Transit Noise and Vibration Impact Assessment

Final Report
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1. INTRODUCTION

1.1 PURPOSE

Noise and vibration assessments are key elements of the environmental impact assessment process for mass transit projects. Experience has shown that noise and vibration are among the major concerns with regard to the effects of a transit project on the surrounding community. A transit system is of necessity placed near population centers and often causes significant noise and vibration at nearby residences and other sensitive types of land use.

This manual is intended to provide guidance in preparing and reviewing the noise and vibration sections of environmental submittals from grant applicants. In the interests of promoting quality and uniformity in assessments, the manual will be used by project sponsors and consultants in performing noise and vibration analyses for inclusion in environmental documents. The manual sets forth the methods and procedures for determining the level of noise and vibration impact resulting from most federally-funded transit projects and for determining what can be done to mitigate such impact. Since the methods have been developed to assess typical transit projects, there will be some situations not explicitly covered in this manual. The exercise of professional judgment may be required to extend the basic methods in these cases.

1.2 THE ENVIRONMENTAL REVIEW PROCESS

The Federal Transit Administration (FTA) provides capital assistance for a wide range of mass transit projects – from completely new rail rapid transit systems to bus maintenance facilities and vehicle purchases. The extent of environmental analysis and review will depend on the scope and complexity of the proposed project and the associated environmental impacts. FTA's environmental impact regulation classifies the most common projects according to the different levels of environmental analysis required, ranging from an Environmental Impact Statement (EIS) to little or no environmental documentation (Categorical Exclusion).   FTA's environmental impact regulation is codified in Title 23, Code of Federal Regulations, Part 771.(1)*

1.2.1 Environmental Impact Statements

Large fixed-guideway projects, such as heavy rail, light rail, commuter rail and automated guideway transit systems, normally require environmental impact statements including an in-depth noise and vibration assessment. While there may be exceptions to the EIS requirement, in the great majority of cases new rail starts or extensions to existing systems involve environmental effects which are significant in the context of the National Environmental Policy Act (NEPA). Because they are located in dense urban areas, noise and vibration impacts are a frequent concern; thus it is likely that for the large infrastructure projects requiring an EIS, the most detailed treatment of noise and/or vibration impacts will also be required.

There are other projects as well which may require a detailed analysis of noise and vibration impacts even if an EIS is not required to comply with NEPA. These could be bus/high-occupancy-vehicle (HOV) lanes built on existing highways or construction of certain bus or rail terminals and storage and maintenance facilities. If the project is proposed to be located in or very close to a sensitive area or site, it is prudent to use the most detailed procedures contained in the manual to predict noise and/or vibration levels since this will provide the most reliable basis for considering measures to mitigate excessive noise/vibration at a specific site.

1.2.2 Categorical Exclusions

At the other extreme is a host of smaller transit improvement projects which normally do not cause significant environmental impacts and do not require noise and vibration assessment. These projects are listed as "categorical exclusions" in FTA's environmental regulation, meaning that FTA has predetermined that there are no significant environmental impacts for those types of projects and no environmental document is required. Examples are: vehicle purchases; track and railbed maintenance; installation of maintenance equipment within the facility, etc. Section 771.117(c) contains a list of transit projects predetermined to be categorical exclusions.

Other types of projects may also qualify as categorical exclusions, for example, certain transit terminals, transfer facilities, bus and rail storage and maintenance facilities (see 23 CFR 771.117(d)). These projects usually involve more construction and a greater potential for off-site impacts. They are presented in the regulation with conditions or criteria which must be met in order to qualify for categorical exclusion. The projects are reviewed individually by FTA to assure that off-site impacts are properly mitigated. Depending on the proposed project site and the surrounding land use, a noise and vibration assessment may be needed even though the project may ultimately qualify as a categorical exclusion. The screening process in Chapters 4 and 9 will be helpful in pointing out potential noise and vibration concerns and the general assessment procedures may then be used to define the level of impact.

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*References are located at the end of each chapter.

1.2.3 Environmental Assessments

When a proposed project is presented to FTA, if it is uncertain whether the project requires an EIS or qualifies as a categorical exclusion, FTA will direct the applicant to prepare an Environmental Assessment (EA). Generally, an EA is selected (rather than trying to process the project as a categorical exclusion) if the FTA reviewer feels that several types of impacts need further investigation, for example, air quality, noise, wetlands, historic sites, traffic, etc. An EA is a relatively brief environmental study undertaken to determine the magnitude of the impacts that will likely be caused by the project. If, during the analysis, it appears that any impacts are significant, an EIS will be prepared. If the analysis shows that none of the impacts is significant or if mitigation measures are incorporated in the project to adequately deal with adverse impact, the Environmental Assessment will fully document this and serve as the basis for a Finding of No Significant Impact issued by FTA. It is important to note that when mitigation measures are relied on, they must be described in detail in the Environmental Assessment since FTA's finding is conditioned on the inclusion of these measures as an integral part of the project.

FTA's environmental regulation does not list typical projects that require Environmental Assessments. An EA may be prepared for any type of project if uncertainty exists about the magnitude or extent of the impacts. Experience has shown that most of the EA's prepared for transit projects require an assessment of noise and/or vibration effects.

1.3 RELATIONSHIP OF NOISE AND VIBRATION ANALYSIS TO TRANSPORTATION PLANNING AND PROJECT DEVELOPMENT

The above discussion on how transit noise and vibration analysis fits into the environmental review process assumes that environmental analysis is focused on a single preferred alternative (with respect to mode, location/alignment, and operating features). This narrow focus is appropriate where reasonable alternatives are limited or non-existent, for example, extension of a rapid transit line on an abandoned railroad right-of-way. However, major infrastructure projects usually evolve from different levels of study which, first, help to define the need for additional capacity and then provide the framework for comparing and contrasting alternative infrastructure investments.

At the early systems planning level, the focus is on predicting future travel demand and identifying the need for additional capacity on segments of the regional transportation network. Environmental concerns may be a consideration at this stage, particularly long-range land-use and development impacts, but noise and vibration assessments are not typically conducted since alternative strategies lack the necessary detail. Once the need for some type of major infrastructure improvement* is established and if there is the potential for federal

* Major mass transportation investments are defined as new fixed-guideway facilities (rapid rail, light rail, commuter rail, busways, automated guideway transit, and people movers) or substantial changes to existing fixed-guideway facilities, such as the addition of lanes or tracks. Extensions of one mile or more to existing systems will generally fit under this definition. Other types of projects may also fit the definition (e.g., large multi-modal terminals) if they are high-cost infrastructure improvements expected to significantly affect capacity, traffic flow, level of service, or mode

funding, the metropolitan area will undertake a Major Investment Study. As set out in the joint Federal Highway Administration (FHWA)/FTA metropolitan planning regulation,[(2)] the Major Investment Study is essentially a structured examination of alternative strategies for the purpose of identifying the best course of action in a specific corridor or subarea. The study is broad-ranging to the extent that it often covers "transportation systems management" actions and multimodal alternatives in addition to traditional highway and transit infrastructure investments.

Provisions in the metropolitan planning regulation describing corridor or sub-area studies make it clear that environmental considerations are an essential part of the analysis of alternatives. These studies will be used as significant input to the federal environmental document (EIS or EA), or the option is given to have the corridor or sub-area study itself serve as the Draft EIS or EA. While there is no requirement that noise and vibration be one of the environmental factors considered, local sponsoring agencies will often elect to address this subject. The screening and general assessment procedures described in this manual are well-suited to compare and contrast noise/vibration effects across different modes and alignments without getting into the detailed analytical procedures which are usually reserved for a single preferred alternative. In fact, the general assessment procedures were developed, in part, to respond to this need. In addition, they can be used for any specific project where the screening procedure indicates the potential for noise/vibration impacts.

The Major Investment Study leads to the selection of a preferred alternative by the state and local agencies involved in the study. If a major infrastructure investment is proposed, the project moves into the preliminary engineering phase. This is the stage at which detailed, site-specific noise and/or vibration analysis is conducted, if it is needed. If federal funding for construction will be sought, the results of this analysis will be reported in the federal environmental document (EIS or EA). The main objectives of the NEPA process are to give a full and accurate reporting of the project's likely impacts and also to describe in specific terms how the federal agency and project sponsor will avoid or mitigate those adverse effects caused by the project. Thus, in the preliminary engineering phase, the emphasis shifts toward refining information for the proposed project. The detailed analysis procedures in this manual depend on the type of information and the level of design produced during preliminary engineering for a major transit project. After the NEPA process is completed for a major project, federal funding for final design and construction may be granted. During the final design phase, more detailed studies may be undertaken, particularly for vibration impacts, in order to further refine the measures which will be used to limit excessive noise/vibration levels.

Considering that transit projects must, of necessity, be located amidst or close to concentrations of people, noise and vibration impacts can be a concern throughout the planning and project development phases. This manual offers the flexibility to address noise and vibration at different stages in the development of a project and in different levels of detail depending on the types of decisions which need to be made.

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share in the corridor or sub-area.

There are three levels of analysis which may be employed, depending on the type and scale of the project, the stage of project development, and the environmental setting. The technical content of each of the three levels is specified in the body of this document, but a summary of each level is given in the following paragraphs:

! **Screening Procedure –** Identifies noise- and vibration-sensitive land uses in the vicinity of a project and whether there is likely to be impact. It also serves to determine the noise and vibration study areas for further analysis when sensitive locations are present. The screening process may be all that is required for many of the smaller transit projects which qualify for categorical exclusion. When noise/vibration-sensitive receivers are found to be present, there are two levels of quantitative analysis available to predict impact and assess the need for mitigation measures.

! **General Assessment –** Identifies location and estimated severity of noise and vibration impacts in the noise and vibration study areas identified in the Screening Procedure. For major capital investments, the General Assessment provides the appropriate level of detail to compare alternative modes and alignments. It can be used in conjunction with established highway noise prediction procedures to compare and contrast highway, transit and multimodal alternatives. For other types of transit projects, this level is used for a closer examination of projects which show possible impacts as a result of screening. For many smaller projects, this level may be sufficient to define impacts and prepare mitigation as necessary.

! **Detailed Analysis –** Quantifies impacts through an in-depth analysis usually only performed for a single alternative. Delineates site-specific impacts and mitigation measures for the preferred alternative in major investment projects during preliminary engineering. For other smaller projects, detailed analysis may be warranted as part of the initial environmental assessment if there are potentially severe impacts due to close proximity of sensitive land uses.

The three levels of noise and vibration assessment are described in the chapters which follow.

1.4 ORGANIZATION OF THE MANUAL

The Guidance Manual is divided into two parts, noise and vibration, with a common introduction. Each part has parallel organization according to the following subjects:

Noise/Vibration

P Basic Concepts

P Criteria

P Screening Procedure

P General Assessment

P Detailed Analysis

Construction Noise/Vibration

Documentation

Appendices

- P Background for Transit Noise Impact Criteria
- P Receiver Selection
- P Existing Noise Determination
- P Noise Source Level Determination
- P Maximum Noise Level Computation

REFERENCES

1. U.S. Department of Transportation, Federal Transit Administration and Federal Highway Administration, "Environmental Impact and Related Procedures." Final Rule, 52 Federal Register 32646 -32669; August 28, 1987 (23 Code of Federal Regulations 771).

2. U.S. Department of Transportation, Federal Transit Administration and Federal Highway Administration, "Statewide Planning; Metropolitan Planning." Final Rule, 58 Federal Register 58040-58079; Octoer 28, 1993 (23 Code of Federal Regulations 450). Refer especially to section 450.318 on major metropolitan transportation investments.

2. BASIC NOISE CONCEPTS

This chapter discusses the basic concepts of transit noise which provide background for Chapters 3 through 6, where transit noise is computed and assessed. The Source-Path-Receiver framework sketched in Figure 2-1 is central to all environmental noise studies. Each transit **source** generates close-by noise levels, which depend upon the type of source and its operating characteristics. Then, along the propagation **path** between all sources and receivers, noise levels are reduced (attenuated) by distance, intervening obstacles and other factors. And finally at each **receiver**, noise combines from all sources to interfere, perhaps, with receiver activities. This chapter contains an overview of this Source-Path-Receiver framework. Following this overview is a discussion of transit-noise descriptors.

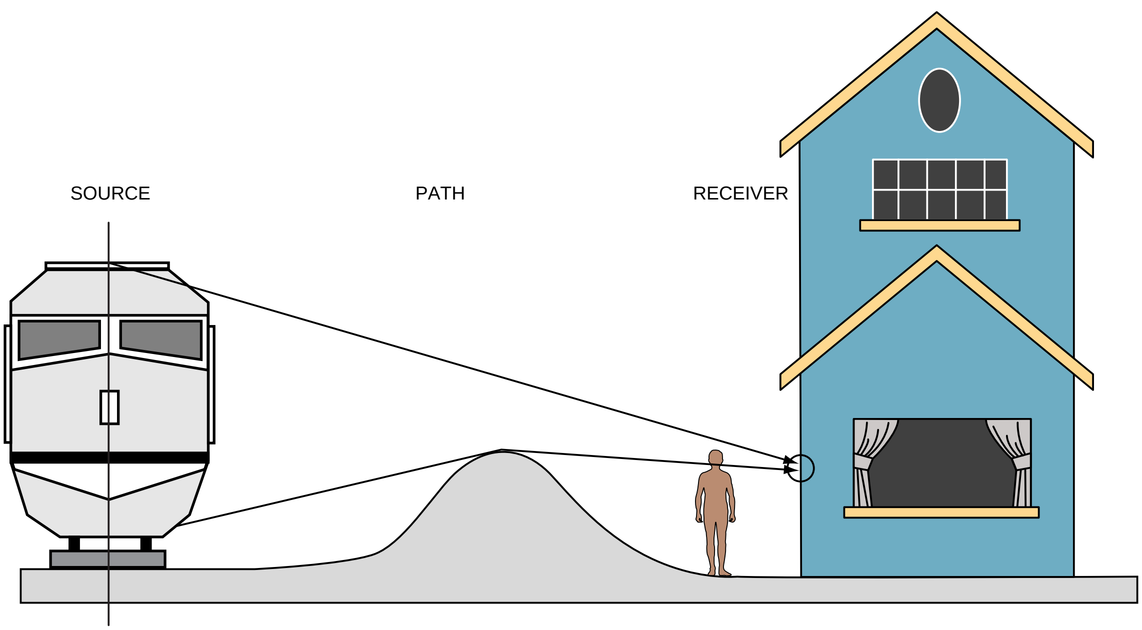


Figure 2-1 The Source-Path-Receiver Framework

In brief, this chapter contains:

- An overview of transit **sources**: a listing of major sources, plus some discussion of noise-generation mechanisms (Section 2.1)
- An overview of noise **paths**: a discussion of the various attenuating mechanisms on the path between source and receiver (Section 2.2)
- An overview of **receiver** response to transit noise: a discussion of the technical background for transit-noise criteria and the distinction between absolute and relative noise impact (Section 2.3)
- A discussion of the **noise descriptors** used in this manual for transit noise (Section 2.4)

2.1 SOURCES OF TRANSIT NOISE

This section discusses major characteristics of the sources of transit noise. Transit noise is generated by transit vehicles in motion. Vehicle propulsion units generate: (1) whine from electric control systems and traction motors that propel rapid transit cars, (2) diesel-engine exhaust noise, from both diesel-electric locomotives and transit buses, (3) air-turbulence noise generated by cooling fans, and (4) gear noise. Additional noise of motion is generated by the interaction of wheels/tires with their running surfaces. Tire noise from rubber-tired vehicles is significant at normal operating speeds. The interaction of steel wheels and rails generates three types of noise: (1) rolling noise due to continuous rolling contact, (2) impact noise when a wheel encounters a discontinuity in the running surface, such as a rail joint, turnout or crossover, and (3) squeal generated by friction on tight curves.

Figure 2-2 illustrates typical dependence of source strength on vehicle speed for two types of transit vehicles. Plotted vertically in this figure is a qualitative indication of the maximum sound level during a passby. In the figure, speed dependence is strong for electric-powered transit trains because wheel/rail noise dominates, and noise from this source increases strongly with increasing speed. On the other hand, speed dependence is less for diesel-powered commuter rail trains, particularly at low speeds where the locomotive exhaust noise dominates. As speed increases, wheel-rail noise becomes the dominant noise source and diesel- and electric-powered trains will generate similar noise levels. Similarly, but not shown, speed dependence is also strong for automobiles, city buses (two-axle) and non-accelerating highway buses (three-axle), because tire/pavement noise dominates for these vehicles; but it is not significant for accelerating highway buses where exhaust noise is dominant.

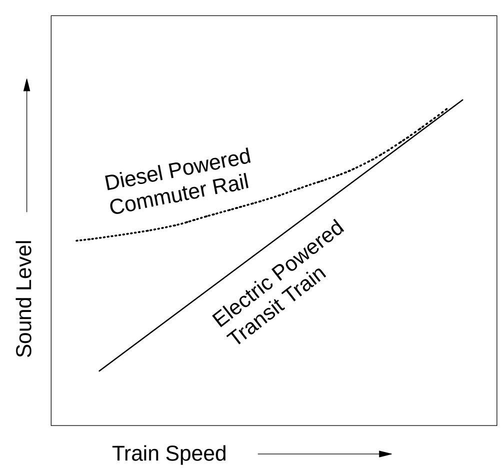


Figure 2-2 Example Sound Level Dependence on Speed

For transit vehicles in motion, close-by sound levels also depend upon other parameters, such as vehicle acceleration and vehicle length, plus the type/condition of the running surfaces. For very high-speed rail vehicles, air turbulence can also be a significant source of noise. In addition, the guideway structure can also radiate noise as it vibrates in response to the dynamic loading of the moving vehicle.

Noise is generated by transit vehicles even when they are stationary. For example, auxiliary equipment often continues to run even when vehicles are stationary – equipment such as cooling fans on motors, radiator fans, plus hydraulic, pneumatic and air-conditioning pumps. Also, transit buses are often left idling in stations or storage yards. Noise is also generated by sources at fixed-transit facilities. Such sources include ventilation fans in transit stations, in subway tunnels, and in power substations, equipment in chiller plants, and many activities within maintenance facilities and shops.

Table 2-1 summarizes sources of transit noise, separately by vehicle type and/or type of facility. Prodecures for computing close-by noise levels for major sources as a function of operating parameters such as vehicle speed are given in Chapters 5 and 6.

Table 2-1 Sources of Transit Noise

Vehicle or Facility	**Dominant Components**	**Comments**
Rail Rapid Transit (RRT), or Light Rail Transit (LRT) on exclusive right-of-way	Wheel/rail interaction and guideway amplification	Depends on condition of wheels and rails.
	Propulsion system	When accelerating and at higher speeds.
	Brakes	When stopping.
	Auxiliary equipment	When stopped.
	Wheel squeal	On tight curves.
	In general	Noise increases with speed and train length.
Light Rail Transit (LRT) in mixed traffic	Wheel squeal	On tight curves.
	Auxiliary equipment	When stopped.
	Horns and crossing bells	At grade crossings.
	In general	Lower speeds mean less noise than for RRT and LRT on exclusive right-of-way.
Commuter Rail	Diesel exhaust	On diesel-hauled trains.
	Cooling fans	On both diesel and electric-powered trains.
	Wheel/rail interaction	Depends on condition of wheels and rails.
	Horns and crossing gate bells	At grade crossings.
	In general	Noise is usually dominated by locomotives.
Low and Intermediate Capacity Transit	Propulsion systems, including speed controllers	At low speeds.
	Ventilation systems	At low speeds.
	Tire/guideway interaction	For rubber-tired vehicles, including monorails.
	Wheel/rail interaction	Depends on condition of wheels and rails.
	In general	Wide range of vehicles: monorail, rubber-tired, steel wheeled, linear induction. Noise characteristics depend upon type.

Table 2-1 Sources of Transit Noise (continued)

Vehicle or Facility	Dominant Components	Comments
Diesel Buses	Cooling fans	While idling.
	Engine casing	While idling.
	Diesel exhaust	At low speeds and while accelerating.
	Tire/roadway interaction	At moderate and high speeds.
	In general	Includes city buses (generally two axle) and commuter buses (generally three axle).
Electric Buses and Trackless Trolleys	Tire/roadway interaction	At moderate speeds.
	Electric traction motors	At moderate speeds.
	In general	Much quieter than diesel buses.
Bus Storage Yards	Buses starting up	Usually in early morning.
	Buses accelerating	Usually near entrances/exits.
	Buses idling	—
	In general	Site specific. Often peak periods with significant noise.
Rail Transit Storage Yards	Wheel squeal	On tight curves.
	Wheel impacts	On joints and switches.
	Wheel rolling noise	—
	Auxiliary equipment	Throughout day and night. Includes air-release noise.
	Coupling/uncoupling	—
	Signal horns	—
	In general	Site specific. Often early morning and peak periods with significant noise.
Maintenance Facilities	Signal horns	—
	PA systems	—
	Impact tools	—
	Car/bus washers/driers	—
	Vehicle activity	—
	In general	Site specific. Considerable activity throughout day and night, some outside.
Stations	Automobiles	Patron arrival/departure, especially in early morning.
	Buses idling	—
	P.A. systems	—
	Locomotive idling	At commuter rail terminal stations.
	Auxiliary systems	At terminal stations and layover facilities.
	In general	Site specific, with peak activity periods.
Subways	Fans	Noise through vent shafts.
	Buses/trains in tunnels	Noise through vent shafts.
	In general	Noise is not a problem.

2.2 PATHS OF TRANSIT NOISE, FROM SOURCE TO RECEIVER

This section contains a qualitative overview of noise-path characteristics from source to receiver, including attenuation along these paths. Equations for specific noise-level attenuations along source-receiver paths appear in Chapters 5 and 6.

Sound paths from source to receiver are predominantly through the air. Along these paths, sound reduces with distance due to (1) divergence, (2) absorption/diffusion and (3) shielding. These mechanisms of sound attenuation are discussed below.

Divergence. Sound levels naturally attenuate due to distance, as shown in Figure 2-3. Plotted vertically is the attenuation at the receiver, relative to the sound level 50 feet from the source. As shown, the sound level attenuates with increasing distance. Such attenuation, technically called "divergence," depends upon source configuration and source-emission characteristics. For sources grouped closely together (called point sources), attenuation with distance is large: 6 decibels per doubling of distance. Point sources include crossing signals along rail corridors, PA systems in maintenance yards and other closely grouped sources of noise. For vehicles passing along a track or roadway (called line sources), divergence with distance is less: 3 decibels per doubling of distance for L_{eq} and L_{dn}, and 3 to 6 decibels per doubling of distance for L_{max}. In Figure 2-3, the line source curve separates into three separate lines for L_{max}, with the point of departure depending on the length of the line source. These three noise descriptors – L_{eq}, L_{dn} and L_{max} – are discussed in Section 2.4. Equations for the curves in Figure 2-3 appear in Chapter 6.

Absorption/Diffusion. In addition to distance alone, sound levels are further attenuated when sound paths lie close to freshly-plowed or vegetation-covered ground. Plotted vertically in Figure 2-4 is this additional attenuation, which can be as large as 5 decibels as close in as several hundred feet. At very large distances, wind and temperature gradients sometimes modify the ground attenuation shown here; such variable atmospheric effects are not included in this manual because they generally occur beyond the range of typical transit-noise impact. Equations for the curves in this figure appear in Chapter 6.

Shielding. Sound paths are sometimes interrupted by man-made noise barriers, by terrain, by rows of buildings, or by vegetation. Most important of these path interruptions are noise barriers, one of the best means of mitigating noise in sensitive areas. A noise barrier reduces sound levels at a receiver by breaking the direct line-of-sight between source and receiver with a solid wall (in contrast to vegetation, which hides the source but does not reduce sound levels significantly). Sound energy reaches the receiver only by bending (diffracting) over the top of the barrier, as shown in Figure 2-5, and this diffraction reduces the sound level at the receiver.

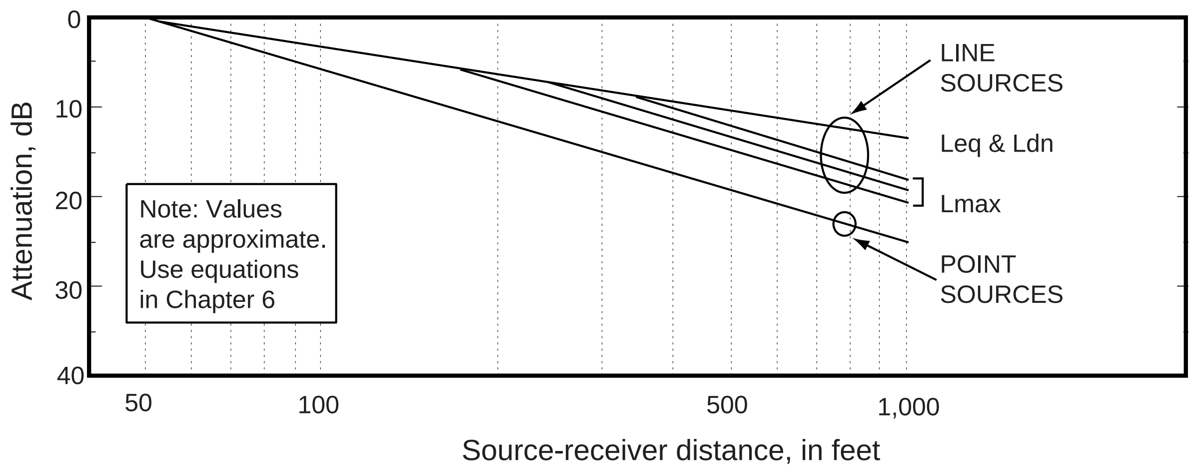


Figure 2-3 Attenuation due to Distance (Divergence)

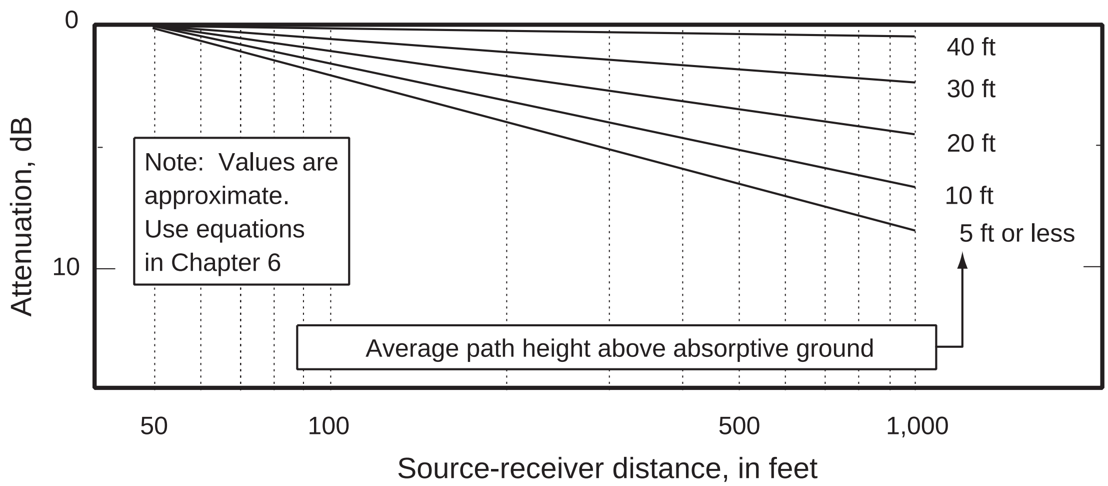


Figure 2-4 Attenuation due to Soft (Sound-Absorptive) Ground

Sound barriers for transportation systems are typically used to attenuate noise at the receiver by 5 to 15 decibels, depending upon barrier height, length, and distance from both source and receiver. Barriers on structure, very close-in to the source, sometimes provide less attenuation than do barriers slightly more distant from the source, due to reverberation (multiple reflections) between the barrier and the body of the vehicle. However, this reverberation is often offset by increased barrier height, which is easy to obtain for such close-in barriers, and/or acoustical absorption on the source side of the barrier. Acoustical absorption is included as a mitigation option in Chapter 6. Equations for barrier attenuation, plus equations for other sound-path interruptions, also appear in Chapter 6.

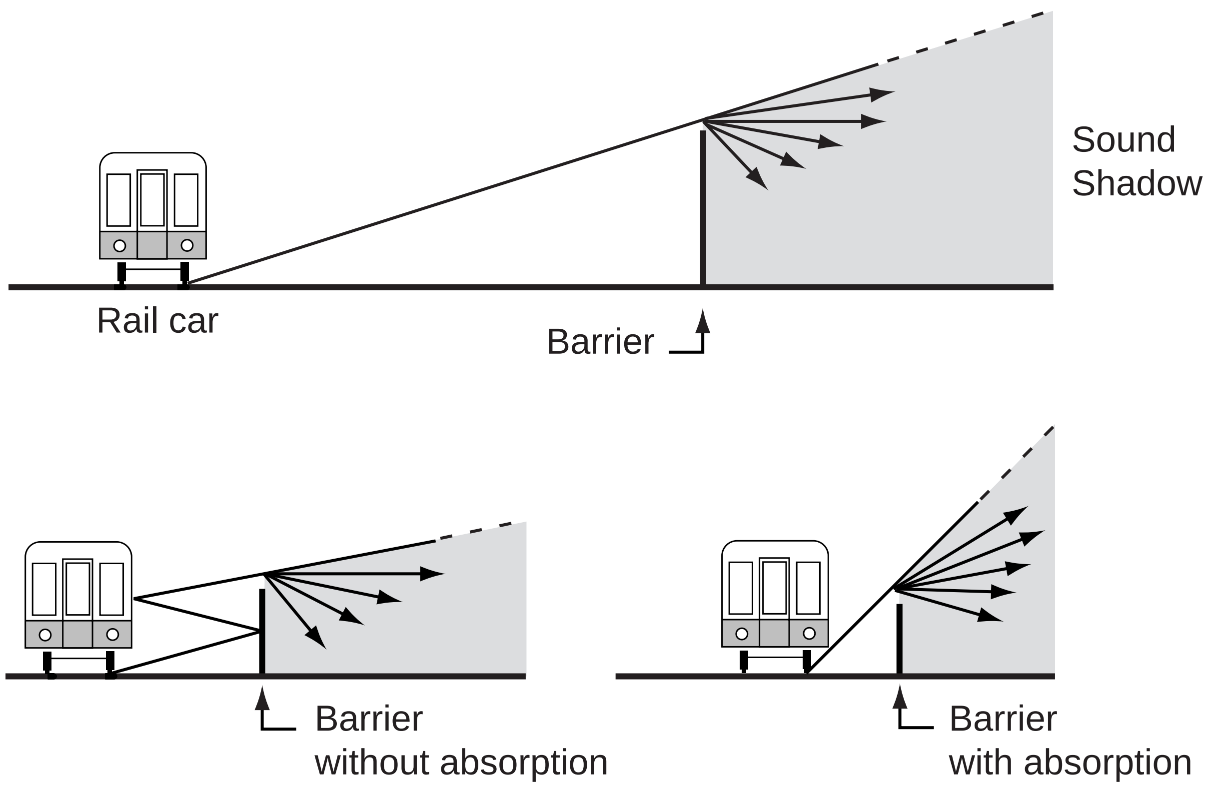


Figure 2-5 Noise Barrier Geometry

Sometimes a portion of the source-to-receiver path is not through the air, but rather through the ground or through structural components of the receiver's building. Discussion of such ground-borne and structure-borne propagation is included in Chapter 7.

2.3 RECEIVER RESPONSE TO TRANSIT NOISE

This section contains an overview of receiver response to noise. It serves as background information for the noise-impact criteria in Chapter 3.

Noise can interrupt ongoing activities and can result in community annoyance, especially in residential areas. In general, most residents become highly annoyed when noise interferes significantly with activities such as sleeping, talking, noise-sensitive work, and listening to radio or TV or music. In addition, some land uses, such as outdoor concert pavilions, are inherently incompatible with high noise levels.

Annoyance to noise has been investigated and approximate dose-response relationships have been quantified by the Environmental Protection Agency (EPA).[(1)(2)] The selection of noise descriptors in this manual is largely based upon this EPA work. Beginning in the 1970s, the EPA undertook a number of research and synthesis studies relating to community noise of all types. Results of these studies have been widely published, and discussed and refereed by many professionals in acoustics. Basic conclusions of these studies have been adopted by the Federal Interagency Committee on Noise, the Department of Housing and Urban Development (HUD), the American National Standards Institute, and even internationally.[(3)(4)(5)(6)] Conclusions from this seminal EPA work remain scientifically valid to this day.

Figure 2-6 contains a synthesis of actual case studies of community reaction to newly introduced sources of noise in a residential urban neighborhood.[(2)] Plotted horizontally in the figure is the new noise's excess above existing noise levels. Both the new and existing noise levels are expressed as Day-Night Sound Levels, L_{dn}, discussed in Section 2.4. Plotted vertically is the community reaction to this newly introduced noise. As shown in the figure, community reaction varies from "No Reaction" to "Vigorous Action," for newly introduced noises averaging from "10 decibels below existing" to "25 decibels above existing." Note that these data points apply only when the stated assumptions are true. For other conditions, the points shift to the right or left somewhat.

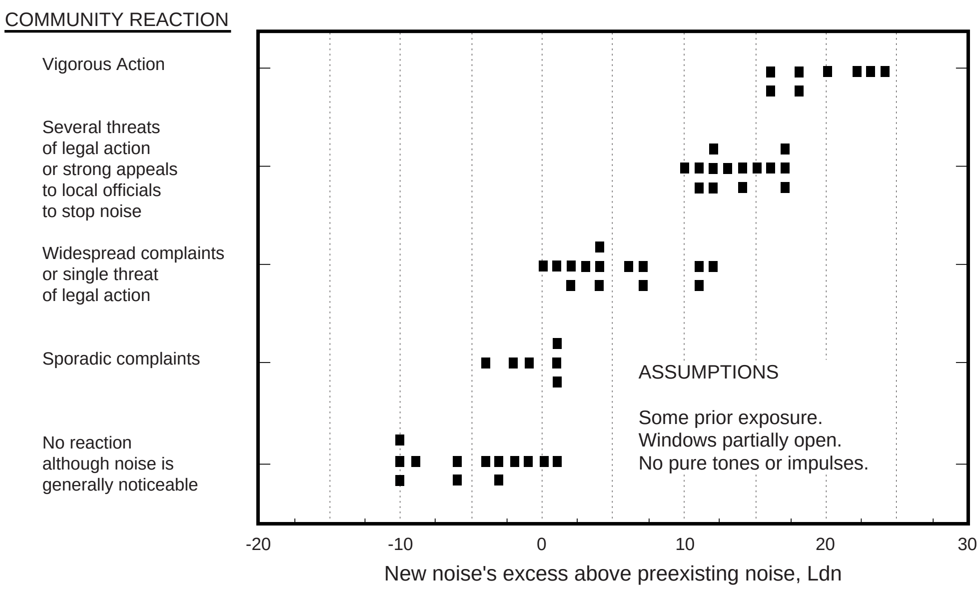


Figure 2-6 Community Reaction to New Noise, Relative to Existing Noise in a Residential Urban Environment

In a large number of community attitudinal surveys, transportation noise has been ranked among the most significant causes of community dissatisfaction. A synthesis of many such surveys on annoyance appears in Figure 2-7.[(7)(8)] Plotted horizontally are different neighborhood noise exposures. Plotted vertically is the percentage of people who are *highly annoyed* by their particular level of neighborhood noise. As shown in the figure, the percentage of high annoyance is approximately 0 percent at 45 decibels, 10 percent around 60 decibels and increases quite rapidly to approximately 70 percent around 85 decibels. The scatter about the synthesis line is due to variation from community to community and to some wording differences in the various surveys. A recent update of the original research, containing several additional railroad, transit and street traffic noise surveys, added confirmation to the shape of the original Schultz curve.[(9)]

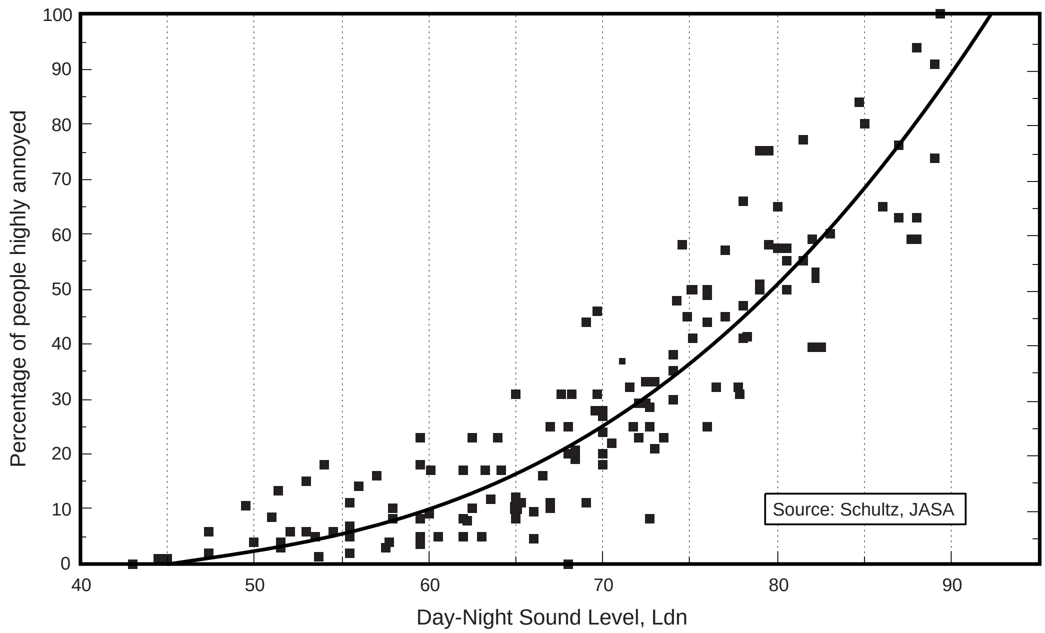


Figure 2-7 Community Annoyance Due to Noise

As indicated by these two figures, introduction of transit noise into a community may have two undesirable effects. First, it may significantly increase existing noise levels in the community, levels that residents have mostly become accustomed to. This effect is called "relative" noise impact. Evaluation of this effect is "relative" to existing noise levels; relative criteria are based upon noise increases above existing levels. Second, newly introduced transit noise may interfere with community activities, independent of existing noise levels; it may be simply too loud to converse or to sleep. This effect is called "absolute" noise impact, because it is expressed as a fixed level not to be exceeded and is independent of existing noise levels. Both these effects, relative and absolute, enter the assessment of transit noise impact in Chapters 4, 5 and 6. These two types of impact, relative and absolute, are merged into the transit noise criteria of Chapter 3.

2.4 DESCRIPTORS FOR TRANSIT NOISE

Environmental noise generally derives, in part, from a conglomeration of distant noise sources. Such sources may include distant traffic, wind in trees, and distant industrial or farming activities, all part of our daily lives. These distant sources create a low-level "background noise" in which no particular individual source is identifiable. Background noise is often relatively constant from moment to moment, but varies slowly from hour to hour as natural forces change or as human activity follows its daily cycle. Superimposed on this low-level, slowly varying background noise is a succession of identifiable noisy events of relatively brief duration. These events may include single-vehicle passbys, aircraft flyovers, screeching of brakes, and other short-term events, all causing the noise level to fluctuate significantly from moment to moment.

It is possible to describe these fluctuating noises in the environment using single-number descriptors. To do this allows manageable measurements, computations, and impact assessment. The search for adequate single-number noise descriptors has encompassed hundreds of attitudinal surveys and laboratory experiments, plus decades of practical experience with many alternative descriptors.

This manual uses the following single-number descriptors for transit-noise measurements, computations, and assessment:

The *A-weighted Sound Level*, which describes a receiver's noise at any moment in time.

The *Maximum Level* (L_{max}) during a single noise event.

The *Sound Exposure Level (SEL)*, which describes a receiver's cumulative noise exposure from a single noise event.

The *Hourly Equivalent Sound Level* ($L_{eq}(h)$), which describes a receiver's cumulative noise exposure from all events over a one-hour period.

The *Day-Night Sound Level* (L_{dn}), which describes a receiver's cumulative noise exposure from all events over a full 24 hours, with events between 10pm and 7am increased by 10 decibels to account for greater nighttime sensitivity to noise.

This section illustrates all of these noise descriptors, in turn, and describes their particular application in this manual. Emphasized here are graphic illustrations rather than mathematical definitions to help the reader gain understanding and to see the interrelationships among descriptors.

2.4.1 A-weighted Sound Level: The Basic Noise Unit

The basic noise unit for transit noise is the A-weighted Sound Level. It describes a receiver's noise at any moment in time and is read directly from noise-monitoring equipment, with the "weighting switch" set on "A." Figure 2-8 shows some typical A-weighted Sound Levels for both transit and non-transit sources.

As is apparent from Figure 2-8, typical A-weighted Sound Levels range from the 30s to the 90s, where 30 is very quiet and 90 is very loud. The scale in the figure is labelled "dBA" to denote the way A-weighted Sound Levels are typically written, for example, 80 dBA. The letters "dB" stand for "decibels" and refer to the general strength of the noise. The decibel is a unit of level which denotes the ratio between two quantities that are proportional to power. When used to describe sound level, the number of decibels is 10 times the logarithm (to the base 10) of the ratio (p^2/p_{ref}^2), where p is the sound pressure (in micro-pascals) and p_{ref} is a reference pressure (20 micro-pascals). The letter "A" indicates that the sound has been filtered to reduce the strength of very low and very high-frequency sounds, much as the human ear does. Without this A-weighting, noise-monitoring equipment would respond to events people cannot hear, events such as high-frequency dog whistles and low-frequency seismic disturbances. On the average, each A-weighted sound level increase of 10 decibels corresponds to an approximate doubling of subjective loudness.

A-weighted sound levels are adopted here as the basic noise unit because: (1) they can be easily measured, (2) they approximate our ear's sensitivity to sounds of different frequencies, (3) they match attitudinal-survey tests of annoyance better than do other basic units, (4) they have been in use since the early 1930s, and (5) they are endorsed as the proper basic unit for environmental noise by nearly every agency concerned with community noise throughout the world.

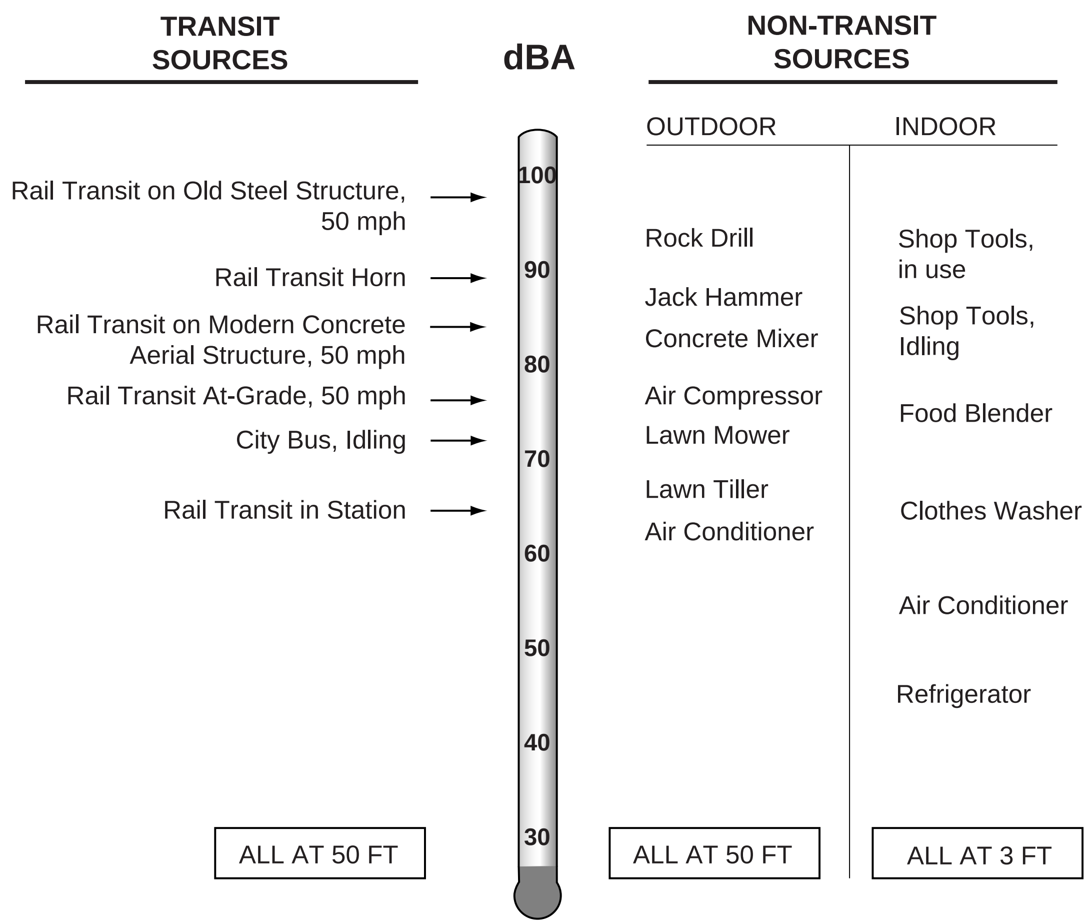


Figure 2-8 Typical A-Weighted Sound Levels

2.4.2 Maximum Level (L_{max}) During a Single Noise Event

As a transit vehicle approaches, passes by, and then recedes into the distance, the A-weighted sound level rises, reaches a maximum, and then fades into the background noise. The maximum A-weighted sound level reached during this passby is called the Maximum Level, abbreviated here as "L_{max}." For noise compliance tests of transient sources, such as moving transit vehicles under controlled conditions with smooth wheel and rail conditions, L_{max} is typically measured with the sound level meter's switch set on "fast." However, for tests of continuous or stationary transit sources, and for the general assessment of transit noise impact, it is usually more appropriate to use the "slow" setting. When set on "slow," sound level meters ignore some of the very-transient fluctuations, which are unimportant to people's overall assessment of the noise. L_{max} is illustrated in Figure 2-9, where time is plotted horizontally and A-weighted sound level is plotted vertically.

Noise guidelines published by the American Public Transit Association (APTA) have been used for a number of years to assess the noise impact of rail transit projects.[10] For moving trains, the APTA guidelines are based on L_{max} during a vehicle passby. They are directed toward conventional rail rapid transit projects and cover all aspects of such systems. Because L_{max} is commonly used in vehicle-noise specifications and because it is commonly measured for individual vehicles, equations are included in Appendices D and E to convert between L_{max} and the cumulative descriptors discussed below. However, L_{max} is not used as the descriptor for transit environmental noise impact assessment for several reasons. L_{max} ignores the number and duration of transit events, which are important to people's reaction to noise, and cannot be totalled into a one-hour or a 24-hour cumulative measure of impact. Moreover, the L_{max} is not conducive to comparison among different transportation modes. For example, noise descriptors used in highway noise assessments are L_{eq} and L_{10}, the noise level exceeded for 10 percent of the peak hour.

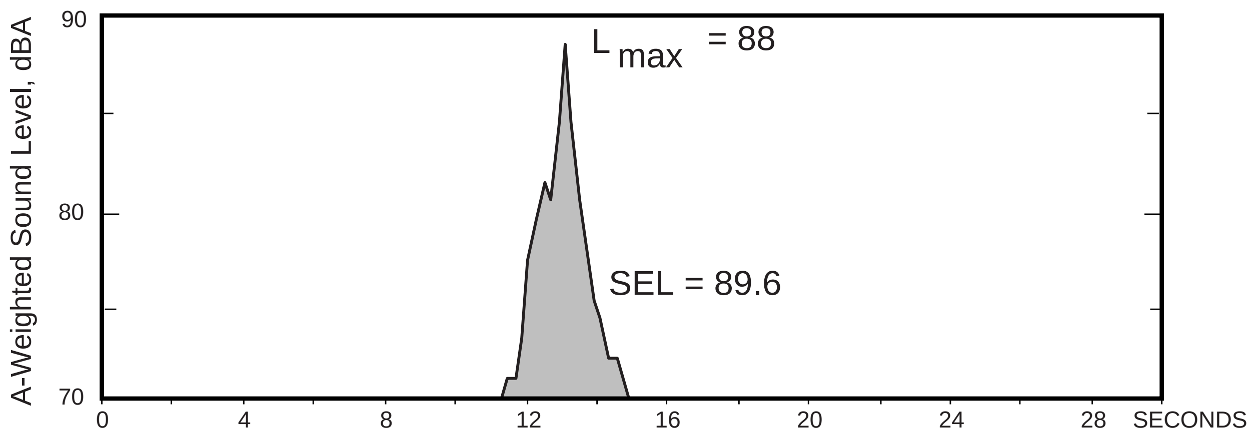


Figure 2-9 Typical Transit-Vehicle Passby

2.4.3 Sound Exposure Level (SEL): The Cumulative Exposure from a Single Noise Event

Shaded in Figure 2-9 is the noise "dose" during a transit-vehicle passby. This dose represents the total amount of sound energy that enters the receiver's ears (or the measurement microphone) during the vehicle passby. Figure 2-10 shows another noise event – this one within a fixed-transit facility as a transit bus is started, warmed up, and then driven away. For this event, the noise dose is large due to *duration*.

The quantitative measure of the noise dose for single noise events is the Sound Exposure Level, abbreviated here as "SEL" and shaded in both these figures. The fact that SEL is a cumulative measure means that (1) louder events have greater SELs than do quieter ones, and (2) events that last longer in time have greater SELs than do shorter ones. People react to the duration of noise events, judging longer events to be more annoying than shorter ones, assuming equal maximum A-Levels. Mathematically, the Sound Exposure Level is computed as:

$$\text{SEL} = 10\log_{10}\begin{bmatrix}\text{Total sound energy}\\ \text{during the event}\end{bmatrix}$$

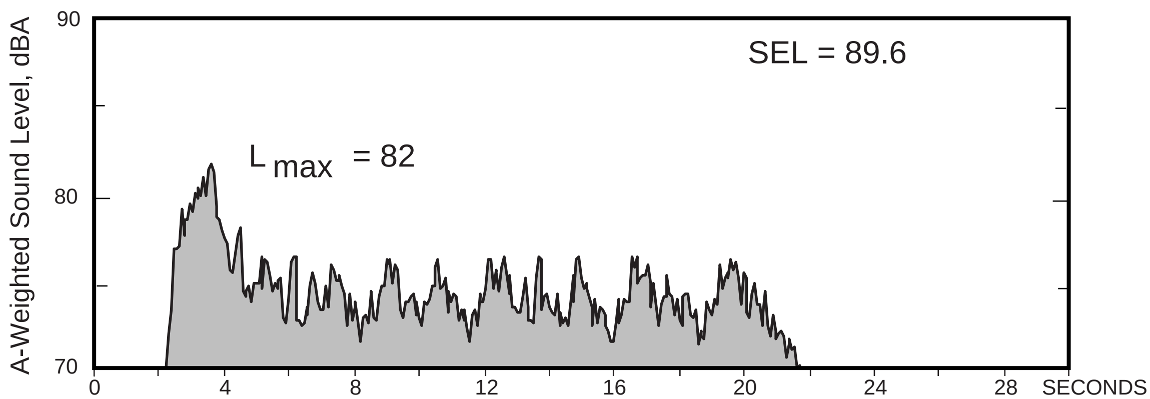


Figure 2-10 Typical Fixed-Facility Noise Event

Figure 2-11 repeats the previous time histories, but with a stretched vertical scale. The stretched scale corresponds to sound "energy" at any moment in time. Mathematically, sound energy is proportional to 10 raised to the (L/10) power, that is, $10^{(L/10)}$. The vertical scale has been stretched in this way because noise doses are "energy" doses. Only in this way do the shaded zones properly correspond to the noise doses that underlie the SEL. Note that the shaded zones in the two frames have equal numerical areas, corresponding to equal SELs for these two very different noise events.

Each frame of the figure also contains a tall, thin shaded zone of one-second duration. This tall zone is another way to envision SELs. Think of the original shaded zone being squeezed shorter and shorter in time, while retaining the same numerical area. As its duration is squeezed, its height must increase to keep the area constant. If an SEL shading is squeezed to a duration of one second, its height will then equal its SEL value; mathematically, its area is now $10^{(L/10)}$ times one second. Note that the resulting height of the squeezed zone depends both upon the L_{max} and the duration of the event -- that is, upon the total area under the original, time-varying A-Level. Often this type of "squeezing" helps communicate the meaning of SELs and noise doses to the reader.

SEL is used in this manual as the cumulative measure of each single transit-noise event because unlike L_{max}: (1) SEL increases with the duration of a noise event, which is important to people's reaction, (2) SEL

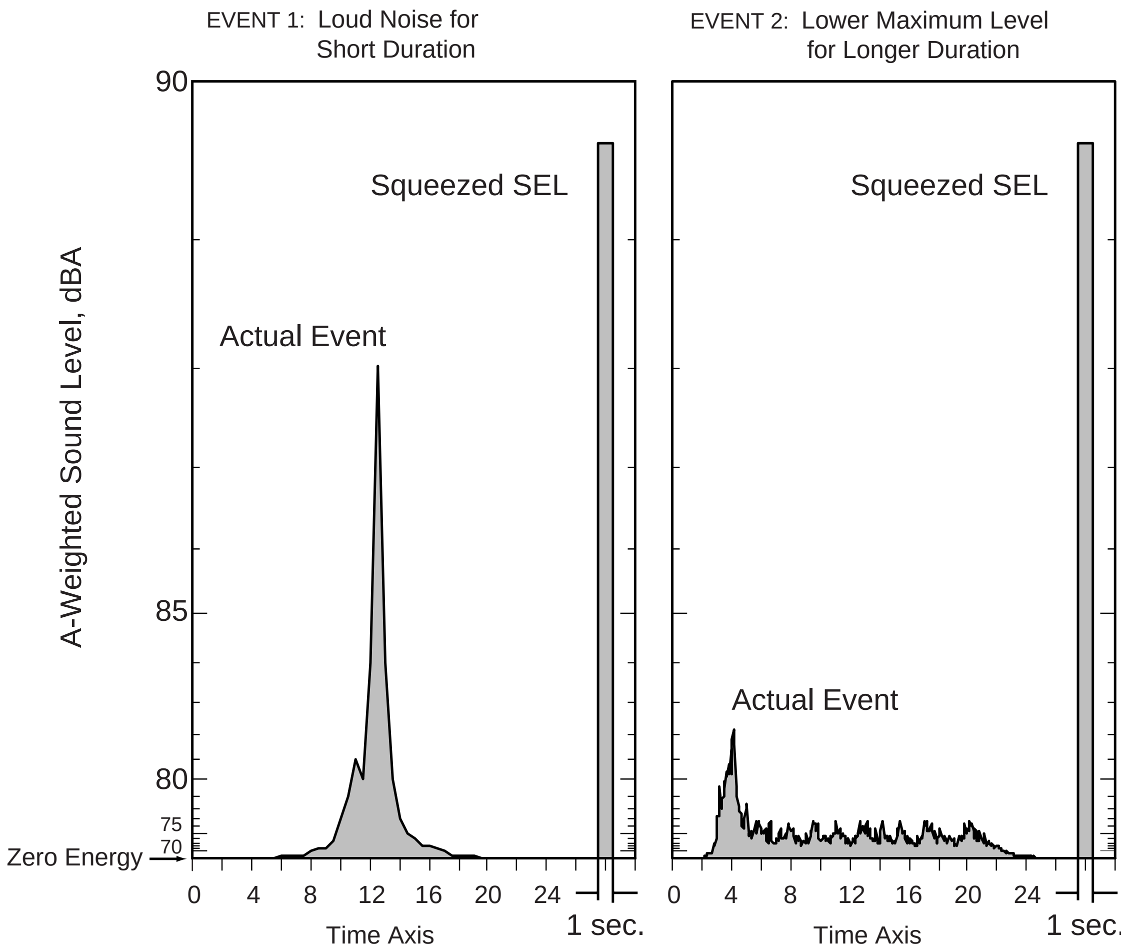


Figure 2-11 An "Energy" View of Noise Events

therefore allow a uniform assessment method for both transit-vehicle passbys and fixed-facility noise events, and (3) SEL can be used to calculate the one-hour and 24-hour cumulative descriptors discussed below.

2.4.4 Hourly Equivalent Sound Level (L_{eq}(h))

The descriptor for cumulative one-hour exposure is the Hourly Equivalent Sound Level, abbreviated here as "L_{eq}(h)." It is an hourly measure that accounts for the moment-to-moment fluctuations in A-weighted sound levels due to all sound sources during that hour, combined. Sound fluctuation is illustrated in the upper frame of Figure 2-12 for a single noise event such as a train passing on nearby tracks. As the train approaches, passes by, and then recedes into the distance, the A-weighted Sound Level rises, reaches a maximum, and then fades into the background noise. The area under the curve in this upper frame is the receiver's noise dose over this five-minute period.

The center frame of the figure shows sound level fluctuations over the one-hour period that includes the five-minute period from the upper frame. Now the area under the curve represents the noise dose for one hour. Mathematically, the Hourly Equivalent Sound Level is computed as:

$$L_{eq}(hour) = 10\ \log_{10}\left[\begin{matrix}\text{Total sound energy}\\ \text{during one hour}\end{matrix}\right] - 35.6$$

Sound energy is totalled here over a full hour; it accumulates from all noise events during that hour. Subtraction of 35.6 from this one-hour dose converts it into a time average, as explained in Section 2.4.6. In brief, if the actual fluctuating noise were replaced by a constant noise equal to this average value, the same total noise dose would enter the receiver's ears. This type of average value is "equivalent" in that sense to the actual fluctuating noise.

A useful, alternative way of computing L_{eq} due to a series of transit-noise events is:

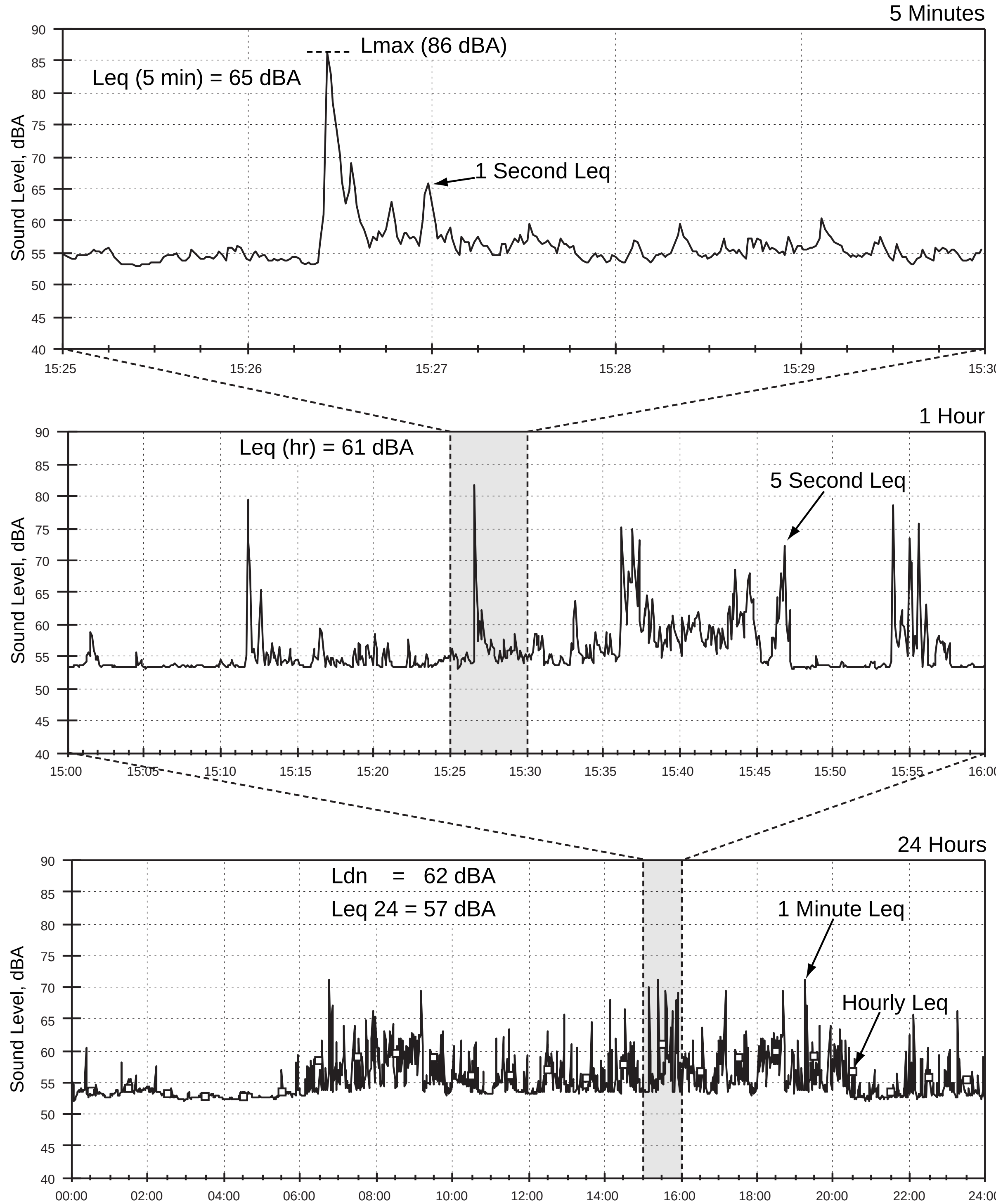
$$L_{eq}(hour) = 10\ \log_{10}\left[\begin{matrix}\text{Energy Sum of}\\ \text{all SELs}\end{matrix}\right] - 35.6$$

This equation concentrates on the cumulative contribution of individual noise events, and is the fundamental equation incorporated into Chapters 5 and 6.

The bottom frame of Figure 2-12 shows the sound level fluctuations over a full 24-hour period. It is discussed in Section 2.4.5.

Figure 2-13 shows some typical hourly L_{eq}'s, both for transit and non-transit sources. As is apparent from the figure, typical hourly L_{eq}'s range from the 40s to the 80s. Note that these L_{eq}'s depend upon the number of events during the hour and also upon each event's duration, which is affected by vehicle speed. Doubling the number of events during the hour will increase the L_{eq} by 3 decibels, as will doubling the duration of each individual event.

Hourly L_{eq} is adopted here as the measure of cumulative noise impact for non-residential land uses (those not involving sleep) because: (1) L_{eq}'s correlate well with speech interference in conversation and on the telephone – as well as interruption of TV, radio and music enjoyment, (2) L_{eq}'s increase with the duration of transit events, which is important to people's reaction, (3) L_{eq}'s take into account the number of transit events over the hour, which is also important to people's reaction, and (4) L_{eq}'s are used by the Federal Highway Administration in assessing highway-traffic noise impact. Thus, this noise descriptor can be used for comparing and contrasting highway, transit and multi-modal alternatives. L_{eq} is computed for the loudest facility hour during noise-sensitive activity at each particular non-residential land use. Section 2.4.6 contains more detail in support of L_{eq} as the adopted descriptor for cumulative noise impact for non-residential land uses.



Typical A-weighted Sound Level Variation over a 24-Hour Period

Figure 2-12 Example A-Weighted Sound Level Time Histories

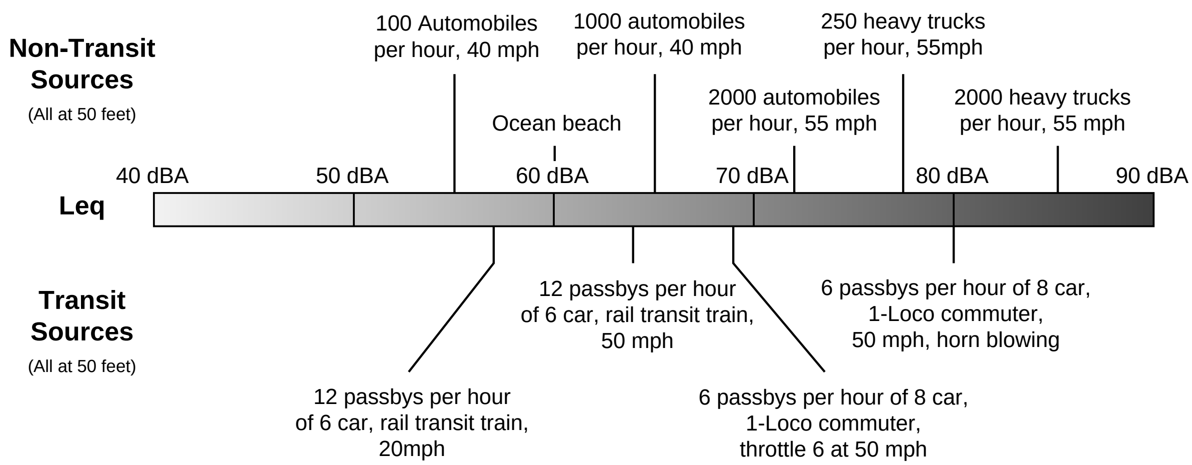


Figure 2-13 Typical Hourly L_{eq}'s

2.4.5 Day-Night Sound Level (L_{dn}): The Cumulative 24-Hour Exposure from All Events

The descriptor for cumulative 24-hour exposure is the Day-Night Sound Level, abbreviated here as "L_{dn}." It is a 24-hour measure that accounts for the moment-to-moment fluctuations in A-Levels due to all sound sources during 24 hours, combined. Such fluctuations are illustrated in the bottom frame of Figure 2-12. Here the area under the curve represents the receiver's noise dose over a full 24 hours. Note that some vehicle passbys occur at night in the figure, when the background noise is less. Mathematically, the Day-Night Level is computed as:

$$L_{dn} = 10 \log_{10} \begin{bmatrix} \text{Total sound energy} \\ \text{during 24 hours} \end{bmatrix} - 49.4$$

where nighttime noise (10pm to 7am) is increased by 10 decibels before totalling.

Sound energy is totalled over a full 24 hours; it accumulates from all noise events during that 24 hours. Subtraction of 49.4 from this 24-hour dose converts it into a type of "average," as explained in Section 2.4.6. In brief, if the actual fluctuating noise were replaced by a constant noise equal to this average value, the same total noise dose would enter the receiver's ears.

An alternative way of computing L_{dn} from twenty-four hourly L_{eq}'s is:

$$L_{dn} = 10 \log_{10} \begin{bmatrix} \text{Energy sum of} \\ \text{24 hourly } L_{eq}\text{s} \end{bmatrix} - 13.8$$

where nighttime L_{eq}'s are increased by 10 decibels before totalling, as in the previous equation.

L_{dn} due to a series of transit-noise events can also be computed as:

$$L_{dn} = 10\log_{10}\left[\begin{matrix}\text{Energy sum of}\\ \text{all SELs}\end{matrix}\right] - 49.4$$

assuming that transit noise dominates the 24-hour noise dose. Here again, nighttime SELs are increased by 10 decibels before totalling. This last equation concentrates upon individual noise events, and is the equation incorporated into Chapters 5 and 6.

Figure 2-14 shows some typical L_{dn}'s, both for transit and non-transit sources. As is apparent from the figure, typical L_{dn}'s range from the 50s to the 70s – where 50 is a quiet 24-hour period and 70 is an extremely loud one. Note that these L_{dn}'s depend upon the number of events during day and night separately – and also upon each event's duration, which is affected by vehicle speed.

L_{dn} is adopted here as the measure of cumulative noise impact for residential land uses (those involving sleep), because: (1) L_{dn} correlates well with the results of attitudinal surveys of residential noise impact, (2) L_{dn}'s increase with the duration of transit events, which is important to people's reaction, (3) L_{dn}'s take into account the number of transit events over the full twenty-four hours, which is also important to people's reaction, (4) L_{dn}'s take into account the increased sensitivity to noise at night, when most people are asleep, (5) L_{dn}'s allow composite measurements to capture all sources of community noise combined, (6) L_{dn}'s allow quantitative comparison of transit noise with all other community noises, (7) L_{dn} is the designated metric of choice of other Federal agencies (Department of Housing and Urban Development (HUD), Federal Aviation Administration (FAA), Environmental Protection Agency (EPA)) and also has wide acceptance internationally. Section 2.4.6 contains more detail in support of L_{dn} as the adopted descriptor for cumulative noise impact for residential land uses.

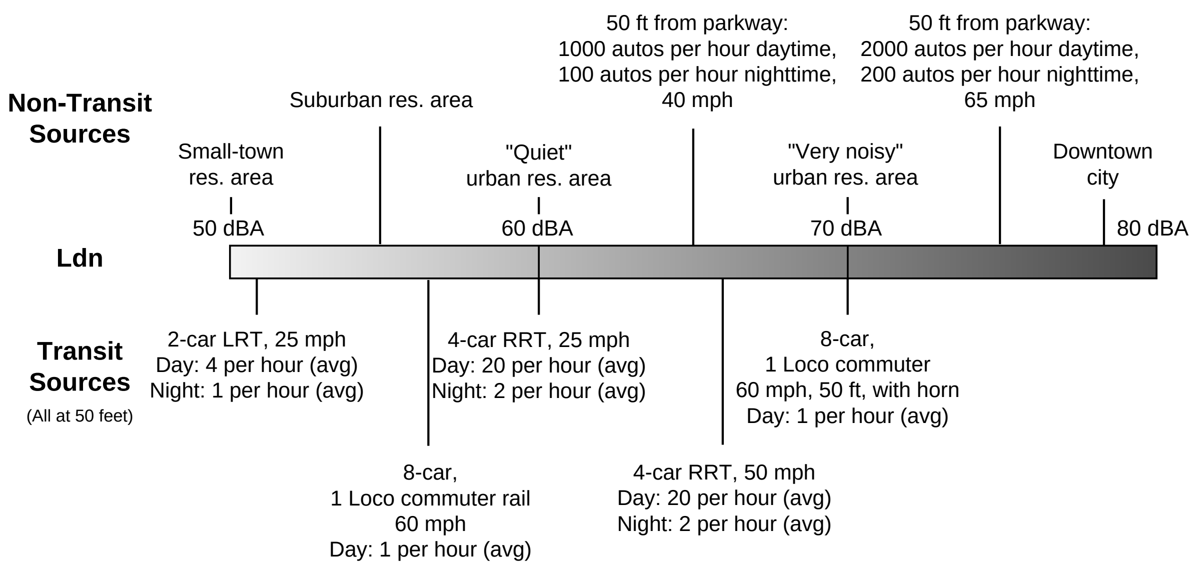


Figure 2-14 Typical L_{dn}'s

2.4.6 A Noise-Dose Analogy for L_{eq} and L_{dn}

In Figure 2-12 (page 2-16), the area under the curves represent noise "doses." An analogy between rainfall and noise is sometimes helpful to further explain these noise doses.

The one-hour noise dose in the middle frame of the figure is analogous to one hour of rainfall; that is, the total accumulation of rain over this one-hour period. Note that every rain shower increases the one-hour rain dose. Also, note that heavier showers increase the dose more than do lighter ones, and longer showers increase the dose more than do shorter ones. The same is true for noise: (1) every transit event increases the one-hour noise dose; (2) loud events increase the noise dose more than do quieter ones; and (3) events that stretch out longer in time increase the noise dose more than do shorter ones.

The moment-to-moment A-level is like the moment-to-moment rate at which the rain is falling. Arithmetically, if this rain rate is measured in "inches of rain per second," then a constant rain rate of 0.001 inches/second, times 3600 seconds in an hour, will total to a one-hour dose of 3.6 inches of rain. This arithmetic appears in the upper center of Table 2-2. Analogously in the upper right, a constant A-level of 60 dBA, plus $10\log_{10}(3600)$, will total to a one-hour noise dose of 95.6. In spite of the logarithmic complication, the analogy holds: a constant A-level (or rain rate), increased by the number of seconds in an hour, yields the one-hour noise dose (or rain dose). In the table, the noise arithmetic is repeated in energy terms, where the analogy is even more direct.

This arithmetic can also be done in reverse, leading to "averages" of the type used for L_{eq} and L_{dn}. This reverse arithmetic appears at the bottom of the table. A total hourly rain dose of 3.6 inches, divided by 3600 seconds, yields an average rain rate of 0.001 inches per second. Similarly, a one-hour noise dose of 95.6, minus $10\log_{10}(3600)$, yields an average A-level of 60 dBA. In other words, a fluctuating noise with a one-hour dose of 95.6 decibels can be "replaced" with an average A-Level of 60 dBA, to yield the same one-hour dose. The actual fluctuating noise and the average 60-dBA noise are "equivalent"; they yield the same total one-hour noise dose. This is the concept behind the word equivalent in the abbreviation "L_{eq}." The same analogy holds for the 24-hour rain dose and the 24-hour noise dose that leads to L_{dn}. Here, however, nighttime A-Levels are increased by 10 decibels before totaling into the 24-hour dose, and the number of seconds involved is 86,400.

Unfortunately, the word "average" leaves many people with the impression that the maximum levels which attract their attention are being devalued or ignored. They are not. Just as all the rain that falls in the rain gauge in one hour counts toward the total, all sounds are included in the one-hour noise dose that underlies L_{eq} and in the 24-hour noise dose that underlies L_{dn}. None of the noise is being ignored, even though the L_{eq} and L_{dn} are often numerically lower than many maximum A-Levels. Their noise doses include all transit events, all noise levels that occur during their time periods -- without exception. Every added event, even the quiet ones, will increase these noise doses, and therefore increase L_{eq} and L_{dn}.

Neither the L_{eq} nor the L_{dn} is an "average" in the normal sense of the word, where introduction of a quiet event would pull down the average. Furthermore, just as in watering a field or garden, scientific evidence strongly indicates that total noise dose is the truest measure of noise impact. Neither the moment-to-moment rain rate nor the moment-to-moment A-level is a good measure of long-term effects.

Table 2-2 Rainfall Analogy with Noise Dose

Computation	Rain	Noise
DOSE	Dose = Rate × Duration = (0.001 inches/sec) × (3600 sec) = 3.6 inches of rain	Dose = Level + 10 log (Duration) = 60 + 10 log (3600) = 60 + 35.6 = 95.6 dB *Or in Energy Terms:* Dose = $10^{(L/10)}$ × Duration = $10^{(60/10)}$ × Duration = 1,000,000 × 3600 = 3,600,000,000 and 10 log (Dose) = 95.6 dB
AVERAGE	Average = Dose ÷ Duration = (3.6 inches) ÷ (3600 sec) = 0.001 inches/sec	Average = Dose − 10 log (Duration) = 95.6 − 10 log (3600) = 95.6 − 35.6 = 60.0 dB *Or in Energy Terms:* Average = (Energy Dose) ÷ Duration = $10^{(95.6/10)}$ ÷ 3600 = 3,630,780,548 ÷ 3600 = 1,008,550 and 10 log (1,008,550) = 60.0 dB

Why not just compute transit noise impact on the basis of the highest L_{max} of the day? – for example, as "loudest L_{max} equals 90 dBA?" If that were done, then there would be no difference in noise impact between a main trunk line and a suburban branch line; one passby per day would be no better than 100 per day, if the loudest level remained unchanged. Clearly such a reduction in number-of-passbys is a true benefit, so it should reduce the numerical measure of impact. It does with L_{eq} and L_{dn}, but not with L_{max}. In addition, if assessments were made just on the loudest passby, then one passby at 90 dBA would be worse than 100 passbys at 89 dBA. Clearly this is not true. Both L_{eq} and L_{dn} increase with the number of passbys, while L_{max} does not. Both the L_{eq} and the L_{dn} combine the number of passbys with each passby's L_{max} and duration, all into a cumulative noise dose, with mathematics that "make sense" from an annoyance point of view. L_{eq} and L_{dn} mathematics produce results that correlate well with independent tests of noise annoyance from all types of noise sources.

In terms of individual passbys, here are some characteristics of both the L_{eq} and the L_{dn}:

When passby L_{max}'s increase: → Both L_{eq} and L_{dn} increase

When passby durations increase:	→	Both L_{eq} and L_{dn} increase
When the number of passbys increases:	→	Both L_{eq} and L_{dn} increase
When some operations shift to louder vehicles:	→	Both L_{eq} and L_{dn} increase
When passbys shift from day to night:	→	L_{dn} increases

All of these increases in L_{eq} and L_{dn} correlate to increases in community annoyance.

2.4.7 Summary of Noise Descriptors

In summary, the following noise descriptors are adopted in this manual for the computation and assessment of transit noise:

The **A-weighted Sound Level,** which describes a receiver's noise at any moment in time. It is adopted here as the basic noise unit, and underlies all the noise descriptors below.

The **Maximum Level (L_{max})** during a single noise event. The L_{max} descriptor is not recommended for transit noise impact assessment, but because it is commonly used in vehicle-noise specifications and because it is commonly measured for individual vehicles, equations are included in Appendices D and E to convert between L_{max} and the cumulative descriptors adopted here.

The **Sound Exposure Level (SEL),** which describes a receiver's cumulative noise exposure from a single noise event. It is adopted here as the primary descriptor for the measurement of transit-vehicle noise emissions, and as an intermediate descriptor in the measurement and calculation of both L_{eq} and L_{dn}.

The **Hourly Equivalent Sound Level (L_{eq}(h)),** which describes a receiver's cumulative noise exposure from all events over a one-hour period. It is adopted here to assess transit noise for non-residential land uses. For assessment, L_{eq} is computed for the loudest transit facility hour during the hours of noise-sensitive activity.

The **Day-Night Sound Level (L_{dn}),** which describes a receiver's cumulative noise exposure from all events over a full 24 hours. It may be thought of as a noise dose, totaled after increasing all nighttime A-Levels (between 10pm and 7am) by 10 decibels. Every noise event during the 24-hour period increases this dose, louder ones more than quieter ones, and ones that stretch out in time more than shorter ones. L_{dn} is adopted here to assess transit noise for residential land uses.

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3. NOISE IMPACT CRITERIA

This chapter presents the criteria to be used in evaluating noise impact from mass transit projects. In general terms, these criteria describe the noise environment considered acceptable for a given situation. Because some projects are strictly transit projects while other projects are basically highway projects that include a transit component, two different sets of criteria are required as follows:

- Rail and Bus Facilities: This category includes all rail projects (e.g., rail rapid transit, light rail transit, commuter rail, and automated guideway transit), as well as fixed facilities such as storage and maintenance yards, passenger stations and terminals, parking facilities, substations, etc. Also included are rail transit projects built within a highway or railroad corridor. Certain bus facilities are included in this category, such as separate roadways built exclusively for buses, and bus operations on local streets and highways where the project does not include roadway construction or modification that significantly changes roadway capacity. The distinguishing feature in all these cases is that the existing noise levels are generated by roadway traffic and other sources that will not change as a result of the project; therefore the project noise is exclusively due to the new transit sources.

- Highway/Transit Projects: Projects in this category involve new highway construction or modifications to existing highways to increase carrying capacity. The project would involve preferential treatment for buses or high-occupancy vehicles (HOV). The distinguishing feature here is that the *project* noise includes a combination of highway and transit sources. Examples are: new highway construction providing general-purpose lanes as well as dedicated bus/HOV lanes and lane additions or reconfigurations on existing highways to accommodate buses/HOVs.

The noise impact criteria for rail and bus facilities are presented in Section 3.1. These criteria were developed specifically for transit noise sources operating on fixed guideways or at fixed facilities. The criterion for the onset of Impact varies according to the existing noise level and the predicted project noise level, and is determined by the threshold at which the percentage of people highly annoyed by the project noise starts to become measurable. The corresponding criterion for Severe Impact similarly varies according to the existing noise level as well as the project noise level, but is determined by a higher, more significant percentage of people highly annoyed by project noise. Guidelines for the application of the criteria are included in Section 3.2, and background material on the development of the criteria are included in Appendix A.

For transit projects integrated with an existing or newly-constructed highway, such as HOV lanes or exclusive bus lanes, the determination of noise impact is based on existing Federal Highway Administration (FHWA) noise prediction procedures and impact criteria, as summarized in Section 3.3 of this chapter. The latter criteria are used to maintain consistency with established noise impact assessment methods for projects that involve modifications to existing roadways or the construction of new roadways.

3.1 NOISE IMPACT CRITERIA FOR TRANSIT PROJECTS

The noise impact criteria for mass transit projects involving rail or bus facilities are shown graphically in Figure 3-1 and are tabulated in Table 3-1. The equations used to define these criteria are included in Appendix A. The criteria apply to all rail projects (e.g., rail rapid transit, light rail transit, commuter rail, and automated guideway transit) as well as fixed facilities such as storage and maintenance yards, passenger stations and terminals, parking facilities, and substations. They may also be used for bus projects operating on local streets and separate roadways built exclusively for buses. In contrast, for busways and HOV lanes which are to be integrated in existing highways (e.g., the addition of new lanes or the redesignation of existing lanes on a highway), the FHWA's noise abatement criteria contained in Federal-Aid Highway Program Manual 7-7-3 are the appropriate noise criteria to use. Likewise, if the project is a new highway involving both general-purpose and dedicated bus/HOV lanes, the FHWA approach is followed. The FHWA criteria are briefly summarized in Section 3.3.

3.1.1 Basis of Noise Impact Criteria

The noise impact criteria in Figure 3-1 and Table 3-1 are based on comparison of the existing outdoor noise levels and the future outdoor noise levels from the proposed project. They incorporate both absolute criteria, which consider activity interference caused by the transit project alone, and relative criteria, which consider annoyance due to the change in the noise environment caused by the transit project.

Whereas noise impact criteria that have been used for previous transit projects take existing ambient noise levels into account based on generalized community categories, the criteria in this manual depend on specific estimates of existing community noise levels as part of the determination of noise impact. These criteria were developed to apply to various transit modes, to recognize the heightened community annoyance caused by late-night or early-morning transit service, and to respond to the varying sensitivity of communities to projects under different background noise conditions.

The noise criteria and descriptors depend on land use, as defined in Table 3-2. Further guidance on the definition of land use, the selection of the appropriate noise metric and the application of the criteria is given in Section 3.2 of this chapter, with more detailed guidelines given in Chapters 5 and 6.

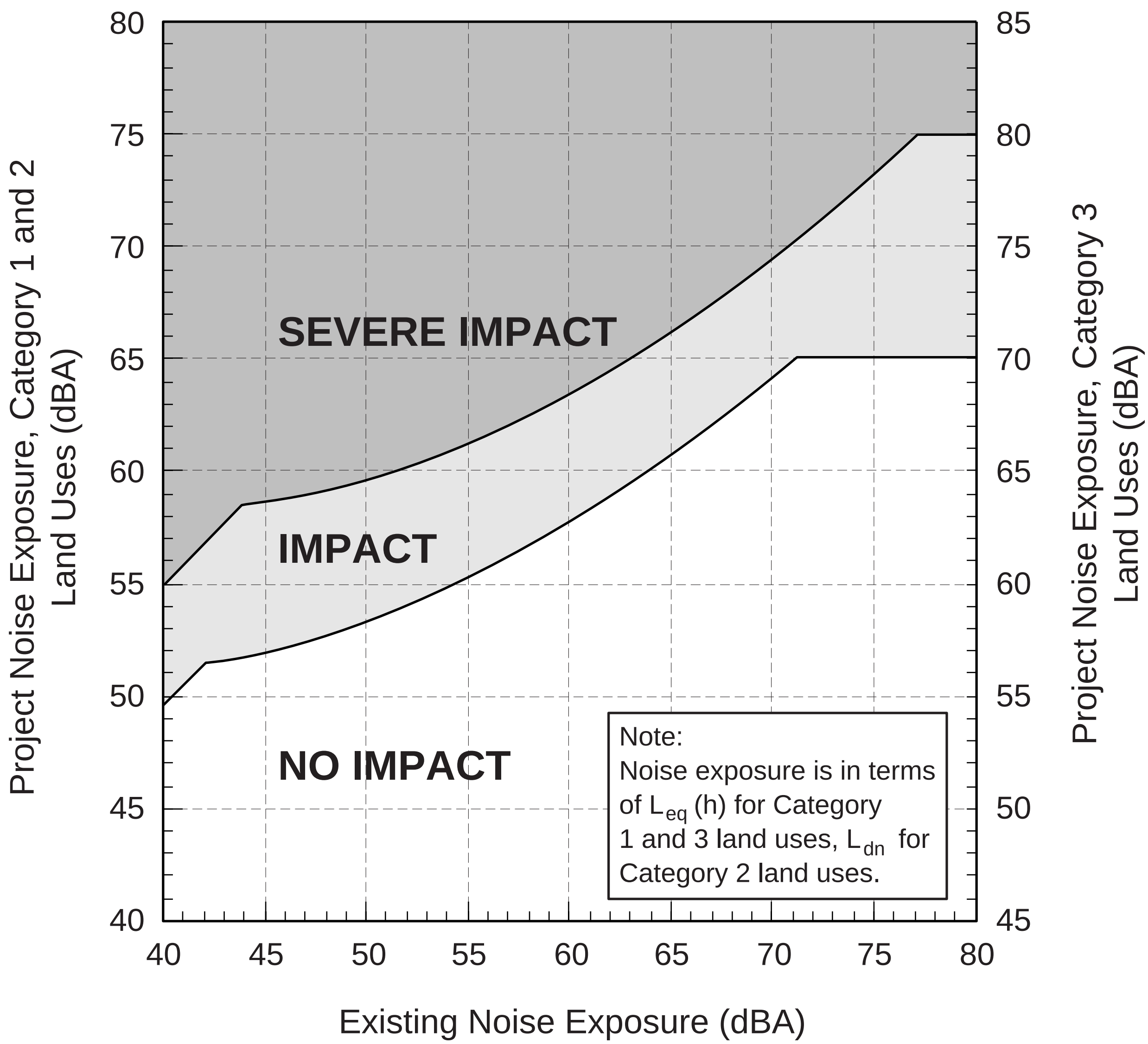

Figure 3-1 Noise Impact Criteria for Transit Projects

Table 3-1 Noise Levels Defining Impact for Transit Projects

Existing Noise Exposure* $L_{eq}(h)$ or L_{dn} (dBA)	**Project Noise Impact Exposure,*** $L_{eq}(h)$ or L_{dn} (dBA)					
	Category 1 or 2 Sites			**Category 3 Sites**		
	No Impact	Impact	Severe Impact	No Impact	Impact	Severe Impact
<43	< Ambient+10	Ambient + 10 to 15	>Ambient+15	<Ambient+15	Ambient + 15 to 20	>Ambient+20
43	<52	52-58	>58	<57	57-63	>63
44	<52	52-58	>58	<57	57-63	>63
45	<52	52-58	>58	<57	57-63	>63
46	<53	53-59	>59	<58	58-64	>64
47	<53	53-59	>59	<58	58-64	>64
48	<53	53-59	>59	<58	58-64	>64
49	<54	54-59	>59	<59	59-64	>64
50	<54	54-59	>59	<59	59-64	>64
51	<54	54-60	>60	<59	59-65	>65
52	<55	55-60	>60	<60	60-65	>65
53	<55	55-60	>60	<60	60-65	>65
54	<55	55-61	>61	<60	60-66	>66
55	<56	56-61	>61	<61	61-66	>66
56	<56	56-62	>62	<61	61-67	>67
57	<57	57-62	>62	<62	62-67	>67
58	<57	57-62	>62	<62	62-67	>67
59	<58	58-63	>63	<63	63-68	>68
60	<58	58-63	>63	<63	63-68	>68
61	<59	59-64	>64	<64	64-69	>69
62	<59	59-64	>64	<64	64-69	>69
63	<60	60-65	>65	<65	65-70	>70
64	<61	61-65	>65	<66	66-70	>70
65	<61	61-66	>66	<66	66-71	>71
66	<62	62-67	>67	<67	67-72	>72
67	<63	63-67	>67	<68	68-72	>72
68	<63	63-68	>68	<68	68-73	>73
69	<64	64-69	>69	<69	69-74	>74
70	<65	65-69	>69	<70	70-74	>74
71	<66	66-70	>70	<71	71-75	>75
72	<66	66-71	>71	<71	71-76	>76
73	<66	66-71	>71	<71	71-76	>76
74	<66	66-72	>72	<71	71-77	>77
75	<66	66-73	>73	<71	71-78	>78
76	<66	66-74	>74	<71	71-79	>79
77	<66	66-74	>74	<71	71-79	>79
>77	<66	66-75	>75	<71	71-80	>80

* L_{dn} is used for land use where nighttime sensitivity is a factor; L_{eq} during the hour of maximum transit noise exposure is used for land use involving only daytime activities.

Table 3-2 Land Use Categories and Metrics for Transit Noise Impact Criteria

Land Use Category	Noise Metric (dBA)	Description of Land Use Category
1	Outdoor $L_{eq}(h)^*$	Tracts of land where quiet is an essential element in their intended purpose. This category includes lands set aside for serenity and quiet, and such land uses as outdoor amphitheaters and concert pavilions, as well as National Historic Landmarks with significant outdoor use.
2	Outdoor L_{dn}	Residences and buildings where people normally sleep. This category includes homes, hospitals and hotels where a nighttime sensitivity to noise is assumed to be of utmost importance.
3	Outdoor $L_{eq}(h)^*$	Institutional land uses with primarily daytime and evening use. This category includes schools, libraries, and churches where it is important to avoid interference with such activities as speech, meditation and concentration on reading material. Buildings with interior spaces where quiet is important, such as medical offices, conference rooms, recording studios and concert halls fall into this category. Places for meditation or study associated with cemeteries, monuments, museums. Certain historical sites, parks and recreational facilities are also included.

* L_{eq} for the noisiest hour of transit-related activity during hours of noise sensitivity.

3.1.2 Defining the Levels of Impact

The noise impact criteria are defined by two curves which allow increasing project noise levels as existing noise increases up to a point, beyond which impact is determined based on project noise alone. Below the lower curve in Figure 3-1, a proposed project is considered to have no noise impact since, on the average, the introduction of the project will result in an insignificant increase in the number of people highly annoyed by the new noise. The curve defining the onset of noise impact stops increasing at 65 dB for Category 1 and 2 land use, a standard limit for an acceptable living environment defined by a number of Federal agencies. Project noise above the upper curve is considered to cause Severe Impact since a significant percentage of people would be highly annoyed by the new noise. This curve flattens out at 75 dB for Category 1 and 2 land use, a level associated with an unacceptable living environment. As indicated by the right-hand scale on Figure 3-1, the project noise criteria are 5 decibels higher for Category 3 land uses since these types of land use are considered to be slightly less sensitive to noise than the types of land use in categories 1 and 2.

Between the two curves the proposed project is judged to have an impact, though not severe. The change in the cumulative noise level is noticeable to most people, but may not be sufficient to cause strong, adverse reactions from the community. In this transitional area, other project-specific factors must be considered to determine the magnitude of the impact and the need for mitigation, such as the predicted level of increase over existing noise levels and the types and numbers of noise-sensitive land uses affected.

Although the curves in Figure 3-1 are defined in terms of the project noise exposure and the existing noise exposure, it is important to emphasize that it is the increase in the cumulative noise – when project is added to existing – that is the basis for the criteria. The complex shapes of the curves are based on the considerations of cumulative noise increase described in Appendix A. To illustrate this point, Figure 3-2 shows the noise impact criteria for Category 1 and 2 land use in terms of the allowable increase in the cumulative noise exposure. The horizontal axis is the existing noise exposure and the vertical axis is the increase in cumulative noise level due to the transit project. The measure of noise exposure is L_{dn} for residential areas and L_{eq} for land uses that do not have nighttime noise sensitivity. Since L_{dn} and L_{eq} are measures of total acoustic energy, any new noise source in a community will cause an increase, even if the new source level is less than the existing level. Referring to Figure 3-2, it can be seen that the criterion for Impact allows a noise exposure increase of 10 dBA if the existing noise exposure is 42 dBA or less but only a 1 dBA increase when the existing noise exposure is 70 dBA.

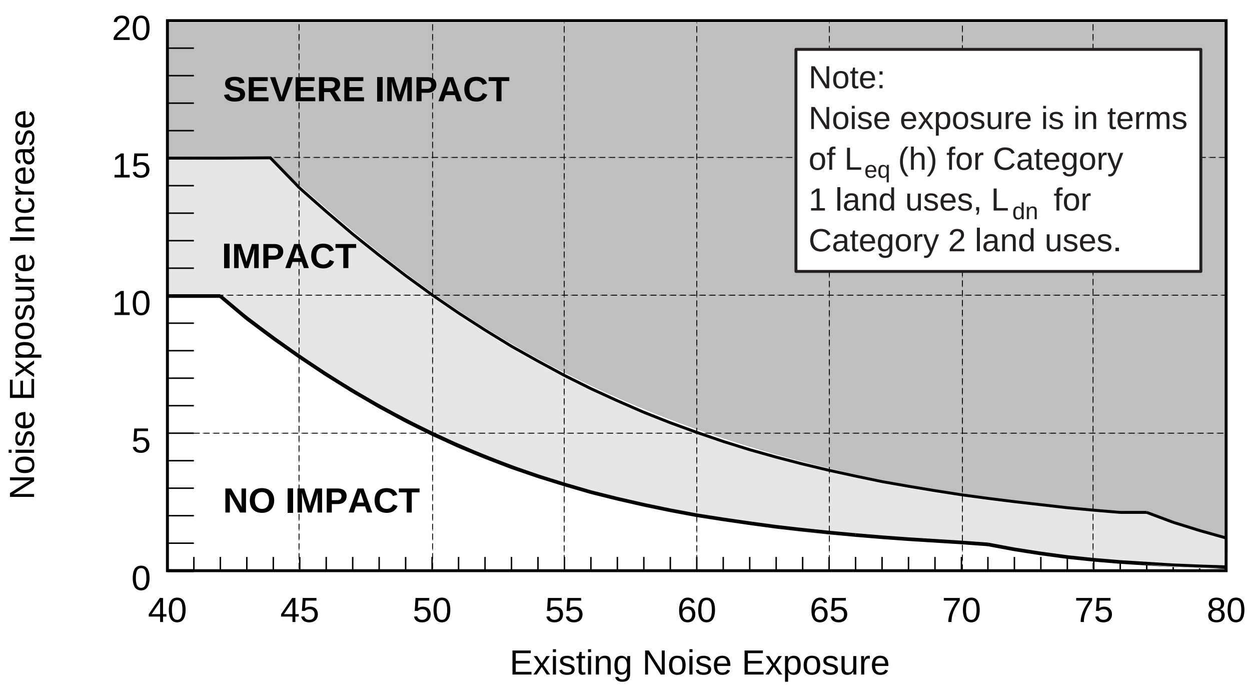

Figure 3-2 Increase in Cumulative Noise Levels Allowed by Criteria (Land Use Cat. 1 & 2)

As the existing level of ambient noise increases, the allowable level of transit noise increases, but the total amount that community noise exposure is allowed to increase is reduced. This accounts for the unexpected result that a project noise exposure which is less than the existing noise exposure can still cause Impact. This is clearer from the examples given in Table 3-3 which indicate the level of transit noise allowed for different existing levels of exposure.

Table 3-3 Noise Impact Criteria: Effect on Cumulative Noise Exposure			
L_{dn} or L_{eq} in dBA (rounded to nearest whole decibel)			
Existing Noise Exposure	**Allowable Project Noise Exposure**	**Allowable Combined Total Noise Exposure**	**Allowable Noise Exposure Increase**
45	51	52	7
50	53	55	5
55	55	58	3
60	57	62	2
65	60	66	1
70	64	71	1
75	65	75	0

Any increase greater than shown above in Table 3-3 will cause Impact. This table shows that as the existing noise exposure increases from 45 dBA to 75 dBA, the allowed transit noise exposure increases from 51 dBA to 65 dBA. However, the allowed increase in the cumulative noise level decreases from 7 dBA to 0 dBA (rounded to the nearest whole decibel). The justification for this is that people already exposed to high levels of noise will notice and be annoyed by only a small increase in the amount of noise in their community. In contrast, if the existing noise levels are quite low, a greater change in the community noise will be required for the equivalent level of annoyance. It should be noted that these annoyance levels are based on general community reactions to noise at varying levels which have been documented in scientific literature and do not account for specific community attitudinal factors which may exist.

3.2 APPLICATION OF NOISE IMPACT CRITERIA

3.2.1 Noise-Sensitive Land Uses

As indicated in Section 3.1.1, the noise impact criteria and descriptors depend on land use, designated either Category 1, Category 2 or Category 3. Category 1 includes tracts of land where quiet is an essential element in their intended purpose, such as outdoor concert pavilions or National Historic Landmarks where outdoor interpretation routinely takes place. Category 2 includes residences and buildings where people sleep, while Category 3 includes institutional land uses with primarily daytime and evening use such as schools, places of worship and libraries.

The criteria do not apply to most commercial or industrial uses because, in general, the activities within these buildings are compatible with higher noise levels. They do apply to business uses which depend on quiet as an important part of operations, such as sound and motion picture recording studios.

Historically significant sites are treated as noise-sensitive depending on the land use activities. Sites of national significance with considerable outdoor use required for site interpretation would be in Category 1.

Historical sites that are currently used as residences will be in Category 2. Historic buildings with indoor use of an interpretive nature involving meditation and study fall into Category 3. These include museums, significant birthplaces and buildings in which significant historical events occurred.

Most busy downtown areas have buildings which are historically significant because they represent a particular architectural style or are prime examples of the work of an historically significant designer. If the buildings or structures are used for commercial or industrial purposes and are located in busy commercial areas, they are not considered noise-sensitive and the noise impact criteria do not apply. Similarly, historical transportation structures, such as terminals and railroad stations, are not considered noise-sensitive land uses themselves. These buildings or structures are, of course, afforded special protection under Section 4(f) of the DOT Act and Section 106 of the National Historic Preservation Act. However, based strictly on how they are used and the settings in which they are located, these types of historical buildings are not considered noise-sensitive sites.

While parks are considered in general to be noise-sensitive sites, there are cases where actual noise-sensitivity depends on how the park is being used. Parks used for passive purposes such as reading, meditation and conversation would be considered more noise sensitive than ones used for sports or other active recreational pursuits.

3.2.2 Noise Metrics

The basis for the development of the noise impact criteria (see Appendix A) has been the relationship between the percentage of highly annoyed people and the noise levels of their residential environment. Consequently, the criteria are centered around residential land use with the use of L_{dn} as the noise descriptor sensitive to noise intrusion at night. The noise criteria use L_{dn} for other land uses where nighttime sensitivity is a factor. The criteria are also to be applied to non-residential land uses that are sensitive to noise during daytime hours. Because the L_{dn} and the maximum daytime hourly L_{eq} have similar values for a typical noise environment, the daytime or early evening L_{eq} can be used for evaluating noise impact at locations where nighttime sensitivity is not a factor. For land use involving only daytime activities (e.g. churches, schools, libraries, parks) the impact is evaluated in terms of L_{eq}(h), defined as the L_{eq} for the noisiest hour of transit-related activity during which human activities occur at the noise-sensitive location.

However, due to the types of land use included in Category 3, the criteria allow the project noise for Category 3 sites to be 5 decibels greater than for Category 1 and Category 2 sites. With the exception of recreational facilities, which are clearly less sensitive to noise than Category 1 and 2 sites, Category 3 sites include primarily indoor activities and thus the criteria account for the noise reduction provided by the building structure.

Although the maximum noise level (L_{max}) is not used in this manual as the basis for the noise impact criteria for transit projects, it is a useful metric for providing a fuller understanding of the noise impact from some transit operations. Specifically, rail transit characteristically produces high intermittent noise levels which may be objectionable depending on the distance from the alignment. Thus, it is recommended that L_{max} information be provided in environmental documents to supplement the noise impact assessment and to help satisfy the "full disclosure" requirements of NEPA. Procedures for computing the L_{max} for a single train passby are provided in Appendix E.

3.2.3 Considerations in Applying the Noise Impact Criteria

The procedure for assessing impact is to determine the existing noise exposure and the predicted project noise exposure at a given site, in terms of either L_{dn} or L_{eq}(h) as appropriate, and to plot these levels on Figure 3-1. The location of the plotted point in the three impact ranges is an indication of the magnitude of the impact. For simplicity, noise impact can also be determined by using Table 3-1, rounding all noise level values to the nearest whole decibel before using the table. This level of precision is sufficient for determining the degree of noise impact at specific locations and should be adequate for most applications. However, a more precise determination of noise impact may be appropriate in some situations, such as when estimating the distance from the project to which noise impact extends. In such cases, more precise noise limits can be determined using the criteria equations provided in Appendix A.

The noise criteria are to be applied outside the *building locations* for residential land use and at the *property line* for parks and other significant outdoor use. However, for locations where land use activity is solely indoors, noise impact may be less significant if the outdoor-to-indoor reduction is greater than for typical buildings (about 25 dB with windows closed). Thus, if the project sponsor can demonstrate that this is the case, mitigation may not be needed.

It is important to note that the criteria specify a comparison of future project noise with existing noise and *not* with projections of future "no-build" noise exposure (i.e. without the project). Furthermore, it should be emphasized that it is not necessary nor recommended that existing noise exposure be determined by measuring at every noise-sensitive location in the project area. Rather, the recommended approach is to characterize the noise environment for "clusters" of sites based on measurements or estimates at representative locations in the community. In view of the sensitivity of the noise criteria to the existing noise exposure, careful characterization of pre-project ambient noise is important. Guidelines for selecting representative receiver locations and determining ambient noise are provided in Appendix B and Appendix C, respectively.

3.2.4 Mitigation Policy Considerations

The Federal Transit Administration does not have a specific noise mitigation policy embodied in a regulation. Rather, the following statutes and implementing regulations concerning environmental protection guide the agency's decision on the need for noise mitigation. While many people are familiar with the environmental impact statement requirement in the National Environmental Policy Act (NEPA), the statute also establishes a broad mandate for Federal agencies to incorporate environmental protection and enhancement measures into the programs and projects they help finance.[1] In conjunction with FHWA, FTA has issued a regulation implementing NEPA which sets out the agencies' general policy on environmental mitigation. There, it states that measures necessary to mitigate adverse impacts are to be incorporated into the project and, further, that such measures are eligible for Federal funding when FTA determines that "...the proposed mitigation represents a reasonable public expenditure after considering the impacts of the action and the benefits of the proposed mitigation measures."[2]

While NEPA provides broad direction, a more explicit statutory basis for mitigating adverse noise impacts is contained in the Federal Transit Laws.[3] Before approving a construction grant under section 5309, FTA must make a finding that "... (ii) the preservation and enhancement of the environment, and the interest of the community in which a project is located, were considered; and (iii) no adverse environmental effect is likely to result from the project, or no feasible and prudent alternative to the effect exists and all reasonable steps have been taken to minimize the effect." (49 U.S.C. 5324 (b) (3)).

3.3 NOISE IMPACT CRITERIA FOR HIGHWAY/TRANSIT PROJECTS

When mass transit projects are integrated with modified or newly-constructed highways (e.g., exclusive bus/HOV lanes constructed within or alongside a highway), noise impact should be determined using existing FHWA assessment procedures and noise abatement guidelines.

FHWA criteria appear in the Code of Federal Regulations[4] and are supplemented by several FHWA advisory memoranda (references 5 through 11). FHWA noise policies and guidelines are expected to be updated and reissued during 1995. The following sections summarize these criteria and their use.

3.3.1 FHWA Impact Criteria

FHWA requires assessment at affected existing activities, developed lands, and undeveloped lands for which development is planned, designed and programmed. At these locations, traffic noise is computed for the project's design year, which is often 20 years from the onset of environmental studies. Used for this computation is traffic for the hour with the worst impact "on a regular basis." In practice, traffic engineers often predict traffic volumes and speeds at several times during an average design-year day, and then noise computations decide the "worst" hour. Because assessment is for a single hour rather than for a 24-hour period, the noise metric is an hourly one. FHWA allows either L_{eq}(h) or L_{10}(h).*

FHWA requires two assessments of noise impact: one related to land-use type and the other to existing noise level. First, noise impact occurs when predicted traffic noise levels approach or exceed the applicable Noise Abatement Criteria (NAC) in Table 3-4. FHWA allows individual state highway agencies to define "approach," as long as it is at least one decibel less than the applicable NAC.

In this table, FHWA requires that primary consideration be given to exterior areas (Activity Categories A, B and C). The table's interior NAC (Category E) is used only where either (1) there are no affected exterior activities or (2) exterior activities are not impacted because they are far from or are physically shielded from the roadway.

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*L_{10}(h) is defined as the A-weighted sound level exceeded for 10% of the hour.

Table 3-4 FHWA Noise Abatement Criteria			
Activity Category	**Hourly A-weighted Sound Level (dBA)**		**Description of Activity Category**
	L_{eq}(h)	**L_{10}(h)**	
A	57 Exterior	60 Exterior	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B	67 Exterior	70 Exterior	Picnic areas, recreation areas, playgrounds, active sports areas, parks, residences, motels, hotels, schools, churches, libraries, and hospitals.
C	72 Exterior	75 Exterior	Developed lands, properties, or activities not included in Categories A or B above.
D	--	--	Undeveloped lands.
E	52 Interior	55 Interior	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, and auditoriums.

In addition, noise impact is considered to occur when predicted traffic noise levels substantially exceed existing noise levels (not future no-build noise levels). FHWA allows individual state highway agencies to define "substantial." Most states consider an increase of 10-15 decibels to be substantial.

3.3.2 Use of Impact Criteria

When impact occurs by either method of assessment, NAC or substantial increase, FHWA requires study of the following noise abatement measures: traffic management, alteration of horizontal and vertical alignments, noise barriers whether within or outside the right-of-way, acquisition of buffer zones, noise insulation of public-use or nonprofit institutional structures. Measures which are reasonable and feasible are to be incorporated in the project.

Feasibility. Feasibility deals with engineering considerations. To be feasible, an abatement measure must first meet all safety, maintenance and other accepted design requirements. After safety/maintenance issues are resolved – they usually can during detailed design, according to FHWA – then FHWA considers a noise-abatement measure to be feasible if that measure can technically achieve a noise reduction of 5 decibels or more, given its physical aspects and those of its surroundings. Such acoustical feasibility is objective, not subjective. It is a matter of acoustical computation, depending upon such factors as topography, location of other nearby sound sources, and location of driveways, ramps, and cross streets.

Reasonableness. In the context of FHWA regulations, reasonableness is a more subjective matter. Reasonableness implies that common sense and good judgment were applied in arriving at a decision concerning the abatement measure. Explicitly, FHWA requires that (1) the views of the impacted residents be a major consideration, and (2) the overall noise abatement benefits outweigh the overall adverse social, economic, and environmental effects, as well as the abatement cost.

Reasonableness also depends upon community wishes, aesthetics, community desires for their surrounding view, projected noise-level increase above existing levels, projected noise-level increase above no-build levels, amount of development that occurred before and after the initial construction of the highway, type of protected development, effectiveness of land-use controls by local jurisdiction, construction effects of the abatement measure on the natural environment, and the potential ability of the abatement measure to reduce noise during project construction, as well.

Reasonableness also depends upon cost effectiveness. It encourages state highway agencies to develop quantitative cost-effectiveness guidelines, which generally consider abatement cost, the number of people protected by the abatement measure, and the amount of noise reduction provided by the abatement measure.

Noise insulation of private residences. As mentioned above, FHWA participates in funding "noise insulation of public use or nonprofit institutional structures." On the other hand, noise insulation of private residences is not normally funded by FHWA. Instead, the agency acknowledges that there may be situations where (1) severe traffic noise impacts exist or are expected, and (2) the abatement measures listed above are physically infeasible or economically unreasonable. In these instances, noise abatement measures other than those listed may be proposed by the highway agency and approved by the FHWA on a case-by-case basis.

REFERENCES

1. United States Congress, National Environmental Policy Act of 1969; P.L. 91-190, January 1, 1970.

2. U.S. Department of Transportation, Federal Transit Administration and Federal Highway Administration, "Environmental Impact and Related Procedures." Final Rule, 52 Federal Register 32646-32669; August 28, 1987 (23 Code of Federal Regulations 771.105(d)).

3. 49 U.S.C. 5301 et seq.

4. Federal Highway Administration. *23 CFR Part 772: Procedures for Abatement of Highway Traffic Noise and Construction Noise* -- *Final rule*. Federal Register, Vol. 47, No. 131, 8 July 1982.

5. Ali F. Sevin, Director, Office of Environmental Policy, (now the Office of Environment and Planning), Federal Highway Administration, "Memorandum: Traffic Noise Analysis for Highway Projects Which Add Through-Traffic Lanes." 5 May 1987.

6. Ali F. Sevin, Director, Office of Environmental Policy, Federal Highway Administration, "FHWA Technical Advisory T 6640.8A Guidance for Preparing and Processing Environmental and Section 4(F) Documents." 30 October 1987.

7. Office of Environmental Policy, Noise and Air Analysis Division, Federal Highway Administration, Discussion Paper: Appropriate Level of Highway Traffic Noise Analysis for CE, EA/FONSI, and EIS." June 1989.

8. Office of Environmental Policy, Noise and Air Analysis Division, Federal Highway Administration, "Field Review Report: Highway Traffic Noise Impact Identification and Mitigation Decisionmaking." June 1989.

9. Kevin E. Heanue (HEP-41), Director, Office of Environment and Planning, Federal Highway Administration. *Memorandum: INFORMATION: Highway Traffic Noise Analysis: Reasonableness and Feasibility of Abatement.* 18 June 1992.

10. Kevin E. Heanue (HEP-41), Director, Office of Environment and Planning, Federal Highway Administration. *Memorandum: ACTION: Guidance for Traffic Noise Analysis.* 1 December 1993.

11. Kevin E. Heanue (HEP-41), Director, Office of Environment and Planning, Federal Highway Administration, *Memorandum: INFORMATION: Highway Traffic Noise.* 12 August 1994. "Highway Traffic Noise in the United States: Problem and Response."

4. NOISE SCREENING PROCEDURE

The noise screening procedure is designed to identify locations where a project has little possibility of noise impact. If no noise-sensitive land uses are present within a defined area of project noise influence, then no further noise assessment is necessary. This approach allows the focusing of further noise analysis on locations where impacts are likely. The screening procedure takes account of the noise impact criteria, the type of project and noise-sensitive land uses. For screening purposes, all noise-sensitive land uses are considered to be in a single category.

4.1 SCREENING DISTANCES

The distances given in Table 4-1 delineate a project's noise study area. The areas defined by the screening distances are sufficiently large to encompass all potentially impacted locations. They were determined using scenarios that were conservative in terms of operating characteristics and source levels. This was done by estimating noise characteristics during maximum operations of a given project type and using the lowest threshold of impact from Chapter 3.

The noise screening procedure is applicable to all types of transit projects. The types of projects listed in Table 4-1 cover nearly all of the kinds of projects expected to undergo environmental assessment. Clarification can be obtained from FTA on any special cases that are not represented in the table.

4.2 STEPS IN SCREENING PROCEDURE

The screening method works as follows:

1. Determine the type of project and locate on Table 4-1.

2. Determine the appropriate column under Screening Distance in Table 4-1. If buildings occur in the sound paths, then use the distances under Intervening Buildings. Otherwise use the distances under "Unobstructed."

3. Note the distance in feet for that project in Table 4-1. Apply this distance from the guideway centerline or nearest right-of-way line on both sides of a highway or access road. In the case of a fixed facility, apply the distance from the center of noise-generating activity for the project site.

4. Within the distance noted above, locate any of the noise-sensitive land uses listed in Table 3-2.

5. If it is determined that none of the listed land uses are within the distances noted in Table 4-1, then no further noise analysis is needed. On the other hand, if one or more of the noise-sensitive land uses are within the screening distances noted in Table 4-1 then further analysis is needed and the procedure described in Chapter 5 is followed.

Table 4-1 Screening Distances for Noise Assessments			
Type of Project		**Screening Distance* (ft)**	
		Unobstructed	**Intervening Buildings**
***Fixed Guideway Systems*:**			
Commuter Rail Mainline		750	375
Commuter Rail Station		450	225
Rail Transit Guideway		700	350
Rail Transit Station		200	100
Access Roads		100	50
Low- and Intermediate-Capacity Transit	Steel Wheel	200	100
	Rubber Tire	125	75
	Monorail	300	150
Yards and Shops		2000	1000
Parking Facilities		150	75
Access Roads		100	50
Ancillary Facilities			
Ventilation Shafts		200	100
Power Substations		250	125
***Bus Systems*:**			
Busway		500	250
Bus Facilities	Access Roads	100	50
	Transit Mall	250	125
	Transit Center	300	150
	Storage & Maintenance	1000	500
	Park & Ride Lots	300	150

* Measured from centerline of guideway/roadway for mobile sources; from center of noise-generating activity for stationary sources.

5. GENERAL NOISE ASSESSMENT

This chapter contains procedures for the computation of both project and existing ambient noise levels for use in noise assessments required beyond the stage of the screening procedure of Chapter 4.

The **Screening Procedure** described in Chapter 4 is used to determine whether any noise-sensitive receivers are within a distance where impact is likely to occur. The distance given in the table defines the study area of any subsequent noise impact assessment. Where there is potential for noise impact, the procedures of Chapters 5 and 6 will be used to determine the extent and severity of impact. In some cases, a general assessment may be all that is needed. On the other hand, if the proposed project is in close proximity to noise-sensitive land uses and it appears at the outset that the impact would be substantial, it is prudent to conduct a detailed noise analysis.

The **General Assessment** is used for a wide range of projects which show potential noise impact from the screening procedure. For a variety of smaller transit projects, a general assessment may be all that is needed to evaluate noise impact and propose mitigation measures where necessary. It is also used to compare alternatives, such as locations of facilities or alignments, or even candidate transportation modes. A General Assessment can provide the appropriate level of detail about noise impacts for a "corridor" or "sub-area" study which is undertaken during the planning of a major transportation investment. The procedure involves noise predictions commensurate with the level of detail of data available in the early stages of major investment planning. Estimates are made of project noise levels and of existing noise conditions to estimate the location of a noise impact contour, defining an impact corridor or area. An inventory of noise impacts within the area identifies locations where noise mitigation is likely and is used in comparing noise impact among alternatives. Noise mitigation policy considerations are discussed in Section 3.2.4 and the application of noise mitigation measures is described in Section 6.7.

Detailed Analysis is undertaken when the greatest accuracy is needed to assess impacts and the effectiveness of mitigation measures on a site-specific basis. In order to do this, the project must be defined to the extent that location, alignment, mode and operating characteristics are determined. Detailed Analysis is often accomplished during the preliminary engineering phase. The results of the Detailed Analysis would be used in predicting the effectiveness of noise mitigation measures on particular noise-sensitive receivers. The procedures for performing a Detailed Analysis are described in Chapter 6.

This chapter describes the procedure for performing a General Noise Assessment. The General Assessment is based on noise source and land use information likely to be available at an early stage in the project development process. Sections of this chapter cover the key elements of the prediction procedure:

- Section 5.2 describes how to predict noise source levels with preliminary estimations of the effect of mitigation.
- Section 5.3 covers a simplified procedure for estimating noise propagation characteristics assuming flat terrain, with approximate shielding by rows of buildings or other barriers.
- Section 5.4 includes a simplified procedure for estimating existing noise.
- Section 5.5 shows how to estimate the Noise Impact Contour that defines the approximate outer limit of noise impact.
- Section 5.6 describes how to conduct the noise impact inventory and how to present the information in an environmental document or a technical noise report.
- Two examples of General Assessments are given at the end of this chapter.

5.1 OVERVIEW

The steps in the General Noise Assessment are shown in Figure 5-1 and are described below. When several alternatives are evaluated in an environmental document, this approach can be applied to each alternative and the results compared.

Project Alternatives – Place the alternative under study into one of three categories, fixed guideway transit, highway/transit, or stationary facility. Determine the Source Reference Level from the tables in Section 5.2. Each Source Reference Level pertains to a typical operation for one hour for a stationary source or one vehicle passby under reference operating conditions. Each utilizes the SEL noise descriptor, as discussed in Chapter 2.

Operational Characteristics – Convert the Source Reference Level to Noise Exposure in terms of L_{eq}(h) or L_{dn} under approximate project operating conditions, using the appropriate equations depending upon the type of source. The noise exposure is determined at the reference distance of 50 feet.

Propagation Characteristics – Draw Noise Exposure vs. Distance Curve for this source, using the graphic in Section 5.3. This curve will show the source's noise exposure as a function of distance, ignoring shielding. To account for shielding attenuation from rows of buildings, use a general rule for estimating the reduction in noise level and draw an adjusted Exposure-vs-Distance Curve.

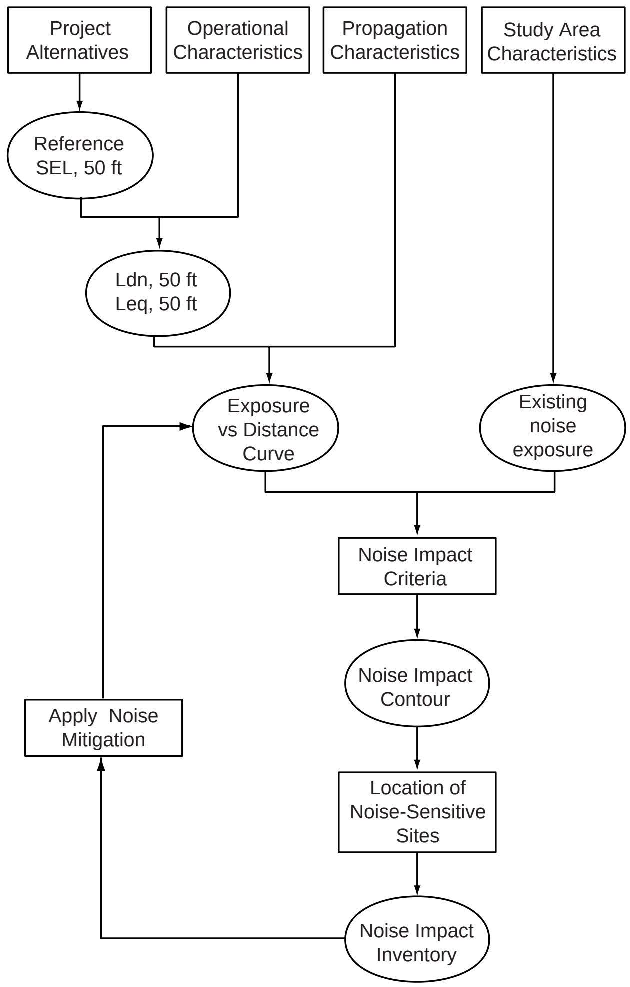


Figure 5-1. Procedure for General Noise Assessment

Study Area Characteristics – Estimate the existing noise exposure for areas surrounding the project from Table 5-7 in Section 5.4.

Noise Impact Contour Estimation – On a point-by-point basis, locate the project noise exposure and existing noise exposure combination that results in Impact according to the impact criteria from Chapter 3. Connect the points to obtain a contour line around the project which signifies the outer limits of Impact.

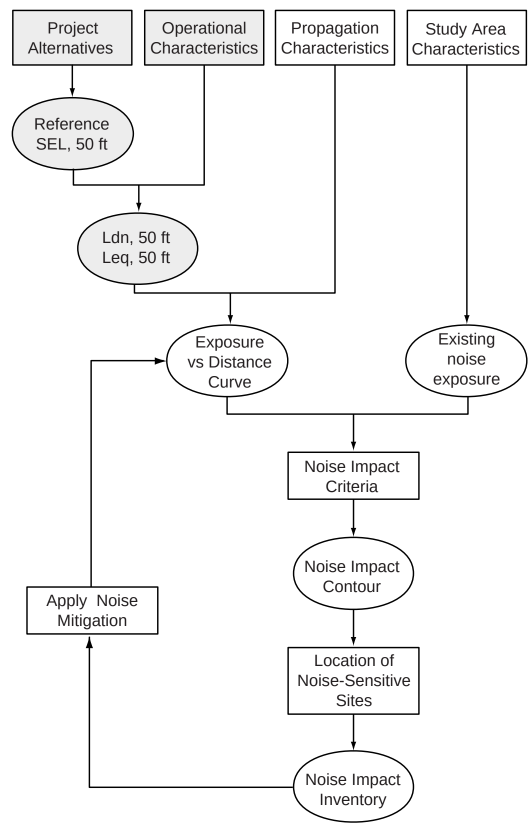
Alternatively, in the case where it is desired to make a comparison among different modal alternatives, specific noise contours can be determined from the Exposure-vs-Distance curves (for example, 60dB, 65dB, 70dB contours).

Noise Impact Inventory – Tabulate noise-sensitive land uses within the specific contours using general assumptions for shielding attenuation from rows of buildings.

Noise Mitigation – Apply estimates of the noise reduction from mitigation in the community areas where potential impact has been identified and repeat the tabulation of noise impacts.

5.2 NOISE SOURCE LEVELS FOR GENERAL ASSESSMENT

The General Noise Assessment procedure begins by determining the project noise exposure at a reference distance for the various project alternatives. The steps involved in this calculation are shaded in the flow chart at right. The reference noise exposure estimation procedures differ depending on the type of project (fixed guideway, highway/transit, or stationary facility) as described in the following sections.



5.2.1 Fixed Guideway Transit Sources

Fixed guideway transit sources include commuter rail, rail rapid transit, light rail transit, automated guideway transit (AGT), monorail, and magnetically levitated vehicles (maglev). The noise characteristics of each depend on the system characteristics described in Chapter 2. At an early project stage, the information available includes:

- Candidate transit mode
- Guideway options
- Time of operation
- Operational headways
- Design speed
- Alternative alignments.

This information is not sufficient to predict noise levels at all locations along the right-of-way, but by using conservative estimates (for example, maximum design speeds and operations at design capacities) it is sufficient to estimate worst case noise impact contours.

Reference Levels in SEL – The procedure starts with predicting the source noise levels, expressed in terms of SEL at a reference distance and a reference speed. These are given in Table 5-1 below.

The reference SEL's are used in the equations of Table 5-2 to predict the noise exposure at 50 feet. Also shown in Table 5-2 are rough estimates of the noise reduction available from wayside noise barriers, the most common noise mitigation measure. See Chapter 6 for a complete description of the benefits resulting from noise mitigation. The approximate noise barrier lengths and locations developed in a General Assessment provide a preliminary basis for evaluating the costs and benefits of impact mitigation.

Table 5-1 Reference SEL's at 50 feet from Track and 50 mph

Source / Type		**Reference Conditions**	**Reference SEL (SEL_{ref}), dBA**
Commuter Rail, At-Grade	Locomotives	Diesel-electric, 3000 hp, throttle 5	92
		Electric	90
	Cars	Ballast, welded rail	82
Rail Transit		At-grade, ballast, welded rail	82
AGT	Steel wheel	Aerial, concrete, welded rail	80
	Rubber Tire	Aerial, concrete guideway	78
Monorail		Aerial straddle beam	82
Maglev		Aerial, open guideway	72

Noise Exposure at 50 feet – After determining the reference levels for each of the noise sources, the next step is to determine the noise exposure at 50 feet expressed in terms of $L_{eq}(h)$ and L_{dn}. The additional data needed include:

- Number of train passbys during the day (defined as 7am to 10 pm) and night (defined as 10 pm to 7 am).
- Maximum number of train passbys during hours that Category 1 or Category 3 land uses are normally in use. This is usually the peak hour train volume.
- Number of vehicles per train (if this number varies during the day, take the average).
- Speed (maximum expected).
- Guideway configuration.
- Noise barrier location (if noise mitigation is determined necessary at the end of the first pass on the General Assessment).

These data are used in the equations in Table 5-2 to obtain adjustment factors to calculate L_{dn} and $L_{eq}(h)$ at 50 feet.

Table 5-2 Computation of Noise Exposure at 50 feet for Fixed Guideway General Assessment

LOCOMOTIVES Hourly L_{eq} at 50 ft:	$L_{eqL}(h) = SEL_{ref} + 10\log(N_{locos}) - 10\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$
RAIL VEHICLES[†] Hourly L_{eq} at 50 ft:	$L_{eqC}(h) = SEL_{ref} + 10\log(N_{cars}) + 20\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$ use the following adjustments as applicable: + 5 → JOINTED TRACK + 3 → EMBEDDED TRACK ON GRADE + 4 → AERIAL STRUCTURE WITH SLAB TRACK (except AGT & monorail) - 5 → if a NOISE BARRIER blocks the line of sight
COMBINED Hourly L_{eq} at 50 ft:	$L_{eq}(h) = 10\log\left[10^{\left(L_{eqL}/10\right)} + 10^{\left(L_{eqC}/10\right)}\right]$
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = L_{eq}(h)\Big\vert_{V=V_d}$
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = L_{eq}(h)\Big\vert_{V=V_n}$
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\times10^{\left(L_{eq}(day)/10\right)} + (9)\times10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$

N_{locos} = average number of locomotives per train

N_{cars} = average number of cars per train

S = train speed, in miles per hour

V = average hourly volume of train traffic, in trains per hour

V_d = average hourly daytime volume of train traffic, in trains per hour

$$= \frac{\text{number of trains, 7 am to 10 pm}}{15}$$

V_n = average hourly nighttime volumes of train traffic, in trains per hour

$$= \frac{\text{number of trains, 10 pm to 7 am}}{9}$$

[†] Includes all commuter rail cars, transit cars, AGT and monorail

5.2.2 Highway/Transit Sources

The highway/transit type sources include most transit modes that do not require a fixed guideway. Examples are high occupancy vehicles, such as city bus, commuter bus, commuter vanpools and carpools. The noise characteristics of each depend on the system characteristics described in Chapter 2. At an early project development stage, the information available is as follows:

- Vehicle type
- Transitway design options
- Time of operation
- Typical headways
- Design speed
- Alternative alignments.

This information is not sufficient to predict noise levels at all locations along the right-of-way, but is sufficient to estimate worst case noise impact contours. The procedure is consistent with the highway noise prediction method authorized by the Federal Highway Administration (see Section 6.6.2 for a discussion of detailed FHWA computation methods), with commuter buses, city buses and vans corresponding to source emission levels for heavy trucks, medium trucks and automobiles, respectively.[1]

Reference Levels in SEL – Projections of noise from highway/transit sources begin by defining the source SEL at a reference distance of 50 feet and a reference speed. These are given in Table 5-3. The reference distance SEL's are used in the equations of Table 5-4 to predict the noise exposure at 50 feet. Also shown in Table 5-4 is a rough estimate of the minimum noise reduction available with wayside sound barriers. See Chapter 6 for descriptions of other mitigation measures and procedures for developing more accurate estimates of noise reduction from mitigation measures. The approximate noise barrier lengths and locations developed in a General Assessment allow preliminary estimates of the costs and benefits of impact mitigation.

Noise Exposure at 50 feet – After determining the reference levels for each of the noise sources, the next step is to determine the noise exposure at 50 feet. The additional data needed include:

- Number of vehicle passbys during the day (7am to 10 pm) and night (10 pm to 7 am).
- Number of vehicle passbys during hours that Category 1 or Category 3 land uses are normally in use.
- Speed (maximum expected).
- Transitway configuration (with or without noise barrier).

These data are used in the equations in Table 5-4 with the reference SEL's to calculate $L_{eq}(h)$ and L_{dn} at 50 feet.

Table 5-3 Source Reference Levels at 50 Feet from Roadway, 50 mph

Source[†]	**Reference SEL (dBA)**
Automobiles and Vans	73
City Buses	84
Commuter Buses	88

† Assumes normal roadway surface conditions

Table 5-4 Computation of L_{eq} and L_{dn} at 50 feet for Highway/Transit General Assessment

Hourly L_{eq} at 50 ft:	$L_{eq}(h) = SEL_{ref} + 10\log(V) + C_S \log\left(\frac{S}{50}\right) - 35.6$
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = L_{eq}(h)\big\vert_{V=V_d}$
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = L_{eq}(h)\big\vert_{V=V_n}$
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$
Speed Constant:	$C_S = 14.6$, Commuter Buses $= 23.9$, City Buses $= 28.1$, Automobile and van pools
Adjustment:	- 5 Noise Barrier

$V =$ hourly volume of vehicles of this type, in vehicles per hour.

$V_d =$ average hourly daytime volume of vehicles of this type, in vehicles per hour

$$= \frac{\text{total vehicle volume, 7 am to 10 pm}}{15}$$

$V_n =$ average hourly nighttime volume of vehicles of this type, in vehicles per hour

$$= \frac{\text{total vehicle volume, 10 pm to 7 am}}{9}$$

$S =$ average vehicle speed, in miles per hour

5.2.3 Stationary Sources

This section covers the general approach to assessment of noise from fixed facilities associated with a transit system. New transit facilities undergo a site review for best location which includes consideration of the noise sensitivity of surrounding land uses. Although many facilities, such as bus maintenance garages, are usually located in industrial and commercial areas, some facilities such as bus terminals, train stations and park and ride lots may be placed near residential neighborhoods where noise impact may occur. Access roads to some of these facilities may also pass through noise-sensitive areas. In a general assessment, only the salient features of each fixed facility are considered in the noise analysis.

Reference Levels in SEL – The source reference levels given in Table 5-5 are determined based on measurements for the peak hour of operation of a typical stationary source of the type and size noted. A large facility, such as a rail yard, is spread out over considerable area with various noise levels depending on the layout of the facility. Specifying the reference SEL at a distance of 50 feet from the property line would be misleading in this case. Consequently, the reference distance is described as "the equivalent distance of 50 feet," which is determined by estimating the noise levels at a greater distance and projecting back to 50 feet, assuming the noise sources are concentrated at the center of the site. If the location of noise sources is known, then the distance should be taken from the point of the noisiest activity on the site. The reference SEL’s are used in the equations of Table 5-6 to predict noise exposure at an equivalent distance of 50 feet from the center of the site. Noise from access roads is treated according to the procedures described in Section 5.2.2.

Table 5-6 also includes an estimate of the minimum noise reduction available with wayside noise barriers. Only approximate locations and lengths for barrier or other noise mitigation measures are developed during a General Assessment to provide a preliminary indication of the costs and benefits of mitigation.

Noise Exposure at Equivalent Distance of 50 feet – After determining the reference SEL's for each of the noise sources, the next step is to determine the noise exposure expressed in terms of L_{eq} and L_{dn} at an equivalent distance of 50 feet. The additional data needed include:

- Number of layover tracks and hours of use.
- Number of buses, if different from assumed reference conditions (if this number varies during the day, take the average).
- Actual capacity of parking garage or lot.

These data are used in the equations in Table 5-6 with the reference SEL's to calculate $L_{eq}(h)$ and L_{dn} at an equivalent distance of 50 feet.

Table 5-5 Source Reference Levels at 50 Feet from Center of Site, Stationary Sources		
Source	**Reference SEL (dBA)**	**Reference Conditions**
Rail System:		
Yards and Shops	118	20 train movements in peak activity hour
Layover Tracks (commuter rail)	116	One train with diesel locomotive idling for one hour
Bus System:		
Storage Yard	111	100 buses accessing facility in peak activity hour
Operating Facility	114	100 buses accessing facility, 30 buses serviced and cleaned in peak activity hour
Transit Center	101	20 buses in peak activity hour
Parking Garage	92	1000 cars in peak activity hour
Park & Ride Lot	101	12 buses, 1000 cars in peak activity hour

Table 5-6 Computation of L_{eq} and L_{dn} at 50 feet for Stationary Source General Assessment

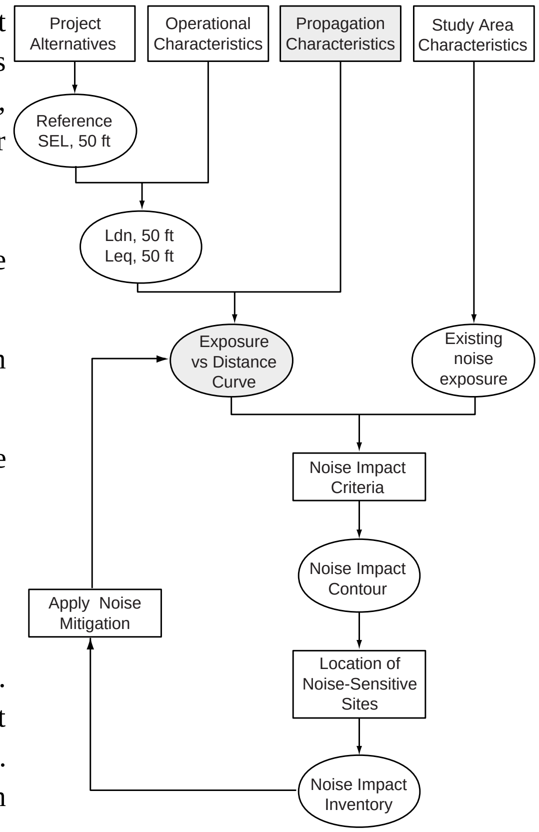
Hourly L_{eq} at 50 ft:	$L_{eq}(h) = SEL_{ref} + C_N - 35.6$	
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = 10\log\left[\left(\frac{1}{15}\right)\sum_{\text{7am-10pm}} 10^{L_{eq}(h)/10}\right]$	
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = 10\log\left[\left(\frac{1}{9}\right)\sum_{\text{10pm-7am}} 10^{L_{eq}(h)/10}\right]$	
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$	
Volume Adjustment:	$C_N = 10\log\left(\frac{N_T}{20}\right)$,	Rail Yards and Shops
	$= 10\log(2N_T)$,	Layover Tracks
	$= 10\log\left(\frac{N_B}{100}\right)$,	Bus Storage Yard
	$= 10\log\left(\frac{N_B}{200} + \frac{N_S}{60}\right)$,	Bus Operating Facility
	$= 10\log\left(\frac{N_B}{20}\right)$,	Bus Transit Center
	$= 10\log\left(\frac{N_A}{1000}\right)$,	Parking Garage
	$= 10\log\left(\frac{N_A}{2000} + \frac{N_B}{24}\right)$,	Park & Ride Lot
Other Adjustment:	-5	Noise Barrier at Property Line

N_T = Number of trains per hour
N_B = Number of buses per hour
N_S = Number of buses serviced and cleaned per hour
N_A = Number of automobiles per hour

Note: If any of these numbers is zero, then omit that term

5.3 COMPUTATION OF NOISE EXPOSURE VS. DISTANCE CURVES

The previous section results in estimates of noise exposure at 50 feet for each type of project. The following procedure is used to estimate the project noise exposure at other distances, resulting in a noise exposure vs. distance curve sufficient for use in a General Assessment. The procedure is as follows:



1. Determine the L_{dn} or L_{eq} at 50 feet for one of the three project types in Section 5.2.

2. Select the appropriate distance correction curve from Figure 5-2.

3. Apply the Distance Corrections ($C_{distance}$) to the noise exposure at 50 feet using:

$$L_{dn} \text{ (or } L_{eq}\text{)}\Big|_{\text{at new distance}} = L_{dn} \text{ (or } L_{eq}\text{)}\Big|_{\text{at 50 feet}} - C_{distance}$$

4. Plot the noise exposure curve as a function of distance. This curve will be used to determine the noise impact contour for the first row of unobstructed buildings. This plot can be used to display noise from both unmitigated and mitigated conditions in order to assess the benefits from mitigation measures.

5. For second row receivers and beyond, it is necessary to account for shielding attenuation from rows of intervening buildings. Without accounting for shielding, impact may be substantially over-estimated. Use the following general rules of thumb to determine the effect of shielding from intervening rows of buildings:

    - Assign -4.5 dB of shielding attenuation for the *first* row of intervening buildings only.

    - Assign -1.5 dB of shielding attenuation for each subsequent row, up to a maximum total attenuation of 10 dB.

    Figure 5-2 can then be used to develop a curve of noise exposure vs. distance when there is shielding. The curve of noise exposure as a function of this distance will be used to determine the location of the noise impact contours.

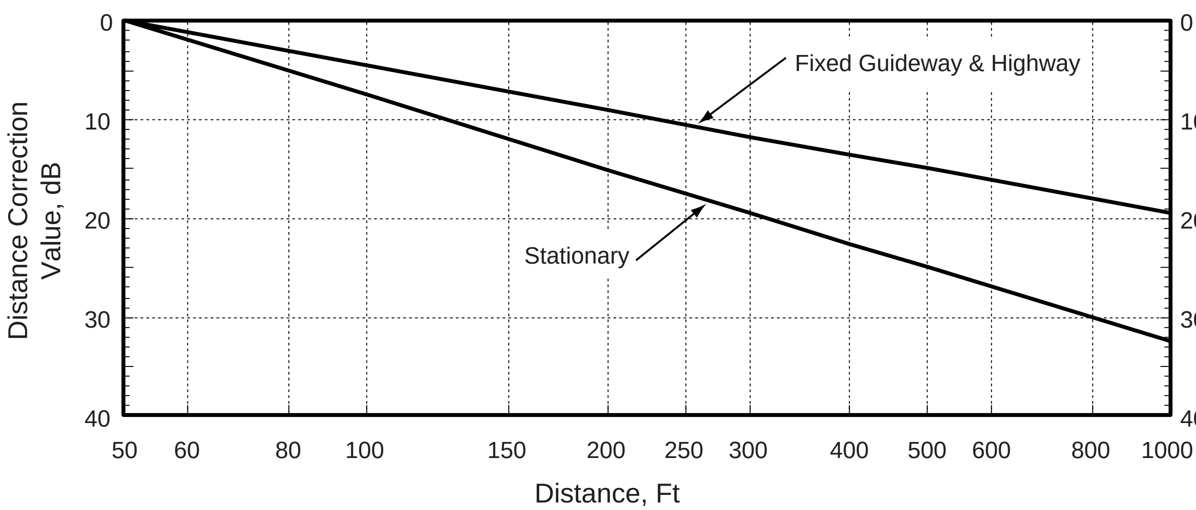
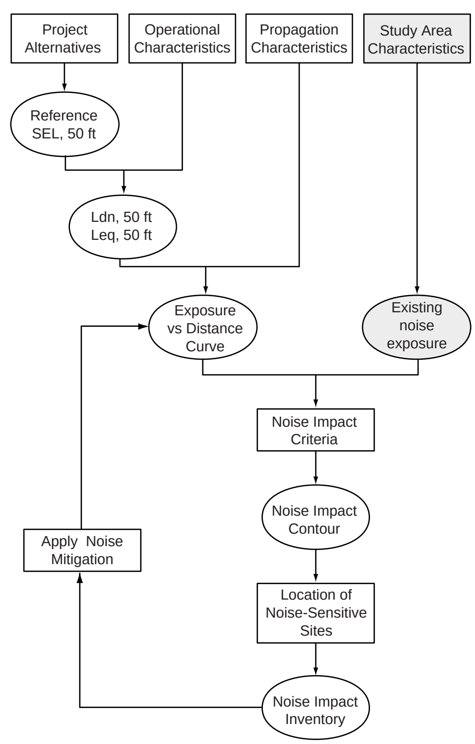


Figure 5-2. Curves for Estimating Exposure vs. Distance in General Noise Assessment

5.4 ESTIMATING EXISTING NOISE EXPOSURE



The existing noise in the vicinity of the project is required to determine the noise impact according to the criteria described in Chapter 3. Recall that impact is assessed based on a combination of the existing ambient noise exposure and the additional noise exposure that will be caused by the project. In the Detailed Analysis, the existing noise exposure is based on noise measurements at representative locations in the community. It is generally a good idea to base all estimates of existing noise on measurements, especially at locations known to be noise-sensitive. However, measurements are not always available at the General Assessment stage. This section describes how to estimate the existing noise in the project study area from general data available early in project planning. The procedure uses Table 5-7, where a neighborhood's existing noise exposure is based on proximity to nearby major roadways or railroads or on population density. The process is as follows:

1. Mapping: Obtain scaled mapping and aerial photographs showing the project location and alternatives. A scale of 1" = 200' or 400' is convenient for the accuracy needed in the noise assessment. The size of the base map should be sufficient to show distances of at least 1000' from the center of the alignment or property center, depending on whether the project is a guideway/roadway or a stationary facility.

2. Identify Sensitive Receivers: Review the maps, together with the most current land use information, to determine the proximity of noise-sensitive land uses to the project and to the nearest major roadways and railroad lines. When necessary, windshield surveys or more detailed land use maps may be used to confirm the location of sensitive receivers. For land uses more than 1000 feet from major roadways or railroad mainlines (see definitions in Table 5-7), obtain an estimate of the population density in the immediate area, expressed in people per square mile.

3. Use Table 5-7 to Estimate Existing Noise Exposure: Existing noise exposure is estimated by first looking at a site's proximity to major roads and railroad lines. If these noise sources are far enough away that ambient noise is dominated by local streets and community activities, then the estimate is made based on population density. The decision of which to use is made by comparing the noise levels from each of the three categories, roadways, railroads and population density, and selecting the highest level.

   Major roadways are separated into two categories: "Interstates," or roadways with four or more lanes that allow trucks; and "Others," parkways without trucks and city streets with the equivalent of 75 or more heavy trucks per hour or 300 or more medium trucks per hour. The estimated roadway noise levels are based on data for light to moderate traffic on typical highways and parkways using the FHWA highway noise prediction model. Where a range of distances is given, the predictions are made at the outer limit, thereby underestimating the traffic noise at the inner distance. For highway noise, distances are measured from the centerline of the near lane for roadways with two lanes, while for roadways with more than two lanes the distance is measured from the geometric mean of the roadway. This distance is computed as follows:

$$D_{GM} = \sqrt{(D_{NL})(D_{FL})}$$

   where D_{GM} is the distance to the geometric mean, D_{NL} and D_{FL} are distances to the nearest lane and farthest lane centerlines, respectively.

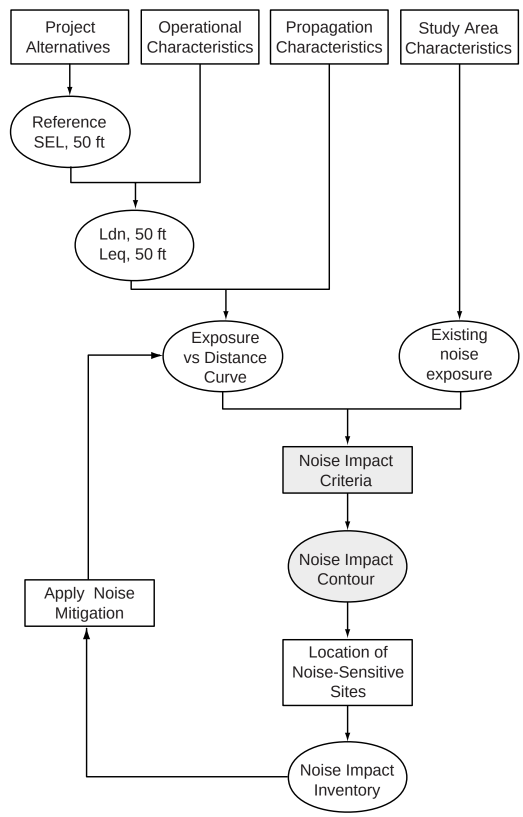
   For railroads, the estimated noise levels are based on an average train traffic volume of 5-10 trains per day at 30-40 mph for main line railroad corridors, and the noise levels are provided in terms of L_{dn} only. Distances are referenced to the track centerline, or in the case of multiple tracks, to the centerline of the rail corridor. Because of the intermittent nature of train operations, train noise will affect the L_{eq} only during certain hours of the day, and these hours may vary from day to day. Therefore, to avoid underestimating noise impact when using the one-hour L_{eq} descriptor, it is recommended that the L_{eq} at sites near rail lines be estimated based on nearby roadways or population density unless very specific train information is available.

In areas away from major roadways, noise from local streets or in neighborhoods is estimated using a relationship determined during a research program by the U.S. EPA.[2] EPA determined that ambient noise can be related to population density in locations away from transportation corridors, such as airports, major roads and railroad tracks, according to the following relation:

$$L_{dn} = 22 + 10\log(p) \qquad \text{(in dBA)}$$

where p = population density in people per square mile.

5.5 DETERMINING NOISE IMPACT CONTOURS



It is often desirable to draw noise impact contours on the land use map mentioned in the previous section to aid the impact inventory. Once the contours are on the map, the potential noise impacts can be estimated by counting the buildings inside the contours.

The first step is to identify the noise-sensitive neighborhoods and buildings and estimate existing noise exposure following the procedures described in Section 5.4. The estimate of existing noise exposure is used along with the Noise Impact Criteria in Figure 3-1 to determine how much additional noise exposure would need to be created by the project before there would be Impact or Severe Impact.

The next step is to determine the distances from the project boundary to the two impact levels using the noise exposure vs. distance curves from Section 5.3. Plot points on the map corresponding to those distances in the neighborhood under study. Continue this process for all areas surrounding the project. The plotted points are connected by lines to represent the Noise Impact Contours.

Alternatively, if it is desired to plot specific noise contours at, for example, 65 dBA, the distances can also be determined directly from the approach described in Section 5.3. Again, the points associated with a given noise level are plotted on the map and connected by lines to represent that contour.

Locations of points will change with respect to the project boundary as the existing ambient exposure changes, as project source levels change, and as shielding effects change. In general, the points should be placed close enough to allow a smooth curve to be drawn. For a General Assessment, the contours may be drawn through buildings and salient terrain features as if they were not present. This practice is acceptable considering the level of detail associated with a project in its early stages of development.

Table 5-7 Estimating Existing Noise Exposure for General Assessment

Distance from Major Noise Source[1] (feet)			Population Density (people per sq mile)	Noise Exposure Estimates			
Interstate Highways[2]	Other Roadways[3]	Railroad Lines[4]		L_{eq} Day	L_{eq} Evening	L_{eq} Night	L_{dn}
10 - 50				75	70	65	75
50 - 100				70	65	60	70
100 - 200				65	60	55	65
200 - 400				60	55	50	60
400 - 800				55	50	45	55
800 and up				50	45	40	50
	10 - 50			70	65	60	70
	50 - 100			65	60	55	65
	100 - 200			60	55	50	60
	200 - 400			55	50	45	55
	400 and up			50	45	40	50
		10 - 30		--	--	--	75
		30 - 60		--	--	--	70
		60 - 120		--	--	--	65
		120 - 240		--	--	--	60
		240 - 500		--	--	--	55
		500 - 800		--	--	--	50
		800 and up		--	--	--	45
			1 - 100	35	30	25	35
			100 - 300	40	35	30	40
			300 - 1000	45	40	35	45
			1000 - 3000	50	45	40	50
			3000 - 10000	55	50	45	55
			10000 - 30000	60	55	50	60
			30000 and up	65	60	55	65

NOTES:

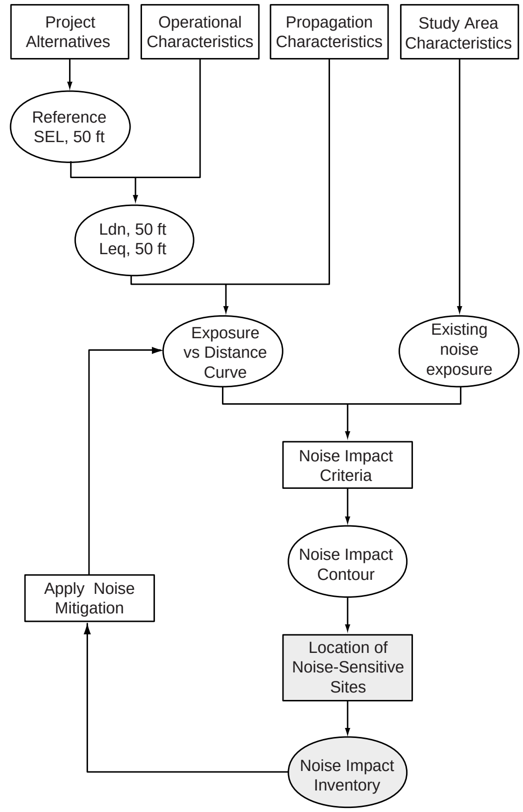
1 Distances do not include shielding from intervening rows of buildings. General rule for estimating shielding attenuation in populated areas: Assume 1 row of buildings every 100 ft; -4.5 dB for the first row, -1.5 dB for every subsequent row up to a maximum of -10 dB attenuation.

2 Roadways with 4 or more lanes that permit trucks, with traffic at 60 mph.

3 Parkways with traffic at 55 mph, but without trucks, and city streets with the equivalent of 75 or more heavy trucks per hour and 300 or more medium trucks per hour at 30 mph.

4 Main line railroad corridors typically carrying 5-10 trains per day at speeds of 30-40 mph.

5.6 INVENTORY NOISE IMPACT



The final step in the General Assessment is to develop an inventory of noise-impacted land uses. Using the land use information and noise impact contours from the Sections 5.4 and 5.5, it should be possible to locate which buildings are within the impact contours. In some cases it may be necessary to supplement the land use information or determine the number of dwelling units within a multi-family building with a visual survey.

The steps for developing the inventory are:

1. Construct tables for all the noise-sensitive land uses identified in the three land use categories from Section 5.4.

2. Tabulate buildings and sites that lie between the impact contours and the project boundary. For residential buildings, estimate the number of dwelling units. This is done for each alternative being considered.

3. Prepare summary tables showing the number of buildings and dwelling units within each impact zone for each alternative. Various alternatives can be compared in this way, including those with and without noise mitigation measures.

4. Determine the need for mitigation based on the policy considerations discussed in Section 3.2.4 and the application guidelines provided in Section 6.8.

Example 5-1. General Noise Assessment for a Transit Center

The following example illustrates the procedure for performing a General Noise Assessment. The example represents a typical FTA-assisted project in an urban area, the siting of a busy transit center in a mixed commercial and residential area, as shown in Figure 5-3.

Assumptions for Example

The assumptions for the Transit Center and its environs are as follows:

- **Main Street Traffic:** Peak hour traffic of 1200 autos, 20 heavy trucks, 300 medium trucks.

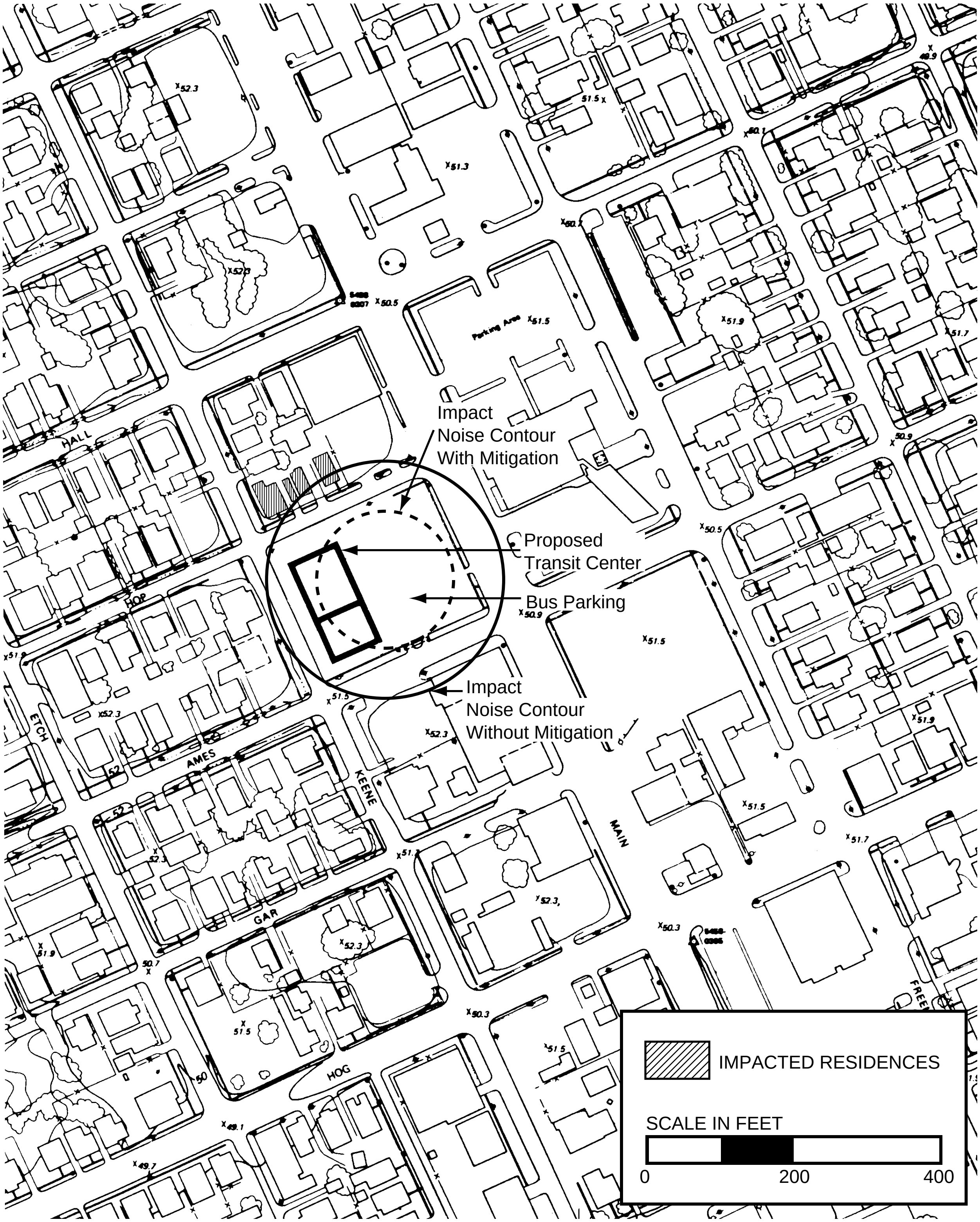


Figure 5-3 Example of Project for General Assessment: Siting of Transit Center in Mixed Commercial/Residential Area

- **Population Density:** 12 houses per block; single family homes; 3 people per family.

  Block area 78,750 square feet.
  Population density = 9,750 people/square mile.

- **Bus Traffic:**

Period	Hours	Buses per Hour
Peak, Morning	7am - 9am	30
Peak, Afternoon	4pm - 6pm	30
Mid-day	9am - 4pm	15
Evening	6pm - 10pm	12
Early Morning (Night)	6am - 7am	15
Late Night	10pm - 1am	4

Procedure

Before beginning the General Assessment, note that the Screening Procedure calls for additional analysis if any residential or other noise-sensitive land use is within 150 feet of a Transit Center when there are intervening buildings. According to Figure 5-3 the nearest residence is about 140 feet from the center of the proposed Transit Center, thereby calling for further analysis. The General Assessment proceeds as follows:

Determination of Noise Exposure at 50 feet

1. Determine the average number of buses per hour during day and night.

   Day (7am - 10pm):

   N_B *(avg day)* = 273 buses/15 hours = 18.2 buses/hour average.

   Night (10pm - 7am):

   N_B *(avg night)* = 27 buses/9 hours = 3 buses/hour average

2. Calculate $L_{eq}(day)$ and $L_{eq}(night)$ at 50 feet, assuming no noise barrier.

   From Table 5-5 and Table 5-6 the levels are determined as follows:

   $$L_{eq}(day) = SEL_{ref} + C_N - 35.6$$
   $$= 101 + 10 \log (18.2/20) - 35.6$$
   $$= 65 \text{ dB}$$
   $$L_{eq}(night) = SEL_{ref} + C_N - 35.6$$
   $$= 101 + 10 \log (3/20) - 35.6$$
   $$= 57 \text{ dB}$$

3. Calculate L_{dn} at 50 ft for the project.

   From Table 5-6 the level at 50 feet is determined as follows:

   $$L_{dn} = 10 \log \left[(15)10^{Leq(day)/10} + (9)10^{(Leq(night)+10)/10}\right] - 13.8$$

   which gives:

   $$L_{dn} = 79.7 - 13.8$$

   or $$L_{dn} = 66 \text{ dB}$$

Estimate Existing Noise Exposure

4. Estimate existing noise at noise-sensitive sites from the dominant noise source, either major roadways or local streets (population density).

    Roadway Noise Estimate - The traffic on Main Street qualifies this street for the "Other Major Roadway" category in Table 5-7. According to the map, the nearest residence is 275 feet from the edge of Main Street. The table shows existing L_{dn} = 55 dB at this distance for representative busy city street traffic.

    Population Density Noise Estimate - As a check on which ambient noise category to use, noise from local streets is estimated from the population density of 9,750 people/square mile. Table 5-7 confirms that the L_{dn} should be approximately 55 dB.

    The existing noise level associated with the residential neighborhood is therefore taken to be L_{dn} = 55 dB.

Noise Impact Contours

5. Distance to Impact Contour - For an existing noise exposure of 55 dB, the noise impact criteria indicate that the onset of Impact will occur at a project noise level of 56 dB, and onset of Severe Impact will occur at 62 dB. The next step is to determine the distances from the center of the property at which these levels are reached. This is accomplished by use of Figure 5-2, the exposure-vs-distance curve. With the project noise level at 50 feet given as 66 dB and the two impact levels at 56 dB and 62 dB, the differences are 10 dB and 4 dB, respectively. Using the curve in Figure 5-2 labeled "Stationary" source, the distance to where the project level drops 10 dB is approximately 160 feet, and 4 dB attenuation occurs at about 80 feet. Consequently, the Impact contour occurs at 160 feet from the center of the property and the Severe Impact contour occurs at 80 feet.

6. Draw Contours - Lines are drawn at 80 feet and 160 feet from the center of the property of the proposed Transit Center. These lines represent the noise impact contours. (Note in Figure 5-4 the Severe Impact contour is left out for clarity: it is just within the dashed line representing the Impact contour after mitigation.)

7. Assessment - Within, or touching, the contour defining "Impact" are three residential buildings (shaded in Figure 5-4). No residences are within the "Severe Impact contour."

Noise Mitigation

8. Noise Barrier - The process is repeated with a hypothetical noise barrier at the property line on the residential side of the Transit Center. This would consist of a wall approximately 15 feet high partially enclosing the transit center, sufficient to screen the residences but not the commercial block facing Main Street. According to Table 5-6, the approximate noise barrier effect is -5 dB. Repeating the procedure above, the effect of the noise barrier is to shrink the Impact contour to 90 feet and the Severe Impact contour to 45 feet, which in this example eliminates all adverse effect on the residences.

End of Example 5-1

Example 5-2. General Noise Assessment for a LRT System in a Highway Corridor

The following example illustrates the General Noise Assessment procedure for a fixed guideway-type project. The hypothetical project is a light rail transit (LRT) system to be built within the median of a busy multi-lane highway. The LRT tracks are grade-separated on aerial structure. The example covers a segment of the corridor that passes through a densely developed area with mixed residential and commercial land use, and a school within 150 feet of the project, as shown in Figure 5-4.

Assumptions for Example

The assumptions for the project are as follows:

- **Project Corridor:** Median of a six-lane interstate highway, with typical vehicle speeds of 60-70 mph during freely flowing traffic conditions.
- **LRT System:** LRT train with two-car consists, 50-ft long cars. Double track system on elevated concrete slab, welded rail. Trains operating with 5 to 10 minute headways at a speed of 60 mph along the segment shown in Figure 5-4.

Operating Schedule:

	Period	**Headway (minutes)**		**Trains per hour**		
		Inbound	**Outbound**	**Inbound**	**Outbound**	**Total**
Daytime	7am - 9am	5	7	12.0	8.6	20.6
	9am - 12am	7	9	8.6	6.7	15.2
	12am - 4pm	8	6	7.5	10.0	17.5
	4pm - 6pm	7	5	8.6	12.0	20.6
	6pm - 8pm	8	6	7.5	10.0	12.0
	8pm - 10pm	10	10	6.0	6.0	6.0
Nighttime	10pm - 1am	15	15	4.0	4.0	8.0
	1am - 5am	--	--	0.0	0.0	0.0
	5am - 6am	10	10	6.0	6.0	12.0
	6am - 7am	6	10	10.0	6.0	16.0

Procedure

The Screening Procedure calls for additional analysis for noise-sensitive land use within 350 feet of a rail transit guideway. Figure 5-4 shows that the closest residences are about 120 ft from the LRT corridor centerline, thereby requiring further noise analysis. The procedure is summarized as follows:

Determination of Noise Exposure at 50 feet

1. Determine average hourly daytime and nighttime volumes of train traffic.

   Daytime (7am - 10pm):

   V_d = 257 trains/15 hours = 17.1 trains/hour

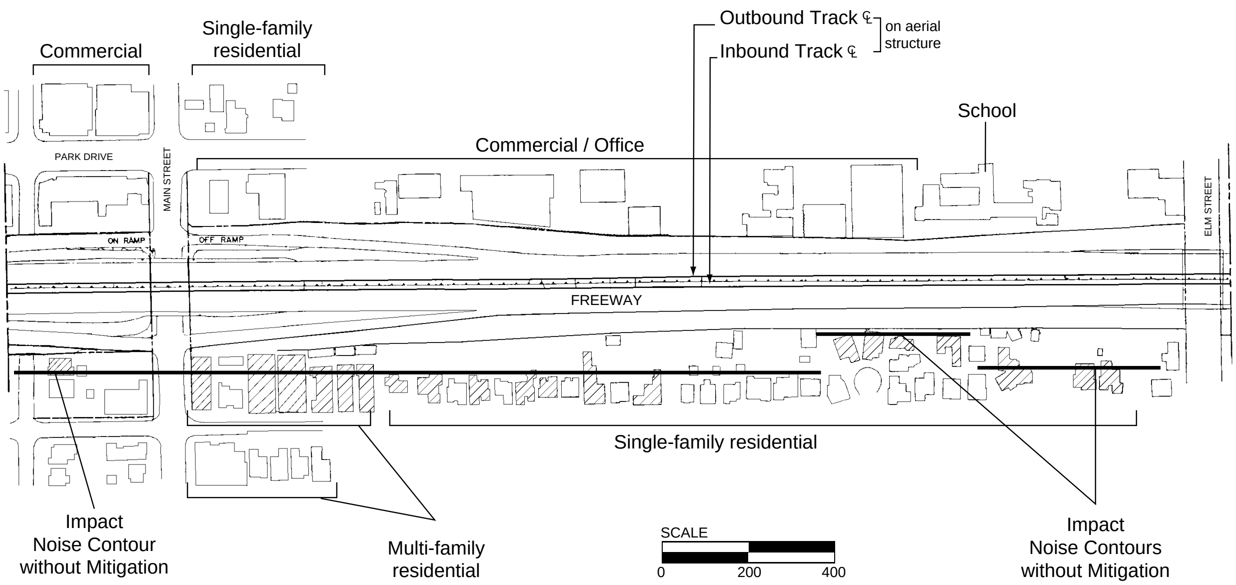


Figure 5-4 Example of Project for General Assessment: LRT System Corridor in Highway Median

Nighttime (10pm - 7am):

V_n = 52 trains/9 hours = 5.8 trains/hour

Peak Hour (of LRT operations during school hours):

V_p = 20.6 trains/hour

2. Calculate L_{eq}(day), L_{eq}(night) and L_{eq}(peak) at 50 ft, assuming no noise barrier.

From Table 5-1 and 5-2 these levels are determined as follows:

$$L_{eq}(day) = SEL_{ref} + 10\log(N_{cars}) + 20\log(S/50) + 10\log(V_d) - 35.6$$
$$= 82 + 4 + 10 \log (2) + 20 \log (60/50) + 10 \log (17.1) - 35.6$$
$$= 67.3 \text{ dB}$$
$$L_{eq}(night) = SEL_{ref} + 10 \log (N_{cars}) + 20 \log (S/50) + 10 \log (V_n) - 35.6$$
$$= 82 + 4 + 10 \log (2) + 20 \log (60/50) + 10 \log (5.8) - 35.6$$
$$= 62.6 \text{ dB}$$
$$L_{eq}(h) = SEL_{ref} + 10 \log (N_{cars}) + 20 \log (S/50) + 10 \log (V_p) - 35.6$$
$$= 82 + 4 + 10 \log (2) + 20 \log (60/50) + 10 \log (20.6) - 35.6$$
$$= 68.1 \text{ dB}$$

(Note that a +4 dB adjustment is added to account for track on aerial structure, per Table 5-2)

3. Calculate project L_{dn} at 50 ft.

From Table 5-2 this level is determined as follows:

$$L_{dn} = 10 \log \left[(15)10^{L_{eq}(day)/10} + (9)10^{(L_{eq}(night)+10)/10}\right] - 13.8$$

which gives

L_{dn} = 83.9 - 13.8

or

L_{dn} = 70 dB

Estimate Existing Noise Exposure

4. Estimate existing noise at noise-sensitive sites. Since the freeway (the dominant noise source) is a major linear source from which noise attenuates rapidly with distance, it is inaccurate in this case to simply assign a "generalized" noise level to characterize a large area, as in Example 5-1. In other words, it is necessary to estimate the existing noise environment as a function of distance from the freeway on a site-specific basis.

   From Figure 5-4, unobstructed residences range from 80 to 200 ft from the freeway, while the school is located 130 ft from the freeway. Based on Table 5-7 the L_{dn} is 70 dB for residences closer than 100 ft from a major interstate, and 65 dB for residences between 100 and 200 ft. For the school, the applicable metric is daytime L_{eq}, which is estimated to be 65 dB at distances of 100 to 200 ft from a major interstate highway.

Noise Impact Contours

5. The following table is constructed using the impact criteria curves (Figure 3-1) to determine the project noise levels which cause impact:

Distance to Freeway	Existing Noise, L_{dn} or L_{eq}(day)	Onset of Impact		Onset of Severe Impact	
		L_{dn}	L_{eq}(h)	L_{dn}	L_{eq}(h)
50 - 100 ft	70 dB	64 dB	n/a	69 dB	n/a
100 - 200 ft	65 dB	61 dB	66 dB	66 dB	71 dB

   Note: The project criteria for L_{eq}(h) are not shown for the 50-100 ft distance range, since L_{eq}(h) only applies to the school in this example which is in the 100-200 ft range.

6. Distance to impact contours are determined using the curve in Figure 5-2 for "Fixed Guideway" and the project impact thresholds obtained above. The results are summarized as follows for the residences and school:

Distance to Freeway	Existing Noise, L_{dn} or L_{eq}(h)	Distance to Noise Impact Threshold, feet			
		Residences		School	
		Impact	Severe Impact	Impact	Severe Impact
50 - 100 ft	70 dB	120	55	n/a	n/a
100 - 200 ft	65 dB	210	90	75	30

7. Draw contours for each affected land use, based on the above table and its distance from the freeway. Note that the impact distances listed are in terms of distance to the *centerline of the LRT corridor*, not the freeway. Note that in Figure 5-4, only distances to "Impact" contours are shown. "Severe Impact" distances do not go beyond the edge of the freeway and are thus omitted for simplicity. The impact noise contours

are drawn at 2 different distances resulting from the change in existing noise for the closer residences.

8. Within the contours defining "Impact" are eighteen residential buildings (shaded in Figure 5-4). The school does not fall into the impact zone.

Noise Mitigation

9. The procedure is repeated assuming a noise barrier to be placed at the highway right-of-way line. The barrier serves to reduce not only project noise from the LRT by at least 5 dB but also the freeway noise. This, however, does not affect the project criteria to be used in determining impact. That is, the same existing noise levels (as the case without a barrier) are used to determine these thresholds.

   In the area of impact, the net effect of the noise barrier is to decrease the impact distance from 120 to 60 ft for residences within 100 feet of the freeway, and from 210 to 90 ft for residences between 100 and 200 feet of the freeway. Hence, the noise barrier eliminates all residential noise impact for this segment of the project area.

End of Example 5-2

REFERENCES

1. U.S. Department of Transportation, Federal Highway Administration. "FHWA Highway Traffic Noise Prediction Model," FHWA-RD-77-108, December 1978.

2. U.S. Environmental Protection Agency, "Population Distribution of the United States as a Function of Outdoor Noise Level," Report 550/9-74-009, June 1974.

6. DETAILED NOISE ANALYSIS

This chapter describes the detailed computation of both project and existing noise levels for a comprehensive assessment of project noise impact. The main purpose of this chapter is to provide a procedure that allows prediction of impact and assessment of the effectiveness of mitigation with greater precision than can be achieved with the General Assessment. In some cases, decisions on appropriate mitigation measures can be made based on the results of the General Assessment. When a more detailed evaluation of mitigation measures is needed, the procedures in this chapter should be followed.

It is important to recognize that use of the Detailed Analysis methods will not provide more accurate results than the General Assessment unless more detailed and specific input data are used. In the case of a transit center for example, the General Assessment provides a source level at a reference distance from the center of the site based on the number of buses at the facility during each hour. Thus, the only information needed for a General Assessment of the transit center is the site location and hourly bus volumes. However, a Detailed Analysis would require specific information on the locations, reference levels, traffic volumes and duration of operations for individual sources that contribute to the total noise output of the transit center. Such information would include a detailed design plan for the facility, the locations of idling buses and the idling durations, as well as the bus and automobile traffic patterns and volumes. A Detailed Analysis cannot be done until such information is available.

Detailed Noise Analysis is appropriate in two main circumstances: first, for major fixed-guideway projects after a preferred alignment has been selected; and second, for any other transit project where potentially severe impacts are identified at an early stage. For fixed-guideway projects, once the preferred mode and alignment are established, the project sponsor begins preliminary engineering and preparation of the environmental document (usually an Environmental Impact Statement). Information required for the Detailed Noise Analysis is generally available at the preliminary engineering stage; such information includes hourly operational schedules during day and night, speed profiles, plan and profiles of guideways, locations of access roads, and landform topography including terrain and building features.

Even for relatively minor transit projects, noise impacts are likely to occur whenever the project is in close proximity to noise-sensitive sites, particularly residences. Some examples are: (1) a terminal or station sited adjacent to a residential neighborhood; (2) a maintenance facility located near a school; (3) a storage yard adjacent to residences; and (4) an electric substation located adjacent to a hospital. As with the larger fixed guideway projects mentioned above, detailed noise analysis for these projects will require information normally developed at the preliminary design stage.

The procedures of this chapter include everything needed for a fully detailed transit noise analysis. They are aimed at major transit projects that have enough lead time for thorough environmental analysis. They need not be followed to the letter; they can be tempered by competent engineering judgment and adapted somewhat to specific project constraints.

This chapter employs equations as the primary mode of computation, rather than graphs or tables of numbers, in order to facilitate the use of spreadsheets and/or programmable calculators. Moreover, these equations and their supporting text have been streamlined to provide as concise a view of the Detailed Noise Analysis as possible. As a result, basic noise concepts are not repeated in this chapter.

The steps in the procedure appear in Figure 6-1 and are described below. They parallel the steps for the General Noise Assessment, though they are more refined in the prediction of project noise and subsequent evaluation of mitigation measures.

1. Receivers of Interest: Select receivers of interest, guided by Section 6.1. The number of receivers will depend upon the land use in the vicinity of the proposed project and the extent of the study area defined by the Screening Procedure. If a General Assessment has been done, this will give a good indication of the extent of potential impacts.

2. Project Noise: Determine whether the project is primarily a fixed-guideway transit, highway/transit, or stationary facility. Note that a major fixed guideway system will have stationary facilities associated with it, and that a stationary facility may have highway/transit elements associated with it. Identify the project noise sources that are in the vicinity of receivers of interest. For these sources, determine the source reference noise in terms of SEL from the tables in Section 6.2. Each reference SEL pertains to reference operating conditions for stationary sources or to one vehicle passby under reference operating conditions for fixed-guideway and highway/transit sources. These reference levels should incorporate source-noise mitigation only if such mitigation will be incorporated into the system specifications. For example, if the specifications include vehicle noise limits, these limits should be used to determine the reference level, and this level should be used in the analysis rather than the standard, tabulated reference level. Convert each source SEL to noise exposure (L_{dn} or L_{eq} (h)) at 50 feet, for the appropriate project operating parameters, using additional equations in Section 6.2.

3. Propagation and Summation of Project Noise at Receivers of Interest: Draw a noise exposure vs. distance curve for each relevant source, using the equations in Section 6.3. This curve will show source noise as a function of distance, accounting for shielding along the path, as well as any propagation-path mitigation that will be included in the project. From these curves, determine the total

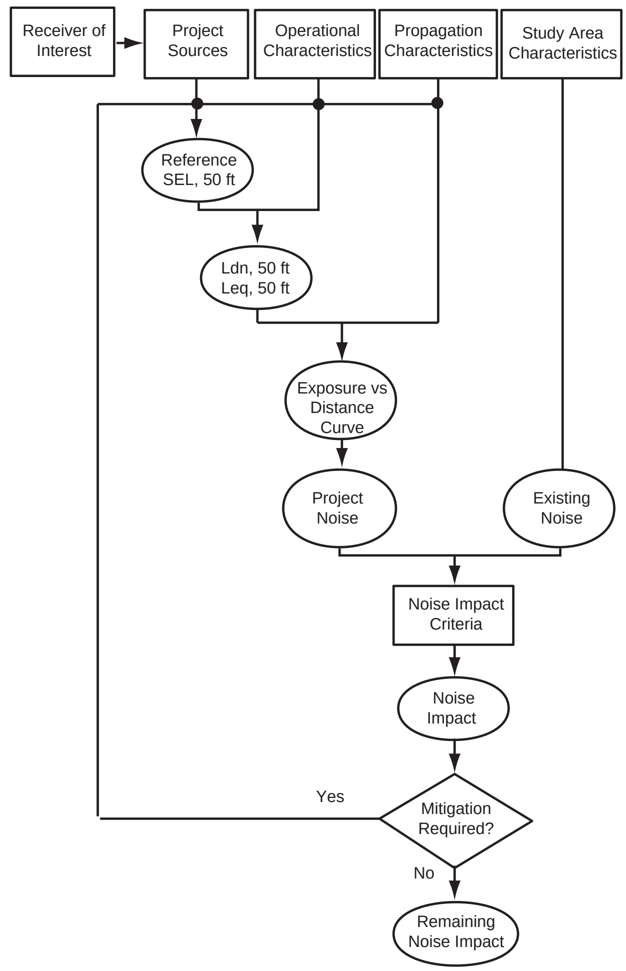


Figure 6-1 Procedure for Detailed Analysis

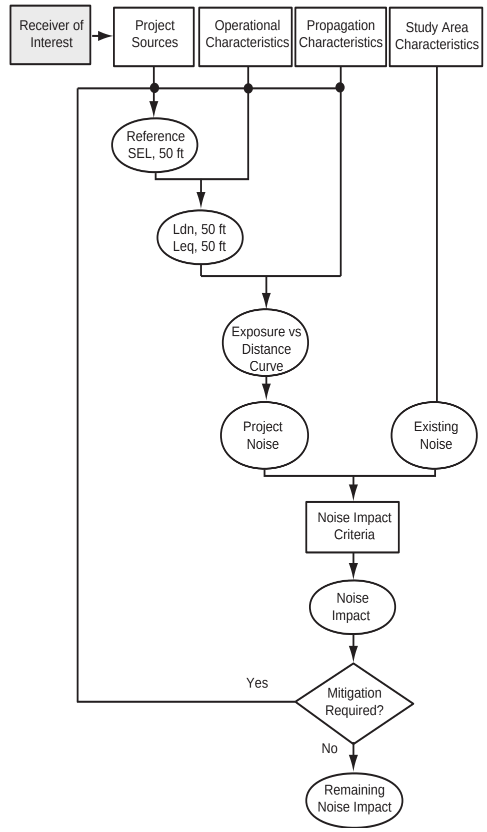
project noise exposure at all receivers of interest by combining the levels from all relevant sources (Section 6.4).

4. Existing Noise in the Study Area: Estimate the existing noise exposure at each receiver of interest, using the methods in Section 6.5.

5. Noise Impact Assessment: Assess noise impact at each receiver of interest using the procedures in Section 6.6 which incorporate the noise impact criteria of Chapter 3.

6. Mitigation of Noise Impact: Where the assessment shows either Severe Impact or Impact, evaluate alternative mitigation measures referring to Section 6.7. Then loop back to modify the project-noise computations, thereby accounting for the adopted mitigation, and reassess the remaining noise impact.

6.1 RECEIVERS OF INTEREST



The steps in identifying the receivers of interest, both the number of receivers needed and their locations, are shown in Figure 6-2. Later sections discuss the measurement/computation of ambient noise, the computation of project noise, and the resulting assessment of noise impact that is done for each receiver. The basic steps, which are discussed in the following subsections, are:

1. Identify all noise-sensitive land uses.
2. Find individual receivers of interest. Examples are isolated residences and institutional resources such as schools.
3. Cluster residential neighborhoods and other relatively large noise-sensitive areas.

6.1.1 Identifying Noise-Sensitive Land Uses

A Detailed Noise Analysis should usually be performed on all noise-sensitive land uses where impact is identified by the General Noise Assessment. If a General Noise Assessment has not been done, but there appears to be potential for noise impacts, all noise-sensitive sites within the area defined by the noise screening procedure should be included. In areas where ambient noise is low, the assessment will include land uses that are farther from the proposed project than for areas with higher ambient levels.

Some of the land-use materials and methods that can be helpful in locating noise-sensitive land uses in the vicinity of the proposed project include:

- **Land-use maps**, prepared by regional or local planning agencies or by the project staff. Area-wide maps often do not have sufficient detail to be of much use. However, they can provide broad guidance and may suggest residential pockets hidden within otherwise commercial zones. Of more use are project-specific maps which provide building-by-building detail on the land nearest the proposed project.
- **USGS maps,** prepared by the United States Geological Survey generally at 2000-foot scale. These maps contain details of house placement, except in highly urbanized areas, and generally show the location of all schools and places of worship, plus many other public-use buildings. In addition, the topographic contours on these maps may be useful later during noise computation.
- **Road and town maps**. These can supplement the USGS maps, are generally more up-to-date, and may be of larger scale.

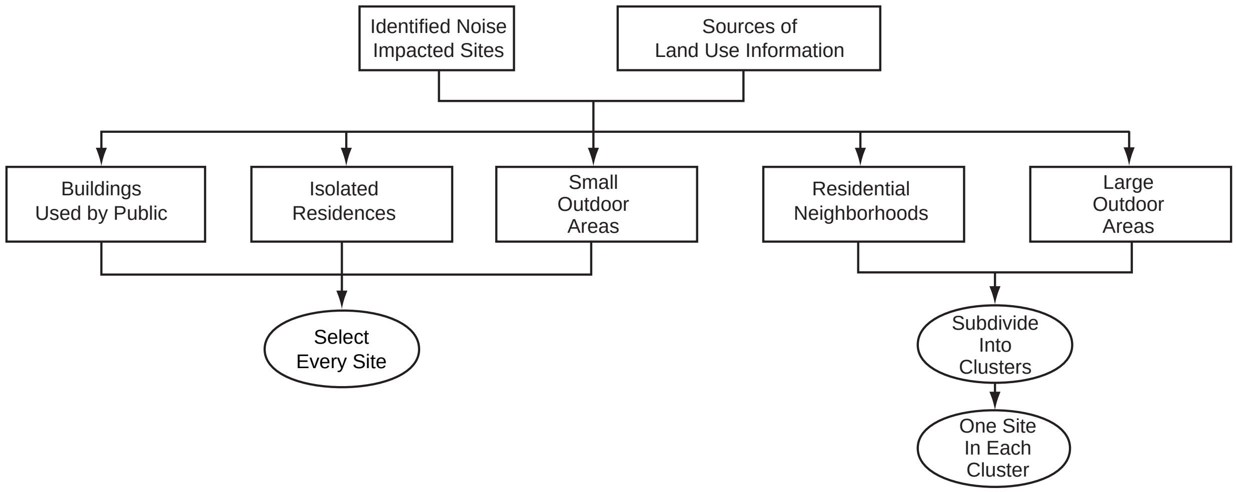


Figure 6-2 Guide to Selecting Receivers of Interest

- **Aerial photographs,** especially those of 400-foot scale or better. When current, aerial photos are valuable in locating all potential noise-sensitive land uses close to the proposed project. In addition, they can be useful in determining the distances between receivers and the project.

- **Windshield survey** of the corridor. Definitive identification of noise-sensitive sites is accomplished by a windshield survey in which the corridor is driven and land uses are annotated on base maps. The windshield survey, supplemented by footwork where needed, is especially useful in identifying newly-constructed sites and in confirming land uses very close to the proposed project.

Table 6-1 contains the types of land use of most interest to transit projects, separated into three types of land use. If noise impact was identified at other types of buildings/areas with noise-sensitive use by the General Noise Assessment, these should be selected also.

6.1.2 Selecting Individual Receivers of Interest

Select as an individual receiver of interest: (1) every major noise-sensitive building used by the public; (2) every isolated residence; and (3) every relatively small outdoor noise-sensitive area. Use judgment here to avoid analyzing noise where such analysis is obviously not needed. For example, many roadside motels are not particularly sensitive to noise from outdoors. On the other hand, be careful to include buildings used by the public or outdoor areas which are considered to be particularly noise-sensitive by the community. Isolated residences that are particularly close to the project should certainly be included, while those at some distance may often be omitted or "clustered" together with other land uses, as described in the next section. Use judgment also concerning relatively small outdoor noise-sensitive areas. For example, playgrounds can often be omitted unless they directly abut the proposed project, since noise sensitivity in playgrounds is generally low.

Table 6-1 Land Uses of Interest

Land Uses	Specific Use	Selecting Receivers
Outdoor noise-sensitive areas	Parks Historic sites used for interpretation Amphitheaters Recreation areas Playgrounds Cemeteries Other outdoor noise-sensitive areas	For relatively small noise-sensitive areas: same as indoor noise-sensitive sites. For relatively large areas: same as for residential areas.
Residences	Single family residences Multi-family residences (apartment buildings, duplexes,etc.)	Select each isolated residence as a receiver of interest. For residential areas, cluster by proximity to project sources, proximity to ambient-noise sources, and location along project line. Choose one receiver of interest in each cluster.
Indoor noise-sensitive sites	Places of worship Schools Hospitals/nursing homes Libraries Public meeting halls Concert halls/auditoriums/theaters Recording/broadcast studios Museums and certain historic buildings Hotels and motels Other public buildings with noise-sensitive indoor use	Select noise-sensitive buildings as separate receivers of interest.

6.1.3 Clustering Residential Neighborhoods and Outdoor Noise-Sensitive Areas

Residential neighborhoods and relatively large outdoor noise-sensitive areas can often be clustered, simplifying the analysis that is required without compromising the accuracy of the analysis. The goal is to subdivide all such neighborhoods/areas into clusters of approximately uniform noise, each containing a collection of noise-sensitive sites. Attempt to obtain uniformity of both project noise and ambient noise, guided by these considerations:

1. In general, project noise drops off with distance from the project. For this reason, project noise uniformity requires nearly equal distances between the project noise source and all points within the cluster. Such clusters will usually be shaped as long narrow strips parallel to the transit corridor and/or circling project point sources such as a maintenance facility. Suggested are clusters within which the project noise will vary over a range of 5 decibels or less. Be guided here by the fact that project noise will drop off approximately 3 decibels per doubling of distance for line sources and 6 decibels per doubling of distance for point sources over open terrain. Drop off with distance will be faster in areas containing obstacles to sound propagation, such as rows of buildings.

2. Ambient noise usually drops off from non-project sources in the same manner as does noise from project sources. For this reason, clustering for uniform ambient noise will usually result in long narrow

strips parallel to major roadways or circling major point sources of ambient noise, such as a manufacturing facility. Suggested are clusters within which the ambient noise will vary over a range of 5 decibels or less, though this may be hard to judge without measurements. In areas without predominant sources of noise, like highways, ambient noise varies with population density, which is generally uniform along the corridor. In situations where ambient noise tends to be uniform, the clusters can encompass relatively large areas.

After defining the cluster, select one receiver as representative in each cluster. Generally choose the receiver closest to the project and at an intermediate distance from the predominant sources of exising noise. Detailed procedures for clustering appear in Appendix B along with an example of clustering for a segment of rail line. This method will generally result in an adequate selection of receivers along the corridor or surrounding the site.

6.2 PROJECT NOISE

Once receivers have been selected, projections of noise from the project must be developed for each receiver. This section describes the first step, calculating the noise exposure at an equivalent distance of 50 feet from each project noise source. As shown in Figure 6-3, the basic procedures for the computation are: (1) Separate nearby sources into these source-type categories: fixed-guideway sources, highway/transit sources, and stationary sources; (2) Determine the reference SEL for each source.; and (3) Use the projected source operating parameters to convert each reference SEL to noise exposure (either L_{dn} or L_{eq}(h)) at 50 feet.

Table 6-2 lists many of the noise sources that are involved in transit projects. The right-hand column of the table indicates whether or not each source is a major contributor to overall noise impact. Note that some noise sources, such as track maintenance equipment, create high noise levels but are not indicated as "major." Although such sources are loud, they rarely stay in a neighborhood for more than a day or two; therefore, the overall noise exposure is relatively minor. Computations are required for all major noise sources in this table. The computations for the three basic groups – fixed-guideway sources, highway/transit sources, and stationary sources – appear in separate sections below.

6.2.1 Fixed-Guideway Sources

This section describes the computation of project noise at 50 feet from fixed-guideway sources of transit noise, identified in the second column of Table 6-2.

<u>Step 1: Source SELs at 50 feet</u>

For each major fixed-guideway noise source, first determine the reference SEL at 50 feet, either by measurement or by table look-up. Table 6-3 provides guidance on which method is preferred for each source type. A "NO" implies that the source levels are based on a solid and consistent data base; a "YES" means that a solid data base is not available. In general, measurements are preferred for source types that vary significantly from project to project, including any emerging technology sources. Table look-up is adequate for source types that do not vary significantly from project to project. In general, table look-up is adequate

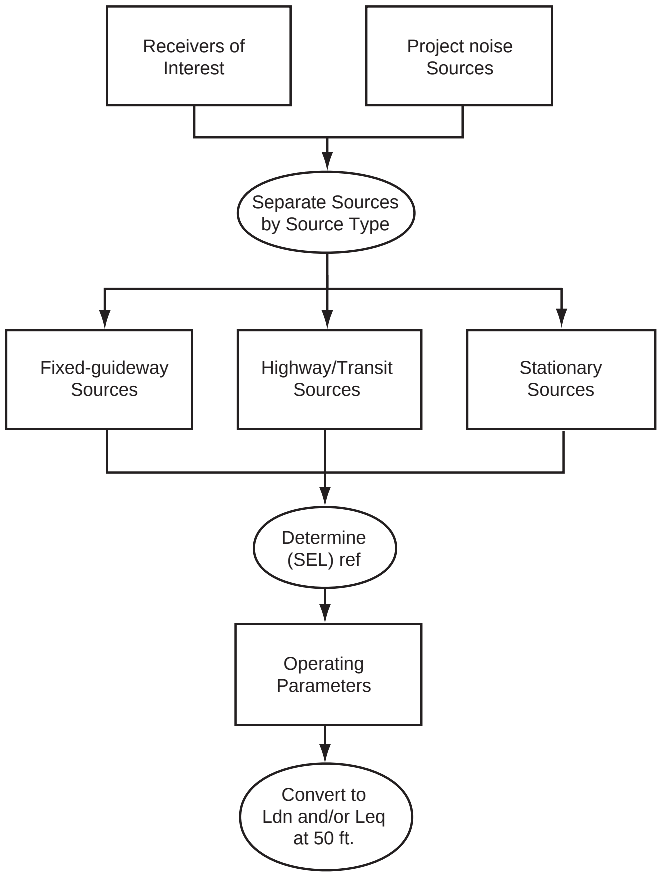


Figure 6-3 Flow Diagram for Determining Project Noise at 50 ft

for fewer source types during Detailed Noise Analysis than during General Noise Assessment where less precision is acceptable.

For sources where measurements are indicated in Table 6-3, Appendix D discusses measurement procedures and conversion of these measurements to the reference conditions of Table 6-3. These procedures have been placed in an appendix because of their relative complexity. For projects where source-noise specifications have been defined (e.g., noise limits are usually included in the specifications for purchase of new transit vehicles), these specifications may be used instead of measurements, after conversion to reference conditions with the equations of Appendix D.

For sources where table look-up is indicated in Table 6-3, the table provides appropriate Source Reference SELs. Approximate L_{max} values also appear in the table for general user information and for comparison with factors such as the noise limits that are included in transit vehicle specifications. As discussed in Chapter 2, L_{max} is not used directly in the evaluation of noise impact.

Table 6-2 Sources of Transit Noise

Project Type	Source Type	Actual Source	Major?
Commuter Rail Light Rail Rail Rapid Transit	Fixed Guideway	Locomotive and rail car passbys	YES
		Horns and whistles	YES
		Crossing signals	YES
		Crossovers/switches	YES
		Squeal on tight curves	YES
		Track-maintenance equipment	NO
	Stationary	Substations	YES
		Chiller plants	NO
Busways Bus Transit Malls	Highway/Transit	Bus passbys	YES
		Buses parking	NO
	Stationary	Buses idling	YES
Automated Guideway Transit Monorail	Fixed Guideway	Vehicle passbys	YES
	Miscellaneous	Line equipment	NO
Terminals Stations Transit Centers	Fixed Guideway	Locomotive and rail car passbys	YES
		Crossovers/switches	YES
		Squeal on tight curves	YES
	Highway/Transit	Bus passbys	YES
		Buses parking	NO
		Automobile passbys	NO
	Stationary	Locomotives idling	YES
		Buses idling	YES
		HVAC equipment	NO
		Cooling towers	NO
		P/A systems	NO
Park-and-Ride Lots	Highway/Transit	Bus passbys	YES
		Buses idling	YES
		Automobile passbys	NO
	Stationary	P/A systems	NO
Traffic Diversion Projects	Highway/Transit	Highway vehicle passbys	YES
Storage Facilities Maintenance Facilities	Fixed Guideway	Locomotive and rail car passbys	YES
		Locomotives idling	YES
		Squeal on tight curves	YES
		Horns, warning signals, coupling/ uncoupling, auxiliary equipment, crossovers/ switches, brake squeal and air release	YES
	Highway/Transit	Bus passbys	YES
	Stationary	Buses idling	YES
		Yard/shop activities	NO
		Car washes	NO
		HVAC Equipment	NO
		P/A Systems	NO

Table 6-3 Source Reference SELs at 50 Feet: Fixed-Guideway Sources

Source	Reference SEL (dBA)	Approximate L_{max} (dBA)	Prefer Measurements?
Rail Cars	82	80	NO
Locomotives - Diesel	92	88	NO
Locomotives - Electric	90	86	NO
AGT - Steel Wheel	80	78	YES
AGT - Rubber Tire	78	75	YES
Monorail	82	80	YES
Maglev	72	70	YES
Locomotive Horns or Whistles	108	105	NO
Transit Car Horns or Whistles	93	90	NO

Step 2: Conversion to Noise Exposure at 50 feet

Step 1 results in reference SELs at 50 feet. Step 2 is to convert from these reference SELs to noise exposure based on operating conditions and parameters such as train consists, speed, and number of trains per hour. The steps are:

1. Identify operating conditions. Trains with different consists require separate conversion since they will produce different noise exposure. The same is true for trains at different speeds, or under different operating conditions. As guidance here, the following percentage changes in operating conditions will produce an approximate 2-decibel change in noise exposure:

   - 40 percent change in number of locomotives or cars per train
   - 40 percent change in number of trains per hour
   - 40 percent change in number of trains per day, or per night (for computation of L_{dn})
   - 15 percent change in train speed
   - change of one notch in diesel locomotive throttle setting (e.g. from notch 5 to notch 6).

   In general, where operating conditions change by these amounts, separate calculations should be made. Without separate conversions, the risk is that the results may not be accurate enough.

2. Establish relevant time periods. For each of these source types/conditions, decide what are the relevant time periods for all receivers that may be affected by this source. For residential receivers, the two time periods of interest for computation of L_{dn} are: daytime (7 am to 10 pm) and nighttime (10 pm to 7 am). If the source will affect non-residential receivers, choose the loudest project hour during noise-sensitive activity. Several different hours may be of interest for non-residential receivers depending on the hours the facility is used.

3. Collect input data.
   - Source reference SELs for locomotives, rail cars, and warning horns.

- N_{cars}, the number of rail cars in the train.
- N_{locos}, the number of locomotives in the train, if any.
- *S*, the train speed, in miles per hour.
- *T*, the average throttle setting of the train's locomotive(s), if it is diesel-electric.* If this input is not available, assume a throttle setting of 8.
- For residential receivers of interest:

  V_d, the average hourly train volume during daytime hours (equals the total number of train passbys between 7 am and 10 pm, divided by 15), and

  V_n, the average hourly train volume during nighttime hours (equals the total number of train passbys between 10 pm and 7 am, divided by 9).

- For non-residential receivers: *V*, the hourly train volume for each hour of interest.
- Track type (continuously welded or jointed) and profile (at-grade or elevated).

4. Calculate L_{eq} at 50 ft for each hour of interest.
   - Compute $L_{eqL}(h)$ for the locomotive(s) using the first equation in Table 6-4.
   - Compute $L_{eqC}(h)$ for the rail car(s) using the second equation in Table 6-4. Use the adjustments indicated in the table, as needed.
   - Compute $L_{eqH}(h)$ for the train horn using the third equation in Table 6-4.
   - Compute the total $L_{eq}(h)$ using the fourth equation in Table 6-4. Two totals may be necessary: one with the warning horn and one without it. These will pertain to different neighborhoods along the corridor, depending upon whether the horn is sounded in that neighborhood or not.

5. Compute L_{dn} at 50 ft. If the project noise will affect any residential receivers, compute the total train L_{dn} from the fifth equation in Table 6-4. Again two totals may be necessary: one with the warning horn and one without it, as explained above.

* Otherwise, this term is not applicable and should be omitted from the equation in Table 6-4.

Table 6-4 Computation of L_{eq} and L_{dn} at 50 feet: Fixed-Guideway Sources

LOCOMOTIVES[†] Hourly L_{eq} at 50 ft:	$L_{eqL}(h) = SEL_{ref} + 10\log(N_{locos}) + C_T - 10\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$ where $C_T = \begin{cases} 0 & \text{for } T < 6 \\ 2(T-5) & \text{for } T \geq 6 \end{cases}$
RAIL VEHICLES Hourly L_{eq} at 50 ft:	$L_{eqC}(h) = SEL_{ref} + 10\log(N_{cars}) + 20\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$ use the following adjustments as applicable: + 5 → JOINTED TRACK + 3 → EMBEDDED TRACK ON GRADE + 4 → AERIAL STRUCTURE WITH SLAB TRACK
WARNING HORNS Hourly L_{eq} at 50 ft:	$L_{eqH}(h) = SEL_{ref} - 10\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$
COMBINED Hourly L_{eq} at 50 ft:	$L_{eq}(h) = 10\log\left[10^{\left(L_{eqL}/10\right)} + 10^{\left(L_{eqC}/10\right)} + 10^{\left(L_{eqH}/10\right)}\right]$
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = L_{eq}(h)\Big\|_{V=V_d}$
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = L_{eq}(h)\Big\|_{V=V_n}$
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\cdot 10^{\left(L_{eq}(day)/10\right)} + (9)\cdot 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$

N_{locos} = average number of locomotives per train
N_{cars} = average number of cars per train
T = average throttle setting of diesel-electric locomotive
S = train speed, in miles per hour
V = average hourly volume of train traffic, in trains per hour
V_d = average hourly daytime volume of traffic, in trains per hour
$= \dfrac{\text{number of trains, 7 am to 10 pm}}{15}$
V_n = average hourly nighttime volume of train traffic, in trains per hour
$= \dfrac{\text{number of trains, 10 pm to 7 am}}{9}$

† assumes a diesel locomotive power rating of approximately 3000 hp.

Example 6-1. Computation of L_{eq} and L_{dn} at 50 feet for Fixed Guideway Source

A commuter train with 1 diesel locomotive and 6 cars will pass close to a school that is in session from 8 am to 4 pm on weekdays. Within this time period, the hour of greatest activity for this train type is 8 to 9 am. For this project source,

SEL_{ref} = 92 for locomotives,
= 82 for rail cars,
= 108 for warning horns.

In addition,

N_{cars} = 6

N_{locos} = 1

S = 43 mph

T = 8

V = 6 trains from 8am to 9am

The track is also jointed in this vicinity. Using Table 6-4, the resulting hourly L_{eq}'s at 50 feet are as follows:

L_{eqL}(8-9am) = 70.9 for locomotives,

L_{eqC}(8-9am) = 65.7 for cars, and

L_{eqH}(8-9am) = 80.9 for horns.

Total L_{eq}(8-9am) = 81.4 in neighborhoods where the horn is sounded, and
= 72.0 in neighborhoods where it is not.

(Note: Computation results should always be rounded to the nearest decibel at the end of the computation. In all examples of this chapter, however, the first decimal place is retained in case readers wish to precisely match their own computations against the example computations.)

This same commuter train will also pass close to a residential area. For this project source, all SEL_{ref}'s are the same as above -- as are values for N_{cars}, N_{locos}, S, and T. In addition,

V_d = (40 trains)/(15 hours) = 2.67 trains per hour, and

V_n = (2 trains)/(9 hours) = 0.22 trains per hour.

Using Table 6-4, the resulting daytime L_{eq}'s at 50 feet are as follows:

L_{eqL}(day) = 67.4 for locomotives,

L_{eqC}(day) = 62.2 for cars, and

L_{eqH}(day) = 77.4 for horns,

Total L_{eq}(day) = 77.9 with horns, and
= 68.5 without horns.

Using Table 6-4, the resulting nighttime L_{eq}'s at 50 feet are as follows:

L_{eqL}(night) = 56.5 for locomotives,

L_{eqC}(night) = 51.3 for cars, and

L_{eqH}(night) = 66.5 for horns,

Total L_{eq}(night) = 67.0 with horns, and
= 57.6 without horns.

Finally, this total day and night traffic results in:

L_{dn} = 77.6 at 50 ft in neighborhoods where horns are sounded, and
= 68.2 at 50 ft in neighborhoods where they are not.

End of Example 6-1

6.2.2 Highway/Transit Sources

This section describes the computation of project noise at 50 feet for highway/transit sources, identified in the second column of Table 6-2. This method is based on the FHWA highway noise prediction model, including the noise emission levels and mathematics.[1] This model can be used because the vehicle equations are applicable to speeds typical of freely-flowing traffic on city streets and access roads. For highway/transit projects with complex geometry or traffic conditions, it may be more appropriate to use the detailed FHWA computation methods discussed in Section 6.6.2.

Step 1: Source SELs at 50 feet

Determine the source reference SEL at 50 feet for each "major" highway/transit source near a receiver of interest. As indicated in the fourth column of Table 6-5, it is usually adequate to use the standard Reference SELs of Table 6-5 for highway/transit sources. If measurements are chosen, however, Appendix D discusses the measurement procedures, plus procedures for the conversion of these measurements to reference conditions of Table 6-5. These measurement/conversion procedures have been placed in an appendix because of their relative complexity.

Table 6-5 Source Reference SELs at 50 Feet: Highway/Transit Sources

Source	Reference SEL (dBA)	Approximate L_{max} (dBA)	Prefer Measurements?
Automobiles	73	70	No
Two-axle (city) Buses	84	81	No
Three-axle (commuter) Buses	88	85	No

Step 2: Conversion to Noise Exposure

Convert the source reference SELs at 50 feet to actual operating conditions such as actual vehicle speed and number of vehicles per hour. Next convert to noise exposure using the following steps:

1. Identify actual source operating conditions. Noise emission from most transit buses does not depend significantly upon whether the buses are accelerating or cruising. On the other hand, accelerating intercity buses are significantly louder than are cruising intercity buses. For this reason, intercity buses

require separate conversion along roadway stretches where they are accelerating. Separate conversion is also needed for all highway/transit vehicles at different speeds, since speed affects noise emissions. As guidance here, the following percentage changes in operating conditions will produce an approximate 2-decibel change in noise exposure:

- 40 percent change in number of vehicles per hour
- 40 percent change in number of vehicles per day, or per night (for computation of L_{dn})
- 15 percent change in vehicle speed.

In general, where operating conditions change by these amounts, separate conversions should be made.

Note that buses on city streets will have lower speeds than on freeways and will often be accelerating. For these reasons, separate conversions are generally needed on these two types of roadways. No other distinctions are needed besides these two; the computations suffice for both. Note also that idling buses are included with other stationary sources.

2. Establish relevant time periods. For each of these source types/conditions, decide what are the relevant time periods for all receivers that may be affected by this source. If the source will affect residential receivers, two time periods are of interest to compute L_{dn}: daytime (7 am to 10 pm) and nighttime (10 pm to 7 am). In addition, if the source will affect non-residential receivers, choose the loudest facility hour during noise-sensitive activity. Several different hours may be of interest for non-residential receivers, depending on the hours the facility is used.

3. Collect input data. Gather the following information:

   - Source reference SELs for the vehicle types of concern.
   - *S*, the average running speed in miles per hour.
   - For residential receivers of interest:

     V_d, the average hourly vehicle volume during daytime hours (equals the total number of vehicle passbys between 7 am and 10 pm, divided by 15), and

     V_n, the average hourly vehicle volume during nighttime hours (equals the total number of vehicle passbys between 10 pm and 7 am the next day, divided by 9).
   - For non-residential receivers of interest: *V*, the hourly vehicle volume for each hour of interest, in vehicles per hour.

4. Calculate L_{eq} at 50 ft for each hour of interest. Compute $L_{eq}(h)$ for the vehicle type using the first equation in Table 6-6.

5. Compute L_{dn} at 50 ft. If this vehicle type will affect any residential receivers, compute the total L_{dn} for the vehicle type using the fourth equation in Table 6-6.

Table 6-6 Computation of L_{eq} and L_{dn} at 50 feet: Highway/Transit Sources	
Hourly L_{eq} at 50 ft:	$L_{eq}(h) = SEL_{ref} + 10\log(V) + C_{emissions} - 10\log\left(\frac{S}{50}\right) - 35.6$
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = L_{eq}(h)\Big\vert_{V=V_d}$
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = L_{eq}(h)\Big\vert_{V=V_n}$
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$
Noise Emissions:	$C_{emissions} = 1.6$ → 3-axle commuter buses, accelerating $= 24.6\times\log\left(\frac{S}{50}\right)$ → 3-axle commuter buses, not accelerating $= 33.9\times\log\left(\frac{S}{50}\right)$ → 2-axle city buses $= 38.1\times\log\left(\frac{S}{50}\right)$ → automobiles
Other adjustments	− 3 → automobiles, open-graded asphalt + 3 → automobiles, grooved pavement

V = hourly volume of vehicles of this type, in vehicles per hour

V_d = average hourly daytime volume of vehicles of this type, in vehicles per hour

$= \frac{\text{total vehicle volume, 7am to 10pm}}{15}$

V_n = average hourly nighttime volume of vehicles of this type, in vehicles per hour

$= \frac{\text{total vehicle volume, 10pm to 7am}}{9}$

S = average vehicle speed in miles per hour (distance divided by time, excluding stop time at red lights)

Note: Idling buses appear under Stationary Sources.

Example 6-2. Computation of L_{eq} and L_{dn} at 50 feet for Highway/Transit Source

A bus route with 2-axle buses will pass close to a school that is in session from 8 am to 4 pm on weekdays. Within this time period, the hour of greatest activity for this bus route is 8 am to 9 am. For this project source,

SEL_{ref} = 84 dB

S = 40 mph, and

V = 30 buses per hour

Using Table 6-6, the resulting hourly L_{eq} at 50 ft = 60.9 dB. (Note: Computation results should always be rounded to the nearest decibel at the end of the computation.)

Continuing the example, this same bus also passes close to a residential area. For this project source, SEL_{ref} is the same as above, as is S. In addition,

V_d = (200 buses)/(15 hours) = 13.33 buses per hour, and
V_n = (20 buses)/(9 hours) = 2.22 buses per hour.

Using Table 6-6, the resulting L_{eq}'s at 50 ft are as follows:

L_{eq}(day) = 57.3 dB and

L_{eq}(night) = 49.5 dB.

Finally, the total day and night traffic results in L_{dn} at 50 ft = 58.3 dB.

End of Example 6-2

6.2.3 Stationary Sources

This section describes the computation of project noise at 50 feet for stationary sources of transit noise, identified in the second column of Table 6-2.

Step 1: Source SELs at 50 feet

Determine the reference SEL at 50 feet for each major source, either by measurement or by table look-up. Table 6-7 provides guidance on which method is preferred for each source type. In general, measurements are preferred for source types that vary significantly from project to project. Table look-up is adequate for source types that do not vary significantly from project to project (crossing signals, for example).

Table 6-7 Source Reference SELs at 50 Feet: Stationary Sources

Source	Reference SEL (dBA)	Approximate L_{max} (dBA)	Prefer Measurements?
Auxiliary Equipment	101	65	YES
Locomotive Idling	116	80	NO
Rail Transit Idling	106	70	NO
Buses Idling	111	75	NO
Curve Squeal	136	100	YES
Car Washes	111	75	YES
Crossing Signals	109	73	NO
Substations	99	63	NO

For sources where measurements are indicated in Table 6-7, Appendix D discusses the measurement procedures, plus procedures for the conversion of these measurements to the reference conditions of Table 6-7.

For sources where table look-up is indicated in Table 6-7, the table provides appropriate reference SELs for one typical noise event at 50 feet and of 1-hour duration (3600 seconds). Approximate L_{max} values are also given in the table for general user information.

Step 2: Conversion to Noise Exposure at 50 feet

Step 1 results in reference SELs at 50 feet. Step 2 is to convert from these reference SELs to actual operating conditions, such as actual event durations and numbers of events, and calculate noise exposure at 50 ft. The steps are:

1. Identify actual source durations and numbers of events. The following percentage changes in durations/numbers will produce an approximate 2-decibel change in noise exposure:

   - 40 percent change in event duration (e.g. from 30 to 42 minutes)
   - 40 percent change in number of events per hour (e.g. from 10 to 14 events per hour).

   In general, where durations/numbers change by these amounts, separate conversions should be made.

2. Establish relevant time periods. For each source, determine the relevant time periods for all receivers that may be affected by the source. For residential receivers, the two time periods of interest to compute L_{dn} are: daytime (7 am to 10 pm) and nighttime (10 pm to 7 am). If the source will affect non-residential receivers, choose the loudest facility hour during noise-sensitive activity.

3. Collect input data. Gather the following input information:

   - Source reference SELs for each relevant source.
   - E, the average duration of one event, in seconds.
   - For residential receivers of interest:

     N_d, the average number of events per hour that occur during the daytime (equals the total number of events between 7 am and 10 pm, divided by 15), and

     N_n, the average number of events per hour that occur during the nighttime (equals the total number of events between 10 pm and 7 am, divided by 9).

   - For non-residential receivers of interest: N, the number of events that occur during each hour of interest, in events per hour.

4. Compute L_{eq} at 50 ft. For each hour of interest, compute the L_{eq} for the source using the first equation in Table 6-8.

5. Compute L_{dn} at 50 ft. If this source will affect any residential receivers of interest, compute the total L_{dn} for the source using the fourth equation in Table 6-8.

Table 6-8 Computation of L_{eq} and L_{dn} at 50 feet: Stationary Sources

Hourly L_{eq} at 50 ft:	$L_{eq}(h) = SEL_{ref} + 10\log(N) + 10\log\left(\frac{E}{3600}\right) - 35.6$
Daytime Leq at 50 ft:	$L_{eq}(day) = L_{eq}(h)\Big\vert_{N=N_d}$
Nighttime Leq at 50 ft:	$L_{eq}(night) = L_{eq}(h)\Big\vert_{N=N_n}$
Ldn at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$

E = duration of one event, in seconds
N = number of events of this type that occur during one hour
N_d = hourly average number of events of this type that occur during daytime (7am to 10pm)
$= \frac{\text{number that occur between 7am and 10pm}}{15}$
N_n = hourly average number of events of this type that occur during nighttime (10pm to 7am)
$= \frac{\text{number that occur between 10pm and 7am}}{9}$

Example 6-3. Computation of L_{eq} and L_{dn} at 50 feet for Stationary Source

A signal crossing lies close to a school that is in session from 8 am to 4 pm on weekdays. Within this time period, the hour of greatest activity for the signal crossing is 8am to 9am. For this project source,

SEL_{ref} = 109 dB

E = 25 seconds (counting both cycles of the signal), and

N = 22.

Using Table 6-8. the resulting $L_{eq}(h)$ = 65.2 from 8 to 9 am. (Computation results should always be rounded to the nearest decibel at the end of the computation.)

This same signal crossing lies close to a residential area. For this project source, SEL_{ref} is the same as above, as is E. In addition,

N_d = (200)/(15 hours) = 13.3 events per hour, and

N_n = (12)/(9 hours) = 1.33 events per hour.

Using Table 6-8, the resulting daytime and nighttime L_{eq}'s are:

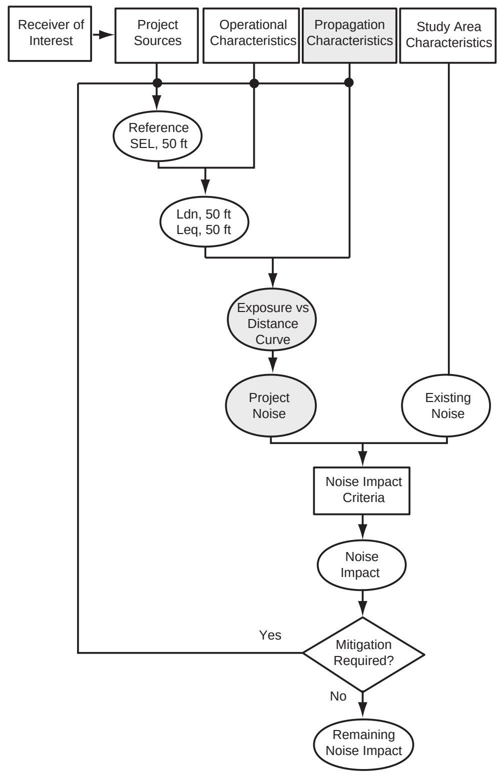
L_{eq}(day) = 63.0 and

L_{eq}(night) = 53.0.

Finally, using the fourth equation in Table 6-8, the resulting L_{dn} at 50 feet = 63.0 dB.

End of Example 6-3

6.3 PROPAGATION CHARACTERISTICS



Once estimates of noise exposure at 50 feet from each source are available, then propagation characteristics must be taken into account to compute the noise exposure at receivers of interest. The steps, shown in Figure 6-4, for this are: 1) determine the propagation characteristics between each source and the receiver of interest; 2) then, draw a noise exposure vs. distance curve outward from each relevant source as a function of distance; and 3) add a final adjustment using the appropriate shielding term based on intervening barriers between source and receiver.

6.3.1 Noise Exposure vs. Distance

The following steps result in a noise exposure vs. distance curve for each project source:

1. Draw several approximate topographic sections, each perpendicular to the path of moving sources or outward from point sources, similar to those shown in Figure 6-5. Draw separate sections, if necessary, to account for significant changes in topography. Use judgment here to prevent an extreme number of different topographic sections. Often, several typical sections will suffice throughout the transit corridor.

2. For each topographic section, use the relationship illustrated in Figure 6-5 to determine the effective path height, H_{eff}, and from it the Ground Factor, G. Larger Ground Factors mean larger amounts of ground attenuation with increasing distance from the source. As shown in the figure, the effective path height depends upon source heights, which are standardized at the bottom of the figure, and upon receiver heights, which can often be taken as 5 feet for both outdoor receivers and first-floor receivers. With these standard heights, only one H_{eff} (and therefore one Ground Factor) results from each cross section. For acoustically "hard" (i.e. non-absorptive) ground conditions, G should be taken to be zero.

3. Then for each L_{dn} and each L_{eq} at 50 feet developed earlier in the analysis, plot a noise exposure vs. distance curve with L_{dn} or L_{eq} represented on the

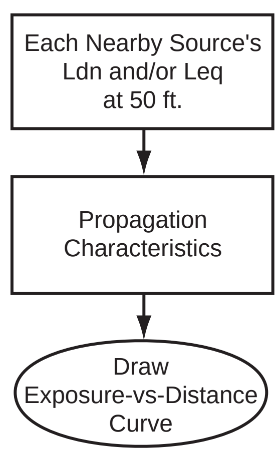


Figure 6-4 Flow Diagram for Determining Project Noise at Receiver Location

vertical axis and distance on the horizontal axis using one of the following equations:

$$L_{dn} \text{ or } L_{eq} = (L_{dn} \text{ or } L_{eq})\Big|_{\text{at 50 ft}} - 20\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{50}\right)$$ for stationary sources

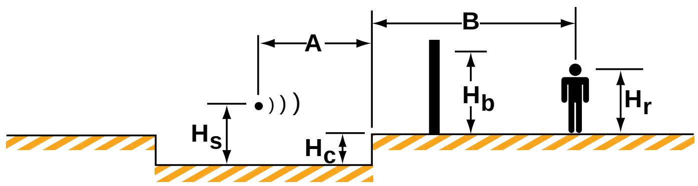
$$= (L_{dn} \text{ or } L_{eq})\Big|_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{42}\right)$$ for fixed-guideway rail car passbys

$$= (L_{dn} \text{ or } L_{eq})\Big|_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{29}\right)$$ for fixed-guideway locomotive and rubber-tired passbys, highway vehicle passbys and horns

IN GENERAL: H_{eff} = sum of average path heights on either side of barrier

$$H_{eff} = \frac{H_s + 2H_b + H_r}{2} \qquad (1)$$

Example 1: Source in shallow cut

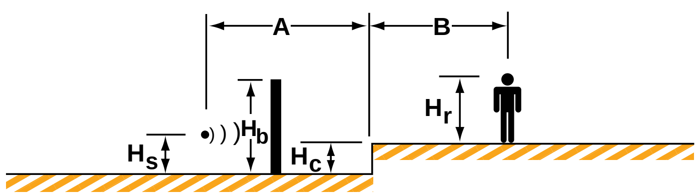


For $B < A/2$,

$$H_{eff} = \frac{H_s + 2H_b + H_c + H_r}{2}$$

* Otherwise use Equation (1)

Example 2: Receiver elevated



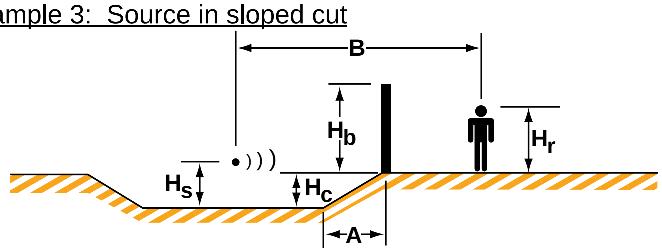
For $H_b > H_c$,

$$H_{eff} = \frac{H_s + 2H_b - H_c + H_r}{2}$$

For $H_b < H_c$,

$$H_{eff} = \frac{H_s + H_c + H_r}{2}$$

Example 3: Source in sloped cut

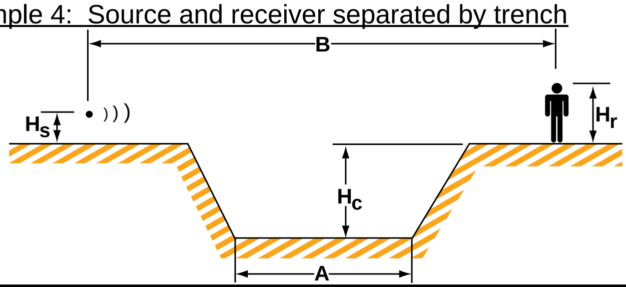


For $A < B/2$,
use Equation (1)

For $A > B/2$,

$$H_{eff} = \frac{H_s + 2H_b + H_c + H_r}{2}$$

Example 4: Source and receiver separated by trench



For $A > B/2$,

$$H_{eff} = \frac{H_s + 2H_c + H_r}{2}$$

For $A < B/2$,

$$H_{eff} = \frac{H_s + H_r}{2}$$

Source Heights:

H_s = 8 ft, trains **with** diesel-electric locomotives
2 ft, trains **without** diesel-electric locomotives
0 ft, automobiles
3 ft, 2-axle city buses
8 ft, 3-axle commuter buses

Note: Equations for H_{eff} remain valid even when $H_b = 0$.

Ground Factor

For soft ground:

$$G = \begin{cases} 0.66 & H_{eff} < 5 \\ 0.75\left(1 - \frac{H_{eff}}{42}\right) & 5 < H_{eff} < 42 \\ 0 & H_{eff} > 42 \end{cases}$$

For hard ground:

$$G = 0$$

Figure 6-5 Computation of Ground Factor G for Ground Attenuation

Example 6-4. Computing Exposure-vs-Distance Curve for Fixed Guideway Source

A commuter train, under the operating conditions in the previous examples, will produce the following levels without horn blowing at 50 feet:

L_{eq}(8-9am) = 72 decibels
L_{dn} = 68 decibels.

For sound propagation over grassland with a flat cross-sectional geometry without a noise barrier, and H_R = 5 feet:

H_{eff} = 6.5 feet

and from Figure 6-5 the resulting Ground Factor is

G = 0.63

Hence the relevant equations from above become:

L_{eq}(8-9am) = 72 - 10 log(D/50) - 6.3 log(D/42)
L_{dn} = 68 - 10 log(D/50) - 6.3 log(D/42)

Plots of these two equations appear in Figure 6-6. From these curves, the noise levels due to this train operation can be determined for a receiver of interest at any distance. The only factor not accounted for is the effect of shielding between source and receiver, which is the subject of the next section.

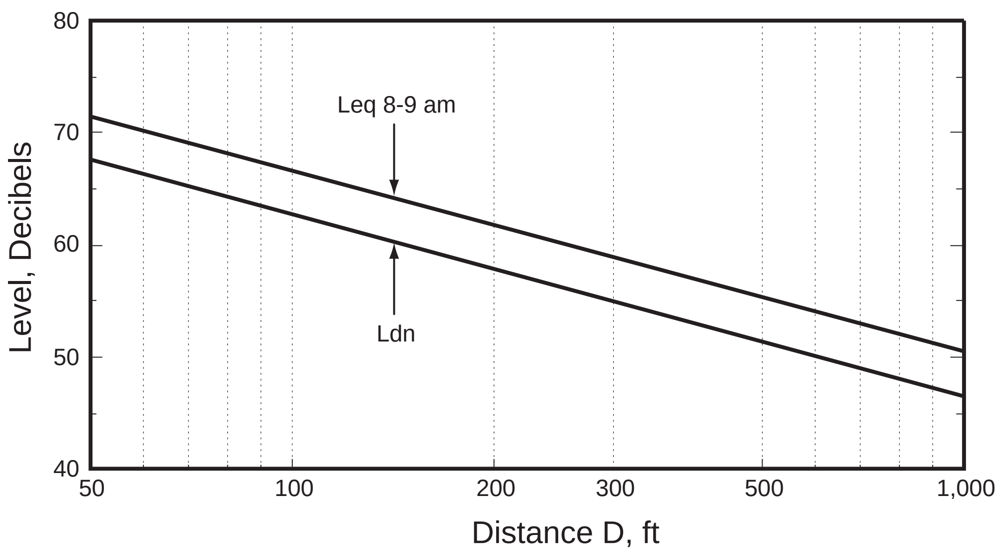


Figure 6-6 Example Exposure vs Distance Curves

End of Example 6-4

6.3.2 Shielding at each Receiver

The resulting L_{eq}'s and L_{dn}'s from the previous section do not include shielding between source and receiver. Such shielding can be due to intervening noise barriers, terrain features, rows of buildings, and dense tree zones. The individual attenuations are computed using the equations from Table 6-9 for barriers and terrain, or from Table 6-10 for rows of buildings and dense tree zones.

The results are attenuation values which are applied to the previously determined project noise at receiver locations (Figure 6-4).

Table 6-9 Computation of Shielding: Barriers and Terrain

Condition	Equation†
For ***non-absorptive*** transit barriers within 5 feet of the track:	$A_{barrier} = \min\left\{12 \text{ or } \left[5.3\times\log(P)+6.7\right]\right\}$
For ***absorptive*** transit barriers within 5 feet of the track:	$A_{barrier} = \min\left\{15 \text{ or } \left[5.3\times\log(P)+9.7\right]\right\}$
For all other barriers, and for protrusion of terrain above the line of sight:	$A_{barrier} = \min\left\{15 \text{ or } \left[20\times\log\left(\frac{2.51\sqrt{P}}{\tanh\left[4.46\sqrt{P}\right]}\right)+5\right]\right\}$
Barrier Insertion Loss	$IL_{barrier} = A_{barrier} - 10\,(G_{NB} - G_B)\log\left(\frac{D}{50}\right)$
Net Attenuation	$A_{shielding} = \max\left\{IL_{barrier} \text{ or } A_{barrier} \text{ or } A_{trees}\right\}$

D = closest distance between the receiver and the source, in feet
P = path length difference, in feet (see figure below)
G_{NB} = Ground factor G computed *without barrier* (see Figure 6-5)
G_B = Ground factor G computed *with barrier* (see Figure 6-5)

† The term "tanh(variable)" stands for hyperbolic tangent, available on many scientific calculators. If "tanh" is not available, then compute E = exp(variable), and set tanh(variable) = (E - 1/E) / (E + 1/E), where exp(variable) is the "exponential" function, also written as e^x on calculator keypads.

BARRIER PARAMETER P

P= A+B-C

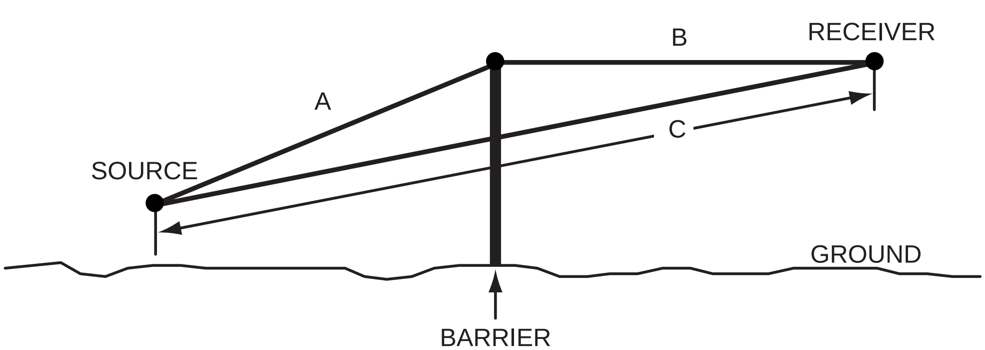


Table 6-10 Computation of Shielding: Rows of Buildings and Dense Tree Zones

Condition	**Equation**
If gaps in the row of buildings constitute less than 35 percent of the length of the row:	$A_{buildings} = \min\left\{10 \text{ or } \left[1.5(R-1)+5\right]\right\}$
If gaps in the row of buildings constitute between 35 and 65 percent of the length of the row:	$= \min\left\{10 \text{ or } \left[1.5(R-1)+3\right]\right\}$
If gaps in the row of buildings constitute more than 65 percent of the length of the row:	$= 0$
Where at least 100 feet of trees intervene between source and receiver, *and* if no clear line-of-sight exists between source and receiver, *and* if the trees extend 15 feet or more above the line-of-sight:	$A_{trees} = \min\left\{10 \text{ or } \frac{W}{20}\right\}$ I
If above conditions do not occur:	$= 0$
NET ATTENUATION	$A_{shielding} = \max\left\{IL_{barrier} \text{ or } A_{buildings} \text{ or } A_{trees}\right\}$

R = number of rows of houses that intervene between source and receiver
W = width of the tree zone along the line-of-site between source and receiver, in feet

Example 6-5. Computation of Shielding

Intervening between the rail corridor and a receiver of interest is the following shielding:

(1) a 15-foot high noise barrier, 40 feet from the closest track and 130 feet from the 5-foot-high receiver, and

(2) a dense tree zone 100 feet thick. The source height H_S = 8 feet, per Figure 6-5.

<u>For the barrier</u>: A = 40.61 feet, B = 130.38 feet, C = 170.03 feet, and therefore P = 0.96 feet, according to Table 6-9.

From Figure 6-5,

H_{eff} (no barrier) = 6.5 feet and

H_{eff} (with barrier) = 21.5 feet,

which result in

G_{NB} = 0.63, and

G_B = 0.37.

From Table 6-9, the resulting barrier attenuation is

$A_{barrier}$ = min{15 *or* 20×log[2.45/tanh(4.37)]+5}

= min{15 *or* 12.8}

= 12.8 dB

and the resulting barrier Insertion Loss is

$IL_{barrier}$ = 12.8 - 10(0.63-0.37)×log(170/50)

```
        =    12.8 - 1.4
        =    11.4 decibels.
```

For the tree zone: The attenuation is estimated to be 5 decibels using Table 6-10. The total shielding is the maximum of the barrier and tree zone shielding, i.e. 11.4 decibels. (Computation results should always be rounded to the nearest decibel at the end of the calculation.)

End of Example 6-5

6.3.3 Combined Propagation Characteristics

The result of combining shielding with geometrical spreading and ground effects involves subtracting the attenuation values obtained from Tables 6-9 and 6-10 from the noise exposure values obtained in Section 6.3.1 at the receiver location.

$L_{dn} \text{ or } L_{eq} = (L_{dn} \text{ or } L_{eq})\big\|_{\text{at 50 ft}} - 20\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{50}\right) - A_{shielding}$	→ for stationary sources
$= (L_{dn} \text{ or } L_{eq})\big\|_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{42}\right) - A_{shielding}$	→ for fixed-guideway rail car passbys
$= (L_{dn} \text{ or } L_{eq})\big\|_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{29}\right) - A_{shielding}$	→ for fixed-guideway locomotive and rubber-tired passbys, highway vehicle passbys and horns

6.4 COMBINED NOISE EXPOSURE FROM ALL SOURCES

Once propagation adjustments have been made for the noise exposure from each source separately, then the sources must be combined to predict the total project noise at the receivers. Table 6-11 contains the equations for combining sources. Total noise exposure is used in Section 6.6 to assess the transit noise at each receiver of interest. Note that in the table a 5 dB penalty is assigned to sources with pure tones that can be particularly annoying to people, such as bells on crossing signals, whistles, and wheel squeal on sharp curves. These sources have noise energy confined to a narrow range of frequency which makes them especially noticeable compared with the ambient, even at relatively low levels. The 5 dB penalty is applied at this point in the procedure when noise levels from individual noise sources are combined as the total project noise. It is important to note that if there is a pure-tone penalty applied, the calculated project noise levels will not correspond to actual measured levels.

Table 6-11 Computing Total Noise Exposure

Total L_{eq} from All Sources Combined, for the hour of interest:	$L_{eq}(total) = 10\log\left(\sum_{\text{all sources}} 10^{L_{eq}/10}\right)$
Total L_{dn} from All sources Combined:	$L_{dn}(total) = 10\log\left(\sum_{\text{all sources}} 10^{L_{dn}/10}\right)$
Pure Tone Adjustment:	C_{adj} = + 5 when pure tones are present (e.g., crossing bells, horns, wheel squeal.)

Example 6-6. Computation of Total Exposure from Combined Sources

A <u>commuter train operation</u> produces the following levels at a certain receiver of interest:

L_{eq}(8-9am) = 72 decibels, and
L_{dn} = 68 decibels.

At this same receiver, a <u>light rail system</u> produces the following levels:

L_{eq}(8-9am) = 69 decibels, and
L_{dn} = 70 decibels.

No other project sources affect this receiver. Using Table 6-11, the receiver's total noise exposures are therefore:

L_{eq}(8-9am, total) = 73.8 decibels, and
L_{dn}(total) = 72.1 decibels.

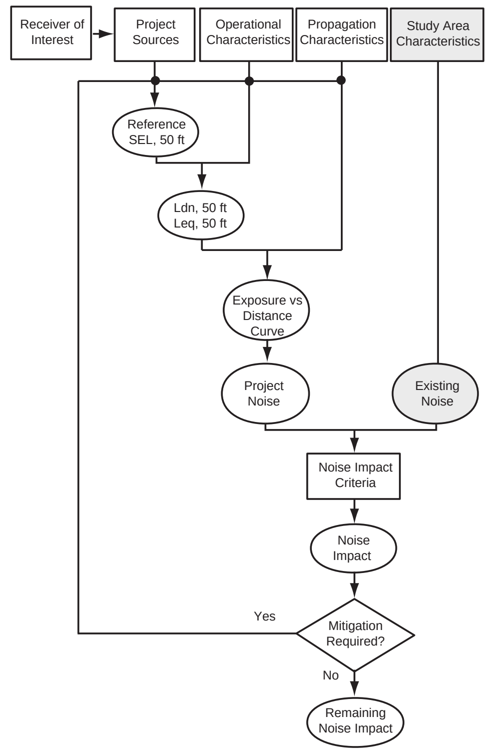
(Computation results should always be rounded to the nearest decibel at the end of the calculation.)

End of Example 6-6

6.5 MAXIMUM NOISE LEVEL FOR FIXED-GUIDEWAY SOURCES

The assessment of noise impact in this manual utilizes either the L_{dn} or the L_{eq} descriptor. As such, in determining impact it is not necessary to determine and tabulate the maximum levels (L_{max}). However, it is often desirable to include computations of L_{max} because it is representative of what people hear at any particular instant and can be measured with a sound level meter. The L_{max} is also the descriptor used in vehicle specifications. Because L_{max} represents the sound level heard during a transportation vehicle passby, people can relate this metric with other noise experienced in the environment. Particularly with rail transit projects, the noise from an individual train passby is quite distinguishable from the existing background noise. A comparison of L_{max} with other sources can be made by referring to Figure 2-8. Thus, although L_{max} is not used in this manual as a basis for assessing noise impact, it can provide people with a more complete description of the noise effects of a proposed project.. Equations for computing L_{max} from SEL are given in Appendix E.

6.6 STUDY AREA CHARACTERISTICS



This section contains procedures to estimate existing noise exposure at each receiver of interest identified previously for use in assessing noise impact. Figure 6-7 shows the flow diagram for estimating ambient noise. First decide whether to measure noise exposure, to compute it from partial measurements, or to estimate it from the table provided in this chapter. Different methods may be used at different receivers along the project. Finally, make the measurements, computations or estimates of the ambient noise at each receiver of interest.

6.6.1 Deciding Whether to Measure, Compute, or Estimate

In general, it is better to measure existing noise than to compute or estimate it. Measurements are more precise than computations and estimates and therefore lead to more precise conclusions concerning noise impact. However, measurements are expensive, are often thwarted by weather, and take significant time in the field. So the choice between measurements and computations/estimates is a choice between the precision of measurements and the convenience of computations/estimates. A mixture of these is generally selected, relying on measurements where the greatest precision is needed.

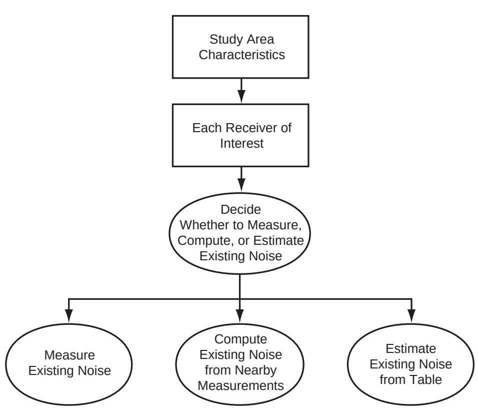


Figure 6-7 Flow Diagram for Determining Existing Noise

A penalty comes along with the convenience of computations and especially of tabular estimates. Because computations/estimates are less precise than measurements, the procedures for them (in Appendix C) are purposely conservative. They are designed to underpredict the ambient noise somewhat, and thereby overpredict relative noise impact. When more precise impact projections are desired, measurements should be chosen instead.

The choice among measurements, computations, or estimates depends partly upon the type of land use. For non-residential land uses with daytime use only, it is usually adequate to measure only one hour's ambient L_{eq}, preferably during the hour when project activity is likely to cause the greatest impact. This is relatively easy to measure. On the other hand, in residential areas that are not near major roadways, a full day's ambient L_{dn} is usually required. The following sections describe the approaches to be taken in each case and how to combine the results to characterize the existing ambient conditions.

6.6.2 Noise Exposure Measurements

Full one-hour measurements are the most precise way to determine ambient noise exposure for non-residential receivers. For residential receivers, full 24-hour measurements are most precise. Such full-duration measurements are preferred over other options, where time and study funds allow. The following procedures apply to full-duration measurements:

- For non-residential land uses, measure a full hour's L_{eq} at the receiver of interest, on at least two non-successive weekdays (generally between noon Monday and noon Friday). Select the hour of the day when the maximum project activity is expected to occur.
- For residential land uses, measure a full 24-hour's L_{dn} at the receiver of interest, for a single weekday (generally between noon Monday and noon Friday).
- Use judgment in positioning the measurement microphone. Location of the microphone at the receiver depends upon the proposed location of the transit noise source. If, for example, a new rail line will be in front of the house, do not locate the microphone in the back yard. Figure 6-8 illustrates recommended measurement positions for various locations of the project, with respect to the house and the existing source of ambient noise.
- Undertake all measurements in accordance with good engineering practice following guidelines given in ASTM and ANSI Standards.[2][3]

6.6.3 Noise Exposure Computations from Partial Measurements

Often measurements can be made at some of the receivers of interest and then these measurements can be used to estimate noise exposure at nearby receivers. In other situations, several hourly L_{eq}'s can be measured at a receiver and then the L_{dn} computed from these. Both of these options require experience and knowledge of acoustics to select representative measurement sites.

Measurements at one receiver can be used to represent the noise environment at other sites, but only when proximity to major noise sources is similar among the sites. For example, a residential neighborhood with otherwise similar homes may have greatly varying noise environments: one part of the neighborhood may be located where the ambient noise is clearly due to highway traffic; a second part, toward the interior of the neighborhood, may have highway noise as a factor but also a significant contribution from other community noise; and a third part located deep into the residential area will have local street traffic and other community activities dominate the ambient noise. In this example, three or more measurement sites would be required to represent the varying ambient noise conditions in a single neighborhood.

Typical situations where representative measurement sites can be used to estimate noise levels at other sites occur when both share the following characteristics:

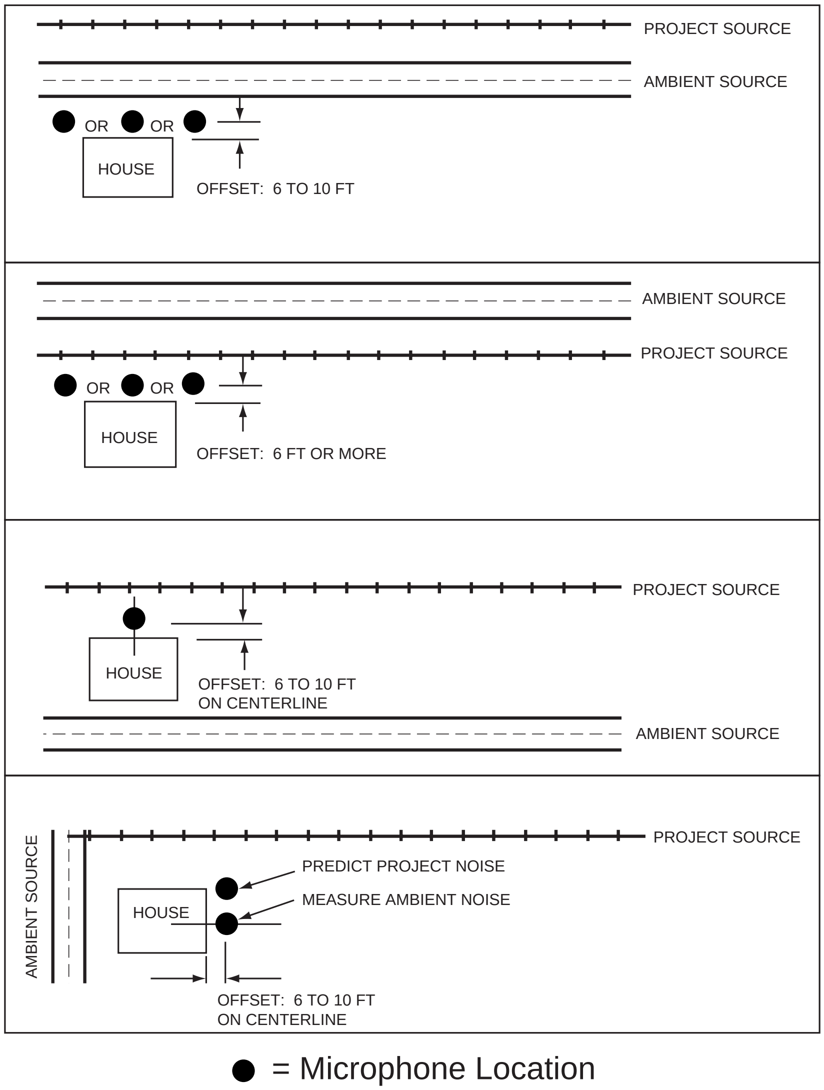


Figure 6-8 Recommended Microphone Locations for Existing Noise Measurements

- proximity to the same major transportation noise sources, such as highways, rail lines and aircraft flight patterns;
- proximity to the same major stationary noise sources, such as power plants, industrial facilities, rail yards and airports;
- similar type and density of housing, such as single-family homes on quarter-acre lots and multi-family housing in apartment complexes.

Acoustical professionals are often adept at such computations from partial data and are encouraged here to use their experience and judgment in fully utilizing the measurements in their computations. Required here is an attempt to somewhat underestimate ambient noise in the process, to account for reduced precision compared to full noise measurements.

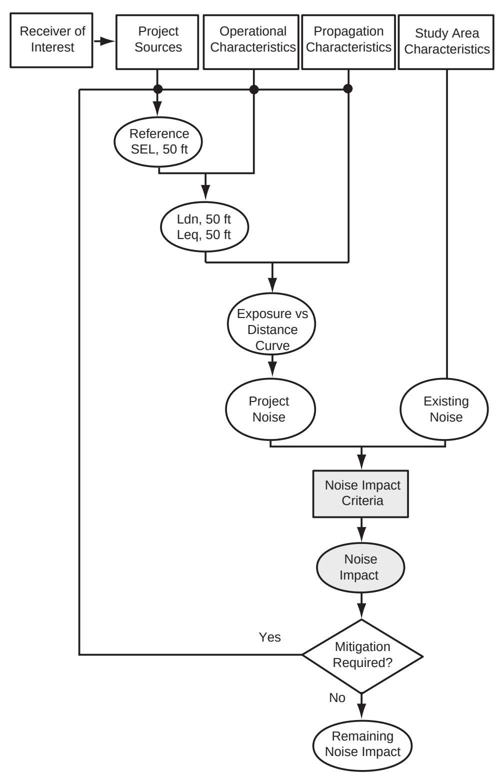
On the other hand, people lacking the background in acoustics are encouraged to use the procedures in Appendix C to accomplish this same aim. These procedures are an attempt to systematize such computations from partial measurements. The methods in Appendix C are designed with a safety factor to underestimate ambient noise to account for reduced precision compared to full noise measurements.

6.6.4 Estimating Existing Noise Exposure

The least precise way to determine noise exposure is to estimate it from a table. This method is appropriate for the General Noise Assessment. The tabular estimate is not generally recommended for a detailed noise analysis. However, it can be used in the absence of better data for locations where roadways or railroads are the predominant ambient noise source. Table 5-7 presents these ambient levels. In general, the tabulated values of noise exposure are underestimates. As explained above, underestimates here are intended to compensate for the reduced precision of the estimated ambient levels compared to the options that incorporate full or partial measurements.

6.7 NOISE IMPACT ASSESSMENT

This section contains procedures for the assessment of project noise impact, utilizing the ambient noise and project noise results from the previous analysis. Figure 6-9 is the flow diagram for the steps in the assessment process. Two assessment methods are included:



- Rail and Bus Facilities: This category includes all rail projects (e.g., rail rapid transit, light rail transit, commuter rail, and automated guideway transit), including rail transit projects built within a highway or railroad corridor. Also included are fixed facilities such as storage and maintenance yards, passenger stations and terminals, parking facilities, substations, etc. Bus facilities include separate roadways built exclusively for buses. Bus operations on local streets and highways are included where the project does not significantly change the roadway capacity.

- Highway/Transit Projects: Projects in this category involve bus facilities with either modifications to existing roadways or construction of new roadways, resulting in a significant change of highway capacity. Included are lane additions or lane reconfigurations on existing highways to accommodate buses and/or HOV's. Also included are newly-constructed highways incorporating a transit or HOV component, such as dedicated bus/HOV lanes.

6.7.1 Assessment for Rail and Bus Facilities

For these types of projects, noise impact is assessed at each receiver of interest using the criteria for transit projects described in Chapter 3. The assessment procedure is as follows:

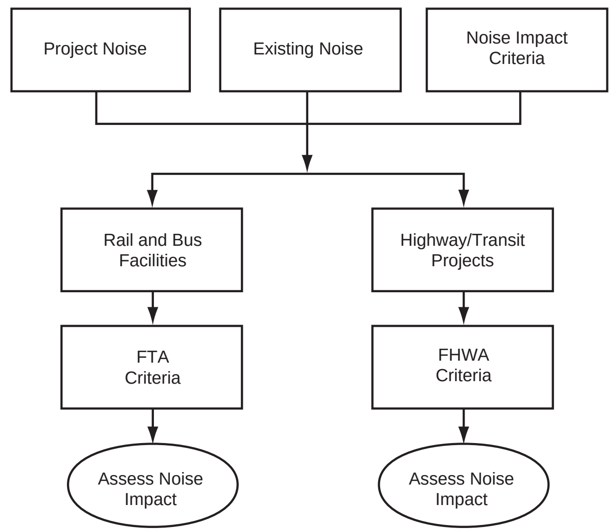


Figure 6-9 Flow Diagram for Noise Impact Assessment

1. Tabulate existing ambient noise exposure (rounded to the nearest whole decibel) at all receivers of interest from earlier in the analysis.
2. Tabulate project noise exposure at these receivers from the analytical procedures described in this chapter.
3. Determine the level of noise impact (No Impact, Impact or Severe Impact) following the procedures in Chapter 3.
4. Document the results in noise-assessment inventory tables. These tables should include the following types of information:
   - Receiver identification and location
   - Land-use description
   - Number of noise-sensitive sites represented (number of dwelling units in residences or acres of outdoor noise-sensitive land)
   - Closest distance to the project
   - Existing noise exposure
   - Project noise exposure
   - Level of noise impact (No Impact, Impact or Severe Impact)

   In addition, these tables should also indicate the total number of receivers, especially numbers of dwelling units, predicted to experience Impact or Severe Impact.
5. Illustrate the areas of Impact and Severe Impact on maps or aerial photographs. This could consist of project noise contours on the maps or aerial photographs, along with the impact areas. This is done by delineating two impact lines: one between the areas of No Impact and Impact and the second between Impact and Severe Impact. Such impact contours would be similar to those estimated in the General Assessment of Chapter 5, but with greater precision. If desired to conform with the practices of another

agency, the contouring may perhaps include several contour lines of constant project noise, such as L_{dn} 65, L_{dn} 70 and L_{dn} 75.

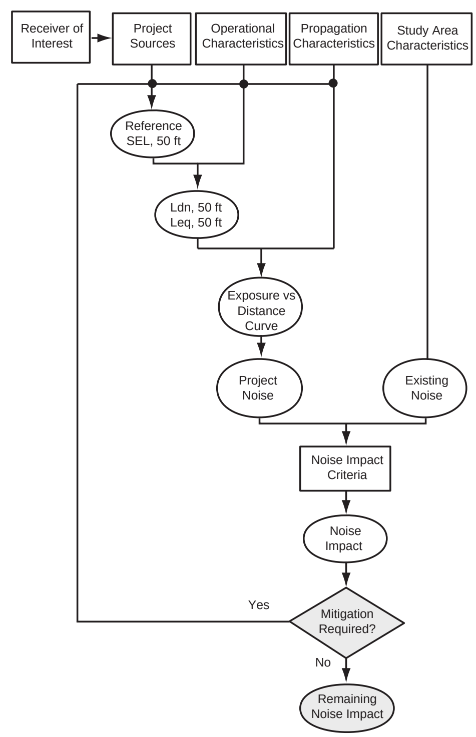
6. Discussion of the magnitude of the impacts is an essential part of the assessment. The magnitude of noise impact is defined by the two threshold curves delineating onset of Impact and Severe Impact. Interpretation of the two impact regimes is discussed in Chapter 3.

6.7.2 Assessment for Highway/Transit Projects

For highway/transit projects, the FHWA procedures and Noise Abatement Criteria should be used. [4][5][6] FHWA's current computation method resides within its computer program Stamina 2.0/OPTIMA. [7] This computation method is now being substantially revised. The revised method is scheduled to be promulgated by FHWA in late 1995 or early 1996, in the form of a new computer program, FHWA TNS (Traffic Noise Software).

6.8 MITIGATION OF NOISE IMPACT

Where the noise impact assessment shows either Severe Impact or Impact, this section provides guidance on considering and implementing noise reduction measures. The following sub-sections discuss the factors considered in determining the need for noise mitigation. Figure 6-10 contains the corresponding flow diagram.



6.8.1 Determining the Need for Noise Mitigation

Because intrusive noise is frequently among the most significant environmental concerns of planned mass transit projects, FTA, working with the project sponsor, makes every reasonable effort to reduce predicted noise to levels deemed acceptable for affected noise-sensitive land uses. The Noise Impact Criteria in Chapter 3 provide the framework for identifying the magnitude of the impact. Then, the need for noise mitigation is determined based on the magnitude and consideration of factors specifically related to the proposed project and affected land uses.

Given the statutory basis for planning and designing mass transit projects which are environmentally compatible, noise impacts in the Severe range represent the most compelling need for mitigation. However, mitigation is not the first-order concern when Severe impacts are predicted. First, the project sponsor should evaluate alternative locations/alignments to determine whether it is feasible to avoid Severe impacts altogether. In densely populated urban areas, this evaluation of alternative locations may reveal a trade-off of one group of impacted noise-sensitive sites for another – especially for surface rail alignments passing through built-up

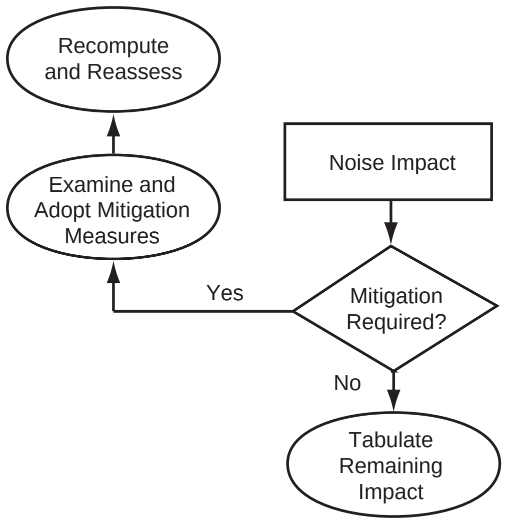


Figure 6-10 Flow Diagram for Mitigation

areas. However, this is not always the case; projects which are characterized more as point sources of noise than line sources often present a greater opportunity for selecting alternative sites. Note that this guidance manual and FTA's environmental impact regulation both attempt to encourage the selection of project sites which are compatible with surrounding development. The regulation designates certain projects as categorical exclusions when located in areas with compatible land use. In this manual, the list of noise-sensitive land uses in Chapter 3 does not include most commercial and industrial land uses, thus obviating the need to consider noise mitigation in areas with predominantly commercial or industrial use.

Predicted impacts in the Severe range are considered to be significant adverse effects in the context of NEPA and will trigger the requirement for an environmental impact statement, irrespective of any other environmental effects associated with the project. Severe impacts are also considered to be an "adverse effect" as this term is used in the regulations governing Section 106 of the National Historic Preservation Act (36 CFR 800). In addition, impacts of this magnitude would normally constitute a "constructive use" of properties afforded protection by Section 4(f) of the DOT Act and implementing regulations (23 CFR 771.135 (p)). The examination of alternatives that would avoid, minimize, or mitigate impacts of this magnitude is explicitly required in the compliance process for all of these statutes.

Only when it has been demonstrated that avoidance is not practical does the study progress to measures which would minimize the adverse affect. Where Severe impacts are predicted, the goal is to gain substantial noise reduction through the use of mitigation measures; it is not simply to reduce the predicted levels to just below the Severe impact threshold. Since FTA must make a judgment on whether the proposed mitigation is feasible and prudent, the study must include the noise reduction potential of the options as well as the effects on transit service, capital and operating costs and any other relevant factors, for example, new environmental impacts originating from the change.

Though of a lesser magnitude, projected noise levels in the Impact range will still require consideration and adoption of mitigation measures when it is considered reasonable. While it might be simpler conceptually to establish a definitive level dictating the need for mitigation, from a practical standpoint there should be an area where professional judgment comes into play. The range of Impact delineates an area where project planners are alerted to the potential for adverse impacts and complaints from the community and must then carefully consider project specifics as well as details concerning the affected properties in determining the need for mitigation.

The following considerations will help project planners and FTA staff in reaching these determinations:

- The number of noise-sensitive sites affected at this level. A row or cluster of residences adjacent to a rail transit line establishes a greater need for mitigation than one or several isolated residences in a mixed-use area.
- The increase over existing noise levels. Since the noise impact criteria are delineated as bands or ranges, project noise can vary 5-7 decibels within the band of Impact at any specific ambient noise level. If the project and ambient noise plot falls just below the Severe range (in Figure 3-1), the need for mitigation is strongest. Similarly, if the plot falls just above the No Impact threshold, the need for mitigation is lessened.
- The noise sensitivity of the property. Table 3-2 gives a comprehensive list of noise-sensitive land uses; yet there can be differences in noise sensitivity depending on individual circumstances. For example, parks and recreational areas vary in their sensitivity depending on the type of use they experience (active vs. passive recreation) and the settings in which they are located.
- Effectiveness of the mitigation measure(s). What is the magnitude of the noise reduction that can be achieved? Are there conditions which limit effectiveness, for example, noise barrier effectiveness for a multi-story apartment building?
- The potential to reduce high preexisting noise exposure due to transportation sources. Sometimes, an existing transportation facility causes intrusive noise and a proposed project sharing the same right-of-way presents the opportunity to lower cumulative noise levels. When a shared right-of-way situation occurs, this type of environmental enhancement is strongly encouraged.
- Community views. This manual provides the methodology to make an objective assessment of the need for noise mitigation. However, the views of the community cannot be overlooked. The NEPA compliance process provides the framework for hearing the community's concerns about a proposed project and then making a good-faith effort to address those concerns. Many projects can be expected to have projected noise levels within the Impact range and decisions regarding mitigation should be made only after considering input from the affected public, relevant government agencies and community organizations. There have been cases where the solution to the noise problem – a sound barrier – was rejected by community members because of perceived adverse visual effects.
- Special protection provided by law. Section 4(f) of the DOT Act and Section 106 of the Historic Preservation Act come into play frequently during the environmental review of transit projects. Section 4(f) protects historic sites and publicly-owned parks, recreation areas and wildlife refuges. Section 106 protects historic and archeological resources. No blanket statement can be made about whether project noise within the Impact range constitutes "constructive use" under Section 4(f) or "adverse effect" under Section 106. Nor can it be said that mitigation is always required when protected resources are impacted at this level. As previously noted, some historic properties are not noise-sensitive at all. It is clear, though, that the regulatory processes stemming from these statutes require coordination and consultation with relevant agencies and organizations. Their views on the project's impact on protected

resources are given careful consideration by FTA and the project sponsor, and their recommendations may influence the decision to adopt noise reduction measures.

The decision to include noise mitigation in a project is made by FTA after public review of the environmental document. It is reached in consultation with the project sponsor. If mitigation measures are deemed necessary to satisfy the statutory requirements, they will be incorporated as an integral part of the project, and subsequent grant documents will reference these measures as contractual obligations on the part of the project sponsor.

6.8.2 Noise Mitigation Measures

In general, mitigation options are chosen from those below, and then portions of the project noise are recomputed and reassessed to account for this mitigation. This allows an accurate prediction of the level of noise reduction. It is important to emphasize that the source levels used in this manual are typical of systems designed according to current engineering practice, but they do not include special noise control features that could be incorporated in the specifications at extra cost. This approach provides a reasonable analysis of conditions without mitigation measures. If special features that result in noise reductions are included in any of the predictions, then the Federal environmental document must include a commitment by the project sponsor to adopt such treatments before the project is approved for construction.

Mitigation of noise impact from transit projects may involve treatments at the three fundamental components of the noise problem: (1) at the noise source, (2) along the source-to-receiver propagation path or (3) at the receiver. Generally, the transit property has authority to treat the source and some elements of the propagation path, but may have little or no authority to modify anything nearby the receiver.

A list of practical noise mitigation measures that should be considered by project sponsors is summarized in Table 6-12 and discussion of the measures follows. This table is organized according to whether the treatment applies to the source, path or receiver, and includes estimates of the acoustical effectiveness of each treatment.

6.8.3 Source Treatments

Vehicle Noise Specifications (Rail and Bus)

Among the most effective noise mitigation treatments is noise control at the outset, during the specification and design of the transit vehicle. Such source treatments apply to all transit modes. By developing and enforcing stringent but achievable noise specifications, the transit property takes a major step in controlling noise everywhere on the system. It is important to ensure that the noise levels quoted in the specifications are achievable with the application of best available technology during the development of the vehicle and reasonable in light of the noise reduction benefits and costs.

Effective enforcement includes significant penalties for non-compliance with the specifications. The noise mitigation achieved by source treatment depends on the quality of installation and maintenance. In the past,

Table 6-12 Transit Noise Mitigation Measures

Application	Mitigation Measure		Effectiveness
SOURCE	Stringent Vehicle & Equipment Noise Specifications		Varied
	Operational Restrictions		Varied
	Resilient or Damped Wheels*	For Rolling Noise on Tangent Track:	2 dB
		For Wheel Squeal on Curved Track:	10-20 dB
	Vehicle Skirts*		6-10 dB
	Undercar Absorption*		5 dB
	Spin-slide control (prevents flats)*		**
	Wheel Truing (eliminates wheel flats)*		**
	Rail Grinding (eliminates corrugations)*		**
	Turn Radii greater than 1000 ft*		(Avoids Squeal)
	Rail Lubrication on Sharp Curves*		(Reduces Squeal)
	Movable-Point Frogs (reduce rail gaps at crossovers)*		(Reduces Impact Noise)
	Engine Compartment Treatments (Buses)		6-10 dB
PATH	Sound Barriers close to Vehicles		6-10 dB
	Sound Barriers at ROW Line		3-5 dB
	Alteration of Horiz. & Vert. Alignments		Varied
	Acquisition of Buffer Zones		Varied
	Ballast on At-Grade Guideway*		3 dB
	Ballast on Aerial Guideway*		5 dB
	Resilient Track Support on Aerial Guideway		Varied
RECEIVER	Acquisition of Property Rights for Construction of Sound Barriers		5-10 dB
	Building Noise Insulation		5-20 dB

* Applies to Rail Projects Only
** These mitigation measures work to maintain a rail system in its as-new condition. Without incorporating them into the system, noise levels could increase up to 10 dB.

transit vehicles have been delivered that did not meet a noise specification, causing complaints from the public and requiring additional noise mitigation measures applied to the wayside.

Stationary Source Noise Specifications

Stringent but achievable noise specifications also represent an effective approach for mitigating noise impact from stationary sources associated with a transit system. Such equipment includes fixed plant equipment (for example, transformers and mechanical equipment) as well as grade-crossing signals. For example, noise impact from grade-crossing signals can be mitigated by specifying equipment that sets the level of the warning signal lower where ambient noise is lower, that minimizes the signal duration, and that minimizes signal noise in the direction of noise-sensitive receivers.

Wheel Treatments (Rail)

A major source of noise from steel-wheel/steel-rail systems is the wheel/rail interaction which has three components: roar, impact and squeal. Roar is the rolling noise caused by small-scale roughness on the wheel tread and rail running surface. Impacts are caused by discontinuities in the running surface of the rail or by a flat spots on the wheels. Squeal occurs when a steel-wheel tread or its flange rubs across the rail, setting up resonant vibrations in the wheel which cause it to radiate a screeching sound. Various wheel designs and other mitigation measures exist to reduce the noise from each of these three mechanisms.

- **Resilient and damped wheels** serve to reduce rolling noise, but only slightly. A typical reduction is 2 decibels on tangent track. This treatment is more effective in eliminating wheel squeal on tight turns; reductions of 10 to 20 decibels for high frequency squeal noise is typical.

- **Spin-slide control systems,** similar to anti-locking brake systems (ABS) on automobiles, reduce the incidence of wheel flats, a major contributor of impact noise. Trains with smooth wheel treads can be up to 20 decibels quieter than those with wheel flats. To be effective, the anti-locking feature should be in operation during all braking phases, including emergency braking. Wheel flats are more likely to occur during emergency braking than during dynamic braking.

- **Maintenance** of wheels by truing eliminates wheel flats from the treads and restores the wheel profile. As discussed above, wheel flats are a major source of impact noise. A good maintenance program includes the installation of equipment to detect and correct wheel flats on a continuing basis.

Vehicle Treatments (Rail and Bus)

Vehicle noise mitigation measures are applied to the various mechanical systems associated with propulsion, ventilation and passenger comfort.

- **Propulsion systems** of transit vehicles include diesel engines, electric motors and diesel-electric combinations. Noise from the propulsion system depends on the type of unit and how much noise mitigation is built into the design. Mufflers on diesel engines are generally required to meet noise specifications; however, mufflers are generally practical only on buses, not on locomotives. Control of noise from engine casings may require shielding the engine by body panels without louvers, dictating other means of cooling and ventilation.

- **Ventilation** requirements for vehicle systems are related to the noise generated by a vehicle. Fan noise often remains a major noise source after other mitigation measures have been instituted, because of the need to have direct access to cooling air. This applies to heat exchangers for electric traction motors, diesel engines and air-conditioning systems. Fan quieting can be accomplished by installation of one of several new designs of quiet, efficient fans. Forced-air cooling on electric traction motors can be quieter than self-cooled motors at operating speeds. Placement of fans on the vehicle can make a significant difference in the noise radiated to the wayside, or to patrons on the station platforms.

- The **vehicle body** design can provide shielding and absorption of the noise generated by the vehicle components. Acoustical absorption under the car has been demonstrated to provide up to 5 decibels of mitigation for wheel/rail noise and propulsion-system noise on rapid transit trains. Similarly, vehicle skirts over the wheels can provide more than 5 decibels of mitigation. By carrying their own noise barriers, vehicles with these features can provide cost-effective noise reduction.

Guideway Support (Bus and Rail)

The smoothness of the running surface is critical in the mitigation of noise from a moving vehicle. Smooth roadways for buses and smooth rail running surfaces for rail systems are required. In either case, roughness of the street, roadway and rail surfaces can be eliminated by resurfacing roads or grinding rails, thereby reducing noise levels by up to 10 decibels. Bridge expansion joints are also a source of noise for rubber-tire vehicles. This source of noise can be reduced by placing expansion joints on an angle or by specifying the serrated type rather than joints with right-angle edges.

In the case of steel-wheel/steel-rail systems with non-steerable trucks and sharp turns, squeal can be mitigated by installation of rail lubricators. Squeal in such systems can usually be eliminated altogether by designing all turn radii to be greater than 1000 feet, or 100 times the truck wheelbase, whichever is less.

Operational Restrictions (Rail and Bus)

Two changes in operations that can mitigate noise are the lowering of speed and the reduction of nighttime (10 pm to 7 am) operations. Because noise from most transit vehicles depends on speed, a reduction of speed results in lower noise levels. The effect can be considerable. For example, the speed dependency of steel-wheel/steel-rail systems for L_{eq} and L_{dn} (see Table 6-4) results in a 6 dB reduction for a halving of the speed. Complete elimination of nighttime operations has a strong effect on reducing the L_{dn}, because nighttime noise is increased by 10 decibels when calculating L_{dn}. Restrictions on operations are usually not feasible because of service demands. However, if early morning idling can be curtailed to the mimimum necessary, this can have a measurable effect on L_{dn}.

Other operational restrictions that can reduce noise impact for light rail and commuter rail systems include minimizing or eliminating horn blowing and other types of warning signals at grade crossings. However, these mitigation options are often limited by safety considerations.

6.8.4 Path Treatments

Sound Barriers

Sound barriers are effective in mitigating noise when they break the line-of-sight between source and receiver. The mechanism of sound shielding is described in Chapter 2. The necessary height of a barrier depends on such factors as the source height and the distance from the source to the barrier. For example, if a barrier is located very close to a rapid transit train, it need only be 3 to 4 feet above the top of rail to be effective. Barriers close to vehicles can provide noise reductions of 6 to 10 decibels. For barriers further away, such as on the right-of-way line or for trains on the far track, the height must be increased to provide equivalent effectiveness. Otherwise, the effectiveness can drop to 5 decibels or less, even if the barrier breaks the line of sight. Where the barrier is very close to the transit vehicle or where the vehicles travel between sets of parallel barriers, barrier effectiveness can be increased by as much as 5 decibels by applying sound-absorbing material to the inner surface of the barrier.

Similarly, the length of the barrier wall is important to its effectiveness. The barrier must be long enough to screen out a moving train along most of its visible path. This is necessary so that train noise from beyond the ends of the barrier will not severely compromise noise-barrier performance at sensitive locations.

Noise barriers can be made of any outdoor weather-resistant solid material that meets a minimum sound transmission loss requirement. The sound requirements are not particularly strict; they can be met by many commonly available materials, such as 16-gauge steel, 1-inch thick plywood, and any reasonable thickness of concrete. The normal minimum requirement is a surface density of 4 pounds per square foot. To hold up under wind loads, structural requirements are more stringent. Achieving the maximum possible noise reduction requires careful sealing of gaps between barrier panels and between the barrier and the ground or elevated guideway deck.

Costs for noise barriers, based on highway installations, range from $15 to $25 per square foot of installed noise barrier at-grade, not counting design and inspection costs. Installation on aerial structure may be a factor of two greater, especially if the structure has to be strengthened to accommodate the added weight and wind load.

Location of a transit alignment in cut, as part of grade separation, can accomplish the same result as installation of a noise barrier at-grade or on aerial structure. The walls of the cut serve the same function as barrier walls in breaking the line-of-sight between source and receiver.

Noise Buffers

Because noise levels attenuate with distance, one noise mitigation measure is to increase the distance between noise sources and the closest sensitive receivers. This can be accomplished by locating alignments away from sensitive sites. Acquisition of land or purchasing easements for noise buffer zones is an option that may be considered if impacts due to the project are severe enough.

Ground Absorption

Propagation of noise over ground is affected by whether the ground surface is absorptive or reflective. Noise from vehicles on the surface is strongly affected by the character of the ground in the immediate vicinity of the vehicle. Roads and streets for buses are hard and reflective, but the ground at the side of a road has a significant effect on the propagation of noise to greater distance. This effect is described in Chapter 2 and taken into account in the computations of this chapter. Guideways for rail systems can be either reflective or absorptive, depending on whether they are concrete or ballast. Ballast on a guideway can reduce train noise 3 decibels at-grade and up to 5 decibels on aerial structure.

6.8.5 Receiver Treatments

Sound Barriers

In certain cases it may be possible to acquire limited property rights for the construction of sound barriers at the receiver. As discussed above, barriers need to break the line-of-sight between the noise source and the receiver to be effective and are most effective when they are closest to either the source or the receiver. Computational procedures for estimating barrier effectiveness are given earlier in this chapter.

Building Insulation

In cases where rights-of-way are tight, the only practical noise mitigation measure may be to provide sound insulation for the building. The most effective treatments are to caulk and seal gaps in the building envelope and to install new windows that are specially designed to meet acoustical transmission-loss requirements. Such windows are usually made of multiple layers of glass and are beneficial for heat insulation as well as for sound insulation. Depending on the quality of the original windows, such treatments can provide noise reductions of 5 to 20 decibels. These windows are usually non-operable so that central ventilation or air conditioning is needed.

Additional building sound insulation, if needed, can be provided by sealing vents and ventilation openings and relocating them to a side of the building away from the noise source. Much practical experience with sound insulation of buildings has been gained through grants for noise mitigation to local airport authorities by the Federal Aviation Administration.

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7. BASIC GROUND-BORNE VIBRATION CONCEPTS

Ground-borne vibration can be a serious concern for nearby neighbors of a transit system route or maintenance facility, causing buildings to shake and rumbling sounds to be heard. In contrast to airborne noise, ground-borne vibration is not a common environmental problem. It is unusual for vibration from sources such as buses and trucks to be perceptible, even in locations close to major roads. Some common sources of ground-borne vibration are trains, buses on rough roads, and construction activities such as blasting, pile driving and operating heavy earth-moving equipment.

The effects of ground-borne vibration include feelable movement of the building floors, rattling of windows, shaking of items on shelves or hanging on walls, and rumbling sounds. In extreme cases, the vibration can cause damage to buildings. Building damage is not a factor for normal transportation projects with the occasional exception of blasting and pile driving during construction. Annoyance from vibration often occurs when the vibration exceeds the threshold of perception by 10 decibels or less. This is an order of magnitude below the damage threshold for normal buildings.

The basic concepts of ground-borne vibration are illustrated for a rail system in Figure 7-1. The train wheels rolling on the rails create vibration energy that is transmitted through the track support system into the transit structure. The amount of energy that is transmitted into the transit structure is strongly dependent on factors such as how smooth the wheels and rails are and the resonance frequencies of the vehicle suspension system and the track support system. These systems, like all mechanical systems, have resonances which result in increased vibration response at certain frequencies, called natural frequencies.

The vibration of the transit structure excites the adjacent ground creating vibration waves that propagate through the various soil and rock strata to the foundations of nearby buildings. The vibration propagates from the foundation throughout the remainder of the building structure. The maximum vibration amplitudes of the floors and walls of a building often will be at the resonance frequencies of various components of the building.

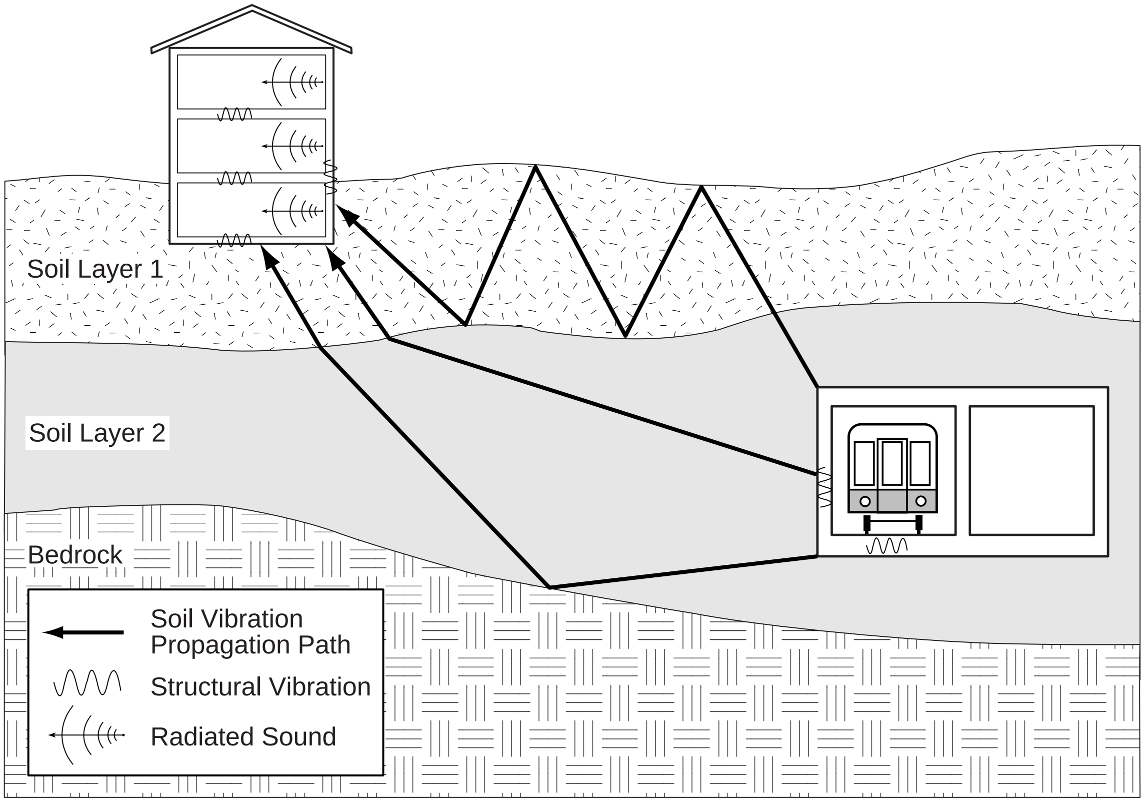


Figure 7-1 Propagation of Ground-Borne Vibration into Buildings

The vibration of floors and walls may cause perceptible vibration, rattling of items such as windows or dishes on shelves, or a rumble noise. The rumble is the noise radiated from the motion of the room surfaces. In essence, the room surfaces act like a giant loudspeaker. This is called ground-borne noise.

Ground-borne vibration is almost never annoying to people who are outdoors. Although the motion of the ground may be perceived, without the effects associated with the shaking of a building, the motion does not provoke the same adverse human reaction. In addition, the rumble noise that usually accompanies the building vibration can only occur inside buildings.

7.1 DESCRIPTORS OF GROUND-BORNE VIBRATION AND NOISE

7.1.1 Vibratory Motion

Vibration is an oscillatory motion which can be described in terms of the displacement, velocity, or acceleration. Because the motion is oscillatory, there is no net movement of the vibration element and the average of any of the motion descriptors is zero. Displacement is the easiest descriptor to understand. For a vibrating floor, the displacement is simply the distance that a point on the floor moves away from its static position. The velocity represents the instantaneous speed of the floor movement and acceleration is the rate of change of the speed.

Although displacement is easier to understand than velocity or acceleration, it is rarely used for describing ground-borne vibration. This is because most transducers used for measuring ground-borne vibration use either velocity or acceleration, and, even more important, the response of humans, buildings, and equipment to vibration is more accurately described using velocity or acceleration.

7.1.2 Amplitude Descriptors

Vibration consists of rapidly fluctuating motions with an average motion of zero. There are several different methods that are used to quantify vibration amplitude. These are shown in Figure 7-2. The raw signal is the lighter weight curve in the top graph. This is the instantaneous vibration velocity which fluctuates positive and negative about the zero point. The peak particle velocity (PPV) is defined as the maximum instantaneous positive or negative peak of the vibration signal. PPV is often used in monitoring of blasting vibration since it is related to the stresses that are experienced by buildings.

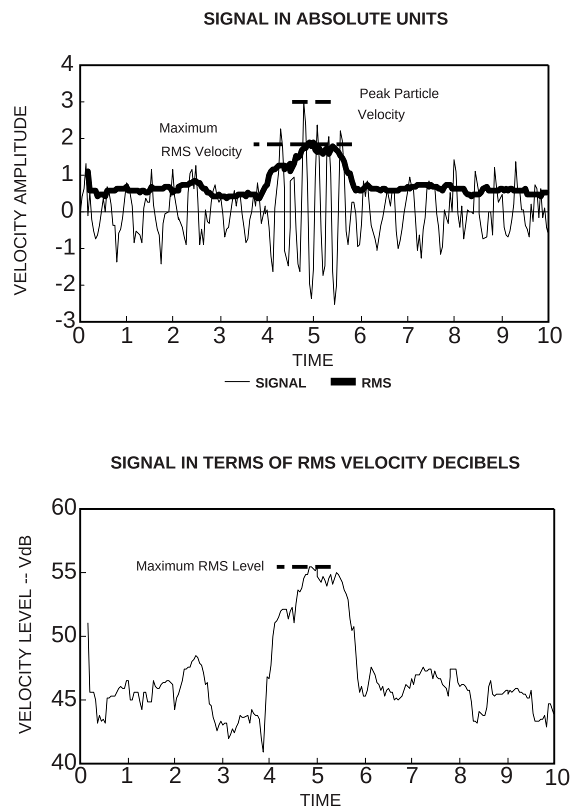


Figure 7-2 Different Methods of Describing a Vibration Signal

Although peak particle velocity is appropriate for evaluating the potential of building damage, it is not suitable for evaluating human response. It takes some time for the human body to respond to vibration signals. In a sense, the human body responds to an average vibration amplitude. Because the net average of a vibration signal is zero, the root mean square (rms) amplitude is used to describe the "smoothed" vibration amplitude. The root mean square of a signal is the average of the squared amplitude of the signal. The average is typically calculated over a 1 second period. The rms amplitude is shown superimposed on the vibration signal in Figure 7-2. The rms amplitude is always less than the PPV* and is always positive.

The PPV and rms velocity are normally described in inches per second in the USA and meters per second in the rest of the world. Although it is not universally accepted, decibel notation is in common use for vibration.

*The ratio of PPV to maximum rms amplitude is defined as the **crest factor** for the signal. The crest factor is always greater than 1.71, although a crest factor of 8 or more is not unusual for impulsive signals. For ground-borne vibration from trains, the crest factor is usually 4 to 5.

Decibel notation acts to compress the range of numbers required to describe vibration. The bottom graph in Figure 7-2 shows the rms curve of the top graph expressed in decibels. Vibration velocity level in decibels is defined as:

$$L_v = 20 \times \log_{10}\left(\frac{v}{v_{ref}}\right)$$

where "L_v" is the velocity level in decibels, "v" is the rms velocity amplitude, and "v_{ref}" is the reference velocity amplitude. A reference must always be specified whenever a quantity is expressed in terms of decibels. The accepted reference quantities for vibration velocity are 1×10^{-6} in./sec in the USA and either 1×10^{-8} m/sec or 5×10^{-8} m/sec in the rest of the world. Because of the variations in the reference quantities, it is important to be clear about what reference quantity is being used whenever velocity levels are specified. ***All** vibration levels in this manual are referenced to 1×10^{-6} in./sec*. Although not a universally accepted notation, the abbreviation "VdB" is used in this document for vibration decibels to reduce the potential for confusion with sound decibels.

There is some movement towards the use of a standardized weighted vibration level when evaluating human response to vibration. This vibration level, often abbreviated VL, is usually referred to as the *weighted acceleration level*. At frequencies greater than 8 Hz, which for all practical purposes is the frequency range of interest to ground-borne vibration:

$$VL \approx L_v - 21$$

where L_v is the vibration velocity level in decibels relative to 1 micro-inch per second (10^{-6} in./sec).

7.1.3 Ground-Borne Noise

As discussed above, the rumbling sound caused by the vibration of room surfaces is called ground-borne noise. The annoyance potential of ground-borne noise is usually characterized with the A-weighted sound level. Although the A-weighted level is almost the only metric used to characterize community noise, there are potential problems when characterizing low-frequency noise using A-weighting. This is because of the non-linearity of human hearing which causes sounds dominated by low-frequency components to seem louder than broadband sounds that have the same A-weighted level. The result is that ground-borne noise with a level of 40 dBA sounds louder than 40 dBA broadband noise. This is accounted for by setting the limits for ground-borne noise lower than would be the case for broadband noise.

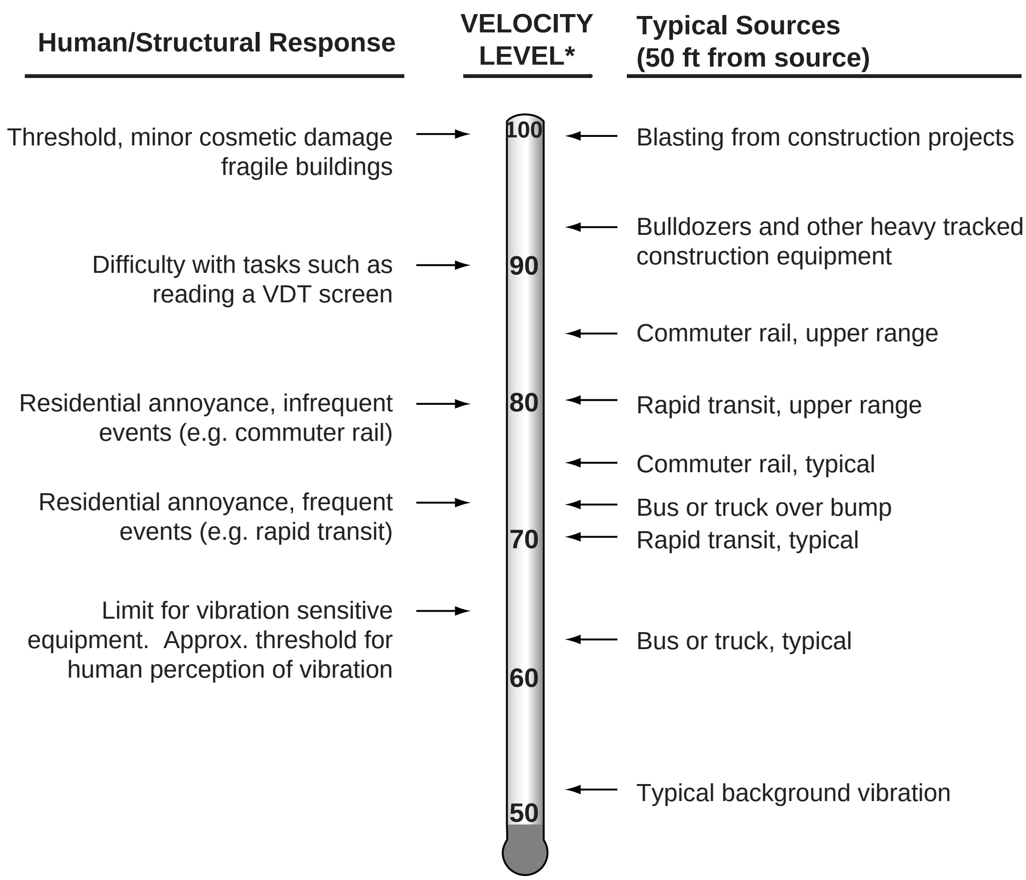
7.2 HUMAN PERCEPTION OF GROUND-BORNE VIBRATION AND NOISE

This section gives some general background on human response to different levels of building vibration laying the ground work for the criteria for ground-borne vibration and noise that are presented in Chapter 8.

7.2.1 Typical Levels of Ground-Borne Vibration and Noise

In contrast to airborne noise, ground-borne vibration is not a phenomenon that most people experience every day. The background vibration velocity level in residential areas is usually 50 VdB or lower, well below the threshold of perception for humans which is around 65 VdB. Most perceptible indoor vibration is caused by sources within buildings such as operation of mechanical equipment, movement of people or slamming of doors. Typical outdoor sources of perceptible ground-borne vibration are construction equipment, steel-wheeled trains, and traffic on rough roads. If the roadway is smooth, the vibration from traffic is rarely perceptible.

Figure 7-3 illustrates common vibration sources and the human and structural response to ground-borne vibration. The range of interest is from approximately 50 VdB to 100 VdB. Background vibration is usually well below the threshold of human perception and is of concern only when the vibration affects very sensitive manufacturing or research equipment. Electron microscopes and high resolution lithography equipment are typical of equipment that is highly sensitive to vibration.



** RMS Vibration Velocity Level in VdB relative to 10^{-6} inches/second*

Figure 7-3 Typical Levels of Ground-Borne Vibration

Although the perceptibility threshold is about 65 VdB, human response to vibration is not usually significant unless the vibration exceeds 70 VdB. This is a typical level 50 feet from a rapid transit or light rail system. Buses and trucks rarely create vibration that exceeds 70 VdB unless there are bumps in the road. Because of the heavy locomotives on diesel commuter rail systems, the vibration levels average about 5 to 10 decibels higher than rail transit vehicles. If there is unusually rough road or track, wheel flats, geologic conditions that promote efficient propagation of vibration, or vehicles with very stiff suspension systems, the vibration levels from any source can be 10 decibels higher than typical. Hence, at 50 feet, the upper range for rapid transit vibration is around 80 VdB and the high range for commuter rail vibration is 85 VdB. If the vibration level in a residence reaches 85 VdB, most people will be strongly annoyed by the vibration.

The relationship between ground-borne vibration and ground-borne noise depends on the frequency content of the vibration and the acoustical absorption of the receiving room. The more acoustical absorption in the room, the lower the noise level will be. For a room with average acoustical absorption, the sound pressure level is approximately equal to the average vibration velocity level of the room surfaces.[*] Hence, the A-weighted level of ground-borne noise can be estimated by applying A-weighting to the vibration velocity spectrum. Since the A-weighting at 31.5 Hz is -39.4 dB, if the vibration spectrum peaks at 30 Hz, the A-weighted sound level will be approximately 40 decibels lower than the velocity level. Correspondingly, if the vibration spectrum peaks at 60 Hz, the A-weighted sound level will be about 25 decibels lower than the velocity level.

7.2.2 Quantifying Human Response to Ground-Borne Vibration and Noise

One of the major problems in developing suitable criteria for ground-borne vibration is that there has been relatively little research into human response to vibration, in particular, human annoyance with building vibration. However, experience with U.S. rapid transit projects over the past 20 years represents a good foundation for developing suitable limits for residential exposure to ground-borne vibration and noise from transit operations.

Figure 7-4 illustrates the relationship between the vibration velocity level measured in 22 homes and the general response of the occupants to the vibration. The data shown were assembled from measurements that had been performed for several transit systems. The subjective ratings are based on the opinion of the person that took the measurements and the response of the occupants. These data were previously published in the "State-of-the-Art Review of Ground-borne Noise and Vibration."[(1)] Both the occupants and the people who performed the measurements agreed that floor vibration in the "Distinctly Perceptible" category was unacceptable for a residence. The data in Figure 7-4 indicate that residential vibration that exceeds 75 VdB is unacceptable for a vibration source such as rapid transit trains that pass every 5 to 15 minutes. Also shown in Figure 7-4 is a curve showing the percent of people annoyed by vibration from high-speed trains in Japan.[(2)] The scale for the percent annoyed is on the right hand axis of the graph. The results of the Japanese study confirm the conclusion that at a vibration velocity level of 75 to 80 VdB, many people will find the vibration annoying.

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[*]The sound level approximately equals the average vibration velocity level *only* when the velocity level is referenced to 1 micro inch/second. When velocity level is expressed using the international standard of $1x10^{-8}$ m/sec, the sound level is approximately 8 decibels lower than the average velocity level.

Table 7-1 describes the human response to different levels of ground-borne noise and vibration. The first column is the vibration velocity level, and the next two columns are for the corresponding noise level assuming that the vibration spectrum peaks at 30 Hz or 60 Hz. As discussed above, the A-weighted noise level will be approximately 40 dB less than the vibration velocity level if the spectrum peak is around 30 Hz, and 25 dB lower if the spectrum peak is around 60 Hz. Table 7-1 illustrates that achieving either the acceptable vibration or acceptable noise levels does not guarantee that the other will be acceptable. That is, the noise caused by vibrating structural components may be very annoying even though the vibration cannot be felt, or the other way around.

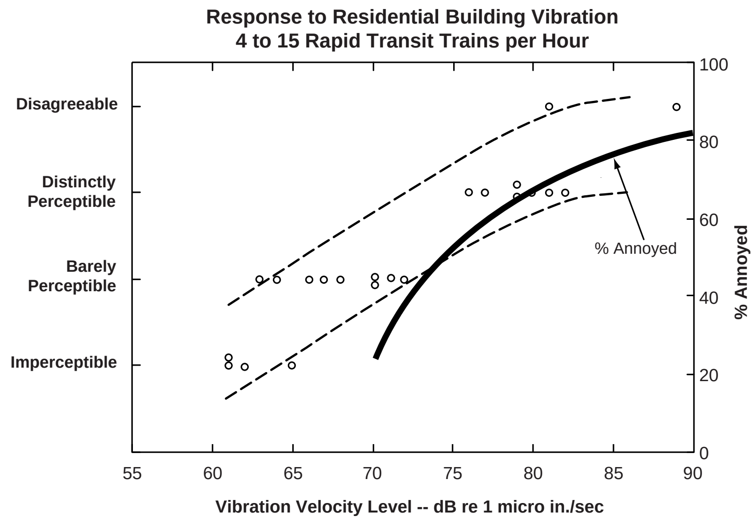

Figure 7-4 Occupant Response to Transit-Induced Residential Vibration

Table 7-1 Human Response to Different Levels of Ground-Borne Noise and Vibration

Vib. Velocity Level	Noise Level		Human Response
	Low Freq[1]	Mid Freq[2]	
65 VdB	25 dBA	40 dBA	Approximate threshold of perception for many humans. Low-frequency sound usually inaudible, mid-frequency sound excessive for quiet sleeping areas.
75 VdB	35 dBA	50 dBA	Approximate dividing line between barely perceptible and distinctly perceptible. Many people find transit vibration at this level unacceptable. Low-frequency noise acceptable for sleeping areas, mid-frequency noise annoying in most quiet occupied areas.
85 VdB	45 dBA	60 dBA	Vibration acceptable only if there are an infrequent number of events per day. Low-frequency noise unacceptable for sleeping areas, mid-frequency noise unacceptable even for infrequent events with institutional land uses such as schools and churches.

Notes:
1. Approximate noise level when vibration spectrum peak is near 30 Hz.
2. Approximate noise level when vibration spectrum peak is near 60 Hz.

7.3 GROUND-BORNE VIBRATION FOR DIFFERENT TRANSIT MODES

This section provides a brief discussion of typical problems with ground-borne vibration and noise for different modes of transit.

Steel Wheel Urban Rail Transit – This category includes both heavy rail transit and light rail transit. Heavy rail is generally defined as electrified rapid transit trains with dedicated guideway, and light rail as electrified transit trains that do not require dedicated guideway. The ground-borne vibration characteristics of heavy and light rail vehicles are very similar since they have similar suspension systems and axle loads. Most of the studies of ground-borne vibration in this country have focused on urban rail transit. Problems with ground-borne vibration and noise are common when there is less than 50 feet between a subway structure and building foundations. Whether the problem will be perceptible vibration or audible noise is strongly dependent on local geology and the structural details of the building. Complaints about ground-borne vibration from surface track are more common than complaints about ground-borne noise. A significant percentage of complaints about both ground-borne vibration and noise can be attributed to the proximity of special trackwork, rough or corrugated track, or wheel flats.

Commuter and Intercity Passenger Trains – This category includes passenger trains powered by either diesel or electric locomotives. In terms of vibration effects at a single location, the major difference between commuter and intercity passenger trains is that the latter are on a less frequent schedule. Both often share track with freight trains, which have quite different vibration characteristics as discussed below. The locomotives usually create the highest vibration levels. There is the potential of vibration-related problems anytime that new commuter or intercity passenger service is introduced in an urban or suburban area.

High Speed Passenger Trains – High-speed passenger trains, such as the Japanese Shinkansen, the French TGV, the German ICE and the Swedish X2000, have the potential of creating high levels of ground-borne vibration. Ground-borne vibration should be anticipated as one of the major environmental impacts of any high speed train located in an urban or suburban area. The Amtrak trains on the Northeast Corridor between Boston and Washington, D.C., which attain moderate to high speeds in some sections with improved track, fit into this category.

Freight Trains – Local and long distance freight trains are similar in that they both are diesel-powered and have the same types of cars. They differ in their overall length, number and size of locomotives, and number of heavily loaded cars. Locomotives and rail cars with wheel flats are the sources of the highest vibration levels. Because locomotive suspensions are similar, the maximum vibration levels of local and long distance freights are similar. It is not uncommon for freight trains to be the source of intrusive ground-borne vibration; however, there are relatively few new freight lines in this country. Most railroad tracks used for freight lines were in existence for many years before the affected residential areas were developed. Vibration from freight trains can be a consideration for FTA- assisted projects when a new transit line will share an existing freight train corridor. Relocating the freight tracks to accommodate the transit system or shifting the freight traffic to other routes can lead to impact from ground-borne vibration, which must be considered an indirect or secondary impact of the transit system.

Automated Guideway Transit Systems (AGT) – This transit mode encompasses a wide range of transportation vehicles providing local circulation in downtown areas, airports and theme parks. In general, ground-borne vibration can be expected to be generated by steel-wheel/steel-rail systems even when limited in size. Because AGT systems normally operate at low speeds, have lightweight vehicles, and rarely operate in vibration sensitive areas, ground-borne vibration problems are very rare.

Bus Projects – Because the rubber tires and suspension systems of buses provide vibration isolation, it is unusual for buses to cause ground-borne noise or vibration problems. When buses cause effects such as rattling of windows, the source is almost always airborne noise. Most problems with bus-related vibration can be directly related to a pothole, bump, expansion joint, or other discontinuity in the road surface. Smoothing the bump or filling the pothole will usually solve the problem.

Problems are likely when buses will be operating inside buildings. Intrusive building vibration can be caused by sudden loading of a building slab by a heavy moving vehicle or by vehicles running over lane divider bumps. A bus transfer station with commercial office space in the same building may have annoying vibration within the office space caused by bus operations.

7.4 FACTORS THAT INFLUENCE GROUND-BORNE VIBRATION AND NOISE

One of the major problems with developing accurate estimates of ground-borne vibration is the large number of factors that can influence the levels at the receiver position. The purpose of this section is to give a general appreciation of which factors have significant effects on the levels of ground-borne vibration. Table 7-2 is a summary of some of the many factors that are known to have, or are suspected of having a significant influence on the levels of ground-borne vibration and noise. As indicated, the physical parameters of the transit facility, the geology, and the receiving building all influence the vibration levels. The important physical parameters can be divided into the following four categories:

Operational and Vehicle Factors – This category includes all of the parameters that relate to the vehicle and operation of the trains. Factors such as high speed, stiff primary suspensions on the vehicle, and flat or worn wheels will increase the possibility of problems from ground-borne vibration.

Guideway – The type and condition of the rails, the type of guideway, the rail support system, and the mass and stiffness of the guideway structure will all have an influence on the level of ground-borne vibration. Jointed rail, worn rail, and wheel impacts at special trackwork can all cause substantial increases in ground-borne vibration. A rail system guideway will be either subway, at-grade, or elevated. It is rare for ground-borne vibration to be a problem with elevated railways except when guideway supports are located within 50 ft of buildings; directly radiated noise is usually the dominant problem from at-grade guideway although vibration can be a problem; and ground-borne vibration is often one of the most important environmental problems for subways. For rubber-tired systems, the smoothness of the roadway/guideway is the critical factor; if the surface is smooth, vibration problems are unlikely.

Geology – Soil conditions are known to have a strong influence on the levels of ground-borne vibration. Among the most important factors are the stiffness and internal damping of the soil and the depth to bedrock. Experience with ground-borne vibration is that vibration propagation is more efficient in stiff clay soils, and shallow rock seems to concentrate the vibration energy close to the surface and can result in ground-borne vibration problems at large distances from the track. Factors such as layering of the soil and depth to water table can have significant effects on the propagation of ground-borne vibration.

Receiving Building – The receiving building is a key component in the evaluation of ground-borne vibration since ground-borne vibration problems occur almost exclusively inside buildings. The train vibration may be perceptible to people who are outdoors, but it is very rare for outdoor vibration to cause complaints. The vibration levels inside a building are dependent on the vibration energy that reaches the building foundation, the coupling of the building foundation to the soil, and the propagation of the vibration through the building. The general guideline is that the heavier a building is, the lower the response will be to the incident vibration energy.

Table 7-2 Factors that Influence Levels of Ground-Borne Vibration and Noise

Factors Related to Vibration Source	
Factors	**Influence**
Vehicle Suspension	If the suspension is stiff in the vertical direction, the effective vibration forces will be higher. On transit cars, only the primary suspension affects the vibration levels, the secondary suspension that supports the car body has no apparent effect.
Wheel Type and Condition	Use of pneumatic tires is one of the best methods of controlling ground-borne vibration. Normal resilient wheels on rail transit systems are usually too stiff to provide significant vibration reduction. Wheel flats and general wheel roughness are the major cause of vibration from steel wheel/steel rail systems.
Track/Roadway Surface	Rough track or rough roads are often the cause of vibration problems. Maintaining a smooth surface will reduce vibration levels.
Track Support System	On rail systems, the track support system is one of the major components in determining the levels of ground-borne vibration. The highest vibration levels are created by track that is rigidly attached to a concrete trackbed (e.g. track on wood half ties embedded in the concrete). The vibration levels are much lower when special vibration control track systems such as resilient fasteners, ballast mats and floating slabs are used.
Speed	As intuitively expected, higher speeds result in higher vibration levels. Doubling speed usually results in vibration levels 4 to 6 decibels higher.
Transit Structure	The general rule-of-thumb is that the heavier the transit structure, the lower the vibration levels. The vibration levels from a lightweight bored tunnel will usually be higher than from a poured concrete box subway.
Depth of Vibration Source	There are significant differences in the vibration characteristics when the source is underground compared to at the ground surface.
Factors Related to Vibration Path	
Factor	**Influence**
Soil Type	It is generally expected that vibration levels will be higher in stiff clay type soils than in loose sandy soils.
Rock Layers	Vibration levels often seem to be high near at-grade track when the depth to bedrock is 30 ft or less. Subways founded in rock will result in lower vibration amplitudes close to the subway. Because of efficient propagation, the vibration level does not attenuate as rapidly in rock as it does in soil.
Soil Layering	Soil layering will have a substantial, but unpredictable, effect on the vibration levels since each stratum can have significantly different dynamic characteristics.
Depth to Water Table	The presence of the water table is often expected to have a significant effect on ground-borne vibration, but evidence to date cannot be expressed with a definite relationship.
Frost Depth	There is some indication that vibration propagation is more efficient when the ground is frozen.
Factors Related to Vibration Receiver	
Factor	**Influence**
Foundation Type	The general rule-of-thumb is that the heavier the building foundation, the greater the coupling loss as the vibration propagates from the ground into the building.
Building Construction	Since ground-borne vibration and noise are almost always evaluated in terms of indoor receivers, the propagation of the vibration through the building must be considered. Each building has different characteristics relative to structureborne vibration, although the general rule-of-thumb is that the more massive a building is, the lower the levels of ground-borne vibration will be.
Acoustical Absorption	The amount of acoustical absorption in the receiver room affects the levels of ground-borne noise.

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2. Y. Tokita, "Vibration Pollution Problems in Japan," In **Inter-Noise 75**, Sendai, Japan, pp. 465-472, 1975.

8. VIBRATION IMPACT CRITERIA

Because of the relatively rare occurrence of annoyance due to ground-borne vibration and noise, there has been only limited sponsored research of human response to building vibration and structure-borne noise. However, with the construction of new rail rapid transit systems in the past 20 years, considerable experience has been gained as to how communities will react to various levels of building vibration. This experience, combined with the available national and international standards,[1][2] represents a good foundation for predicting annoyance from ground-borne noise and vibration in residential areas.

The criteria for environmental impact from ground-borne vibration and noise are based on the maximum levels for a single event. The criteria presented in Table 8-1 account for variation in project types as well as the frequency of events, which differ widely among transit projects. Most experience is with the community response to ground-borne vibration from rail rapid transit systems with typical headways in the range of 3 to 10 minutes and each vibration event lasting less than 10 seconds. It is intuitive that when there will be many fewer events each day, as is typical for commuter rail projects, it should take higher vibration levels to evoke the same community response. This is accounted for in the criteria by distinguishing between projects with frequent and infrequent events where *Frequent Events* is defined as more than 70 events per day. Most commuter rail projects will fall into the infrequent event category, although some commuter rail lines serving major cities are in the frequent event category.

The criteria are primarily based on experience with passenger train operations with only limited experience from freight train operations. The difference is that passenger train operations whether rapid transit, commuter rail, or intra-city create vibration events that last less than about 10 seconds. A typical line haul freight train is about 5000 feet long. At a speed of 30 mph, it will take a 5000-foot freight train approximately two minutes to pass. Even though the criteria are primarily based on experience with shorter vibration events and this manual is oriented to transit projects, there will be situations where potential impacts from freight train ground-borne vibration will need to be evaluated. The prime example is when freight train tracks must be relocated to provide space for a transit project within a railroad right-of-way. Some guidelines for applying these criteria to freight train operations are given later in this chapter.

The criteria for acceptable ground-borne vibration are expressed in terms of rms velocity levels in decibels and the criteria for acceptable ground-borne noise are expressed in terms of A-weighted sound level. The limits are specified for the three land use categories defined below:

Vibration Category 1: High Sensitivity – Included in Category 1 are buildings where low ambient vibration is essential for the operations within the building, which may be well below levels associated with human annoyance. Concert halls and other special use facilities are covered separately in Table 8-2. Typical land uses covered by Category 1 are: vibration-sensitive research and manufacturing, hospitals with vibration-sensitive equipment, and university research operations. The degree of sensitivity to vibration will depend on the specific equipment that will be affected by the vibration. Equipment such as electron microscopes and high resolution lithographic equipment can be very sensitive to vibration, and even normal optical microscopes will sometimes be difficult to use when vibration is well below the human annoyance level. Manufacturing of computer chips is an example of a vibration-sensitive process.

The vibration limits for Vibration Category 1 are based on acceptable vibration for moderately vibration-sensitive equipment such as optical microscopes and electron microscopes with vibration isolation systems. Defining limits for equipment that is even more sensitive requires a detailed review of the specific equipment involved. This type of review is usually performed during the final design phase and not as part of the environmental impact assessment. Mitigation of transit vibration that affects sensitive equipment typically involves modification of the equipment mounting system or relocation of the equipment rather than applying vibration control measures to the transit project.

Note that this category does not include most computer installations or telephone switching equipment. Although the owners of this type of equipment often are very concerned about the potential of ground-borne vibration interrupting smooth operation of their equipment, it is rare for computer or other electronic equipment to be particularly sensitive to vibration. Most such equipment is designed to operate in typical building environments where the equipment may experience occasional shock from bumping and continuous background vibration caused by other equipment.

Vibration Category 2: Residential – This category covers all residential land uses and any buildings where people sleep, such as hotels and hospitals. No differentiation is made between different types of residential areas. This is primarily because ground-borne vibration and noise are experienced indoors and building occupants have practically no means to reduce their exposure. Even in a noisy urban area, the bedrooms often will be quiet in buildings that have effective noise insulation and tightly closed windows. Hence, an occupant of a bedroom in a noisy urban area is likely to be just as sensitive to ground-borne noise and vibration as someone in a quiet suburban area.

Vibration Category 3: Institutional – Vibration Category 3 includes schools, churches, other institutions, and quiet offices that do not have vibration-sensitive equipment, but still have the potential for activity-interference. Although it is generally appropriate to include office buildings in this category, it is not appropriate to include all buildings that have any office space. For example, most industrial buildings have office space, but it is not intended that buildings primarily for industrial use be included in this category.

Table 8-1 Ground-Borne Vibration and Noise Impact Criteria

Land Use Category	Ground-Borne Vibration Impact Levels (VdB re 1 micro inch/sec)		Ground-Borne Noise Impact Levels (dB re 20 micro Pascals)	
	Frequent[1] Events	Infrequent[2] Events	Frequent[1] Events	Infrequent[2] Events
Category 1: Buildings where low ambient vibration is essential for interior operations.	65 VdB[3]	65 VdB[3]	[4]	[4]
Category 2: Residences and buildings where people normally sleep.	72 VdB	80 VdB	35 dBA	43 dBA
Category 3: Institutional land uses with primarily daytime use.	75 VdB	83 VdB	40 dBA	48 dBA

Notes:
1. "Frequent Events" is defined as more than 70 vibration events per day. Most rapid transit projects fall into this category.
2. "Infrequent Events" is defined as fewer than 70 vibration events per day. This category includes most commuter rail systems.
3. This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. Vibration sensitive manufacturing or research will require detailed evaluation to define the acceptable vibration levels. Ensuring lower vibration levels in a building often requires special design of the HVAC systems and stiffened floors.
4. Vibration-sensitive equipment is not sensitive to ground-borne noise.

There are some buildings, such as concert halls, TV and recording studios, and theaters, that can be very sensitive to vibration and noise but do not fit into any of the three categories. Because of the sensitivity of these buildings, they usually warrant special attention during the environmental assessment of a transit project. Table 8-2 gives criteria for acceptable levels of ground-borne vibration and noise for various types of special buildings.

The criteria in Tables 8-1 and 8-2 are related to ground-borne vibration causing human annoyance or interfering with use of vibration-sensitive equipment. It is extremely rare for vibration from train operations to cause any sort of building damage, even minor cosmetic damage. However, there is sometimes concern about damage to fragile historic buildings located near the right-of-way. Even in these cases, damage is unlikely except when the track will be very close to the structure. Damage thresholds that apply to these structures are discussed in Section 12.2.2.

Table 8-2 Ground-Borne Vibration and Noise Impact Criteria for Special Buildings

Type of Building or Room	Ground-Borne Vibration Impact Levels (VdB re 1 micro-inch/sec)		Ground-Borne Noise Impact Levels (dB re 20 micro-Pascals)	
	Frequent[1] Events	Infrequent[2] Events	Frequent[1] Events	Infrequent[2] Events
Concert Halls	65 VdB	65 VdB	25 dBA	25 dBA
TV Studios	65 VdB	65 VdB	25 dBA	25 dBA
Recording Studios	65 VdB	65 VdB	25 dBA	25 dBA
Auditoriums	72 VdB	80 VdB	30 dBA	38 dBA
Theaters	72 VdB	80 VdB	35 dBA	43 dBA

Notes:
1. "Frequent Events" is defined as more than 70 vibration events per day. Most transit projects fall into this category.
2. "Infrequent Events" is defined as fewer than 70 vibration events per day. This category includes most commuter rail systems.
3. If the building will rarely be occupied when the trains are operating, there is no need to consider impact. As an example consider locating a commuter rail line next to a concert hall. If no commuter trains will operate after 7 pm, it should be rare that the trains interfere with the use of the hall.

One factor not incorporated in the criteria is how to account for existing vibration. In most cases, the existing environment does not include a significant number of perceptible ground-borne vibration or noise events. The most common example of needing to account for the pre-existing vibration is when the project will be located in an existing rail corridor. Following are methods of handling representative scenarios:

1. *Infrequently-used rail corridor:* Use the standard vibration criteria when the existing rail traffic consists of at most one or two trains per day.

2. *Moderately-used rail corridor:* If the existing traffic consists of more than about 10 trains per day and the train vibration substantially exceeds the impact criteria, there is no impact as long as the project vibration levels estimated using the procedures outlined in either Chapter 10 or 11 are at least 5 to 10 decibels less than the existing vibration. The existing train vibration can be either measured or estimated using the General Assessment procedures in Chapter 10. It is usually preferable to measure vibration from existing train traffic.

3. *Heavily-used rail corridor:* If the project will not significantly increase the number of vibration events, there will not be additional impact unless the project vibration, estimated using the procedures of Chapters 10 or 11, will be higher than the existing vibration. Approximately doubling the number of events is required for a significant increase. An example of this case would be a new commuter rail line sharing part of a corridor with an existing rapid transit system with both systems carrying similar volumes of traffic. When the project will cause vibration higher than the existing, the existing source can be ignored and the standard vibration criteria applied to the project.

4. *Moving existing tracks:* Another scenario where existing vibration can be significant is when a new project will use an existing rail right-of-way and result in shifting the location of existing tracks. The track relocation and reconstruction can result in lower vibration levels, in which case this aspect of the project represents a benefit not an adverse impact. If the track relocation will cause higher vibration

levels at sensitive receptors, then the projected vibration levels must be compared to the appropriate impact criterion to determine if there will be impact. Most freight lines have two to six trains per day, but each train may take several minutes to pass by. For typical freight trains, the locomotive vibration is 5 to 10 decibels higher than vibration from the rail cars.

Although the impact thresholds given in Tables 8-1 and 8-2 are based on experience with vibration from rail transit systems, they can be applied to freight train vibrations as well. A dual approach is recommended with separate consideration of the locomotive and rail car vibration. Because the locomotive vibration only lasts for a few seconds, the infrequent event limit is appropriate. However, for a typical line-haul freight train where the rail car vibration lasts for several minutes, the frequent event limits should be applied to the rail car vibration. Some judgment must be exercised to make sure that the approach is reasonable. For example, some spur rail lines carry very little rail traffic (sometimes only one train per week) or have short trains, in which case the infrequent limits are appropriate.

REFERENCES

1. Acoustical Society of America, "American National Standard: Guide to Evaluation of Human Exposure to Vibration in Buildings," ANSI S3.29-1983 (ASA 48-1983).

2. International Standards Organization, "Evaluation of Human Exposure to Whole-Body Vibration, Part 2: Continuous and Shock-Induced Vibrations in Buildings (1-80Hz)," ISO-2361-2, 1989.

9. VIBRATION SCREENING PROCEDURE

The vibration screening procedure is designed to identify projects that have little possibility of creating significant adverse impact. If the screening procedure does not identify any potential problem areas, it is usually safe to eliminate further consideration of vibration impact from the environmental analysis.

9.1 STEPS IN SCREENING PROCEDURE

The steps in the vibration screening procedure are summarized in Figure 9-1 in a flow chart format. Following is a summary of the steps:

Initial Decision – If the project includes any type of steel-wheeled/steel-rail vehicle, there is potential for vibration impact. Proceed directly to the evaluation of screening distances. Transit projects that do not involve vehicles, such as a station rehabilitation, do not have potential for vibration impact unless the track system will be modified (e.g., tracks moved or switches modified). Rail systems include urban rapid transit, light rail transit, commuter rail, and steel-wheel intermediate capacity transit systems. For projects that involve rubber-tire vehicles, vibration impact is unlikely except in unusual situations. Three specific factors shown in Figure 9-1 should be checked to determine if there is potential vibration impact from bus projects or any other projects that involve rubber-tire vehicles:

1. Will there be expansion joints, speed bumps, or other design features that result in unevenness in the road surface near vibration-sensitive buildings? Such irregularities can result in perceptible ground-borne vibration at distances up to 75 feet away.

2. Will buses, trucks or other heavy vehicles be operating close to a sensitive building? Research using electron microscopes and manufacturing of computer chips are examples of vibration sensitive activities.

3. Does the project include operation of vehicles inside or directly underneath buildings that are vibration-sensitive? Special considerations are often required for shared use facilities such bus

stations located inside an office building complex.

No Impact (Box A) – The decisions in step 1 lead to either box A, "No vibration impact likely," or box B. Reaching box A indicates that further analysis is not required. The majority of smaller FTA-assisted projects, such as bus terminals and park-and-ride lots, will be eliminated from further consideration of ground-borne vibration impact in the first step.

Screening Distances (Box B) – If the result of the first step is that there is potential for vibration impact, determine if any vibration-sensitive land uses are within the screening zones. Vibration-sensitive land uses are identified in Chapter 8. Tables 9-1 and 9-2 are used to determine the applicable vibration screening distances for the project.

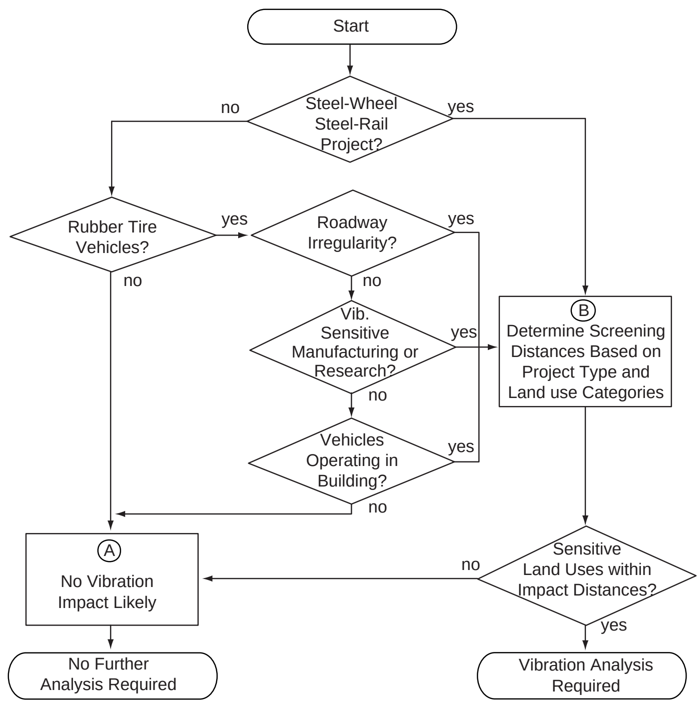

Figure 9-1 Flow Chart of Vibration Screening Process

Impact – If there are any vibration-sensitive land uses within the screening distances, there is the potential for vibration impact. The result of the screening procedure is that vibration impact should be assessed as part of the environmental analysis.

9.2 SCREENING DISTANCES

9.2.1 Project Categories

The vibration screening procedure is applicable to all types of FTA-assisted projects. The project categories for the vibration screening procedure are summarized in Table 9-1 for four types of rail transit. The fifth category includes all bus projects. Any project that does not include some type of vehicle is not likely to cause vibration impact.

With respect to Project Type 5, the rubber-tire vehicle category, most complaints about vibration caused by buses and trucks are related to rattling of windows or items hung on the walls. These vibrations are usually the result of airborne noise and not ground-borne vibration. In the case where ground-borne vibration is the source of the problem, the vibration can usually be related to potholes, some sort of bump in the road, or other irregularities.

9.2.2 Distances

The screening distances are given in Table 9-2. These distances are based on the criteria presented in Chapter 8, with a 5 decibel factor of safety included. The distances have been determined using vibration prediction procedures that are summarized in Chapter 10 assuming "normal" vibration propagation. As discussed in Chapter 10, efficient vibration propagation can result in substantially higher vibration levels. Because of the 5 decibel safety factor, even with efficient propagation, the screening distances will identify most of the potentially impacted areas. By not specifically accounting for the possibility of efficient vibration propagation, there is some possibility that some potential impact areas will not be identified in the screening process. When there is evidence of efficient propagation, such as previous complaints about existing transit facilities or a history of problems with construction vibration, the distances in Table 9-2 should be increased by a factor of 1.5.

Table 9-1 Project Types for Vibration Screening Procedure

Project Type	Description
1. Conventional Commuter Railroad	Both the locomotives and the passenger vehicles create significant vibration. The highest vibration levels are usually created by the locomotives. Electric commuter rail vehicles create levels of ground-borne vibration that are comparable to electric rapid transit vehicles.
2. Rail Rapid Transit	Ground-borne vibration impact from rapid transit trains is one of the major environmental issues for new systems. For operation in subway, the ground-borne vibration is usually a significant environmental impact. It is less common for at-grade and elevated rapid transit lines to create intrusive ground-borne vibration.
3. Light Rail Transit	The ground-borne vibration characteristics of light rail systems are very similar to those of rapid transit systems. Because the speeds of light rail systems are usually lower, the typical vibration levels usually are lower. Steel-wheel/steel-rail Automated Guideway Transit (AGT) will fall into either this category or the Intermediate Capacity Transit category depending on the level of service and train speeds.
4. Intermediate Capacity Transit	Because of the low operating speeds of most ICT systems, significant vibration problems are not common. However, steel wheel ICT systems that operate close to vibration sensitive buildings have the potential of causing intrusive vibration. With a stiff suspension system, an ICT system could create intrusive vibration.
5. Bus and Rubber-Tire Transit Projects	This category encompasses most projects that do not include steel-wheel trains of some type. Examples are diesel buses, electric trolley buses, and rubber tired people movers. Most projects that do not include steel-wheel trains do not cause significant vibration impact.

Table 9-2 Screening Distances for Vibration Assessments

Type of Project	Critical Distance for Land Use Categories* Distance from Right-of-Way or Property Line		
	Cat. 1	Cat. 2	Cat. 3
Conventional Commuter Railroad	600	200	120
Rail Rapid Transit	600	200	120
Light Rail Transit	450	150	100
Intermediate Capacity Transit	200	100	50
Bus Projects (if not previously screened out)	100	50	--

* The land use categories are defined in Chapter 8. Some vibration-sensitive land uses are not included in these categories. Examples are: concert halls and TV studios which, for the screening procedure, should be evaluated as Category 1; and theaters and auditoriums which should be evaluated as Category 2.

10. GENERAL VIBRATION ASSESSMENT

This chapter outlines procedures that can be used to develop generalized predictions of ground-borne vibration and noise. This manual includes three different levels of detail for projecting ground-borne vibration:

Screening – The screening procedure is discussed in Chapter 9. A standard table of impact distances is used to determine if ground-borne vibration from the project may affect sensitive land uses. More detailed analysis is required if any sensitive land uses are within the screening distances. The screening procedure does not require any specific knowledge about the vibration characteristics of the system or the geology of the area.

General Assessment – The general level of assessment, as described in this chapter, is an extension of the screening procedure. It uses generalized data to develop a curve of vibration level as a function of distance from the track. The vibration levels at specific buildings are estimated by reading values from the curve and applying adjustments to account for factors such as track support system, vehicle speed, type of building, and track and wheel condition. The general level deals only with the overall vibration velocity level and the A-weighted sound level. It does not consider the frequency spectrum of the vibration or noise.

Detailed Analysis – Discussed in Chapter 11, the Detailed Analysis involves applying all of the available tools for accurately projecting the vibration impact at specific sites. The procedure outlined in this manual includes a test of the vehicle (or similar vehicle) to define the forces generated by the vibration source and tests at the site in question to define how the local geology affects vibration propagation. It is considerably more complex to develop detailed projections of ground-borne vibration than it is to develop detailed projections of airborne noise. The vibration projection procedure is not only complex, but, at this time, also has not been standardized. Accurate projections of ground-borne vibration require professionals with experience in performing and interpreting vibration propagation tests. As such, detailed vibration predictions are usually performed during the final design phase of a project when there is sufficient reason to suspect adverse vibration impact from the project. The procedure for

Detailed Vibration Analysis presented in Chapter 11 is based on measurements to characterize vibration propagation at specific sites.

There is not always a clear distinction between general and detailed predictions. For example, it is often appropriate to use several representative measurements of vibration propagation along the planned alignment in developing generalized propagation curves. Other times, generalized prediction curves may be sufficient for the majority of the alignment, with detailed analysis applied to particularly sensitive buildings such as a concert hall.

The purpose of the General Assessment is to provide a relatively simple method of developing estimates of the overall levels of ground-borne vibration and noise that can be compared to the acceptability criteria given in Chapter 8. For many projects, particularly when comparing alternatives, this level of detail will be sufficient for the environmental assessment. Where there are potential problems, the Detailed Analysis is then undertaken during final design of the selected alternative to accurately define the level of impact and design mitigation measures. A Detailed Analysis usually will be required when designing special track-support systems such as floating slabs or ballast mats. Detailed Analysis is not usually required if, as is often the case, the mitigation measure consists of relocating a crossover or turnout.

The basic approach for the General Assessment is to define a curve, or set of curves, that predicts the overall ground-surface vibration as a function of distance from the source, then apply adjustments to these curves to account for factors such as vehicle speed, building type, and receiver location within the building. Section 10.1 includes curves of vibration level as a function of distance from the source for the common types of vibration sources such as rapid transit trains and buses. When the vehicle type is not covered by the curves included in this section, it will be necessary to define an appropriate curve either by extrapolating from existing information or performing measurements at an existing facility.

10.1 SELECTION OF BASE CURVE FOR GROUND SURFACE VIBRATION LEVEL

The base curves for three standard transportation systems are defined in Figure 10-1. This figure shows typical ground-surface vibration levels assuming equipment in good condition and speeds of 50 mph for the rail systems and 30 mph for buses. The levels must be adjusted to account for factors such as different speeds and different geologic conditions than assumed. The adjustment factors are discussed in Section 10.2.

The curves in Figure 10-1 are based on measurements of ground-borne vibration at a number of North American transit systems (references 1 through 9). The top curve applies to trains that are powered by diesel-electric locomotives. It includes intercity passenger trains and commuter rail trains. The curve for rapid transit rail cars covers both heavy and light-rail vehicles on at-grade and subway track. It is somewhat surprising that subway and at-grade track can be represented by the same curve since ground-borne vibration created by a train operating in a subway has very different characteristics than vibration from at-grade track. However, in spite of these differences, the overall vibration velocity levels are comparable. Subways tend to have more vibration problems than at-grade track; this is probably due to two factors: (1) subways are usually located in more densely developed areas, and (2) the airborne noise is usually a more serious problem for at-grade systems than the ground-borne vibration. Another difference between subway and at-grade track is that the ground-borne vibration from subways tends to be higher frequency than the vibration from at-grade track, which makes the ground-borne noise more noticeable.

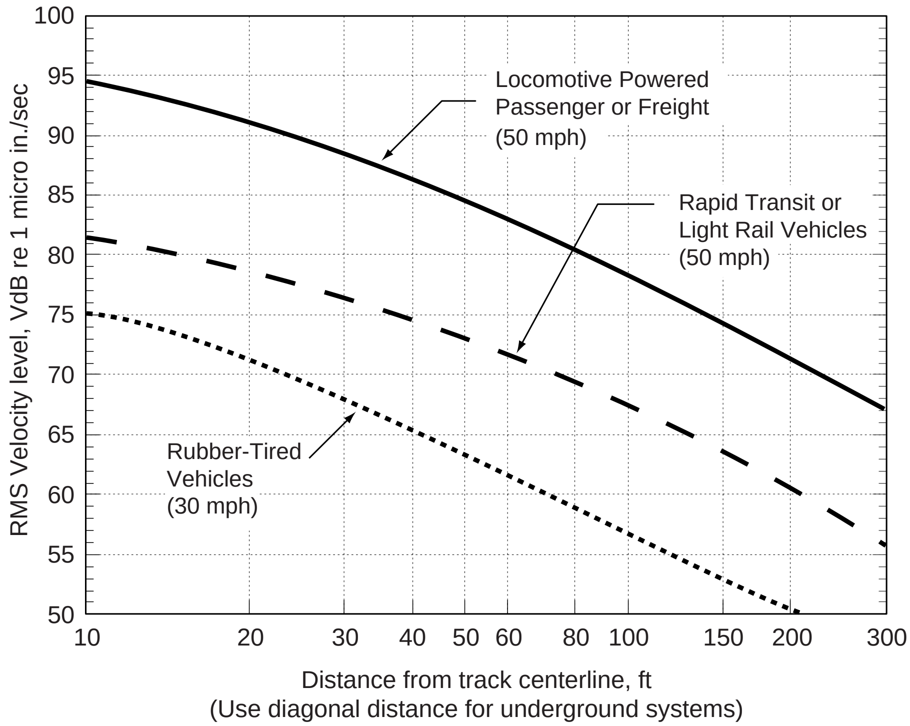

Figure 10-1 Generalized Ground Surface Vibration Curves

The curves in Figure 10-1 were developed from numerous measurements of ground-borne vibration. Experience with ground-borne vibration data is that, for any specific type of transit mode, a 10 decibel fluctuation in vibration levels under apparently similar conditions is not uncommon. The curves in Figure 10-1 represent the upper range of the measurement data, which means that although actual levels fluctuate widely, it is rare that ground-borne vibration will exceed the curves in Figure 10-1 by more than one or two decibels unless there are extenuating circumstances, such as rail corrugations or wheel flats.

One approach to dealing with the normal fluctuation is to show projections as a range. For example, the projected level from Figure 10-1 for an LRT system with train speeds of 50 mph is about 72 VdB at a distance of 60 feet from the track centerline, just at the threshold for acceptable ground-borne vibration for residential land uses. To help illustrate the normal fluctuation, the projected level of ground-borne vibration might be given as 67 to 72 VdB. This approach is not recommended since it tends to confuse the interpretation of whether the projected vibration levels exceed the impact threshold. However, because actual levels of ground-borne vibration will sometimes differ substantially from the projections, some care must be taken when interpreting projections. Some guidelines are given below:

1. Projected vibration is below the impact threshold. Vibration impact is unlikely in this case.

2. Projected ground-borne vibration is 0 to 5 decibels greater than the impact threshold. In this range there is still a significant chance (at least 50%) that actual ground-borne vibration levels will be below the impact threshold. In this case, the impact would be reported in the environmental document as exceeding the applicable threshold and a commitment would be made to conduct more detailed studies to refine the vibration impact analysis and determine appropriate mitigation during final design. A site-specific Detailed Analysis may show that vibration control measures are not needed.

3. Projected ground-borne vibration is 5 decibels or more greater than the impact threshold. Vibration impact is probable and some type of vibration control should be planned for the final design of the project.

The two most important factors that must be accounted for in a General Assessment are the type of vibration source (the mode of transit) and the vibration propagation characteristics. It is well known that there are situations where ground-borne vibration propagates much more efficiently than normal. The result is unacceptable vibration levels at distances two to three times the normal distance. Unfortunately, the geologic conditions that promote efficient propagation have not been well documented and are not fully understood. Shallow bedrock or stiff clay soil often are involved. One possibility is that shallow bedrock acts to keep the vibration energy near the surface. Much of the energy that would normally radiate down is directed back towards the surface by the rock layer with the result that the ground surface vibration is higher than normal.

The selection of a base curve depends on the mode of rail transit under consideration. Appropriate correction factors are then added to account for any unusual propagation characteristics. For less common modes such as magnetically-levitated vehicles (maglev), monorail, or AGT, it is necessary to either make a judgment about which curve and adjustment factors best fit the mode or to develop new estimates of vibration level as a function of distance from the track. For example, the vibration from a rubber-tire monorail that will be operating on aerial guideway can be approximated using the bus/rubber tire systems with the appropriate adjustment for the aerial structure. Another example is a magnetic levitation system. There is very little data available on the noise and vibration characteristics of maglev vehicles. However, as long as there will be little direct contact between the vehicle and the guideway, the vibration forces should be low enough that ground-borne vibration can be ignored.

Considerations for selecting a base curve are discussed below:

Intercity Passenger Trains – Although intercity passenger trains can be an important source of environmental vibration, it is rare that they are significant for FTA-funded projects unless a new transit mode will use an existing rail alignment. When a new transit line will use an existing rail alignment, the changes in the intercity passenger traffic can result in either positive or negative impacts. Unless there are specific data available on the ground-borne vibration created by the train operations, the upper curve in Figure 10-1 should be used for intercity passenger trains.

Locomotive Powered Commuter Rail – The locomotive curve from Figure 10-1 should be used for any commuter rail system powered by either diesel or electric locomotives. The locomotives often create vibration levels that are 3 to 8 decibels higher than those created by the passenger vehicles. Self-powered electric commuter rail trains can be considered to be similar to rapid transit vehicles. Although they are relatively rare in the U.S., self-powered diesel commuter rail cars create vibration levels somewhere between rapid transit vehicles and locomotive-powered passenger trains. As long as the axle loads and suspension parameters are comparable to typical rapid transit vehicles, the rapid transit curve in Figure 10-1 can be used for self-powered diesel commuter rail cars.

Subway Heavy Rail – Complaints about ground-borne vibration are more common near subways than near at-grade track. This is not because subways create higher vibration levels than at-grade systems, rather it is because subways are usually located in high density areas in close proximity to building foundations. When applied to subways, the rapid transit curve in Figure 10-1 assumes a relatively lightweight bored concrete tunnel in soil. The vibration levels will be lower for heavier subway structures such as cut-and-cover box structures and stations.

At-Grade Heavy Rail or LRT – The available data show that heavy rail and light rail transit vehicles create similar levels of ground-borne vibration. This is not surprising since the vehicles have similar suspension systems and axle loads. Light-rail systems tend to have fewer problems with ground-borne vibration because of the lower operating speeds. Similar to the subway case, an adjustment factor must be used if the transit vehicle has a primary suspension that is stiff in the vertical direction.

Intermediate Capacity Transit – The vibration levels created by an intermediate capacity transit system or an AGT system will depend on whether the vehicles have steel wheels or rubber wheels. If they have steel wheels, the transit car curve in Figure 10-1 should be used with appropriate adjustments for operating speed. The bus/rubber tire curve should be used for rubber-tired ICT systems.

Bus/Rubber Tire – Rubber-tire vehicles rarely create ground-borne vibration problems unless there is a discontinuity or bump in the road that causes the vibration. The curve in Figure 10-1 shows the vibration level for a typical bus operating on smooth roadway.

10.2 ADJUSTMENTS

Once the base curve has been selected, the adjustments in Table 10-1 can be used to develop vibration projections for specific receiver positions inside buildings. All of the adjustments are given as single numbers to be added to, or subtracted from, the base level. The adjustment parameters are speed, wheel and rail type and condition, type of track support system, type of building foundation, and number of floors above the basement level. It should be recognized that many of these adjustments are strongly dependent on the frequency spectrum of the vibration source and the frequency dependence of the vibration propagation. The single number values are suitable for generalized evaluation of the vibration impact and vibration mitigation measures since they are based on typical vibration spectra. However, the single number adjustments are not adequate for detailed evaluations of impact of sensitive buildings or for detailed specification of mitigation measures. Detailed Analysis requires consideration of the relative importance of different frequency components.

Table 10-1 Adjustment Factors for Generalized Predictions of Ground-Borne Vibration and Noise

Factors Affecting Vibration Source

Source Factor	Adjustment to Propagation Curve	Comment
Speed	Reference Speed Vehicle Speed / 50 mph / 30 mph 60 mph: +1.6 dB / +6.0 dB 50 mph: 0.0 dB / +4.4 dB 40 mph: -1.9 dB / +2.5 dB 30 mph: -4.4 dB / 0.0 dB 20 mph: -8.0 dB / -3.5 dB	Vibration level is approximately proportional to 20*log(speed/speed$_{ref}$). Sometimes the variation with speed has been observed to be as low as 10 to 15 log(speed/speed$_{ref}$).
Vehicle with stiff primary suspension	+8 dB	Transit vehicles with stiff primary suspensions have been shown to create high vibration levels. Include this adjustment when the primary suspension has a vertical resonance frequency greater than 15 Hz.
Resilient Wheels	0 dB	Resilient wheels do not generally affect ground-borne vibration except at frequencies greater than about 80 Hz.
Worn Wheels or Wheels with Flats	+10 dB	Wheel flats or wheels that are unevenly worn can cause high vibration levels. This can be prevented with wheel truing and slip-slide detectors to prevent the wheels from sliding on the track.
Worn or Corrugated Track	+10 dB	If both the wheels and the track are worn, only one adjustment should be used. Corrugated track is a common problem, however, it is difficult to predict the conditions that cause corrugations to occur. Rail grinding can remove rail corrugations. Mill scale on new rail can cause higher vibration levels until the rail has been in use for some time.
Crossovers and Other Special Trackwork	+10 dB	Wheel impacts at special trackwork will significantly increase vibration levels. The increase will be less at greater distances from the track.
Jointed Track	+5 dB	Jointed track causes higher vibration levels than welded track. The difference depends on the condition of the rail joints.
Floating Slab Trackbed	-15 dB	The reduction achieved with a floating slab trackbed is strongly dependent on the frequency characteristics of the vibration.
Ballast Mats	-10 dB	Actual reduction is strongly dependent on frequency of vibration.
High Resilience Fasteners	-5 dB	Slab track with track fasteners that are very compliant in the vertical direction can reduce vibration at frequencies greater than 40 Hz.
Resiliently Supported Ties	-10 dB	Resiliently supported tie systems have been found to provide very effective control of low-frequency vibration.
Type of Transit Structure	Relative to at-grade tie & ballast: Elevated structure -10 dB Open Cut 0 dB Relative to bored subway tunnel in soil: Station -5 dB Cut and Cover -3 dB Rock-Based -15 dB	The general rule is the heavier the structure the lower the vibration levels. Putting the track in cut may reduce the vibration levels slightly. Rock based subways will create higher-frequency vibration.

Table 10-1 continued...		
Factors Affecting Vibration Path		
Path Factor	**Adjustment to Propagation Curve**	**Comment**
Geologic conditions that promote efficient vibration propagation	Efficient propagation in soil +10 dB	Refer to the text for guidance on identifying areas where efficient propagation is possible.
	Propagation in rock layer **Dist.** / **Adjust.** 50 ft +2 dB 100 ft +4 dB 150 ft +6 dB 200 ft +9 dB	The positive adjustment accounts for the lower attenuation of vibration in rock compared to soil. Because it is more difficult to get vibration energy into rock, propagation through rock usually results in lower vibration than propagation through soil.
Coupling to building foundation	Wood Frame -5 dB 1-2 Story Commercial -7 dB 2-4 Story Masonry -10 dB Large Masonry on Piles -10 dB Large Masonry on Spread Footings -13 dB Foundation in Rock 0 dB	The general rule is the heavier the building construction, the greater the coupling loss.
Factors Affecting Vibration Receiver		
Receiver Factor	**Adjustment to Propagation Curve**	**Comment**
Floor-to-floor attenuation	1 to 5 floors above grade: -2 dB/floor 5 to 10 floors above grade: -1 dB/floor	This factor accounts for dispersion and attenuation of the vibration energy as it propagates through a building.
Amplification due to resonances of floors, walls, and ceilings	+6 dB	The actual amplification will vary greatly depending on the type of construction. The amplification is lower near the wall/floor and wall/ceiling intersections.
Radiated Sound	Peak frequency of ground vibration: Low frequency (<30 Hz): -50 dB Typical (peak 30 to 60 Hz): -35 dB High frequency (>60 Hz): -20 dB	Use these adjustments to estimate the A-weighted sound level given the average vibration velocity level of the room surfaces. See text for guidelines for selecting low, typical or high frequency characteristics. Use the high-frequency adjustment for subway tunnels in rock or if the dominant frequencies of the vibration spectrum are known to be 60 Hz or greater.

Without careful consideration of the shape of the actual vibration spectra, an inappropriate vibration control measure may be selected that could actually cause an increase in the vibration levels.

The following guidelines are used to select the appropriate adjustment factors. Note that the adjustments for wheel and rail condition are not cumulative. The general rule-of-thumb to use when more than one adjustment may apply is to apply only the largest adjustment. For example: the adjustment for jointed track is 5 decibels and the adjustment for wheel flats is 10 decibels. In an area where there is jointed track and many vehicles have wheel flats, the projected vibration levels should be increased by 10 decibels, not 15 decibels.

Train Speed – The levels of ground-borne vibration and noise vary approximately as 20 times the logarithm of speed. This means that doubling train speed will increase the vibration levels approximately 6 decibels and halving train speed will reduce the levels by 6 decibels. Table 10-1 tabulates the adjustments for reference vehicle speeds of 30 mph for rubber-tired vehicles and 50 mph for steel-wheel vehicles. The relationship:

$$\textbf{adjustment (dB)} = \mathbf{20 \times \log\left(\frac{speed}{speed_{ref}}\right)}$$

should be used to calculate the adjustments for other speeds.

Vehicle – The most important factors for the vehicles are the suspension system, wheel condition, and wheel type. Most new heavy rail and light rail vehicles have relatively soft primary suspensions. However, there were a number of vehicles delivered to U.S. transit systems in the past 20 years with very stiff primary suspensions. Experience in Atlanta, New York, and other cities has demonstrated that a stiff primary suspension (vertical resonance frequency greater than 15 Hz) can result in higher than normal levels of ground-borne vibration. Vehicles for which the primary suspension consists of a rubber or neoprene "donut" around the axle bearing usually have a very stiff primary suspension with a vertical resonance frequency greater than 40 Hz.

Deteriorated wheel condition is another factor that will increase vibration levels. It can be assumed that a new system will have good condition wheels. However, when older vehicles will be used on new track, it may be appropriate to include an adjustment for wheel condition. Wheels with flats or corrugations can cause vibration levels that are 10 decibels higher than normal. Resilient wheels will reduce vibration levels at frequencies greater than the effective resonance frequency of the wheel. Because this resonance frequency is relatively high, often greater than 80 Hz, resilient wheels usually have only a marginal effect on ground-borne vibration.

Track System and Support – This category includes the type of rail (welded, jointed or special trackwork), the track support system, and the condition of the rail. The base curves all assume good condition welded rail. Jointed rail causes higher vibration levels than welded rail; the amount higher depends on the condition of the joints. The wheel impacts at special trackwork, such as frogs at crossovers, create much higher vibration forces than normal. Because of the higher vibration levels at special trackwork, crossovers often end up being the principal areas of vibration impact on new systems. Modifying the track support system is one method of mitigating the vibration impact. Special track support systems such as ballast mats, high resilience track fasteners, resiliently supported ties, and floating slabs have all been shown to be effective in reducing vibration levels.

The condition of the running surface of the rails can strongly affect vibration levels. Factors such as corrugations, general wear, or mill scale on new track can cause vibration levels that are 5 to 15 decibels higher than normal. Mill scale will usually wear off after some time in service, however, the track must be ground to remove corrugations or to reduce the roughness from wear.

Transit Structure – The weight and size of a transit structure affects the vibration radiated by that structure. The general rule-of-thumb is that vibration levels will be lower for heavier transit structures. Hence, the vibration levels from a cut-and-cover concrete double-box subway can be assumed to be lower than the vibration from a lightweight concrete-lined bored tunnel. The vibration from elevated structures is lower than from at-grade track because of the mass of the structure and the extra distance that the vibration must travel before it reaches the receiver.

Propagation Characteristics – In the General Assessment it is necessary to make a selection among the general propagation characteristics. For a subway, the selection is a fairly straightforward choice of whether or not the subway will be founded in bedrock. Bedrock is considered to be hard rock. It is usually appropriate to consider soft siltstone and sandstone to be more similar to soil than hard rock. As seen in Table 10-1, whether the subway is founded in soil or rock will make up to a 15 decibel difference in the vibration levels.

When considering at-grade vibration sources, the selection is between "normal" vibration propagation and "efficient" vibration propagation. Efficient vibration propagation results in approximately 10 decibels higher vibration levels. This more than doubles the potential impact zone for ground-borne vibration. One of the problems with identifying the cause of efficient propagation is the difficulty in determining whether higher than normal vibration levels are due to geologic conditions or due to special source conditions (e.g. rail corrugations or wheel flats).

Although it is known that geologic conditions have a significant effect on the vibration levels, it is rarely possible to develop more than a broad-brush understanding of the vibration propagation characteristics for a General Assessment. The conservative approach would be to use the 10 decibel adjustment for efficient propagation to evaluate all potential vibration impact. The problem with this approach is that it tends to greatly overstate the potential for vibration impact. Hence, it is best to review available geological data and any complaint history from existing transit lines and major construction sites near the transit corridor to identify areas where efficient propagation is possible. If there is any reason to suspect efficient propagation conditions, then a Detailed Analysis during final design would include vibration propagation tests at the areas identified as potentially efficient propagation sites.

Some geologic conditions are repeatedly associated with efficient propagation. Shallow bedrock, less than 30 ft below the surface, is likely to have efficient propagation. Other factors that can be important are soil type and stiffness. In particular, stiff clayey soils have sometimes been associated with efficient vibration propagation. Investigation of soil boring records can be used to estimate depth to bedrock and the presence of problem soil conditions.

A factor that can be particularly complex to address is the effect of vibration propagation through rock. There are three factors from Table 10-1 that need to be included when a subway structure will be founded in rock. First is the -15 decibel adjustment in the "Type of Transit Structure" category. Second is the adjustment based on the propagation distance in the "Geologic Conditions" category. This positive adjustment increases with distance because vibration attenuates more slowly in rock than in soil. The third factor is in the "Coupling to Building" category. When a building foundation is directly on the rock layer, there is no "coupling loss" due to the weight and stiffness of the building. Use the standard coupling factors if there is at least a 10-foot layer of soil between the building foundation and the rock layer.

Type of Building and Receiver Location in Building – Since annoyance from ground-borne vibration and noise is an indoor phenomenon, the effects of the building structure on the vibration must be considered. Wood frame buildings, such as the typical residential structure, are more easily excited by ground vibration than heavier buildings. In contrast, large masonry buildings with spread footings have a low response to ground vibration.

Vibration generally reduces in level as it propagates through a building. As indicated in the table, a 1 to 2 decibel attenuation per floor is usually assumed. Counteracting this, resonances of the building structure, particularly the floors, will cause some amplification of the vibration. Consequently, for a wood-frame structure, the building-related adjustments nearly cancel out. The adjustments for the first floor assuming a basement are: -5 decibels for the coupling loss; -2 decibels for the propagation from the basement to the first floor; and +6 decibels for the floor amplification. The total adjustment is -1 decibel.

Vibration to Ground-Borne Noise Adjustment – It is possible to estimate the levels of radiated noise given the average vibration amplitude of the room surfaces (floors, walls and ceiling), and the total acoustical absorption in the room. The average result is that the sound pressure level is approximately equal to the vibration velocity level when the velocity level is referenced to $1x10^{6}$ in./sec. However, to estimate the A-weighted sound level from the velocity level, it is necessary to have some information about the frequency spectrum. The A-weighting adjustment drops rapidly at low frequencies reflecting the relative insensitivity of human hearing to low frequencies. For example, A-weighting is -16 dB at 125 Hz, -26 dB at 60 Hz and -40 dB at 30 Hz. Table 10-1 provides adjustments for vibration depending on whether it has low-frequency, typical or high-frequency characteristics. Some general guidelines for classifying the frequency characteristics are:

- Low Frequency: Low-frequency vibration characteristics can be assumed for subways surrounded by cohesiveless sandy soil or whenever a vibration isolation track support system will be used. Low-frequency characteristics can be assumed for most surface track.
- Typical: The typical vibration characteristic is the default assumption for subways. It should be assumed for subways until there is information indicating that one of the other assumptions is appropriate. It should be used for surface track when the soil is very stiff with a high clay content.
- High Frequency: High-frequency characteristics should be assumed for subways whenever the transit structure is founded in rock or when there is very stiff clayey soil.

10.3 INVENTORY OF VIBRATION-IMPACTED LOCATIONS

This chapter includes generalized curves for surface vibration for different transit modes along with adjustments to apply for specific operating conditions and buildings. The projected levels are then compared with the criteria in Chapter 8 to determine whether vibration impact is likely. The results of the General Assessment are expressed in terms of an inventory of all sensitive land uses where either ground-borne vibration or ground-borne noise from the project may exceed the impact thresholds. The General Assessment may include a discussion of mitigation measures which would likely be needed to reduce vibration to acceptable levels.

The purpose of the procedure is to develop a reasonably complete inventory of the buildings that may experience ground-borne vibration or noise that exceed the impact criteria. At this point, it is preferable to make a conservative assessment of the impact. That is, it is better to include some buildings where ground-borne vibration may be below the impact threshold than to exclude buildings where it may exceed the impact threshold. The inventory should be organized according to the categories described in Chapter 8. For each building where the projected ground-borne vibration or noise exceeds the applicable impact threshold , one or more of the vibration control options from Section 11.4 should be considered for applicability. See Section 11.3 for a more complete description of how the General Vibration Assessment fits into the overall procedure.

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11. DETAILED VIBRATION ANALYSIS

The goal of the Detailed Analysis is to use all available tools to develop accurate projections of potential ground-borne vibration impact and, when necessary, to design mitigation measures. This is appropriate when the General Assessment has indicated impact and the project has entered the final design and engineering phase. It may also be appropriate to perform a Detailed Analysis at the outset when there are particularly sensitive land uses within the screening distances. Detailed Analysis will require developing estimates of the frequency components of the vibration signal, usually in terms of 1/3 octave band spectra. Analytical techniques for solving vibration problems are complex and the technology continually advances. Consequently, the approach presented in this chapter focuses on the key steps usually taken by a professional in the field.

Three examples of cases where Detailed Vibration Analysis might be required are:

Example 1: A particularly sensitive building such as a major concert hall is within the impact zone. A Detailed Analysis would ensure that effective vibration mitigation is feasible and economically reasonable.

Example 2: The General Assessment indicates that a proposed commuter rail project has the potential to create vibration impact for a large number of residential buildings adjacent to the alignment. The projections for many of the buildings exceed the impact threshold by less than 5 decibels, which means that more accurate projections may show that vibration levels will be below the impact criterion. If the cost of the vibration mitigation measures would have a significant impact on the project costs, a Detailed Analysis to determine the impact as accurately as possible is warranted.

Example 3: A transit alignment will be close to university research buildings where vibration-sensitive optical instrumentation is used. Vibration from the trains could make it impossible to continue using the building for this type of research. A Detailed Analysis would determine if it is possible to control the vibration from the trains such that sensitive instrumentation will not be affected.

A Detailed Vibration Analysis consists of three parts:

1. **Survey Existing Vibration.** Although knowledge of the existing levels of ground-borne vibration is not usually required for the assessment of vibration impact, there are times when a survey of the existing vibration is valuable. Examples include documenting existing background vibration at sensitive buildings, measuring the vibration levels created by sources such as existing rail lines, and, in some cases, characterizing the general background vibration in the project corridor. Characterizing the existing vibration is discussed in Section 11.1.

2. **Predict Future Vibration and Vibration Impact.** All of the available tools should be applied in a Detailed Analysis to develop the best possible estimates of the potential for vibration impact. Section 11.2 discusses an approach to projecting ground-borne vibration that involves performing tests to characterize vibration propagation at sites where significant impact is probable. Section 11.3 describes the vibration propagation test procedure and Section 11.4 discusses the assessment of vibration impact.

3. **Develop Mitigation Measures.** Controlling the impact from ground-borne vibration requires developing cost-effective measures to reduce the vibration levels. The Detailed Analysis helps to select practical vibration control measures that will be effective at the dominant vibration frequencies and compatible with the given transit structure and track support system. Vibration mitigation measures are discussed in Section 11.5.

The discussion in this chapter generally assumes that detailed vibration analysis applies to a steel-wheel rail system. The procedures could be adapted to bus systems. However, this is rarely necessary because vibration problems are very infrequent with rubber-tired transit.

11.1 CHARACTERIZING EXISTING VIBRATION CONDITIONS

Environmental vibration is rarely of sufficient magnitude to be perceptible or cause audible ground-borne noise unless there is a specific vibration source close by, such as a rail line. In most cases, feelable vibration inside a building is caused by equipment or activities within the building itself, such as heating and ventilation systems, footsteps or doors closing. Because the existing environmental vibration is usually below human perception, a limited vibration survey is sufficient even for a Detailed Analysis. This contrasts with analysis of noise impact where documenting the existing ambient noise level is required to assess the impact.

Examples of situations where measurements of the ambient vibration are valuable include:

- **Determining existing vibration at sensitive buildings.** Serious vibration impact may occur when there is vibration-sensitive manufacturing, research, or laboratory activities within the screening distances. Careful documentation of the pre-existing vibration provides valuable information on the real sensitivity of the activity to external vibration and gives a reference condition under which vibration is not a problem.

- **Using existing vibration sources to characterize propagation.** Existing vibration sources such as freight trains, industrial processes, quarrying operations, or normal traffic sometimes can be used to characterize vibration propagation. Carefully designed and performed measurements may eliminate the need for more complex propagation tests.

- **Documenting existing levels of general background.** Some measurements of the existing levels of background vibration can be useful simply to document that, as expected, the vibration is below the normal threshold of human perception. Existing vibration in urban and suburban areas is usually due to traffic. If a measurement site has existing vibration approaching the range of human perception (e.g., the maximum vibration velocity levels are greater than about 65 VdB), then this site should be carefully evaluated for the possibility of efficient vibration propagation. Areas with efficient vibration propagation could have vibration problems when the project is built.

- **Documenting vibration from existing rail lines.** Measurements to document the levels of vibration created by existing rail lines can be important in evaluating the impact of the new vibration source and determining vibration propagation characteristics in the area. As discussed in Chapter 8, if vibration from an existing rail line will be higher than that from the transit trains, there may not be impact even though the normal impact criterion would be exceeded.

Although ground-borne vibration is almost exclusively a problem inside buildings, measurements of existing ambient vibration generally should be performed outdoors. Two important reasons for this are: (1) equipment inside the building may cause more vibration than exterior sources, and (2) the building structure and the resonances of the building can have strong, but difficult to predict, effects on the vibration. However, there are some cases where measurements of indoor vibration are important. Documenting the vibration levels inside a vibration-sensitive building can be particularly important since equipment and activities inside the building sometimes causes vibration greater than that due to external sources such as street traffic or aircraft overflights. Floor vibration measurements are taken near the center of a floor span where the vibration amplitudes are the highest.

The goal of most ambient vibration tests is to characterize the rms vertical vibration velocity level at the ground surface. In almost all cases it is sufficient to measure only vertical vibration and ignore the transverse components of the vibration. Although transverse components can transmit significant vibration energy into a building, the vertical component usually has greater amplitudes than transverse vibration. Moreover, vertical vibration is usually transmitted more efficiently into building foundations than transverse vibration.

The manner in which a transducer is mounted can affect the measured levels of ground-borne vibration. However, research has shown that, at the frequencies usually of concern for ground-borne vibration (less than about 200 Hz), straightforward methods of mounting transducers on the ground surface or on pavement are adequate for vertical vibration measurements.[1][2][3] Quick-drying epoxy or beeswax are often used to mount transducers to smooth paved surfaces or to metal stakes driven into the ground. Rough concrete or rock surfaces require special mountings. One approach is to use a liberal base of epoxy to attach small aluminum blocks to the surface and then mount the transducers on the aluminum blocks.

Selecting sites for an ambient vibration survey primarily requires good common sense. Sites selected to characterize a transit corridor should be distributed along the entire project and should be representative of the types of vibration environments found in the corridor. This would commonly include:

- measurements in quiet residential areas removed from major traffic arterials to characterize low-ambient vibrations;
- measurements along major traffic arterials and highways or freeways to characterize high vibration areas;
- measurements in any area with vibration-sensitive activities; and
- measurements at any significant existing source of vibration such as railroad lines.

The transducers should be located near the building setback line for background vibration measurements. Ambient measurements along railroad lines ideally will include: multiple sites; several distances from the rail line at each site; and 4 to 10 train passbys for each test. Because of the irregular schedule for freight trains and the low number of operations each day, it is often impractical to perform tests at more than two or three sites along the rail line or to measure more than two or three passbys at each site. Rail type and condition strongly affect the vibration levels. Consequently, it is important to inspect the track at each measurement site to locate any switches, bad rail joints, corrugations, or other factors that could be responsible for higher than normal vibration levels.

The appropriate methods of characterizing ambient vibration are dependent on the type of information required for the analysis. Following are some examples:

Ambient Vibration – Ambient vibration is usually characterized with a continuous 10 to 30 minute measurement of vibration. The L_{eq} of the vibration velocity level over the measurement period gives an indication of the average vibration energy. L_{eq} is equivalent to a long averaging time rms level. Specific events can be characterized by the maximum rms level (L_{max}) of the event or by performing a statistical analysis of rms levels over the measurement period. An rms averaging time of 1 second should be used for statistical analysis of the vibration level.

Specific Events – Specific events such as train passbys should be characterized by the rms level during the time that the train passes by. If the locomotives have vibration levels more than 5 dB higher than the vehicles, a separate rms level for the locomotives should be obtained. The locomotives can usually be characterized by the L_{max} during the train passby. The rms averaging time or time constant should be 1 second when determining L_{max}. Sometimes it is adequate to use L_{max} to characterize the train passby, which is simpler to obtain than the rms averaged over the entire train passby.

Spectral Analysis – When the vibration data will be used to characterize vibration propagation or for other special analysis, a spectral analysis of the vibration is required. An example would be if vibration transmission characteristics of the ground are suspected of having particular frequency characteristics. For many analyses, 1/3-octave band charts are best for describing the vibration characteristics. Narrowband spectra also can be valuable, particularly for identifying pure-tone characteristics and designing mitigation measures.

Note it is preferable that ambient vibration be characterized in terms of the rms velocity level, not the peak particle velocity (ppv), which is commonly used to monitor construction vibration. As discussed in Chapter 7, rms is considered more appropriate than ppv for describing human response to building vibration.

11.2 VIBRATION PREDICTION PROCEDURE

Predicting ground-borne vibration associated with a transportation project is a developing field. Because ground-borne vibration is a complex phenomenon that is difficult to model and predict accurately, most projection procedures that have been used for transit projects rely on empirical data. Although no single method stands out as the best approach for all situations, the procedure described in this section is one of the most promising because it is based on site-specific tests of vibration propagation. The procedure, which was developed under an FTA (formerly UMTA) research contract,[(4)] is recommended for detailed evaluations of ground-borne vibration. There have been other approaches to a prediction procedure including some that use pure numerical methods. An approach using finite elements showed potential,[(5)] however, to date none of the numerical approaches has been developed beyond the conceptual stage.

11.2.1 Overview of Prediction Procedure

The prediction method described in this section was developed to allow using data collected in one city to accurately predict vibration levels in another city where the geologic conditions may be completely different. The procedure is based on using a special measured function, called *transfer mobility*. Transfer mobility measured at an existing transit system is used to normalize ground-borne vibration data and remove the effects of geology. The normalized vibration is referred to as the force density. The force density can be combined with transfer mobility measurements at sensitive sites along a new project to develop projections of future ground-borne vibration.

Transfer mobility represents the relationship between a vibration source that excites the ground and the resulting vibration of the ground surface. It is a function of both frequency and distance from the source. The transfer mobility between two points completely defines the composite vibration propagation characteristics between the two points. In most practical cases, receivers are close enough to the train tracks that the vibration cannot be considered to be originating from a single point. The vibration source must be modeled as a line source. Consequently, the point transfer mobility must be modified to account for a line source. In the following text, TM_{point} is used to indicate the measured point source transfer mobility and TM_{line} is used for the line source transfer mobility derived from TM_{point}.

The prediction procedure considers ground-borne vibration to be divided into several basic components as shown schematically in Figure 11-1. The components are:

1. **Excitation Force:** The vibration energy is created by oscillatory and impulsive forces. Steel wheels rolling on smooth steel rails create random oscillatory forces. When a wheel encounters a discontinuity such as a rail joint, an impulsive force is created. The force excites the transit structure, such as the subway tunnel, or the ballast for at-grade track. In the prediction method, the combination of the actual

force generated at the wheel/rail interface and the vibration of the transit structure are usually combined into an equivalent force density level. The force density level describes the force that excites the soil/rock surrounding the transit structure.

2. **Vibration Propagation:** The vibration of the transit structure causes vibration waves in the soil that propagate away from the transit structure. The vibration energy can propagate through the soil or rock in a variety of wave forms. All ground vibration includes shear and compression waves. In addition, Rayleigh waves, which propagate along the ground surface, can be a major carrier of vibration energy. The mathematical modeling of vibration is complicated when, as is usually the case, there are soil strata with different elastic properties. As indicated in Figure 11-1, the propagation through the soil/rock is modeled using the transfer mobility, which is usually determined experimentally.

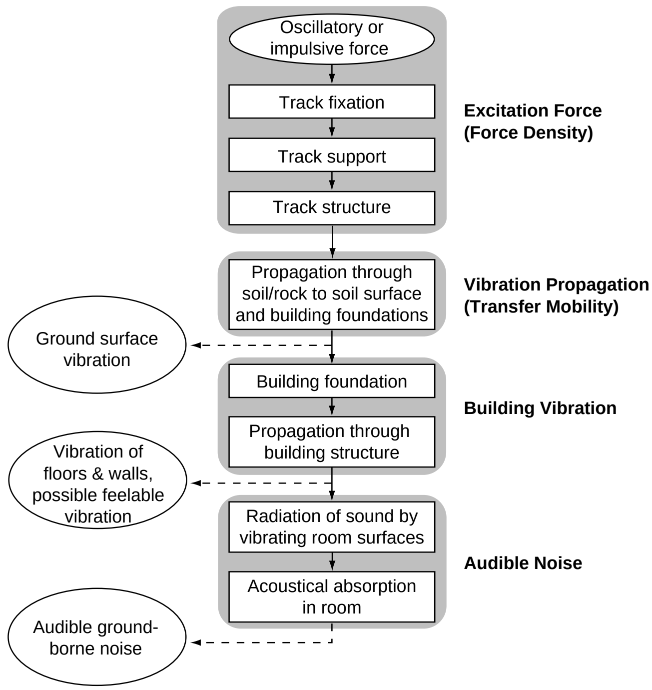

Figure 11-1 Block Diagram of Ground-Borne Vibration and Noise Model

The combination of the force density level and the transfer mobility is used to predict the ground-surface vibration. Here is the essential difference between the General and Detailed approaches: the projection process is simplified in a General Assessment by going directly to generalized estimates of the ground-surface vibration.

3. **Building Vibration:** When the ground vibration excites a building foundation, it sets the building into vibration motion and starts vibration waves propagating throughout the building structure. The interaction between the ground and the foundation causes some reduction in vibration levels. The amount of reduction is dependent on the mass and stiffness of the foundation. The more massive the foundation, the lower the response to ground vibration. As the vibration waves propagate through the building, they can create feelable vibration and can cause annoying rattling of windows and decorative items either hanging or on shelves.

4. **Audible Noise:** In addition to feelable vibration, the vibration of room surfaces radiates low-frequency sound that may be audible. As indicated in Figure 11-1, the sound level is affected by the amount of acoustical absorption in the receiver room.

A fundamental assumption of the prediction approach outlined here is that the force density, transfer mobility, and the building coupling to the ground are all independent factors. The following equations are the basis for the prediction procedure where all of the quantities are in decibels with consistent reference values:

$$\mathbf{L_v = L_F + TM_{line} + C_{build}}$$

$$\mathbf{L_A = L_v + K_{rad} + K_{A\text{-}wt}}$$

where:

$\mathbf{L_v}$	=	rms vibration velocity level in one 1/3 octave band,
$\mathbf{L_A}$	=	A-weighted sound level in one 1/3 octave band,
$\mathbf{L_F}$	=	force density for a line vibration source such as a train,
$\mathbf{TM_{line}}$	=	line source transfer mobility from the tracks to the sensitive site,
$\mathbf{C_{build}}$	=	adjustments to account for ground–building foundation interaction and attenuation of vibration amplitudes as vibration propagates through buildings,
$\mathbf{K_{rad}}$	=	adjustment to account for conversion from vibration to sound pressure level including accounting for the amount of acoustical absorption inside the room (A value of zero can be used for $\mathbf{K_{rad}}$ for typical residential rooms when the decibel reference value for $\mathbf{L_v}$ is 1 micro in./sec.[4]),
$\mathbf{K_{A\text{-}wt}}$	=	A-weighting adjustment at the 1/3 octave band center frequency.

All of the quantities given above are functions of frequency. The standard approach to dealing with the frequency dependence is to develop projections on a 1/3 octave band basis using the average values for each 1/3 octave band. The end result of the analysis is the 1/3 octave band spectra of the ground-borne vibration and the ground-borne noise. The spectra are then used to calculate the overall vibration velocity level and the A-weighted sound level. This is in contrast to the General Assessment where the overall vibration velocity level and A-weighted sound level are predicted without any consideration of the particular frequency characteristics of the propagation path.

11.2.2 Major Steps in Detailed Analysis

The major steps in performing a Detailed Analysis are intended to obtain quantities for the equations given above. These are:

1. Develop estimates of the force density. The estimate of force density can be based on previous measurements (e.g., References 4, 9, 10 or 11) or a special test program can be designed to measure the force density at an existing facility. If no suitable measurements are available, testing should be done at a transit facility with equipment similar to the planned vehicles. Adjustments for factors such as train speed, track support system, and vehicle suspension may be needed to match the force density to the conditions at specific sites. Some appropriate adjustments can be found in the report "State-of-the-Art Review: Prediction and Control of Ground-Borne Noise and Vibration from Rail Transit Trains."[6]

2. Measure the point source transfer mobility at representative sites. The transfer mobility is a function of both frequency and distance from the source.

3. Use numerical integration to estimate a line source transfer mobility from the point source transfer mobilities. The combination of force density and line source transfer mobility is used to project ground-surface vibration.

4. Add adjustment factors to estimate the building response to the ground-surface vibration and to estimate the A-weighted sound level inside buildings.

The two key elements of the transfer mobility procedure are a measured force function that represents the vibration energy put into the ground and a measured transfer mobility that characterizes the propagation of the vibration from the source to the receiver. The unit of force density is force divided by square root of train length; represented here in decibels relative to 1 lb/(ft)$^{1/2}$. The force density represents an incoherent line of vibration force equal to the length of transit trains. The process of estimating force density from train vibration and transfer mobility tests is discussed in Section 11-3. Figure 11-2 shows some trackbed force densities that have been developed from measurements of vibration from heavy and light rail transit vehicles. This figure provides a comparison of the vibration forces from vehicles with two different types of primary suspensions illustrating that vibration forces can be up to 10 to 15 dB higher in important frequency ranges for vehicles with stiff primary suspensions. Adjustments must be made to the force density to account for differences between the facility where the force density was measured and the new system. Reference 6 discusses a number of potential adjustments.

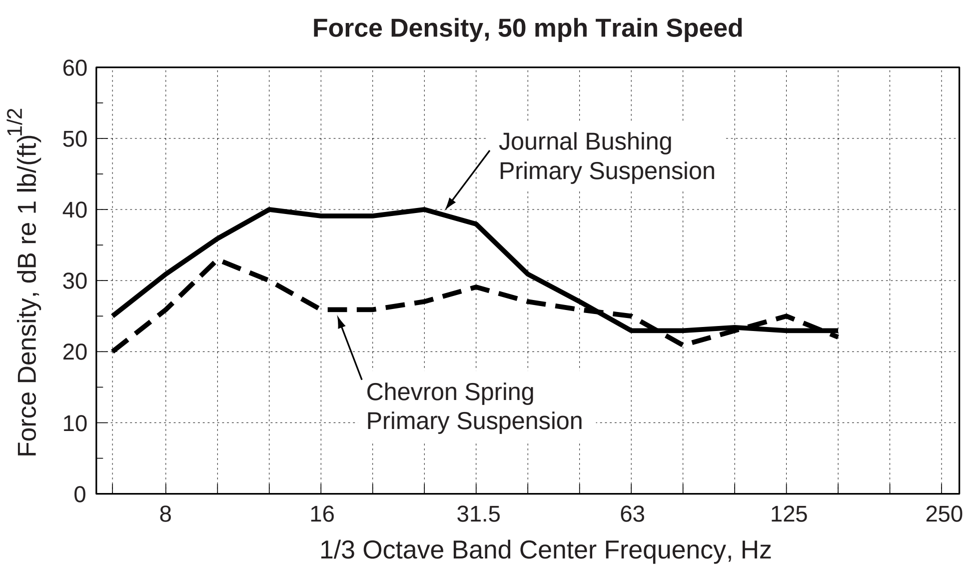

Figure 11-2 Force Densities for Rail Transit Vehicles

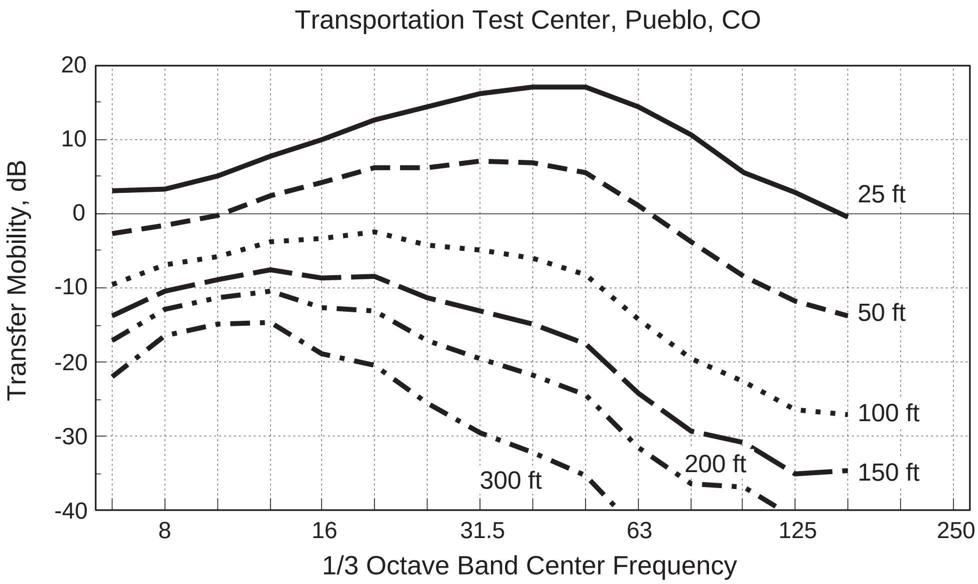

Figure 11-3 Average Point-Source Transfer Mobility

The key elements of the vibration prediction procedure are implementation of field tests to measure the transfer mobility and the subsequent use of transfer mobility to characterize vibration propagation. The process of measuring transfer mobility involves impacting the ground and measuring the resulting vibration pulse at various distances from the impact. Standard signal processing techniques are used to determine the transfer function, or frequency response function, between the exciting force and the resultant ground-surface vibration. Numerical regression methods are used to combine a number of two point transfer functions into a smooth point source transfer mobility that represents the average vibration propagation characteristics of a site as a function of both distance from the source and frequency. The transfer mobility is usually expressed in terms of a group of 1/3 octave band transfer mobilities. Because typical spectrum analyzers are not capable of obtaining 1/3 octave band transfer functions, this processing is performed after transferring the data to a computer. Figure 11-3 shows the point source transfer mobilities from a series of tests at the Transportation Test Center in Pueblo, Colorado.[7][8][9][10][11]

Once the point source transfer mobility has been defined, the line source transfer mobility can be calculated using numerical integration techniques. This process has been described in a Transportation Research Board paper [4] and a U.S. DOT report.[12] Figure 11-4 shows the line source transfer mobilities that were derived from the point source transfer mobilities shown in Figure 11-3. The line source transfer mobilities are used to normalize measured vibration velocity levels from train passbys and to obtain force density.

The propagation of vibration from the building foundation to the receiver room is a very complex problem dependent on the specific design of the building. Detailed evaluation of the vibration propagation would require extensive use of numerical procedures such as the finite element method. Such a detailed evaluation is generally not practical for individual buildings considered in this manual. The propagation of vibration through a building and the radiation of sound by vibrating building surfaces is consequently estimated using

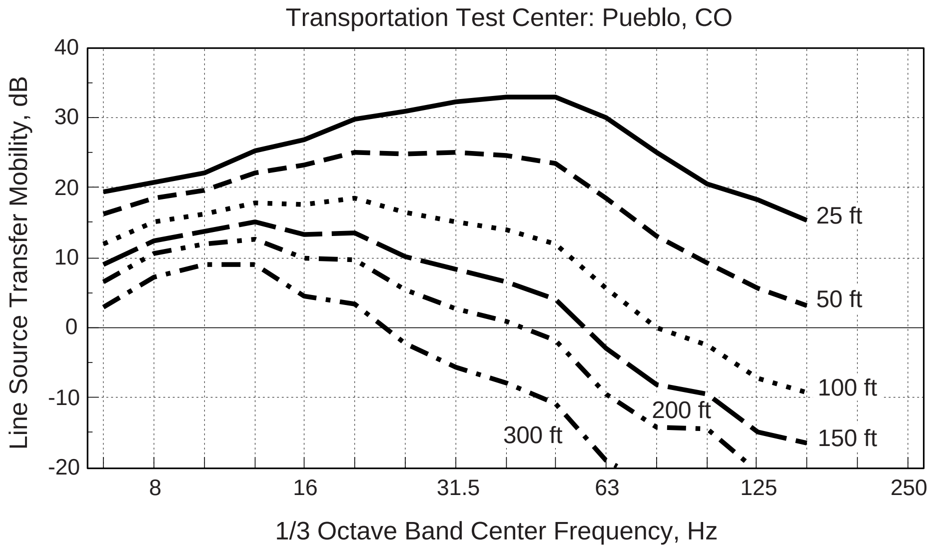

Figure 11-4 Average Line-Source Transfer Mobility

simple empirical or theoretical models. The recommended procedures are outlined in the *Handbook of Urban Rail Noise and Vibration Control*.(13) The approach consists of adding the following adjustments to the 1/3 octave band spectrum of the projected ground-surface vibration:

1. **Building response or coupling loss.** This represents the change in the incident ground-surface vibration due to the presence of the building foundation. The adjustments in the *Handbook*, which were originally developed by Wilson,(14) are shown in Figure 11-5. Note that the correction is zero when estimating basement floor vibration or vibration of at-grade slabs.

2. **Transmission through the building.** The vibration amplitude will decrease as the vibration energy propagates from the foundation through the remainder of the building. The normal assumption is that vibration attenuates by 1 to 2 dB for each floor.

3. **Floor resonances.** Vibration amplitudes will be amplified because of resonances of the floor/ceiling systems. For a typical wood frame residential structure, the fundamental resonance is usually in the 15 to 20 Hz range. Reinforced-concrete slab floors in modern buildings will have fundamental resonance frequencies in the 20 to 30 Hz range. An amplification resulting in a gain of approximately 6 dB should be used in the frequency range of the fundamental resonance.

The projected floor vibration is used to estimate the levels of ground-borne noise. The primary factors affecting noise level are the average vibration level of the room surfaces and the amount of acoustical absorption within the room. As discussed above, the radiation adjustment is zero for typical rooms, which gives:

$$\mathbf{L_A \approx L_v + K_{A\text{-}wt}}$$

where L_A is the A-weighted sound level in a 1/3 octave band, L_v is the average vibration velocity level, and $K_{A\text{-}wt}$ is the A-weighting adjustment at the center frequency of the 1/3 octave band. The A-weighted levels in the 1/3 third octave bands are then combined to give the overall A-weighted sound level.

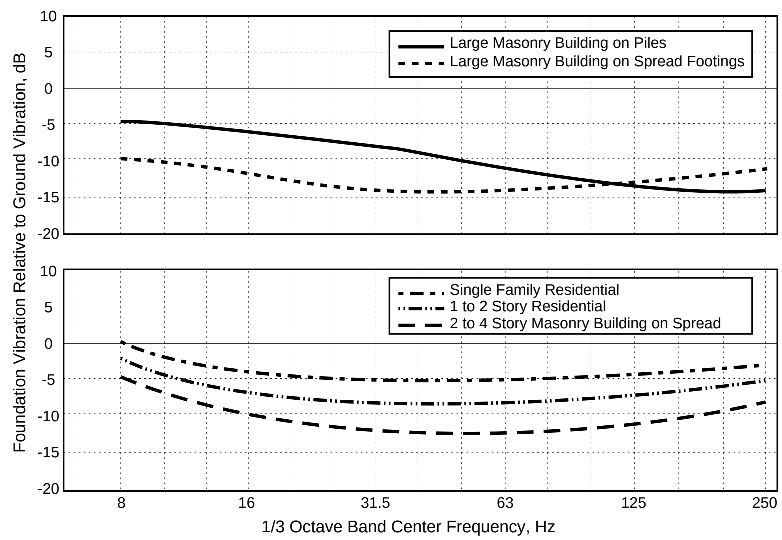

Figure 11-5 Foundation Response for Various Types of Buildings

11.3 MEASURING TRANSFER MOBILITY AND FORCE DENSITY

The test procedure to measure transfer mobility basically consists of dropping a heavy weight on the ground and measuring the force into the ground and the response at several distances from the impact. The goal of the test is to create vibration pulses that travel from the source to the ground surface using the same path that will be taken by the transit system vibration. The transfer mobility expresses the relationship between the input force and the ground-surface vibration.

Figure 11-6 illustrates the field procedure for at-grade and subway testing of transfer mobility. A weight is dropped from a distance of 3 to 4 feet onto a force transducer. The responses of the force and vibration transducers are recorded on a multichannel tape recorder for later analysis in the laboratory. An alternative approach is to set up the analysis equipment in the field and capture the signals directly. This complicates the field testing but eliminates the laboratory analysis of tape recorded data.

When the procedure is applied to subways, the force must be located at the approximate depth of the subway. This is done by drilling a bore hole and locating the force transducer at the bottom of the hole. The tests are usually performed at the same time that the bore holes are drilled. This allows using the soil-sampling equipment on the drill rig for the transfer mobility testing. The force transducer is attached to the bottom of the drill string and lowered to the bottom of the hole. A standard soil sampling hammer, which is usually

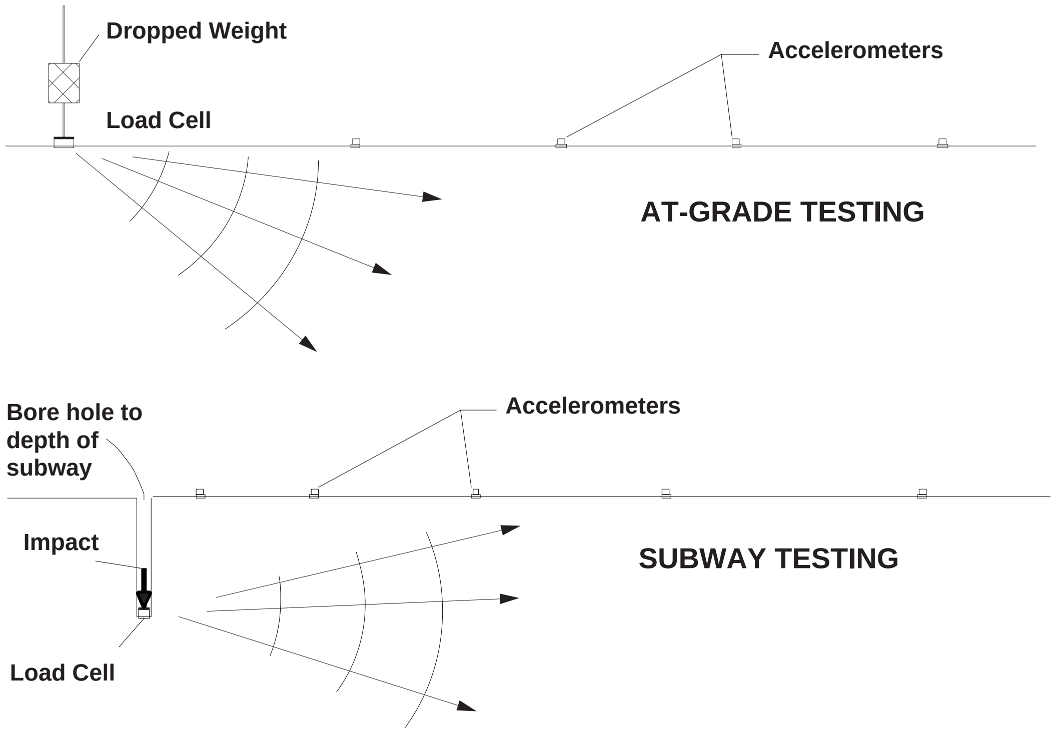

Figure 11-6 Test Configuration for Measuring Transfer Mobility

a 140 lb weight dropped 18 inches on to a collar attached to the drill string, is used to excite the ground. The force transducer must be capable of operating under water if the water table is near the surface or a slurry drilling process is used.

11.3.1 Instrumentation

Performing a transfer mobility test requires specialized equipment. Most of the equipment is readily available from several commercial sources. Commercially available load cells can be used as the force transducer. For borehole testing, the load cells must be hermetically sealed and capable of being used at the bottom of a 30 to 100 foot deep hole partially filled with water. A typical instrumentation array for the field testing and laboratory analysis of transfer mobility is shown in Figure 11-7. The force transducer should be capable of impact loads of 5,000 to 10,000 lb. Either accelerometers or geophones can be used as the vibration transducers. The requirement is that the transducers with the associated amplifiers be capable of accurately measuring levels of 0.0001 in./sec at 40 Hz and have a flat frequency response from 6 Hz to 400 Hz. The tape recorder also must have a flat response over the 6 to 400 Hz frequency range. Adequate low-frequency response usually requires either an instrumentation-quality FM recorder or a digital recorder. The response of most normal direct-record tape recorders is inadequate at frequencies below about 30 Hz.

The narrowband spectrum analyzer is the key element of the laboratory instrumentation. The analyzer must be capable of capturing impulses from at least two channels and calculating the frequency spectrum of the transfer function between the force and vibration channels. All transfer functions should include the average of at least 20 impulses. The averaging of the impulses will provide significant signal enhancement, which is usually required to accurately characterize the transfer function. Signal enhancement is particularly important when the vibration transducer is more than 100 ft from the impact.

The laboratory array in Figure 11-7 shows the spectrum analyzer interfaced with a computer. The computer is usually required to adapt the narrowband transfer function data into a format suitable for evaluation of 1/3 octave band transfer mobility. The raw transfer function data usually include several hundred frequency bands. By transforming a narrowband spectrum into a 1/3 octave band spectrum, each spectrum is reduced to 15 to 20 bands. This step reduces the amount of data that must be evaluated to develop the generalized curves. There are specialized multi-channel spectrum analyzers which have built-in capabilities that are sufficient for this data analysis.

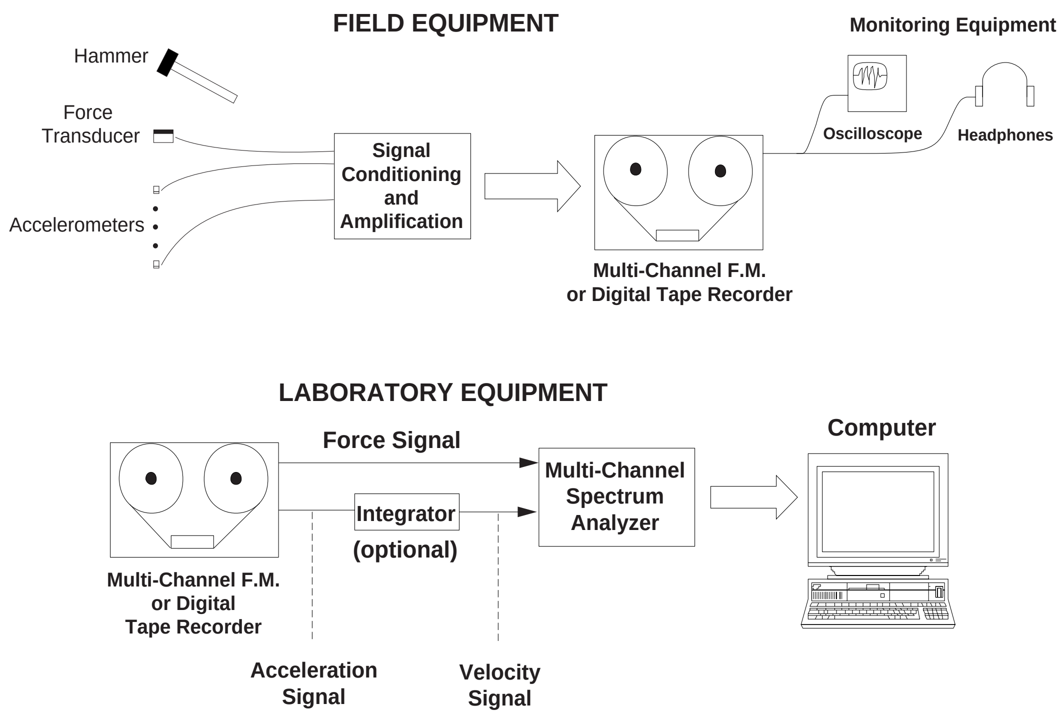

Figure 11-7 Equipment Required for Field Testing and Laboratory Analysis

11.3.2 Analysis of Transfer Mobility Data

Two different approaches have been used to develop estimates of line-source transfer mobility. The first consists of using lines of transducers and the second consists of a line of impact positions. The steps to develop line-source transfer mobility curves from tests using one or more lines of transducers are shown in Figure 11-8. The procedure starts with the narrowband transfer function between source and receiver at each measurement position. There should be a minimum of four distances in any test line. Because of the possibility of local variations in propagation characteristics, if at all possible, two or more lines should be used to characterize a site. A total of 10 to 20 transducer positions are often used to characterize a site. Assuming that the spectrum analyzer calculates 400 line narrowband transfer functions for each position, this means a total of 4,000 to 8,000 numbers for each site.

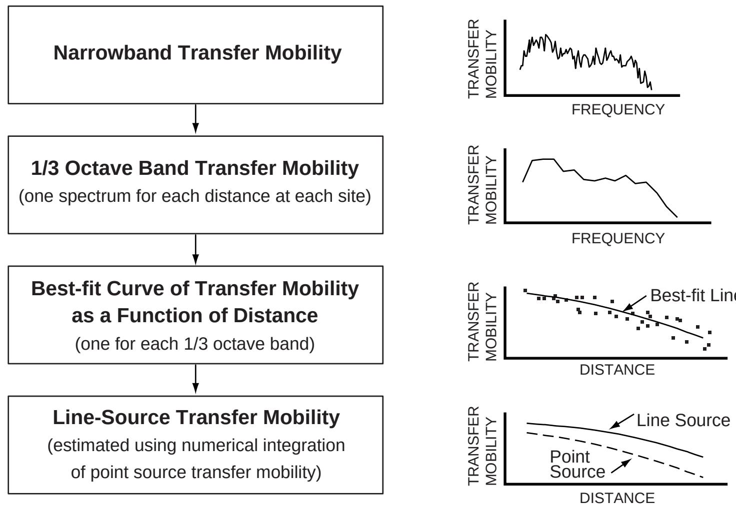

Figure 11-8 Analysis of Transfer Mobility

The first step in the analysis procedure is to calculate the equivalent 1/3 octave band transfer functions. This reduces each spectrum from 400 to 15 numbers. As shown in Figure 11-8, the 1/3 octave band spectrum is much smoother than the narrow-band spectrum. The next step is to calculate a best-fit curve of transfer mobility as a function of distance for each 1/3 octave band. When analyzing a specific site, the best-fit curve will be based on 10 to 20 points. Up to several hundred points could be used to determine average best-fit curves for a number of sites.

The 1/3 octave band best-fit curves can be directly applied to point vibration sources. Buses can usually be considered to be point sources. However, for a line vibration source such as a train, numerical integration must be used to calculate an equivalent line source transfer mobility. The numerical integration procedures are detailed in Reference 4.

The second procedure for estimating line-source transfer mobility, shown schematically in Figure 11-9, is best for detailed assessment of specific vibration paths or specific buildings. The vibration transducers are located at specific points of interest and a line of impacts is used. For example, a 200 foot train might be represented by a line of 21 impact positions along the track centerline at 10 foot intervals. It is possible to sum the point source results using Simpson's rule for numerical integration to directly calculate line-source transfer mobility. This is a considerably more direct approach than is possible with lines of vibration transducers.

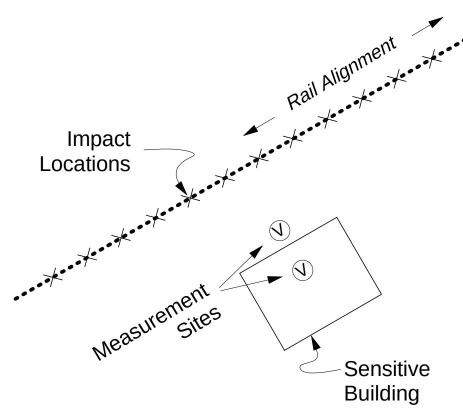

Figure 11-9 Schematic of Transfer Mobility
Measurements Using a Line of Impacts

11.3.3 Deriving Force Density

Force Density is not a quantity that can be measured directly, it must be inferred from measurements of transfer mobility and train vibration at the same site. For deriving force density, deriving line-source transfer mobility from a line of impacts gives the best results. The force density for each 1/3 octave band is then simply:

$$\mathbf{L_F = L_v - TM_{line}}$$

where L_F is the force density, L_v is measured train ground-borne vibration and TM_{line} is the line source transfer mobility. The standard approach is to use the average force density from measurements at three or more positions.

11.4 ASSESSMENT OF VIBRATION IMPACT

The goals of the vibration assessment are to inventory all sensitive land uses that may be adversely impacted by the ground-borne vibration and noise from the proposed project and to determine the mitigation measures that will be required to eliminate or minimize the impact. This requires projecting the levels of ground-borne vibration and noise, comparing the projections with the criteria, and developing a list of suitable mitigation measures. Note that the General Assessment is incorporated as an intermediate step in the impact assessment because of its relative simplicity and potential to narrow the areas where Detailed Analysis needs to be done.

The assessment of vibration impact should proceed according to the following steps:

1. Screen the entire proposed transit alignment to identify areas where there is the potential of impact from ground-borne vibration. The vibration screening method is described in Chapter 9. If no sensitive land uses are within the screening distances, it is not necessary to perform any further assessment of ground-borne vibration.

2. Define the curves of ground-surface vibration level as a function of distance that can be used with the General Assessment. Usually this will mean selecting the appropriate curve from Chapter 10 for the proposed transit mode. For less common transit modes, it may be necessary to make measurements at an existing facility.

3. Use the General Assessment Procedure to estimate vibration levels for specific buildings or groups of buildings. The projected levels are compared with the impact criteria given in Chapter 8 to determine whether vibration impact is likely. The goal of this step is to develop a reasonably accurate catalog of the buildings that will experience ground-borne vibration or noise levels that exceed the criteria. It is generally best to make a conservative assessment of the impact. That is, it is better to include some buildings that may not be impacted than to exclude some buildings that are likely to be impacted. In locations where General Assessment indicates impact, the more refined techniques of Detailed Analysis would be employed.

4. In some cases it will be necessary to perform a vibration survey to characterize existing ambient vibration. As discussed in Section 11.1, although knowledge of the existing ambient vibration is not

generally required to evaluate vibration impact, there are times when a survey of existing conditions is valuable. One common example is when the rail project will be located in an existing rail right-of-way shared by freight trains. Chapter 8 includes some guidelines on how to account for existing vibration that is higher than the impact limit for the project vibration.

5. For the areas where the impact criteria may be exceeded, review potential mitigation measures and assemble a list of feasible approaches to vibration control. To be feasible, the measure, or combination of measures, must be capable of providing a significant reduction of the vibration levels, at least 5 dB, while being reasonable from the standpoint of the added cost. Because vibration control is frequency-dependent, specific recommendations of vibration control measures can be made only after evaluating the frequency characteristics of the vibration.

6. Use the Detailed Vibration Analysis to develop detailed vibration mitigation measures. It is usually necessary to project vibration spectra at buildings which will be affected at levels higher than the impact thresholds. This type of assessment is normally performed as part of the final design rather than during the environmental impact assessment stage. Because a Detailed Analysis is more accurate than a General Assessment, there will be times that the Detailed Analysis will show that the vibration and noise levels will be below the applicable criteria and that mitigation is not required. If the projected levels are still above the limits, the spectra provided by the Detailed Analysis will be needed to evaluate vibration control approaches.

11.5 VIBRATION MITIGATION

The purpose of vibration mitigation is to minimize the adverse effects that the project ground-borne vibration will have on sensitive land uses. Because ground-borne vibration is not as common a problem as environmental noise, the mitigation approaches have not been as well defined. In some cases it has been necessary to develop innovative approaches to control the impact. Examples are the floating slab systems that were developed for the Washington, D.C. and Toronto transit systems and wheel-flat detectors that have been used to identify vehicles in need of maintenance.

The discussion in this section focuses on rail systems, the source of most problems with ground-borne vibration. When buses do cause annoying ground-borne vibration, it is usually clear that the source of the problem is roadway roughness or unevenness caused by bumps, pot holes, expansion joints, or driveway transitions. Smoothing the roadway surface will usually solve the problem.

The importance of adequate wheel and rail maintenance in controlling levels of ground-borne vibration cannot be overemphasized. Problems with rough wheels or rails can increase vibration levels by 20 dB, negating the effects of even the most effective vibration control measures. It is rare that practical vibration control measures will provide more than 15 to 20 dB attenuation. When there are ground-borne vibration problems with existing transit equipment, the best vibration control measure often is to implement new or improved maintenance procedures. Grinding rough or corrugated rail and wheel truing to eliminate wheel flats and restore the wheel contour may provide more vibration reduction than would be obtainable from completely replacing the existing track system with floating slabs.

Given that the track and vehicles are in good condition, the options for further reductions in the vibration levels fit into one of seven categories: (1) maintenance procedures, (2) location and design of special trackwork, (3) vehicle modifications, (4) changes in the track support system, (5) building modifications, (6) adjustments to the vibration transmission path, and (7) operational changes.

Maintenance – As discussed above, effective maintenance programs are essential for controlling ground-borne vibration. When the wheel and rail surfaces are allowed to degrade the vibration levels can increase by as much as 20 dB compared to a new or well maintained system. Some maintenance procedures that are particularly effective at avoiding increases in ground-borne vibration are:

- Rail grinding on a regular basis. Rail grinding is particularly important for rail that develops corrugations.
- Wheel truing to re-contour the wheel, provide a smooth running surface and remove wheel flats. The most dramatic vibration reduction results from removing wheel flats. However, significant improvements also can be observed simply from smoothing the running surface.
- Implement vehicle reconditioning programs, particularly when components such as suspension system, brakes, wheels, and slip-slide detectors will be involved.
- Install wheel-flat detector systems to identify vehicles which are most in need of wheel truing.

Planning and Design of Special Trackwork – A large percentage of vibration impact from a new transit facility is often caused by wheel impacts at the special trackwork for turnouts and crossovers. When feasible, the most effective vibration control measure is to relocate the special trackwork to a less vibration-sensitive area. Sometimes this requires adjusting the location by several hundred feet and will not have a significant adverse impact on the operation plan for the system. Careful review of crossover and turnout locations during the preliminary engineering stage is an important step to minimizing potential for vibration impact. Another approach is to use special devices at turnouts and crossovers, special "frogs," that incorporate mechanisms to close the gaps between running rails. Frogs with spring loaded mechanisms and frogs with movable points can significantly reduce vibration levels near crossovers.

Vehicle Specifications – The ideal rail vehicle, with respect to minimizing ground-borne vibration, should have a low unsprung weight, a soft primary suspension, a minimum of metal-to-metal contact between moving parts of the truck, and smooth wheels that are perfectly round. A limit for the vertical resonance frequency of the primary suspension should be included in the specifications for any new vehicle. A vertical resonance frequency of 12 Hz or less is sufficient to control the levels of ground-borne vibration. Some have recommended that transit vehicle specifications require that the vertical resonance frequency be less than 8 Hz.[15]

Special Track Support Systems – When the vibration assessment indicates that vibration levels will be excessive, it is usually the track support system that is changed to reduce the vibration levels. Floating slabs, resiliently supported ties, high resilience fasteners, and ballast mats have all been used in subways to reduce the levels of ground-borne vibration. To be effective, all of these measures must be optimized for the frequency spectrum of the vibration. Most of these relatively standard procedures have been successfully used on several subway projects. Applications on at-grade and elevated track are less common. This is because vibration problems are less common for at-grade and elevated track; cost of the vibration control measures is a higher percentage of the construction costs of at-grade and elevated track; and exposure to the elements can require significant design modifications.

Each of the major vibration control measures for track support is discussed below:

- Resilient Fasteners: Resilient fasteners are used to fasten the rail to concrete track slabs. Standard resilient fasteners are very stiff in the vertical direction, usually in the range of 200,000 lb/in., although they do provide vibration reduction compared to some of the rigid fastening systems used on older systems (e.g., wood half ties embedded in concrete). Special fasteners with vertical stiffness in the range of 30,000 lb/in. will reduce vibration by as much as 5 to 10 dB at frequencies above 30 to 40 Hz.

- Ballast Mats: A ballast mat consists of a rubber or other type of elastomer pad that is placed under the ballast. The mat generally must be placed on a concrete pad to be effective. They will not be as effective if placed directly on the soil or the sub-ballast. Consequently, most ballast mat applications are in subway or elevated structures. Ballast mats can provide 10 to 15 dB attenuation at frequencies above 25 to 30 Hz. Ballast mats are often a good retro-fit measure for existing tie-and-ballast track where there are vibration problems.

- Resiliently Supported Ties: The resiliently supported tie system consists of concrete ties supported by rubber pads. The rails are fastened directly to the concrete ties using standard rail clips. Existing measurement data indicate that resiliently supported ties may be very effective in reducing low-frequency vibration in the 15 to 40 Hz range. This makes them particularly appropriate for transit systems with vibration problems in the 20 to 30 Hz range.

- Floating Slabs: Floating slabs can be very effective at controlling ground-borne vibration and noise. They basically consist of a concrete slab supported on resilient elements, usually rubber or a similar elastomer. A variant that was first used in Toronto and is generally referred to as the double tie system, consists of 5-foot-long slabs with 4 or more rubber pads under each slab. Floating slabs are effective at frequencies greater than their single-degree-of-freedom vertical resonance frequency. The floating slabs used in Washington DC, Atlanta, and Boston were all designed to have a vertical resonance in the 14 to 17 Hz range. A special London Transport floating slab that is under the Barbican Redevelopment uses a very heavy design with a resonance frequency in the 5 to 10 Hz frequency range.[16] The primary disadvantage of floating slabs is that they tend to be the most expensive of the vibration control treatments.

- Other Marginal Treatments: Changing any feature of the track support system can change the levels of ground-borne vibration. Approaches such as using heavier rail, thicker ballast, or heavier ties can be expected to reduce the vibration levels. There also is some indication that vibration levels are lower with wood ties compared to concrete ties. However, there is little confirmation that any of these approaches will make a significant change in the vibration levels. This is unfortunate since modifications to the ballast, rails, or ties are virtually the only options for normal at-grade, tie-and-ballast track without resorting to a different type of track support system or widening the right-of-way to provide a buffer zone.

Building Modifications – In some circumstances, it is practical to modify the impacted building to reduce the vibration levels. Vibration isolation of buildings basically consists of supporting the building foundation on elastomer pads similar to bridge bearing pads. Vibration isolation of buildings is seldom an option for existing buildings; normal applications are possible only for new construction. This approach is particularly important for shared-use facilities such as office space above a transit station or terminal. When vibration-sensitive equipment such as electron microscopes will be affected by transit vibration, specific modifications to the building structure may be the most cost-effective method of controlling the impact. For example, the floor upon which the vibration-sensitive equipment is located could be stiffened and isolated from the remainder of the building to reduce the vibration.

Trenches – Use of trenches to control ground-borne vibration is analogous to controlling airborne noise with sound barriers. Although this approach has not received much attention in the U.S., there are cases where a trench can be a practical method for controlling transit vibration from at-grade track. A rule-of-thumb given by Richert and Hall(17) is that if the trench is located close to the source, the trench bottom must be at least 0.6 times the Rayleigh wavelength below the vibration source. For most soils, Rayleigh waves travel at around 600 ft/sec which means that the wavelength at 30 Hz is 20 ft. This means that the trench must be approximately 15 ft deep to be effective at 30 Hz.

A trench can be effective as a vibration barrier if it is either open or solid. The Toronto Transit Commission did a test with a trench filled with styrofoam to keep it open. They reported successful performance over a period of at least one year.(18) Solid barriers can be constructed with sheet piling or concrete poured into a trench.

Operational Changes – The most obvious operational change is to reduce the vehicle speed. Reducing the train speed by a factor of two will reduce vibration levels approximately 6 dB. Other operational changes that can be effective in special cases are:

- Use the equipment that generates the lowest vibration levels during the nighttime hours when people are most sensitive to vibration and noise.
- Adjust nighttime schedules to minimize movements in the most sensitive hours.

While there are tangible benefits from speed reductions and limits in operations during the most sensitive time periods, these types of measures may not be practical from the standpoint of service requirements. Furthermore, vibration reduction achieved through operating restrictions requires continuous monitoring and will be negated if vehicle operators do not adhere to established policies.

Buffer Zones – Expanding the rail right-of-way sometimes will be the most economical method of controlling the vibration impact. A similar approach is to negotiate a vibration easement from the affected property owners.

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12. NOISE AND VIBRATION DURING CONSTRUCTION

Construction often generates community noise/vibration complaints despite the limited time frame over which it takes place. Complaints typically arise from interference with people's activities, especially when the community has no clear understanding of the extent or duration of the construction. Misunderstandings can arise when the contractor is considered to be insensitive by the community even though he believes he is in compliance with local ordinances. This situation underscores the need for early identification and assessment of potential problem areas. An assessment of the potential for complaints can be made by following procedures outlined in this chapter. That assessment can aid contractors in making bids by allowing changes in construction approach and including mitigation costs before the construction plans are finalized. Publication of an assessment including a description of the construction noise and vibration environment can lead to greater understanding and tolerance in the community.

Control of construction noise and vibration occurs in three steps:

1. **Assessment and Reporting:** The environmental impact assessment identifies the potential problem areas during the construction phase of a project and serves to inform the public of the project's construction effects. This is important for new major infrastructure projects where heavy construction can take place over a lengthy period of time.

2. **Construction specifications:** Most large construction projects incorporate noise specifications on construction equipment, but sometimes additional measures are needed to minimize community complaints. Special mitigation measures can be written into the construction documents where necessary as identified by the impact assessment. The documents should include realistic specifications which lessen community annoyance without forcing unreasonable constraints on the contractors.

3. **Compliance verification:** Field inspectors need to be given clear direction on conducting and reporting measurements for compliance with noise specifications in noise-sensitive areas.

12.1 CONSTRUCTION NOISE

The noise levels created by construction equipment will vary greatly depending on factors such as the type of equipment, the specific model, the operation being performed, and the condition of the equipment. The equivalent sound level (L_{eq}) of the construction activity also depends on the fraction of time that the equipment is operated over the time period of construction. This section provides information on typical levels generated by various construction equipment and provides guidance on assessment of noise from the construction activities related to transit facilities. It should be noted that the level of noise analysis should be commensurate with the type and scale of the project, and the presence of noise-sensitive land uses in the construction zone.

12.1.1 Noise from Typical Construction Equipment and Operations

The dominant source of noise from most construction equipment is the engine, usually a diesel, without sufficient muffling. In a few cases, such as impact pile driving or pavement breaking, noise generated by the process dominates. For considerations of noise assessment, construction equipment can be considered to operate in two modes, stationary and mobile. Stationary equipment operates in one location for one or more days at a time, with either a fixed power operation (pumps, generators, compressors) or a variable noise operation (pile drivers, pavement breakers). Mobile equipment moves around the construction site with power applied in cyclic fashion (bulldozers, loaders), or to and from the site (trucks). The movement around the site is handled in the construction noise prediction procedure discussed later in this chapter. Variation in power imposes additional complexity in characterizing the noise source level from a piece of equipment. This is handled by describing the noise at a reference distance from the equipment operating at full power and adjusting it based on the duty cycle of the activity to determine the L_{eq} of the operation. Standardized procedures for measuring the exterior noise levels for the certification of mobile and stationary construction equipment have been developed by the Society of Automotive Engineers.[1][2] Typical noise levels from representative pieces of equipment are listed in Table 12-1.

Construction activities are characterized by variations in the power expended by equipment, with resulting variation in noise levels with time. Variation in the power is expressed in terms of the "usage factor" of the equipment, the percentage of time during the workday that the equipment is operating at full power. Time-varying noise levels are converted to a single number (L_{eq}) for each piece of equipment during the operation. Besides having daily variations in activities, major construction projects are accomplished in several different phases. Each phase has a specific equipment mix depending on the work to be accomplished during that phase.

Each phase has its own noise characteristics; some have higher continuous noise levels than others, some have high impact noise levels. The purpose of the assessment is to determine not only the levels, but also the duration of the noise. The L_{eq} of each phase is determined by combining the L_{eq} contributions from each piece of equipment used in that phase. The impact and the consequent noise mitigation approaches depend on the criteria to be used in assessing impact, as discussed in the next section.

Table 12-1 Construction Equipment Noise Emission Levels

Equipment	Typical Noise Level (dBA) 50 ft from Source
Air Compressor	81
Backhoe	80
Ballast Equalizer	82
Ballast Tamper	83
Compactor	82
Concrete Mixer	85
Concrete Pump	82
Concrete Vibrator	76
Crane, Derrick	88
Crane, Mobile	83
Dozer	85
Generator	81
Grader	85
Impact Wrench	85
Jack Hammer	88
Loader	85
Paver	89
Pile Driver (Impact)	101
---"------ (Sonic)	96
Pneumatic Tool	85
Pump	76
Rail Saw	90
Rock Drill	98
Roller	74
Saw	76
Scarifier	83
Scraper	89
Shovel	82
Spike Driver	77
Tie Cutter	84
Tie Handler	80
Tie Inserter	85
Truck	88

Table based on an EPA Report,(3) measured data from railroad construction equipment taken during the Northeast Corridor Improvement Project(4) and other measured data.(5)(6)

12.1.2 Construction Noise Assessment

The level of detail of a construction noise assessment depends on the scale and the type of project and the stage of environmental review. Where the project is major – the construction duration is expected to last for more than several months, noisy equipment will be involved, or the construction is expected to take place near a noise-sensitive site – then construction noise impacts may be determined in considerable detail, as described in this section. Otherwise, the assessment may simply be a description of the equipment to be used, the duration of construction, and any mitigation requirements placed on particularly noisy operations.

A construction noise assessment for a major project is performed by comparing the predicted noise levels with criteria established for the type of project. The approach requires an appropriate descriptor, a standardized prediction method and a set of recognized criteria for assessing the impact.

The *descriptor* used for construction noise is the L_{eq}. This unit is appropriate for the following reasons:

- It can be used to describe the noise level from operation of each piece of equipment separately and is easy to combine to represent the noise level from all equipment operating during a given period.
- It can be used to describe the noise level during an entire phase.
- It can be used to describe the average noise over all phases of the construction.

The recommended *method* for predicting construction noise impact for major urban transit projects is similar to that suggested by the Federal Highway Administration (FHWA).[7] The FHWA prediction method is used to estimate the construction noise levels associated with the construction of a highway, but it can be used for any transportation project. The method requires:

1. An emission model to determine the noise generated by the equipment at a reference distance.
2. A propagation model that shows how the noise level will vary with distance.
3. A way of summing the noise of each piece of equipment at locations of noise-sensitivity.

The first two components of the model are related by the following equation:

$$L_{eq}(equip) = E.L. + 10\log(U.F.) - 20\log\left(\frac{D}{50}\right) - 10\,G\log\left(\frac{D}{50}\right)$$

where: L_{eq} *(equip)* is the L_{eq} at a receiver resulting from the operation of a single piece of equipment over a specified time period

E.L. is the noise emission level of the particular piece of equipment at the reference distance of 50 feet, taken from Table 12-1

G is a constant that accounts for topography and ground effects, taken from Figure 6-5 (Chapter 6)

D is the distance from the receiver to the piece of equipment, and

U.F. is a usage factor that accounts for the fraction of time that the equipment is in use over the specified time period.

The combination of noise from several pieces of equipment operating during the same time period is obtained from decibel addition of the L_{eq} of each single piece of equipment found from the above equation.

Major Construction Projects

The approach can be as detailed as necessary to characterize the construction noise by specifying the various quantities in the equation. For projects in an early assessment stage when the equipment roster and schedule are undefined, only a rough estimate of construction noise levels is practical.

The following assumptions are adequate for a general assessment of each phase of construction:

1. Full power operation for a time period of one hour is assumed because most construction equipment operates continuously for periods of one hour or more at some point in the construction period. Therefore, U.F. = 1, and 10 log(U.F.) = 0.
2. Free field conditions are assumed and ground effects are ignored. Consequently, G = 0.
3. Emission level at 50 feet, E.L., is taken from Table 12-1.
4. All pieces of equipment are assumed to operate at the center of the project, or centerline, in the case of a guideway or highway construction project.
5. The predictions include only the two noisiest pieces of equipment expected to be used in each construction phase.

A more detailed approach can be used if warranted, such as when a known noise-sensitive site is adjacent to a construction project or where contractors are faced with stringent local ordinances or specifications as a result of public concern. Additional details include:

1. Accounting for the duration of the construction. Long-term construction project noise impact is based on a 30 day average L_{dn}, the times of day of construction activity (nighttime noise is penalized by 10 dB in residential areas), and the percentage of time the equipment is to be used during a period of time which will affect U.F. For example, an 8-hour L_{eq} is determined by making **U.F.** the percentage of time each individual piece of equipment operates under full power in that period. Similarly, the 30-day average L_{dn} is determined from the **U.F.** expressed by the percentage of time the equipment is used during the daytime hours (7 a.m. to 10 p.m.) and nighttime (10 p.m. to 7 a.m.), separately over a 30 day period. However, to account for increased sensitivity to nighttime noise, the nighttime percentage is multiplied by 10 before performing the computation.
2. Taking into account the site topography, natural and man-made barriers and ground effects. This will change the factor G. Use Figure 6-5 (Chapter 6) to calculate G.
3. Measuring or certifying the emission level of each piece of equipment. This will refine E.L.
4. Determining the location of each piece of equipment while it is working. The distance factor D is therefore specified more exactly.

5. Including all pieces of equipment in the computation of the 8-hour L_{eq} and the 30-day average L_{dn}. The total noise levels are determined using Table 6-11 (Chapter 6).

Minor Construction Projects

Most minor projects need no construction noise assessment at all. However, there may be cases involving a limited period of construction time – less than a month in a noise-sensitive area – where there may be a temporary effect where a qualitative treatment is appropriate. Community relations will be important in these cases; early information disseminated to the public about the kinds of equipment, expected noise levels and durations will help to forewarn potentially affected neighbors about the temporary inconvenience. In these cases, a general description of the variation of noise levels during a typical construction day may be helpful. The first method above will be sufficient to provide the estimated noise levels. The criteria suggested below are not applicable in these cases.

Criteria

No standardized *criteria* have been developed for assessing construction noise impact. Consequently, criteria must be developed on a project-specific basis unless local ordinances can be found to apply. Generally, local noise ordinances are not very useful in evaluating construction noise. They usually relate to nuisance and hours of allowed activity and sometimes specify limits in terms of maximum levels, but are generally not practical for assessing the impact of a construction project. Project construction noise criteria should take into account the existing noise environment, the absolute noise levels during construction activities, the duration of the construction, and the adjacent land use. While it is not the purpose of this manual to specify standardized criteria for construction noise impact, the following guidelines can be considered reasonable criteria for assessment. If these criteria are exceeded, there may be adverse community reaction.

General Assessment – Estimate the combined noise level in one hour from the two noisiest pieces of equipment, assuming they both operate at the same time. Then identify locations where the level exceeds the following:

Land Use	One-hour L_{eq} (dBA)	
	Day	Night
Residential	90	80
Commercial	100	100
Industrial	100	100

Detailed Assessment – Predict the noise level in terms of 8-hour L_{eq} and 30-day averaged L_{dn} and compare to criteria in the following table:

Land Use	8-hour L_{eq} (dBA) Day	8-hour L_{eq} (dBA) Night	L_{dn} (dBA) 30-day Average
Residential	80	70	75[a]
Commercial	85	85	80[b]
Industrial	90	90	85[b]

(a) In urban areas with very high ambient noise levels (L_{dn} > 65 dB), L_{dn} from construction operations should not exceed existing ambient + 10 dB.
(b) Twenty-four hour L_{eq}, not L_{dn}.

12.1.3 Mitigation of Construction Noise

After using the above approach to locate potential impacts from construction noise, the next step is to identify appropriate control measures. Three categories of noise control approaches, with examples, are given below:

1. *Design considerations and project layout:*

   - Construct noise barriers, such as temporary walls or piles of excavated material, between noisy activities and noise-sensitive receivers.
   - Re-route truck traffic away from residential streets, if possible. Select streets with fewest homes, if no alternatives are available.
   - Site equipment on the construction lot as far away from noise-sensitive sites as possible.
   - Construct walled enclosures around especially noisy activities, or clusters of noisy equipment. For example, shields can be used around pavement breakers, loaded vinyl curtains can be draped under elevated structures .

2. *Sequence of operations:*

   - Combine noisy operations to occur in the same time period. The total noise level produced will not be significantly greater than the level produced if the operations were performed separately.
   - Avoid nighttime activities. Sensitivity to noise increases during the nighttime hours in residential neighborhoods.

3. *Alternative construction methods:*

   - Avoid impact pile driving where possible in noise-sensitive areas. Drilled piles or the use of a sonic or vibratory pile driver are quieter alternatives where the geological conditions permit their use.

- Use specially quieted equipment, such as quieted and enclosed air compressors, mufflers on all engines.
- Select quieter demolition methods, where possible. For example, sawing bridge decks into sections that can be loaded onto trucks results in lower cumulative noise levels than impact demolition by pavement breakers.

The environmental assessment should include description of how each impacted location will be treated with one or more mitigation approaches.

12.2 CONSTRUCTION VIBRATION

Construction activity can result in varying degrees of ground vibration, depending on the equipment and methods employed. Operation of construction equipment causes ground vibrations which spread through the ground and diminish in strength with distance. Buildings founded on the soil in the vicinity of the construction site respond to these vibrations, with varying results ranging from no perceptible effects at the lowest levels, low rumbling sounds and feelable vibrations at moderate levels and slight damage at the highest levels. Ground vibrations from construction activities very rarely reach the levels that can damage structures, but can achieve the audible and feelable ranges in buildings very close to the site. A possible exception is the case of old, fragile buildings of historical significance where special care must be taken to avoid damage. The construction vibration criteria include special consideration for fragile historical buildings. The construction activities that typically generate the most severe vibrations are blasting and impact pile driving.

Vibration levels for construction equipment have been published based on measured data near various types of equipment (see Table 12-2). Since the primary concern with regard to construction vibration is building damage, construction vibration is generally assessed in terms of peak particle velocity (PPV), as defined in Chapter 7.1.2. Peak particle velocity is typically a factor of 1.7 to 6 times greater than root mean square (rms) vibration velocity; a factor of 4 has been used to calculate the approximate rms vibration velocity levels indicated in Table 12-2.

12.2.1 Vibration Source Levels from Construction Equipment

Various types of construction equipment have been measured under a wide variety of construction activities with an average of source levels reported in terms of velocity levels as shown in Table 12-2 . Although the table gives one level for each piece of equipment, it should be noted that there is a considerable variation in reported ground vibration levels from construction activities. The data provide a reasonable estimate for a wide range of soil conditions.

Table 12-2 Vibration Source Levels for Construction Equipment (From measured data.[8][9][10][11])

Equipment		PPV at 25 ft (in/sec)	Approximate L_v† at 25 ft
Pile Driver (impact)	upper range	1.518	112
	typical	0.644	104
Pile Driver (sonic)	upper range	0.734	105
	typical	0.170	93
Clam shovel drop (slurry wall)		0.202	94
Hydromill (slurry wall)	in soil	0.008	66
	in rock	0.017	75
Large bulldozer		0.089	87
Caisson drilling		0.089	87
Loaded trucks		0.076	86
Jackhammer		0.035	79
Small bulldozer		0.003	58

† RMS velocity in decibels (VdB) re 1 μinch/second

12.2.2 Construction Vibration Assessment

Construction vibration should be assessed in cases where there is a significant potential for impact from construction activities. Such activities include blasting, pile driving, demolition and drilling or excavation in close proximity to sensitive structures. The recommended procedure for estimating vibration impact from construction activities is as follows:

- Select the equipment and associated vibration source levels at a reference distance of 25 feet from Table 12-2.

- Make the propagation adjustment according to the following formula (this formula is based on point sources with normal propagation conditions):

$$PPV_{equip} = PPV_{ref} \times \left(\frac{25}{D}\right)^{1.5}$$

where: PPV (equip) is the peak particle velocity in in/sec of the equipment adjusted for distance

PPV (ref) is the reference vibration level in in/sec at 25 feet from Table 12-2

D is the distance from the equipment to the receiver.

- Apply the vibration damage threshold criterion of 0.20 in/sec (approximately 100 VdB) for fragile buildings, or 0.12 in/sec (approximately 95 VdB) for extremely fragile historic buildings.[12]

- If desired for considerations of annoyance or interference with vibration-sensitive activities, estimate the vibration level L_v at any distance D from the following equation and apply the vibration impact criteria in Chapter 8 for vibration-sensitive sites:

$$L_v(D) = L_v(25\text{ ft}) - 20\log\left(\frac{D}{25}\right)$$

12.2.3 Construction Vibration Mitigation

After using the above approach to locate potential impacts (or damage) from construction vibrations, the next step is to identify control measures. Similar to the approach for construction noise, mitigation of construction vibration requires consideration of equipment location and processes, as follows:

1. *Design considerations and project layout:*

   - Route heavily loaded trucks away from residential streets, if possible. Select streets with fewest homes, if no alternatives are available.
   - Operate earthmoving equipment on the construction lot as far away from vibration-sensitive sites as possible.

2. *Sequence of operations:*

   - Phase demolition, earthmoving and ground-impacting operations so as not to occur in the same time period. Unlike noise, the total vibration level produced could be significantly less when each vibration source operates separately.
   - Avoid nighttime activities. People are more aware of vibration in their homes during the nighttime hours.

3. *Alternative construction methods:*

   - Avoid impact pile driving where possible in vibration-sensitive areas. Drilled piles or the use of a sonic or vibratory pile driver causes lower vibration levels where the geological conditions permit their use (however, see cautionary note below).
   - Select demolition methods not involving impact, where possible. For example, sawing bridge decks into sections that can be loaded onto trucks results in lower vibration levels than impact demolition by pavement breakers, and milling generates lower vibration levels than excavation using clam shell or chisel drops.
   - Avoid vibratory rollers and packers near sensitive areas.

Pile driving is potentially the greatest source of vibration associated with equipment used during construction of a project. The source levels in Table 12-2 indicate that sonic pile drivers may provide substantial reduction of vibration levels. However, there are some additional vibration effects of sonic pile drivers that may limit their use in sensitive locations. A sonic pile driver operates by continuously shaking the pile at a fixed frequency, literally vibrating it into the ground. Vibratory pile drivers operate on the same principle, but at a different frequency. However, continuous operation at a fixed frequency may be more noticeable to nearby residents, even at lower vibration levels. Furthermore, the steady-state excitation of the ground may increase resonance response of building components. Resonant response may be unacceptable in cases of fragile historical buildings or vibration-sensitive manufacturing processes. Impact pile drivers, on the other hand, produce a high vibration level for a short time (0.2 seconds) with sufficient time between impacts to allow any resonant response to decay.

REFERENCES

1. Society of Automotive Engineers, "Exterior Sound Level Measurement Procedure for Powered Mobile Construction Equipment," SAE Recommended Practice J88a, 1976.

2. Society of Automotive Engineers, "Sound Levels for Engine Powered Equipment," SAE Standard J952b, 1976.

3. U.S. Environmental Protection Agency, "Noise from Construction Equipment and Operations, Building Equipment and Home Appliances," NTID300.1, December 31, 1971.

4. U.S. Department of Transportation, "Final Environmental Impact Statement, 4(f) Statement; Replacement of Shaw's Cove Bridge and Approaches," FRA-RNC-EIS-80-02-F, September 16, 1981.

5. C.F. Rosenberg and C.M. Salter, "Noise of Pile Driving Equipment," Presentation at Acoustical Society of America Meeting, Washington DC, 20-22 April 1971.

6. William R. Fuller and Ron Brown, "Analysis and Abatement of Highway Construction Noise," EPA 550/9-81-314-A, U.S. Environmental Protection Agency, Office of Noise Abatement and Control and U.S. Department of Transportation, Federal Highway Administration, June 1981.

7. Jerry A. Reagan and Charles A. Grant, "Special Report - Highway Construction Noise: Measurement, Prediction and Mitigation," U.S. Department of Transportation, Federal Highway Administration, 1977.

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9. J.F. Wiss, "Vibrations During Construction Operations," Journal of Construction Division, Proc. American Society of Civil Engineers, 100, No. CO3, pp. 239 - 246, September 1974.

10. J.F. Wiss, "Damage Effects of Pile Driving Vibrations," Highway Research Record, No. 155, Highway Research Board, 1967.

11. David A. Towers and Yuki Kimura, "Central Artery / Tunnel Project: Hydromill Vibration Testing," report prepared for Massachusetts Highway Department, February 1995.

12. Swiss Consultants for Road Construction Association, "Effects of Vibration on Construction," VSS-SN640-312, Zurich, Switzerland, November 1978.

13. DOCUMENTATION OF NOISE AND VIBRATION ASSESSMENT

To be effective, the noise and vibration analysis must be presented to the public in a clear, yet comprehensive manner. The mass of technical data and information necessary to withstand scrutiny in the environmental review process must be documented in a way that remains intelligible to the public. Justification for all assumptions used in the analysis, such as selection of representative measurement sites and all baseline conditions, must be presented for review. For large-scale projects, the environmental document contains a condensation of essential information in order to maintain a reasonable size. For these projects, separate technical reports are usually prepared as supplements to the Environmental Impact Statement (EIS) or Environmental Assessment (EA). For smaller projects, or ones with minimal noise or vibration impact, all the technical information may be presented in the environmental document itself. This chapter gives guidance on how the necessary noise and vibration information should be included in the project's environmental documentation.

13.1 THE TECHNICAL REPORT ON NOISE AND VIBRATION

A separate technical report is often prepared as a supplement to the environmental document (EIS or EA). A technical report is appropriate in cases when the wealth of data can not all be placed in the environmental document. The details of the analysis are important for establishing the basis for the assessment. Consequently, all the details in the technical report should be contained in a well-organized format for easy access to the information. While the technical report is not intended to be a primer on the subject, the technical data and descriptions should be presented in a manner that can be understood by the general public. All the necessary background information should be present in the technical report, including tables, maps, charts, drawings and references that may be too detailed for the environmental document, but which are important in helping to draw conclusions about the project's noise and vibration impacts and mitigation options.

13.1.1 Organization of Technical Report

The Technical Report on Noise/ Vibration should contain the following major subject headings, along with the key information content described below. If both noise and vibration have been analyzed, it is generally preferable to separate the noise and vibration sections; as shown in this Guidance Manual, the approaches to the two topics are quite different.

Overview – This section contains a brief description of the project and an overview of the noise/vibration concerns. It sets forth the initial considerations in framing the scope of the study.

Inventory of Noise/Vibration-Sensitive Sites – The approach for selecting noise/vibration- sensitive sites should be described in sufficient detail to demonstrate completeness. Sites and site descriptions are to be included.

Measurements of Existing Noise/Vibration Conditions – The basis for selecting measurement sites should be documented, along with tables of sites coordinated with maps showing locations of sites. If the measurement data are used to estimate existing conditions at other locations, the rationale and the method should be included. Measurement procedures should be fully described. Tables of measurement instruments should include manufacturer, type, serial number and date of most recent calibration by authorized testing laboratory. Measurement periods, including time of day and length of time at each site should be shown to demonstrate adequate representation of the ambient conditions. The measurement data should be presented in well organized form in tables and figures. A summary and interpretation of measured data should be included.

Special Measurements Related to the Project – Some projects require specialized measurements at sensitive sites, such as outdoor-to-indoor noise level reduction of homes, or transmission of vibrations into concert halls and recording studios. Other projects may need special source level characterization. Full description of the measurements and the results should be included.

Predictions of Noise/Vibration from the Project – The prediction model used for estimating future project conditions should be fully described and referenced. Any changes or extensions to the models recommended in this manual should be fully described so that the validity of the adjustments can be confirmed. Specific data used as input to the models should be listed. Computed levels should be tabulated and illustrated by contours, cross-sections or shaded mapping. It is important to illustrate noise/vibration impacts with base maps at a scale with enough detail to provide location reference for the reader.

Noise/Vibration Criteria – Impact criteria for the project should be fully described and referenced (refer to Chapters 3 and 8). In addition, any applicable local ordinances should be described. Tables specifying the criteria levels should also be included. If the project involves considerable construction, and a separate construction noise and vibration analysis will be included, then construction criteria should appear in a separate section with its own assessment.

Noise/Vibration Impact Assessment – The impact assessment should be described according to the procedures outlined in this manual. A resulting impact inventory should be presented for each alternative mode or alignment in a format that allows ready comparison among alternatives. The inventory should be tabulated according to the different types of land uses affected. The results of the assessment may be presented both before and after mitigation.

Noise/Vibration Mitigation – The mitigation section of the technical report should begin with a summary of all treatments considered, even if some are not carried to final consideration. Final candidate mitigation treatments should be considered separately with description of the features of the treatment, costs, expected benefit in reducing impacts, locations where the benefit would be realized and discussion of practicality of implementing alternative treatments. Enough information is to be included to allow the project sponsor and FTA to reach decisions on mitigation prior to issuance of the final environmental document.

Construction Noise/Vibration Impacts – Criteria adopted for construction noise or vibration should be described, if appropriate. According to Chapter 12, these may be adopted on a project-specific basis. The method used for predicting construction noise or vibration should be described along with inputs to the models, such as equipment roster by construction phase, equipment source levels, assumed usage factors and other assumed site characteristics. The predicted levels should be shown for sensitive sites and short-term impacts should be identified. Feasible abatement methods should be discussed in enough detail such that construction contract documents could include mitigation measures.

References – Documentation is an important part of the validation of the technical report. References should be provided for all criteria, approaches and data used in the analyses, including other reports related to the project which may be relied on for information, e.g., geotechnical reports.

13.2 THE ENVIRONMENTAL DOCUMENT

The environmental document typically includes noise and vibration information in three places: a section of the chapter on the affected environment (existing conditions) and two sections in the chapter on environmental consequences (long-term and short-term impacts). The noise and vibration information presented in the environmental document is a summary of the comprehensive information from the technical report with emphasis on presenting the salient points of the analysis in a format and style which affected property owners and other interested citizens can understand. Smaller projects may have all of the technical information contained within the environmental document, requiring special care in summarizing technical details to convey the information adequately.

The environmental document provides full disclosure of noise and vibration impacts, including identification of locations where impacts cannot be mitigated satisfactorily. An EIS describes significant impacts and tells what the Federal agency intends to do about them. Issuing a Finding of No Significant Impact (FONSI) may depend on mitigation being included. The specific way mitigation is handled in the environmental document depends on the stage of project development and the stage of environmental review. For example, a Draft EIS may discuss different options to mitigate noise or vibration, deferring the final selection of measures to the Final EIS. It may be particularly important to present mitigation options at an early stage, especially if there is a benefit in receiving input from the public on the choices.

The final environmental document (Final EIS or FONSI) contains a commitment to mitigate. Two approaches can be taken for expressing this commitment. The document could describe the actual mitigation measures that will be employed, along with the reductions in noise or vibration expected to occur. In this case, the write-up includes language that makes it clear that the measures will be implemented if the project is approved. However, in some cases, mitigation measures are still under study in the environmental review and will not be selected until the final design stage. In such cases, the final environmental document expresses a commitment to mitigate impacts that are verified during final design. Mitigation in these cases is addressed in the form of a "performance standard" to be met by using one or more of the measures under study.

After a final environmental document is approved, the described mitigation measures are incorporated by reference in the actual grant agreements signed by FTA and the project sponsor. Thus, they become contractual conditions that must be adhered to by the project sponsor.

13.2.1 Organization of Noise and Vibration Sections of Environmental Documents

Chapter on Affected Environment (Existing Conditions)

This chapter describes the pre-project setting, including the existing noise and vibration conditions, that will likely be affected by one or more of the alternatives. The primary function of this chapter is to establish the focus and baseline conditions for later chapters discussing environmental impacts. Consequently, it is a good place to put basic information on noise and vibration descriptors and effects, as well as describing the characteristics in the vicinity of the project. Again, it is preferable to separate the noise and vibration sections.

- **Description of Noise/Vibration Descriptors, Effects and Typical Levels.** Information from Chapters 2 and 7 of this manual can be used to provide a background for the discussions of noise/vibration levels and characteristics to follow. Illustrative material to guide the reader in understanding typical levels is helpful.

- **Inventory of Noise/Vibration-Sensitive Sites.** The approach for selecting noise/vibration-sensitive sites should be described in sufficient detail to demonstrate completeness. Sites and site descriptions are to be included.

- **Noise/Vibration Measurements.** A summary of the site selection procedure should be included along with tables of sites coordinated with maps showing locations of sites. The measurement approach should be summarized with justification for the measurement procedures used. The measurement data should be presented in well organized form in tables and figures. To save space, the results are often included with the table of sites described above. In some cases, measurements may be supplemented or replaced by collected data relevant to the noise and vibration characteristics of the area. For example, soils information for estimating ground-borne vibration propagation characteristics may be available from other projects in the area. Fundamental to this section is a summary and interpretation of how the collected data define the project setting.

Chapter on Environmental Consequences.

The section on long-term impacts -- the impacts due to operation of the project -- should be organized according to the following order.

- **Overview of Approach.** A summary of the assessment procedure for determining noise/vibration impacts is provided as a framework for the following sections.

- **Estimated Noise/Vibration Levels.** A general description of prediction models used to estimate project noise/vibration levels should be provided. Any distinguishing features unique to the project, such as source levels associated with various technologies, should be described. The results of the predictions for various alternatives should be described in general terms first, followed by a detailed accounting of predicted noise levels. This information should be supplemented with tables and illustrated by contours, cross-sections or shaded mapping. If contours are included in a technical report, then it is not necessary to repeat them here.

- **Criteria for Noise/Vibration Impact.** Impact criteria for the project should be fully described and referenced (refer to Chapters 3 and 8). In addition, any applicable local ordinances should be described. Tables listing the criterion levels should be included.

- **Impact Assessment.** The impact assessment can be a section by itself or can be combined with the section above. It is important to provide a description of locations where noise/vibration impact is expected to occur without implementation of mitigation measures, based on the predicted future levels, existing levels and the criteria for impact. Inventory tables of impacted land uses should be used to quantify the impacts for comparisons among alternatives. The comprehensive list of noise/vibration sensitive sites identified in the Affected Environment chapter should be included in this inventory table.

- **Noise/Vibration Mitigation Measures.** Perhaps the most significant difference between the technical report and the environmental document is in the area of mitigation. Whereas the technical report discusses options and may make recommendations, the environmental document provides the vehicle for reaching decisions on appropriate mitigation measures with consideration given to environmental benefits, feasibility and cost. This section should begin with a summary of all noise/vibration mitigation measures considered for the impacted locations. The specific measures selected for implementation should be fully described. However, for projects where technical details of the mitigation measures cannot be specified at the environmental assessment stage, a commitment is made to the level of abatement; the EIS must demonstrate that mitigation measures under consideration will achieve the necessary reduction. Reasons for dismissing any abatement measures should also be clearly stated, especially if such non-implementation results in significant adverse effects. The expected benefits for each treatment in reducing impact should be given for each location.

- **Unavoidable Adverse Environmental Effects.** If it is projected that adverse noise/vibration impacts will result after all reasonable abatement measures have been incorporated, these impacts are identified in this section.

Impacts During Construction

The environmental document may have a separate section on short-term impacts due to project construction, depending on the scale of the project. For a major project there may be a special section on construction noise/vibration impacts; this section should be organized according to the comprehensive outline described above. For projects with relatively minor effects, a briefer format should be utilized, with a section included in the chapter on Environmental Consequences.

APPENDICES

APPENDIX A. BACKGROUND FOR TRANSIT NOISE IMPACT CRITERIA

The noise criteria, presented in Chapter 3 of this manual, have been developed based on well-documented criteria and research into human response to community noise. The primary goals in developing the noise criteria were to ensure that the impact limits be firmly founded in scientific studies, be realistically based on noise levels associated with new transit projects, and represent a reasonable balance between community benefit and project costs. This appendix provides the background information.

A.1 Relevant Literature

Following is an annotated list of the documents that are particularly relevant to the noise impact criteria:

1. US Environmental Protection Agency "Levels Document":[1] This report identifies noise levels consistent with the protection of public health and welfare against hearing loss, annoyance, and activity interference. It has been used as the basis of numerous community noise standards and ordinances.

2. CHABA Working Group 69, "Guidelines for Preparing Environmental Impact Statements on Noise":[2] This report was the result of deliberations by a group of leading acoustical scientists with the goal of developing a uniform national method for noise impact assessment. Although the CHABA's proposed approach has not been adopted, the report serves as an excellent resource documenting research in noise effects. It provides a strong scientific basis for quantifying impacts in terms of L_{dn}.

3. American Public Transit Association Guidelines:[3] The noise and vibration sections of the APTA Guidelines have been used successfully in the past for the design of rail transit facilities. The APTA Guidelines include criteria for acceptable community noise and vibration. Experience has shown that meeting the APTA Guidelines will usually result in acceptable noise levels. However, there are some problems in using the APTA Guidelines for environmental assessment purposes. The criteria are in terms of L_{max} for conventional rail rapid transit vehicles and they cannot be used to compare among

different modes of transit. Since the APTA Guidelines are expressed in terms of maximum passby noise, they are not sensitive to the frequency or duration of noise events for transit modes other than conventional rail rapid transit operations with 5 to 10 minute headways. Therefore, the APTA criteria are questionable for assessing the noise impact of other transit modes which differ from conventional rapid transit with respect to source emission levels and operating characteristics (e.g., commuter rail, AGT and a variety of bus projects).

4. "Synthesis of Social Surveys on Noise Annoyance":(4) In 1978, Theodore J. Schultz, an internationally known acoustical scientist, synthesized the results of a large number of social surveys, each concerning annoyance due to transportation noise. Remarkable consistency was found in a group of these surveys, and the author proposed that their average results be taken as the best available prediction of transportation noise annoyance. This synthesis has received essentially unanimous acceptance by acoustical scientists and engineers. The "universal" transportation response curve developed by Schultz (Figure 2-7) shows that the percent of the population highly annoyed by transportation noise increases from zero at an L_{dn} of approximately 50 dBA to 100-percent when L_{dn} is about 90 dBA. Most significantly, this curve indicates that for the same increase in L_{dn}, there is a greater increase in the number of people highly annoyed at high noise levels than at low noise levels. In other words, a 5 dB increase at low ambient levels (40 - 50 dB) has less impact than at higher ambient levels (65 - 75 dB). A recent update of the original research, containing several railroad, transit and street traffic noise surveys, confirmed the shape of the original Schultz curve.[5]

5. HUD Standards:(6) The U.S. Department of Housing and Urban Development has developed noise standards, criteria and guidelines to ensure that housing projects supported by HUD achieve the goal of a suitable living environment. The HUD site acceptability standards define 65 dB (L_{dn}) as the threshold for a normally unacceptable living environment and 75 dB (L_{dn}) as the threshold for an unacceptable living environment.

A.2 Basis for Noise Impact Criteria Curves

The lower curve in Figure 3-1 representing the onset of Impact is based on the following considerations:

- The EPA finding that a community noise level of L_{dn} less than or equal to 55 dBA is "requisite to protect public health and welfare with an adequate margin of safety."[1]

- The conclusion by EPA and others that a 5 dB increase in L_{dn} or L_{eq} is the minimum required for a change in community reaction.

- The research finding that there are very few people highly annoyed when the L_{dn} is 50 dBA, and that an increase in L_{dn} from 50 dBA to 55 dBA results in an average of 2% more people highly annoyed (see Figure 2-7 in Chapter 2).

Consequently, the change in noise level from an existing ambient level of 50 dBA to a cumulative level of 55 dBA caused by a project is assumed to be a minimal impact. Expressed another way, this is considered to be the lowest threshold where impact starts to occur. Moreover, the 2% increment represents the minimum measurable change in community reaction. Thus the curve's hinge point is placed at a project noise level of 53 dBA and an existing ambient noise level of 50 dBA, the combination of which yields a cumulative level of 55 dBA. The remainder of the lower curve in Figure 16 was determined from the annoyance curve (Figure 2-7) by allowing a fixed 2% increase in annoyance at other levels of existing ambient noise. As cumulative noise increases, it takes a smaller and smaller increment to attain the same 2% increase in highly annoyed people. While it takes a 5 dB noise increase to cause a 2% increase in highly annoyed people at an existing ambient noise level of 50 dB, an increase of only 1 dB causes the 2% increase of highly annoyed people at an existing ambient noise level of 70 dB.

The upper curve delineating the onset of Severe Impact was developed in a similar manner, except that it was based on a total noise level corresponding to a higher degree of impact. The Severe Noise Impact curve is based on the following considerations:

- The Department of Housing and Urban Development (HUD) in its environmental noise standards defines an L_{dn} of 65 as the onset of a normally unacceptable noise zone.[6] Moreover, the Federal Aviation Administration (FAA) considers that residential land uses are not compatible with noise environments where L_{dn} is greater than 65 dBA [7].

- The common use of a 5 dBA increase in L_{dn} or L_{eq} as the minimum required for a change in community reaction.

- The research finding that the foregoing step represents a 6.5% increase in the number of people highly annoyed (see Figure 2-7 in Chapter 2).

Consequently, the increase in noise level from an existing ambient level of 60 dBA to a cumulative level of 65 dBA caused by a project represents a change from an acceptable noise environment to the threshold of an unacceptable noise environment. This is considered to be the level at which severe impact starts to occur. Moreover, the 6.5% increment represents the change in community reaction associated with severe impact. Thus the upper curve's hinge point is placed at a project noise level of 63 dBA and existing ambient noise level of 60 dBA, the combination of which yields a cumulative level of 65 dBA. The remainder of the upper curve in Figure 3-1 was determined from the annoyance curve (Figure 2-7) by fixing the 6.5% increase in annoyance at all existing ambient noise levels.

Both curves incorporate a maximum limit for the transit project noise in noise-sensitive areas. Independent of existing noise levels, Impact for land use categories 1 and 2 is considered to occur whenever the <u>transit</u> L_{dn} equals or exceeds 65 dBA and Severe Impact occurs whenever the <u>transit</u> L_{dn} equals or exceeds 75 dBA. These absolute limits are intended to restrict activity interference caused by the transit project alone.

Both curves also incorporate a maximum limit for cumulative noise increase at low existing noise levels (below about 45 dBA). This is a conservative measure that reflects the lack of social survey data on people's reaction to noise at such low ambient levels. Similar to the FHWA approval in assessing the relative impact of a highway project, the transit noise criteria include caps on noise increase of 10 dB and 15 dB for Impact and Severe Impact, respectively, relative to the existing noise level.

Finally, it should be noted that due to the types of land use included in Category 3, the criteria allow the project noise for Category 3 sites to be 5 decibels greater than for Category 1 and Category 2 sites. This difference is reflected by the offset in the vertical scale on the right side of Figure 3-1. With the exception of active parks, which are clearly less sensitive to noise than Category 1 and 2 sites, Category 3 sites include primarily indoor activities and thus the criteria account for the noise reduction provided by the building structure.

A.3 Equations for Noise Impact Criteria Curves

The noise impact criteria can be quantified through the use of mathematical equations which approximate the curves shown in Figure 3-1. These equations may be useful when performing the noise assessment methodology through the use of spreadsheets, computer programs or other analysis tools. Otherwise, such mathematical detail is generally not necessary in order to properly implement the criteria, and direct use of Figure 3-1 is likely to be adequate and less time-consuming.

A total of four continuous curves are obtained from the criteria: two threshold curves ("Impact" and "Severe Impact") for Category 1 and 2; and two for Category 3. Note that for each level of impact, the overall curves for Categories 1 and 2 are offset by 5 dB from Category 3. While each curve is graphically continuous, it is defined by a set of three discrete equations which represent three "regimes" of existing noise exposure. These equations are approximately continuous at the transition points between regimes.

The first equation in each set is a linear relationship, representing the portion of the curve in which the existing noise exposure is low and the allowable increase is capped at 10 dB and 15 dB for Impact and Severe Impact, respectively. The second equation in each set represents the impact threshold over the range of existing noise exposure for which a fixed percentage of increase in annoyance is allowed, as described in the previous section. This curve, a third-order polynomial approximation derived from the Schultz curve,[(4)] covers the range of noise exposure encountered in most populated areas and is used in determining noise impact in the majority of cases for transit projects. Finally, the third equation in each of the four sets represents the absolute limit of project noise imposed by the criteria, for areas with high existing noise exposure. For land use category 1 and 2, this limit is 65 dBA for Impact and 70 dBA for Severe Impact. For land use category 3, the limit is 75 dBA for Impact and 80 dBA for Severe Impact.

The four sets of equations corresponding to the curves are given below. Each curve represents a threshold of noise impact, with impact indicated for points on or above the curve.

Threshold of Impact:

$$L_P = \begin{cases} 11.450 + 0.953\, L_E & L_E < 42 \\ 71.662 - 1.164\, L_E + 0.018\, L_E^{\,2} - 4.088 \times 10^{-5}\, L_E^{\,3} & 42 \le L_E \le 71 \\ 65 & L_E > 71 \end{cases} \quad \text{Category 1 and 2}$$

$$L_P = \begin{cases} 16.450 + 0.953\, L_E & L_E < 42 \\ 76.662 - 1.164\, L_E + 0.018\, L_E^{\,2} - 4.088 \times 10^{-5}\, L_E^{\,3} & 42 \le L_E \le 71 \\ 70 & L_E > 71 \end{cases} \quad \text{Category 3}$$

Threshold of Severe Impact:

$$L_P = \begin{cases} 17.322 + 0.940\, L_E & L_E < 44 \\ 96.725 - 1.992\, L_E + 3.02 \times 10^{-2}\, L_E^{\,2} - 1.043 \times 10^{-4}\, L_E^{\,3} & 44 \le L_E \le 77 \\ 75 & L_E > 77 \end{cases} \quad \text{Category 1 and 2}$$

$$L_P = \begin{cases} 22.322 + 0.940\, L_E & L_E < 44 \\ 101.725 - 1.992\, L_E + 3.02 \times 10^{-2}\, L_E^{\,2} - 1.043 \times 10^{-4}\, L_E^{\,3} & 44 \le L_E \le 77 \\ 80 & L_E > 77 \end{cases} \quad \text{Category 3}$$

where L_E is the existing noise exposure in terms of L_{dn} or L_{eq}(h) and L_P is the project noise exposure which determines impact, also in terms of L_{dn} or L_{eq}(h).

REFERENCES

1. U.S. Environmental Protection Agency, "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," EPA report number 550/9-74-004, March 1974.

2. National Academy of Sciences, "Guidelines for Preparing Environmental Impact Statements on Noise," Report from Committee on Bioacoustics and Biomechanics (CHABA) Working Group 69, February 1977.

3. American Public Transit Association, *1981 Guidelines for Design of Rapid Transit Facilities*, Section 2.7, "Noise and Vibration," 1981.

4. T.J. Schultz, "Synthesis of Social Surveys on Noise Annoyance," Journal of the Acoustical Society of America, Vol. 64, No. 2, pp. 377-405, August 1978.

5. S. Fidell, D.S. Barber and T.J. Schultz, "Updating a Dosage-Effect Relationship for the Prevalence of Annoyance Due to General Transportation Noise," Journal of the Acoustical Society of America, Vol. 89, No. 1, January 1991.

6. U.S. Department of Housing and Urban Development, "Environmental Criteria and Standards", 24 CFR Part 51,v 12 July 1979; amended by 49 FR 880, 6 January 1984.

7. U.S. Department of Transportation, Federal Aviation Administration, "Federal Aviation Regulations Part 150: Airport Noise Compatibility Planning," January 1981.

APPENDIX B. SELECTING RECEIVERS OF INTEREST

This appendix provides additional detail in selecting receivers of interest for those users desiring such detail. The general approach given in Chapter 6 includes the following guidelines:

- Every major public building or site with noise-sensitive indoor use within the noise study area should be selected as a separate receiver of interest.
- Each isolated residence and small outdoor noise-sensitive area within the noise study area should be selected as a separate receiver of interest in the same manner as for public buildings.
- In contrast, groups of residences and larger outdoor noise-sensitive areas within the noise study area should be "clustered" and a receiver of interest selected from each cluster. Clustering reduces the number of computations later needed, especially for large-scale projects where a great number of noise-sensitive sites may be affected. For this approach to work, however, it is essential that the receiver selected provide an accurate representation of the noise environment of the cluster.

This appendix elaborates on the clustering procedure. In brief: (1) cluster boundaries are first drawn relative to the proposed project, either running parallel to a linear project or circling major stationary sources. These boundaries approximate contours of equal project noise. (2) Then a separate set of cluster boundaries is drawn parallel to, or circling, major sources of ambient noise to approximate contours of ambient noise. (3) Finally, a third set of cluster boundaries may further subdivide the noise study area, if there are changes in project layout or operations along the corridor.

Following are suggested procedures for drawing cluster boundaries and for selecting a receiver of interest from each cluster:

> **Boundaries along the proposed project**. First draw cluster boundaries along the proposed project, to separate clusters based upon distance from the project. Draw such cluster boundaries for all sources that are listed as "Major" in Table 6-2.

Within both residential and noise-sensitive outdoor areas:

- **Primary project source.** Draw cluster boundaries at the following distances from the near edge of the primary project source: 0 feet, 50 feet, 100 feet, 200 feet, 400 feet, and 800 feet. If the primary project source is a linear source, such as a rail line, draw these boundaries as lines parallel to the proposed right-of-way line. Around major stationary sources, draw these boundaries as approximate circles around the source, starting at the property line. Do not extend boundaries beyond the noise study area, identified in the Screening Procedure of Chapter 4 or the General Assessment of Chapter 5.

- **Remaining project sources**. Repeat this for all other project sources listed as Major in Table 6-2, such as substations and crossing signals. If several project sources are located approximately together, only one need be considered here, since the others would produce approximately the same boundaries. It is good practice to optimize the number of clusters for a project, to avoid needlessly complicating the procedure.

Where rows of buildings parallel the transit corridor:

- Check that cluster boundaries fall between the following rows of buildings, counting back away from the proposed project:

  Between rows 1 and 2

  Between rows 2 and 3

  Between rows 4 and 5

  If not, add cluster boundaries between these rows.

Boundaries along sources of ambient noise. Next, draw cluster boundaries along all major sources of ambient noise, based upon distance from these sources.

- Along all interstates and major roadway arterials, draw cluster boundaries at the following distances from the near edge of the roadway: 0 feet, 100 feet, 200 feet, and 500 feet.

- Along all other roadways that have state or county numbering, draw cluster boundaries at 0 feet and 100 feet from the near edge of the roadway.

- For all major industrial sources of noise, draw cluster boundaries that circle the source, at the following distances from the near property line of the source: 0 feet, 100 feet, 200 feet, 400 feet.

Further boundaries based upon changes in project layout or operations along the corridor. Where proposed project layout or operating conditions change significantly along the corridor, further subdivision is needed to account for changes in project noise. Draw a cluster boundary perpendicular to the corridor, extending straight outward to both sides, at the following locations:

- Where parallel tracks, previously separated by more than 100 feet or so, come closer together

- Approximately where speed and/or throttle is reduced approaching stations and where steady service speed is reached after departing stations.
- Approximately 200 feet up and down the line from grade-crossing bells
- At transitions from jointed to welded rail
- At transitions from one type of cross section to another -- from among these types: on structure, on fill, at grade, and in cut.
- At transitions from open terrain to heavily wooded terrain
- At transitions between areas free of locomotive-horn noise and areas subject to this noise source
- Any other positions along the line where project noise is expected to change significantly -- such as up and down the line from tight curves where wheels may squeal

Selection of a receiver of interest from each cluster. The cluster boundaries divide the land area into clusters of miscellaneous shape. Each of these pieces constitutes an area that will be represented by a single receiver of interest.

- For residential clusters, locate this receiver of interest within the cluster at the house closest to the proposed project. If in doubt, select the one furthest from significant sources of ambient noise.
- For outdoor noise-sensitive clusters, such as an urban park or amphitheater, locate this receiver of interest within the cluster at the closest point of active noise-sensitive use. If in doubt, select the one furthest from significant sources of ambient noise.

In following the foregoing procedures, some clusters may fall between areas with receivers of interest. This could occur, for example, when operational changes or track layouts change in an open undeveloped area. Retain such clusters -- that is, do not merge them with adjacent ones -- but do not select a receiver of interest from them.

Example B-1. Receivers of Interest and Cluster Boundaries

An example of receivers of interest and cluster boundaries is shown in Figure B-1. In this hypothetical situation, a new rail transit line, labeled "new rail line," is proposed along a major urban street with commercial land use. A residential area is located adjacent to the commercial strip, starting about one-half block from the proposed transit alignment. A major arterial, labeled "highway," crosses the alignment.

Following the procedure described in this appendix, the first step is to draw cluster boundaries along the **proposed primary project source** (in this case, the new rail line) at distances of 0 feet from the right-of-way line (edge of the street in this example), 50 feet, 100 feet, 200 feet, 400 feet, and 800 feet. These lines are shown with distances labeled at the top of the figure. This is proposed to be a constant speed section of track, so there are no changes in boundaries due to changes in operations along the corridor. Moreover, no **other project sources** are shown here, although if there had been a station with a parking lot, lines would have been drawn enveloping the station site at the specified distances from the property line. However, this example does show **rows of buildings parallel** to the transit corridor. The first set of lines satisfies the requirement that cluster boundaries fall between rows 1 and 2, and between rows 2 and 3, but there is no line between rows 4 and 5. Consequently, a cluster boundary (labeled "R" at the top of the figure) has been drawn between the 4th and 5th row of buildings.

Next, cluster boundaries are to be drawn along major sources of ambient noise. The roadway arterial (labeled "highway") is the only major source of ambient noise shown. Again following the procedure described in this appendix, cluster boundaries are drawn at 0 feet, 100 feet, 200 feet and 500 feet from the near edge of the roadway, both sides. These lines are shown with distances labeled at the side of the figure.

The foregoing describes the procedures for drawing all the lines defining the cluster boundaries shown in Figure B-1. The next step is to **select a receiver of interest within each cluster**. These are shown as filled circles in the figure. Some receivers of interest are labeled for use as examples in Appendix C. Taking the shaded cluster with "Rec 3" as an example: the cluster is located at the outer edge of influence from the major source ("highway"), where local street traffic takes over from the highway as the dominant source for ambient noise, which would be verified by a measurement. "Rec 3" is chosen to represent this cluster because it is among the houses closest to the proposed project source in this cluster and it is in the middle of the block affected by the dominant local street. Ambient noise levels at one end of the cluster may be influenced more by the highway and the other end may be affected more by the cross street, but the majority of the cluster would be represented by receiver site "Rec 3."

End of Example B-1

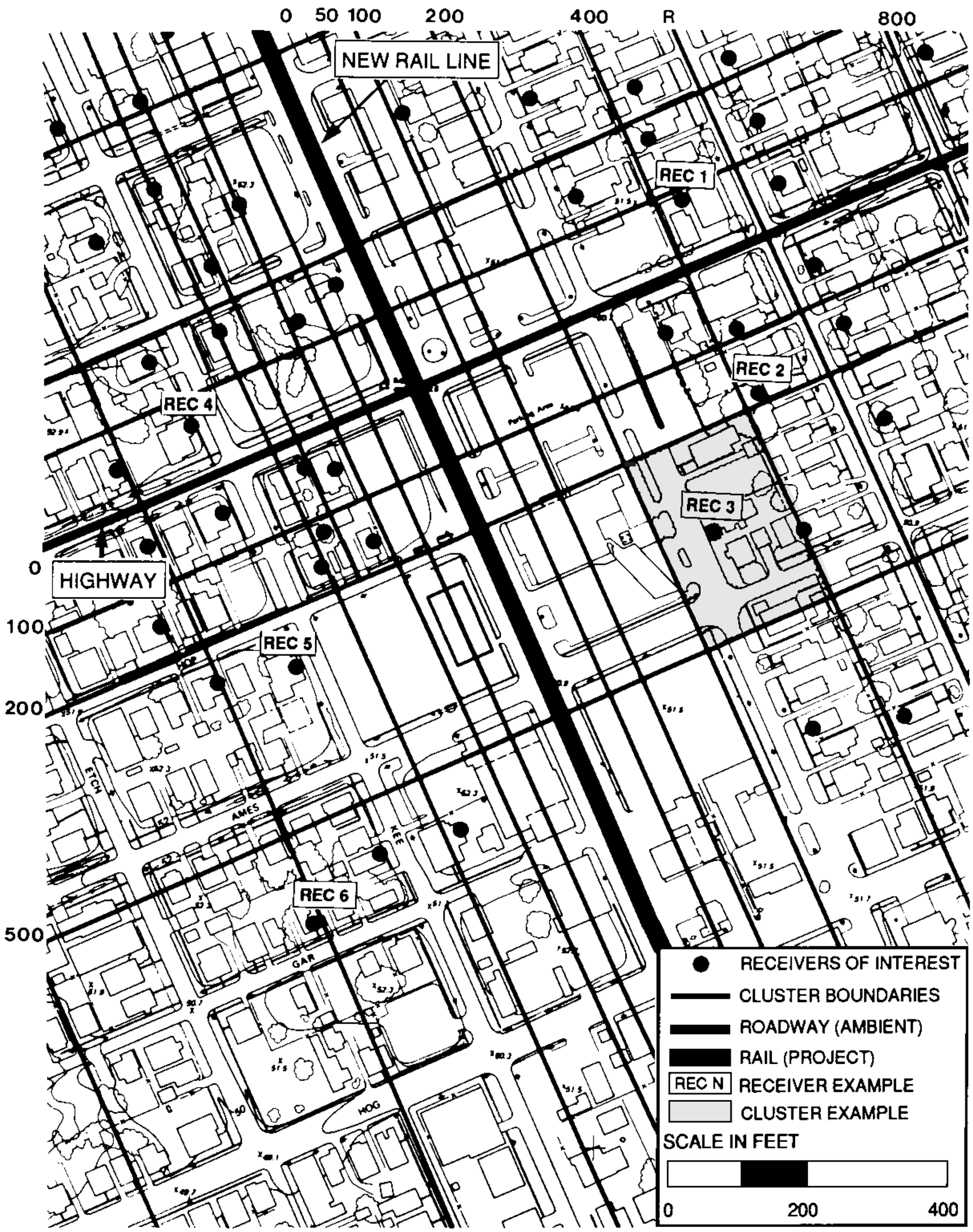

Figure B-1. Example of Receiver Map Showing Cluster Boundaries

APPENDIX C. DETERMINING EXISTING NOISE

This appendix provides additional detail in determining existing noise by: (1) full measurement, (2) computation from partial measurements, and (3) tabular look-up. Note that the words "existing noise" and "ambient noise" are often used interchangeably.

Continuing with the example from Figure B-1, the ambient noise at the selected receivers of interest, labeled "REC 1,2,3...," can be determined according to the following methods.

- Existing noise at REC 1 is due to the highway at the side of this church. L_{eq} during a typical church hour was measured in full. – OPTION 1 below
- Existing noise at REC 2, a residence, is due to a combination of the highway and local streets. L_{dn} was measured in full. – OPTION 2 below
- Existing noise at REC 3 is due to the street in front of this residence. L_{dn} was computed from three hourly L_{eq} measurements. – OPTION 3 below
- Existing noise at REC 4, a residence, is due to the highway. Since the highway has a predictable diurnal pattern, L_{dn} was computed from one hourly L_{eq} measurement. – OPTION 4 below
- Existing noise at REC 5, a residence, is due to Kee Street. L_{dn} was computed from L_{dn} at the comparable REC 3, which is also affected by local street traffic and is a comparable distance from the highway. – OPTION 5 below
- Existing noise at REC 6, a residence, is due to local traffic. L_{dn} was estimated by table look-up, based upon population density along this corridor. – OPTION 6 below

The full set of options for determining existing noise at receivers of interest is as follows:

- For non-residential land uses, measure a full hour's L_{eq} at the receiver of interest, during a typical hour of use on two non-successive days. The hour chosen should be the one in which maximum project activity will occur. The L_{eq} will be accurately represented.-- OPTION 1
- The three option for residential land uses are
  - Measure a full day's L_{dn}. The L_{dn} will be accurately represented. – OPTION 2
  - Masure the hourly L_{eq} for three typical hours: peak traffic, midday and late night. Then compute the L_{dn} from these three hourly L_{eq}'s. The computed L_{dn} will be slightly underestimated. – OPTION 3
  - Masure the hourly L_{eq} for one hour of the day only, preferably during midday. Then compute the L_{dn} from this hourly L_{eq}. The computed L_{dn} will be moderately underestimated. – OPTION 4
- For all land uses, compute either the L_{eq} or the L_{dn} from a measured value at a nearby receiver – one where the ambient noise is dominated by the same noise source. The computed value will be represented with only moderate precision. – OPTION 5
- For all land uses, estimate either the L_{eq} or the L_{dn} from a table of typical values, depending upon distance from major roadways or upon population density. The resulting values will be significantly underestimated. – OPTION 6

Option 1: For non-residential land uses, measure the hourly L_{eq} for the hour of interest

Full one-hour measurements are the most precise way to determine existing noise for non-residential receivers of interest. Such full-duration measurements are preferred over all other options. The following procedures apply to full-duration measurements:

- Measure a full hour's L_{eq} at the receiver of interest on at least two non-successive days during a typical hour of use. This would generally be between noon Monday and noon Friday, but weekend days may be appropriate for places of worship. On both days, the measured hour must be the same as that for which project noise is computed: the loudest facility hour that overlaps hours of noise-sensitive activity at the receiver.
- At all sites, locate the measurement microphone as shown in Figure 6-8, depending upon the relative orientation of project and ambient sources. Desired is a microphone location that is shielded somewhat from the ambient source. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.
- Undertake all measurements in accordance with good engineering practice (see References 1 and 2 of Chapter 6).

Option 2: For residential land uses, measure the L_{dn} for a full 24 hours

Full 24-hour measurements are the most precise way to determine ambient noise for residential receivers of interest. Such full-duration measurements are preferred over all other options. The following procedures apply to full-duration measurements:

- Measure a full 24-hour's L_{dn} at the receiver of interest, for a single weekday (generally between noon Monday and noon Friday).
- At all sites, locate the measurement microphone as shown in Figure 6-8, depending upon the relative orientation of project and ambient sources. Desired is a microphone location that is shielded somewhat from the ambient source. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.
- Undertake all measurements in accordance with good engineering practice (see References 1 and 2 of Chapter 6).

Option 3: For residential land uses, measure the hourly L_{eq} for three hours and then compute L_{dn}

An alternative way to determine L_{dn}, less precise than its full-duration measurement, is to measure hourly L_{eq}'s for three typical hours of the day and then to compute the L_{dn} from these three hourly L_{eq}'s. The following procedures apply to this partial-duration measurement option for L_{dn}:

- Measure the one-hour L_{eq} during each of the following time periods: once during peak-hour roadway traffic, once midday between the morning and afternoon roadway-traffic peak hours, and once during late night between midnight and 5 am.
- Compute L_{dn} with the following equation:

$$L_{dn} \approx 10\log\left[(3)\cdot 10^{\frac{L_{eq}(\text{peakhour})-2}{10}} + (12)\cdot 10^{\frac{L_{eq}(\text{midday})-2}{10}} + (9)\cdot 10^{\frac{L_{eq}(\text{latenight})+8}{10}}\right] - 13.8$$

  This value of L_{dn} will be slightly underestimated, due to the subtraction of 2 decibels from each of the measured levels before their combination. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn} here, compared to its full-duration measurement.

- At all sites, locate the measurement microphone as shown in Figure 6-8, depending upon the relative orientation of project and ambient sources. Desired is a microphone location that is shielded somewhat from the ambient source. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.

- Undertake all measurements in accordance with good engineering practice (see References 1 and 2 of Chapter 6).

Option 4: For residential land uses, measure the hourly L_{eq} for one hour and then compute L_{dn}

The next level down in precision is to determine L_{dn} by measuring the hourly L_{eq} for one hour of the day and then to compute L_{dn} from this hourly L_{eq}. This method is useful when there are many sites in a General Assessment, or when checking whether a particular receiver of interest represents a cluster in a Detailed Analysis. The following procedures apply to this partial-duration measurement option for L_{dn}:

- Measure the one-hour L_{eq} during any hour of the day. The loudest hour during the daytime period is preferable. If this hour is not selected, then other hours may be used with less precision.

- Convert the measured hourly L_{eq} to L_{dn} with the applicable equation:

$$\begin{aligned} &\text{For measurements between 7am and 7pm:} && L_{dn} \approx L_{eq} - 2 \\ &\text{For measurements between 7pm and 10pm:} && L_{dn} \approx L_{eq} + 3 \\ &\text{For measurements between 10pm and 7am:} && L_{dn} \approx L_{eq} + 8 \end{aligned}$$

The resulting value of L_{dn} will be moderately underestimated, due to the use of the adjustment constants in these equations. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn} here, compared to the more precise methods of determining L_{dn}.

- At all sites, locate the measurement microphone as shown in Figure 6-8, depending upon the relative orientation of project and existing sources. Desired is a microphone location that is shielded somewhat from the ambient source. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.

- Undertake all measurements in accordance with good engineering practice (see References 1 and 2 of Chapter 6).

Option 5: For all land uses, compute either L_{eq} or L_{dn} from a nearby measured value

A computation method comparable in precision to Option 4 is to determine the ambient noise, either $L_{eq}(h)$ or L_{dn}, from a *measured* value at a nearby receiver – one where the ambient noise is dominated by the same noise source. This method is used to characterize noise in several neighborhoods by using a single representative receiver. Care must be taken to ensure that the measurement site has a similar noise environment to all areas represented. If measurements made by others are available, and the sites are equivalent, they can be used to reduce the amount of project noise monitoring. The following procedures apply to this computation of ambient noise at the receiver of interest:

- Choose another receiver of interest, called the "comparable receiver," at which:
  - The same source of ambient noise dominates.
  - The ambient $L_{CompRec}$ was **measured** with either OPTION 1 or OPTION 2 above.
  - The ambient measurement at the comparable receiver was made in direct view of the major source of ambient noise, unshielded from it by noise barriers, terrain, rows of buildings, or dense tree zones.
- From a plan or aerial photograph, determine: (1) the distance $D_{CompRec}$ from the comparable receiver to the near edge of the ambient source, and (2) the distance $D_{ThisRec}$ from this receiver of interest to the near edge of the ambient source.
- Also determine N, the number of rows of buildings that intervene between the receiver of interest and the ambient source.
- Compute the ambient at this receiver of interest with the applicable equation:

  If roadway sources dominate: $$L_{ThisRec} \approx L_{CompRec} - 15\log\left(\frac{D_{ThisRec}}{D_{CompRec}}\right) - 3N$$

  If other sources dominate: $$L_{ThisRec} \approx L_{CompRec} - 25\log\left(\frac{D_{ThisRec}}{D_{CompRec}}\right) - 3N$$

  The resulting value of $L_{ThisRec}$ will be moderately underestimated. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn} here, compared to the more precise methods of determining ambient noise levels.

Option 6: For all land uses, estimate either $L_{eq}(h)$ or L_{dn} from a table of typical values

The least precise way to determine the ambient noise is to estimate it from a table. A tabular look-up can be used to establish baseline conditions for a General Noise Assessment if a noise measurement can not be made. It should not be used for a Detailed Noise Analysis. For this estimate of ambient noise:

- Read the ambient noise estimate from the relevant portion of Table 5-7. These tabulated estimates depend upon distance from major roadways, rail lines or upon population densities. In general, these tabulated values are significant underestimates. As explained previously, underestimates here are intended to compensate for the reduced precision of the estimated ambients, compared to the options that incorporate some degree of measurements.

APPENDIX D. COMPUTING SOURCE REFERENCE LEVELS FROM MEASUREMENTS

This appendix contains the procedures for computing source reference levels (SEL_{ref}) from source measurements in cases where the Source Reference Tables in Chapter 6 indicate measurements are preferred.

For vehicle passbys, the closeby source measurements may be either of the vehicle's sound exposure level (SEL) or of its maximum noise level (L_{max}). Both these descriptors can be measured directly by commonly available sound level meters. L_{max}'s are allowed here for several reasons. Often L_{max} measurements are available from transit-equipment manufacturers. For some transit systems, equipment specifications will limit closeby L_{max}'s to some particular value. And in some situations, closeby source measurements may be taken as part of the environmental study for more precision than is possible with the reference-level table.

For non-passby sources, the closeby source measurements must be of the source's SEL over one source "event." The source "event" duration may be chosen for measurement convenience; it will subtract out of the computation when the measured value is converted to reference operating conditions later in this section.

This manual does not specify elaborate methods for undertaking such closeby source measurements, nor that these measurements be at the reference conditions discussed in the main text. Required are measurements that conform to good engineering practice, guided by the standards of the American National Standards Institute and other such organizations (see References 1 and 2 of Chapter 6).

For passbys of both highway and rail vehicles, the following conditions are required in addition to good engineering practice:

- Measured vehicles must be representative of project vehicles in all aspects, including representative acceleration and speed conditions for 3-axle buses.
- Track must be relatively free of corrugations and train wheels relatively free of flats, unless these conditions are typical of the proposed project.

- Perpendicular distance between the measurement position and the source's centerline must be 100 feet or less.
- Vehicle speed must be 30 miles per hour or greater, unless typical project speeds are less than that.
- No noise barriers, terrain, buildings, or dense tree zones may break the lines-of-sight between the source and the measurement position.

For sources other than vehicle passbys, the following conditions are required in addition to good engineering practice:

- Measured source operations must be representative of project operations in all aspects.
- The following ratio must be 2 or less:

  distance to the furthest source component
  divided by
  distance to the closest source component

  In addition, the distance to the closest source component must be 200 feet or less. If both these conditions cannot simultaneously be met, then separate closeby measurements must be made of individual components of this source, for which these distance conditions can be met.
- The following ratio must be 2 or less:

  lateral length of the source area, measured perpendicular to the general line-of-sight between source and measurement position
  divided by
  distance to the closest source component

  If this condition cannot be met, then separate closeby measurements must be made of individual components of this source, for which this condition can be met.
- No noise barriers, terrain, buildings, or dense tree zones may break the lines-of-sight between the source and the measurement position.

When closeby source measurements are made under non-reference conditions, the equations in Table D-1 are used to convert the measured values to Source Reference Levels. Detailed procedures follow. Note that each vehicle type must be measured and converted separately. Note that this computation requires that all measured vehicles be of the same type. For trains of mixed consists, see Appendix E. For rail vehicles, measure/convert a group of locomotives **or** a group of cars separately.

<u>If SEL was measured for a highway-vehicle passby, or a passby of a group of identical rail vehicles:</u>

- Collect the following input information:
  - SEL_{meas}, the measured SEL for the vehicle passby

- N, the consist of the measured group of rail cars or group of locomotives
- T, the average throttle setting of the measured diesel-powered locomotive(s)
- S_{meas}, the measured passby speed, in miles per hour
- D_{meas}, the closest distance between the measurement position and the source, in feet

● Compute the Source Reference Level -- SEL_{ref} -- from the **first** equation in Table D-1.

Example D-1. Computation of SEL_{ref} from SEL Measurement of Fixed-Guideway Source

```
A passby of two diesel-powered locomotives was measured at
     SEL_meas    =    90.
For this measurement,
          N    =    2
          T    =    6
        S_meas =    55 miles per hour, and
        D_meas =    65 feet.
The resulting SEL_ref = 86.5 dB.
```

End of Example D-1

<u>If SEL was measured for a stationary noise source:</u>

● Collect the following input information:

- SEL_{meas}, the measured SEL for the noise source, for whatever source "event" is convenient to measure
- E_{meas}, the event duration, in seconds
- D_{meas}, the closest distance between the measurement position and the source, in feet

● Compute the Source Reference Level -- SEL_{ref} -- from the **second** equation in Table D-1.

Example D-2. Computation of SEL_{ref} from SEL Measurement of Stationary Source

```
A signal crossing was measured for a 10-second "event" at
     SEL_meas    =    70.
For this measurement,
     E_meas =    10 seconds and
     D_meas =    25 feet.
The resulting SEL_ref = 71.8 dB.
```

End of Example D-2

If L_{max} was measured for a passby of a group of identical rail vehicles:

- Collect the following input information:
  - L_{max}, measured for the group passby
  - N, the consist of the measured group of rail cars or group of locomotives
  - T, the average throttle setting of the measured diesel-powered locomotive(s)
  - S_{meas}, the measured passby speed, in miles per hour
  - D_{meas}, the closest distance between the measurement position and the source, in feet
  - L_{meas}, the total length of the measured group of locomotives or group of rail cars, in feet
- Compute the Source Reference Level -- SEL_{ref} -- from the **third or fourth** equations in Table D-1, depending on whether the sources are locomotives or rail cars.

Example D-3. Computation of SEL_{ref} from L_{max} Measurement of Fixed-Guideway Source

```
A passby of a 4-car consist of 70-ft long rail cars was measured at
     Lmax   = 90.
For this measurement,
     N      = 4
     Smeas  = 70 miles per hour
     Dmeas  = 65 feet, and
     Lmeas  = 280 feet.
Using the fourth equation in Table D-1,
     α      = 1.14
and the resulting SELref = 86.7 dB.
```

End of Example D-3

If L_{max} was measured for a highway-vehicle passby:

- Collect the following input information:
  - L_{max}, measured for the highway-vehicle passby
  - S_{meas}, the vehicle speed, in miles per hour
  - D_{meas}, the closest distance between the measurement position and the source, in feet
- Compute the Source Reference Level -- SEL_{ref} -- from the **fifth** equation in Table D-1.

Example D-4. Computation of SEL_{ref} from L_{max} Measurement of Highway Vehicle Source

A 3-axle bus was measured at

L_{max} = 78, under full throttle, accelerating conditions.

For this measurement,

S_{meas} = 22 miles per hour and

D_{meas} = 80 feet.

Using the fifth equation in Table D-1, the resulting SEL_{ref} = 83.8 dB.

End of Example D-4

Table D-1 Conversion to Source Reference Levels at 50 feet for Transit Noise Sources

Measured Quantity	Noise Source	Equation
SEL	Vehicle passby	$SEL_{ref} = SEL_{meas} + 10\log\left(\frac{S_{meas}}{50}\right) + 10\log\left(\frac{D_{meas}}{50}\right) + C_{consist} + C_{emissions}$
	Stationary noise source	$SEL_{ref} = SEL_{meas} - 10\log\left(\frac{E_{meas}}{60}\right) + 20\log\left(\frac{D_{meas}}{50}\right)$
L_{max}	Rail-vehicle passby, locomotives	$SEL_{ref} = L_{max} + 10\log\left(\frac{L_{meas}}{50}\right) + 10\log\left(\frac{D_{meas}}{50}\right) - 10\log(2\alpha) + C_{consist} + C_{emissions} + 3.3$
	Rail-vehicle passby, cars only	$SEL_{ref} = L_{max} + 10\log\left(\frac{L_{meas}}{50}\right) + 10\log\left(\frac{D_{meas}}{50}\right) - 10\log[2\alpha + \sin(2\alpha)] + C_{consist} + C_{emissions} + 3.3$
	Highway-vehicle passby	$SEL_{ref} = L_{max} + 20\log\left(\frac{D_{meas}}{50}\right) + C_{emissions} + 3.3$

Vehicle Type		Expression for $C_{consist}$	Expression for $C_{emissions}$
Locomotives		$-10\log(N)$	0 for $T < 6$ $-2(T-5)$ for $T \geq 6$
Rail Cars		$-10\log(N)$	$-30\log\left(\frac{S_{meas}}{50}\right)$
Three-axle (commuter) Buses	accelerating	0	-1.6
	not accelerating	0	$-24.6 \times \log\left(\frac{S_{meas}}{50}\right)$
Two-axle (city) Buses		0	$-33.9 \times \log\left(\frac{S_{meas}}{50}\right)$
Automobiles		0	$-38.1 \times \log\left(\frac{S_{meas}}{50}\right)$

N = consist, (number of locomotives *or* rail cars in the measured group)

T = average throttle setting of measured diesel-electric locomotive(s)

D_{meas} = closest distance between measurement position and source, in feet

E_{meas} = event duration of measurement, in seconds

L_{meas} = total length of measured group of locomotives *or* rail cars, in feet

S_{meas} = speed of measured vehicle(s), in miles per hour

$\alpha = \arctan\left(\frac{L_{meas}}{2D_{meas}}\right)$, in radians

APPENDIX E. COMPUTING MAXIMUM NOISE LEVEL (L_{max}) FOR A SINGLE TRAIN PASSBY

This appendix provides procedures for the computation of L_{max} for a single train passby, for those readers desiring such procedures. Table E-1 contains the equations to compute L_{max}. The procedure is summarized as follows.

- Collect the following input information:
  - SEL_{ref}'s from Chapter 6, specific to both the locomotive type and car type of the train
  - N_{locos}, the number of locomotives in the train
  - N_{cars}, the number of cars in the train
  - L_{locos}, the total length of the train's locomotive(s), in feet (or N_{locos}×unit length)
  - L_{cars}, the total length of the train's set of rail car(s), in feet (or N_{cars}×unit length)
  - S, the train speed, in miles per hour
  - D, the closest distance between the receiver of interest and the train, in feet
- Compute $L_{max,locos}$ from the locomotive(s) using the first equation in Table E-1.
- Compute $L_{max,cars}$ from the rail car(s) using the second equation in Table E-1.
- Choose the larger of the two L_{max}'s as the L_{max} for the total train passby.

Table E-1 Conversion to L_{max} at the Receiver, for a Single Train Passby

Source	Equation
Locomotives	$L_{max,locos} = SEL_{locos} + 10\log\left(\frac{S}{50}\right) - 10\log\left(\frac{L}{50}\right) + 10\log(2\alpha) - 3.3$
Rail Cars	$L_{max,cars} = SEL_{cars} + 10\log\left(\frac{S}{50}\right) - 10\log\left(\frac{L}{50}\right) + 10\log[2\alpha + \sin(2\alpha)] - 3.3$
Total Train	$L_{max,total} = \max\left[L_{max,locos} \textit{ or } L_{max,cars}\right]$

D = closest distance between receiver and source, in feet

L = total length of measured group of locomotive(s) *or* rail car(s), in feet

S = vehicle speed, in miles per hour

$\alpha = \arctan\left(\frac{L}{2D}\right)$, in radians

Example E-1. Computation of L_{max} for Train Passby

A commuter train will pass by a receiver of interest and its L_{max} is desired. For this train, the following conditions apply:

SEL_{ref} = 92 dB for locomotives and
= 82 dB for rail cars

N_{locos} = 1

N_{cars} = 6

S = 43 miles per hour

D = 125 feet.

The locomotive and rail cars each have a unit length of 70 feet. Therefore,

L_{locos} = 70 feet

L_{cars} = 420 feet

Using the equations in Table E-1,

α_{locos} = 0.27

α_{cars} = 1.03

and the resulting Lmax’s are as follows:

$L_{max,locos}$ = 84 dBA

$L_{max,cars}$ = 74 dBA

$L_{max,total}$ = 84 dBA.

End of Example E-1