway Noise Prediction Flow Diagram.

Railway Worksheet 1

Building Project ____________ Railway Number ____________

Location ____________ Site point or building room for which sound pressure levels are being estimated ____________

Owner ____________ Designer ____________ Date ____________ Revised ____________

Railway—Building Site Distance: D (Feet) ____________

	Freight Trains		Conventional Passenger Trains		Rapid Transit Trains	
Does this type of train use the track being analyzed?						
Diesel-Electric or All-Electric Locomotive		NL		NL		
Average Train Speed, S, mph						
Average number of cars, nc						
Average train length, LT, feet						
Average Number of Passbys						
a) Leq(1) : N1						
b) Leq(8) : N8						
c) Leq(24) : N24						
d) Ldn	ND	NN	ND	NN	ND	NN
Diesel-Electric Locomotive						
Reference Level, LS						
Distance Attenuation, DAL						
Railway Cars						
Reference Level, CL						
Duration Factor, CD						
Track Characteristics, CT						
Distance Attenuation, DAC						

Predicted Noise Levels		Diesel-Electric Locomotive	Railway Cars	Diesel-Electric Locomotive	Railway Cars	Railway Cars
a) Leq(1)	CN1					
	C1					
	Leq(1) No Shielding					
	Total Shielding Correction (Railway Worksheet 2)					
	Leq(1) Corrected for Shielding					
b) Leq(8)	CN8					
	C8					
	Leq(8) No Shielding					
	Total Shielding Correction (Railway Worksheet 2)					
	Leq(8) Corrected for Shielding					
c) Leq(24)	CN24					
	C24					
	Leq(24) No Shielding					
	Total Shielding Correction (Railway Worksheet 2)					
	Leq(24) Corrected for Shielding					
d) Ldn	CN					
	CDN					
	Ldn No Shielding					
	Total Shielding Correction (Railway Worksheet 2)					
	Ldn Corrected for Shielding					
Total Railway Noise						

Figure 5.3-2. Railway Worksheet 1

Railway Worksheet 2

Building Project ____________	Railway Number ____________
	Site point or building room for which sound pressure levels are being estimated ____________
Location ____________	Designer ____________
Owner ____________	Date ____________ Revised ____________

Railway--Building Site Distance: D (Feet) ____________

	Barrier				Elevated Railway			Depressed Railway			
Shielding Geometry	DB	HB	hB	a	DE	HE	a	DD	HD	hD	a

Path Length Difference					
	Railway Cars	Ac	Bc	Cc	Lc
	Diesel-Electric Locomotive	Al	Bl	Cl	Ll

Correction For "Infinite" Shielding Element	Railway Cars	Diesel-Electric Loc.
	CSC	CSL

Correction For "Finite" Shielding Element		
	Included Angle Ratio, RA	
	Railway Cars	Diesel-Electric Loc.
	CSC	CSL

Building Barrier	nr		CSB	
Vegetation	dw		CSV	

Total Shielding Correction	Railway Cars	Diesel-Electric Loc.
	CSC + CSB + CSV	CSL + CSB + CSV

Track Characteristics						
a		b	c	d		
				Bridgework		
Welded Track	Jointed Track	Presence of Switching Frog or Grade Crossing	Radius of Tight Curve (< 900 Feet) in Feet	Concrete Structure	Steel Girder with Concrete or Open Tie Deck	Steel Girder with Steel Plate Deck

Figure 5.3-3. Railway Worksheet 2.

Before proceeding, you should briefly study the flow diagram of Figure 5.3–1 which outlines the steps necessary to estimate railway noise. Starting at the top of the chart and moving downward, you will first obtain the required train, track and railway shielding input data (STEPS R1 and R2). Then using these data, you will calculate the sound levels corresponding to the diesel-electric locomotive and railway car components of the three types of trains affecting your site (STEPS R3 to R10). Then you will make shielding corrections (R11 to R15) for any barriers. Following this you will determine the total noise level due to this railway by combining the contributions from its various components (STEP R16). All steps should be recorded on Railway Worksheets 1 and 2 shown in Figures 5.3–2 and 5.3–3. A detailed example showing the step-by-step calculations is given in Section 5.5.

Railway Noise Prediction Method

STEP R1 *PHYSICAL SITE AND TRACK DATA*

Information on railway geometry and track characteristics can usually be obtained from area maps and the appropriate department of the railway company as discussed in Chapter 2. The data should be obtained for each railway that is listed on the Preliminary Source Evaluation Worksheet with a *yes* answer in Column 2. The required data are:

1. Nearest perpendicular distance between the centerline of the railway and the point you have chosen for analysis on the building site, D, in feet.

   See Figure 5.3–4 for an example of how D is determined, and record this value on Railway Worksheets 1 and 2.

2. The physical characteristics of the track:
   a. Type of track: welded or jointed
   b. Presence of switches or grade crossing
   c. Radius of tight (less than 900 feet) curve in feet
   d. Presence of a bridge
      - concrete structure
      - steel girder with either concrete or open tie deck
      - steel girder with steel plate deck

   A switch, grade crossing, tight radius curve, or bridge should only be considered when it is located within a distance of 2D on either side of the point of intersection of the railway with the nearest perpendicular distance. See Figure 5.3–4 for an illustration of this distance requirement. Record this information on Railway Worksheet 2.

3. Location and geometry of any obstruction that visually shields the railway from the building, in feet

   Determine if any barriers, elevated railways, or depressed railways are present, and then obtain the appropriate distances as shown on Figures 5.3–5, 5.3–6 and 5.3–7 and listed below. Distances should be determined as accurately as possible. If there is no shielding, omit this part of STEP R1 and all of STEPS R11, R12 and R13.

   Barrier: D, DB, HB, hB, a
   Elevated Railway: D, DE, HE, a
   Depressed Railway: D, DD, HD, hD, a

   Note that the distances hB and hD can be positive or negative; be sure to record the appropriate sign on Railway Worksheet 2.

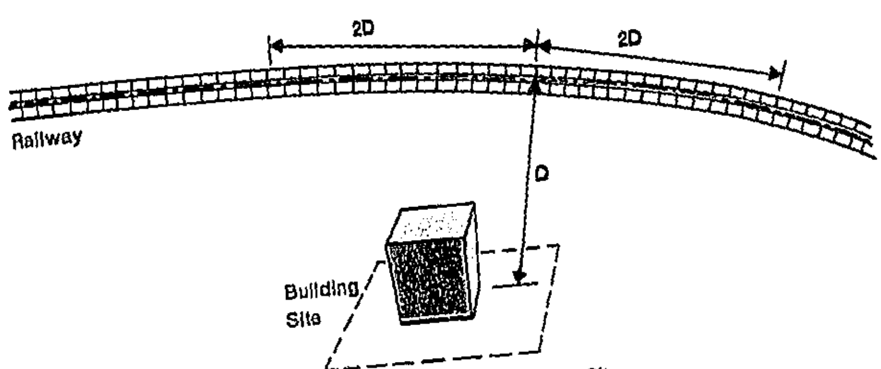


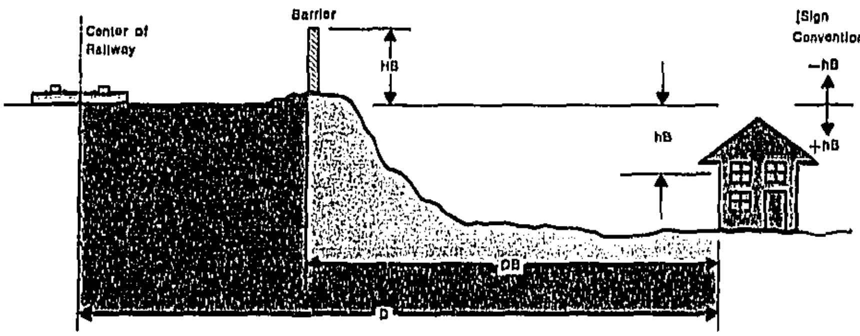
Figure 5.3–4. Railway-Building Site Distance, D.

4. Presence of any rows of buildings or belts of vegetation that shield your building site from the railway

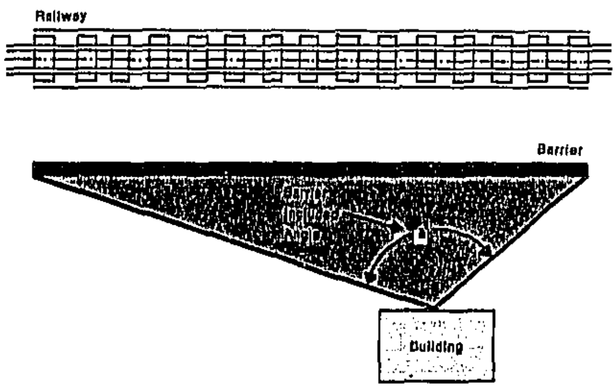
Use the criteria discussed in Section 5.1 to determine if there is any significant shielding due to buildings or belts of vegetation. If there is, gather the data listed below.

a) Buildings as Barriers: nr—number of rows of buildings
b) Vegetation: dw—depth of woods

Record these values on Railway Worksheet 2.

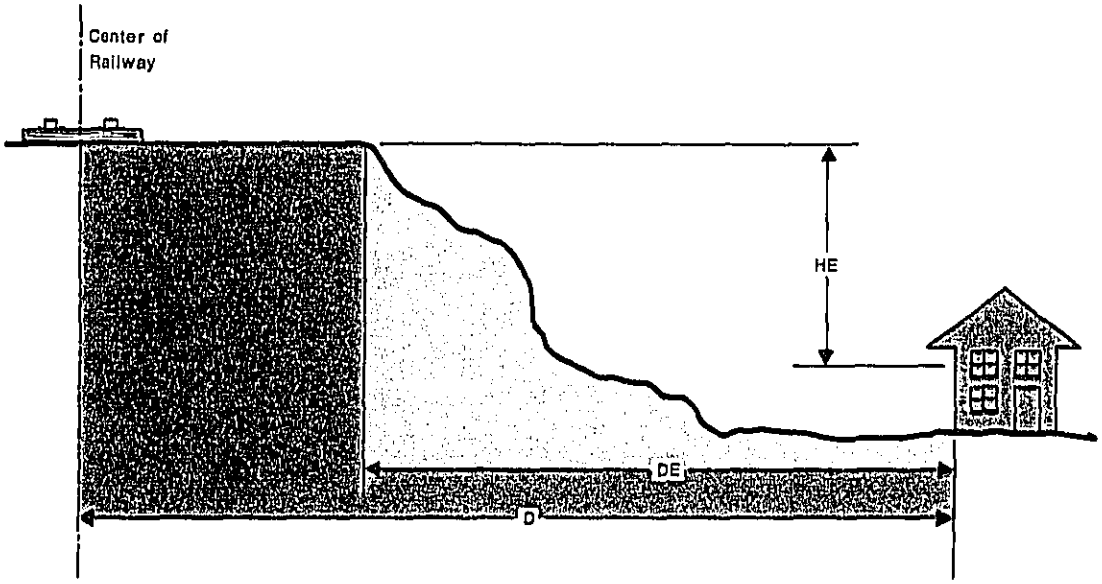


(a) Barrier linear dimensions. *Be sure to note the sign convention for hB; positive below the plane of the railway and negative above.*

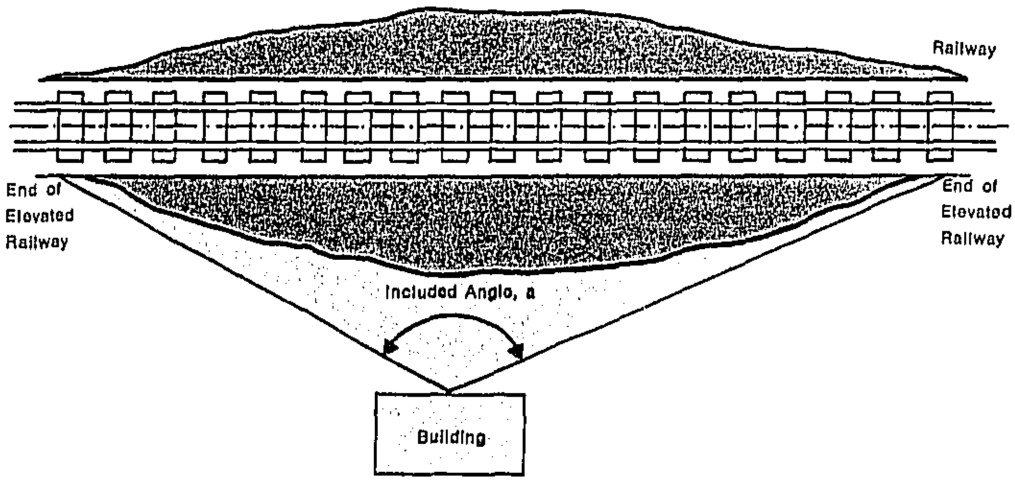


(b) Barrier included angle.

Figure 5.3-5. Dimensions for Shielding by a Railway Barrier.

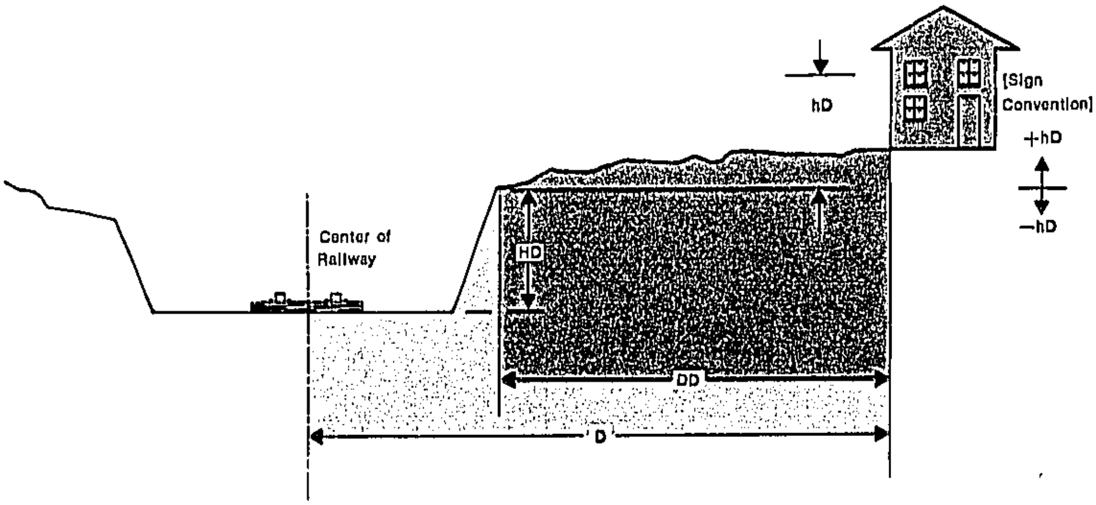


(a) Elevated railway linear dimensions.

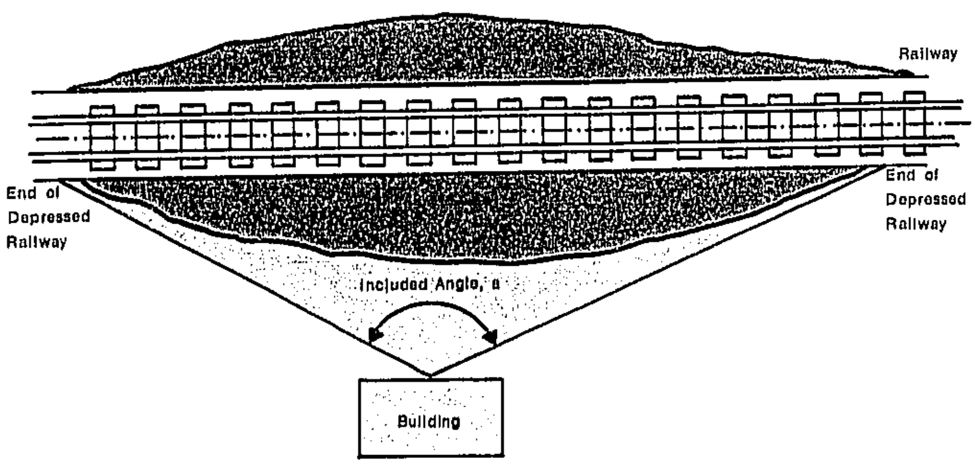


(b) Elevated railway included angle.

Figure 5.3–6. Dimensions for Shielding By an Elevated Railway.



(a) Depressed railway linear dimensions. *Be sure to note the sign convention for hD; negative below the top of the depression and positive above—different from barrier notation.*



(b) Depressed railway includeu angle.

Figure 5.3-7. Dimensions for Shielding By a Depressed Railway.

STEP R2 TRAIN DATA

The information that is required on trains can be obtained from the agencies listed in Chapter 2. These data should be gathered for each railway listed on the Preliminary Source Evaluation Worksheet with a *yes* answer in Column 2. The values should be the average for all tracks and should be based on typical operating conditions. The required data to be recorded on Railway Worksheet 1 are:

1. Types of trains which normally use the track.

   If there are no freight trains, or no conventional passenger trains, or no rapid transit trains write "NONE" in the appropriate space on Railway Worksheet 1 for that train type.
2. Type of locomotive which normally is used to pull the train: diesel-electric or all-electric. This information on locomotions is only needed for freight trains or conventional passenger trains. If this information is not readily available, assume the locomotive to be diesel-electric since this is the predominant type, and the worst case acoustically. Also determine the average number of diesel-electric locomotives, NL, used to pull the train.
3. Average train speed, S, in miles per hour for each type of train.
4. Average train length, LT, in feet for each type of train.

   If the average length is not available, determine the average number of cars, nc, in the train. The length is then obtained by multiplying nc by 55 feet for freight cars and by 75 feet for passenger coaches and rapid transit vehicles [7].
5. Average number of passbys for each type of train.

   The time period for which the typical number of operations is determined depends upon the metric being used for the noise criterion for your proposed building: Leq(1), Leq(8), Leq (24), or Ldn. Obtain only the data required to calculate the metric you are using.

   - **Leq(1)**

     Determine the average number of passbys during the one selected hour of critical building (or outdoor activity area) use, N1.

   - **Leq(8)**

     Determine the average number of passbys during the eight hours of building use, N8.

   - **Leq(24)**

     Determine the average number of passbys during a typical twenty-four hour day, N24.

   - **Ldn**

     Determine the number of passbys during the "daytime" (7 A.M. to 10 P.M. and the "night time" (10 P.M. to 7 A.M.), ND and NN, respectively.

. . . . .

Now you have the necessary input data for the prediction of railway noise. This prediction, outlined in the following steps, consists of determining various factors which are combined to give the estimated noise level. The factors are based on the railway model discussed previously and are normalized to a reference distance of one-hundred feet. Noise levels for the idealized model are then corrected to account for actual conditions. Computations are simplified as much as possible by graphs, charts, and tables.

The remainder of this section is divided into four separate subsections. Subsection A contains the directions for estimating the unshielded noise level of freight trains, conventional passenger trains and rapid transit trains. Subsection B contains the predictive steps for calculating diesel-electric locomotive noise and railway car noise. Shielding adjustments are made in subsection C; and in subsection D, separate noise contributions are combined to get the total railway noise.

Your approach should be to use Subsection A to determine which steps of the noise production computations you must perform. Estimate the unshielded noise level for diesel-electric locomotives and cars in B. Then in C, estimate the shielding corrections, if any, and finally, in D combine the noise levels generated by each type of train to get the total railway noise at your building site. Record the calculated values on Railway Worksheets 1 and 2 as directed.

A. Steps for Predicting Railway Noise

Freight Trains

Freight train noise has two distinct components: diesel-electric locomotive noise and freight car noise. These two components must be treated separately. Follow STEPS R3, R4 and R5 to get the locomotive component, and STEPS R6 through R10 to get the car component. Use the appropriate input data from Railway Worksheet 1 for freight trains.

Conventional Passenger Trains

Conventional passenger train noise depends upon the type of locomotive. If it is all-electric, treat the locomotive as another passenger coach and perform STEP R7 through R10.

If diesel-electric locomotives are the predominant type, a locomotive component must be included. Perform STEPS R3, R4 and R5 to get the locomotive component, and STEPS R6 through R10 to get the car component. Use the appropriate input data from Railway Worksheet 1.

Rapid Transit Trains

Rapid transit train noise is predominantly wheel-rail noise, with no locomotive component. Perform STEPS R6 through R10 using appropriate input data from Railway Worksheet 1.

B. Noise Prediction Calculations

STEP R3 DIESEL-ELECTRIC LOCOMOTIVES—REFERENCE LEVEL

Compute the factor LS for the diesel-electric locomotives at the reference distance of 100 feet from the centerline of the railway. LS is determined by locating on the horizontal axis of Figure 5.3-8, the speed, S, for this type of train. Read up until intersecting the curve. The value of LS can be read off the vertical axis directly left of the intersection.

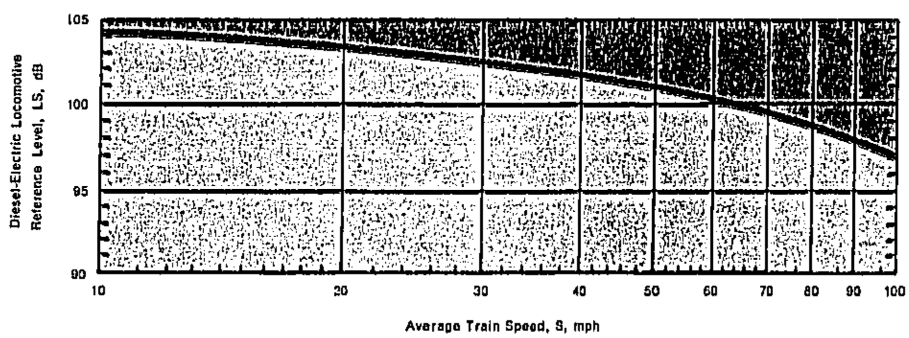


Figure 5.3-8. Diesel-Electric Locomotive Reference Level, LS, at 100 feet [1].

STEP R4 DIESEL-ELECTRIC LOCOMOTIVES—DISTANCE ATTENUATION

Compute the distance attenuation factor, DAL for diesel-electric locomotive noise.

DAL is determined by locating on the horizontal axis of Figure 5.3-9 the distance, D. Read up until intersecting the curve for the locomotive correction. The value of DAL can be read off the vertical axis directly left of the intersection.

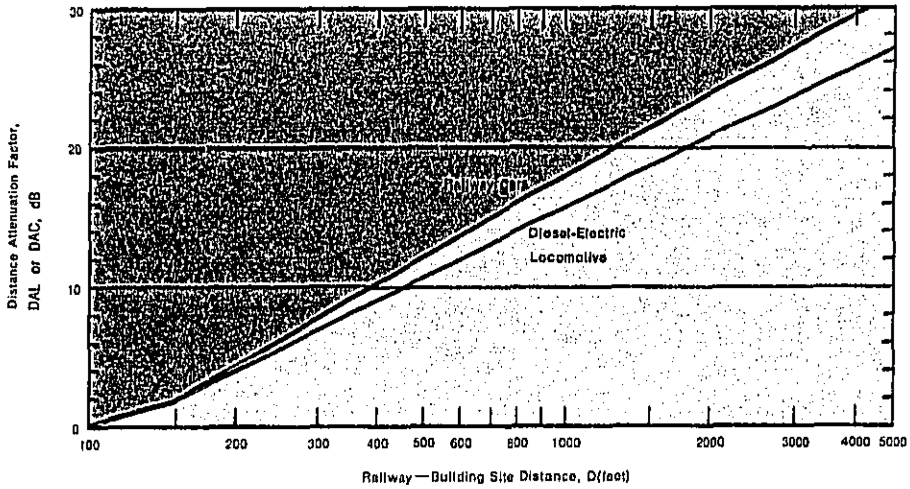


Figure 5.3-9. Railway Noise Attenuation With Distance [1].

STEP R5 DIESEL-ELECTRIC LOCOMOTIVES—UNSHIELDED NOISE LEVEL

Perform the calculations appropriate for the noise criterion, or metric, for your proposed building. Record all values on Railway Worksheet 1.

Leq(1)

Compute C1, which is a correction for the number of passbys during the selected hour of critical building use. C1 is determined from the total number of passbys, CN1, defined as,

$$CN1 = N1 \times NL,$$

where N1 is the average number of passbys for this type of train during the selected hour, and NL is the average number of diesel-electric locomotives pulling the train. On the horizontal axis of Figure 5.3-10 locate the value of CN1 for this type of train. Read up until intersecting the curve. Read the value of C1 from the vertical axis directly left of the intersection. Using this value and the values of LS and DAL, calculate Leq(1) from the following equation:

$$Leq(1) = LS + C1 - DAL - 36.$$

Leq(8)

Compute C8, which is a correction for the number of passbys during the eight hours of building use. It is determined from the total number of passbys, CN8, defined as,

$$CN8 = N8 \times NL,$$

where N8 is the average number of passbys by this type of train during the eight hours, and NL is the average number of diesel-electric locomotives pulling the train. Locate on the horizontal axis of Figure 5.3-10, the value of CN8 for this type of train. Read up until intersecting the curve. Read the value of C8 from the vertical axis directly left of the intersection. Using this value and the values of LS and DAL, calculate Leq(8) from the following equation:

$$Leq(8) = LS + C8 - DAL - 45.$$

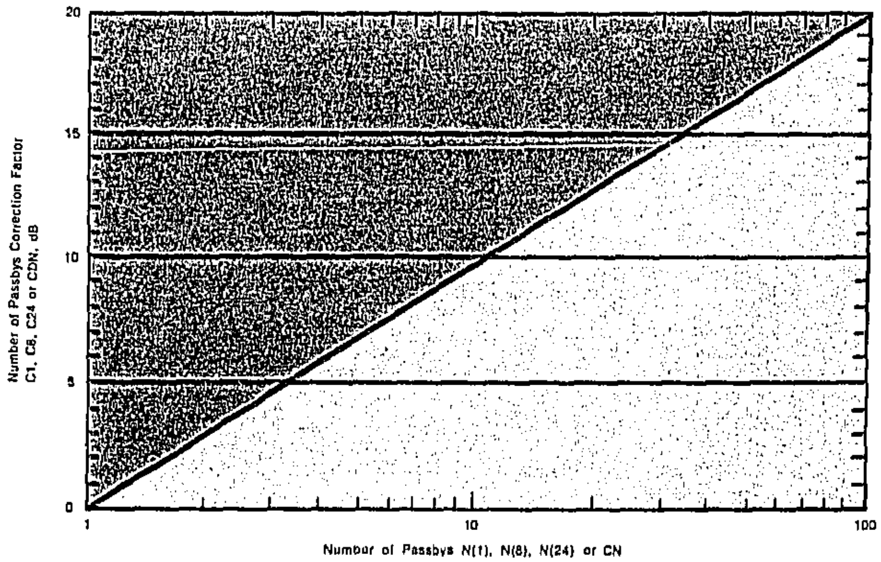


Figure 5.3–10. Correction for the Number of Passbys.

Leq(24)

Compute C24, which is a correction for the number of passbys during a twenty-four hour day. It is determined from the total number of passbys, CN24, defined as,

$$CN24 = N24 \times NL,$$

where N24 is the average number of passbys by this type of train during the twenty-four hours, and NL is the average number of diesel-electric locomotives pulling the train. Locate on the horizontal axis of Figure 5.3–10 the value of CN24 for this type of train. Read up until intersecting the curve. Read the value of C24 from the vertical axis directly left of the intersection. Using this value and the values of LS and DAL, calculate Leq(24) from the following equation:

$$Leq(24) = LS + C24 - DAL - 49.$$

Ldn

Compute CDN, which is a correction for the number of "daytime" and "nighttime" passbys. It is determined from the corrected number of passbys, CN, defined as

$$CN = (ND + 6NN)\,NL$$

where ND is the number of "daytime", and NN is the number of "nighttime" passbys for this type of train, and NL is the average number of diesel-electric locomotives pulling the train. Locate on the horizontal axis of Figure 5.3–10 the value of CN. Read up until intersecting the curve. Read the value of CDN from the vertical axis directly left of the intersection. Using this value and the values of LS and DAL, calculate Ldn from the following equation:

$$Ldn = LS + CDN - DAL - 49.$$

STEP R6 RAILWAY CARS—REFERENCE LEVEL

Compute the factor CL at the reference distance of 100 feet from the centerline of the railway. CL is determined by locating on the horizontal axis of Figure 5.3–11 the speed, S, for this type of train. Read up until intersecting the appropriate curve for this type of railway car. The value of CL can be read off the vertical axis directly left of the intersection.

STEP R7 RAILWAY CARS—PASSBY DURATION

Compute the passby duration factor CD. CD is determined by locating on the horizontal axis of Figure 5.3–12 the train length, LT, for this type of train. Read up until intersecting the curve corresponding to the speed, S, for this train category. The value of CD can be read off the vertical axis directly left of the intersection.

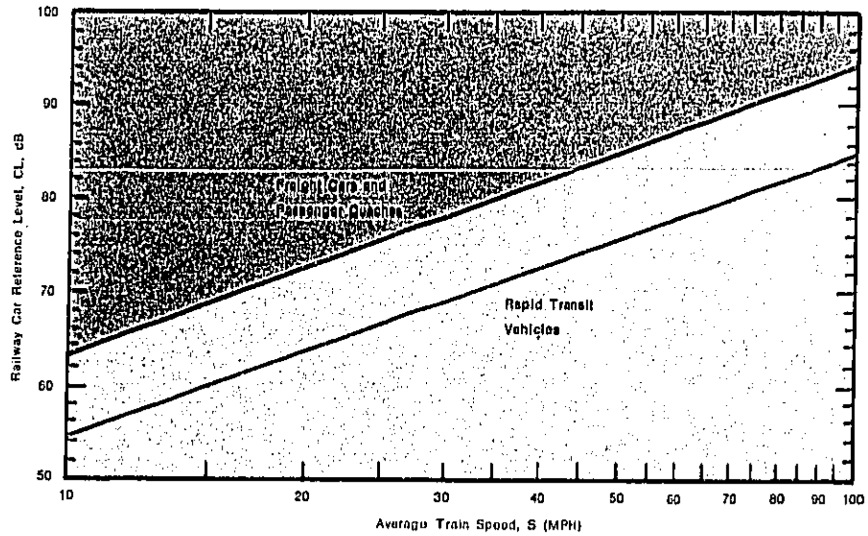


Figure 5.3-11. Railway Car Reference Level at 100 feet [2].

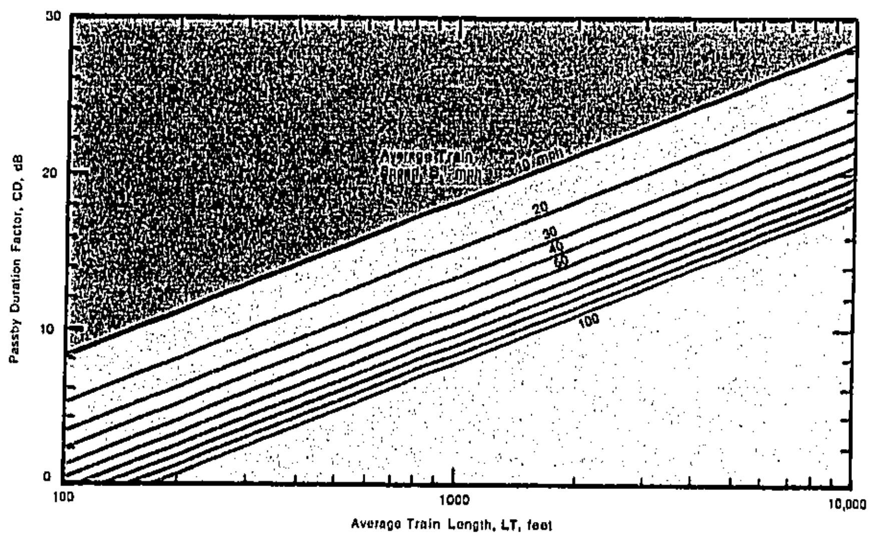


Figure 5.3-12. Duration Correction for Train Passbys.

STEP R8 RAILWAY CARS—TRACK CHARACTERISTICS

Compute the track adjustment factor, CT. This factor accounts for track characteristics other than the standard, straight, mainline, welded track [1, 4, 8]. This adjustment should be made only if the track variation occurs within a distance of 2D on either side of the point of intersection of the railway with the nearest perpendicular distance. See Figure 5.3-4 for an illustration of this distance requirement. From Table 5.3-1 select the appropriate value of CT corresponding to the physical characteristics of the track segment under investigation. In case of simultaneous occurrence of these variations the *single largest correction* should be used.

STEP R9 RAILWAY CARS—DISTANCE ATTENUATION

Compute the distance attenuation factor, DAC, for railway car noise. DAC is determined by locating on the horizontal axis of Figure 5.3-9 the distance D. Read up until intersecting the appropriate curve for railway cars. The value of DAC can be read off the vertical axis directly left of the intersection.

Table 5.3-1. Adjustment Factors for Track Characteristics [1, 4, 8].

TRACK CHARACTERISTICS		CT
1	Straight, Mainline, Welded Track	0
2	Straight, Jointed Track	4
3	Presence of Switches or Grade Crossing	4
4	Tight Radius Curve	
	Radius < 600 Ft.	4
	Radius 600 Ft. to 900 Ft.	1
	Radius > 900 Ft.	0
5	Presence of a Bridge	
	Concrete	0
	Steel Girder with Either Concrete or Open Tie Deck	5
	Steel Girder with Steel Plate Deck	14

STEP R10 RAILWAY CARS—UNSHIELDED NOISE LEVEL

Depending upon the type of noise criterion, or metric, for your proposed building, perform the calculations listed below.

Leq(1)

Compute the factor C1, which is a correction for the number of passbys during the one selected hour of critical building use. C1 is determined by locating on the horizontal axis of Figure 5.3-10 the value of N1 for this type of train. Read up until intersecting the curve. The value of C1 can be read off the vertical axis directly left of the intersection. Using this value and the values of CL, CD, CT, and DAC calculate Leq(1) from the following equation:

$$\text{Leq}(1) = \text{CL} + \text{CD} + \text{CT} + \text{C1} - \text{DAC} - 36.$$

Leq(8)

Compute the factor C8, which is a correction for the number of passbys during the eight hours of building use. C8 is determined of Figure 5.3-10 by locating on the horizontal axis the value of N8 for this type of train. Read up until intersecting the curve. The value of C8 can be read off the vertical axis directly left of the intersection. Using this value and the values of CL, CD, CT and DAC, calculate Leq(8) from the following equation:

$$\text{Leq}(8) = \text{CL} + \text{CD} + \text{CT} + \text{C8} - \text{DAC} - 45.$$

Leq(24)

Compute the factor C24, which is a correction for the number of passbys during a typical twenty-four hour day. C24 is determined by locating on the horizontal axis of Figure 5.3-10 the value of N24 for this type of train. Read up until intersecting the curve. The value of C24 can be read off the vertical axis directly left of the intersection. Using this factor and the values of CL, CD, CT, and DAC, calculate Leq(24) from the following equation:

$$\text{Leq}(24) = \text{CL} + \text{CD} + \text{CT} + \text{C24} - \text{DAC} - 49.$$

Ldn

Compute the factor CDN, which is a correction for the number of "daytime" and "nighttime" passbys. It is determined from the corrected number of passbys, CN, defined as

$$\text{CN} = \text{ND} + 6\text{NN},$$

where ND is the number of "daytime", and NN is the number of "nighttime" passbys for this type of train. CDN is determined by locating on the horizontal axis of Figure 5.3-10 the value of CN.

Read up until intersecting the curve. The value of CDN can be read off the vertical axis directly left of the intersection. Using this value and the values of CL, CD, CT, and DAC, calculate Ldn from the following equation:

$$\text{Ldn} = \text{CL} + \text{CD} + \text{CT} + \text{CDN} - \text{DAC} - 49.$$

• • • • •

C. Shielding Adjustments

The previous steps assumed that there was no shielding between the railway and the building site. If there is any shielding due to a barrier, elevated railway, depressed railway, rows of buildings or a belt of vegetation, it must be taken into account. This is done in STEPS R11 through R15.

The corrections for shielding due to barriers, elevated railways and depressed railways are a function of the railway vehicle type, because of the different locations of the major noise sources. For freight cars, conventional passenger coaches, and rapid transit vehicles, the predominant noise source is the wheel-rail interaction located close to the ground; while for diesel-electric locomotives, the major source of noise is the exhaust outlet located approximately fifteen feet above the rails. Thus, there are two shielding corrections; one for railway cars, CSC, and one for diesel-electric locomotives, CSL. These corrections are determined by calculating the path length differences for railway cars and for diesel-electric locomotives using STEP R11 for the type of shielding present. For these calculations, this design guide assumes that the frequency spectrum for railway car (wheel-rail) noise is similar to highway traffic noise, and employs 500 Hz as the frequency. However, a frequency of 125 Hz is used for diesel-electric locomotive noise. To account for these frequencies being different, a factor of ¼ (125 ÷ 500) is used in calculating path length difference, *Ll*. Using these values of L, CSC and CSL are determined for an "infinitely" long barrier in STEP R12. If the barrier is "finite" in length, the necessary adjustments are made in STEP R13.

The shielding corrections for rows of buildings which act as barriers and for vegetation are related to the physical layout of the railway and the location of your proposed building. The correction for shielding due to rows of buildings which act as barriers, CSB, is computed in STEP R13. The correction for shielding due to vegetation, CSV, is computed in STEP R14. Note that the attenuation due to rows of buildings which act as barriers, and to vegetation is added to the attenuation due to barriers and elevated or depressed railways. For example, if the A-weighted sound level attenuations of a barrier, two rows of buildings and a 100 feet of dense woods are 5, 6, and 5 dB, respectively, the total A-weighted sound level attenuation is 16 dB.

After these shielding corrections are determined, the individual noise contributions are calculated and combined to get the total railway noise in STEP R16.

If there are no barriers, the noise levels calculated in the previous steps are the values to be used to predict noise levels in your building and on its site. Omit STEPS R11 through R15 and proceed to STEP R16 to get the total noise due to railways.

STEP R11 PATH LENGTH DIFFERENCE

Compute the path length difference for railway cars, LC, and for diesel-electric locomotives, *Ll*, for the type of barrier present. Be sure the obstruction blocks the line-of-sight between the source and receiver, being careful about diesel-electric locomotives which have the noise source located fifteen feet above the railway. If the line-of-sight is not blocked, there will be no attenuation.

1. Barrier:

$$Ac = \sqrt{HB^2 + (D - DB)^2}$$
$$Al = \sqrt{(HB - 15)^2 + (D - DB)^2}$$
$$Bc = Bl = \sqrt{(HB + hB)^2 + DB^2}$$
$$Cc = \sqrt{hB^2 + D^2}$$
$$Cl = \sqrt{(hB + 15)^2 + D^2}$$

2. Elevated Railway:

$$Ac = [D - DE]$$
$$Al = \sqrt{225 + (D - DE)^2}$$
$$Bc = Bl = \sqrt{HE^2 + DE^2}$$
$$Cc = \sqrt{HE^2 + D^2}$$
$$Cl = \sqrt{(HE + 15)^2 + D^2}$$

3. Depressed Railway:

$$Ac = \sqrt{HD^2 + (D - DD)^2}$$
$$Al = \sqrt{(HD - 15)^2 + (D - DD)^2}$$
$$Bc = Bl = \sqrt{hD^2 + DD^2}$$
$$Cc = \sqrt{(HD + hD)^2 + D^2}$$
$$Cl = \sqrt{(HD + hD - 15)^2 + D^2}$$

From these values the path length differences are calculated from the following equations:

$$Lc = Ac + Bc - Cc$$
$$Ll = .25\,[Al + Bl - Cl].$$

Record these values on Railway Worksheet 2 and proceed to the next step.

STEP R12 SHIELDING CORRECTION— "INFINITE" BARRIER

Compute the shielding corrections CSC and CSL. These values are determined from the path length differences calculated in the previous step [9]. If the path length difference is negative or less than 0.01 ft, there is no appreciable shielding and the correction is zero; if the path length difference is positive and greater than 0.01 ft, the shielding correction is determined by locating on the horizontal axis of Figure 5.3–13 the value of the path length difference. Read up until intersecting the curve. The value of the shielding correction can be read off the vertical axis directly left of the intersection. This procedure is followed using Lc to determine CSC, and Ll to determine CSL. Record these values on Railway Worksheet 2. If the included angle, a, is less than 170, the barrier is of "finite" length, and you must proceed to STEP R13. But if the included angle, a, is greater than 170, no adjustment to the shielding corrections is needed. Omit STEP R13 and continue the design guide analysis.

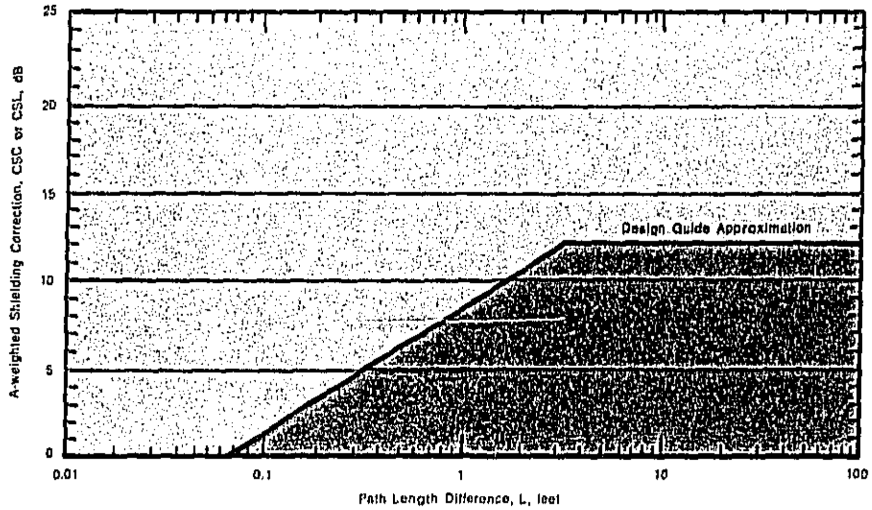


Figure 5.3–13. A-weighted Shielding Correction Versus Path Length Difference for Barriers.

Table 5.3–2. Shielding Corrections for a Finite Barrier.

Infinite Barrier Shielding Correction CSC or CSL	RA = a/180°										
	0	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
1	0	0	0	0	0	0	1	1	1	1	1
2	0	0	0	1	1	1	1	1	2	2	2
3	0	0	0	1	1	1	2	2	2	3	3
4	0	0	1	1	1	2	2	2	3	3	4
5	0	0	1	1	1	2	2	3	3	4	5
6	0	0	1	1	2	2	3	3	4	5	6
7	0	0	1	1	2	2	3	4	4	6	7
8	0	0	1	1	2	2	3	4	5	6	8
9	0	0	1	1	2	3	3	4	5	7	9
10	0	0	1	1	2	3	3	4	6	7	10
11	0	0	1	1	2	3	3	4	6	8	11
12	0	0	1	1	2	3	4	5	6	8	12

STEP R13 SHIELDING CORRECTION—"FINITE" BARRIER

Compute the adjusted values of CSC and CSL to account for shielding elements of finite length. These adjusted corrections are determined from the factor RA, which is calculated from the included angle, a (in degrees), by using the following equation:

$$RA = \frac{a^\circ}{180}.$$

Now go to Table 5.3-2 and enter the first column at the value of CSC and read across that row to the column corresponding to the value of RA. This is the adjusted value of CSC. Repeat this procedure using the value of CSL to get the finite shielding correction for diesel-electric locomotives. Record these adjusted shielding corrections on Railway Worksheet 2, and continue the design guide analysis.

STEP R14 SHIELDING CORRECTION—BUILDINGS ACTING AS BARRIERS

Calculate the correction, CSB, for rows of buildings which shield the railway from your building. This correction depends on the number of rows of intervening buildings, nr, and is determined from Table 5.3-3. Record this correction on Railway Worksheet 2, and continue the design guide analysis.

Table 5.3-3. Shielding Corrections for Buildings Acting as Barriers [8].

Number of Rows	Shielding Correction, CSB
1	4.5
2	6.0
3	7.5
4	9.0
5 or more	10.0

STEP R15 SHIELDING CORRECTION—VEGETATION

Calculate the correction, CSV, for a belt of vegetation of depth, dw, which shields the railway from your building. This correction is simply an A-weighted sound level attenuation of 5 dB for the first 100 feet of woods and 10 dB for woods over 200 feet in depth. Interpolation between these values is left to the discretion of the user of this design guide. Record this correction on Railway Worksheet 2 and continue the design guide analysis.

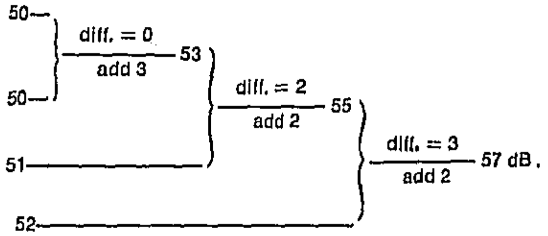
STEP R16 TOTAL RAILWAY NOISE

Compute the total noise at the building site due to the railway. First sum the shielding corrections on Railway Worksheet 2. Subtract these total shielding corrections from the unshielded noise levels to get the individual components of the total railroad noise at the building site. Since these levels are logarithmic, they cannot be simply added together or averaged to get the total noise level. Instead, they must be combined, two values at a time, with the use of Table 5.3-4. Start with the two smallest levels, and subtract one from the other to get the difference.

Table 5.3-4. Level Adjustment for Summing Noise Levels.

Difference of Two Noise Levels, dB	Level Adjustment (To be Added to the Larger of the Two Values)
10 or more	0
4-9	1
2-3	2
0-1	3

With this value go to Table 5.3-4 and determine the level adjustment which is to be added to the larger of the two original noise levels. Now repeat this procedure with this adjusted level and another of the railway noise components. Continue this computation until all components have been combined into one value. For example, if the A-weighted levels of the diesel-electric locomotives and railway cars for freight trains are 50 and 52 dB respectively, and the A-weighted sound levels of the diesel-electric locomotives and passenger coaches for conventional passenger trains are 51 and 50 dB respectively, the total noise is,



Record this total noise level on Railway Worksheet 1.

* * * * *

This completes the prediction of railway noise. These procedures should be repeated for each railway that is listed on the Preliminary Source Evaluation Worksheet with a *yes* answer in Column 2, and for each point on the site or building room that you analyze. The total noise at any point on the building site due to all railways is the summation of the noise contributions from each railway. This summation is accomplished by the same method as used in STEP R16. Refer to this step for the procedure of summing noise levels. Record the total noise level on Railway Worksheet 1.

Now proceed to Section 5.4 and predict the noise level due to aircraft. If aircraft do not affect your building site proceed directly to Chapter 6.

References Chapter 5 Section 3 Railway Passby Noise

[1] Swing, J. W., and Pies, D. B., Assessment of noise environments around railroad operations, Wyle Laboratories Report WCR73-5 (Wyle Laboratories, El Segundo, California, July 1973).

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[6] Anon., Transportation noise and noise from equipment powered by internal combustion engines, U.S. Environmental Protection Agency Report No. NTID 300.03 (Wyle Laboratories, El Segundo, California, December 1971). Available from the U.S. Environmental Protection Agency, Washington, D.C. 20460.

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[8] Swing, J. W., Simplified procedure for developing railroad noise exposure contours, S/V Sound and Vibration, *9* (2), 22-23 (February 1975).

[9] Kugler, B. A., and Piersol, A. G., Highway noise: a field evaluation of traffic noise reduction measures, NCHRP Report 144 (Bolt Beranek and Newman Inc., Canoga Park, California, 1973). Available from the Highway Research Board, 2101 Constitution Ave., Washington, D.C. 20418.

[10] Fath, J. M., Blomquist, D. S., Heinen, J. M., and Tarica, M., Measurements of railroad noise—line operations, yard boundaries and retarders, EPA Report No. 550/9-74-007 (National Bureau of Standards, Washington, D.C., December 1974).

How to Estimate Aircraft Noise

The noise at the building or site due to aircraft flyovers depends upon such variables as: the distance between the building site and the aircraft; type and size of the aircraft and its operating characteristics (primarily its thrust level); and, atmospheric conditions. Unlike automobiles, trucks, and trains, aircraft are not confined to a specific route—even at airports there will be a number of runways, hence a number of possible paths for takeoffs and landings. Also, depending on the type of aircraft, loading weights, the volume of air traffic, and weather conditions, approach and takeoff profiles can vary widely. To handle these variables, the models of aircraft noise, like those for highways, usually depend upon computers for numerical results. Whereas computers can manage these complexities, they are obviously beyond the scope of this design guide.

Instead, the design guide analysis* relies either upon—(a) existing measures of the noise near the airport such as NEF or CNR ratings, which are the most common measures of aircraft noise in the United States, or—(b) a few simple estimates of the noise level based on the airport type and level of activity.

The CNR, or Composite Noise Rating, was one of the first methods developed to assess the effect of aircraft operations on airport communities. The CNR is obtained by making corrections to the noise levels of the various aircraft expressed in terms of the "perceived noise level" (PNL), which is a measure of the relative acceptability of aircraft sounds. The PNL is a quantity, calculated from measured noise levels (it cannot be read directly from a meter), that correlates well with subjective responses to various kinds of aircraft noise [1]. The corrections to the PNL account for the number of aircraft flights, the time of day, and seasons of the year. These corrections are needed since human tolerance of aircraft noise depends not only upon the noise level for each noise event, but also the number of events. Thus, an aircraft noise problem may result from a small number of very loud aircraft or from a much larger number of quieter aircraft [2]. Since CNR accounts for numerous noise events over an extended time period, it is essentially an integrated descriptor of total noise exposure. Unlike Leq or Lmax, which can be measured, CNR is always calculated from other acoustic descriptors. Sites with a CNR value of 100 or less will normally be acceptable for your proposed buildings [3].

* The design guide analysis of aircraft noise is based on work performed by Bolt Beranek and Newman, Inc. for the U.S. Department of Housing and Urban Development [10].

The NEF, or Noise Exposure Forecast, system of rating aircraft noise is rapidly superceding the CNR method. The NEF single number rating is similar to the CNR except that the perceived noise level is replaced by the effective perceived noise level, which is equal to the perceived noise level plus corrections for the duration of the noise event and for the presence of pure tone components which are not included in the CNR. This latter correction has been included because it has been found that discrete frequency components, such as jet engine whine, are the principal cause of annoyance to persons living near airports [2]. The NEF numerical values differ considerably from the corresponding CNR values; e.g., an NEF of 30 corresponds approximately to a CNR of 100. This difference was introduced intentionally so that the two ratings would not be confused. Like CNR, NEF is an integrated descriptor of total noise exposure, and is calculated from other quantities rather than being directly measured. Sites with a NEF value of 30 or less will normally be acceptable for your proposed building [3].

The total noise exposure due to aircraft operations has been determined for many communities on the basis of the CNR or NEF indices, and the results mapped as contours of equal CNR or NEF values. For an example of such a contour map, see Figure 5.4-1 [4]. If these contour maps exist for the airport near the site for your proposed building, the maps can be used to estimate noise due to aircraft flyovers. These procedures are given in STEPS A2 and A4. NEF contours for many airports are available in reports cited in this design guide [5-10].

If these contour maps do not exist, the aircraft noise at your building site can be estimated by an alternative technique. First, the airport is classified into one of four general categories based on the "effective" number of jet operatons, NJeff, which is defined as NJday—the number of "daytime" (7 A.M. to 10 P.M.) jet operations, plus seventeen times NJnight—the number of "nighttime" (10 P.M. to 7 A.M.) jet operations [3].

The airport categories are then defined as: Category 1: 0 to 50 "effective" jet operations; Category 2: 51 to 500 "effective" jet operations; Category 3: 501 to 1300 "effective" jet operations; and Category 4: over 1300 "effective" jet operations. If there are no jet operations, the airport is placed in Category 1. (Placing all airports without jet operations in Category 1 may be too severe, particularly for very small aiports which have only a lim-

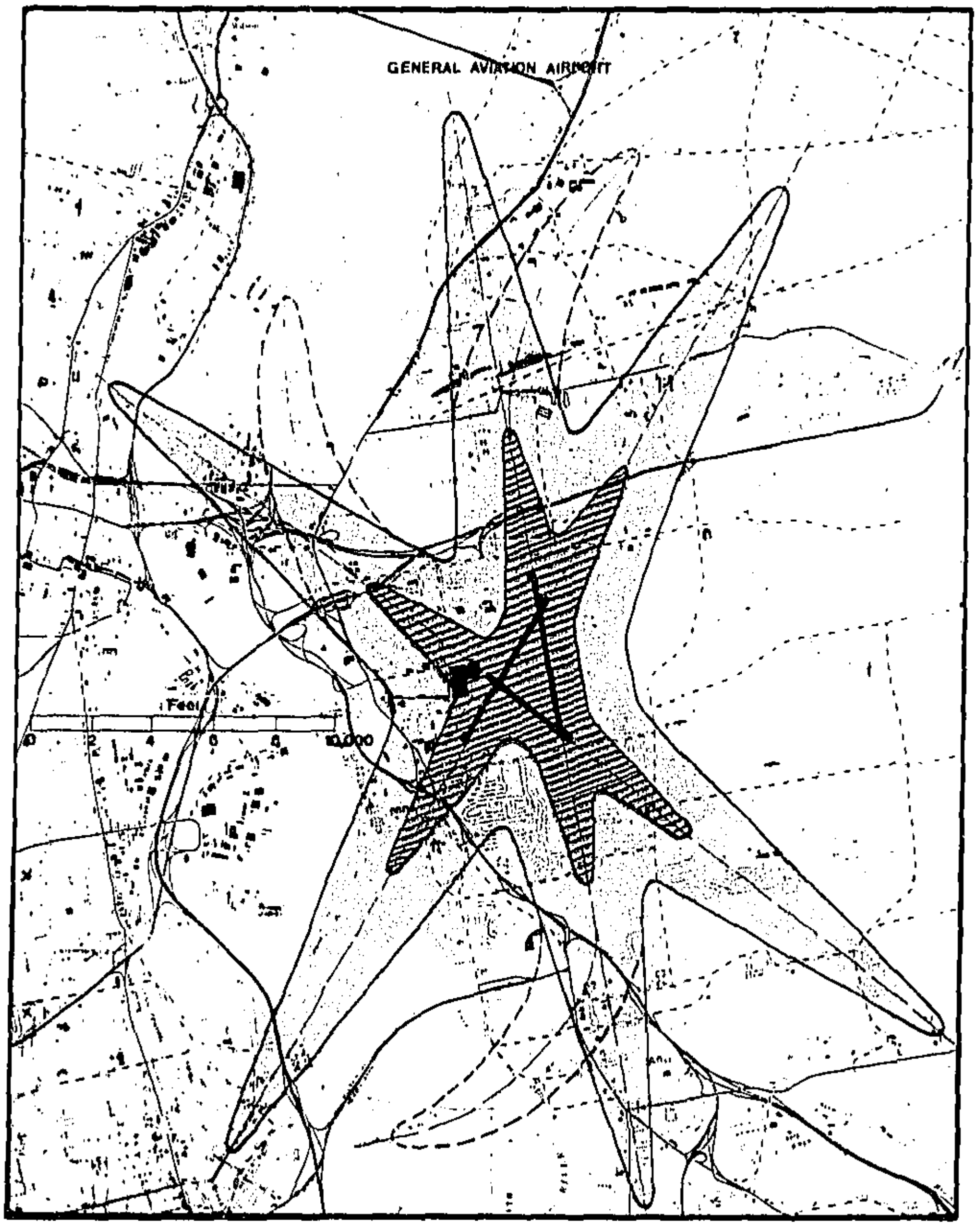

Figure 5.4-1. Rating Contours Superimposed on a Map of the Local Area [4].

Table 5.4-1. Effective Number of Jet Aircraft Operations for Various U.S. Airports [3].

Airport Category	City and State	Number Of Jet Aircraft Operations		
		NJday	NJnight	NJeff.
	Wisconsin Rapids, Wis.	1	0	1
	Ithaca, N.Y.	5	0	5
1	Concord, Calif.	6	0	6
	Columbia, Mo.	3	½	11
	Atlanta, Ga. (Fulton)	13	0	13
	Van Nuys, Calif.	22	0	22
	Huntsville, Ala.	98	0	98
	Erie, Pa.	40	4	108
	Colorado Springs, Colo.	80	5	165
2	Little Rock, Ark.	106	7	227
	Melbourne, Fla.	67	20	427
	Raleigh/Durham, N.C.	130	19	453
	Tulsa, Okla.	199	16	471
	Nashville, Tenn.	164	27	623
	Hartford, Conn.	115	32	659
3	El Paso, Tex.	130	36	742
	Milwaukee, Wis.	210	38	856
	San Diego, Calif.	267	46	1049
	Portland, Ore.	360	64	1448
	Washington, D.C. (National)	614	64	1702
	Washington, D.C. (Dulles)	332	82	1726
	Kansas City, Mo.	302	86	1764
4	Seattle/Tacoma, Wash.	280	88	1776
	Tampa, Fla.	366	120	2406
	Detroit, Mich.	544	114	2482
	Dallas/Ft. Worth, Tex.	704	131	2931
	Boston, Mass.	680	136	2992
	New York, N.Y. (Kennedy)	1020	171	3927
	Los Angeles, Calif.	1089	185	4234
	Chicago, Ill.	1636	315	6991

Table 5.4-2. Approximate Distances to NEF 40 and NEF 30 Contours [3].

Airport Category	Effective Number of Jet Operations, NJeff.	Distances to NEF 40 Contour		Distances to NEF 30 Contour	
		From Side of Runway DS-40	From End of Runway DE-40	From Side of Runway DS-30	From End of Runway DE-30
1	0–50	0	0	1000 Feet	1 Mile
2	51–500	1000 Feet	1 Mile	0.5 Mile	3 Miles
3	501–1300	2000 Feet	2.5 Miles	1.5 Miles	6 Miles
4	More Than 1300	3000 Feet	4 Miles	2 Miles	10 Miles

ited number of operations. You can visit the site and judge for yourself the magnitude of the aircraft noise, then decide if the airport should be considered.) Examples of U.S. airports which fall into these four categories are given in Table 5.4-1 [3].

After the airport has been classified into one of the four categories, approximate NEF 40 and NEF 30 contours can be constructed on a local map showing your building site (Figure 5.4-2) using the distances of Table 5.4-2, which are average values for typical U.S. airports [3]. With this approximate contour map you can estimate the noise level at your site due to aircraft flyovers. These procedures are given in STEPS A3 and A4.

Before proceeding, study briefly the flow diagram of Figure 5.4-3 which outlines the steps necessary to estimate aircraft noise. First obtain the required airport input data (STEP A1), which are then used to calculate the CNR or NEF value at your proposed building location (either STEP A2 or STEP

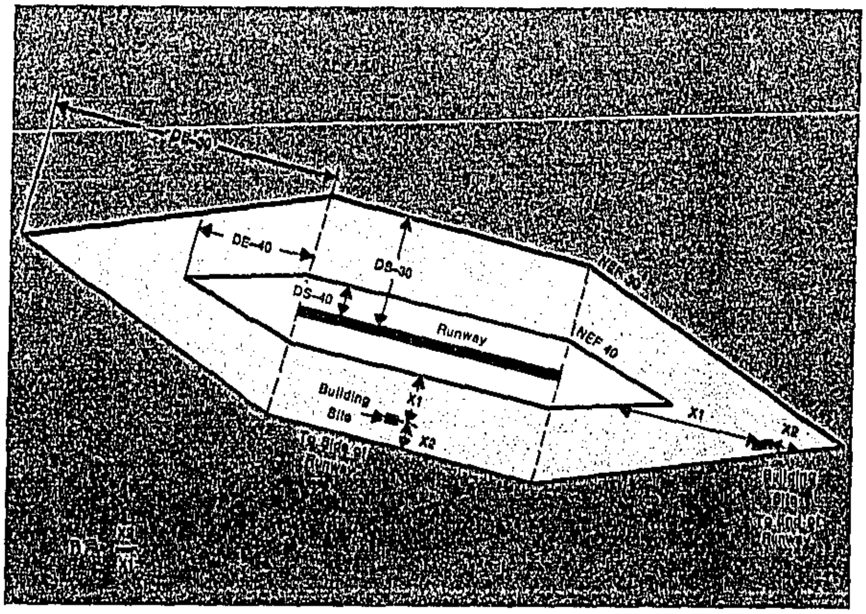

Figure 5.4-2. Layout of Approximate NEF Contours. *Dimensions X1 and X2 should be measured on a line perpendicular to the runway for building sites located at the side of the runway; and on a line parallel to the runway for building sites located beyond the end of the runway.*

A3). Finally, calculate the noise level due to aircraft operations from this airport (STEP A4). An example of the step-by-step calculations is given in Section 5.5.

Before you can estimate the noise levels, you will need to obtain certain information about the airport near your building site. The information, described in STEP A1, should be recorded in Aircraft Worksheet 1, shown in Figure 5.4-4.

Aircraft Noise Prediction Method

STEP A1 AIRPORT DATA

The information that is required on airports may be obtained from the Federal Aviation Administration (FAA) Area Office for commercial airports; or, when the information can be released, from the military agency in charge for military airports. The data should be gathered for each airport (if more than one) that is listed on the Preliminary Source Evaluation Worksheet with a *yes* answer in Column 2.

1. First you should determine if either CNR or NEF contours have been mapped for the airport. If contour maps are available complete substeps 2 and 4; but, if not, complete substeps 3 and 4.
2. CNR or NEF Contour Maps Available.

Lay out your building site on the contour map and examine its position relative to the CNR or NEF contours. If located on or very near one of the contours, the only information to be entered in Aircraft Worksheet 1 is the CNR or NEF value for that contour. If the building site falls between two contours, enter the CNR or NEF values for both, and the distances from each contour to the building as shown in Figure 5.4-5.

If your site is located inside the NEF 40 (CNR 100) contour, you will probably have a serious noise problem. You should obtain the services of a consultant to consider in detail the continued advisability of construction on or rejection of the site, or the special adaptations which may be required.

If your site is located outside the last contour that is mapped, your use of the predictive schemes of this design guide will be limited. It is a rule of thumb that if the building site is farther outside the NEF 30 (CNR 100) contour than the distance between the NEF 30 and 40 (CNR 100 and 110) contours, there probably will be no problem with aircraft noise [3]. Aside from this your only alternative is to employ an acoustical consultant.

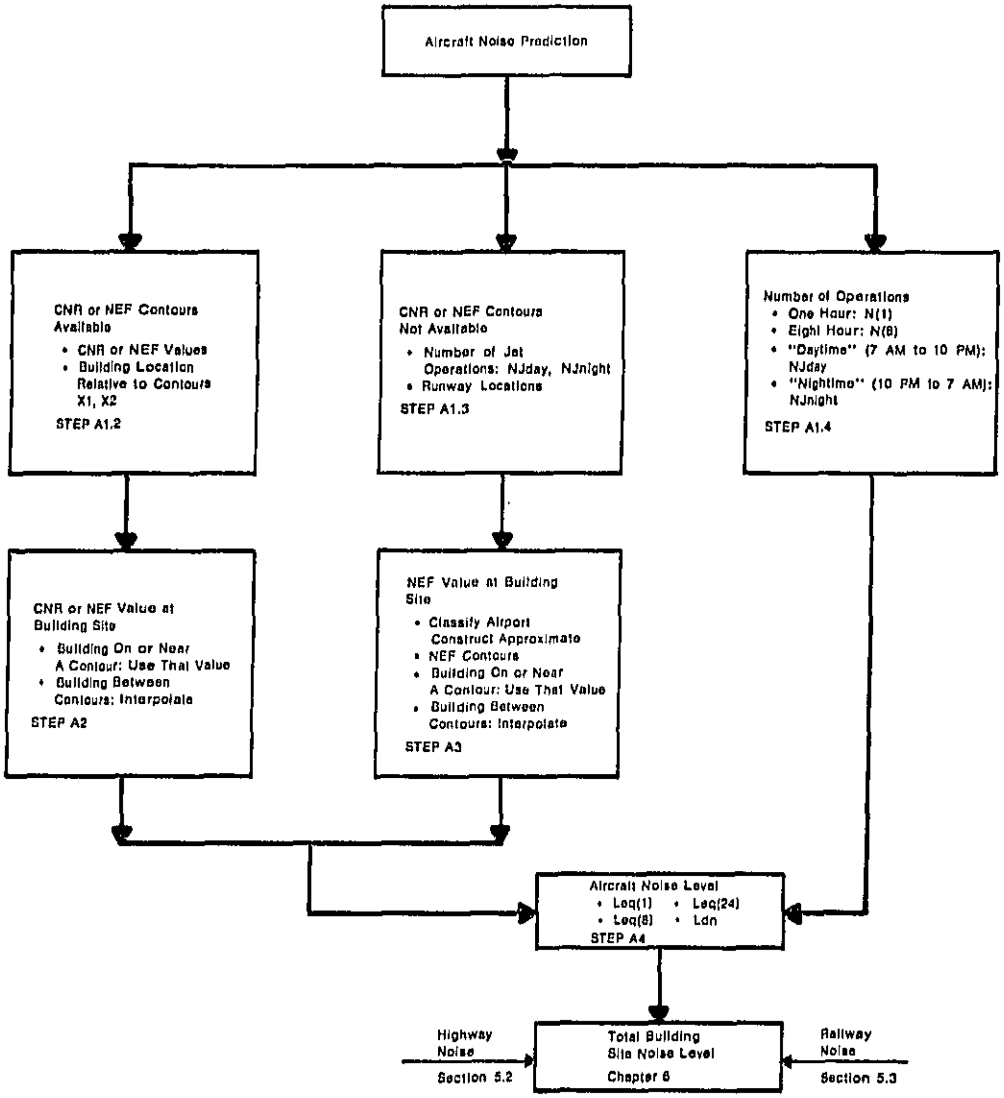

Figure 5.4-3. Aircraft Noise Prediction Flow Diagram.

Aircraft Worksheet 1

Building Project ______________ Site point or building room for which sound pressure levels are being estimated ______________

Location ______________ Designer ______________

Owner ______________ Date ______________ Revised ______________

Contour Maps Available ______						
1	If Building is on or very near Contour #1 or #2, Record that value on Line 11. If not, obtain the data of Lines 2 and 3					
2	Contour Values	CNR or NEF #1		CNR or NEF #2		
3	Building Location Between Contours #1 and #2	X1	X2	R	C5	C10
4	CNR or NEF Value At The Building Site				Also Record on Line 11	
Contour Maps Not Available						
5	Number of Jet Operations	NJday	NJnight	NJeff		
6	Airport Category (Check One)	1	2	3	4	
7	If building is on or very near the NEF 30 or NEF 40 Contour, record that value on Line 11. If not, obtain the data on Line 8.					
8	Building Location Between NEF 30 and NEF 40 Contours	X1	X2	R	C10	
9	NEF Value At The Building Site			Also Record on Line 11		
10	Number of Operations	NJday	NJnight	N(8)	N(1)	
11	CNR or NEF Value At The Building Site					
12	Convert CNR to NEF Value					
13	Aircraft Noise Level At The Building Site					
	Leq(1)	R1	C1	Leq(1)		
	Leq(8)	R8	C8	Leq(8)		
	Leq(24)	R24	C24	Leq(24)		
	Ldn			Ldn		

Figure 5.4-4. Aircraft Worksheet 1.

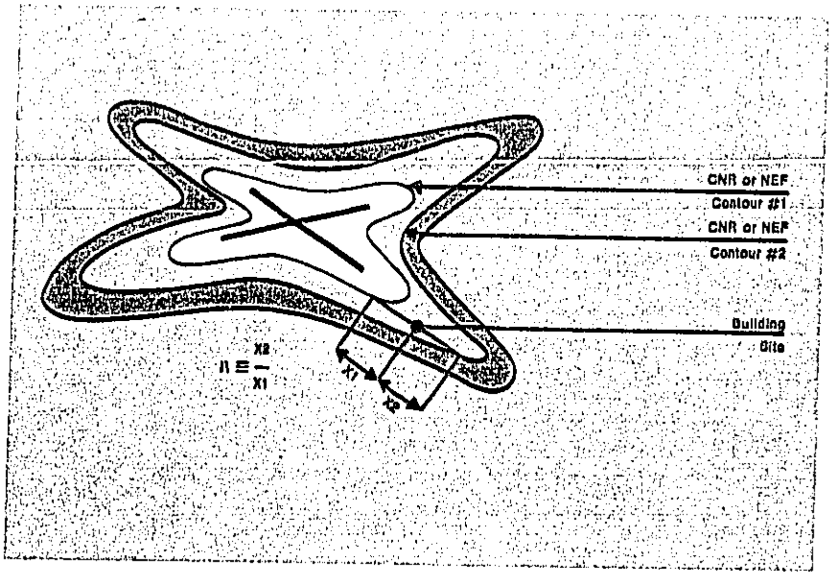

Figure 5.4-5. Geometry for Estimating CNR or NEF rating at the Building Site.

Dimensions x1 and x2 should be measured on a line perpendicular to the runway for building sites located to the side of the runway and on a line parallel to the runway for building sites located beyond the end of the runway.

3. CNR or NEF Contour Maps Not Available.
   You should determine the average number of "daytime" (7 A.M. to 10 P.M.) jet operations, NJday; and the average number of "nighttime" (10 P.M. to 7 A.M.) jet operations, NJnight. If there are no jet operations note this on Aircraft Worksheet 1. You must also determine the location and direction of major runways of the airport, and show these on a map of the local area which includes your building site.
4. Number of Operations.
   Depending upon the metric being used to estimate noise for your building and site, information on the number of flight operations may also be required. Obtain only those data necessary to make calculations for the metric you have selected. The data should be for average airport operations.
   - Leq(1)—NJday, NJnight, and N(1), which is the total number of operations in the one selected hour of critical building use.
   - Leq(8)—NJday, NJnight and N(8), which is the total number of operations in the eight-hour period of building use.
   - Leq(24)—NJday, NJnight
   - Ldn—no further data needed

* * * * *

The procedures for predicting noise levels at the building site due to aircraft are given in the following steps. If CNR or NEF contour maps are available, use STEP A2; if not, use STEP A3. The results for either step is an approximate CNR or NEF value at the building site, which can then be used to estimate noise levels for the metric you have chosen: Leq(1), Leq(8), Leq(24) or Ldn. The relationships between these various metrics and the CNR or NEF values are given in STEP A4 [11, 12].

STEP A2 CNR OR NEF VALUE AT THE BUILDING SITE—CONTOUR MAPS AVAILABLE

If the building is located on or very near a contour, you can use its value and proceed directly to STEP A4. But if the building falls between two contours, you must calculate an approximate CNR or NEF value for that location. First, determine the distance ratio, R, as defined in Figure 5.4-5. With this value go either to Table 5.4-3 and determine the factor C5 (if contours are mapped in increments of 5), or to Table 5.4-4 and determine the factor

C10 (if contours are mapped in increments of 10). The rating at the building site is then estimated by one of the following equations. For contours in increments of 5,

CNR (or NEF) = CNR (or NEF) value of contour #1 − C5.

For contours in increments of 10,

CNR (or NEF) = CNR (or NEF) value of contour #1 − C10.

Record this value on Aircraft Worksheet 1.

STEP A3 NEF RATING AT BUILDING SITE—CONTOUR MAPS NOT AVAILABLE

Using the data obtained in STEP A1.3, classify the airport near your site in one of the four categories defined in Table 5.4–2. The airport classification is based on the "effective" number of jet operations, which is defined as the number of "daytime" jet operations plus seventeen times the number of "nighttime" jet operations.

$$NJeff = NJday + 17\ NJnight$$

With this value determine the airport category from Table 5.4–2. If there are no jet operations, the airport is placed in Category 1.

Now with the airport classified in one of the four categories, you can construct approximate NEF contours. On a map of the area which shows the principal runways, mark the location of the building and site, and determine which runway is most likely to affect the site. Then using the distances of Table 5.4–2 construct approximate NEF 40 and NEF 30 contours as shown in Figure 5.4–2. Note that for airports in Category 1, NEF 40 corresponds to the runway itself. If the building site is located on or very near one of these contours, use that value and proceed directly to STEP A4. If your building or site is located inside the NEF 40 contour or outside the NEF 30 contour, follow the instructions of STEP A2.2 (above).

But if the building or site falls between two contours, you must calculate an approximate NEF value for that location. First, calculate the distance ratio, R, as defined in Figure 5.4–2. Then determine the factor C10 from Table 5.4–4. The rating at the building site is given by

$$NEF = 40 - C10.$$

STEP A4 AIRCRAFT NOISE LEVEL

With the CNR or NEF value at the building site determined in either STEP A2 or STEP A3, you can now calculate aircraft noise in terms of the metric you have selected. First, convert any CNR value to a corresponding NEF value. This conversion is made by the equation [11]

$$NEF = CNR - 70.$$

Table 5.4–3. Factor, C5, for Interpolating Between CNR or NEF Contours in Increments of 5.

Distance Ratio $R = \frac{x2}{x1}$	Factor C5 to be subtracted from larger CNR or NEF value.
>12.3	0
3.21 — 12.3	1
1.41 — 3.2	2
0.61 — 1.4	3
0.21 — 0.6	4
<0.2	5

Table 5.4–4. Factor C10 for Interpolating Between CNR or NEF Contours in Increments of 10.

Distance Ratio $R = \frac{x2}{x1}$	Factor C10 to be subtracted from larger CNR or NEF value
>35.0	0
10.41–35.0	1
5.51–10.4	2
3.31–5.5	3
2.21–3.3	4
1.51–2.2	5
0.91–1.5	6
0.61–0.9	7
0.31–0.6	8
0.11–0.3	9
<0.1	10

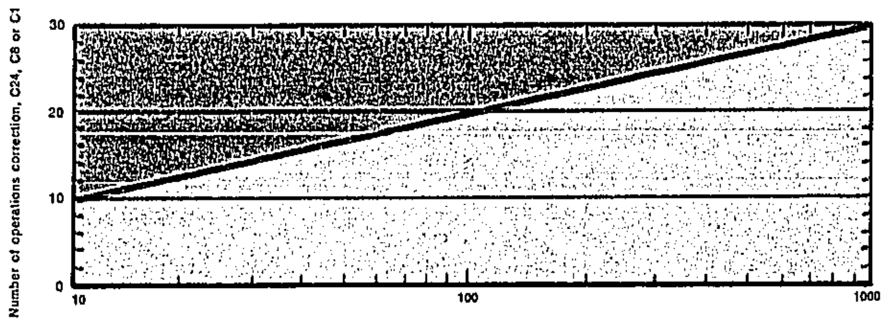

Figure 5.4–6. Correction For Number of Operations.

Now perform the appropriate calculation given in the list below for the metric you selected.

- **Leq(1)** [12]

Compute the factor C1, which is a correction for the number of operations based on the one selected hour of critical building use. It is determined from the number of operations ratio, R1, defined as,

$$R1 = \frac{NJday + 17\ NJnight}{N(1)}.$$

To determine C1, locate along the horizontal axis of Figure 5.4–6 the point corresponding to the value of R1. Read up until intersecting the curve. The value of C1 can be read off the vertical axis directly left of the intersection. Using this value and the NEF value at your site, calculate Leq(1) from the following equation:

$$Leq(1) = NEF + 41 - C1.$$

- **Leq(8)** [12]

Compute the factor C8, which is a correction for the number of operations based on the eight hours of building use. It is determined from the number of operations ratio, R8, defined as,

$$R8 = \frac{8(NJday + 17\ NJnight)}{N(8)}.$$

To determine C8 locate along the horizontal axis of Figure 5.4-6 the point corresponding to the value of R8. Read up until intersecting the curve. The value of C8 can be read off the vertical axis directly left of the intersection. Using this value and the NEF value at your site, calculate Leq(8) from the following equation:

$$Leq(8) = NEF + 41 - C8.$$

- **Leq(24)** [12]

Compute the factor C24, which is a correction for the number of operations based on a twenty-four hour average. It is determined from the number of operations ratio, R24, defined as,

$$R24 = \frac{24\ (NJday + 17\ NJnight)}{(NJday + NJnight)}.$$

To determine C24, locate along the horizontal axis of Figure 5.4–6 the point corresponding to the value of R24. Read up until intersecting the curve. The value of C24 can be read off the vertical axis directly left of the intersection. Using this value and the NEF value at your site, calculate Leq(24) from the following equation:

$$Leq(24) = NEF + 41 - C24.$$

- **Ldn** [11]

Using the NEF value at your site, calculate Ldn from the following equation:

$$Ldn = NEF + 35.$$

This completes the prediction of aircraft noise. These procedures should be repeated for each airport (if more than one) that is listed on the Preliminary Source Evaluation Worksheet with a *yes* answer in Column 2.

This also completes the prediction of transportation system noise. Now proceed to Chapter 6 and compute the total sound level in the outdoor activity area or room of your proposed building.

References Chapter 5 Section 4 Aircraft Noise

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Chapter 5 Section 5 Illustrative Example of How to Estimate Building Site Noise

Consider the hypothetical example shown in Figure 5.5-1. The building being considered is 70 feet wide by 150 feet long, and is 10 stories or approximately 100 feet high. As an apartment, it is classified as a residential occupancy. Thus, based on the discussion of Chapter 3, the appropriate metric for evaluating the building is Ldn. The total outdoor noise at this building site is a combination of sounds from two highways, a railway and an airport. The prediction of the noise generated by each of these sources is outlined below.

Highway Noise Prediction

As seen from the map of the area, Figure 5.5-2, there are two highways which affect the building site. Highway #1 consists of two lanes in each direction, separated by a

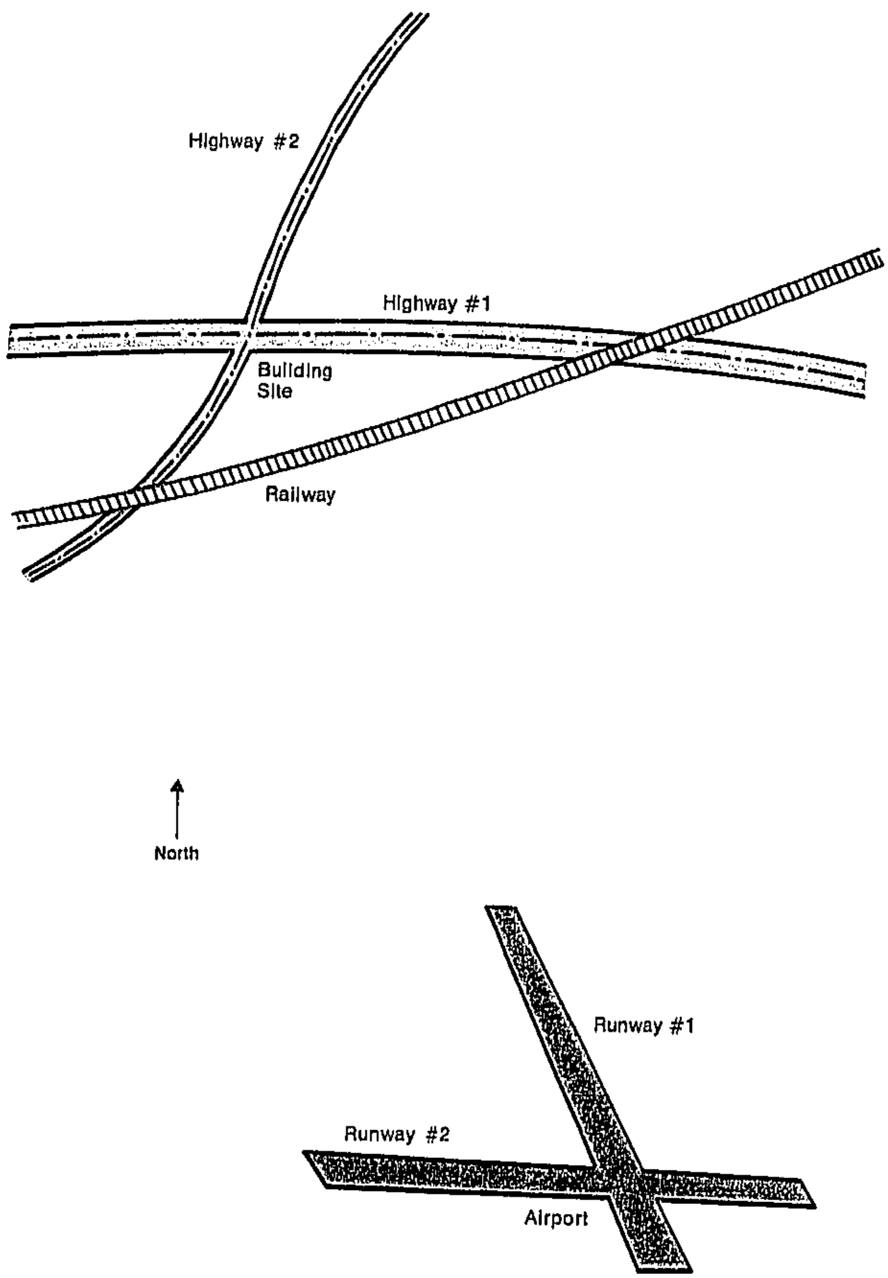


Figure 5.5-1. Local Map Showing the Location of the Building Site and Transportation Noise Sources.

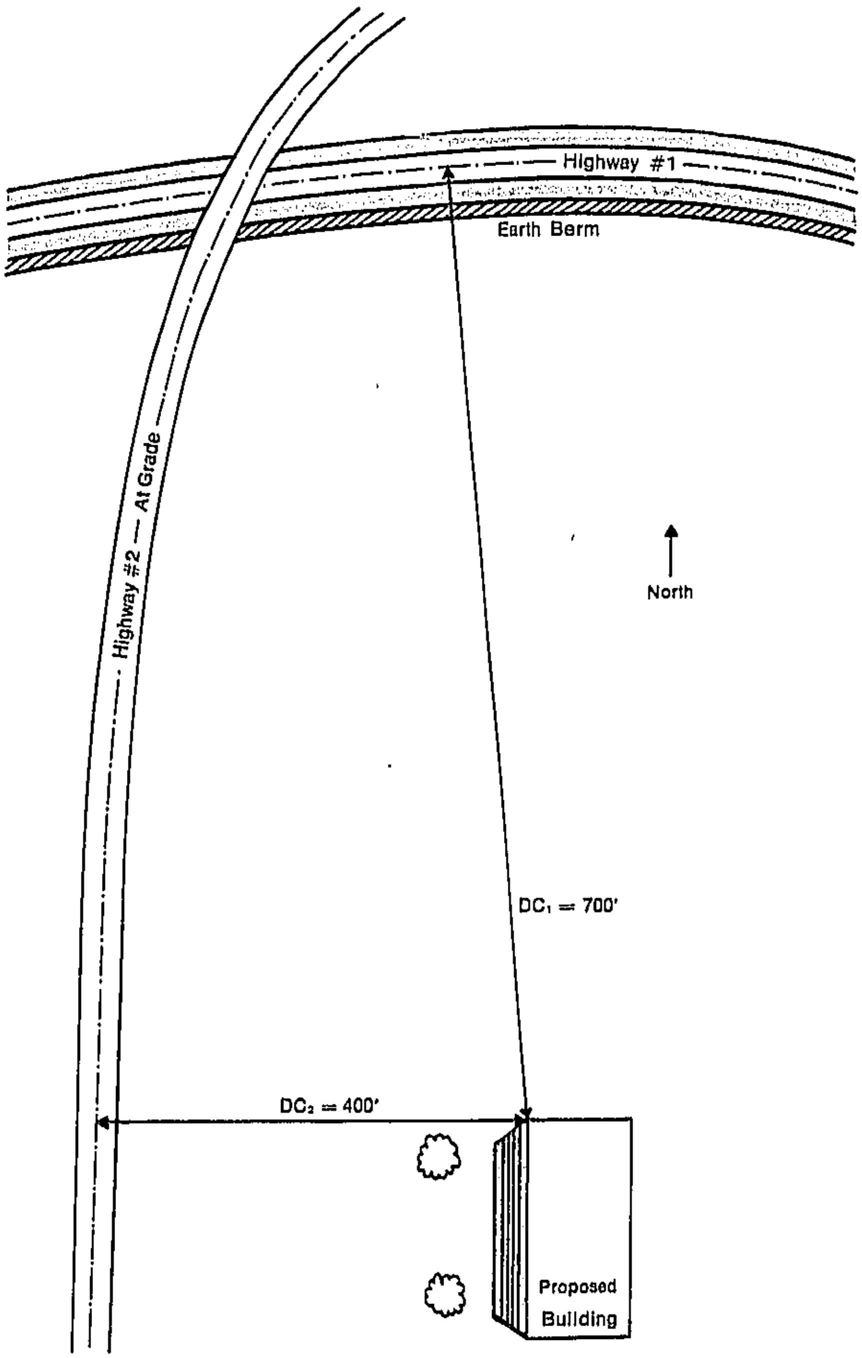


Figure 5.5–2. Local Map Showing Details of Highways.

Highway Worksheet 1

Building Project 10-STORY Apartment — Highway Number 2

Location Near Highways 1 & 2 — Site point or building room for which sound pressure levels are being estimated Top Floor NW

Owner Modern Realty — Designer C. Suggs — Date 1 July '77 — Revised

Roadway—Building Site Distance, DC (Feet) 700'

		Autos		Medium Trucks		Heavy Trucks	
Average Vehicle Speed, mph		SA	50	SM	50	SH	50
Total Number of Vehicles							
a) Leq(1)		VA(1)		VM(1)		VH(1)	
b) Leq(8)		VA(8)		VM(8)		VH(8)	
c) Leq(24)		VA(24)		VM(24)		VH(24)	
d) Ldn		DVA	NVA	DVM	NVM	DVH	NVH
		46,500	23,710	2,550	1300	4,350	2,220
Average Vehicle Volume (veh/hr)		VA	3,100	VM 170	VMC 1700	VH	290
Predicted Noise Levels							
a) Leq(1)	Leq(1) No Shielding						
	Total Shielding Correction (Highway Worksheet 2)						
	Leq(1) Corrected for Shielding						
b) Leq(8)	Leq(8) No Shielding						
	Total Shielding Correction (Highway Worksheet 2)						
	Leq(8) Corrected for Shielding						
c) Leq(24)	Leq(24) No Shielding						
	Total Shielding Correction (Highway Worksheet 2)						
	Leq(24) Corrected for Shielding						
d) Ldn	HNL	55		52		61	
	RDN	0.51		0.51		0.51	
	CDN	4		4		4	
	Ldn No Shielding	59		56		65	
	Total Shielding Correction (Highway Worksheet 2)	6		6		0	
	Ldn Corrected for Shielding	53		50		65	
Total Highway Noise		65 dB					
Building Site Noise Due To Several Highways				66 dB			

Figure 5.5-3. Highway Worksheet 1 For Highway #1 of Example.

Highway Worksheet 1

Building Project: 10-Story Apartment	Highway Number: 2
Location: Near Highways 1 & 2	Site point or building room for which sound pressure levels are being estimated: Top floor NW
Owner: Modern Realty Designer: C. Suggs.	Date: 1 July '77 Revised:

Roadway—Building Site Distance: DC (Feet) 400'

	Autos		Medium Trucks		Heavy Trucks	
Average Vehicle Speed, mph	SA	45	SM		SH	40
Total Number of Vehicles						
a) Leq(1)	VA(1)		VM(1)		VH(1)	
b) Leq(8)	VA(8)		VM(8)		VH(8)	
c) Leq(24)	VA(24)		VM(24)		VH(24)	
d) Ldn	DVA	NVA	DVM	NVM	DVH	NVH
	10,650	2,660			465	120
Average Vehicle Volume (veh/hr)	VA	710	VM	VMC	VH	31

Predicted Noise Levels		Autos	Medium Trucks	Heavy Trucks
a) Leq(1)	Leq(1) No Shielding			
	Total Shielding Correction (Highway Worksheet 2)			
	Leq(1) Corrected for Shielding			
b) Leq(8)	Leq(8) No Shielding			
	Total Shielding Correction (Highway Worksheet 2)			
	Leq(8) Corrected for Shielding			
c) Leq(24)	Leq(24) No Shielding			
	Total Shielding Correction (Highway Worksheet 2)			
	Leq(24) Corrected for Shielding			
d) Ldn	HNL	51		56
	RDN	0.25		0.25
	CDN	2		2
	Ldn No Shielding	53		58
	Total Shielding Correction (Highway Worksheet 2)			
	Ldn Corrected for Shielding	53		58
Total Highway Noise		59 dB		
Building Site Noise Due To Several Highways			66 dB	

Figure 5.5–4. Highway Worksheet 1 for Highway #2 of Example

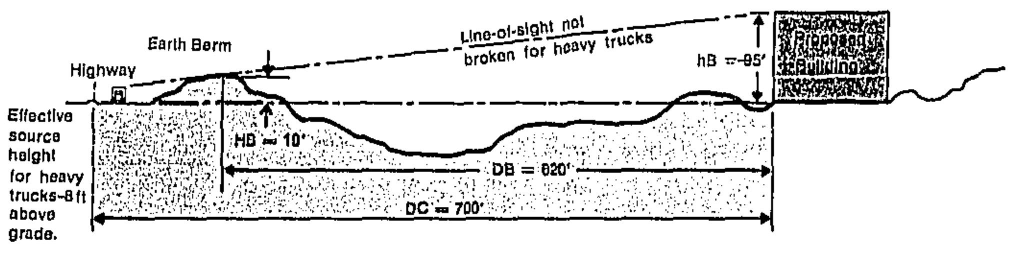


Figure 5.5–5. Cross-section Showing Highway #1 and Earth Berm.

median. This highway is shielded from the building by an earth berm. Highway #2 is a two-lane roadway that lies at grade with respect to the building site.

STEP H1.1 HIGHWAY TO BUILDING OR SITE DISTANCE

First, the highway to building site distances are determined from a map of the local area (Figure 5.5–2). These values, 700 feet for Highway #1 and 400 feet for Highway #2, are recorded on separate copies of Highway Worksheet 1, Figures 5.5–3 and 5.5–4, respectively.

STEP H1.2 BARRIER DATA

Only Highway #1 is shielded from the building site. The necessary distances for evaluating an earth berm are determined from a cross-sectional diagram of the highway (Figure 5.5–5). These distances, which are determined for the top floor (worst case as far as shielding is concerned), are:

DC = 700 ft. HB = 19 ft. a = 180°
DB = 620 ft. hB = −95 ft.

These values are recorded on Highway Worksheet 2 (Figure 5.5–6).

STEP H1.3 VEGETATION AND BUILDINGS AS BARRIERS

There are no intervening rows of buildings and no vegetation which would effectively shield the roadway from a room on the top floor. Thus, for this case, these types of shielding are neglected.

However, if a room on the ground floor were analyzed, shielding due to vegetation or intervening rows of buildings would have to be taken into account. Also, the shielding due to the earth berm is different for the ground floor. The distance hB changes from −95 feet to about −5 feet for a ground floor room. This changes the path length difference and hence the attenuation. This illustrates that the attenuation should be recalculated for rooms on different floors.

STEP H2 TRAFFIC DATA FOR HIGHWAY #1

For Highway #1 the average speed is 50 mph for all vehicle classifications. The "daytime" and "nighttime" traffic volumes are,

DVA = 46,500 vehicles,
DVM = 2550 vehicles,
DVH = 4350 vehicles
NVA = 23,710 vehicles,
NVM = 1300 vehicles,
NVH = 2220 vehicles.

From these values the average daytime hourly vehicle volumes are calculated to be,

$$VA = \frac{46{,}500}{15} = 3100 \text{ veh/hr;}$$

$$VM = \frac{2550}{15} = 170 \text{ veh/hr;}$$

$$VH = \frac{4350}{15} = 290 \text{ veh/hr.}$$

These values are recorded on Highway Worksheet 1 for Highway #1 (Figure 5.5–3).

STEP H2 TRAFFIC DATA FOR HIGHWAY #2

For Highway #2, data are available only in terms of automobiles and trucks. The average speed for autos is 45 mph and for heavy trucks is 40 mph. The "daytime" and "nighttime" traffic volumes are,

DVA = 10,650 vehicles,
NVA = 2660 vehicles,
DVH = 465 vehicles,
NVH = 120 vehicles.

From these values the hourly average daytime vehicle volumes are calculated to be,

Highway Worksheet 2

Building Project 10-Story Apartment	Highway Number 1
Location Near highways I.E. 2	Site point or building room for which sound pressure levels are being estimated Top floor NW
Owner Modern Realty	Designer C. Suggs
	Date 1 July 77 Revised -

Roadway—Building Site Distance: DC (Feet) 700'

Shielding Geometry	Barrier				Elevated Roadway			Depressed Roadway			
	DB	HB	hB	a	DE	HE	a	DD	HD	hD	a
	620'	19'	-95'	180°							

Path Length Difference					
	Autos And Medium Trucks	Aa/m	Ba/m	Ca/m	La/m
		82.23'	624.64'	706.42'	0.45'
	Heavy Trucks	A_h	B_h	C_h	L_h

Correction For "Infinite" Shielding Element	Auto	Medium Truck	Heavy Truck
	CSA/M	CSA/M	CSH
	6	6	0

Correction For "Finite" Shielding Element	Auto	Medium Truck	Heavy Truck
	Included Angle Ratio, RA		
	Auto	Medium Truck	Heavy Truck
	CSA/M	CSA/M	CSH

Building Barrier	nt		CSB		
Vegetation	dw		CSV		

Total Shielding Correction	Auto	Medium Truck	Heavy Truck
	CSA/M + CSB + CSV	CSA/M + CSB + CSV	CSH + CSB + CSV
	6	6	0

Figure 5.5-6 Highway Worksheet 2 for Highway #1 of Example.

$$VA = \frac{10{,}650}{15} = 710 \text{ veh/hr;}$$

$$VH = \frac{465}{15} = 31 \text{ veh/hr}$$

These values are recorded on Highway Worksheet 1 for Highway #2 (Figure 5.5–4).

STEPS H3–H6 AUTOMOBILE NOISE LEVEL FOR HIGHWAY #1

Predict the noise generated by each of the three vehicle classifications. Using the values SA = 50 mph, VA = 3100 veh/hr and DC = 700 ft, STEPS H3, H4 and H5 are performed to predict the noise level of automobiles (see the nomogram of Figure 5.5–7). The value of HNL is determined to be an A-weighted sound level of 55 dB. Since the metric being used is Ldn, STEP H6 is performed. First, the ratio RDN is calculated for automobiles,

$$RDN = \frac{NVA}{DVA} = \frac{23{,}710 \text{ vehicles}}{46{,}500 \text{ vehicles}} = 0.51.$$

With this value, CDN is determined from Figure 5.2–10 to be 4 dB, when rounded to the nearest integer. The unshielded, A-weighted day-night sound level for automobiles on Highway No. 1 is then calculated to be:

$$Ldn = HNL + CDN = 55+4 = 59 \text{ dB.}$$

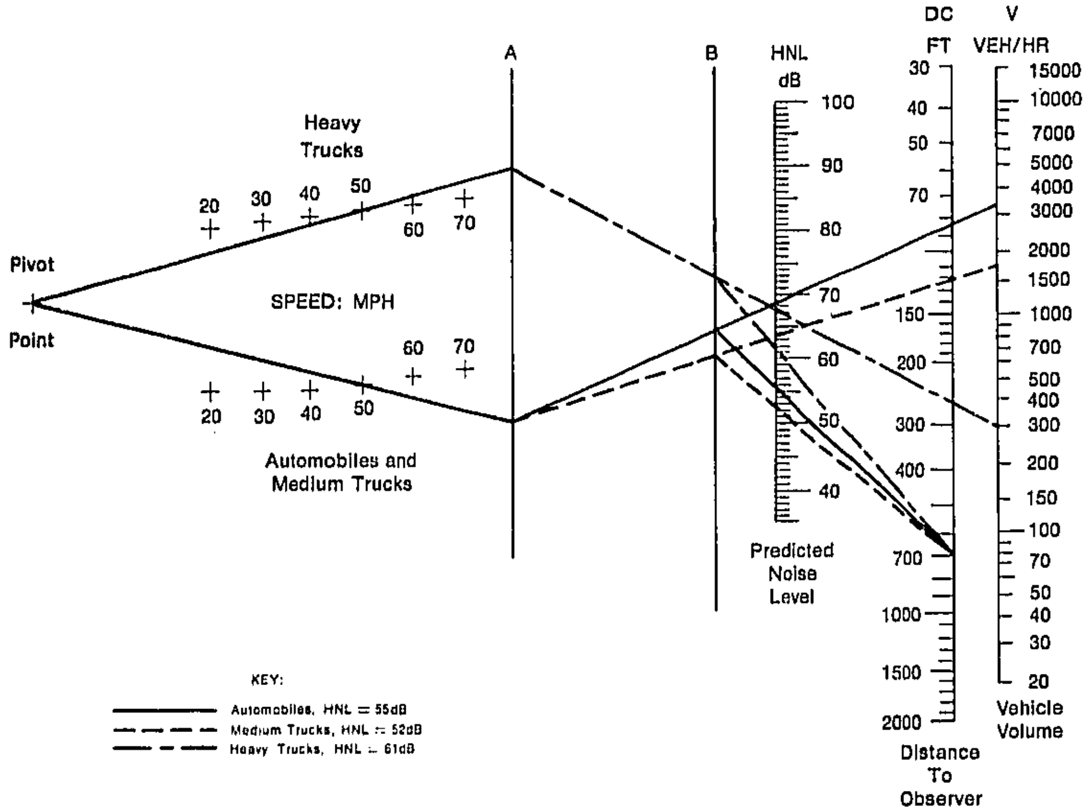


Figure 5.5–7. Highway Noise Nomogram for Highway #1 of Example.

STEP H7 MEDIUM TRUCK NOISE LEVEL FOR HIGHWAY #1

This general procedure is repeated for medium trucks using a corrected vehicle volume, VMC, calculated as:

$$VMC = 10\ VM = 10 \times 170 = 1700\ \text{veh/hr},$$

and using the values SM = 50 mph and DC = 700 ft. The predicted value of Ldn is an A-weighted sound level of 56 dB.

STEP H8 HEAVY TRUCK NOISE LEVEL FOR HIGHWAY #1

For heavy trucks the procedure is again repeated (using the top scale of vehicle speeds) with the values SH = 50 mph, VH = 290 veh/hr and DC = 700 ft. The predicted value of Ldn is an A-weighted sound level of 65 dB.

STEP H9 PATH LENGTH DIFFERENCE

Next, the shielding adjustments are determined for the earth berm of Highway #1. The path length difference for autos and medium trucks is,

$$Aa/m = \sqrt{HB^2 + (DC - DB)^2} = \sqrt{19^2 + (700 - 610)^2} = 82.23\ \text{ft},$$

$$Ba/m = \sqrt{(HB + hB)^2 + DB^2} = \sqrt{(19 + (-95))^2 + 620^2} = 624.64\ \text{ft},$$

$$Ca/m = \sqrt{hB^2 + DC^2} = \sqrt{(-95)^2 + 700^2} = 706.42\ \text{ft},$$

$$La/m = Aa/m + Ba/m - Ca/m = 0.45\ \text{ft}.$$

STEP H10 SHIELDING CORRECTION— "INFINITE" BARRIER

The A-weighted shielding correction, CSA/M, is determined from Figure 5.2-11 to be approximately 6 dB. [Note that this value of attenuation is for the top floor, which for this example is the worst case. If some other floor is of interest, the value of CSA/M should be recalculated.] This value is recorded on Highway Worksheet 2 (Figure 5.5-6). Since the included angle is approximately 180°, the earth berm can be considered infinite and no further adjustment is needed.

As shown in Figure 5.5-5, the line-of-sight between the top floor and the effective source height for heavy trucks is not broken. Thus, there is no shielding for the upper floors for the noise from heavy trucks and the value of CSH for the top floor is zero.

STEP H14 TOTAL NOISE LEVEL FOR HIGHWAY #1

The total noise from Highway #1 is computed by logarithmic combination of the levels of the three types of vehicles after shielding corrections have been subtracted from unshielded levels. Then, the levels (automobiles—53 dB; medium trucks—50 dB; and heavy trucks—65 dB) are summed to give,

$$\left.\begin{array}{l} \left.\begin{array}{l}50\\53\end{array}\right\}\dfrac{\text{diff.} = 3}{\text{add } 2}\ 55 \\ 65 \end{array}\right\}\dfrac{\text{diff.} = 10}{\text{add } 0}\ 65\ \text{dB}.$$

These calculations indicate that heavy truck traffic is the predominant source of noise from Highway #1, even though heavy trucks comprise only 7 percent of the total daily traffic volume. The total noise due to Highway #1 could be lowered if the height of the earth berm were increased (hence, the attenuation), or if the truck traffic volume were reduced.

STEPS H3–H6, H14 TOTAL NOISE LEVEL FOR HIGHWAY #2

Similar results are obtained for Highway #2 by performing these same calculations, except there is no medium truck component and no shielding corrections. The A-weighted day-night sound levels are 52 and 58 dB for autos and heavy trucks, respectively. The total noise due to Highway #2 at the building site is an A-weighted day-night sound level of 59 dB.

Heavy truck noise is also the predominant source of noise from Highway #2. The total noise due Highway #2 could be lowered if the heavy truck traffic volume were reduced or if a barrier of sufficient height were constructed.

STEP H15 TOTAL NOISE LEVEL FROM HIGHWAYS #1 AND #2

The levels from the two highways are combined to obtain the total level at the building site due to all highways. This combination gives a total A-weighted day-night sound level of 66 dB. From these values, it is seen that the total noise at the building site from the two highways is predominantly due to the heavy truck component of Highway #1.

Railway Noise Prediction

As seen from the map of the area, Figure 5.5-8, there is also a railway which affects this hypothetical building site. This railway consists of two tracks and is shielded from the building by an earth berm.

STEP R1.1 RAILWAY TO BUILDING SITE DISTANCE

First, the railway-building site distance is

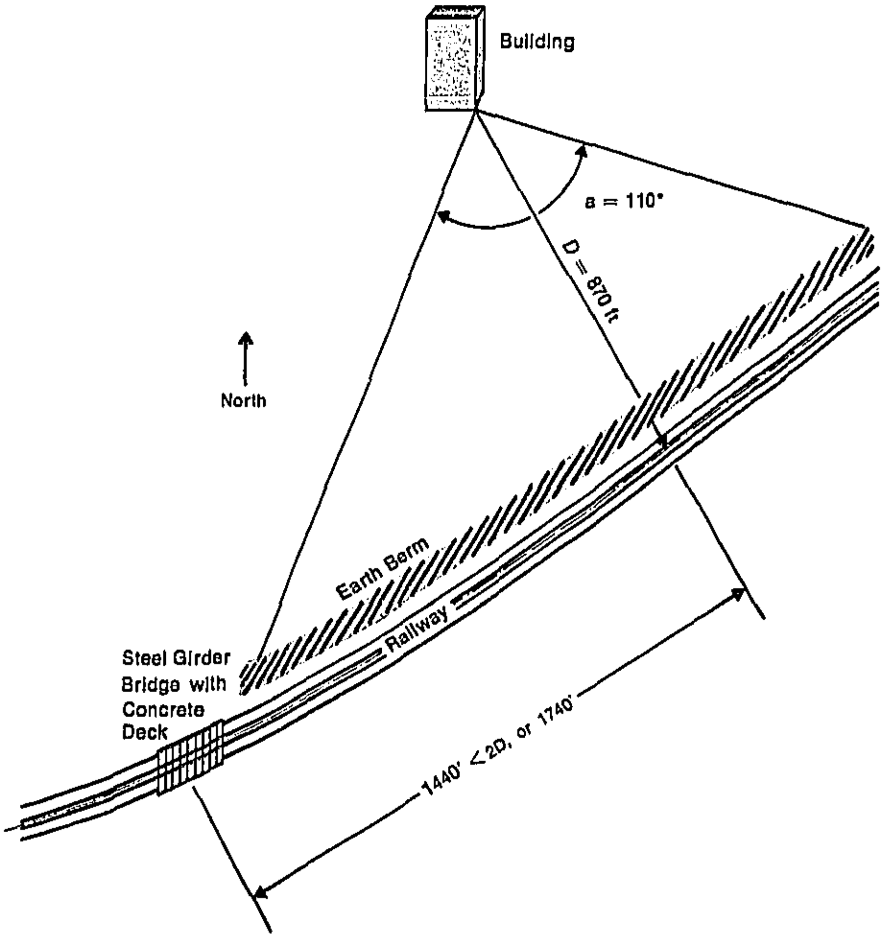


Figure 5.5-8. Local Map Showing Details of Railway.

Railway Worksheet 1

Building Project 10-Story Apartment	Railway Number 1
Location Near Highways 1 & 2	Site point or building room for which sound pressure levels are being estimated Top floor NW
Owner Modern Realty Designer C. Suggs	Date 1 July 77 Revised

Railway—Building Site Distance: D (Feet) 870'

	Freight Trains		Conventional Passenger Trains		Rapid Transit Trains	
Does this type of train use the track being analyzed?	YES		YES			
Diesel-Electric or All-Electric Locomotive	DE	NL 2	DE	NL 1		
Average Train Speed, s mph	50		80			
Average number of cars, nc	100		10			
Average train length, LT, feet	5500		750			
Average Number of Passbys						
a) Leq(1) : N1						
b) Leq(8) : N8						
c) Leq(24) : N24						
d) Ldn	ND 15	NN 5	ND 30	NN 10	ND	NN
Diesel-Electric Locomotive						
Reference Level, LS	99		97			
Distance Attenuation, DAL	15		15			
Railway Cars						
Reference Level, CL	84		90			
Duration Factor, CD	19		8			
Track Characteristics, CT	5		5			
Distance Attenuation, DAC	17		17			

Predicted Noise Levels		Diesel-Electric Locomotive	Railway Cars	Diesel-Electric Locomotive	Railway Cars	Railway Cars
a) Leq(1)	CN1					
	C1					
	Leq(1) No Shielding					
	Total Shielding Correction (Railway Worksheet 2)					
	Leq(1) Corrected for Shielding					
b) Leq(8)	CN8					
	C8					
	Leq(8) No Shielding					
	Total Shielding Correction (Railway Worksheet 2)					
	Leq(8) Corrected for Shielding					
c) Leq(24)	CN24					
	C24					
	Leq(24) No Shielding					
	Total Shielding Correction (Railway Worksheet 2)					
	Leq(24) Corrected for Shielding					
d) Ldn	CN	90	45	90	90	
	CDN	20	17	20	20	
	Ldn No Shielding	55	59	53	57	
	Total Shielding Correction (Railway Worksheet 2)	2	4	2	4	
	Ldn Corrected for Shielding	53	55	51	53	
Total Railway Noise	59					

Figure 5.5–9. Railway Worksheet 1 for Railway of Example.

Railway Worksheet 2

Building Project 10-Story Apartment
Location Near Highways 1+2
Owner Modern Realty

Railway Number 1
Site point or building room for which sound pressure levels are being estimated Top floor NW
Designer C. Suggs
Date 1 July 77 Revised -

Railway—Building Site Distance: D (Feet) ————

Shielding Geometry	Barrier,				Elevated Railway			Depressed Railway			
	DB	HB	hB	a	DE	HE	a	DD	HD	hD	a
	810'	32'	-65'	110'							

Path Length Difference					
Railway Cars	Ac	Bc	Cc	Lc
	68.0'	810.67'	872.42'	6.25'
Diesel-Electric Locomotive	Al	Bl	Cl	Ll
	62.36'	810.67'	871.44'	0.40'

Correction For "Infinite" Shielding Element	Railway Cars	Diesel-Electric Loc.
	CSC	CSL
	12	5

Correction For "Finite" Shielding Element	Railway Cars	Diesel-Electric Loc.
	Included Angle Ratio, RA	
	CSC	CSL
	4	2

Building Barrier	nr		CSB	
Vegetation	dw		CSV	

Total Shielding Correction	Railway Cars	Diesel-Electric Loc.
	CSC + CSB + CSV	CSL + CSB + CSV
	4	2

Track Characteristics

a		b	c	d		
				Bridgework		
Welded Track	Jointed Track	Presence of Switching Frog or Grade Crossing	Radius of Tight Curve (< 900 Feet) in Feet	Concrete Structure	Steel Girder with Concrete or Open Tie Deck	Steel Girder with Steel Plate Deck
✓					✓	

Figure 5.5–10. Railway Worksheet 2 for Railway Example.

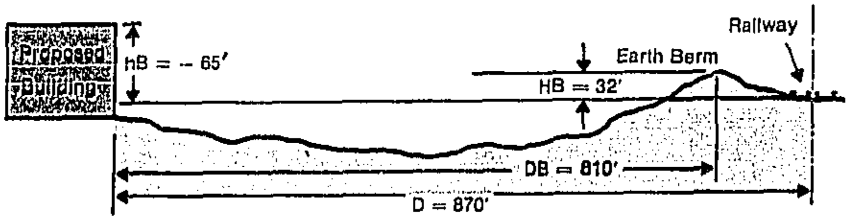


Figure 5.5–11. Cross-Section Showing Railway Earth Berm.

determined from a map of the local area (Figure 5.5–8). This distance is approximately 870 feet. This value is recorded on both Railway Worksheets 1 and 2, Figures 5.5–9 and 5.5–10, respectively.

STEP R1.2 TRACK CHARACTERISTICS

The track is welded and there is a steel girder bridge with a concrete deck within 2D (1740 feet) of the intersection of the railway with the nearest perpendicular distance (see Figure 5.5–8).

STEP R1.3 BARRIER DATA

The necessary distances for evaluating the shielding provided by the earth berm are determined from a cross-sectional drawing of the railway (Figure 5.5–11). These distances, which are determined for the top floor (worst case as far as shielding is concerned), are:

D = 870 ft	HB = 32 ft	a = 110°
DB = 810 ft	hB = −65 ft	

These values are recorded on Railway Worksheet 2 (Figure 5.5–10).

STEP R1.4 VEGETATION AND BUILDINGS AS BARRIERS

There is no vegetation or intervening rows of buildings that would effectively shield the roadway from a room on the top floor.

As mentioned previously in the highway noise predictions, if a room on the ground floor were analyzed, shielding due to vegetation or intervening rows of buildings might have to be taken into account. Also, the shielding due to the earth berm would be different for the ground floor.

STEP R2 TRAIN DATA

It is determined that only freight trains and conventional passenger trains use the track and that they are normally pulled by diesel-electric locomotives—on average, two locomotives for freight trains and one for passenger trains. Average train speeds are 50 mph for freight trains and 80 mph for conventional passenger trains. The average train length is not available, but the average number of cars is estimated to be 100 for freight trains and 10 for conventional passenger trains. The train lengths are then estimated to be

LT = 55 × nc = 55 × 100 = 5500 feet (freight trains),
LT = 75 × nc = 75 × 10 = 750 feet (conventional passenger trains).

The average number of passbys is

ND = 15, NN = 5 (freight trains),
ND = 30, NN = 10 (conventional passenger trains).

These values are recorded on Railway Worksheet 1 (Figure 5.5–9).

STEPS R3–R5 *DIESEL-ELECTRIC LOCOMOTIVE NOISE LEVEL FOR FREIGHT TRAINS*

Using the average speed, S = 50 mph, the reference level is determined from Figure 5.3–8, LS = 99 dB (STEP R3). From Figure 5.3–9 (STEP R4) the distance attenuation is determined to be,

DAL = 15 dB. The factor CN (STEP R5.4) is calculated as:

CN = (ND + 6NN) NL = (15 + 6 × 5)2 = 90

With this value, CDN is determined from Figure 5.3–10 to be approximately 20 dB. The unshielded A-weighted day-night sound level is then calculated,

Ldn = LS + CDN − DAL − 49 = 99 + 20 − 15 − 49 = 55 dB.

STEPS R6–R10 RAILWAY CAR NOISE LEVEL FOR FREIGHT TRAINS

Using the average speed of 50 mph, the reference level is determined from Figure 5.3–11, CL = 84 dB (STEP R6). The passby duration factor (STEP R7) is determined from Figure 5.3–12 to be, CD = 19 dB. For welded track and a steel girder bridge with a concrete deck within 2D (1740 ft), the track adjustment factor (STEP R8) is 5 dB (Table 5.3–1). The distance attenuation for railway cars (STEP R9) is determined from Figure 5.3–9, DAC = 17 dB. The factor CN (STEP R10.4) is calculated as,

$$CN = ND + 6NN = 15 + 6 \times 5 = 45$$

With this value for CN, CDN is determined from Figure 5.3–10 to be approximately 17 dB. The unshielded A-weighted day-night sound level is then calculated,

$$Ldn = CL + CD + CT + CDN - DAC - 49,$$

$$Ldn = 84 + 19 + 5 + 17 - 17 - 49 = 59 \text{ dB}.$$

STEPS R3–R10 CONVENTIONAL PASSENGER TRAIN NOISE LEVEL

These procedures are repeated for conventional passenger trains using the appropriate speed, train length, and number of passbys listed on Railway Worksheet 1 (Figure 5.5–9). The calculated results, excluding shielding, are, Ldn = 53 dB for the diesel-electric locomotives and Ldn = 57 dB, for the passenger coaches.

STEP R11 PATH LENGTH DIFFERENCE

Next, the shielding adjustments are determined for the earth berm. The path length difference for railway cars is,

$$Ac = \sqrt{HB^2 + (D - DB)^2} = \sqrt{32^2 + (870 - 810)^2} = 68.0 \text{ ft},$$

$$Bc = \sqrt{(HB + hB)^2 + DB^2} = \sqrt{(32 + (-65))^2 + 810^2} = 810.67 \text{ ft},$$

$$Cc = \sqrt{hB^2 + D^2} = \sqrt{(-65)^2 + 870^2} = 872.67 \text{ ft},$$

$$Lc = Ac + Bc - Cc = 6.25 \text{ ft}.$$

Similarly the path length difference for diesel-electric locomotives is,

$$Al = \sqrt{(HB - 15)^2 + (D - DB)^2} = \sqrt{(32 - 15)^2 + (870 - 810)^2} = 62.36 \text{ ft},$$

$$Bl = Bc = 810.67 \text{ ft},$$

$$Cl = \sqrt{(hB + 15)^2 + D^2} = \sqrt{((-65) + 15)^2 + 870^2} = 871.44 \text{ ft},$$

$$Ll = 0.25\,(Al + Bl - Cl) = 0.40 \text{ ft}.$$

STEP R12 SHIELDING CORRECTION—"INFINITE" BARRIER

The A-weighted shielding corrections are determined from Figure 5.3–13 to be,

CSC = 12 dB (railway cars),
CSL = 5 dB (diesel-electric locomotives).

[Note that these values of attenuation are for a room on the building's top floor, which for this example is the worst case. If a room on some other floor is of interest, the values of CSC and CSL should be recalculated.] These values of CSC and CSL are recorded on Railway Worksheet 2 (Figure 5.5–10).

STEP R13 SHIELDING CORRECTION—"FINITE" BARRIER

For this case the included angle ($a = 110°$) is less than 170°, and the shielding corrections must be adjusted to account for this. The factor RA is calculated to be,

$$RA = \frac{a}{180°} = \frac{110°}{180°} = 0.61.$$

With this value the adjusted shielding corrections are determined from Table 5.3–2,

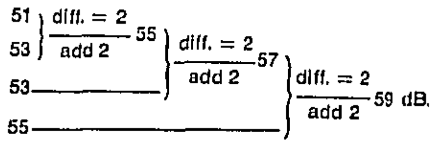
CSC = 4 dB; CSL = 2 dB.

These values are recorded on Railway Worksheet 2 (Figure 5.5–10). Note the large reduction in barrier attenuation, particularly for railway cars (12 dB to 4 dB), because of the barrier's finite length ($a < 170°$). This illustrates the importance of maximizing a barrier's length, hence its included angle so that sound cannot propagate around the ends.

Now skip to Step R16, since Steps R14 and R15 are not needed for this example.

STEP R16 TOTAL RAILWAY NOISE LEVEL

The total railway noise level is computed by combining the individual components calculated in the previous steps. First, the shielding corrections from Railway Worksheet 2 (Figure 5.5–10) are subtracted from the unshielded levels. Then the levels are combined using Table 5.3–4 to give the total A-weighted day-night sound level for railways to be used in Chapter 6.



Aircraft Worksheet 1

Building Project *10-Story Apartment*
Location *Near Highways 1 & 2*
Owner *Modern Realty*

Site point of building room for which sound pressure levels are being estimated *Top floor NW*
Designer *C. Suggs*
Date *1 July 77* Revised

	Contour Maps Available					
1	If Building is on or very near Contour #1 or #2, Record that value on Line 11. If not, obtain the data of Lines 2 and 3.					
2	Contour Values	CNR or NEF #1		CNR or NEF #2		
3	Building Location Between Contours #1 and #2	X1	X2	R	C5	C10
4	CNR or NEF Value At The Building Site				Also Record on Line 11	
	Contour Maps Not Available					
5	Number of Jet Operations	NJday	NJnight	NJeff		
		25	10	195		
6	Airport Category (Check One)	1	2	3	4	
			✓			
7	If building is on or very near the NEF 30 or NEF 40 Contour, record that value on Line 11. If not, obtain the data on Line 8.					
8	Building Location Between NEF 30 and NEF 40 Contours	X1	X2	R	C10	
		4,500	5,000	1.1	6	
9	NEF Value At The Building Site			34	Also Record on Line 11	
10	Number of Operations	NJday	NJnight	N(8)	N(1)	
11	CNR or NEF Value At The Building Site	NEF 34				
12	Convert CNR to NEF Value					
13	Aircraft Noise Level At The Building Site					
	1) 1-Hour Energy Equivalent Sound Level, Leq(1)	R1	C1	Leq(1)		
	2) 8-Hour Energy Equivalent Sound Level, Leq(8)	R8	C8	Leq(8)		
	3) 24-Hour Energy Equivalent Sound Level, Leq(24)	R24	C24	Leq(24)		
	4) Day-Night Sound Level, Ldn			Ldn		
				69		

Figure 5.5-12. Aircraft Worksheet 1 for Airport of Example.

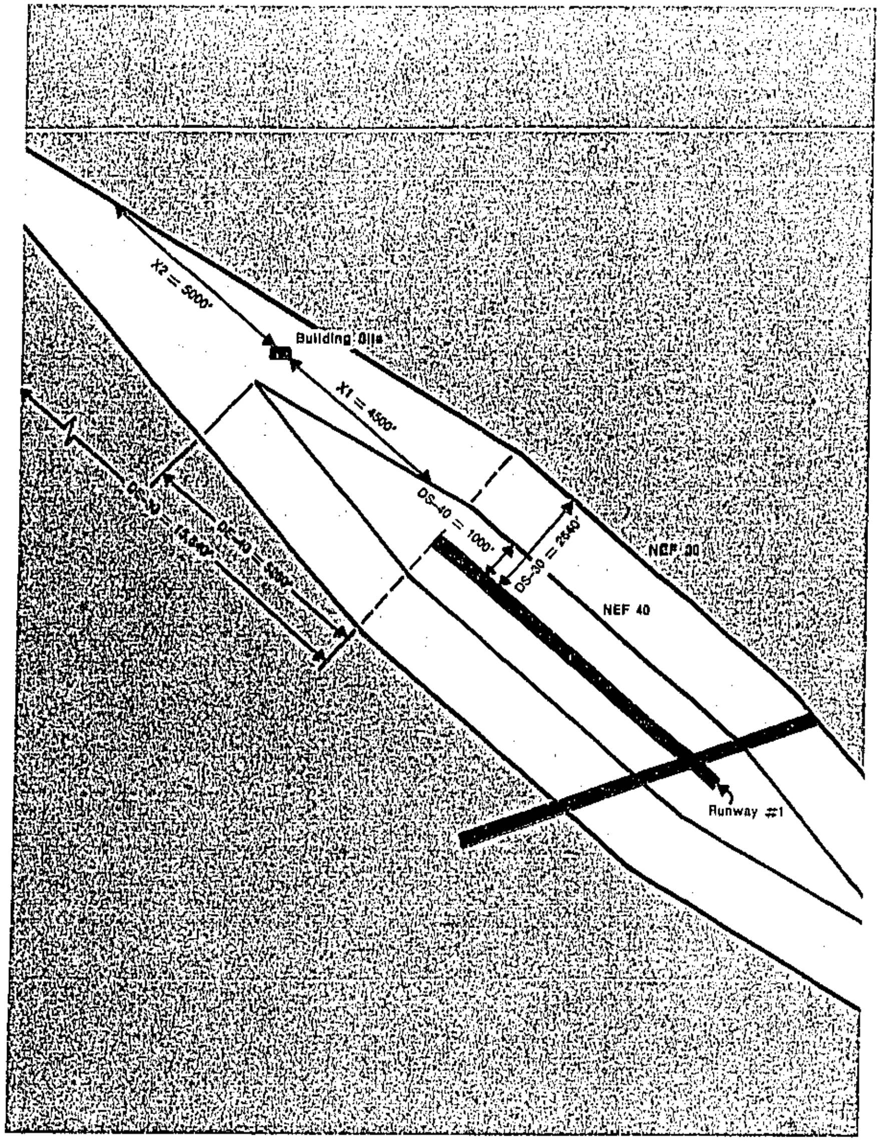


Figure 5.5–13. Mapping of Approximate NEF Contours for Runway #1.

Since the four component noise levels are about the same value, there is no dominant component as there is for highway noise (heavy trucks). Comparing the total highway noise level to the total railway noise level (about 66 dB versus 59 dB), it is obvious that highway traffic is the predominant source of noise for the building site (without considering aircraft noise). Hence, even though the railway noise level could be lowered by increasing the height or the length of the barrier, the total site noise would not significantly change.

Aircraft Noise Prediction

As seen from the map of the area, Figure 5.5-1, there is an airport which affects this hypothetical building site. This commercial airport consists of two major runways which handle a variety of air traffic including jet aircraft. The end of Runway #1 is about one mile from the building site.

STEP A1 AIRPORT DATA

First, it is determined that noise rating contour maps have not been constructed. Since there are no contour maps, STEP A1.3 must be performed. The number of "daytime" jet operations is, NJday = 25; and the number of "nighttime" jet operations is NJnight = 10. Since the metric being used is Ldn, no further information is needed on the number of operations (STEP A1.4). These values are recorded on Aircraft Worksheet 1, (Figure 5.5-12).

Now skip to Step A3, since Step A2 is not needed for this example.

STEP A3 NEF RATING AT BUILDING SITE—CONTOUR MAPS NOT AVAILABLE

The "level of activity" of the airport is based on the effective number of jet operations given by,

$$NJeff = NJday + 17\ NJnight = 25 + 10 \times 17 = 195.$$

From the data of Table 5.4-2, this corresponds to airport category 2. Approximate NEF contours are mapped as shown on Figure 5.5-13 for Runway #1, because this is the runway nearest to the building site and hence the one most likely to affect the proposed building. Since the building is located between the NEF 30 and NEF 40 contours, an interpolated value must be calculated. First, the distance ratio, R, is calculated as follows:

$$R = \frac{X2}{X1} = \frac{5000}{4500} = 1.1.$$

With this value, the factor C10 is determined from Table 5.4-4 to be C10 = 6. The rating at the building site is then approximated as,

$$NEF = 40 - C10 = 40 - 6 = 34.$$

STEP A4 AIRCRAFT NOISE LEVEL

The A-weighted day-night sound level is then calculated to be,

$$Ldn = NEF + 35 = 34 + 35 = 69\ dB.$$

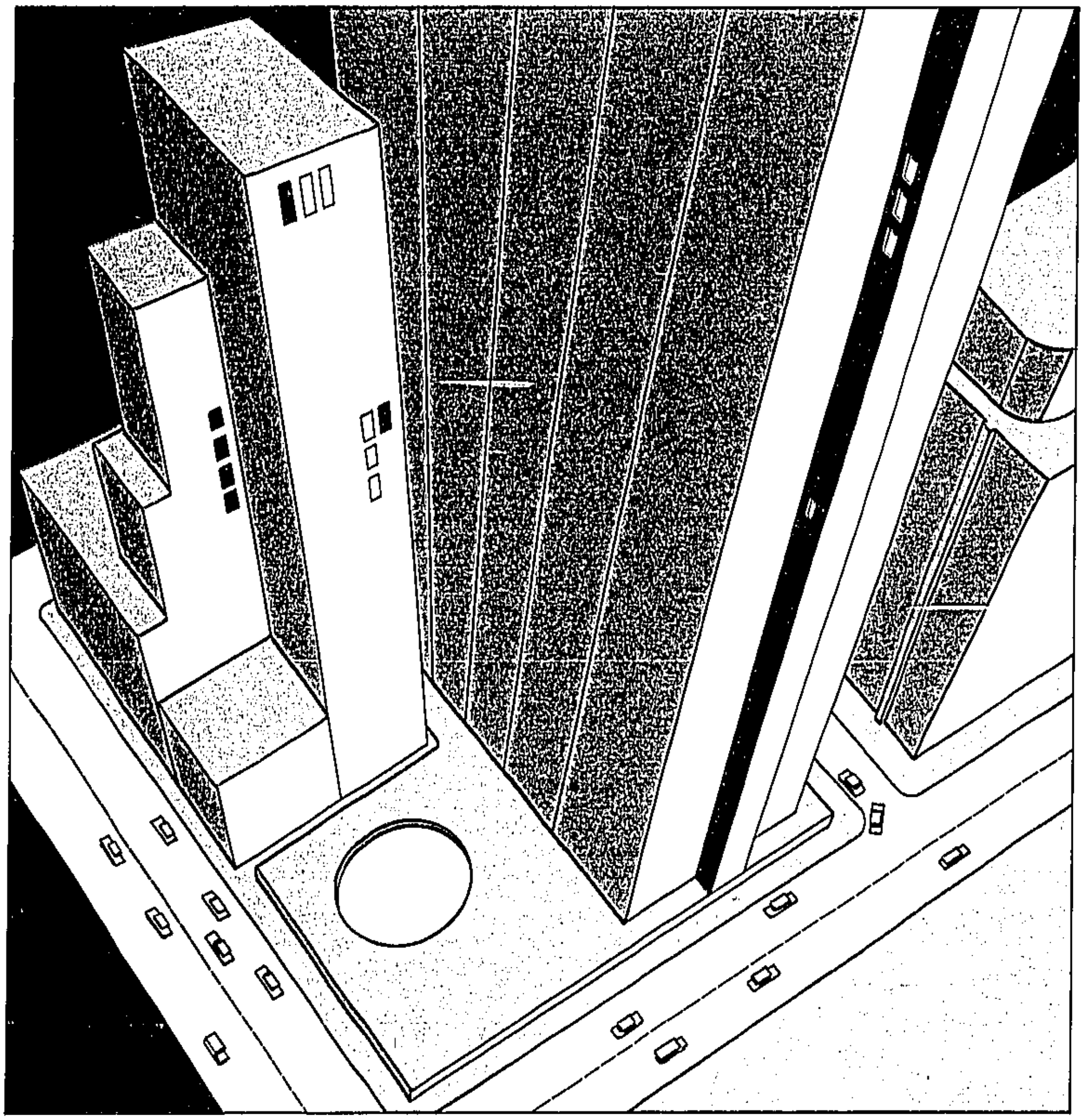
Thus, the A-weighted day-night sound level for aircraft to be used in Chapter 6 is 69 dB.

Total Building Site Noise Level

The A-weighted day-night sound level contributions from the two highways, railway and airport are,

Highway Traffic	66 dB,
Railway	59 dB,
Aircraft	69 dB.

The total exterior noise level at the building site, which is the summation of these four contributions, is an A-weighted day-night sound level of 71 dB. The two predominant sources of noise at the site are aircraft and heavy truck traffic on Highway #1. The highway traffic noise could be reduced by increasing the height of the earth berm along Highway #1, but this would have no effect on aircraft noise. The aircraft noise level could be lowered by reducing the number of operations, in particular the number of "nighttime" operations, but to effectively lower the total exterior noise level at the site, the contributions from both sources would have to be reduced.



Chapter 6
How to Make an Analysis of Outdoor Activity Area and Indoor Sound

You have now identified potentially troublesome sources of highway, railway, and/or aircraft noise near your building site; in Chapter 4 you selected a point, or points, on your site for estimating the summed effects of sound from more than one transportation system source; and in Chapter 5, you estimated these separate source levels. Here in Chapter 6 you will make an estimate of the sound levels. Here in Chapter 6 you will make an estimate of the sound levels in outdoor activity areas and an initial analysis of the rooms in your building scheme to see if the indoor sound levels will exceed the noise criterion levels you selected in Chapter 3. If the sound levels in your outdoor activity areas or building's interior rooms do not exceed the selected noise criterion levels, you have a building scheme which should be satisfactorily quiet for its occupants. If, however, the sound levels exceed the selected noise criterion levels, you will probably want to reduce the sound levels in the rooms by employing some of the design alternatives discussed in Chapter 7.

Outdoor Activity Areas

On your proposed site you may have certain areas designated for outdoor activities. The particular use of these outdoor areas depends on the type of building you are designing, and could be the yard around a family dwelling, a park or walking mall adjacent to an office building, a courtyard for an apartment building, a schoolyard, a playground, etc. Since these areas are designed mainly for recreational use over extended periods of time, you must be concerned with their outdoor noise levels, and you will recall from Chapter 3, that the suggested noise criterion for outdoor noise (especially for residential occupancies) is an Leq or Ldn of 55dB.

The total outdoor noise level is obtained by combining the noise levels generated by each of the transportation systems, as calculated in Chapter 5. Since these levels are logarithmic in nature, they cannot be simply added together or averaged to get the total noise level. Instead, they are combined, two values at a time, with the use of Table 6–1 (same procedure as STEPS H14 and R16 for combining individual components to get the total highway and railway noise level respectively). Starting with the two smallest levels, subtract one from the other to get the difference. With this value go to Table 6–1 and determine the level adjustment which is to be added to the larger of the two original noise levels. Now repeat this procedure with this adjusted level and another of the transportation system noise levels. Continue this computation until all components have been combined into one value. For example, consider the hypothetical case given in Section 5.5, where there are two highways, a railway, and an airport which generate noise heard at the building site. The A-weighted day-night sound levels are:

highway .... 66 dB
railway .... 59 dB
aircraft .... 69 dB.

The total outdoor day-night sound level is,

59 } diff. = 7, add 1 → 67
66 }
67 } diff. = 2, add 2 → 71dB.
69 }

Table 6–1. Transmission and Level Adjustments for Shell Isolation Ratings and Noise Levels.

Absolute Difference Between SIRs or Noise Levels	Transmission and Level Adjustment
>10	0
4–9	1
2–3	2
0–1	3

After you have determined the total sound levels for the outdoor activity areas on your site, compare their values with the noise criterion levels for such areas as discussed in Chapter 3. If the estimated sound levels are less than the noise criterion levels there will probably be no noise problems; but if the noise criterion levels are exceeded, these areas may not be fit for outdoor use. If noise problems are due to aircraft flyovers, there is no simple solution aside from choosing a new site. If noise problems are due to ground transportation (highways and/or railways) you may be able to construct sound barriers which can reduce the outdoor noise levels below the noise criterion levels. Also, you may be able to orient the building in such a way that the building itself will act as a barrier and shield the outdoor areas. This, of course, will depend on the size and location of the outdoor areas relative to your proposed building. These and other design alternatives are discussed in Chapter 7.

Interior Sound Level

The prediction of interior sound levels due to exterior transportation system noise sources will be determined by combining information obtained in preceding chapters on exterior noise levels with estimates of the noise isolation that will be afforded by the building shell, consisting of walls, roofs, and floors exposed to exterior noise. This guide's method is to perform an analysis, which presumes that you now have completed a building scheme in sufficient detail to perform such an analysis. It is further presumed that your building scheme is somewhat fixed, but still sufficiently flexible to permit room-by-room design revisions to reduce sound levels in these rooms below the noise criterion levels.

The acoustic analysis of your building is to be made on a room-by-room basis. This approach respects the physics of sound propagation . . . the sound travels from its source to the proposed building shell, and then is partially transmitted to the interior through the shell itself, or penetrates the shell through any openings. Once inside a room, the sound is absorbed by the surfaces of the room and its furnishings. The guide's method presumes that interior room walls prevent the spread of sound to adjacent rooms.

It is presumed that you will want to estimate the *maximum* protection against external noise that your building can provide. Obviously, protection is reduced by such elements as open windows and doors, or by ventilation ducts or apertures leading directly to the exterior through which sound energy can enter the building. For this reason, the design guide's procedures assume that all ventilation is forced, that the ventilation openings to the exterior are well muffled, and that all windows and doors are closed. Brief indications are given toward the end of this chapter of a procedure which may be used to estimate the amount of protection provided by the building shell when the windows or doors are open, although you will ordinarily not be concerned with the (reduced) protection provided in this circumstance.

Design Strategies

Although this design guide simplifies the calculations, these computations take time, and you will probably not want to make a calculation for each room . . . at least, not at the outset. Instead, you will want to select representative rooms, determine whether or not their sound levels will exceed the noise criterion levels, and then extrapolate these findings to other rooms.

Moreover, you will probably want to adopt in advance some strategy for dealing with the results of your room-by-room calculations to keep the number of computations to a minimum. If you could be sure that the sound level for each room in your building scheme would just meet its selected noise criterion level, such a strategy would not be needed; but, such an ideal situation is unlikely. Here are some suggested strategies to reduce the number of room calculations. Figure 6–1 illustrates three strategies.

Strategy 1. *No room shall have a sound level which exceeds its selected noise criterion level.* To pursue this strategy, choose the room in your building which has the lowest noise criterion level, and the greatest exposure to exterior transportation system noise. This room presents a potentially difficult design challenge and is called a "worst case" room. Run a calculation on this trial room. If the sound level within this room is at or below the selected noise criterion level, you have satisfied the strategy's objective for this room, and perhaps for all rooms in the building. If, however, there is excessive noise in this room . . . interior sound level greater than the noise criterion level . . . you should improve the room's acoustical properties and run the calculations again. This should be repeated until the noise criterion is satisfied for this first trial room. Then, select the next "worse case" room, and proceed in the same manner until its noise criterion is satisfied. Then select the third "worst case" room,

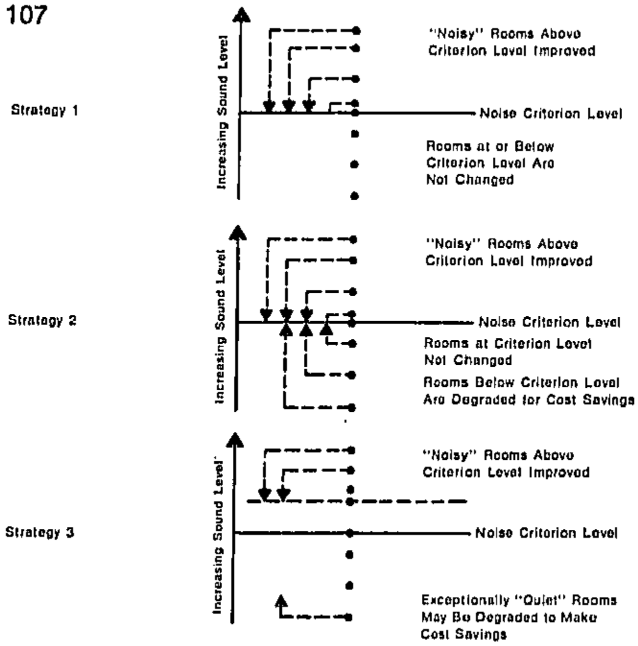


Figure 6–1. Suggested Strategies for Dealing with Noise Criteria.

and so on, until you come to the room which just satisfies its noise criterion. Then stop. At this point you can presume that all other rooms satisfy their noise criteria. Hence, you have satisfied the objective of this strategy.

Strategy 2. *The sound level for every room shall just meet its indoor noise criterion level.* The disadvantage of Strategy 1, is that it may be overly expensive, since there will be rooms, perhaps many rooms, which might have sound levels lower than their noise criterion levels. Strategy 2 requires first that Strategy 1 be followed for all rooms with noise problems, improving them one by one until each room just satisfies its noise criterion. Strategy 2 then adds a second stage, that of degrading the acoustical properties of all rooms which have sound levels less than the noise criterion levels. Of course, judgment must be exercised to ensure that cost savings would result from the design degradation of these "over-designed" rooms. If there would be no savings, it is obvious that the rooms should not be degraded.

Strategy 3. *The average sound level for the building's rooms shall not exceed their respective noise criterion levels.* The essence of this strategy is that by averaging the difference between the selected noise criterion levels and the interior sound levels, and by requiring that the average difference be zero, the average noise level of the rooms of the building will not be greater than the noise criterion level. The risk here is that a solution satisfying an average sound level could be achieved by virtue of a large number of rooms which have sound levels far above their noise criterion levels, balanced by rooms with sound levels well below their noise criterion levels. The occupants of noisy rooms would suffer from these noise conditions, and would hardly be comforted by the knowledge that other occupants had highly favorable sound conditions. To overcome this, you could set an upper limit, say 5 decibels above the noise criterion level, which would be the maximum sound level for any room. You will want to adopt some special version of this strategy to account for variations in room-by-room noise criterion levels and noise exposures.

The above are three strategies which you may wish to adopt to reduce the number of room calculations, and to deal with the results of your calculations. Perhaps you can adopt other strategies which are equally useful. In any event, you should probably begin by running two trial rooms . . . your "worst case", the room with the lowest noise criterion level and the greatest exposure to transportation system noise, and . . . your "best case", namely, the room with the highest noise criterion level and the least exposure, but still some exposure, to exterior transportation system noise. The results of these two room calculations will give you the expected range of indoor sound levels which you can then compare with noise criterion levels.

How to Choose "Worst Case" and "Best Case" Rooms for Trial Calculations

Choosing "worst case" and "best case" rooms depends upon . . . (1) the location of the sources of transportation noise as discussed in Chapter 4, (2) the type of building or room occupancy and its occupants, and (3) the physical characteristics of the building shell and the room whose sound level is to be calculated. These building shell and room characteristis are as follows:

- Shell construction . . . "monolithic" or composite
- Shell porosity, or air leakage, particularly that associated with "cracks" around doors and operable windows, and the joints of curtain walls, etc.
- The area of shell members enclosing a room . . . a *shell member* is defined as a portion of the exterior walls, roofs, or exposed exterior floors of a building

which separate a room from the out-of-doors. A *component* is a portion of a shell member having a construction or materials different from the parent shell member; for example, a window is a component of a wall.

- Room geometry . . . includes the area of the shell member(s) transmitting sound from the exterior, and the total surface area of the room.
- Room absorption . . . based upon the total area of all walls, floors, and ceilings of the room together with the combined surfaces of equipment and furnishings in the room, and the sound absorptivity of these various surfaces.

The above characteristics permit the calculation of the sound isolation of each shell member transmitting exterior sound to a room. The sound isolation for each shell member is then combined with that for all other room shell members to yield the total sound isolation for the room.

We noted previously that you won't want to make any more room calculations than necessary. If, however, you have a building scheme with rooms that vary widely in floor area, room geometry, room sound absorption, and room occupancy (hence noise criterion levels) . . . and if the rooms also have varying exposures and differing shell member constructions . . . then no one room is representative, and you will need to make separate calculations for each room. On the other hand, many proposed buildings will have rooms that are similar in floor area, geometry, sound absorption, occupancy, exterior noise exposure, shell construction, and so forth. For these buildings you can choose representative rooms for interior sound level calculations, and spare yourself a good deal of time and effort.

One option is to make calculations for a single room which you think has "average" design features and "average" exposure to transportation system noise. Hopefully, such a single set of room calculations would yield the "average" indoor sound level for your building scheme. More likely, however, you will remain in doubt as to whether or not the selected room was truly representative of average conditions.

A better option is to run calculations on the "worst case" and "best case" rooms. This adds only one set of calculations and tends to establish not only the range of high and low indoor sound levels, but also permits you to make a better estimate of "average" conditions midway within this range.

Examples of Choice of Representative Rooms

Now let us discuss how to choose representative rooms for a detached, single-family dwelling, a school, and a ten-story apartment building.

For the single-family dwelling, especially a small or medium-sized one, the building itself would not provide much shielding as a noise barrier; and thus in many cases the exterior sound level can be assumed to be equal on all four sides of the dwelling. Hence, the room selections could disregard the relative locations of the transportation system sound sources, and be based solely upon room configurations and room noise criteria. If one noise criterion level were selected for all rooms, then the room having the greatest external surface area . . . probably the living room . . . should constitute the "worst case", and perhaps the kitchen should constitute the "best case". If different noise criterion levels were selected for different rooms, the lowest noise criterion levels would probably be for the bedrooms . . . thus, the bedroom having the greatest external surface area should be taken as the "worst case"; conversely, a large room with the smallest external exposure and the highest noise criterion level should become the "best case".

Now consider the selection of representative rooms for a school like the one shown in Figure 6-2. Since the building is only three stories high, and the transportation system sound source is a few feet above grade, the distance from source to receiver, hence the resultant sound pressure level would vary little from one story to the next.

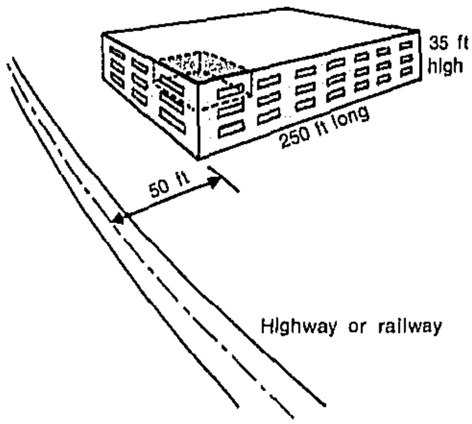


Figure 6-2. "Worst Case" Room for School.

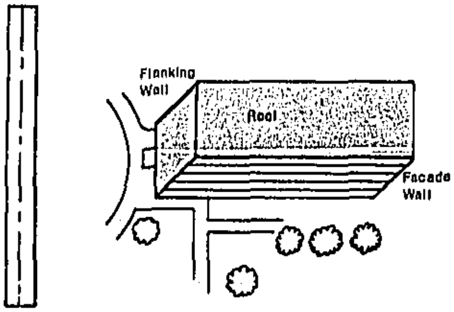
A top story room would receive almost the same sound level as a lower story room, but would have roof exposure in addition to wall exposure. Hence, a top story room near the transportation source should be selected as a "worst case" representative room. However, since the building is very long and wide, the horizontal distances from the sound source could be an important consideration and may cause sound levels to drop appreciably from a near corner of the school to a distant corner. Naturally, this variance is increased when the sound source is quite near the building. Moreover, the type of room occupancy will vary greatly in a school, and this variance may be reflected in different noise criteria, say, for an auto mechanics shop or a library. The shop could have a noise criterion level of 60 dB, whereas the level for the library could be as low as 30 dB. In addition if the principal source of noise is located on one side of the building, the building itself may provide beneficial shielding for rooms facing away from the sound source. An allowance of 3 dB may be made for this shielding effect. You will need to consider all these factors in choosing the "worst case" and "best case" rooms.

As a third example, consider the ten-story apartment building shown in Figure 6–3. Assume that this simple tower has two windowed facades and two flanking walls. In such a building it has been customary to charge a higher rent for higher floors than for lower floors. Accordingly, the designer may wish to provide a relatively quieter environment on the upper floors and select for them a lower noise criterion level. Aside from this sort of consideration, however, you can treat all stories equal, and let the location of the transportation system sound source and the building characteristics control your selection of representative rooms for trial calculations.

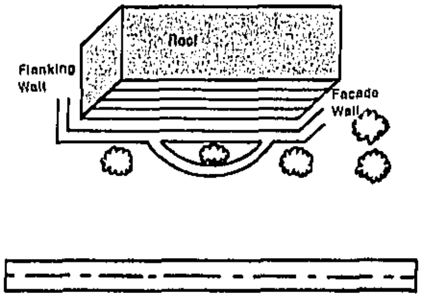
The apartment tower we are considering is a good example for our purposes since it is representative of many buildings having heavy end-walls and windowed facade walls.

We will discuss the building with respect to the three types of transportation system noise as it might come from several source locations.

Usually, if a building is exposed solely to aircraft noise, the building's orientation will make little difference, particularly if air traffic patterns vary. When averaged over many flyovers, sound pressures will not be consistently lower at any one side of the building shell. Thus, the selection of a trial room can be based upon the room's exterior shell area, and upon critical



(6–3a) Highway or Railway Noise Impinging Upon a Flanking Wall.



(6–3b) Highway or Railway Noise Impinging Upon a Facade Wall.

Figure 6–3. "Worst Case" Room for a Ten-Story Apartment Building.

noise criteria. Moreover, since apartment buildings will usually have a single noise criterion for all outside rooms, the trial room can be selected solely on the basis of exterior shell area. Hence, a large, top-story, corner room should be chosen as the "worst case" for trial calculations. A lower floor, small, non-corner, outside room should be taken for the "best case." Note that this recommended "best case" room is still an outside room, and consequently will have some exposure to aircraft noise. As such, this "best case" room could obviously not be as quiet as an interior room . . . one having no exterior shell exposure to aircraft noise. Following the above approach, the sound levels in the "worst case" and "best case" rooms will thus be representative of the range of sound levels in the rooms exposed to aircraft noise.

Now consider highway and railway noise sources. For these, the selection of trial rooms will depend heavily upon the location of the source, keeping in mind that highways and railways constitute line sources. If the sound propagates toward a flanking wall, as in drawing "a" of Figure

6–3, then the distribution of sound levels over the two facade walls will be similar with higher sound levels at the end of the facade wall near the source, diminishing to lower levels away from the source. Thus, representative trial rooms can be selected from either of the two facade walls because it is probable that the flanking walls of heavy construction and with no windows would not transmit as much sound energy as either of the facade walls. The "worst case" should be selected from rooms near the source which have low noise criteria and large exterior shell areas; the "best case" should be chosen from rooms far from the source which have high noise criteria and small exterior shell areas.

If the highway or railway sound propagates toward a facade wall, as in drawing "b" of Figure 6–3, not one but two pairs of representative rooms will be needed. The reason for this is that the building itself acts as a barrier which shields rooms on the facade wall away from the source. Hence "worst case" and "best case" rooms should be chosen from both the near and the distant facade walls.

The distribution of sound levels across the facade wall near the source is often fairly uniform. The prediction of interior sound levels for rooms with exterior walls on this facade can be handled readily by the procedures in this design guide. However, this does not hold for the facade wall facing away from the source. Here, the sound level distribution is not regular . . . sound will be diffracted around the corners of the building possibly making the end, outside rooms noisier than central, outside rooms. The same phenomenon may cause sound levels to be higher for top-story rooms than ground-floor rooms.

To estimate room sound levels on the far facade. The sound levels at the far facade shielding effect of the building itself be disregarded, which is a conservative approach, or that a maximum reduction of 3 dB be made at the central portion of the shielded facade. The sound levels at the far facade wall will, of course, be somewhat lower due to the greater distance of this facade from the source (without consideration of the shielding effect). These levels can be estimated by a set of Chapter 5 calculations separate from those for the facade wall near the sound source; or, these latter calculations can simply be reduced by the very crude rule of thumb that sound levels decrease by about 4 to 6 dB for every doubling of the distance from the source.

With respect to exterior transportation sources, all the other outside rooms of each facade of the building should have sound conditions falling between your "best case" and "worst case" rooms. However, don't hesitate to make additional trial calculations if needed to positively identify your "best case" and "worst case".

If the sound source is nearby and low, choose a first-story, outside, corner room from the facade facing the noise source as your "worst case"; and from the same facade a top story, outside, central room as your "best case". It is common practice in such buildings to design the ground level story for non-residential uses and to construct this first story differently from upper stories. If you have followed this practice, choose your "worst case" apartment room from the second story. Note that in all these selections, the "best case" is not one which would receive the least exposure to exterior, transportation system sound, because both basement rooms and inside rooms would receive less exposure to sound than the "best cases" selected above. Instead, it is the "best case" selected from rooms having a reasonable amount of exposure to the sound source.

How to Predict the Sound Level in a Trial Room

Once you select the trial rooms, you can proceed to predict their sound levels using the special procedure developed for this design guide. Your calculations will be aided by the use of two worksheets for each trial room. One worksheet provides a procedure for computing the cumulative Shell Isolation Rating (SIR) for the room in question, and is called the SIR Worksheet (See Figure 6–4). The second worksheet uses this room SIR together with the sound levels at the building estimated in Chapter 5, to predict the sound level inside the trial room. The second worksheet is called the Room Noise Worksheet (See Figure 6–5).

The purposes of the following explanation are twofold . . . one, to familiarize you with some of the principles of sound transmission through a building's shell; and . . . two, to guide you through the calculations using the worksheets. A detailed example of the calculations is presented in the concluding portion of this chapter, and you may find it helpful to refer both to the example and to the following instructions as you make your own worksheet calculations.

The amount by which the exterior sound levels are reduced by the building shell is determined by several factors . . .

(1) the area of the room's exterior shell

Building Project ______________ Owner ______________ Designer ______________

Location ______________ Site point or building room for which sound pressure levels are being estimated ______________ Date ______________ Revised ______________

		1				2				3				4				5			
a	Shell Member Number	1				2				3				4				5			
b	Shell Member Name																				
c	Shell Member Area in square feet																				
d	Shell Member Components	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
e	Component Description. Arrange components of shell members in order of decreasing SIR for each shell member. Order of shell members is optional.																				
f	Shell Member or Component SIR from Appendix A																				
g	Room Dimensions in Feet: Width																				
h	Room Dimensions in Feet: Length																				
i	Room Dimensions in Feet: Height																				
j	Room Floor Area in square feet—w × l																				
k	Component Face Dimension No. 1 in feet																				
l	Component Face Dimension No. 2 in feet																				
m	Component Area in square feet																				
n	Component B Fractional Area (Component B Area/Shell Member Area)																				
o	Difference: (SIR A − SIR B)																				
p	Composite SIR Correction Factor from Table 6-2																				
q	SIR AB = SIR B + Composite SIR Correction Factor																				
r	Component C Fractional Area (Component C Area/Shell Member Area)																				
s	Difference = (SIR AB − SIR C)																				
t	Composite SIR Correction Factor from Table 6-2																				
u	SIR ABC = SIR C + Composite SIR Correction Factor																				
v	Component D Fractional Area (Component D Area/Shell Member Area)																				
w	Difference = (SIR ABC − SIR D)																				
x	Composite SIR Correction Factor from Table 6-2																				
y	SIR ABCD = SIR D + Composite SIR Correction Factor																				
aa	Estimate of Air Leakage in square inches/100 square feet																				
bb	Adjusted SIR Based on Air Leakage from Table 6-3																				
cc	Ratio of Shell Member Area to Floor Area—Room Geometry																				
dd	Room Geometry Correction Factor from Table 6-4																				
ee	Enter +2 if acoustic ceiling or if drapes cover 50% of wall area																				
ff	Enter −4 if no carpet																				
gg	SIR Adjusted for Leakage, Area and Absorption Correction Factors																				
hh	Absolute Difference = SIR 1 − SIR 2																				
ii	Transmission Adjustment from Table 6-1																				
jj	SIR 1,2 = SIR (lower) − Transmission Adjustment																				
kk	Absolute Difference = SIR 1,2 − SIR 3																				
ll	Transmission Adjustment from Table 6-1																				
mm	SIR 1,2,3 = SIR (lower) − Transmission Adjustment																				
nn	Absolute Difference = SIR 1,2,3 − SIR 4																				
oo	Transmission Adjustment from Table 6-1																				
pp	SIR 1,2,3,4 − SIR (lower) − Transmission Adjustment																				
qq	Absolute Difference = SIR 1,2,3,4 − SIR 5																				
rr	Transmission Adjustment from Table 6-1																				
ss	Room SIR = SIR (lower) − Transmission Adjustment																				

Figure 6-4. SIR Worksheet.

Building Project ______________________ Site point of building room for which sound pressure levels are being estimated ____________

Location ______________________ Designer ____________

Owner ______________________ Date ________ Revised ________

External Noise Source	Source Level (dB) (Chap. 5)	Difference Between Highway and Railway Sound Levels (dB)	Level Adjustment (From Table 6-1)	Total Highway and Railway Sound Level (dB)	Difference Between Total Highway and Railway and Aircraft Sound Levels (dB)	Level Adjustment (From Table 6-1)	Total Exterior Sound Level (dB)	Room SIR (SIR Worksheet)	Indoor Sound Level Due to External Sources (dB)	Noise Criterion Level (dB)
A	B	C	D	E	F	G	H	I	J	K
Highway										
Railway										
Aircraft										

Is the Total Indoor Sound Level Due to External Sources Greater Than the Noise Criterion Level?	Yes ____	A Noise Problem Exists
	No ____	The Design is Satisfactory

Figure 6–5. Room Noise Worksheet.

exposed to sound . . . the greater the exposed area the more the acoustical energy (sound) transmitted;

(2) the mass, or weight, per square foot of area of such room shell members as exterior walls, roofs, and (possibly) floors which may be cantilevered, supported on piles, or otherwise exposed to exterior noise . . . heavy shell members, such as concrete or masonry walls, transmit less sound than lightweight shell members, such as curtain walls;

(3) air leakage . . . sound energy can readily enter a building even through very small openings. Thus quality of construction is important to seal small pores and cracks. Componentized construction can transmit noise because of such leakage through joints between the components;

(4) the room geometry (the ratio of exterior shell members to room floor area) . . . important in determining the relationship between the amount of energy entering the room and its sound level;

(5) the average acoustical absorptivity of the room's interior surfaces . . . carpeted floors absorb more sound than hard floors; acoustic ceilings absorb more than smooth plaster or gypsum board ceilings; and over-stuffed or heavily upholstered furniture, drapes, and other sound absorptive elements reduce room sound levels.

A precise estimate of the sound isolation of the shell would involve an analysis by discrete frequency bands using transmission coefficient data. However, to simplify the estimation of the isolation provided by the exterior building shell, a single-figure rating system, the Shell Isolation Rating (SIR), has been especially devised for this guide. The SIR number is a measure of the A-weighted sound level reduction that can be expected when certain building shell materials are used. This rating number is determined from available laboratory measurements of acoustic transmission loss data versus frequency. Selected shell assemblies and components are tabulated with their SIR values in Appendix A. The technical basis for the SIR method and a technique for determining this rating for shell assemblies not listed in Appendix A is explained in Appendix *B*.

To account specifically for the above effects of the building shell in reducing exterior sound levels, you will be using one SIR Worksheet for each room in your proposed building for which interior sound level estimates are needed. Let's scan the SIR Worksheet in Figure 6–4 and the flow chart of Figure 6-6 to become familiar with the necessary calculations. The SIR Worksheet can account for one room having as many as five shell members, enumerated in Column (a) of the worksheet. Thus, the SIR Worksheet can handle a free-standing room such that four walls and the roof are exposed to sound energy, or a room cantilevered from the face of a building such that three walls and the floor and roof of the room are exposed. If you have a room with more than five shell members, you can disregard one or two shell members which acting by themselves would transmit the least amount of sound; or, you can combine pairs of adjacent, similar shell members, treating each pair as if it were a single shell member having the size and componentization of the two shell members put together. For most rooms, however, the SIR Worksheet's accommodation for five shell members should suffice.

Since many shell members (such as walls) are made up of more than one component (such as windows, doors, subpanels, etc.), the SIR Worksheet is arranged to account for as many as four components within each shell member; the four being labeled A, B, C, and D down Column (d) of the worksheet. If you have shell members with more than

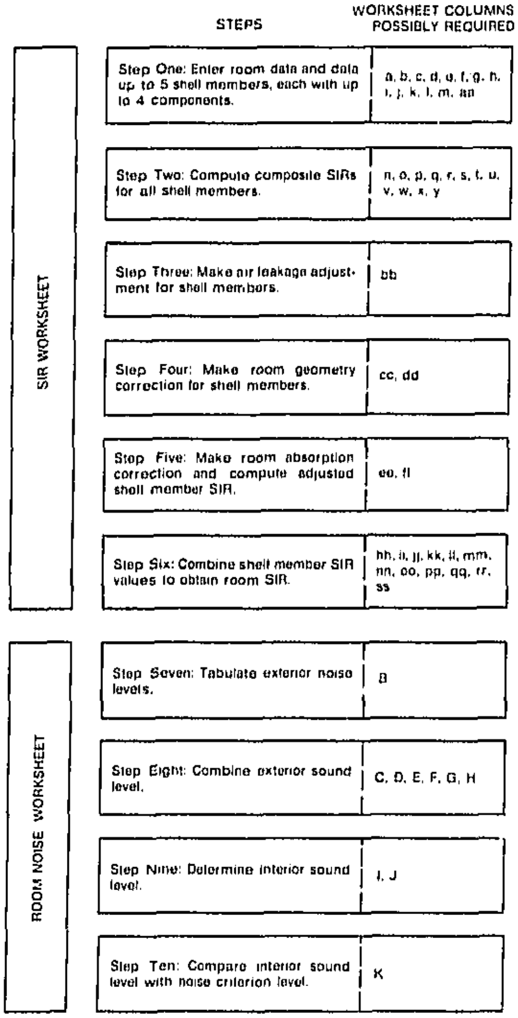


Figure 6–6. Flow Chart for Steps of the SIR and Room Noise Worksheets.

four components, you will have to extend the step-wise procedure for combining SIR values to yield the appropriate composite SIR value. The step-wise procedure is straightforward enough that you will have little difficulty in extending the procedure; although you may want to make your own specialized SIR Worksheet for this unusual case.

In summary, then, the SIR Worksheet can readily provide the shell isolation rating for a single room in your building, when the room has a maximum of five shell members, and when the shell members have a maximum of four components. If these maxima are exceeded, the special procedures described above can fit your room into the SIR Worksheet. Now, let's glance further at the provisions of the worksheet.

Columns (a, b, c, d, and e, g, h, i, j, k, l, and m) are used to enter descriptive and dimensional data from your building scheme, as is Column (aa) which provides an estimate of the air leakage based on the level of workmanship for each shell member. Column (f) receives one SIR for each monolithic shell member or one SIR for each component of componentized shell members.

The twelve columns after Column (m) are used in groups of four to calculate composite SIRs for consecutive pairs of shell members components. Thus, Columns (n, o, p, and q) are used for the composite SIR of the two components having the highest component SIR values (Components A and B); Columns (r, s, t, and u) are used for the composite SIR for Composite A–B and Component C; and, Columns (v, w, x, and y) are used for the composite SIR for Composite A–B–C and Component D. Monolithic shell members having a single type of construction require none of the Column (n) through (y) calculations . . . the shell member SIR is simply used for calculations beyond Column (y). Componentized shell members having two types of construction require the calculations of Columns (n, o, p, and q); shell members with three components require the calculations of the latter columns plus those of Columns (r, s, t, and u); and shell members with four components require the calculations of all twelve columns . . . (n) through (y).

After the composite SIR (if a composite SIR is needed) has been calculated for Shell Member Number 1, the other composite SIRs are calculated in turn for all other shell members, as required.

Then all composite (or shell member) SIRs are corrected for air leakage, room geometry, and room surface absorptivity in Columns (aa) through (gg).

Finally, these corrected SIRs for the shell members are accumulated pairwise to ultimately yield the room SIR. These calculations are made in Columns (hh, ii, and jj; kk, ll, and mm; nn, oo, and pp; and qq, rr, and ss) using three columns for each pair of shell members. The cumulative SIR for the last pair of shell members is the Room SIR, which is to be used as the entry in the Room Noise Worksheet to compute the room sound level; and in turn, to compare these sound levels with your pre-selected noise criteria.

Having described the SIR Worksheet in general terms, let us now follow its procedures step by step:

Shell Isolation Rating Prediction Method

STEP ONE: ENTER ROOM AND SHELL MEMBER DATA

Enter shell member data in Columns (b, c, and aa); and enter room data in Columns (g, h, i, and j). Note that rooms having suspended lightweight ceilings can receive exterior sound through portions of shell members extending up through the dead space of the suspended ceiling. Hence, the room "height" for noise calculations is not from the floor to the suspended ceiling, but from the floor to the underside of the floor or roof slab above the ceiling space.

In using the worksheets all values should be rounded off to the nearest whole number in feet or decibels (or decibel equivalents). The only exceptions are the interpolation factors, and the fractional area ratios which should be computed to two places to the right of the decimal point.

If the shell member is monolithic . . . all of brick veneer, or all wood frame construction, or all cinder block . . . then it is a single component shell member; Columns (k through x) can be left blank; and the shell member SIR from Column (f) can be copied into Column (y) for the monolithic shell member SIR value.

On the other hand, if the shell member has more than one component, then Columns (k, l, and m) must have entered data. *Note that the components must be arranged in the order of decreasing SIR values.* This will often mean that Component A for a shell member will overlay the shell member, and will have the SIR value, area, and overall face dimensions of the shell member itself. However, some care must be taken in this, for it presumes that the overall shell member will have a SIR value higher than any other components of the shell member. Naturally, this would be true for a masonry shell member (Component A) pierced by a window (Component B) . . . the masonry has a higher SIR value than the window. However, consider a lightweight curtain wall containing several granite panels. The stone panels, having the higher SIR value, would in this case constitute Component A, and the curtain wall would constitute Component B.

The computational procedure requires the area of each component in a componentized shell member, with the exception of the area of the component with the largest SIR number. In the case of a masonry shell pierced by a window, the area of the overall shell member is entered in Column (c), but is not required in line A of Column (m); while the area of the window is required and would be entered in line B of Column (m). For the case of the curtain wall with several granite panels, the area of the overall shell member is once again to be entered in Column (c). The total area of the several granite panels is not required; while the area of the remaining portion of the curtain wall is required and would be entered in line B of Column (m).

When a shell member has more than one component, the shell member's composite SIR may take a value only slightly higher than that of the component having the lowest SIR value.

STEP TWO: COMPUTE COMPOSITE SIR VALUES

For a shell member having two components (the shell member itself plus one other component), complete the procedures and entries of Columns (n, o, p, and q). The component fractional area of Column (n) is the ratio of the area of the component with the lower SIR value to the area of the shell member itself. The component fractional area is expressed as a decimal fraction and carried to two places to the right of the decimal point.

The difference between SIR A (for Component A) and SIR B (for Component B) is entered as a whole number in Column (o). Column (n and o) values are then used to determine a composite correction factor from Table 6-2, which is entered in column (p).

This composite correction factor is then added to SIR B to yield the composite SIR A-B to be entered in Column (q). This value is also entered in Column (y) to serve as the composite SIR for the two-component shell member.

ABSOLUTE DIFFERENCE OF SIR VALUES

COMPONENT FRACTIONAL AREA	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	38	40 AND ABOVE
1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
.90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
.80	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
.70	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
.60	0	0	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
.50	0	0	1	1	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
.40	0	1	1	2	2	2	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
.30	0	1	1	2	2	3	3	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
.25	0	1	1	2	3	3	4	4	4	5	5	5	5	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
.20	0	1	2	2	3	3	4	4	5	5	6	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
.19	0	1	2	2	3	4	4	5	5	5	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
.18	0	1	2	2	3	4	4	5	5	5	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
.17	0	1	2	2	3	4	4	5	5	5	6	6	7	7	7	7	7	7	7	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
.16	0	1	2	2	3	4	4	5	5	6	6	6	7	7	7	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
.15	0	1	2	2	3	4	4	5	5	6	6	7	7	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
.14	0	1	2	2	3	4	4	5	6	6	6	7	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	9	9	9	9	9	9	9	9	9	9	9	9
.13	0	1	2	2	3	4	5	5	6	6	7	7	7	8	8	8	8	8	8	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
.12	0	1	2	3	3	4	5	5	6	6	7	7	8	8	8	8	8	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
.11	0	1	2	3	3	4	5	5	6	6	7	7	8	8	8	9	9	9	9	9	9	9	9	9	9	9	9	10	10	10	10	10	10	10	10	10	10	10	10	10	10
.10	0	1	2	3	3	4	5	6	6	7	7	8	8	8	9	9	9	9	9	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
.09	0	1	2	3	3	4	5	6	6	7	7	8	8	9	9	9	9	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
.08	0	1	2	3	4	4	5	6	6	7	7	8	9	9	9	10	10	10	10	10	10	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
.07	0	1	2	3	4	4	5	6	6	7	8	8	9	9	10	10	10	11	11	11	11	11	11	11	11						11	12	12	12	12	12	12	12	12	12	12
.06	0	1	2	3	4	4	5	6	7	7	8	9	9	10	10	10	11	11	11	11						11	11	11	11	11	12	12	12	12	12	12	12	12	12	12	12
.05	0	1	2	3	4	5	5	6	7	7	8	9	10	10	11	11	11	12	12	12	12	12	12	12	12	12	12	12	12	12	13	13	13	13	13	13	13	13	13	13	13
.04	0	1	2	3	4	5	5	6	7	8	8	9	10	11	11	12	12	12	13	13	12	12	13	13	13	13	13	13	13	13	14	14	14	14	14	14	14	14	14	14	14
.03 50	0	1	2	3	4	5	6	6	7	8	9	10	10	11	11	12	12	13·	13	13	13	13	13	13	14	14	14	14	14	14	14	14	14	14	15	15	15	15	15	15	15
.03 00	0	1	2	3	4	5	6	6	7	8	9	10	10	11	12	12	13	13	13	14	14	14	14	14	14	14	14	14	14	14	15	15	15	15	15	15	15	15	15	15	15
.02 50	0	1	2	3	4	5	6	7	7	8	9	10	11	11	12	13	13	14	14	14	14	14	14	15	15	15	15	15	15	15	16	16	16	16	16	16	16	16	16	16	16
.02 00	0	1	2	3	4	5	5	7	8	8	9	10	11	12	12	13	14	14	14	15	15	15	15	15	15	16	16	16	16	16	17	17	17	17	17	17	17	17	17	17	17
.01 90	0	1	2	3	4	5	6	7	8	8	9	10	11	12	12	13	14	14	15	15	15	16	16	16	16	16	16	17	17	17	17	17	17	17	17	17	17	17	17	17	17
.01 80	0	1	2	3	4	5	6	7	8	8	9	10	11	12	12	13	14	14	15	15	15	16	16	16	16	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17
.01 70	0	1	2	3	4	5	6	7	8	9	9	10	11	12	12	13	14	14	15	15	16	16	16	16	17	17	17	17	17	17	17	18	18	18	18	18	18	18	18	18	18
.01 60	0	1	2	3	4	5	6	7	8	9	9	10	11	12	12	13	14	14	15	15	16	16	17	17	17	17	17	17	18	18	18	18	18	18	18	18	18	18	18	18	18
.01 50	0	1	2	3	4	5	6	7	8	9	9	10	11	12	13	13	14	15	15	16	16	16	17	17	17	17	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
.01 40	0	1	2	3	4	5	6	7	8	9	9	10	11	12	13	13	14	15	15	16	16	17	17	17	17	18	18	18	18	18	18	18	18	18	18	18	18	18	18	19	19
.01 30	0	1	2	3	4	5	6	7	8	9	9	10	11	12	13	14	14	15	15	16	16	17	17	17	18	18	18	18	18	18	19	19	19	19	19	19	19	19	19	19	19
.01 20	0	1	2	3	4	5	6	7	8	9	10	10	11	12	13	14	14	15	16	16	17	17	17	18	18	18	18	19	19	19	19	19	19	19	19	19	19	19	19	19	19
.01 10	0	1	2	3	4	5	6	7	8	9	10	10	11	12	13	14	14	15	16	16	17	17	18	18	18	18	19	19	19	19	19	19	19	19	19	19	19	20	20	20	20
.01 00	0	1	2	3	4	5	6	7	8	9	10	10	11	12	13	14	15	15	16	16	17	17	18	18	19	19	19	19	19	19	20	20	20	20	20	20	20	20	20	20	20
.00 90	0	1	2	3	4	5	6	7	8	9	10	11	11	12	13	14	15	15	16	17	17	18	18	19	19	19	19	20	20	20	20	20	20	20	20	20	20	20	20	20	20
.00 80	0	1	2	3	4	5	6	7	8	9	10	11	12	12	13	14	15	16	16	17	17	18	18	19	19	20	20	20	20	20	20	21	21	21	21	21	21	21	21	21	21
.00 70	0	1	2	3	4	5	6	7	8	9	10	11	12	12	13	14	15	16	16	17	18	18	19	19	20	20	20	20	21	21	21	21	21	21	21	21	21	21	21	21	21
.00 60	0	1	2	3	4	5	6	7	8	9	10	11	12	13	13	14	15	16	17	17	18	19	19	20	20	20	21	21	21	21	22	22	22	22	22	22	22	22	22	22	22
.00 50	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14	15	16	17	18	18	19	19	20	20	21	21	22	22	22	22	22	22	23	23	23	23	23	23	23	23
.00 40	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	14	15	16	17	18	19	19	20	20	21	21	22	22	23	23	23	23	23	23	24	24	24	24	24	24	24
.00 35	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	15	16	17	18	19	19	20	21	21	22	22	23	23	23	23	24	24	24	24	24	24	24	24	24	24
.00 30	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	16	17	18	19	20	20	21	22	22	23	23	23	24	24	24	24	25	25	25	25	25	25	25	25
.00 25	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	16	17	18	19	20	21	21	22	22	23	23	24	24	25	25	25	25	25	26	26	26	26	26	26
.00 20	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	17	18	19	20	21	22	22	23	23	24	24	25	25	26	26	26	26	26	26	27	27	27	27
.00 19	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	18	19	20	21	22	22	23	24	24	25	25	25	26	26	26	26	27	27	27	27	27	27
.00 18	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	18	19	20	21	22	22	23	24	24	25	25	26	26	26	26	27	27	27	27	27	27	27
.00 17	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	18	19	20	21	22	22	23	24	24	25	25	26	26	26	27	27	27	27	27	27	27	27
.00 16	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	18	19	20	21	22	22	23	24	24	25	25	26	26	27	27	27	27	27	27	23	28	28
.00 15	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	19	20	21	22	23	23	24	25	25	26	26	26	27	27	27	27	28	28	23	28	28
.00 14	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	19	20	21	22	23	23	24	25	25	26	26	27	27	27	27	28	28	28	23	28	28
.00 13	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	19	20	21	22	23	24	24	25	25	26	26	27	27	27	28	28	28	28	23	28	29
.00 12	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	20	21	22	23	24	24	25	26	26	27	27	27	28	28	28	28	29	23	29	29
.00 11	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	20	21	22	23	24	24	25	26	26	27	27	28	28	28	28	29	29	23	29	29
.00 10	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	20	21	22	23	24	25	25	26	25	27	27	28	28	29	29	29	29	23	29	30

Table 6–2. Composite SIR correction factors.

For a shell member having three components (the shell member itself plus two other components), complete the above procedures and entries for Columns (n, o, p, and q) and then go on to repeat similar procedures and entries for Columns (r, s, t, and u). In this process, the composite SIR A–B is combined with the SIR C (for Component C). The resultant SIR A–B–C in Column (u) is also entered in Column (y) as the composite SIR for the three-component shell member.

For a shell member having four components still another series of similar procedures and entries are completed, those for Columns (v, w, x, and y). Here, the composite SIR for the four-component shell member is the SIR A–B–C–D which appears in Column (y).

* * * * * *

The SIR value for each shell member must next be adjusted to account for air leakage. The SIR values of Appendix A assume superior workmanship which virtually eliminates air leakage. Merely "good" or "average" workmanship will result in holes or cracks which reduce the sound isolation of the building shell. In addition to holes, cracks at doors and windows, permanently open ventilators, and even open fireplace flues can reduce sound isolation.

STEP THREE: MAKE AIR LEAKAGE ADJUSTMENT

If the workmanship for any shell member is to be "excellent," you need no adjustment for air leakage (aa): simply enter the SIR from Column (y) in Column (bb). If, however, the workmanship is to be "good" or "average," refer to Table 6–3 to obtain an adjusted SIR value accounting for air leakage based upon an estimate of the opening in square inches per 100 square feet for the shell member in question entered in Column (aa).

You may be able to make a good estimate of air openings in square inches per 100 square feet from project drawings and specifications. If not you can use as a guide the estimates of air leakage given below for good and average workmanship and various types of shell member construction. To estimate air leakage corresponding to *good workmanship*, use one of the following estimates:

a) monolithic walls .... 0.75 to 1.5 $in^2/100\ ft^2$,

Table 6–3. Adjusted SIR of Composite Shell Member Dependent Upon Air Leakage Through Member

SIR of Composite Partition	Air Openings $in^2/100\ ft^2$										
	0.1	0.25	0.50	0.75	1.5	.0	4.5	6.0	7.5	9.0	12.0
62	52	48	45	43	40	37	35	34	33	32	31
61	51	48	45	43	40	37	35	34	33	32	31
60	51	48	45	43	40	37	35	34	33	32	31
59	51	48	45	43	40	37	35	34	33	32	31
58	51	48	45	43	40	37	35	34	33	32	31
57	51	47	45	43	40	37	35	34	33	32	31
56	51	47	45	43	40	37	35	34	33	32	31
55	50	47	45	43	40	37	35	34	33	32	31
54	50	47	44	43	40	37	35	34	33	32	31
53	49	47	44	43	40	37	35	34	33	32	31
52	49	47	44	42	40	37	35	34	33	32	31
51	48	46	44	42	40	37	35	34	33	32	31
50	48	46	44	42	40	37	35	34	33	32	31
49	47	45	44	42	39	37	35	34	33	32	31
48	47	45	43	42	39	37	35	34	33	32	31
47	46	44	43	42	39	37	35	34	33	32	31
46	45	44	42	41	39	36	35	34	33	32	31
45	44	43	42	41	39	36	35	34	33	32	31
44	43	43	41	40	39	36	34	33	33	32	31
43	42	42	41	40	38	36	34	33	33	32	31
42	42	41	40	39	38	36	34	33	32	32	31
41	41	40	40	39	37	36	34	33	32	31	31
40	40	39	39	38	37	35	34	33	32	31	30
39	39	38	38	38	38	35	34	33	32	31	30
38	38	38	37	37	36	34	33	33	32	31	30
37	37	37	36	36	35	34	33	32	32	31	30
36	36	36	35	35	35	33	32	32	31	31	30
35	35	35	35	34	34	33	32	31	31	30	30
34	34	34	34	33	33	32	31	31	30	30	29
33	33	33	33	33	32	32	31	30	30	29	29
32	32	32	32	32	31	31	30	30	29	29	28
31	31	31	31	31	30	30	30	29	29	28	28
30	30	30	30	30	30	29	29	29	28	28	27
29	29	29	29	29	29	28	28	28	28	27	27
28	28	28	28	28	28	27	27	27	27	27	26
27	27	27	27	27	27	27	26	26	26	26	26
26	26	26	26	26	26	25	25	25	25	25	25
25	25	25	25	25	25	25	24	24	24	24	24

b) walls with fixed windows or other panels .... 1.5 to 3.0 in²/100 ft²,
c) walls with weather stripped operable windows .... 3.0 to 4.5 in²/100 ft²,
d) walls with non-weather stripped operable windows .... 4.5 to 6.0 in²/100 ft².

To estimate air leakage corresponding to *average workmanship*, use one of the following estimates:

a) monolithic walls .... 1.5 to 3.0 in²/100 ft²,
b) walls with fixed windows or other panels .... 3.0 to 4.5 in²/100 ft²,
c) Walls with weather stripped operable windows .... 4.5 to 6.0 in²/100 ft²,
d) walls with non-weather stripped operable windows .... 6.0 to 7.5 in²/100 ft².

Enter the appropriate value of "Adjusted SIR based on Air Leakage" in Column (bb) of the SIR Worksheet.

* * * * *

A portion of the sound energy transmitted through the shell members is absorbed inside the room. This absorption is proportional to the total surface area of the interior of the room and the absorptivity of these surfaces. The information of Column (cc) is based upon an approximation of the total interior surface area. The Column (dd) value then enables you to estimate the correction required for the total surface area, and hence, absorption. This factor, taken from Table 6-4, is based upon consideration of the room depth as related to its height and length in terms of the ratio of shell member area to floor area.

The computations by which the SIR method was derived were initially based upon the assumption that the ratio of exterior partition area to floor area would be between 0.28 to 0.36. (For a rectilinear room having an eight-foot ceiling, this corresponds to a room depth from the shell member to the interior opposite the shell member of 22 to 28 feet.) If the ratio is larger, as is the case when the room depth is smaller, the room surface area and absorption will be smaller, and the sound level larger. To account for these geometrical considerations, the SIR value must be adjusted according to Step Four. Table 6-4 presents values of the "Room Geometry Correction Factor" to account for the room surface area.

STEP FOUR: MAKE ROOM GEOMETRY CORRECTION

For each shell member, enter in Column (cc) of the SIR Worksheet the ratio of the shell member area (from Column (c)) to the room floor area (from Column (j)). Refer to Table 6-4 for the value of the room geometry correction factor, and enter it in Column (dd). Note that for all roofs, whether flat or pitched, the value of the correction factor is −2.

Table 6-4. Room Geometry Correction Factors.

Exterior Shell Member Area / Room Floor Area	Correction Factor *
0.94 to 1	−2
0.67 to 0.93	−1
0.50 to 0.66	0
0.37 to 0.49	+1
0.28 to 0.36	+2
0.22 to 0.27	+3
0.17 to 0.21	+4
0.13 to 0.16	+5
0.10 to 0.12	+6

* *For all roofs regardless of pitch, use a correction factor of −2.*

* * * * *

The data of Table 6-4 are for carpeted rooms without an acoustical ceiling and without heavy drapes. Such a room is presumed to have "medium" reverberation properties. Rooms having additional acoustical absorption such as an acoustical ceiling or drapes covering 50% or more of the wall area will have lower sound levels. Conversely, rooms without carpet will have higher sound levels. These differences in room absorption require adjustments in the shell member SIRs as calculated in Step Five.

STEP FIVE: MAKE ROOM ABSORPTION CORRECTION AND COMPUTE ADJUSTED SHELL MEMBER SIR

For each shell member of your trial room determine whether an adjustment should be made for acoustical absorption other than "medium".

If the room has an acoustic tile ceiling, or 50% or more of the wall area is covered with draperies, enter a +2 in Column (ee).

If there is no carpet on the floor, no acoustic tile on the ceiling, and no heavy draperies, enter −4 as the absorption correction in Column (ff).

These corrections, taken jointly, imply that a room with wall-to-wall carpeting and acoustical tile ceiling will be approximately 6 dB quieter than an otherwise comparable room with hard ceiling and floors.

Now compute the value of the adjusted SIR which is the algebraic sum of the adjusted SIR from Column (bb) plus or minus corrections for room geometry and absorption. Enter this value in Column (gg) of the SIR Worksheet. Column (gg) values are the adjusted SIRs for each shell member.

* * * * *

The next step consists of determining a total room SIR by combining the SIR values for each of the room's shell members. If there happens to be only one shell member, the room SIR value is merely the SIR value for this shell member. If, however, there is more than one shell member, you will have to combine their SIR values in a manner similar to the method you used in Chapter 5 to combine noise levels.

STEP SIX: COMBINE SHELL MEMBER SIRs TO OBTAIN ROOM SIR

If there is only one shell member, copy its adjusted SIR value from Column (gg) in Column (ss) . . . it is your Room SIR.

If there is more than one shell member, you must complete a pairwise process of logarithmic addition, as you have done previously when combining noise levels. The SIR values in Column (gg) indicate the reduction in sound which would occur for otherwise similar rooms, each of which has only one shell member transmitting sound energy. When there are several shell members transmitting sound, the room SIR must be less than the SIR for any one shell member because of the additional energy transmitted through the other shell members.

Thus, enter in Column (hh) the absolute difference between SIR 1 (for Shell Member Number 1) and SIR 2 (for Shell Member Number 2). Refer to Table 6–1 to obtain the value of the transmission adjustment to be entered in Column (ii).

Note that when there is little difference (0 to 1) between the SIR values, the correction factor is largest, amounting to 3 dB. Correspondingly, if the difference is large (> 10), the transmission adjustment is zero.

Now compute the value of SIR 1,2 for the two shell members by subtracting the transmission adjustment from the smaller of the two SIR values, SIR 1 or SIR 2. The new quantity, termed SIR 1,2, is the SIR which should be entered in Column (jj).

If there is a third shell member, now combine its SIR value, SIR 3, with the value of SIR 1,2 to obtain the value for the effective three shell member combination, termed SIR 1,2,3, and entered in Column (mm).

Repeat this pairwise combination process until you have considered all shell members and have arrived at a Room SIR value, to be entered in Column (ss) of the SIR Worksheet. Then proceed to the next worksheet, the Room Noise Worksheet.

* * * * * *

The basic procedure is indicated in the flow chart of Figure 6–6, and requires the tabulation of the exterior sound level(s) for the three types of noise sources listed in Column A of the Room Noise Worksheet: highway noise, railway line operation noise, and aircraft noise. The sound levels calculated in Chapter 5 are to be entered in Column B for any of the transportation noise sources affecting your building site. These sound levels are combined to yield the total exterior sound level at the selected trial room. The Room SIR value is then used to obtain the interior sound levels which would exist due to the external sources. These values are then compared with the desired noise criterion level. This procedure is detailed in the following steps Seven through Ten.

Room Noise Prediction Method

STEP SEVEN: TABULATE EXTERIOR NOISE LEVELS

Refer to the computations of Chapter 5 to obtain the values of sound level at the trial room for the three possible types of noise sources. In the event that there is more than one source of highway, railway or aircraft noise, you will have to sum them for each type of source as shown in Chapter 5.

These values should be entered in Column B.

STEP EIGHT: COMBINE EXTERIOR NOISE LEVELS

If there are both highway and railway noise components, determine the absolute difference between the two, and enter this in Column C.

Refer to Table 6–1 to obtain the appropriate level adjustments corresponding to the difference in sound levels. Enter this in Column D.

Add this level adjustment to the larger of the two sound levels to obtain the total exterior highway and railway sound level at the trial room. Enter this in Column E.

Next, determine the difference between the total highway-railway sound level and the aricraft sound level, if any, and enter this in Column F. Once again, combine the sound levels by obtaining from Table 6–1 the appropriate level adjustment to be entered in Column G.

Add this level adjustment to the larger of the two sound levels, to obtain the total exterior sound level. Enter this in Column H.

You have now completed the prediction of the exterior sound level due to external transportation system noise sources at the trial room.

STEP NINE: DETERMINE THE INTERIOR SOUND LEVEL

Enter in Column I the Room SIR value from Column (ss) of the SIR Worksheet.

Subtract the Room SIR value from the Total Exterior Sound Level to obtain the Interior Sound Level, and enter it in Column J.

You have now completed the prediction of the trial room sound level due to external transportation system noise sources.

STEP TEN: COMPARE THE INTERIOR SOUND LEVEL WITH THE NOISE CRITERIA LEVEL

In Column K of the Room Noise Worksheet, enter the interior noise criterion level you selected in Chapter 3.

Compare the value of the interior sound level which you have predicted with the noise criterion level. If you have selected Strategy 1 described earlier in this chapter, and if the interior sound level is less than or equal to the noise criterion level, you have an acceptable design, and the sources of exterior noise will probably not be troublesome in your trial room. However, if the interior sound level is larger than the noise criterion level, it is probable that external noise will be troublesome, and you will want to modify your design by implementing some of the design alternatives suggested in the next chapter.

How to Account for Open Windows, Doors, and Through-the-Wall Ventilators

Open doors and windows offer almost no sound isolation. When doors and windows can be expected to be open, they should be listed along with any other shell member components and assigned a SIR of zero. Obviously, this will result in a severe degradation of the shell member SIR if the door or window has even a moderately large area. Operable louvres offer little sound isolation whether open or closed, and should be assigned a SIR of zero. Through-the-wall ventilators and unit ventilators with through-the-wall ducts pose a difficult problem since they may have sound baffles or insulating duct linings and may or may not lead directly from the exterior to the room. If acoustic transmission loss data are available from ventilator manufacturers, you may be able to calculate ventilator SIRs using the procedures of Appendix B. If not, it's best to be conservative and assign ventilators a SIR of zero.

Illustrative Example

Let us now demonstrate these noise calculations for a typical room. Consider a ten-story apartment building similar to the one described earlier in this chapter. It is to be located at the building site considered in the illustrative example of Chapter 5. The building consists of a simple tower with two windowed facades and two flanking walls (See Figure 6–3). The site is exposed to all three types of transportation noise, but aircraft noise was found to be the major source with a sound level of 69 dB. We will choose an outside corner room on the top floor as a "worst case" for initial consideration. Although the possibility of a premium rent for a prime site location might warrant a lower noise criterion level, we will select an indoor noise criterion level of 40 dB and an outdoor level of 55 dB. Moreover, since the metric should be appropriate for residential buildings, we will adopt the Ldn metric. Our room design will therefore be adequate if its interior sound level is less than Ldn = 40 dB. If the predicted interior sound level is higher, it will be too noisy and we must consider design alternatives.

The Chapter 5 example yielded the following estimates of the individual exterior Ldn sound levels.

Highway	66 dB
Railway	59 dB
Aircraft	69 dB

Since each of these noise levels is individually in excess of 55 dB, it is clear that any outdoor activity spaces will not be acceptable for recreational purposes for which speech intelligibility is critical. Furthermore, there is a difficult design challenge for indoor spaces as well, inasmuch as the site is within one mile of a moderate (category 2) airport, and is close to two highways.

With these factors in mind, let us consider the sound levels within our typical "worst case" room. We will assume that the dimensions of the trial room are 12 feet wide by 16 feet deep by 8 feet high, and that the room is to be carpeted, but not draped and not supplied with an acoustical ceiling.

Remember that rooms having suspended lightweight ceilings can receive exterior sound through portions of shell members (walls) extending up through the dead space of the suspended ceilings. Hence, for such rooms the height to be used for noise calculations is not from the floor to the suspended ceiling, but from the floor to the underside of the floor or roof slab above the ceiling space. For our example, there is no suspended ceiling space; thus, the room and shell member heights are both taken as 8 feet.

The shell construction of the building consists of 8-inch hollow core concrete block masonry flanking walls plastered inside. The flanking wall has a 5-foot high by 12-foot long fixed window glazed with heavy plate glass opening to the "worst case" room. The facade walls are of metal frame, insulated, brick veneer construction with a 4-foot high by 10-foot long fixed window glazed with heavy plate glass, and a 2-foot high by 8-foot long decorative spandrel panel. This panel is of 20-gauge steel, insulated with glass fiber 2½-inches thick. The roof consists of a 3-inch steel deck with rigid fiberglass insulation and built-up roofing.

Step One

Refer now to the SIR Worksheet (Figure 6–7) and enter the room's flanking wall, facade wall, and roof as the three shell members of the room. For the flanking wall there are two components, and for the facade wall, there are three components which must be listed in sequence of their SIR values, with the highest one first. Refer to Appendix A to obtain the SIR values. For the flanking wall, the hollow core block has the higher SIR number (50) and the glass windows the lower (28). For the facade wall, the brick veneer construction has the highest SIR number (51), the glass window second (28), and the steel panel has the lowest (26). Enter the SIR values on the worksheet in Column (f).

- The shell member number is indicated in Column (a) . . . only 2 of the 5 shell member spaces will be needed for the flanking wall and only 3 of the 5 shell member spaces for the facade wall.
- The shell member name appears in Column (b), and its area appears in Column (c).
- For Column (d), the flanking wall has two components—A and B; the facade wall has three components—A, B, and C; and, the roof has only one component—A.
- The shell member's component descriptions are listed in Column (e).
- The SIRs are listed in Column (f).
- The room dimensions are listed in Columns (g, h, and i) and the room floor area is entered in Column (j).
- The two dimensions of the shell member components are listed in Columns (k and l).

Using these data, the component areas are computed and are listed in Column (m). Note that these Columns (k, l, and m) are not needed for shell members with only one component, nor are they needed for Component A of componentized shell members. Now, since the flanking wall and the facade wall have several components, we must calculate their composite SIRs.

Step Two

Compute the Component B fractional area; that is, the ratio of component area to the total wall (shell member) area. For the flanking wall, this value is 60 ÷ 128 = 0.47 which is entered in Column (n). Now determine the difference between the two highest SIR numbers; i.e., the difference between the SIR for block masonry and the window . . . 50 − 28 = 22. Enter this value in Column (o). Now refer to Table 6–2 to determine the composite SIR correction factor corresponding to the fractional area of 0.47 and a SIR difference of 22. This value is 4 and is entered in Column (p). Now add this value (4) to the lower SIR number (28) and enter the result (32) in Column (q). This is the composite SIR for the flanking wall.

For the facade wall, the Component B fractional area is 40 ÷ 96 = 0.42, which is entered in Column (n). Now determine the difference between the two highest SIR numbers; i.e., the difference between the SIR for brick veneer and the window . . . 51 − 28 = 23. Enter this value in Column (o). Now refer to Table 6–2 to determine the composite SIR correction factor corresponding to the fractional area of 0.42 and a SIR difference of 23. This value is 4 and is entered in Column (p). Now add this value (4) to the lower SIR number (28) and enter the result (32) in Column (q). This SIR number describes the properties of an 8 ft x 12 ft brick wall with a 10 ft by 4 ft glass window.

Now consider the effect of the steel panel with a fractional area of 0.17 to be entered in Column (r). The difference between the SIR value for the brick and window wall (32) and the steel panel (26) is 6. Enter this value in Column (s). Now from Table 6–2 find the composite SIR correction factor corresponding to the values 0.17 and 6. This value (4) is entered in Column (t) and is added to the lower SIR value, 26. The sum, 30, is entered in Column (u).

Building Project: *10-Story Apartment* Owner: *Modern Realty* Designer: *C. Suggs*

Location: *Near Highways 1 & 2* Site point or building room for which sound pressure levels are being estimated: *Top Floor NW* Date: *1 July '77* Revised: ____

Shell Member Number	Shell Member Name	Shell Member Area in square feet	Shell Member Components	Component Description — Arrange components of shell members in order of decreasing SIR for each shell member. Order of shell members is optional.	Shell Member or Component SIR from Appendix A	Room Dimensions in Feet			Room Floor Area in square feet—W × L	Component Face Dimension No. 1 in feet	Component Face Dimension No. 2 in feet	Component Area in square feet	Component B Fractional Area (Component B Area/Shell Member Area)	Difference, (SIR A − SIR B)	Composite SIR Correction Factor from Table 6-2	SIR AB = SIR B + Composite SIR Correction Factor	Component C Fractional Area (Component C Area/Shell Member Area)	Difference = (SIR AB − SIR C)	Composite SIR Correction Factor from Table 6-2	SIR ABC = SIR C + Composite SIR Correction Factor	Component D Fractional Area (Component D Area/Shell Member Area)	Difference = (SIR ABC − SIR D)	Composite SIR Correction Factor from Table 6-2	SIR ABCD = SIR D + Composite SIR Correction Factor	Estimate of Air Leakage in square inches/100 square feet	Adjusted SIR Based on Air Leakage from Table 6-3	Ratio of Shell Member Area to Floor Area—Room Geometry	Room Geometry Correction Factor from Table 6-4	Enter +2 if acoustic ceiling or if drapes cover 50% of wall area	Enter −4 if no carpet	SIR Adjusted for Leakage, Area and Absorption Correction Factors	Absolute Difference: SIR 1 − SIR 2	Transmission Adjustment from Table 6-1	SIR 1,2 = SIR (lower) + Transmission Adjustment	Absolute Difference: SIR 1,2 − SIR 3	Transmission Adjustment from Table 6-1	SIR 1,2,3 = SIR (lower) + Transmission Adjustment	Absolute Difference: SIR 1,2,3 − SIR 4	Transmission Adjustment from Table 6-1	SIR 1,2,3,4 = SIR (lower) + Transmission Adjustment	Absolute Difference: SIR 1,2,3,4 − SIR 5	Transmission Adjustment from Table 6-1	Room SIR = SIR (lower) + Transmission Adjustment
						Width	Length	Height																																			
a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	aa	bb	cc	dd	ee	ff	gg	hh	ii	jj	kk	ll	mm	nn	oo	pp	qq	rr	ss
1	FLANKING WALL	128	A	8×8×16" HOLLOW CORE CONCRETE BLOCK	50	12	16	8	192	16	8																																
			B	HEAVY GLASS, FIXED WINDOW	28					12	5	60	.47	22	4	32																											
			C																																								
			D																					32	4.5	30	0.67	-1			29												
2	FACADE WALL	96	A	METAL FRAME, INSULATED, BRICK VENEER	51					12	8																																
			B	HEAVY GLASS, FIXED WINDOW	28					10	4	40	.42	23	4	32																											
			C	20 GAUGE STEEL PANEL	26					8	2	16					.17	6	4	30																							
			D																					30	4.5	29	0.5	0			29	0	3	26									
3	ROOF	192	A	3" STEEL DECK, INSULATED	43																																						
			B																																								
			C																																								
			D																					43	3.0	36	1.0	-2			34				8	1	25						
4			A																																								
			B																																								
			C																																								
			D																																								
5			A																																								
			B																																								
			C																																								
			D																																								25

Figure 6–7. SIR Worksheet for Example.

Building Project: *10-Story Apartment*

Location: *Near Highways 1 & 2*

Owner: *Modern Realty*

Site point or building room for which sound pressure levels are being estimated: *Top Floor NW*

Designer: *C. Suggs*

Date: *1 July 77* Revised: ____

External Noise Source	Source Level (dB) (Chap. 5)	Difference Between Highway and Railway Sound Levels (dB)	Level Adjustment (From Table 6-1)	Total Highway and Railway Sound Level (dB)	Difference Between Total Highway and Railway and Aircraft Sound Levels (dB)	Level Adjustment (From Table 6-1)	Total Exterior Sound Level (dB)	Room SIR (SIR Worksheet)	Indoor Sound Level Due to External Sources (dB)	Noise Criterion Level (dB)
A	B	C	D	E	F	G	H	I	J	K
Highway	66									
Railway	59	7	1	67						
Aircraft	69				2	2	71	25	46	40

Is the Total Indoor Sound Level Due to External Sources Greater Than the Noise Criterion Level?		
	Yes ✓	A Noise Problem Exists
	No ____	The Design is Satisfactory

Figure 6–8. Room Noise Worksheet for Example.

To simplify their visualization in the SIR Worksheet, the SIRs for the flanking wall (32) for the facade wall (30) and for the roof (43) are carried forward to Column (y) before making further computations.

Now you must perform air leakage adjustments.

Step Three

Since the roof is essentially monolithic without penetrations, and assuming average workmanship the area of openings can be taken as equivalent to 3.0 $in^2/100\ ft^2$. For the componentized flanking and facade walls, there will be somewhat more air leakage, and 4.5 $in^2/100\ ft^2$ is appropriate assuming average workmanship. These values should be entered in Column (aa).

For a 4.5 $in^2/100\ ft^2$ leakage and a SIR of 32, Table 6-3 indicates an adjusted SIR of 30. Enter this as the adjusted SIR for the flanking wall in Column (bb). The values for the facade wall and roof are determined in a similar manner. These values are 29 and 36, respectively. Enter these values in Column (bb).

Now you must make the room geometry correction.

Step Four

In Column (cc), enter the ratios of the shell member areas to the floor area of the room. These values are 128 ÷ 192 = 0.67 for the flanking wall and 96 ÷ 192 = 0.5 for the facade wall.

Now refer to Table 6-4 to obtain the room geometry correction factors and enter them in Column (dd). These values are − 1 for the flanking wall, 0 for the facade wall, and − 2 for the roof.

Step Five

Since the room is to be carpeted but not heavily draped, you do not enter additional values for the absorption corrections in Columns (ee) and (ff).

Now add the adjusted SIR value from Column (bb) to the room geometry correction for each shell member and enter in Column (gg). These SIRs (29, 29, and 34) describe the sound isolation properties of the flanking wall, facade wall, and roof, respectively.

These shell member SIRs must now be combined to get the room SIR.

Step Six

Consider the combination of SIR values for the flanking and facade walls. The difference between these two numbers is 0 (29 — 29 = 0). Enter this value in Column (hh). Referring to Table 6–1, enter the transmission adjustment of 3 in Column (ii). Now subtract this from the smaller of the two exterior wall SIR values (29 – 3 = 26), and enter the value of 26 in Column (jj). This describes the sound isolation properties of the two walls.

Now combine the two walls with the roof. The difference between the two SIRs is 8 (34 — 26 = 8) entered in Column (kk), and the corresponding transmission adjustment is 1, entered in Column (ll). Subtract this transmission adjustment from the smaller of the two SIRs yielding a Room SIR of 25 entered in Column (mm). For future reference also enter this value in Column (ss).

Now we need to complete the Room Noise Worksheet, Figure 6–8.

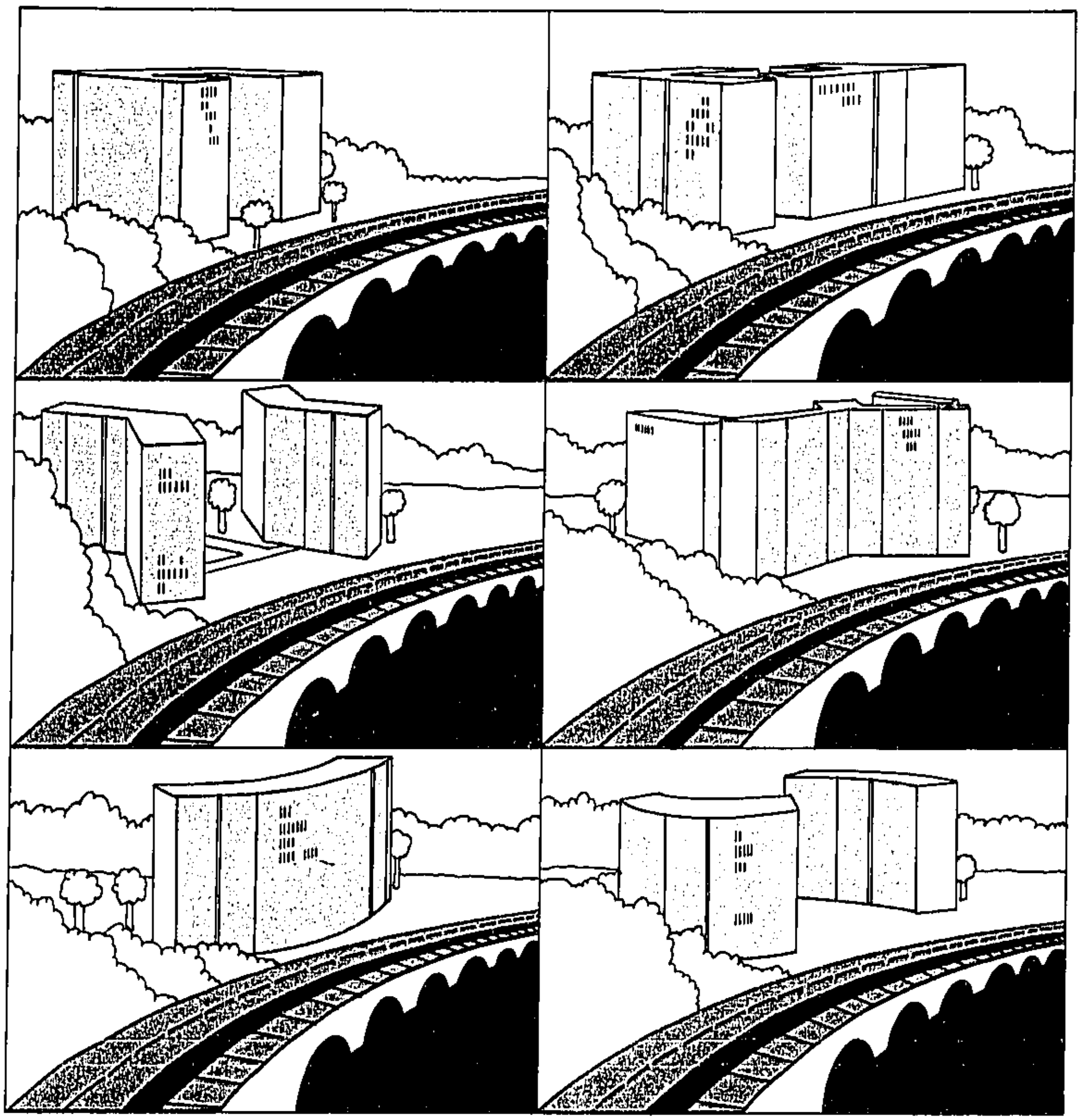
Step Seven

Transfer the exterior noise levels due to the three types of exterior noise source cited at the beginning of this example to Column B of the Room Noise Worksheet.

Now begin the step-wise process of computing the total outdoor noise by determining that the difference between the highway noise (66 dB) and railway noise (59 dB) is 7 dB, and entering this in Column C. The corresponding level adjustment is 1 dB, entered in Column D. The total of all highway and railway noise would be obtained by adding the level adjustment (1 dB) to the higher of the two component levels (66 dB); here 67 dB is entered in Column E. The difference between this total and the aircraft noise (69 dB) is 2 dB, entered in Column F; yielding a level adjustment of 2 dB, entered in Column G. The total of all outdoor noise is thus 71 dB, obtained by adding the level adjustment (2 dB) to the larger of the two component levels (here that due to aircraft, 69 dB) and entered in Column H.

Now enter the Room SIR as determined in the previous SIR Worksheet in Column I, and subtract the Room SIR (25 dB) from the total outdoor noise (71 dB) to estimate the Indoor Sound Level (46 dB), entered in Column J. This is 6dB higher than the noise criterion level established at the outset of this example. There is therefore a noise problem in the "worst case" trial room. Needed design changes to remedy this problem are indicated in the next chapter.

Realize, however, that this "worst case" trial room has exterior exposure on three surfaces (facade and flanking walls and roof). Rooms on the first through ninth floors, not on the ends, will have only the facade wall exposed to the exterior sound energy. For these rooms, the adjusted facade wall SIR will be equivalent to the room SIR, in this case 29, 4 dB larger than the room SIR for the "worst case" room. So the level in such rooms will be 42 dB (72 – 29 = 42), which is relatively close to the desired criterion.



Chapter 7
Design Alternatives

If your Chapter 6 calculations predict noise levels for indoor rooms or outdoor activity areas greater than noise criterion levels, you will be seeking design alternatives to overcome your noise problems. Possible design alternatives will be discussed in this chapter.

In addition to design alternatives, it may be feasible to control noise at its source by making operational changes to reduce noise generated by transportation systems. Rerouting truck traffic, the imposition of curfews, etc. can substantially reduce noise levels. If such operational changes can be worked out through local elected officials or planning authorities, the predictive models of Chapter 5 will be useful in assessing possible noise level reductions.

There are four types of design approaches to reduce noise. Two of these types of approaches can prevent noise from becoming an annoyance for outdoor activities. These are (1) to locate, orient, or configure the building to reduce noise at the chosen building site, and (2) to provide additional exterior barriers such as walls or berms. These two approaches are also useful in protecting the building's interior from unwanted sound, and for this purpose are joined by two other approaches which are (3) to fortify the building shell, and finally, (4) to vary the interior sound absorption.

One thing is certain . . . anything you do to rearrange the building site or to build upon it will change its acoustic climate. Probably the building itself will cause the most drastic changes. Hence, you should deploy the building creatively to secure the best results. The building can be used to shield selected outdoor activity areas from noise, and barriers put up to protect outdoor activity areas from noise or wind can also shield portions of the building.

Let us discuss in turn the four methods of providing design alternatives: (1) siting, (2) barriers, (3) building shell, and (4) furnishings.

Siting Alternatives

For siting there are three options . . . site selection . . . building location and orientation, and . . . building configuration. These options could be pursued independently in design and will be discussed separately, recognizing however, that in a design process which truly involves synthesis, the three options would be carried on simultaneously.

Site Selection: The best way to control noise is to avoid it. This can most effectively be done if the first design task is that of selecting the building site, because careful selection can steer the proposed building away from noise problems. Likewise, for some projects it may be cheaper to abandon a site already selected and relocate to a quieter area, than to make extensive revisions to an acoustically unacceptable scheme. For many projects, however, other considerations than sound may preclude the selection of a quiet site or relocation to a quiet site.

Keep in mind that acoustic conditions are rarely stagnant and you should consult zoning and planning authorities to determine future plans for the surrounding area. A seemingly suitable site can later be surrounded by industrial areas or traffic arteries, or subjected to aircraft overflights greatly increasing on-site levels. Therefore, it would be wise to attempt to predict future noise levels at your site to determine the impact of plans for the surrounding area.

In selecting a quiet site, refer to Table 2–2 in Chapter 2 which gives desirable minima for the distances from transportation system sound sources to a building or site. Also, look for existing natural and man-made sound barriers, examples of which are shown in the figures of Section 1

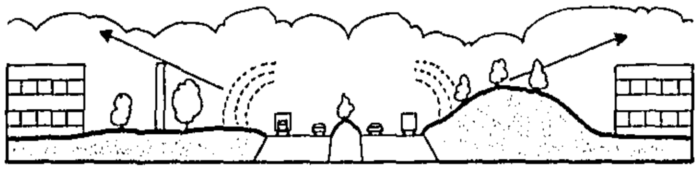


Figure 7–1. Use of Various Noise Barriers.

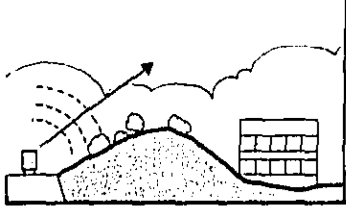


Figure 7–2. Use of Natural Noise Barriers.

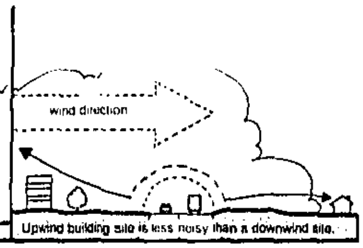


Figure 7–3. Selection of Building Sites Relative to Wind Direction.

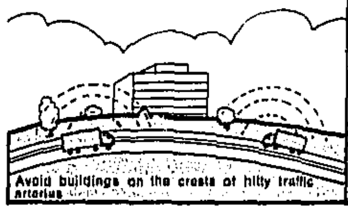


Figure 7–4. Building Sites near Hilly Traffic Areas.

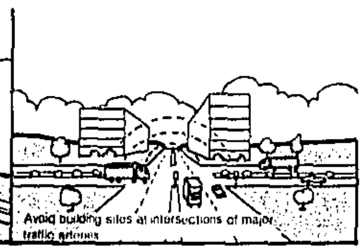


Figure 7–5. Building Sites near Traffic Junctions.

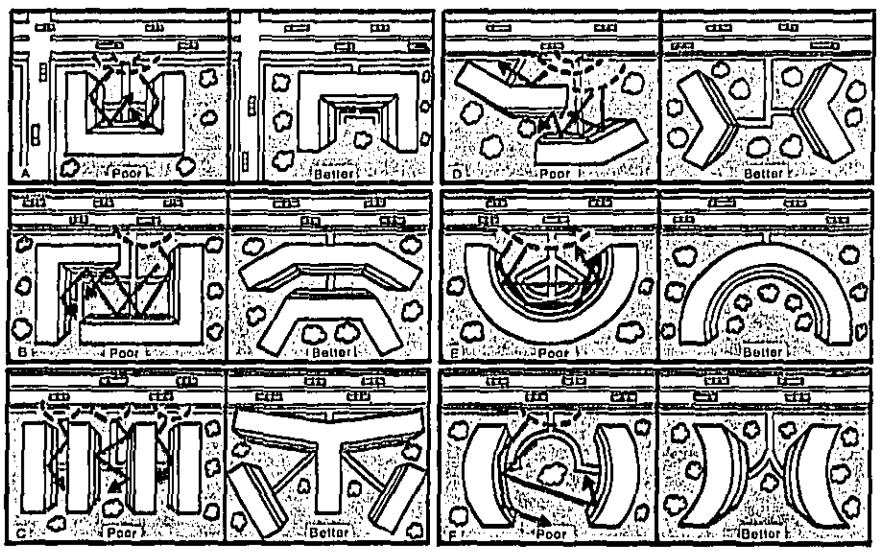


Figure 7–6. Orientation of Buildings on Sites.

of Chapter 5 and in Figures 7-1 and 7-2. Sites on rolling terrain separated from railways and highways by heavy, wide stands of trees are generally quieter than sites located in hollows or on flat, open ground.

Give preference to sites which are predominantly upwind of noise sources. At large distances the upwind side is generally quieter than the downwind side of a noise source. The wind tends to bend the sound path upwards, as shown in Figure 7-3, thereby reducing the sound energy that impinges on an upwind site.

Sites near hills or traffic intersections are generally unfavorable due to the acceleration, deceleration and braking of vehicles, especially if the traffic includes heavy truck traffic like that in Figure 7-4. Most of all, congested areas of heavy traffic should be avoided as shown in Figure 7-5.

Building Location and Orientation: The thoughtful location and orientation of buildings on a site can aid in controlling noise. In order to determine whether or not there is apt to be a preferred "quiet" location on a site, it is generally necessary to consider several locations, and to perform several detailed calculations as outlined in Chapters 5 and 6. A recommended procedure is to choose a trial building location on the site and to perform the detailed calculations . . . then compare the estimated sound levels propagated from any nearby transportation noise sources to determine if any one of these sources is predominant at the trial location. If one is, then consider whether or not the distance to that source can be substantially increased by moving the building to another location on your site. For each doubling of the distance away from a highway you can expect a reduction of about 4 dB; for each doubling of the distance away from a railway you can expect a reduction of about 6 dB (there is no simple rule of thumb for aircraft noise). Buildings can be located in the quiet areas of a site with windowed facades facing the quiet areas, and with heavy, windowless walls facing the sources of sound. In general, the noise level near the facade of a building facing away from the predominant source of sound will be 3 dB less than near a facade facing the source. Acoustical shielding can be provided by the existing terrain, natural landscaping, or wooded areas.

If the building site is relatively close to a major highway or railway, and if the building is to be fairly long, two design concepts can be employed. One is to orient the building's major axis perpendicular to the direction of the highway or railway, and then to locate the noise-sensitive exterior rooms at the end of the building farthest from the roadway or track. A second design concept is to orient the building's axis parallel to the highway or railway and to provide materials having an extremely high SIR on the facade facing the noise source, while placing noise-sensitive rooms on the facade shielded by the building itself.

It is especially important that buildings not be parallel when located on both sides of an expressway in order to avoid multiple reflections of sound waves which increase sound levels. A random or staggered building layout or a cluster of buildings with no parallel building faces will avoid this problem of multiple reflections of sound waves between opposite buildings. Slightly curved buildings can be beneficial when the curvature is convex relative to the direction of the greatest noise source. U-shaped buildings or semi-enclosed courtyards provide areas for multiple reflections and should not be used as outdoor activity areas, because they tend to be quite reverberant and noisy. These layouts are shown in Figure 7-6.

Building Configuration: Buildings can be arranged with noisy and quiet sides as previously mentioned, if the principal noise source is relatively near. Try to have rooms with low noise level criteria located on the quiet side, and rooms with high criteria located on the noisy side. For example, the mechanical rooms and shops of secondary schools can be gathered together and arranged on the noisy side (particularly since these rooms also are noise sources) while libraries, auditoria, and classrooms are deployed on the quiet side.

The facade treatment of the building presents more difficult choices. The total amount of sound penetrating a building is proportional to the area of exterior shell of the building. Hence, a highly compact building is desired. Ideally the building would approach a spherical shape so as to enclose the greatest volume within the smallest shell area. Spheres are impractical shapes for buildings, however, and a more practical compact shape is the cube. On the other hand, a ground-hugging, rambling building having a relatively high shell area to enclosed volume might benefit from noise attenuation barriers which are too low to benefit a tall building.

There is one such effect that can actually increase interior sound levels . . . it occurs when projections or depressions such as wing walls and balconies create a number of reverberant enclosures or cavities. These are especially troublesome when located at a curtain wall or windowed wall, since the reverberant cavities will tend to raise sound levels at the wall line, and give rise to increased interior sound levels as a consequence. Caution should be exercised to ensure that no such reverberant cavities are established. Also, it is wise to prevent roadway sound from being reflected from the under side of a balcony toward a wall having windows or doors. The underside of such balconies can sometimes be treated with absorptive materials to partially control such sound reflections.

Barriers

The designer usually has no control of transportation noise at its source, but the designer can provide some form of shielding between the source and the receiver, or building. This shielding can be in the form of walls, natural barriers such as earth berms, rows of intervening buildings, vegetation, etc., as discussed previously in Section 5.1 and reviewed here.

There are economic limits to providing sound barriers since it is costly to construct barriers which block all paths along which sound can travel from a transportation system noise source to a building and site; but, if any worthwhile barrier attenuation is to be achieved, the barrier must block all or most of these paths. In order to block the direct path of sound over the top of a wall or earth berm, it must be high enough to block the line-of-sight between the transportation system noise source, which is estimated to be 8 ft high for heavy trucks and 15 ft high for diesel-electric locomotives. Also, noise propagating in a direct path around the ends of the barrier can severely limit its attenuation. The barrier included angle should be made as large as possible by extending the ends of a barrier as shown in Figure 5.1–19.

To prevent sound transmission directly through the sound barrier, it should be constructed of a material whose surface weight density is greater than 4 lb/ft.^{2} Table 7-1 gives approximate surface weight densities for a variety of materials which may be suitable for barrier construction. When choosing a material you must also consider the cost, ease of construction, and durability with respect to weather conditions. (Reference [1] lists some types of existing and proposed barriers in the United States and describes the details of construction and the materials used. This reference may be helpful to you in designing a barrier.)

Also important in preventing sound transmission directly through a barrier is the elimination of any holes or openings in the barrier. The area of any openings in the barrier must be kept well below 10 percent of the total barrier area, or better yet, completely eliminated to give a solid continuous barrier with no direct paths to your building.

The location of a barrier is important in determining its attenuation. The barrier should be located either close to the source or close to your building so that the angle of diffraction, hence the attenuation, is maximized. If your proposed building is to be several stories high, you will probably want to locate the barrier as close to the source as possible, since a barrier close to the building would not shield its upper floors. On the other hand, if your proposed building is to be only one-story high, the barrier could be located close to the building, thus reducing the needed length of barrier. There are situations when it is better to locate the barrier at some intermediate point. For example, a considerable savings might be achieved by locating the barrier on a hill or embankment lying between the

Table 7–1. Approximate Surface Weight Densities for Various Materials.

Material	Surface Weight Density, lb/ft^2
Timber, Fir (1½ inch thick)	5.0
Timber, Fir (2 inch thick)	6.7
Plywood (1¼ inch thick)	4.2
Cinder Block Hollow Core (6 inch thick)	25.0
Concrete Block Hollow Core (4 inch thick)	23.3
Concrete Block Hollow Core (6 inch thick)	35.0
Brick (4 inch thick)	43.3
Concrete, Dense (4 inch thick)	50.0
Plaster on Metal Lath (½ inch thick)	4.5

source and your site. Keep in mind that the angle of diffraction (or in other words the path length difference), and the barrier included angle are crucial in controlling barrier attenuation. You can choose several alternative barrier locations and then determine the required barrier size needed to provide the desired attenuation for your building and site.

Rely upon your own ingenuity in the use of barriers. An existing earth berm should be left undisturbed or augmented. Through careful planning, you can utilize non-critical buildings such as warehouses, garages, and storage sheds as barriers for occupancies having more critical noise criteria. Or, you can provide heavy sound isolation on the facade of a building facing a noise source, and then use this building as a barrier for other buildings. When extensive right-of-ways are available, vegetation shielding may be an available solution. Vegetation, however, takes a considerable amount of time to grow, and its noise reduction potential is limited. Moreover, shielding from deciduous trees is greatly reduced when the trees lose their leaves.

Obviously cost and aesthetics are important. Costs vary considerably depending in general upon the barrier height required and the construction materials. The cheapest barrier is usually the earth berm, which on some projects can be built from excess fill at very low cost. The appearance of earth berms is usually good, since landscaping can virtually hide them from sight, or disguise them as natural hills.

In summary, barriers can be useful in reducing the noise levels at your site, but there are limits to their effectiveness. It is possible to obtain a barrier attenuation of 10 decibels without too much difficulty, but it may be wise to have the barrier designed by an acoustical consultant or noise control engineer to ensure that the barrier will achieve this attenuation and solve your noise problem.

Building Shell

The building shell is the last line of defense against noise, and a line of defense decidedly under the control of the designer. As you have seen, the noise isolation provided by the building shell can be seriously degraded by a single weak link . . . a fundamental you must fully grasp if you are to effectively control sound transmission. The weak link principle states simply that the sound isolation of any shell member is reduced substantially by shell member components having low sound isolation ratings. This was demonstrated by the example of Chapter 6 where the brick veneer facade member having a SIR of 51 was reduced first by the fixed single glazed window (SIR of 28) to a composite SIR of 32, and then by a decorative 20-gauge steel panel (SIR of 26) to a composite facade SIR of 30. Whereas the final composite SIR was not quite as low as the SIR of the steel panel, it was substantially reduced from 51 to 30. Obviously, the steel panel, constituting only 17 percent of the facade wall's area, was accountable for much of the sound transmitted through the facade wall.

In the same fashion, the cumulative SIR for the trial room in the example of Chapter 6 was reduced from a SIR number of 34 for the roof to the room SIR value 25, when adjusted for the weaker flanking and facade wall members.

The sound transmission contributed by any component to its shell member is, of course, not only affected by its materials, but also by the area of the component relative to both the area of the shell member, and to the materials and areas of other components. Thus, a small window will not be as weak a link as a large window.

Likewise, the sound transmission contributed by any shell member to a building room depends upon the area and materials of the shell member in relationship to areas and materials of the other shell members of the room.

To improve the sound isolation of a shell member, then, it is more important to improve the weaker components than the stronger ones; for example, double glazing a window may prove to be more cost effective than building up the wall that receives the window. Of course, the higher the SIR, the less sound transmited through the shell. From this type of information you will gain an understanding of the weak link principle; open windows and doors can destroy the sound isolation of a wall no matter how massive.

The overall sound isolation of a shell member is related to its mass, stiffness, continuity of construction, sound absorbency of interior wall coverings, and freedom from cracks or holes (usually achieved by high quality construction). All of these shell member characteristics resist the penetration of sound through the member and resist member vibration in response to incident sound. The greater the mass, the less a shell member will be excited into vibration by incident souds, assuming the shell member's stiffness is held constant.

Holes and cracks are the worst offenders in admitting sound. A hole occupying only 0.01 percent of a total shell member's area, limits its sound isolation to 40 dB. Thus, a highly sound-resistant shell member, such as one of a hundred square feet with a SIR of 60, would be reduced to a SIR of 40 by a hole 1½ square inches. A shell member of the same size but having a SIR of 40 would be dropped by the same size hole to a SIR of 37. For the former shell member, at least 90 percent of the sound energy entering the building would pass through the hole; for the latter shell member, 50 percent of the energy would be transmitted via the hole. Clearly, it is an acoustic error to specify heavy construction if the heavy construction has penetrations which are not well-sealed.

Similarly, open windows can destroy the sound isolation of a building. The recent interest in energy conservation has caused a reexamination of the trend toward year-round air conditioning with sealed windows (especially for office buildings). Some experts believe that a return to buildings with operable sash and natural ventilation can save energy used for cooling in spring and fall in most parts of the country. Other experts argue that any such energy savings are lost through air infiltration around operable sash in winter and summer, which are peak periods for heat loss and heat gain. In any event, sealed, fixed windows provide better noise attenuation than comparable operable windows. Even a reasonably tight-fitting operable window is apt to have a crack width of 0.03 inches [2]. If the window is only 2-feet wide by 3-feet high, it will have ten feet of crack equivalent in area to a hole of 3.6 square inches. Some fifty percent of the sound impinging upon the window may enter the building through the crack. Weather-stripping can improve the window's acoustical and thermal performance, and double glazing is superior to single glazing. In general, those principles which provide desirable thermal insulation will also provide sound isolation.

How much sound isolation does a "typical" building provide? The Environmental Protection Agency (EPA) has published this type of information for dwellings subjected to aircraft noise [3]. The EPA categorized houses as "warm climate" and "cold climate," and reported findings for open-window and closed-window conditions for both categories of house. The "open-window condition" corresponded to an opening of 2 square feet, and a room absorption typical of bedrooms and living rooms. Based upon this "open window condition," and aiming at conservative values of the sound levels inside dwellings, the EPA published the values of Table 7-2.

The sound level reductions provided by the exterior shells of buildings in a given community have a wide range due to differences in the use of materials, building techniques, and individual building plans. Nevertheless, for general planning purposes, the Table 7–2 reductions in sound level from outside to inside a house can be used. However, their use in connection with this guide is limited since they reflect average sound level reductions, and are, therefore, not completely compatible with this design guide's room-by-room shell isolation rating method of calculation.

To fortify the shell against sound, one should—(1) use heavy, monolithic materials (concrete, brick, and block are more sound resistant than wood or steel frame construction or curtain walls),—(2) reduce the area of cracks and holes penetrating the shell by careful architectural detailing and through quality construction,—(3) design for sealed windows with year-round air conditioning where noise conditions are serious,—(4) reduce the size of windows and provide them with double glazing keeping the size of operable sash, hence crack length, to a minimum,—(5) avoid weak links by ensuring that SIRs for shell member components are comparable and as large as possible. Naturally, the designer must use judgment in applying these sound control guidelines to particular building projects, which will surely have many other concerns competing against acoustic considerations.

Table 7–2. Sound Level Reduction Due to Houses* in Warm and Cold Climates, with Windows Open and Closed.

	Windows Open	Windows Closed
Warm climate	12 dB	24 dB
Cold climate	17 dB	27 dB
Approx. national average	15 dB	25 dB

* Attenuation of outdoor noise by exterior shell of the house.

Furnishings

Do not overlook the possibilities of acoustically absorptive materials for floor, wall, and ceiling coverings and for interior furnishings. The calculations of Chapter 6 indicate a maximum sound level difference of approximately 6 dB between a bare room with a hard ceiling and no carpet, and a room that has an acoustic ceiling and is fully carpeted. Moderately absorptive decorations and furnishings in an office or classroom would reduce noise levels by, say, 2 dB below that for a bare, reflective room. A difference of a few decibels, while modest, may have a favorable psychological impact upon building occupants, especially when made aware by the presence of these appointments, that attempts have been made to reduce noise levels.

It may be possible to further reduce noise levels, through the use of acoustically absorptive interior partitions. Also, interior furnishings such as chairs, sofas, etc., which are relatively heavily padded and covered with soft fabrics can achieve another noise level reduction amounting to 1 or 2 dB.

Illustrative Example

To illustrate some of these design alternatives, let us once again consider the example cited in Chapters 5 and 6. Recall that for this example, the site is located near two major highways, a railway, and an airport; and the "'worst case" room selected for calculations was a corner, top-floor room in the ten-story apartment building.

Because the noise from the airport and highway is dominant, it is impossible to make effective use of any of the suggested siting alternatives short of a completely new site selection. If one could disregard the air traffic as a noise source, it would be beneficial to re-position the building a little closer to the railway line, since its noise component is smaller than that of the highway. But since the building is subjected principally to aircraft noise, it would not be very helpful to make use of building location and orientation options.

Building configuration will not be an important factor either, since nearly all of the noise sources are at a considerable distance and arranged around the site so that the building will have no quiet side.

Barriers will not be feasible as design alternatives because the dominant source of noise is aircraft.

Thus, the building shell offers the principal opportunities for design alternatives. In review of the SIR worksheet (Figure 6–7), you can quickly realize that there are three "weak links" in the building design for the "worst case" room—the window in the flanking wall, and the window and decorative steel panel in the facade wall. To increase the total room SIR, these "weak links" must be strengthened by reducing the areas of the "weak link" components or replacing them with components having higher SIRs. Or, the quality of workmanship could be improved to reduce air leakage.

If (a) the steel panel is replaced with an identically dimensioned stucco panel (SIR of 41), (b) the single glass fixed windows are replaced with double glazed fixed windows (two panes of ¼ inch glass plus a 2¼ inch air space—SIR of 37) in both the flanking and facade walls, and (c) average workmanship is assumed, the total room SIR can be increased to 29, an increase of 4. If in addition to these modifications the workmanship is improved from average to good, the total room SIR can be increased to 30. Moreover by adding an acoustic tile ceiling, the room SIR would be increased by 2 to a value of 32. The predicted total sound level in the "worst case" room would then be 71 − 32 = 39 dB, which is below the noise criterion level of 40 dB. As another alternative, eliminating the window in the flanking wall would increase the total room SIR to 32 without using acoustic tile ceiling. Noise predictions for this last alternative—no flanking wall window, stucco panel and double glazed window in the facade wall, and good workmanship—are illustrated in the SIR Worksheet of Figure 7–7 and the Room Noise Worksheet of Figure 7–8.

Building Project: *10-Story Apartment* Owner: *Modern Realty* Designer: *C. Suggs*

Location: *Near Highways 1 E, 2* Site point or building room for which sound pressure levels are being estimated: *Top Floor-NW Revised wall design* Date: *1 July '77* Revised: *7 July '77*

Shell Member Number (a)	Shell Member Name (b)	Shell Member Area in square feet (c)	Shell Member Components (d)	Component Description — Arrange components of shell members in order of decreasing SIR for each shell member. Order of shell members is optional. (e)	Shell Member or Component SIR from Appendix A (f)	Room Dimensions in Feet: Width (g)	Length (h)	Height (i)	Room Floor Area in square feet—w × l (j)
1	FLANKING WALL	128	A	8"x8"x16" HOLLOW CORE CONCRETE BLOCK	50	12	16	8	192
			B						
			C						
			D						
2	FACADE WALL	96	A	METAL FRAME, INSULATED, BRICK VENEER	51				
			B	STUCCO PANEL	41				
			C	HEAVY, DOUBLE GLAZE, FIXED WINDOW	37				
			D						
3	ROOF	192	A	3" STEEL DECK, INSULATED	43				
			B						
			C						
			D						
4			A						
			B						
			C						
			D						
5			A						
			B						
			C						
			D						

Shell Member Number (a)	Component (d)	Component Face Dimension No. 1 in feet (k)	Component Face Dimension No. 2 in feet (l)	Component Area in square feet (m)	Component B Fractional Area (Component B Area/Shell Member Area) (n)	Difference = (SIR A − SIR B) (o)	Composite SIR Correction Factor from Table 6-2 (p)	SIR AB = SIR B + Composite SIR Correction Factor (q)	Component C Fractional Area (Component C Area/Shell Member Area) (r)	Difference = (SIR AB − SIR C) (s)	Composite SIR Correction Factor from Table 6-2 (t)	SIR ABC = SIR C + Composite SIR Correction Factor (u)	Component D Fractional Area (Component D Area/Shell Member Area) (v)	Difference = (SIR ABC − SIR D) (w)	Composite SIR Correction Factor from Table 6-2 (x)
1	A														
	B														
	C														
	D														
2	A	12	8												
	B	8	2	16	.17	10	6	47							
	C	10	4	40					.42	10	3	40			
	D														
3	A														
	B														
	C														
	D														
4	A														
	B														
	C														
	D														
5	A														
	B														
	C														
	D														

Shell Member Number (a)	Component (d)	SIR ABCD = SIR D + Composite SIR Correction Factor (y)	Estimate of Air Leakage in square inches/100 square feet (aa)	Adjusted SIR Based on Air Leakage from Table 6-3 (bb)	Ratio of Shell Member Area to Floor Area—Room Geometry (cc)	Room Geometry Correction Factor from Table 6-4 (dd)	Enter +2 if acoustic ceiling or if drapes cover 50% of wall area (ee)	Enter −4 if no carpet (ff)	SIR Adjusted for Leakage, Area and Absorption Correction Factors (gg)	Absolute Difference = SIR 1 − SIR 2 (hh)	Transmission Adjustment from Table 6-1 (ii)	SIR 1,2 = SIR (lower) − Transmission Adjustment (jj)	Absolute Difference = SIR 1,2 − SIR 3 (kk)	Transmission Adjustment from Table 6-1 (ll)	SIR 1,2,3 = SIR (lower) − Transmission Adjustment (mm)	Absolute Difference = SIR 1,2,3 − SIR 4 (nn)	Transmission Adjustment from Table 6-1 (oo)	SIR 1,2,3,4 = SIR (lower) − Transmission Adjustment (pp)	Absolute Difference = SIR 1,2,3,4 − SIR 5 (qq)	Transmission Adjustment from Table 6-1 (rr)	Room SIR = SIR (lower) − Transmission Adjustment (ss)
1	A																				
	B																				
	C																				
	D	50	1.5	40	0.67	-1			39												
2	A																				
	B																				
	C																				
	D	40	3.0	35	0.5	0			35	4	1	34									
3	A																				
	B																				
	C																				
	D	43	1.5	38	1.0	-2			36				2	2	32						
4	A																				
	B																				
	C																				
	D																				
5	A																				
	B																				
	C																				
	D																				32

Figure 7–7. SIR Worksheet for Revised Example.

Building Project: 10-Story Apartment

Location: Near Highways 1 & 2

Owner: Modern Realty

Site point or building room for which sound pressure levels are being estimated: Top Floor NW Revised Wall design

Designer: C. Suggs

Date: 1 July '77 Revised: 7 July '77

External Noise Source	Source Level (dB) (Chap. 5)	Difference Between Highway and Railway Sound Levels (dB)	Level Adjustment (From Table 6-1)	Total Highway and Railway Sound Level (dB)	Difference Between Total Highway and Railway and Aircraft Sound Levels (dB)	Level Adjustment (From Table 6-1)	Total Exterior Sound Level (dB)	Room SIR (SIR Worksheet)	Indoor Sound Level Due to External Sources (dB)	Noise Criterion Level (dB)
A	B	C	D	E	F	G	H	I	J	K
Highway	66									
Railway	59	7	1	67						
Aircraft	69				2	2	71	32	39	40

Is the Total Indoor Sound Level Due to External Sources Greater Than the Noise Criterion Level?		
	Yes ____	A Noise Problem Exists
	No ✓	The Design is Satisfactory

Figure 7-8. Room Noise Worksheet for Revised Example.

Recall, further, that the room chosen was a "worst case" corner room with two walls and a roof exposed to sound pressures. Other rooms having only one facade wall exposed would have noise levels reduced by 3 dB relative to the noise levels for comparable rooms with roof and flanking wall exposure. The sound level within such a "typical" non-corner, exterior room using a stucco panel would be 36 dB, which is well below the selected noise criterion for this apartment building. An additional increment of 2 dB would be achieved if an acoustic tile ceiling were employed. In this case the sound level would be 34 dB. Table 7-3 summarizes these alternative designs and the resulting interior sound levels in the "worst case" corner room and in other non-corner rooms.

Table 7–3. Summary of room SIR and interior sound level calculations for "worst cases" top-floor corner room and comparable interior rooms for the original and two alternative building designs.

Design	Description	"Worst Case" Top-floor Corner Room	Non-corner Room
Oirginal Configuration	Flanking Wall—8" X 8" X 16" Hollow Core Concrete Block 12' X 5' Heavy Glass Fixed Window Facade Wall—Metal Frame Frame Insulated Brick Veneer 10' x 4' Heavy Glass Fixed Window 8' x 2' Steel Panel Roof—Insulated 3" Steel Deck Workmanship—Average Interior Furnishings—Carpet, No Acoustic Tile Ceilings or Heavy Drapes		
Alternative No. 1	Flanking Wall—8" X 8" X 16" Hollow Core Concrete Block 12' X 5' Heavy Double Glazed Fixed Window Facade Wall—Metal Frame Insulated Brick Veneer 10' X 4' Heavy Double Glazed Fixed Window 8' X 2' Stucco Panel Roof—Insulated 3" Steel Deck Workmanship—Good Interior Furnishings—Carpet and Acoustic Tile Ceiling, No Heavy Drapes		
Alternative No. 2	Flanking Wall—8" X 8" X 16" Hollow Core Concrete Block No window Facade Wall—Metal Frame Insulated Brick Veneer 10' X 4' Heavy Double Glazed Fixed Window 8' X 2' Stucco Panel Roof—Insulated 3" Steel Deck Workmanship—Good Interior Furnishings—Carpet, No Acoustic Tile Ceiling or Heavy Drapes		

References
Chapter 7
Design Alternatives

[1] Anderson, G. S., Miller, L. N., and Shadley, J. R., "Fundamentals and abatement of highway traffic noise: Volume Two—noise barriers design and example abatement measures" (Federal Highway Administration, Washington, D.C., 1973). Available from National Technical Information Service, Springfield, Virginia, Accession No. PB 222-703.

[2] *ASHRAE Handbook of Fundamentals*, Infiltration and Natural Ventilation, Chapter 19 (American Society of Heating, Refrigerating, and Air Conditioning Engineers, New York, 1972).

[3] Anon. Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety. EPA Report No. 550/9–74–004 (U.S. Environmental Protection Agency, Washington, D.C., March 1974).

Appendix A

SIR Values for Building Shell Members and Components

Introduction

The SIR values for walls, roofs, windows, and doors presented in this appendix have been obtained, together with descriptions of the construction details, from published literature [1–13] on the sound isolation, or transmission loss properties of building shell members and their components.

Effort has been expended to include in this list only those building constructions which have adequate descriptions of construction details, and those which appear to be technically consistent and accurate. Unfortunately, the literature on this topic is not well organized; and the data should be more thoroughly and accurately compiled in the future. The data of references [1], [3] and [4] are perhaps the most comprehensive.

Should you require the SIR value for some building shell member or component not listed in Appendix A, and if you have the necessary transmission loss data, you can derive the SIR value using the procedure outlined in Appendix B ("Determination of the Shell Isolation Rating"). Alternatively, you can estimate a SIR value by comparing the shell member or component you have in mind with ones of similar construction listed herein.

For some constructions, more details can be obtained from references [1–13], although pertinent details have been included herein insofar as possible.

In some cases, manufacturer's names or designations are indicated in the "Remarks" portion of the listing. This information is based upon available published literature, and may not represent currently available products or product performance. The reader is encouraged to seek out specifications pertaining to currently available products, to determine the relevant SIR values, and to up-date and supplement these listings as appropriate. The inclusion of those manufacturers names and proprietary designations, or the omission of others, does not constitute any endorsement or criticism of product performance on the part of the National Bureau of Standards. Rather, the data are given to provide a limited sample of available building components for the users of this design guide.

Walls

Description	Weight lbs/ft²	Remarks	Ref.	STR
Concrete Walls				
4 in. thick dense poured concrete, or solid block	50	(estimate)	[5]	41
4 in. dense poured concrete	50		[2]	47
6 in. thick dense poured concrete, or solid block	73	(estimate)	[5]	43
8 in. thick dense poured concrete, or solid block	95	(estimate)	[5]	46
8 in. dense poured concrete	100		[2]	52
12 in. thick dense poured concrete, or solid block	145	(estimate)	[5]	49
16 in. thick dense poured concrete, or solid block	190	(estimate)	[5]	51
Brick, Block, and Tile Walls				
4 in. lightweight concrete block	24	unpainted	[2]	27
4 in. lightweight concrete block	24	sealed with 2 coats of paint	[2]	43
6 in. thick hollow concrete block, 6 in. x 8 in. x 16 in.	21		[13]	41
6 in. thick hollow concrete block, 6 in. x 8 in. x 16 in.	34	1 wall painted	[4]	45
6 in. thick hollow concrete block, 6 in. x 8 in. x 16 in., ½ in. gypsum wallboard fastened on furring strips inside	27	exterior wall painted	[13]	46
8 in. thick hollow concrete block, 8 in. x 8 in. x 16 in.	30		[13]	43
8 in. thick hollow concrete block, 8 in. x 8 in. x 16 in.	30	painted both sides	[13]	43
8 in. thick hollow concrete block, 8 in. x 8 in. x 16 in., gypsum wallboard fastened on furring strips inside	43	exterior wall painted	[13]	46
12 in. thick solid concrete block, 12 in. x 8 in. x 16 in., ⅝ in. gypsum wallboard fastened on furring strips inside	124		[13]	54
12 in. thick combination wall, 8 in. x 8 in. x 12 in., and 8 in. x 4 in. x 16 in., hollow concrete blocks	79		[4]	49
slotted lightweight concrete block, 8 in. x 8 in. x 16 in.	—	2 coats of bondex cement base paint on one side, Soundblox Type "A" The Proudfoot Co., Inc.	[3]	44
8 in. dense concrete block	50	sealed with 2 coats of paint	[2]	52
8 in. dense concrete block	50	unpainted	[2]	52
12 in. thick brick wall	121		[4]	54
perforated glazed tile, 3¾ in. x 7¾ in. x 15¾ in., fiberglass core	—	Arketex Ceramic Corp.	[3]	44
acoustic ceramic glazed structural facing tile, 3¾ in. x 5$\frac{1}{16}$ in. x 11¾ in.	—	SCR Acoustile Stark Ceramics, Inc.	[3]	48
3½ in. thick (approx.), 18 ga. steel panels filled with 6–8 lb/cu ft insulation	—	joints and edges sealed (estimate)	[5]	38
Brick Veneered Frame Walls				
face brick veneer, ½ in. air space with metal ties, ¾ in. insulation board sheathing, 2 in. x 4 in. wood studs, 16 in. o.c., resilient channel, ½ in. gypsum wallboard screwed to channel	—		[1]	48
face brick veneer, ½ in. air space with metal ties, ¾ in. insulation board sheathing, 2 in. x 4 in. wood studs, 16 in. o.c., fiberglass building insulation, ½ in. gypsum wallboard screwed to studs	—		[1]	51

137	face brick veneer, ½ in. air space with metal ties, ¾ in. insulation board sheathing, 2 in. x 4 in. wood studs, 16 in. o.c., fiberglass building insulation, resilient channel, ½ in. gypsum wallboard screwed to channel	—		[1]	53
	Stuccoed Frame Walls				
	⅞ in. stucco, no. 15 felt building paper and 1 in. wire mesh, 2 in. x 4 in. wood studs, 16 in. o.c., ⅝ in. gypsum wallboard fastened to studs	—		[2]	34
	⅞ in. stucco, no. 15 felt building paper and 1 in. wire mesh, 2 in. x 4 in. staggered wood studs, 16 in. o.c., ⅝ in. gypsum wallboard fastened to studs	—		[2]	41
	⅞ in. stucco, no. 15 felt building paper and 1 in. wire mesh, 2 in. x 4 in. wood studs, 16 in. o.c., fiberglass building insulation, ½ in. gypsum wallboard screwed to stud	—		[1]	43
	⅞ in. stucco, no. 15 felt building paper and 1 in. wire mesh, 2 in. x 4 in. wood studs, 16 in. o. c., resilient channel, ½ in. gypsum wallboard screwed to channel	—		[1]	43
	⅞ in. stucco, no. 15 felt building paper and 1 in. wire mesh, 2 in. x 4 in. wood studs, 16 in. o. c., fiberglass building insulation, resilient channel, ½ in. gypsum wallboard screwed to channel	—		[1]	52
	Frame Walls With Wood Siding				
	⅝ in. x 10 in. redwood siding, ½ in. insulation board sheathing, 2 in. x 4 in. wood studs, 16 in. o. c., fiberglass building insulation, ½ in. gypsum wallboard screwed to studs	—		[1]	33
	⅝ in. x 10 in. redwood siding, ½ in. insulation board sheathing, 2 in. x 4 in. wood studs, 16 in. o. c., ½ in. gypsum wallboard screwed to studs	—		[1]	34
	⅝ in. x 10 in. redwood siding, ½ in. insulation board sheathing, 2 in. x 4 in. wood studs, 16 in. o. c., resilient channel, ½ in. gypsum wallboard screwed to channel	—		[1]	37
	⅝ in. x 10 in. redwood siding, ½ in. insulation board sheathing, 2 in. x 4 in. wood studs, 16 in. o. c., fiberglass building insulation, resilient channel, ½ in. gypsum wallboard screwed to channel	—		[1]	40
	Metal Walls, Curtainwalls				
	fluted 18 ga. sheet metal	4.4	prefabricated building component	[2]	25
	2½ in. thick panel, 20 ga. galvanized steel channel wall, perforated 18 ga. galvanized steel B-liner, fiberglass sealed in polyethylene bags	4.5	Elwin G. Smith Div.	[3]	26
	2½ in. thick panel, 20 ga. galvanized steel channel wall, perforated 18 ga. galvanized steel C-liner, fiberglass sealed in polyethylene bags	—	Elwin G. Smith Div.	[3]	29
	common curtainwall spandrel panel, 16 ga. sheet metal exterior, insulation and ⅝ in. gypsum wallboard interior	7.8		[2]	38
	2¼ in. thick panel, welded steel ribs, vertical 1 ga. steel stiffeners, rockwool insulation between 20 ga. steel sheets	5.13	Corporate MS–454 Virginia Metal Products Div.	[3]	34
	2¼ in. thick panel stiffeners, rockwool insulation between 20 ga. steel sheets	4.46	Monoline wall partition Virginia Metal Products Div.	[3]	37

2½ in. thick panel, 20 ga. galvanized steel channel wall, perforated 18 ga. galvanized steel C-liner, fiberglass sealed in polyethylene bags	—	Shadowall Elwin G. Smith Div.	[3]	39
20 ga. galvanized steel channel wall, perforated 18 ga. galvanized steel C-liner, fiberglass, ⅝ in. gypsum wallboard *	—	Shadowall Elwin G. Smith Div.	[3]	41

** Some of the metal partitions listed here are not principally intended for use as exterior partitions. However, the description and inclusion of SIR values are included to provide a basis for estimation of the shell isolation properties of comparable metal exterior wall systems.*

Roofs

Description	Weight lbs/ft²	Remarks	Ref.	SIR
Wood Roofs				
built-up, insulated roof over 2 in. tongue and groove wood planking	13	exposed planking and beams	[2]	37
shingle roof with attic, ½ in. gypsum wallboard ceiling, framed independently of roof	10	attic ventilation	[2]	40
built-up, insulated roof over 2 in. tongue and groove wood planking, ½ in. gypsum wallboard with cavity insulation	15		[2]	42
Steel Roofs				
built-up insulated roof over 18 ga. metal decking	10		[2]	36
1½ in. thick roof, 22 ga. steel roof decking	—	Type S Acoustideck Inland Ryerson Co.	[3]	42
1½ in. thick roof, 20 ga. steel roof decking	—	Type S and B Acoustideck Inland Ryerson Co.	[3]	43
3 in. thick roof, 20 ga. steel roof decking	—	Type 3 in. H & N Acoustideck Inland Ryerson Co.	[3]	43
1½ in. thick roof, 18 ga. steel roof decking	—	Type S and B Acoustideck Inland Ryerson Co.	[3]	44
4½ in. thick roof, 20 ga. steel roof decking	—	Type 4½ in. H Acoustideck Inland Ryerson Co.	[3]	44
1⅝ in. thick roof, 18-18 ga. steel roof decking	—	Type 1⅝ in. NF Inland Ryerson Co.	[3]	46
4½ in. thick roof, 20-18 ga. steel roof decking	—	Type 4½ in. H Acoustideck Inland Ryerson Co.	[3]	46
1⅝ in. thick roof, 18-18 ga. steel roof decking	—	Type 1⅝ in. NF Inland Ryerson Co.	[3]	47
4½ in. thick roof, 20 ga. steel roof decking	—	Type 4½ in. HF Acoustideck Inland Ryerson Co.	[3]	47
6 in. thick roof, 18 ga. steel roof decking	—	Type 6 in. H Acoustideck Inland Ryerson Co.	[3]	47
4½ in. thick roof, 16 ga. steel roof decking	—	Type H Acoustideck Inland Ryerson Co.	[3]	48
7½ in. thick roof, 18 ga. steel roof decking	—	Type 7½ in. N Acoustideck Inland Ryerson Co.	[3]	48

1⅝ in. thick roof, 16-18 ga. steel roof decking	—	Type 1⅝ in. NF Inland Ryerson Co.	[3]	49
3 in. thick roof, 18-18 ga. steel roof decking	—	Type 3 in. NF Acoustideck Inland Ryerson Co.	[3]	49
6 in. thick roof, 16 ga. steel roof decking	—	Type 6 in. H Acoustideck Inland Ryerson Co.	[3]	49
4½ in. thick roof, 18-18 ga. steel roof decking	—	Type 4½ in. HF Acoustideck Inland Ryerson Co.	[3]	49
4½ in. thick roof, 16-18 ga. steel roof decking	—	Type 4½ in. HF Acoustideck Inland Ryerson Co.	[3]	50
6 in. thick roof, 16-16 ga. steel roof decking	—	Type 6 in. HF 16-16 ga. Acoustideck Inland Ryerson Co.	[3]	51
built-up, insulated roof over 4 in. concrete slab	50		[2]	49

Windows

Description	Weight lbs/ft²	Remarks	Ref.	STL
Fixed Windows, Single Glazed				
single strength glass (3/32 in.)	—	four lights	[12]	22
single strength glass (3/32 in.)	1.3	fixed window, divided lights, 16 panes, 3/16 in. glass, ⅝ in. airspace	[1]	25
double strength glass	1.63	single light	[1]	26
2 mm glass	—	wood frame	[12]	26
3 mm glass	—	single light	[12]	26
4 mm glass	—	plastic frame, 3 lights	[12]	26
¼ in. glass	—	wood frame, 3 lights	[12]	26
4 mm glass	—	wood frame	[12]	28
¼ in. glass	3.2	sealed	[2]	28
5/16 in. glass	—	wood and steel frame	[12]	28
9.5 mm glass	—	metal frame, glass set in ferromastic putty	[12]	28
5.5 mm glass	—	two lights	[12]	29
⅜ in. glass	—	wood and steel frame	[12]	29
½ in. glass	—		[12]	30
10 mm glass	—		[12]	31
laminated glass [3/16 in. glass, 0.045 in. interlayer, 3/16 in. glass]	—		[12]	31
laminated glass	—	3 plies, 10 mm thick glass with 2 damping layers	[12]	31
9.5 mm glass	—	glass mounted in neoprene gasket	[12]	32
15.9 mm glass	—		[12]	32
laminated glass	—	double ⅛ in. sheets laminated to inner clear damping layer, sealed in heavy wood frame	[1]	32

¼ in. acoustic glass	3.2	sealed	[2]	33
⅝ in. glass	—	wood frame	[12]	33
laminated glass [¼ in. glass, 0.045 in. interlayer, ¼ in. glass]	—		[12]	33
15 mm glass	—		[12]	34
¾ in. glass	—		[12]	34
⅞ in. glass	—		[12]	34
1 in. glass	—	wood frame	[12]	34
laminated glass [⅛ in. glass, 0.045 in. interlayer, ⅜ in. glass]	—		[12]	35
½ in. acoustic glass	6.4	sealed	[2]	36
laminated glass	—	4 plies, ⅛ in. thick glass with 3 interlayers of 0.045 in.	[12]	36
laminated glass [⅜ in. glass, 0.045 in. interlayer, ⅜ in. glass]	—		[12]	37
½ in. acoustic safety glass	—	Soundtropane 40 Dearborn Glass Co.	[10]	37
½ in. laminated glass	—	Series 324 Starline, Inc.	[3]	38
laminated glass	—	3 plies, ¼ in. thick glass with 2 interlayers of 0.045 in.	[12]	38
laminated glass	—	6 plies, ⅛ in. thick glass with 5 interlayers of 0.045 in.	[12]	39
Fixed Windows Double Glazed				
3 mm glass, 4.8 mm airspace, 3 mm glass	—	metal frame, weather-stripped, 6 lights	[12]	2
2.9 mm glass, 4.9 mm airspace, 2.9 mm glass	—	sealed, 2 lights	[12]	22
3 mm glass, 12 mm airspace, 3 mm glass	—		[12]	25
6 mm glass, 12 mm airspace, 6 mm glass	—		[12]	27
6.2 mm glass, 11 mm airspace, 6.2 mm glass	—	sealed unit	[12]	27
¼ in. glass, ½ in. airspace, ¼ in. glass	—	wood frame, 3 lights	[12]	28
3 mm glass, 51 mm airspace, 3 mm glass	—	separate wood frames, 20 lights	[12]	30
3 mm glass, 32 mm airspace, 3 mm glass	—	wood frame	[12]	30
4.9 mm glass, 18 mm airspace, 7.6 mm glass	—	sealed unit	[12]	30
6 mm glass, 12 mm airspace, 8 mm glass	—		[12]	30
12 mm glass, 12 mm airspace, 12 mm glass	—		[12]	30
⅛ in. plate glass, 2¼ in. airspace, ⅛ in. plate glass	—		[3]	32
6.1 mm glass, 21.5 mm airspace, 9.4 mm glass	—	sealed unit	[12]	32
6 mm glass, 13.3 mm airspace, 8 mm glass	—	sealed unit	[12]	32
7.7 mm glass, 13.5 mm airspace, 9.5 mm glass	—	sealed unit	[12]	32
8 mm glass, 12 mm airspace, 10 mm glass	—		[12]	31
6.1 mm glass, 27 mm airspace, 9.1 mm glass	—	sealed unit	[12]	33
¼ in. glass, 1 in. airspace, ¼ in. glass	—	figured glass, 3 lights	[12]	33
¼ in. glass, 1 in. airspace, ⅜ in. glass	—	figured glass, 3 lights	[12]	33
3 mm glass, 75 mm airspace, 3 mm glass	—		[12]	34
3 mm glass, 10 cm airspace, 3 mm glass	—		[9]	34
4 mm inner glass, 56 mm airspace, 10 mm outer glass	—	wood plastic composite window, 1 lip sealed	[8]	34
⅜ in. glass, 1 in. airspace, ⅜ in. glass	—	figured glass, 3 lights	[12]	34

141	6 mm glass, 13.3 mm airspace, 10 mm glass	—	sealed unit	[12]	34
	4 mm glass, 8.5 cm airspace, 4 mm glass	—		[9]	35
	¼ in. glass, 2 in. airspace, ¼ in. glass	—	separate wood frames, 20 lights	[12]	35
	6 mm glass, 10 cm airspace, 6 mm glass	—		[9]	36
	3/16 in. glass, 2 in. airspace, ¼ in. glass	—		[12]	36
	⅜ in. glass, 2 in. airspace, ⅜ in. glass	—	figured glass, 3 lights	[12]	36
	3 mm glass, 10 cm airspace, 6 mm glass	—		[9]	37
	4 mm glass, 10 cm airspace, 4 mm glass	—		[9]	37
	¼ in. glass, 2 in. airspace, ½ in. glass	—		[12]	37
	¼ in. plate glass, 2¼ in. airspace, ¼ in. plate glass	—	aluminum frame, DeVac, Inc.	[3]	37
	3 mm glass, 10 cm airspace, 3 mm glass	—	10 cm x 10 cm deep absorbing material in frame channel	[9]	38
	3 mm glass, 10 cm airspace, 6 mm glass	—		[9]	38
	4 mm glass, 10 cm airspace, 4 mm glass	—	10 cm x 2.5 cm deep absorbing material in frame channel	[9]	38
	4 mm glass, 10 cm airspace, 4 mm glass	—	10 cm x 5 cm deep absorbing material in frame channel	[9]	38
	3/16 in. glass, 2½ in. airspace, ¼ in. glass	5.7	neoprene gasketed aluminum frame	[2]	38
	¼ in. plate glass, 2½ in. airspace, 5/16 in. plate glass	—		[3]	38
	¼ in. glass, 2 in. airspace, ⅜ in. glass	—		[12]	38
	4 mm glass, 10 cm airspace, 4 mm glass	—	10 cm x 10 cm deep absorbing material in frame channel	[9]	39
	6 mm glass, 10 cm airspace, 6 mm glass	—	10 cm x 2.5 cm deep absorbing material in frame channel	[9]	39
	6 mm glass, 10 cm airspace, 6 mm glass	—	10 cm x 5 cm deep absorbing material in frame channel	[9]	39
	6.25 mm glass, 70 mm airspace, 19 mm glass	—		[12]	39
	3/16 in. glass, 2 in. airspace, ⅜ in. glass	—		[12]	40
	7/32 in. glass, 2½ in. airspace, ¼ in. glass	—		[2]	40
	¼ in. plate glass, 2¼ in. airspace, ¼ in. plate glass	—		[3]	40
	6 mm glass, 10 cm airspace, 6 mm glass	—	10 cm x 10 cm deep absorbing material in frame channel	[9]	41
	3 mm glass, 10 cm airspace, 6 mm glass	—	10 cm x 10 cm deep absorbing material in frame channel	[9]	42
	3 mm glass, 10 cm airspace, 6 mm glass	—	10 cm x 10 cm deep absorbing material in frame channel	[9]	42
	3/16 in. glass, 4 in. airspace, ¼ in. glass	—	aluminum frame, Sitelines, Inc.	[11]	45
	3/16 in. plate glass, 4¾ in. airspace, ¼ in. plate glass	—		[3]	45
	7/32 in. glass, 3¾ in. airspace, ¼ in. glass	6.1	neoprene gasketed aluminum frame	[2]	45
	7/32 in. glass, 3¾ in. airspace, ¼ in. glass	—		[12]	45

7/32 in. plate glass, 3¾ in. airspace, ¼ in. plate glass	—	Miller Bldg. Supply Co.	[3]	45
¼ in. plate glass, 4 in. airspace, 5/16 in. plate glass	—		[3]	48
Single Hung Windows, Single and Double Glazed				
double glazed (7/16 in.)	—	aluminum frame, locked	[1]	26
¼ in. plate glass	—		[3]	28
Double Hung Windows, Single Glazed				
single strength glass (3/32 in.)	—	wood frame	[2]	20
single strength glass (3/32 in.)	1.3	single light	[1]	22
single strength glass (3/32 in.)	1.3	single light, locked	[1]	24
Double Hung Windows, Double Glazed				
3/32 in. single strength glass, 3/16 in. airspace,	—	wood frame	[7]	20
3/32 in. single strength glass, ⅜ in. airspace	2.6	single light, locked	[1]	25
3/32 in. single strength glass, 3/16 in. airspace, 3/32 in. single strength glass with storm sash		wood frame	[7]	28
⅜ in. glass with 3/32 in. single strength glass storm sash	—	single lights, locked	[1]	29
Casement Windows, Single Glazed				
single strength glass (3/32 in.)	—	steel frame	[7]	19
double strength glass (⅛ in.)	1.63	aluminum frame, locked	[1]	20
double strength glass (⅛ in.)	1.63	operable locked	[1]	28
double strength glass (⅛ in.)	1.63	single light	[1]	29
Horizontal Sliding Windows				
single strength glass (3/32 in.)	—	aluminum frame	[2]	16
single strength glass (3/32 in.)	—	aluminum frame, locked	[1]	24
¼ in. glass	—	aluminum frame	[7]	24
Pivoted Windows, Single and Double Glazed				
¼ in. plate glass	—	vertical pivoted window	[3]	29
double glazed, 3/16 in. plate glass, 2 in. airspace, ¼ in. plate glass	—	pivoted window with thermal and sun control Kawneer Co., Inc.	[3]	38
Miscellaneous Windows, Various Glazing				
3 mm glass	—	operable window, aluminum frame, 20 lights	[12]	21
¼ in. glass	—	operable window, aluminum frame, 20 lights	[12]	22
2.9 mm glass	—	operable window, wood frame, glass set in mastic, 2 lights	[12]	23
double glazed, ¼ in. plate glass, ½ in. airspace, ¼ in. plate glass	—	venetian blind window Amelco Window Corp.	[3]	31

double glazed, ¼ in. plate glass, 1⅞ in. airspace, ¼ in. plate glass	—	venetian blind window Alpara Aluminum Prod. Inc.	[3]	42
¼ in. glass	—	jalousie window, 4½ in. wide louvers with ½ in. overlap, cranked tight	[1]	18
single strength glass (3/32 in.) with single strength glass (3/32 in.) storm sash with 2¼ in. separation between upper pane and 3⅝ in. separation between lower pane and storm sash	—	locked	[1]	27
single strength glass (3/32 in.) with double strength glass (3/32 in.) storm sash with 3¾ in. separation between storm sash and glass	—	fixed window, divided lights, 16 panes, storm sash with single light	[1]	33
glass block window, 3⅝ in. thick	—	fixed window	[2]	39

Doors

Construction	Weather-stripping	Weight lbs/ft²	Thick-ness	Remarks	Ref.	SIR
Glass Doors						
safety glass, sliding door	—	2.6	3/16 in.	6 x 7 ft.	[1]	24
wood, French door, single-strength glass	brass	2.85	1¾ in.	12 lights	[1]	24
Wood Hollow Core Doors						
—	—	2.5	1¾ in.	1/16 in. crack at threshold	[2]	14
—	yes	1.4	1¾ in.	1/16 in. crack at threshold	[7]	15
—	yes	2.5	1¾ in.		[2]	17
—	bronze	1.4	1¾ in.		[7]	17
—	brass	1.25	1¾ in.		[1]	19
—	—	5.1	1¾ in.	Perma Strait Midwest Woodworking Co.	[3]	26
Wood Solid Core Doors						
—	—	4.5	1¾ in.	1/16 in. crack at threshold	[7]	16
—	extruded plastic	3.9	1¾ in.		[1]	24
—	brass	3.9	1¾ in.		[1]	25
—	extruded plastic	—	1¾ in.	includes 1 in aluminum frame storm door with single-strength glass	[1]	30
Miscellaneous Wood Doors						
paneled	—	5.0	1¾ in.	1/16 in. crack at threshold	[2]	18
solid panel	bronze	2.9	—		[7]	21
hardwood, acoustical door	—	4	2⅛ in.	Munchhausen Soundproofing Co. Inc.	[3]	26
acoustical door	—	4	1⅞ in.	Munchhausen Soundproofing Co. Inc.	[3]	26
flush	—	8.1	1¾ in.	STC 30 sound door Republic Steel Corp.	[3]	30

Construction	Weather-stripping	Weight lbs/ft²	Thick-ness	Remarks	Ref.	SIR
hardwood surfaces, high density core, sound retardant door	—	—	2¼ in.	Timeblend core Weyerhauser Co.	[3]	39
Plywood Doors						
acoustical door	—	6.7	1¾ in.	STC 36 door sys. Republic Steel Corp.	[3]	34
—	—	6.7	1¾ in.	STC 40 door U.S. Plywood	[3]	39
—	—	9.2	1¾ in.	STC 49 door U.S. Plywood	[3]	47
Steel Doors						
20 ga. steel facing, fiberglass core	—	3.9	1¾ in.		[3]	21
steel facing, polyurethane foam core	—	—	1¾ in.	Tearma-Tru entry System, Lakeshore Industries, Inc.	[3]	27
16 ga. steel facing	—	5.4	1¾ in.	Fenestra F6 C4072–M, Fenestra Door Products	[3]	29
hollow core	magnetic	1.25	1¾ in.		[1]	29
—	—	6.7	1¾ in.	3500 series Amweld Build. Prod.	[3]	34
18 or 16 ga. CRS surface, kraft E11–99–1AS honeycomb paper core	—	21	1¾ in.	Sound Sentry Door Emerson Engin. Co.	[3]	38
16 ga. steel facing, flush hollow metal, single-glazed, internally reinforced acoustical door	—	11.3	1¾ in.	Overly Manu. Co.	[3]	38
16 ga. steel facing, acoustical door	—	7.9	1¾ in.	Overly Manu. Co.	[3]	38
hollow metal	—	8.1	1¾ in.	sound door Bob Lench Co.	[3]	39
18 ga. steel facing, single-glazed acoustical door	—	6.8	1¾ in.	Overly Manu. Co.	[3]	39
18 ga. steel facing, flush hollow metal, louver, acoustical door	—	7.4	1¾ in.	Overly Manu. Co.	[3]	40
hollow metal	—	9.3	1¾ in.	Hol-O-Met Corp.	[3]	40
16 ga. steel facing, acoustical door, double glazed	—	11.3	1¾ in.	Overly Manu. Co.	[3]	41
16 ga. steel facing, acoustical fire door	—	9.5	1¾ in.	Overly Manu. Co.	[3]	44
masonry core with steel facing	—	7.5	2½ in.	cam-seal door Industrial Acous. Co., Inc.	[3]	45
masonry core with metal facing	—	7.1	1¾ in.	industrial door Industrial Acous. Co., Inc.	[3]	46
metal facing, concrete core	—	14.8	4 in.	industrial door Industrial Acous. Co., Inc.	[3]	47
12 ga. steel facing, acoustical door	—	21.9	2½ in.	Overly Manu. Co.	[3]	47

16 ga. steel facing, acoustical door	—	8.6	1¾ in.	Overly Manu. Co.	[3]	47
18 ga. steel facing	—	14.9	3 in.	industrial door Industrial Acous. Co., Inc.	[3]	48
16 ga. steel facing, internally reinforced acoustical door	—	23	4 in.	Overly Manu. Co.	[3]	50
—	—	3.4	1⅜ in.	Amweld 1500 Series Amweld Build. Prod.	[3]	30
Composite Doors						
flush, wood, plastic laminate	—	4.1	1¾ in.	Perma Strait Midwest Woodworking Co.	[3]	17
concrete block core, acoustical door	—	—	2⅝ in.	#873 acous. door Hupp Corp.	[3]	37
fiberglass reinforced plastic panel	extruded plastic	2.35	1¾ in.	rigid polyurethane core	[1]	26

References— Appendix A SIR Values

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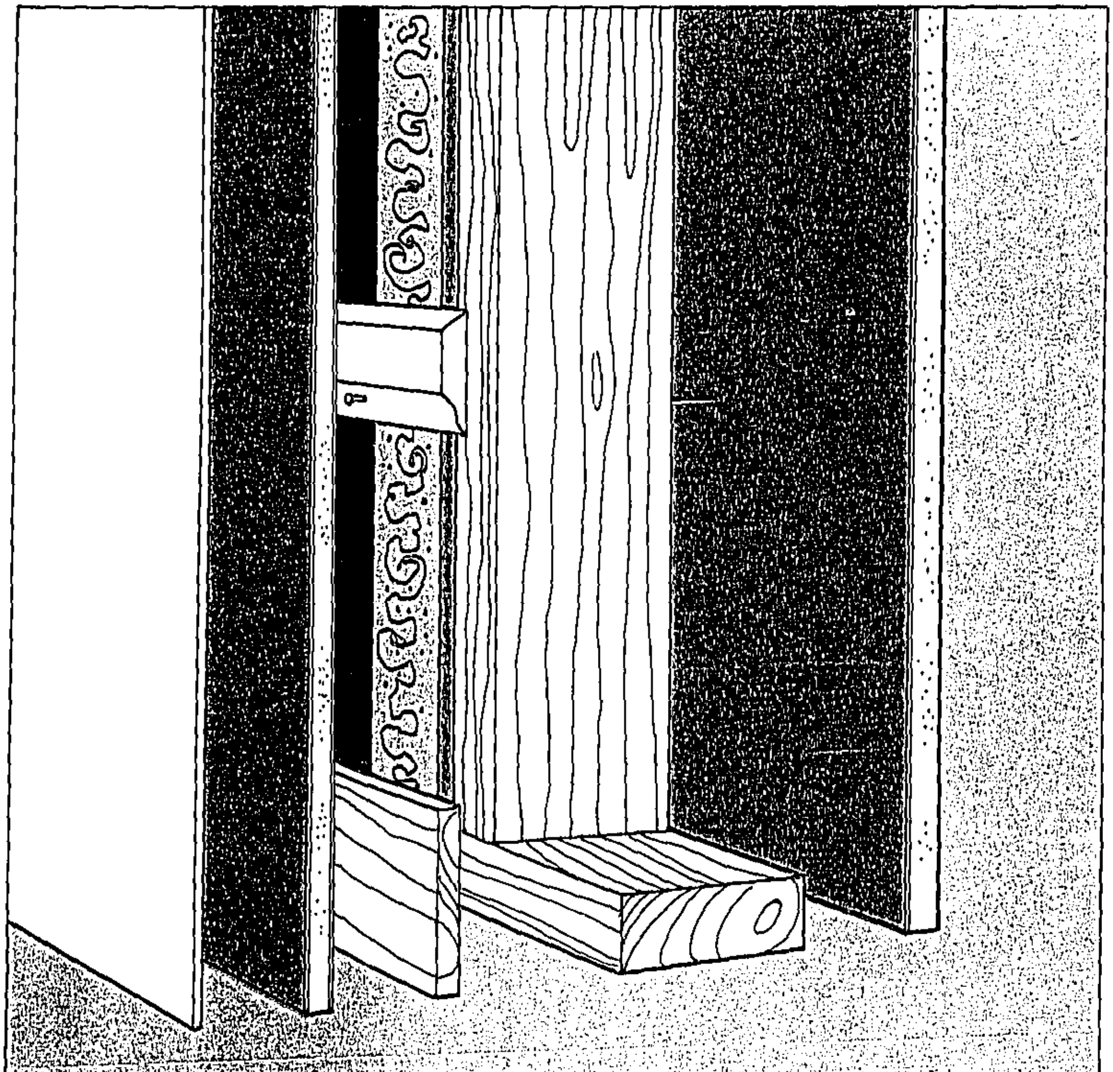

Appendix B

Technical Basis of the SIR Method

Objective

The objective of the study that led to the evolution of the SIR method was to derive a simple system to predict the attenuation of A-weighted sound provided by building shells from information about the construction of the exterior partitions. It appeared that such a system would ideally be based upon some single-figure rating of the acoustical transmission properties of the partition, would simply account for the exterior surface area and interior furnishings, and would be relatively insensitive to the details of the external noise. This appendix briefly describes the evolution of the system which appears to satisfy these objectives, and which is used in this report.

Physical Parameters

In a typical measurement of the noise isolation between two adjacent rooms, measurements of the space and time averaged mean sound pressure levels are obtained in the two rooms, and the difference in levels is obtained. Mathematically, if the sound level in the first room (chosen as the one with the higher noise level, because it is assumed to contain the major source of noise) is denoted by SPL1, and the sound level in the second room is denoted by SPL2, then the term (SPL1 − SPL2) is termed the "noise reduction" [1], denoted NR,

$$NR = SPL1 - SPL2.$$

Throughout this design guide, all sound levels are actually A-weighted sound pressure levels, and SPL1 and SPL2 would each be measured with the use of the A-weighting network.

The noise reduction is a physical quantity of great interest, because it tells us about the magnitude of the isolation between the rooms. This isolation is provided by the noise insulation properties of the separating partition. But although the noise reduction accounts for some of the noise insulation properties of the partition, it is also dependent upon details of the furnishings and dimensions of the second ("receiving") room as well as the workmanship in the installation of the partition.

In particular, the total amount of absorptive material in the second room is an important factor which must be taken into account. This absorption is measured in terms of the equivalent area of an opening through which the sound may be totally absorbed or leave the room, as through an open doorway. The absorption of the receiving room is thus given by a term A2 (in square meters, or "metric sabines").

The area of the partition separating the two rooms is also an important factor. Since all of the sound energy is assumed to pass through the partition, more sound energy will pass through a large partition than through a small one, and (all other factors being equal) a (receiving) room with a large partition will be noisier than would be the case for a small partition. The area of the partition separating two adjacent rooms is termed Sw.

In order to eliminate these complicating factors when considering the relative noise isolating properties of alternative partitions, a physical parameter related to the (measured) noise reduction is used. This is the "transmission loss", termed TL. Mathematically [1, 2],

$$TL = NR + 10 \log_{10} (Sw) - 10 \log_{10} (A2).$$

The transmission loss is the ratio, expressed in decibels, of the incident sound power per unit area (incident intensity) to that transmitted through and radiated by a unit area of *the partition*, independent of the properties of the receiving room. Laboratory data for the transmission loss properties of partitions are frequently measured and can be found in the literature. These data are generally measured and reported upon in octave-band or one-third-octave bands, when the acoustic fields in the two adjacent rooms are diffuse as in a reverberant room. The reverberant room environment makes it possible to accurately measure the space-averaged sound levels mentioned earlier, and also makes it possible to assume that the acoustic field incident upon the partition in the first (source) room is such that sound energy is incident with equal probability from all directions.

The exterior facade of a building should provide adequate attenuation of sound arriving from a number of directions. For design purposes, it is often appropriate to make use of sound transmission loss data which correspond to an average over many angles of incidence. For some situations, such as the upper floors of a high rise building very near a highway, the traffic noise will arrive at near grazing incidence and data for the transmission loss at this angle would ideally be selected if available. However, the majority of circumstances are such that sound can be expected to arrive from essentially all angles with equal probability. For this design guide, the "random incidence" transmission loss data were used in developing the SIR method. These data are appropriate when there is equal probability of sound arriving from any direction. For design purposes, these data are conservative for sound arriving at the partition from 0° (normal) to beyond 45°. Unless it is known that sound will usually impinge at near grazing incidence, the use of data obtained under random incidence conditions should be suitable for exterior walls.

Published transmission loss data are frequently obtained making use of laboratory measurement procedure; however, procedures for determining the airborne sound insulation in building elements are also available [3]. The recommended practice cited in [3] is specifically directed toward the problems involved in measurement of the performance of a partition element when installed as a part of a building, whatever the configuration, as opposed to a controlled laboratory environment.

Neglecting the fact that exterior facades are not usually used to separate two acoustically reverberant systems, for this design guide we are interested in differences in sound levels on the two sides of the facade (interior and exterior) of buildings. A slight complication is introduced if we actually attempt to measure the sound levels in the immediate vicinity of the partition on the exterior side; the sound level there may be as much as 6 dB higher than a little further away. This stems from a pressure doubling effect due to reflections or the presence of the rigid partition, but it is restricted to the region close to the wall and is not a source of complication when we wish to consider the difference in diffuse field or random incidence and reverberant field space averaged sound levels. These differences are given by the noise reduction, NR.

Thus to estimate the noise reduction due to a given exterior partition, we need to know the TL data (from the literature), the area of the partition Sw, and the total acoustical absorption of the room, A2. Rearranging the previous expression for transmission loss,

$$NR = TL - 10 \log_{10} (Sw) + 10 \log_{10} (A2).$$

For many architectural acoustics problems, the majority of the acoustical absorption is provided by materials used as either floor or ceiling coverings (e.g., carpets and acoustical ceilings) or as furniture. A smaller amount is provided by wall coverings such as drapes. The total absorption (A2) is therefore often crudely proportional to the floor area. As we shall see, this observation is used in developing the SIR method, and corresponds to practical rules of thumb frequently used by architectural acousticians.

The term (A2), like the term TL, is a function of frequency. Typically, an absorptive material such as acoustical tile may have a much higher absorptivity for high frequencies than for low. Thus, an evaluation of "the" noise reduction provided by a partition or enclosure must be conducted on a narrow band basis, and separate estimates of the noise reduction for each octave or one-third octave band are generated.

To thoroughly evaluate the difference in A-weighted levels on two sides of a partition from published data, several steps are required. First one obtains narrow band spectral information describing the nature of the sound produced by the noise source located on the exterior side, applies the A-weighting characteristic, and then determines the overall A-weighted exterior sound pressure level. Secondly, one evalutes the partition used in conjunction with the receiving room, using the expression for NR to generate a table or chart showing the noise reduction provided by the enclosure for each narrow frequency band. These values are then subtracted from the spectrum level data characterizing the noise source, to yield the spectrum levels which characterize the noise within the interior room. The A-weighting characteristic is then applied, and the overall A-weighted interior sound pressure level is then determined. The difference in the two overall A-weighted levels can then be obtained, and will be a measure of the protection from external noise provided by the building shell.

Obviously this can be a rather complicated process. To simplify the computational process, reliance is sometimes placed upon single figure ratings.

Single-figure rating systems are frequently used in the evaluation of the elements of complex systems. Architectural acoustics is a field in which several such systems are found. The American Society for Testing and Materials has published the details of a single-figure rating system appropriate for rating the sound transmission properties of interior partitions by the appropriate sound transmission class (STC) number [4]. Other single-figure rating systems found in this field include the impact isolation class (IIC) system for rating the impact noise properties of floor-ceiling assemblies [5], and the shell isolation rating (SIR) system devised for this report.

The technical basis for the SIR system used in this report is similar in many respects to that for the STC system. Both of these systems rely upon test data which characterize the acoustic transmission loss properties of test assemblies.

One significant difference between the two systems (STC and SIR) lies in the fact that the STC single figure rating is a rating describing the noise insulation properties of a partition itself, whereas the SIR is a single figure rating which is used both to describe the noise insulation properties of a partition element ("member SIR") and to describe the noise isolation properties of an enclosure ("room SIR") which has partitions as its members. It might have been preferable to consistently distinguish between the SIR numbers appropriate to the shell members or components in contrast with that for the total enclosure or room but no real confusion should exist as one becomes familiar with the important concept that ultimately the room SIR number is used to estimate the difference in A-weighted (equivalent) sound levels between interior and exterior of the room, corresponding to the attenuation (noise isolation) provided by the building shell or the noise reduction.

STC Rating System

For the STC rating system [4] partition transmission loss data are compared with a reference contour in a series of 16 one-third-octave bands ranging from 125 Hz to 4000 Hz. The sound transmission class (for the partition) may be determined by comparison of the transmission losses for the test specimen plotted on a graph with a transparent overlay on which the STC reference contour is drawn. Figure B-1 illustrates an STC reference contour. The STC contour is shifted vertically relative to the test curve until some of the measured TL values for the test specimen fall below those of the STC contour, and the following conditions are fulfilled:

(a) the sum of the deficiencies (i.e., the deviations below the STC contour) shall not be greater than two times the total number of frequency bands for which data are available, and

(b) the maximum deficiency at a single test point shall not exceed 8 dB.

When the contour is adjusted to the highest value (in integer decibels) that meets these requirements, the sound transmission class for the specimen is the TL value corresponding to the intersection of the reference contour at 500 Hz and the ordinate of the TL data plot [4]. Note that the reference contour is an essential element in this rating system.

Basis for Evaluation of Alternative Single Figure Rating Curves

At the outset of the study which led to the SIR method it was realized that any rating contour chosen for evaluation of the exterior partitions ought to properly account for the different frequency spectra of the external noise sources. Thus, it was agreed that the study should include use of several spectra for each of several types of external noise sources; e.g., highway, railway and aircraft.

Because several alternative rating curves were included in the study, it was decided to use simple (although extensive) statistical studies for choice of the most suitable rating curve.

The basis of the process of evaluation consisted of repeated comparison of the single figure rating number (obtained for a given exterior partition member or component, using a specific rating curve and curve fitting rule applied to the corresponding partition transmission loss data) with the average shell isolation computed by explicit detailed evaluation of the differences in

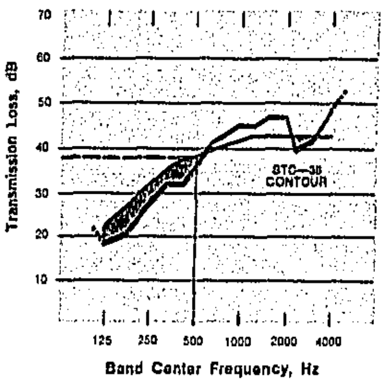

Figure B-1. An example of the application of the STC contour to transmission loss data.

A-weighted levels which would exist for several given noise source spectra, partition elements, and trial room configurations. Because all sound levels to be used in this design guide were to be A-weighted, the single figure method was to correlate with the difference in A-weighted levels, rather than with other differences of weighted levels.

More explicitly, realize that the use of the rating curve and curve fitting procedure yields a single figure indirectly corresponding to the noise reduction properties, since the noise reduction is a consequence of the transmission loss provided by the partition. For comparison purposes, explicit evaluation of the difference in A-weighted noise levels (by the detailed method of calculation) also yields estimates of the shell isolation or noise reduction properties. We sought to choose a rating curve yielding a predictable systematic mean difference between: (1) the single numbers derived from consideration of the partition itself, and (2) the achieved detailed estimates of the enclosure's (room's) noise reduction.

Furthermore we sought to select a curve for which the standard deviation of the differences between the systematic mean difference and the achieved noise reductions was small. Smallness of the standard deviation was considered to indicate that, for the statistical set in consideration, the derived single figure and the differences in A-weighted sound levels were reasonably well correlated, and that, further, the single figure numbers characterizing the properties of the partition could be used as the basis of simple estimates of the noise reduction properties of the enclosure, by accounting for the mean difference appropriately.

Thus, the choice of an appropriate rating curve became an exercise in statistical consideration of the available data.

For this study, spectral data were obtained from the literature, for eleven examples of highway noise, eleven examples of railway noise, and five examples of aircraft noise [6–18]. Figures B-2 through B-4 illustrate the general characteristics of these spectra, when normalized to equal A-weighted levels.

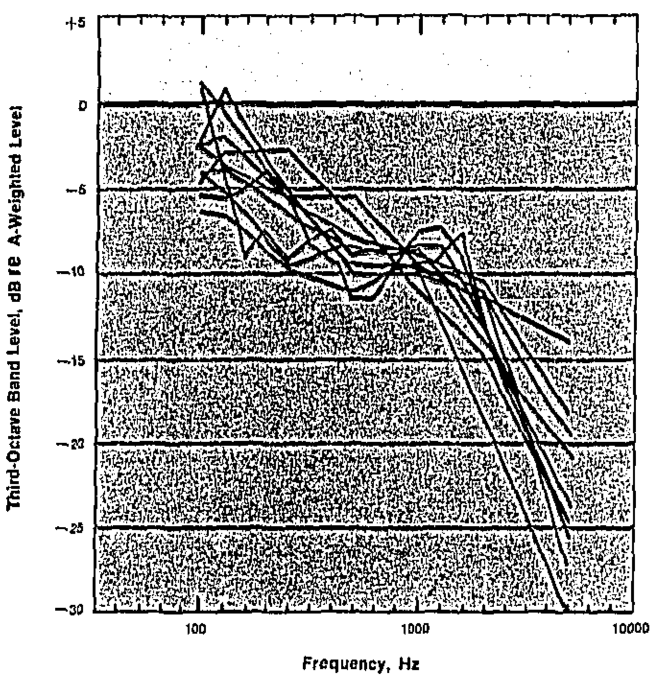

Figure B-2. Eleven highway spectra normalized to equivalent A-weighted sound pressure levels.

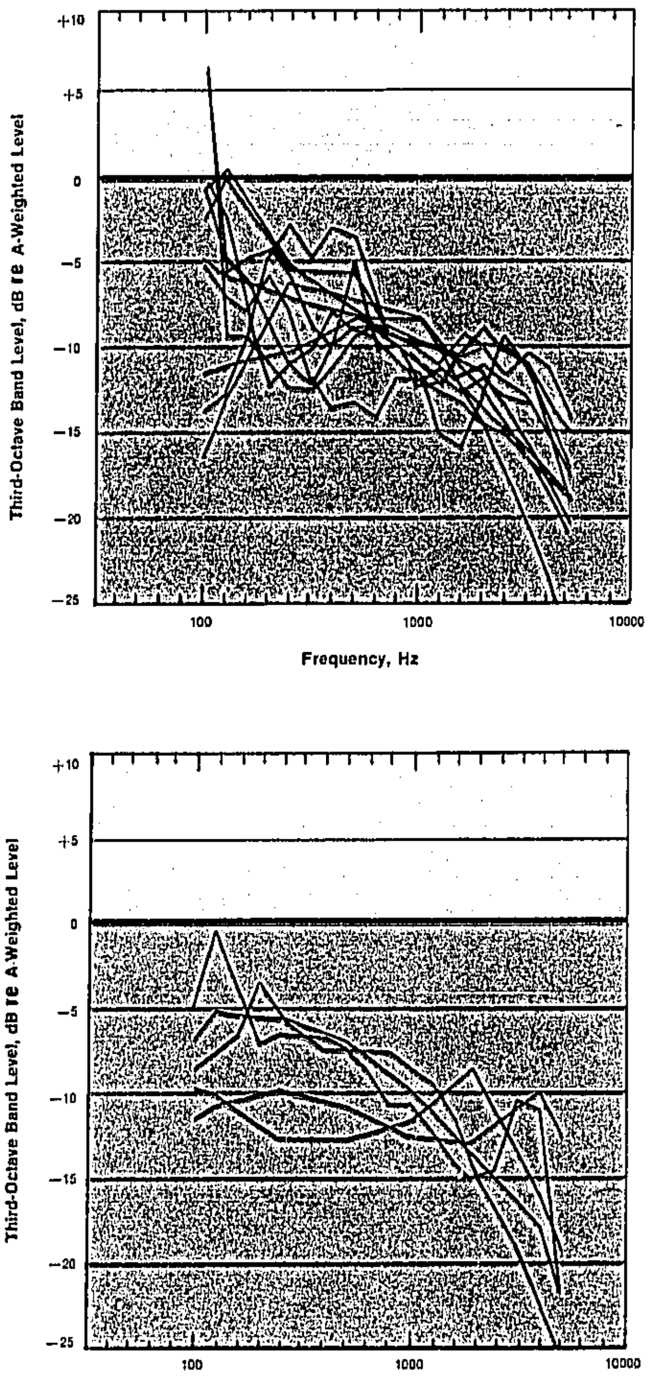

Figure B-4. Five aircraft spectra normalized to equivalent A-weighted sound pressure levels.

Prior work of Ljunggren [19] had suggested that a single number rating should be chosen upon some measure of the degree to which partition transmission loss data "fit" the A-weighted typical exterior noise band levels. For the noise spectra chosen in his study, these considerations led to choice of a rating contour consisting of a straight line sloped at +3 dB/octave, and this contour was selected for evaluation.

Much published data are available, however, for the STC single figure ratings characteristic of partitions, and it was thought prudent to consider whether the use of this rating contour (and thus, these published data) would be desirable for the purposes of this design guide.

Still a third trial contour was considered: a straight line with zero slope (a "flat" contour). This was thought to be desirable on the basis of certain simple curve-fitting properties.

These three trial contours were to be applied to the transmission loss data for a large number of exterior partitions and partition components such as doors, windows, decorative panels, etc. The available literature was extensively reviewed to obtain these data. It should be noted that there are some contradictory data to be found in the literature, i.e., discrepant data published for nominally identical constructions, and that, as well, the descriptions of construction details are often imprecise. Ideally, the data should be critically reviewed and a representative selection of exterior partition elements and components chosen. For this study, transmission loss data for more than 500 exterior partition elements were collected from the literature [19–31].

A trial room was selected, with dimensions of 12 ft wide by 8 ft high by 25 ft deep. Because of the possible sensitivity of single number curve fitting procedures to the details of interior absorption, three different interior configurations were studied for the trial room. These correspond to acoustically "hard", "medium", and "soft" rooms. The absorption coefficients were computed from published data. The "hard" room was assumed to have a floor of vinyl asbestos tile on concrete, walls of gypsum board on 2 in. by 4 in. wooden studs spaced 16 in. on center, and a concrete ceiling. No allowance was made for absorption due to furniture or occupants for any of the configurations, so that it is probable that the "hard" configuration represents an extreme not often found in practice. In the "medium" room, the absorption coefficients for a carpet and pad were substituted for those of the vinyl asbestos tile. For the "soft" configuration, a fissured tile ceiling was also included. Data for the average sound absorption coefficient, corresponding to the term (A2) divided by the total interior surface area are given in Figure B–5 for the three configurations.

Statistical Studies

Initially, for each of the 27 examples of exterior noise spectra, computations of the difference in A-weighted levels were made for each of 507 exterior partitions or partition elements, for the "medium" configurations of the trial room. For comparison, the 507 partitions were assigned single number ratings using a simple curve fitting procedure and the "flat" reference contour. The mean difference between the single numbers thus obtained and the differences in

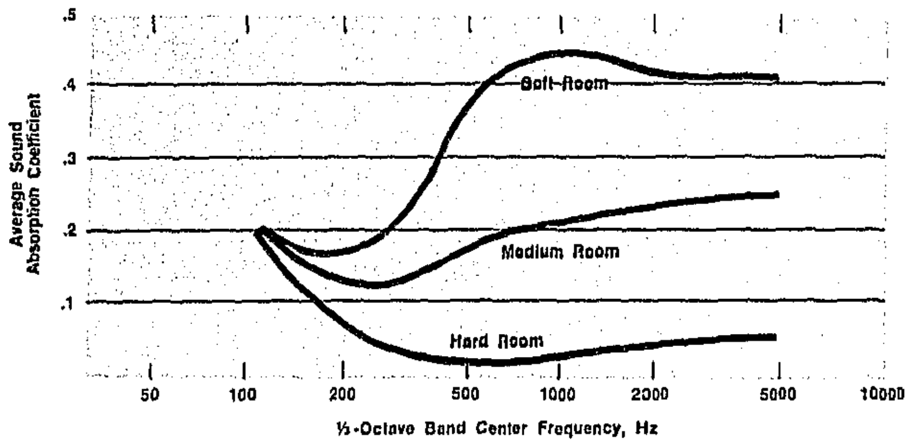

Figure B–5. Average sound absorption coefficients versus frequency for three room configurations.

A-weighted levels computed using the detailed transmission loss data was then obtained by averaging over the 507 partition elements for each of the 27 spectra. The standard deviation about the mean difference was also computed.

The magnitude of the standard deviation for each of the 27 sets of data was such that the differences between the magnitude of the mean differences were small in comparison. Thus, an insensitivity of the comparison to the details of the spectral characteristics was indicated. This indicated that, at the least, data for subsets of different class of noise source would be adequate as opposed to computations for each specific source, and that a method involving averaging over *all* exterior noises might be successful. "Success", or "adequacy" of these studies was understood to be primarily that the standard deviations were not appreciably enlarged when comparing the standard deviations for subsets with the 27 individual standard deviations.

Studies were next conducted by computing the corresponding statistics again for the twenty-seven spectra, but including the use of "flat", +3 dB/octave, and STC rating contours, again for the more than 500 partitions, and including the three trial room configurations. However, because of the noted insensitivity to details of the spectral characteristics, the statistics were this time computed for each of the three subsets corresponding to different classes of external noise source (highway, railway and aircraft) as well as when averaged over the complete set of twenty-seven noise source spectra. Thirty-six values of the mean differences and standard deviations were thus computed; corresponding to four sets of source spectra (3 sub sets of class of source plus the complete set including the 27 source spectra); three rating curves; and three absorption configurations. These data are shown in Table B-1.

It is apparent that the differences between the data for each of the subsets corresponding to differing classes of sources were modest relative to the sizes of the standard deviations so that the separate considerations of different classes of source is probably not warranted. Consideration of these data was thus subsequently restricted to the statistical data for the complete set which include consideration of all 27 source spectra.

The most desirable single figure rating system would be that characterized by a small value of standard deviation. For the "medium" room configuration, the data obtained using the 3 dB/octave curve are characterized by the smallest standard deviation (2.10 dB), followed by the "flat" (2.19 dB) and STC (2.69 dB) data. For the "soft" room configuration, the relative rank orderings, in terms of increasing size of the standard deviation, are the "flat", 3 dB/octave, and STC data. Finally, for the "hard" configuration, the rank orderings are STC, 3 dB/octave, and "flat". Though no one rating curve is superior for all room configurations, the differences between the "3 dB/octave" and "flat" data for the two most representative room configurations are small and the data using these two curves are superior to those for the STC contour. In view of the fact that the 3 dB/octave data are superior to the "flat" contour (and only slightly inferior to the STC contour data) for the "hard" room configuration, a slight overall preference is shown for the 3 dB/octave contour as Ljunggren suggested.

In order to test the sensitivity of this choice

Table B-1

Statistical analysis of mean differences and standard deviations between the single figure derived by curve fitting to partition transmission loss data and the level difference. Three room absorption configurations, twenty-seven noise spectra, 507 partitions and three contours were considered. All data are units of dB.

	3 dB/octave Contour		STC Contour		"Flat" Contour	
	Mean Diff.	Std. Dev.	Mean Diff.	Std. Dev.	Mean Diff.	Std. Dev.
Hard Room Configuration						
11 Highway Spectra	−2.32	1.57	−5.47	1.53	−0.71	2.63
11 Railway Spectra	−1.85	1.76	−5.00	1.58	−0.24	2.91
5 Aircraft Spectra	−1.46	1.98	−4.61	1.66	+0.15	3.21
Complete Set of 27 Spectra	−1.97	1.76	−5.12	1.61	−0.36	2.88
Medium Room Configuration						
11 Highway Spectra	+2.01	1.94	−1.13	2.66	+3.63	1.78
11 Railway Spectra	+2.75	2.09	−0.39	2.67	+4.37	2.23
5 Aircraft Spectra	+3.39	2.12	+0.25	2.50	+5.01	2.56
Complete Set of 27 Spectra	+2.57	2.10	−0.58	2.69	+4.19	2.19
Soft Room Configuration						
11 Highway Spectra	+3.77	2.31	+0.63	3.19	+5.39	1.65
11 Railway Spectra	+4.65	2.51	+1.50	3.24	+6.27	2.23
5 Aircraft Spectra	+5.42	2.33	+2.27	2.92	+7.03	2.39
Complete Set of 27 Spectra	+4.44	2.48	+1.29	3.22	+6.05	2.14

of preferred rating curve to the composition of the set of trial partitions, a subset of 50 external partition elements was chosen, with attention to selection of a more representative assortment of walls, windows and doors. (It had been noted that the set involving 507 partition elements included more windows and doors than external partitions. Thus it was decided to select a subset which contained a smaller relative number of windows and doors, and to see if the statistical studies differed appreciably.) Once again, statistical analysis of the data was conducted, averaging over the one set of 27 external noise spectra, for three configurations of absorption, and three rating curves. Nine values of the mean differences and standard deviations were thus obtained. For the medium room absorption this time the rank orderings are "flat", 3 dB/octave and STC. For the "soft" configuration, the orderings are "flat", "3 dB/octave", and "STC", while for the "hard" configuration, the orderings are "STC", "3 dB/octave", and "flat". Here the differences are slightly in favor of the "flat" contour as opposed to the 3 dB/octave contour for the two most representative room configurations, with a preference shown to the STC and 3 dB/octave contour for the "hard" configuration.

Comparison of the results of these two studies shows that there is not really any marked superiority to either use of the 3 dB/octave or "flat" contour, but that the STC contour is generally not favored in this study. A more detailed and exhaustive study than that conducted here would be essential to clearly show the superiority of any method. However, such a study should include adequate definition of "typical" long term time averaged exterior noise source spectra, consideration of the transmission loss characteristics of a representative selection of "typical" exterior partition elements, careful definition of "typical" absorption data for "hard", "medium", and "soft" room configurations, and variation of room geometrical parameters. In the absence of these data, a decision to make use of the 3 dB/octave contour as suggested by Ljunggren was made. This decision was motivated by the absence of clear demonstration of the superiority of the alternative contours ("flat" and STC contours), because of the apparent adequacy of such a contour (as demonstrated by these statistical studies), and by a desire to avoid advocacy of any additional reference contours.

Evolution of The SIR Method from the Statistical Data

In order to make use of the single figure ratings characterizing the partition's noise isolation properties (the "member SIR") in order to predict the difference in A-weighted levels, it is necessary to account for obvious systematic factors relating to the room and partition which enter into the relationship. Two of the immediate factors entering into the analysis are the differences due to room absorptivity and partition area.

By comparing the data for the hard, medium, and soft room configurations when averaged over the smaller set of partitions and 27 spectra, when using the chosen 3 dB/octave rating curve, the mean differences are −1.8, +2.3, and +4.3 dB. That is, on the average, the single number assigned to the partition differs from the actual computed difference in A-weighted sound levels by these amounts. To the nearest integer, these are −2, +2, and +4 dB. Thus, for example, the change from "medium" to "soft" room configuration increases the mean difference by 2 dB. This difference is probably principally due to the additional absorption at high frequencies provided by the "soft" room configuration. Therefore, a simple method of accounting for differences in room absorption is suggested; namely, adding appropriate correction factors to the partition's single figure (member SIR) number to allow for the absorptivity of the interior volume. These considerations led to the room absorption corrections on the SIR worksheet for the hard and soft configurations, and the additional mean difference for the medium room configuration of +2 dB is "built into" the room geometry correction.

The next parameter to be systematically studied was the effect of variation of the area of the test panel relative to the total absorptive area of the room. The total amount of acoustical absorption in this model is approximately proportional to the floor area (particularly for the "soft" configuration). It is apparent that otherwise identical rooms will be such that rooms with larger total floor areas will have the larger absorption, and hence, lower interior noise. Considerations of variation of the exterior wall area (corresponding to the term Sw), relative to the floor area led to the evolution of Table 6-4, which allows us to adapt the SIR predictive method to account for rooms with various ratios of exterior wall to floor area.

In order, then, to obtain the difference in A-weighted levels in the room and at the exterior of the building, the following steps are indicated:

1) Obtain the SIR single-figure rating appropriate for the exterior partition wall through the use of the selected curve-fitting procedure and the +3 dB/

octave contour. This is a "member SIR".

2) Account for the average absorptivity of the room's surface absorption characteristics by allowing absorption corrections of +2 dB for the soft room configuration, and −4 dB for the hard room configuration.

3) Account for the specific room geometry (floor area/partition area) by consulting Table 6–4 to derive a correction factor which accounts for the factors [10 $\log_{10}$ (Sw)] and [−10 $\log_{10}$ A2], and which also incorporates a factor of +2 dB to account for a systematic mean difference noted in the statistical analysis for the medium room configuration.

To this point, the SIR procedure provides an estimate of the difference in levels (the "room SIR") based upon three factors:

. . . a single figure rating derived from, and proportional to, the external partition transmission loss data.

. . . the room acoustic absorption, corresponding to the frequency characteristics of the three differing room absorption configurations.

. . . the room geometry correction factor accounts for the relative sizes of the exterior partition and the total amount of acoustic absorption, (proportional to the floor area).

To illustrate these facts, consider the case of the trial room used for the study. Assume that the exterior partition wall is 8 ft by 12 ft, with a SIR number of 30. The floor area is (12 ft × 25 ft = 300 ft²). The room geometry correction factor is +2 dB because the ratio of exterior partition wall area to floor area is 0.32 (see Table 6–4). For the "medium" room case (carpeted floor, bare walls and hard ceiling) no additional correction factor is required. Thus, the level difference is (30 + 2) = 32 dB. That is, the A-weighted sound level of the acoustic field incident upon the exterior side of the wall will be 32 dB larger than the A-weighted sound level in the interior of the room.

Next, it is necessary to consider the effect of the presence of several partitions. The analytic model chosen for this case assumes in effect that the room can always be regarded as a superposition of several nominally identical rooms, each of which has only one wall exposed to the exterior noise. In such a case, simple logarithmic combination of the levels within each of the individual rooms of the analytic model will yield the level corresponding to the case which has several exterior partitions with one room. This is because the individual rooms of the analytic model each have a sound pressure level which arises as a consequence of the acoustic power flowing through the individual exterior walls, and because logarithmic combination of sound pressure levels is the proper way to account for the addition of quantities proportional to power.

To account for the derivation of the SIR number appropriate for composite partitions, it is necessary to account for two factors; the areas of the individual components and the differences in their sound transmission properties. The data of Table 6–2 were generated from consideration of an expression derived for the transmission loss of composite partitions, accounting for these two variable factors. An incremental change in transmission loss will correspondingly affect the SIR number.

The tabulated data to account for the presence of leaks is obtained from considerations similar to those used to account for the existence of composite partitions. Here, the analytic model assumed that the leaks constitute finite openings with a zero transmission loss. Although this is an oversimplified model, and does not account for the possible resonance effects known to occur for narrow slot-like openings, it is nonetheless relatively simple, and may be adequate for typical leaks which occur due to poor and moderate workmanship.

Determination of the Shell Isolation Rating

The SIR rating of partitions or partition elements not listed in Appendix A may be determined by using laboratory test data of transmission loss versus one-third octave or octave band frequency, if these data are available. For the SIR single-figure rating system, the transmission loss data are compared with the SIR reference curve (a + 3 dB/octave straight line with an intercept of the 0 dB axis at 500 Hz) in each of the one-third octave or octave bands of data. The curve fitting technique used to determine the SIR number for a particular partition or element is related to that used to determine the STC rating [4]. That is, the transmission loss data for the test specimen is plotted on a graph with a transparent overlay on which the SIR reference contour is drawn. The SIR contour is shifted vertically relative to the test curve until some of the measured TL values for the test specimen fall below those of the SIR contour such that the sum of the deficiencies (i.e., the deviations below the SIR contour) in one-third octave or octave bands is less than two times the total number of frequency bands for which data are given. An example of this curve fitting process is shown in

Figure B-6. For this example, data are given for 16 bands. The sum of the deficiencies must be less than 32 dB in this case.

When the contour is adjusted to the highest value (in integer decibels) that meets this requirement, the SIR number for the specimen is the TL value corresponding to the position of the 500 Hz coordinate of the SIR curve. Note that the primary difference between the SIR and STC curve fitting techniques, aside from the difference in reference contours, is that the requirement that the maximum deficiency at a single test point not exceed 8 dB is not used in the SIR system. Also, it should be pointed out that the use of one-third-octave band data is preferable to the use of octave band data because there are more data points and thus finer resolution of the actual transmission loss characteristics of the test specimen.

Discussion

There are several readily identifiable deficiencies of this method of accounting for building shell sound transmission, and it is important to state some of the limitations so that there is no misunderstanding about the range of validity of this analysis.

As previously mentioned, in a typical urban noise situation, the acoustic field incident upon the building exterior will not be a diffuse acoustic field as is assumed in both the STC and SIR models, but is more probably a wave incident at some specific angle (or narrow range of angles) of incidence. Under these conditions, the transmission loss data, already known to be frequency dependent, are also dependent on the angle of incidence. These complications were judged to be beyond the scope of this report.

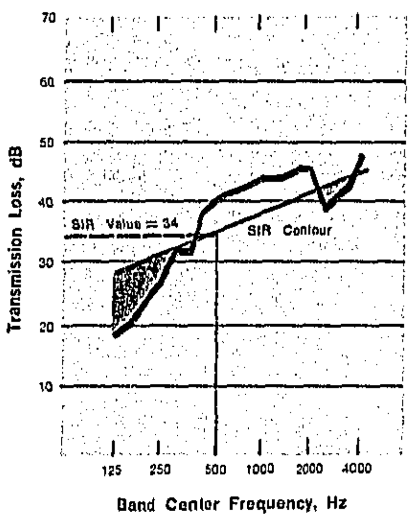

Figure B-6. Example of curve-fitting technique for determination of SIR value of a test specimen based upon one-third octave band transmission loss data. SIR contour is +3 db/octave straight line with ordinate intercept at 500 Hz equal to the test specimen SIR value.

The choice of the +3 dB/octave contour for the evaluation of the SIR method was predicated upon comparative consideration of more than 500 exterior partitions or partition elements with three trial contours, twenty-seven source spectra, and three room absorption configurations. While this is not as exhaustive a study as might be conceived, this choice of reference contour does have the virtue of relative simplicity, and the averaged standard deviations of the difference between the computed A-weighted level difference and the results of the SIR method in the statistical analysis are typically of the order of 2 dB, and the mean differences have been accommodated in the adaptations of the "member SIR" into the "room SIR".

The optimum choice of a reference curve is undoubtedly dependent upon the details of the exterior noise spectra under consideration [33]. In the absence of long-term time-averaged exterior noise spectral data, as would be most appropriate for a design method keyed to equivalent sound level metrics, the present selection of a reference curve should be adequate for interior usage.

It is also important to acknowledge that the choice of representative room absorption characteristics will influence the details of the method. In reality, few rooms are as "hard" as the "hard" room approximation and it is certain that other "representative" room absorption data and correction factors can be conceived. Furthermore, the correction factor for "leaks" could be more sophisticated than that suggested here. But once again, it was thought desirable to provide a simplified model and computational method.

Finally, it must be admitted that the evolution (and evaluation) of single-figure computational methods for the estimation of acoustical properties is an important research topic. The present method is only one example of such a procedure, and this method may be subject to modification as data on its utility and comparisons with experimental data become available. Current research at the National Research Council in Canada [34, 35] has led to the evolution of an alternative simplified method directed toward control of aircraft noise in buildings, and the work of Ljunggren in Sweden [19] can be cited as yet another example directed toward traffic noise design considerations. The authors of this design guide encourage the interested reader to make use of alternative simplified computational methods and to consider the use of more detailed methods as their understanding of the acoustics involved in designing for noise control increases. Such an increased understanding can only lead to a better environment.

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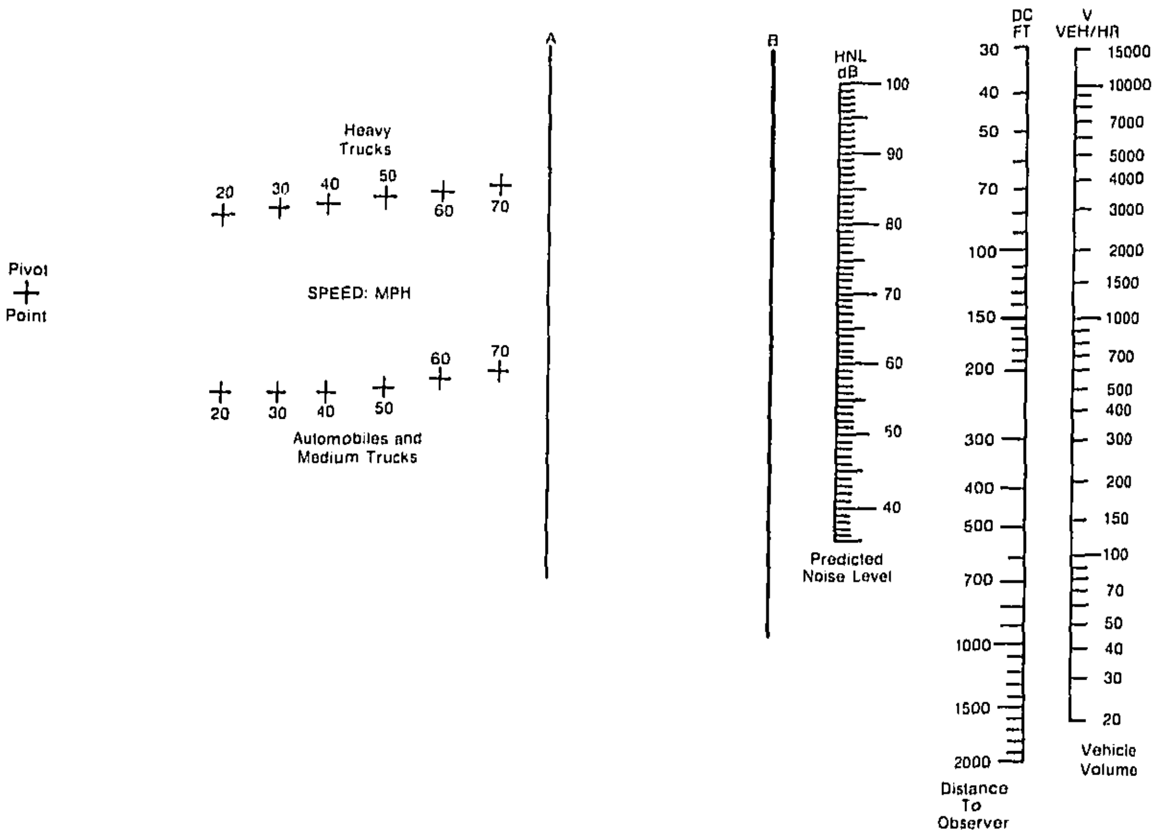
Appendix C
Sample Worksheets

PRELIMINARY SOURCE EVALUATION WORKSHEET

Noise Source		1 Building-Source Distance	2 Might there be excessive noise? (yes or no) [See Table 2-2]	3 If the answer is no in all cases, for highways, railways, or airports *	4 If the answer is yes for one or more of the sources,
Highway	#1	feet		Omit Section 2 of Chapter 5	Obtain the data and perform the computations outlined in Sec. 2 of Chapter 5 for each highway with a *yes* answer.
	#2	feet			
	#3	feet			
	#4	feet			
Railway	#1	feet		Omit Section 3 of Chapter 5	Obtain the data and perform the computations outlined in Sec. 3 of Chapter 5 for each railway with a *yes* answer.
	#2	feet			
	#3	feet			
	#4	feet			
Airport	#1	miles		Omit Section 4 of Chapter 5	Obtain the data and perform the computations outlined in Sec. 4 of Chapter 5 for each airport with a *yes* answer.
	#2	miles			
	#3	miles			
	#4	miles			

** If the answer is no for all three types of transportation system noise source, this design guide evaluation is not necessary.*



Highway Noise Prediction Nomogram

Highway Worksheet 1

Building Project ______________ Highway Number ______________

Location ______________ Site point or building room for which sound pressure levels are being estimated ______________

Owner ______________ Designer ______________ Date ______________ Revised ______________

Roadway—Building Site Distance: DC (Feet)

	Autos		Medium Trucks		Heavy Trucks	
Average Vehicle Speed, mph	SA		SM		SH	
Total Number of Vehicles						
a) Leq(1)	VA(1)		VM(1)		VH(1)	
b) Leq(8)	VA(8)		VM(8)		VH(8)	
c) Leq(24)	VA(24)		VM(24)		VH(24)	
d) Ldn	DVA	NVA	DVM	NVM	DVH	NVH
Average Vehicle Volume (veh/hr)	VA		VM	VMC	VH	

Predicted Noise Levels		Autos	Medium Trucks	Heavy Trucks
a) Leq(1)	Leq(1) No Shielding			
	Total Shielding Correction (Highway Worksheet 2)			
	Leq(1) Corrected for Shielding			
b) Leq(8)	Leq(8) No Shielding			
	Total Shielding Correction (Highway Worksheet 2)			
	Leq(8) Corrected for Shielding			
c) Leq(24)	Leq(24) No Shielding			
	Total Shielding Correction (Highway Worksheet 2)			
	Leq(24) Corrected for Shielding			
d) Ldn	HNL			
	RDN			
	CDN			
	Ldn No Shielding			
	Total Shielding Correction (Highway Worksheet 2)			
	Ldn Corrected for Shielding			
Total Highway Noise				
Building Site Noise Due To Several Highways				

Highway Worksheet 2

Highway Number ______________________

Building Project ______________________

Site point or building room for which sound pressure levels are being estimated ______________________

Location ______________________

Designer ______________________

Owner ______________________

Date ____________ Revised ____________

Roadway—Building Site Distance: DC (Feet)

	Barrier				Elevated Roadway			Depressed Roadway			
Shielding Geometry	DB	HB	hB	a	DE	HE	a	DD	HD	hD	a

Path Length Difference					
	Autos And Medium Trucks	$A_{a/m}$	$B_{a/m}$	$C_{a/m}$	$L_{a/m}$
	Heavy Trucks	A_h	B_h	C_h	L_h

Correction For "Infinite" Shielding Element	Auto	Medium Truck	Heavy Truck
	CSA/M	CSA/M	CSH

Correction For "Finite" Shielding Element	Included Angle Ratio, RA		
	Auto	Medium Truck	Heavy Truck
	CSA/M	CSA/M	CSH

Building Barrier	nr		CSB	
Vegetation	dw		CSV	

Total Shielding Correction	Auto	Medium Truck	Heavy Truck
	CSA/M + CSB + CSV	CSA/M + CSB + CSV	CSH + CSB + CSV

Railway Worksheet 1

Building Project ______________________ Railway Number ______________________

Location ______________________ Site point or building room for which sound pressure levels are being estimated ______________________

Owner ____________ Designer ____________ Date ____________ Revised ____________

Railway—Building Site Distance: D (Feet) ____________

	Freight Trains		Conventional Passenger Trains		Rapid Transit Trains	
Does this type of train use the track being analyzed?						
Diesel-Electric or All-Electric Locomotive		NL		NL		
Average Train Speed, S, mph						
Average number of cars, nc						
Average train length, LT, feet						
Average Number of Passbys						
a) Leq(1) : N1						
b) Leq(8) : N8						
c) Leq(24) : N24						
d) Ldn	ND	NN	ND	NN	ND	NN
Diesel-Electric Locomotive						
Reference Level, LS						
Distance Attenuation, DAL						
Railway Cars						
Reference Level, CL						
Duration Factor, CD						
Track Characteristics, CT						
Distance Attenuation, DAC						

Predicted Noise Levels		Diesel-Electric Locomotive	Railway Cars	Diesel-Electric Locomotive	Railway Cars	Railway Cars
a) Leq(1)	CN1					
	C1					
	Leq(1) No Shielding					
	Total Shielding Correction (Railway Worksheet 2)					
	Leq(1) Corrected for Shielding					
b) Leq(8)	CN8					
	C8					
	Leq(8) No Shielding					
	Total Shielding Correction (Railway Worksheet 2)					
	Leq(8) Corrected for Shielding					
c) Leq(24)	CN24					
	C24					
	Leq(24) No Shielding					
	Total Shielding Correction (Railway Worksheet 2)					
	Leq(24) Corrected for Shielding					
d) Ldn	CN					
	CDN					
	Ldn No Shielding					
	Total Shielding Correction (Railway Worksheet 2)					
	Ldn Corrected for Shielding					
Total Railway Noise						

Railway Worksheet 2

Building Project ______________________

Location ______________________

Owner ______________________

Railway Number ______________________

Site point or building room for which sound pressure levels are being estimated ______________________

Designer ______________________

Date ______________ Revised ______________

Railway—Building Site Distance; D (Feet) ______________

Shielding Geometry	Barrier				Elevated Railway			Depressed Railway			
	DB	HB	hB	a	DE	HE	a	DD	HD	hD	a

Path Length Difference					
	Railway Cars	Ac	Bc	Cc	Lc
	Diesel-Electric Locomotive	Al	Bl	Cl	Ll

Correction For "Infinite" Shielding Element	Railway Cars	Diesel-Electric Loc.
	CSC	CSL

Correction For "Finite" Shielding Element		
	Included Angle Ratio, RA	
	Railway Cars	Diesel-Electric Loc.
	CSC	CSL

Building Barrier	nr		CSB	
Vegetation	dw		CSV	

Total Shielding Correction	Railway Cars	Diesel-Electric Loc.
	CSC + CSB + CSV	CSL + CSB + CSV

Track Characteristics

a		b	c	d		
				Bridgework		
Welded Track	Jointed Track	Presence of Switching Frog or Grade Crossing	Radius of Tight Curve (< 900 Feet) in Feet	Concrete Structure	Steel Girder with Concrete or Open Tie Deck	Steel Girder with Steel Plate Deck

Aircraft Worksheet 1

Building Project ______________________ Site point or building room for which sound pressure levels are being estimated ____________

Location ______________________ Designer ______________________

Owner ______________________ Date ____________ Revised ____________

Contour Maps Available ________							
1	If Building is on or very near Contour #1 or #2, Record that value on Line 11. If not, obtain the data of Lines 2 and 3						
2	Contour Values	CNR or NEF #1		CNR or NEF #2			
3	Building Location Between Contours #1 and #2	X1	X2	R	C5	C10	
4	CNR or NEF Value At The Building Site				Also Record on Line 11		
Contour Maps Not Available							
5	Number of Jet Operations	NJday	NJnight	NJeff			
6	Airport Category (Check One)	1	2	3	4		
7	If building is on or very near the NEF 30 or NEF 40 Contour, record that value on Line 11. If not, obtain the data on Line 8.						
8	Building Location Between NEF 30 and NEF 40 Contours	X1	X2	R	C10		
9	NEF Value At The Building Site				Also Record on Line 11		
10	Number of Operations	NJday	NJnight	N(8)	N(1)		
11	CNR or NEF Value At The Building Site						
12	Convert CNR to NEF Value						
13	Aircraft Noise Level At The Building Site						
	Leq(1)	R1	C1	Leq(1)			
	Leq(8)	R8	C8	Leq(8)			
	Leq(24)	R24	C24	Leq(24)			
	Ldn			Ldn			

Building Project ____________________ Owner ____________________ Designer ____________________

Location ____________________ Site point or building room for which sound pressure levels are being estimated ____________________ Date __________ Revised __________

Shell Member Number	Shell Member Name	Shell Member Area in square feet	Shell Member Components	Component Description Arrange components of shell members in order of decreasing SIR for each shell member. Order of shell members is optional.	Shell Member or Component SIR from Appendix A	Room Dimensions in Feet Width	Length	Height	Room Floor Area in square feet—ø × I	Component Face Dimension No. 1 in feet	Component Face Dimension No. 2 in feet	Component Area in square feet	Component B Fractional Area (Component B Area/Shell Member Area)	Difference: (SIR A — SIR B)	Composite SIR Correction Factor from Table 6-2	SIR AB = SIR B + Composite SIR Correction Factor	Component C Fractional Area (Component C Area/Shell Member Area)	Difference = (SIR AB — SIR C)	Composite SIR Correction Factor from Table 6-2	SIR ABC = SIR C + Composite SIR Correction Factor	Component D Fractional Area (Component D Area/Shell Member Area)	Difference = (SIR ABC — SIR D)	Composite SIR Correction Factor from Table 6-2	SIR ABCD = SIR D + Composite SIR Correction Factor	Estimate of Air Leakage in square inches/100 square feet	Adjusted SIR Based on Air Leakage from Table 6-3	Ratio of Shell Member Area to Floor Area—Room Geometry	Room Geometry Correction Factor from Table 6-4	Enter +2 if acoustic ceiling or if drapes cover 50% of wall area	Enter −4 if no carpet	SIR Adjusted for Leakage, Area and Absorption Correction Factors	Absolute Difference = SIR 1 — SIR 2	Transmission Adjustment from Table 6-1	SIR 1,2 = SIR (lower) — Transmission Adjustment	Absolute Difference = SIR 1,2 — SIR 3	Transmission Adjustment from Table 6-1	SIR 1,2,3, = SIR (lower) — Transmission Adjustment	Absolute Difference = SIR 1,2,3 — SIR 4	Transmission Adjustment from Table 6-1	SIR 1,2,3,4 = SIR (lower) — Transmission Adjustment	Absolute Difference = SIR 1,2,3,4 — SIR 5	Transmission Adjustment from Table 6-1	Room SIR = SIR (lower) — Transmission Adjustment
a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	aa	bb	cc	dd	ee	ff	gg	hh	ii	jj	kk	ll	mm	nn	oo	pp	qq	rr	ss
1			A																																								
			B																																								
			C																																								
			D																																								
2			A																																								
			B																																								
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4			A																																								
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5			A																																								
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			C																																								
			D																																								

Building Project ______________________________

Location ______________________________

Owner ______________________________

Site point or building room for which sound pressure levels are being estimated ______________

Designer ______________

Date ______________ Revised ______________

External Noise Source	Source Level (dB) (Chap. 5)	Difference Between Highway and Railway Sound Levels (dB)	Level Adjustment (From Table 6-1)	Total Highway and Railway Sound Level (dB)	Difference Between Total Highway and Railway and Aircraft Sound Levels (dB)	Level Adjustment (From Table 6-1)	Total Exterior Sound Level (dB)	Room SIR (SIR Worksheet)	Indoor Sound Level Due to External Sources (dB)	Noise Criterion Level (dB)
A	B	C	D	E	F	G	H	I	J	K
Highway										
Railway										
Aircraft										

Is the Total Indoor Sound Level Due to External Sources Greater Than the Noise Criterion Level?	Yes ______	A Noise Problem Exists
	No ______	The Design is Satisfactory

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This design guide presents a unified procedure for the selection of noise criteria in and around buildings, for the prediction of exterior and interior noise levels arising as a consequence of transportation systems operations, and for the evaluation of the adequacy of building designs with regard to environmental noise. Noise criteria levels are suggested in terms of equivalent sound levels (Leq). Simplified predictive methods enable the estimation of noise levels arising as a consequence of highway, railway, and aircraft operations. The sound isolation provided by the building shell is estimated by means of a new single-figure rating system. Finally, design manipulations which may make possible the improvement of the acoustic conditions in and around buildings are suggested.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Acoustics; architectural acoustics; building acoustics; environmental noise; noise; noise control; sound; transportation system noise.

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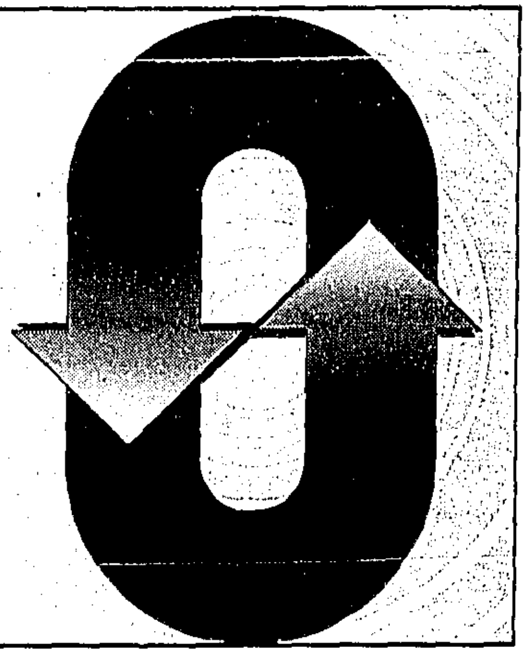
Waste Heat Management Guidebook



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JOURNAL OF RESEARCH—The Journal of Research of the National Bureau of Standards reports NBS research and development in those disciplines of the physical and engineering sciences in which the Bureau is active. These include physics, chemistry, engineering, mathematics, and computer sciences. Papers cover a broad range of subjects, with major emphasis on measurement methodology, and the basic technology underlying standardization. Also included from time to time are survey articles on topics closely related to the Bureau's technical and scientific programs. As a special service to subscribers each issue contains complete citations to all recent NBS publications in NBS and non-NBS media. Issued six times a year. Annual subscription: domestic $17.00; foreign $21.25. Single copy, $3.00 domestic; $3.75 foreign.

Note: The Journal was formerly published in two sections: Section A "Physics and Chemistry" and Section B "Mathematical Sciences."

DIMENSIONS/NBS

This monthly magazine is published to inform scientists, engineers, businessmen, industry, teachers, students, and consumers of the latest advances in science and technology, with primary emphasis on the work at NBS. The magazine highlights and reviews such issues as energy research, fire protection, building technology, metric conversion, pollution abatement, health and safety, and consumer product performance. In addition, it reports the results of Bureau programs in measurement standards and techniques, properties of matter and materials, engineering standards and services, instrumentation, and automatic data processing.

Annual subscription: Domestic, $12.50; Foreign $15.65.

NONPERIODICALS

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Applied Mathematics Series—Mathematical tables, manuals, and studies of special interest to physicists, engineers, chemists, biologists, mathematicians, computer programmers, and others engaged in scientific and technical work.

National Standard Reference Data Series—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a world-wide program coordinated by NBS. Program under authority of National Standard Data Act (Public Law 90-396).

NOTE: At present the principal publication outlet for these data is the Journal of Physical and Chemical Reference Data (JPCRD) published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements available from ACS, 1155 Sixteenth St. N.W., Wash., D.C. 20056.

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NBS Interagency Reports (NBSIR)—A special series of interim or final reports on work performed by NBS for outside sponsors (both government and non-government). In general, initial distribution is handled by the sponsor; public distribution is by the National Technical Information Services (Springfield, Va. 22161) in paper copy or microfiche form.

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