FTA

FEDERAL TRANSIT ADMINISTRATION

Transit Noise and Vibration Impact Assessment Manual

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Federal Transit Administration

PREPARED BY
John A. Volpe National Transportation Systems Center

U.S. Department of Transportation
Federal Transit Administration

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

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14. ABSTRACT
This report is the third edition of a guidance manual originally issued in 1995. It includes clarifications to existing policy and updates to outdated references where applicable. Topics presented in this manual include procedures for predicting and assessing noise and vibration impacts of proposed transit projects for different stages of project development and different levels of analysis. Additional topics include descriptions of noise and vibration mitigation measures, construction noise and vibration, and how to present these analyses in the Federal Transit Administration's environmental documents. This guidance is for technical specialists who conduct the analyses, as well as project sponsor staff, Federal agency reviewers, and members of the general public who may be affected by the projects.

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Abstract

This report is the third edition of a guidance manual originally issued in 1995. It includes clarifications to existing policy and updates to outdated references where applicable. Topics presented in this manual include procedures for predicting and assessing noise and vibration impacts of proposed transit projects for different stages of project development and different levels of analysis. Additional topics include descriptions of noise and vibration mitigation measures, construction noise and vibration, and how to present these analyses in the Federal Transit Administration's environmental documents. This guidance is for technical specialists who conduct the analyses, as well as project sponsor staff, Federal agency reviewers, and members of the general public who may be affected by the projects.

Acknowledgments

The original 1995 version of this manual was developed by the firm Harris Miller Miller & Hanson Inc. (HMMH) and peer-reviewed by a group of specialists in the fields of acoustics and environmental planning and analysis. HMMH updated the original manual in 2006.

The updates for this current version were provided by the John A. Volpe National Transportation Systems Center, Cross Spectrum Acoustics, and FTA, and it was peer-reviewed by a panel of experts.

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SECTION

1

Introduction

1.1 Purpose

The Council on Environmental Quality (CEQ) regulations for implementing the procedural provisions of the National Environmental Policy Act of 1969 (NEPA)[1,2] require that a federally-funded project be assessed for its impact on the human and natural environment prior to implementation. The Federal Transit Administration (FTA), in conjunction with the Federal Highway Administration (FHWA), has issued detailed regulations implementing NEPA for transit and highway projects. The regulations are codified in part 771 of title 23, Code of Federal Regulations, and are titled "Environmental Impact and Related Procedures." (23 CFR part 771).[3]

The Federal Transit Administration (FTA) provides financial assistance for a range of public transportation projects from new rail rapid transit (RRT) systems to bus maintenance facilities and vehicle purchases. As required by NEPA and its implementing regulations, each project must undergo environmental review.

Noise and vibration are sometimes among the major concerns regarding the effects of a transit project on the surrounding community and are key elements of the environmental impact assessment process for public transportation projects. A transit system is often placed near population centers by necessity and may cause noise and vibration at nearby residences and other sensitive types of land use.

This manual provides technical guidance for conducting noise and vibration analyses for transit projects, as well as direction regarding preparation of the information for FTA's environmental documents. Some situations may not be explicitly covered in this manual; the exercise of professional judgment may be required to extend the basic methods in these cases and frequent consultation with FTA staff is important to ensure the methods used meet the requirements for environmental reviews. See Appendix G for information on using non-standard modeling procedures.

In general, the noise and vibration impact assessment process for projects includes the following steps:

1. Determine appropriate impact criteria (Section 4.1).
2. Conduct screening and determine appropriate level of noise analysis, analyze project noise impacts, and evaluate mitigation options if appropriate (Sections 4.2–4.5).
3. Determine appropriate level of vibration analysis, analyze project vibration impacts, and evaluate mitigation options if appropriate (Sections 6.1–6.5).
4. Analyze construction noise and vibration impacts (Section 7).
5. Document findings (Section 8).

1.2 Organization of the Manual

This guidance manual is organized by the following recommended analysis workflow. A glossary of terms used throughout this manual is available in Appendix A. Detailed information on the fundamentals of noise, noise impact criteria, clustering receivers, determining existing noise, computing source levels from measurements, and using non-standard methodology is available in the appendices.

Section 2: Project Class of Action and Planning – This section describes the first step in the analysis process that is applicable to both noise and vibration analyses.

Section 3: Transit Noise – This section provides the reader with background information specific to transit noise.

Section 4: Noise Impact Analysis – This section provides a general outline of the entire noise impact analysis process: guidelines on determining noise impact criteria, methods for choosing the appropriate level of noise analysis ("Screening," "General," or "Detailed"), steps for evaluating noise impacts with the Noise Screening Procedure (a simplified method of evaluating the potential for noise impact from transit projects), steps for evaluating noise impact with the General Noise Assessment procedure (a simplified assessment method to estimate noise impact and compare alternatives for transit projects), and steps for evaluating noise impact with the Detailed Noise Analysis procedure (a comprehensive assessment method to produce the most accurate estimates of noise impact intended for certain major public transportation projects).

Section 5: Transit Vibration – This section contains background information specific to transit vibration.

Section 6: Vibration Impact Analysis – This section provides a general outline of the entire vibration impact analysis process: guidelines on determining vibration impact criteria, methods for choosing the appropriate level of vibration analysis ("Screening," "General," or "Detailed"), steps for evaluating vibration impact with the vibration screening procedure (a simplified method of evaluating the potential for vibration impact from transit projects), steps for evaluating vibration impact with the general vibration assessment procedure (a simplified assessment method to estimate vibration impact and compare alternatives for transit projects), and steps for evaluating vibration impact with the detailed vibration analysis procedure (a comprehensive assessment method to produce the most accurate estimates of vibration impact intended for certain major public transportation projects).

Section 7: Noise and Vibration During Construction – This section presents the process of assessing noise and vibration impact during construction, including determination of level of assessment, source levels, impact criteria, and mitigation.

Section 8: Documentation of Noise and Vibration Assessment – This section includes guidance for documenting the noise and vibration assessment in technical reports and environmental documents.

SECTION 2

Project Class of Action and Planning

The level of environmental analysis and review depends on the significance of any potential associated environmental impacts, which in turn depends in part on the scope and complexity of the proposed project. The goals of a transit noise and vibration impact assessment are to:

1. Determine existing noise and vibration levels.
2. Assess project noise and vibration for potential impact.
3. Evaluate the effect of mitigation options on impacts.

The class of action determination will inform the required level of analysis. The FTA Regional office[i] determines the class of action based on project information provided by the project sponsor. The following types of information can assist the FTA Regional office in an initial class of action determination for a project:

- Project description
- Project-specific graphics, including:
  - Project location/sizes
  - Known land use and environmental features
- Additional information, as appropriate:
  - Summary of prior planning
  - Draft purpose and need statement

Project classes of action are described in Section 2.1. Project planning and development guidelines are presented in Section 2.2.

2.1 Project Class of Action

FTA's environmental regulations classify projects by level of environmental analysis. The class of action will determine the appropriate level of analysis and documentation for a project. Details of each class are described in the following sections. For more information, review FTA's environmental impact and related procedures at 23 CFR part 771.

Environmental Impact Statements

Environmental impact statements (EISs) apply to projects that are expected to cause significant environmental effects in the NEPA context. Typical examples include new or extensions of fixed-guideway projects, such as heavy rail, light rail, commuter rail, and automated guideway transit (AGT) systems that are not located within existing transportation right-of-way (ROW). It is likely that for major infrastructure projects requiring an EIS, the most detailed treatment of noise and vibration impacts will often be required.

Categorical Exclusions

Categorical exclusions (CEs) cover actions that are excluded from requiring an EIS or environmental assessment (EA) because FTA has determined that they do

[i] http://www.fta.dot.gov/12926.html.

not routinely cause significant environmental impacts. FTA's CEs are located at 23 CFR §§ 771.118(c) and (d), commonly referred to as the c-list and d-list, respectively. Examples of projects that would normally be CEs include vehicle purchases, maintenance of equipment, vehicles, or facilities, and ROW acquisition.
In general, CEs for transit capital construction projects often require at least a screening of noise impacts.

Environmental Assessments
When a proposed project is presented to FTA and it is uncertain whether the project requires an EIS or qualifies for a CE, FTA will normally direct the project sponsor to prepare an environmental assessment (EA) to assist in making the determination. An EA may be prepared for any type of project if uncertainty exists about the magnitude or extent of the impacts. Generally, an EA is selected over a CE if FTA determines that several types of potential impacts require further investigation, for example, air quality, noise, wetlands, historic sites, and/or traffic, but FTA's environmental regulation does not list typical projects that require EAs.
Experience shows that most of the EAs prepared for transit projects require at least a general assessment of noise impacts.

2.2 Project Planning and Development

Capital transit projects are ordinarily developed initially from a comprehensive transportation planning process conducted in metropolitan areas (see 23 CFR § 450.300).[4] The metropolitan planning process often includes some early consideration of social, economic, and environmental effects of proposed major infrastructure improvements. At this stage, environmental effects are usually considered on a broad scale—for example, overall development patterns, impacts on green space, and regional air quality. Noise and vibration assessments are not typically performed at this stage because the proposed infrastructure improvements lack the necessary detail.

Once the need for a capital transit project in a corridor is established in the metropolitan transportation plan, the transit mode and general alignment best suited for the corridor are identified. The Screening and General noise assessment procedures and the vibration screening procedure described in this manual may be used to compare noise and vibration effects among different transit modes and alignments at an early stage of the project planning. The analysis that results is documented through the environmental review process.

NEPA establishes a broad policy regarding mitigation as a means of accomplishing its environmental objectives. Other Federal laws, such as Section 4(f) (49 U.S.C. 303) and Section 404 (33 U.S.C. 1344), have explicit mitigation requirements for certain resources. The decision to include noise or vibration mitigation for a project is made by FTA and the project sponsor after public review of the environmental document, as appropriate. If mitigation measures are deemed necessary to protect the environment or to satisfy 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. Through that process, FTA ensures that the project sponsor complies with all design and mitigation commitments contained in the environmental record.

Once the project enters construction, noise or vibration may need to be reassessed in some circumstances. Some large construction projects in densely populated residential areas may require noise monitoring to ensure agreed-upon noise limits are not exceeded. Vibration testing may be needed in the final stages of construction to determine whether vibration control measures have the predicted effect.

Considering that transit projects must be located amid or very close to concentrations of people, noise and vibration impacts can be a concern throughout the environmental review process, design, and construction 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.

2.3 Mitigation Policy Considerations

Because noise is frequently among the greatest environmental concerns of planned transit projects, FTA and the project sponsor should make reasonable efforts to reduce predicted noise to levels considered acceptable for affected noise-sensitive land uses. The need for noise mitigation is determined based on the magnitude of impact and consideration of factors specifically related to the proposed project and affected land uses.

The goal of providing noise mitigation is to gain substantial noise reduction, not simply to reduce the predicted levels to just below the "severe" impact threshold. For FTA to determine whether the mitigation is reasonable, the evaluation of specific mitigation measures should include the noise reduction potential, the cost, the effect on transit operations and maintenance, and any other relevant factors, such as any new environmental impacts that may be caused by the implementation of a noise reduction measure. A thorough evaluation enables FTA to make the findings required by NEPA and other statutes, such as Section 4(f) or Section 106 requirements and their implementing regulations.

Severe impacts have the greatest adverse impact on the community, and mitigation should be strongly considered. Areas with "moderate" impacts also have potential for effects on the community and therefore should also include consideration and possible adoption of mitigation measures when considered reasonable.

Since reasonableness is not strictly defined, FTA recommends that project sponsors work with the affected public and FTA staff during the environmental review process to decide appropriate mitigation strategies. A project sponsor may also consider developing and formally adopting a mitigation policy to aid in the determination of appropriate and applicable mitigation measures for current and proposed projects and anticipated impacts. Having such a policy in place can aid in the project planning up front and help to expedite mitigation decisions.

The following considerations can assist in determining circumstances that trigger the need for mitigation and include examples of how they can be applied in a noise mitigation policy:

- **Number of Noise-Sensitive Sites Affected**
  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. Single residences may not be able to meet a cost-effectiveness criterion for mitigation.

  Example Mitigation Policy Consideration: Set a minimum number of noise-sensitive sites as a threshold, combined with a reference to a cost-effectiveness criterion.

- **Increase over Existing Noise Levels**
  Since the noise impact criteria are delineated as bands or ranges, project noise can vary 5 to 7 decibels (dB) within the band of moderate impact at any specific ambient noise level. If the project and ambient noise plot falls just below the severe range, the need for mitigation is strongest for a moderate impact. Similarly, if the plot falls within the moderate range just above the no impact threshold, the impacts are expected to be less, so the justification for mitigation would not be as strong.

  Example Mitigation Policy Consideration: Set a strong need for mitigation when a moderate impact is 2 dB (for example) over the no impact threshold.

- **Noise Sensitivity of the Property**
  Section 4.1 includes 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.

  Example Mitigation Policy Consideration: Cite the use of the property as a determination of sensitivity for parks and recreational areas.

- **Effectiveness of the Mitigation Measure(s)**
  Determine the magnitude of the noise reduction that can be achieved, and consider whether there are conditions that limit effectiveness, such as noise barrier effectiveness for a multi-story apartment building.

  Example Mitigation Policy Consideration: Set a minimum reduction in noise level to be considered effective. A 5-dB reduction is typically considered an effective reduction from mitigation.

- **Feasibility of the Mitigation Measure(s)**
  Determine if the mitigation measure is feasible from an engineering, operations or safety perspective. In some cases, it may not be possible to construct mitigation (noise barriers) due to physical or structural limitations

or because of safety concerns, especially related to sight lines for pedestrians and vehicles.

Example Mitigation Policy Consideration: State that the engineering design of the mitigation must be feasible, that it must be implementable in light of operations, and that mitigation must not compromise safety.

- **Fairness and Equity of the Mitigation Measure(s)**
  Ensure that mitigation measures are applied in a fair and equitable manner. In many cases, small differences in distances or operations can result in small differences in projected noise levels. For example, all the residences in a row could have a projected moderate impact except for one residence at the end of the row that falls just under the moderate criteria due to being set slightly further back from the alignment. In a case like this, mitigation should be applied for the entire row of residences if possible.

  Example Mitigation Policy Consideration: State that mitigation should be applied equitably.

- **Existing Transportation Noise**
  Neighborhoods with ambient noise levels already heavily influenced by transportation noise, especially the same type of noise source as the project, should be considered. Often adding a new similar noise source will not add to the ambient noise levels or only slightly increase it to within acceptable levels. Whereas, impacts would be more likely, if the new noise was added to a neighborhood with minimal transportation noise. However, it is important to note that per (Section 4.1, Step 3) the higher the existing noise, the lower the allowable noise increase from new sources. A new cumulative noise environment may be very objectionable because people will not be compartmentalizing the existing noise versus the new noise and reacting only to the new noise. In this circumstance, impacts predicted in the moderate range could be treated as if they were severe.

  Example Mitigation Policy Consideration: Set a policy that moderate impacts under these circumstances be treated as severe and cite the potential for reducing noise from existing transportation noise, as well as from project noise.

- **Community Views**
  This manual provides the methodology to make an objective assessment of the need for noise mitigation. However, the views of the community should be considered where there are potential noise impacts predicted through this manual. 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 moderate impact range and, where possible, decisions regarding mitigation should be made 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 noise barrier, was not preferable to community members because of perceived adverse visual effects.

Example Mitigation Policy Consideration: State that community input in determining the need for mitigation will be included whenever possible.

- **Implementation Cost**
  Cost is an important consideration in reaching decisions about noise mitigation measures. One guideline for gauging the reasonableness of the cost of mitigation is the state DOT's procedures on the subject. Many states have established their own cost threshold per benefited residence for determining whether installation of noise barriers for noise reduction is a reasonable expenditure. Several airport authorities have placed limits on the costs they will incur for sound insulation per residence for homes, and FTA assesses cost in a similar manner by benefited residence. Higher costs may be justified depending on the specific set of circumstances of a project.

  Example Mitigation Policy Consideration: State the adopted cost threshold per benefited receiver for typical circumstances.

SECTION 3

Transit Noise

This section presents the basic concepts of transit noise as background for computation methods and transit noise assessment procedures presented in Section 4. An overview of fundamental noise topics, including amplitude, frequency, time pattern, and decibel addition, is presented in Appendix B.

The Source-Path-Receiver framework for noise illustrated in Figure 3-1 is central to all environmental noise studies. Each transit source generates noise that depends upon the type of source and its operating characteristics. Along the propagation path, between all sources and receivers, noise levels can be reduced (attenuated) by distance depending on ground type, intervening obstacles, and other factors. Finally, noise combines from multiple sources at each receiver and potentially interferes with activities at that location.

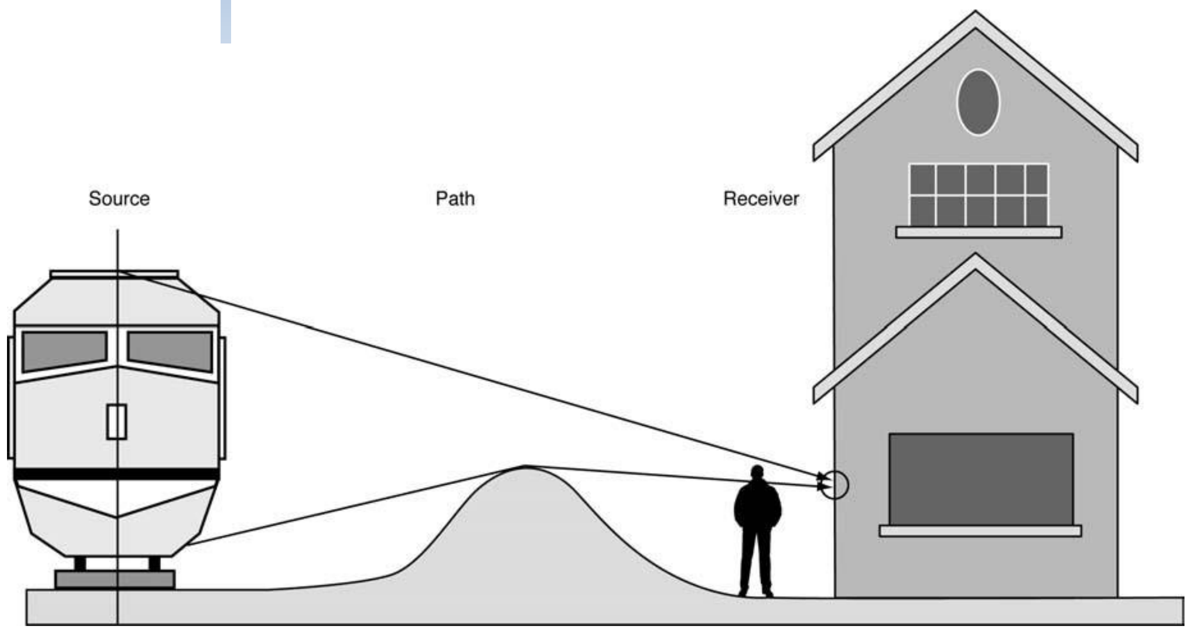

Figure 3-1 Source-Path-Receiver Framework

This section contains the following:

- Section 3.1 presents the noise metrics used in this manual.
- Section 3.2 provides an overview of transit noise sources, including a listing of major sources and a discussion of noise-generation mechanisms.
- Section 3.3 provides an overview of noise paths, including a discussion of the various attenuating mechanisms on the path between source and receiver.
- Section 3.4 provides an overview of receiver response to transit noise, including a discussion of the technical background for transit noise criteria and the distinction between absolute and relative noise impact.

3.1 Noise Metrics

This manual uses the noise metrics outlined in Table 3-1 for transit noise measurements, computations, and assessment. The terminology is consistent with common usage in the United States. All of these noise metrics are expressed in units of A-weighted decibels (dBA). A-weighted sound levels represent the overall noise at a receiver that is adjusted in frequency to approximate typical human hearing sensitivity. This is the basic noise unit for transit noise analyses.

Table 3-1 Noise Metrics

Metric	Abbreviation	Definition
A-weighted Sound Level	dBA	A-weighted sound levels represent the overall noise at a receiver that is adjusted in frequency to approximate typical human hearing sensitivity. This is expressed as A-weighted decibels (dBA), the basic noise unit for transit noise analyses.
Sound Exposure Level	*SEL*	SEL is the cumulative noise exposure from a single noise event, normalized to one second. SEL contains the same overall sound energy as the actual varying sound energy during the event. It is the primary metric for the measurement of transit vehicle noise emissions, and is an intermediate metric in the measurement and calculation of both $L_{eq(t)}$ and L_{dn}.
Equivalent Sound Level	$L_{eq(t)}$	The equivalent sound level $L_{eq(t)}$ describes a receiver's cumulative noise exposure from all events normalized to a specified period of time "t". $L_{eq(t)}$ represents a hypothetical, constant sound level and contains the same overall sound energy as the actual varying sound energy during the time period "t". For transit noise impact assessments, the equivalent sound level metric is A-weighted and all events are normalized over a one-hour time period, $L_{eq(1hr)}$. For transit noise assessments, this metric is appropriate for non-residential land uses and is computed for the loudest hour of project related activity during hours of noise sensitivity.
Day-Night Sound Level	L_{dn}	L_{dn} describes a receiver's cumulative noise exposure from all events over 24 hours. Events between 10 p.m. and 7 a.m. are increased by 10 dB to account for humans' greater nighttime sensitivity to noise. L_{dn} is used to assess transit noise for residential land uses.
Maximum Sound Level	L_{max}	The maximum level describes the maximum noise level reached during a single noise event. For transit noise impact assessments, it is appropriate to consider the A-weighted maximum level (L_{max}) to understand the full context of the scenario. It is not appropriate to use this metric for transit noise impact assessments. This metric is commonly used in vehicle noise specifications and commonly measured for individual vehicles.

The noise metrics, including their application to transit noise and vibration impact assessment, are described in more detail in Appendix B.1.4. Mathematical definitions and graphic illustrations are presented to facilitate understanding and the interrelationships among metrics.

3.2 Sources of Transit Vehicle Noise

This section discusses major characteristics of the sources of transit noise. Transit noise can be generated by transit vehicles in motion, stationary transit vehicles, and fixed-transit facilities. Procedures for computing nearby noise levels for major sources as a function of operating parameters such as vehicle speed are given in Sections 4.4 and 4.5.

Transit Vehicles in Motion

Transit vehicles most noticeably create noise when in motion. Noise from transit vehicles in motion can come from multiple sources, including the propulsion unit (i.e., the engine and engine components), the interaction of the wheels and/or tires and the running surface, and warning bells and horns.

Vehicle propulsion units generate:

- Whine from electric control systems and traction motors that propel rapid transit cars
- Diesel-engine exhaust noise from both diesel-electric locomotives and transit buses
- Air-turbulence noise generated by cooling fans
- Gear noise

Noise is also generated by the interaction of wheels and/or tires with their running surfaces. Tire noise from rubber-tired vehicles is generated at normal operating speeds. The interaction of steel wheels and rails generates:

- Rolling noise due to continuous rolling contact
- Impact noise when a wheel encounters a discontinuity in the running surface such as a rail joint, turnout or crossover (where the train or rail vehicle switches off one track and onto another)
- Impact noise from the wheel and running surface if the wheel is not completely round (wheel flat) or if the running surface is not completely flat
- Squeal generated by friction between wheels and rail on tight curves

Transit vehicles are equipped with horns and bells for use in emergency situations and as a general audible warning to track workers and trespassers within the ROW, pedestrians, and motor vehicles at highway grade crossings. Horns and bells on the moving transit vehicle combined with stationary bells at-grade crossings can generate high noise levels for nearby residents and are often sources of complaints.

For many noise sources, such as transit vehicles, the sound level is dependent on the speed of the noise source. In other cases, such as for stationary sources or horns mounted on vehicles, the sound level is not dependent on speed. Figure 3-2 illustrates sound level dependence on speed for a diesel-powered commuter rail train and an electric-powered transit train assuming all other parameters, such as weight, are equal. Plotted vertically in this figure is a notional indication of the maximum sound level during a passby. Speed dependence is strong for electric-powered transit trains because wheel/rail noise is the dominant noise source and noise from this type of source increases strongly with speed. Diesel-powered commuter rail train noise is dominated by the locomotive exhaust noise at slower speeds. As speed increases, wheel-rail noise becomes the dominant noise source and diesel- and electric-powered trains generate similar noise levels. Similarly, speed dependence is also strong for automobiles, city buses (two-axle), and non-accelerating highway buses (three-axle), because tire/pavement noise is the dominant noise source for these vehicles. Accelerating highway bus noise is dominated by exhaust noise.

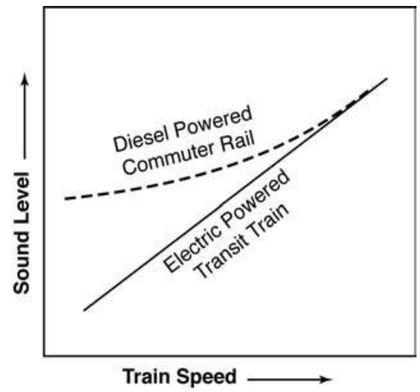

Figure 3-2 Sound Level Dependence on Speed

Sound levels close to the source are also dependent on vehicle acceleration, vehicle length, running surface type, and running surface condition. For high-speed rail vehicles (vehicles with an operating speed of 90–250 mph are typically beyond the scope of this manual), air turbulence can also be a source of noise. In addition, for an elevated structure, the guideway can radiate noise as it vibrates in response to the dynamic loading of the moving vehicle.

Stationary Transit Vehicles

Noise can be generated by transit vehicles even when they are stationary. For example, auxiliary equipment such as cooling fans on motors, radiator fans, plus hydraulic, pneumatic, and air-conditioning pumps, often continue to run when vehicles are stationary. Transit buses are also often left idling in stations or storage yards.

Fixed-transit Facilities

Noise can also be generated by sources at fixed-transit facilities. Such sources include ventilation fans in transit stations, subway tunnels, and electric power substations, as well as equipment in chiller plants, and many activities within maintenance facilities and shops.

Common Noise Sources

Table 3-2 summarizes common sources of transit noise by vehicle and facility type.

Table 3-2 Sources of Transit Noise

Vehicle or Facility*	Dominant Components	Comments
RRT or Light Rail Transit (LRT) on exclusive ROW	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
LRT in Mixed Traffic	Wheel squeal	On tight curves
	Auxiliary equipment	When stopped
	Horns and crossing bells	At-grade crossings and stations
	In general	Traveling at lower speeds in mixed traffic produces less noise than when traveling at higher speeds in exclusive ROW
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 and stations
	In general	Noise is usually dominated by locomotives and horns/bells at-grade crossings
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
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 most disruptive in the early morning
	Buses accelerating	Usually near entrances/exits and/or locations that require buses to accelerate (tight turns)
	Buses idling	Warm-up areas
	In general	Site specific: often peak periods with considerable noise
Rail Transit Storage Yards	Wheel squeal	On tight curves
	Wheel impacts	On joints and switches
	Wheel rolling noise	On tangent track
	Auxiliary equipment	Throughout day and night; includes air-break release noise
	Coupling/uncoupling	On storage tracks
	Signal horns	Throughout yard site
	In general	Site specific: often early morning and peak periods with considerable noise

Maintenance Facilities	Signal horns	Throughout facility
	Intercoms	Throughout facility
	Impact tools	Shop buildings
	Car/bus washers/driers	Wash facility
	Vehicle activity	Throughout facility
	In general	Site specific: considerable activity throughout day and night, some outside.
Stations	Automobiles	Patron arrival/departure, especially in early morning
	Buses idling	Bus loading zone
	Intercoms	Platform area
	Locomotive idling	At commuter rail terminal stations
	Auxiliary systems	At terminal stations and layover facilities
	Horns	At stations, if applicable
	In general	Site specific, with peak activity periods
Subways	Fans	Noise through vent shafts/structures
	Buses/trains in tunnels	Noise through vent shafts/structures
	In general	Noise is not a problem, except in the immediate vicinity of vent shafts/structures.

* Refer to Appendix A for additional information.

3.3 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 are included in Sections 4.4 and 4.5.

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

Divergence

Sound levels naturally attenuate with distance, as shown in Figure 3-3. The plot shows attenuation at the receiver relative to the sound level 50 ft from the source. This type of attenuation is called divergence and is dependent upon source configuration (line or point source) or other source-emission characteristics. Localized sources (point sources) grouped closely together attenuate greatly with distance at a rate of approximately 6 dB per doubling of distance. Examples of point sources include highway grade-crossing signals along rail corridors, intercoms in maintenance yards and other closely grouped sources of noise. Vehicles passing along a track or roadway forming a line are called line sources. Line sources attenuate less than point sources with distance. Rate of attenuation for line sources varies depending on the noise metric. $L_{eq(1hr)}$ and L_{dn} noise levels attenuate at a rate of 3 dB per doubling of distance and L_{max} noise levels attenuate at a rate of 3 to 6 dBs per doubling of distance.

Figure 3-3 illustrates approximate attenuation with distance between the source and receiver for point and line sources. The line source curve for the L_{max} noise metric separates into three curves because it is dependent on the length of the line source. Equations for the curves in Figure 3-3 are included in Section 4.5.

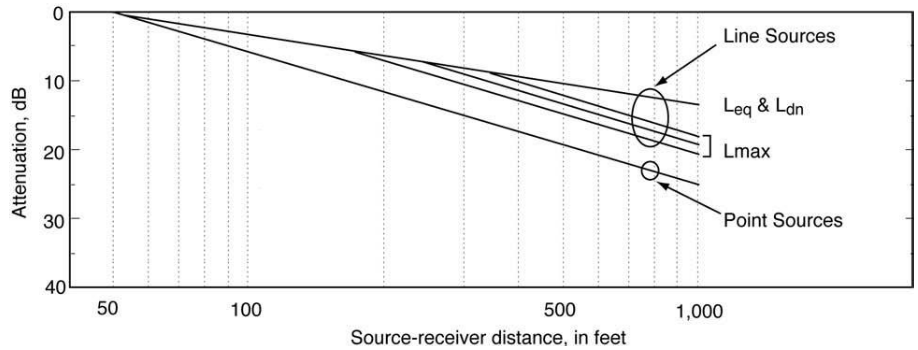

Figure 3-3 Attenuation Due to Distance (Divergence)

Absorption/Diffusion

In addition to distance, sound levels can be attenuated depending on the type of ground between the source and receiver. A portion of the sound energy is absorbed by the ground and only the remaining energy travels to the source. How much energy the ground absorbs is dependent on the ground type (characterized as acoustically "hard" or "soft") and geometry. Example absorptive ground types include freshly-plowed or vegetation-covered ground. Figure 3-4 illustrates approximate attenuation due to ground type by source to receiver path distance and height. Ground attenuation can be as large as 5 dB over a path distance of several hundred ft. At very large distances, wind and temperature gradients could modify the expected ground attenuation. However, these 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 are included in Section 4.5.

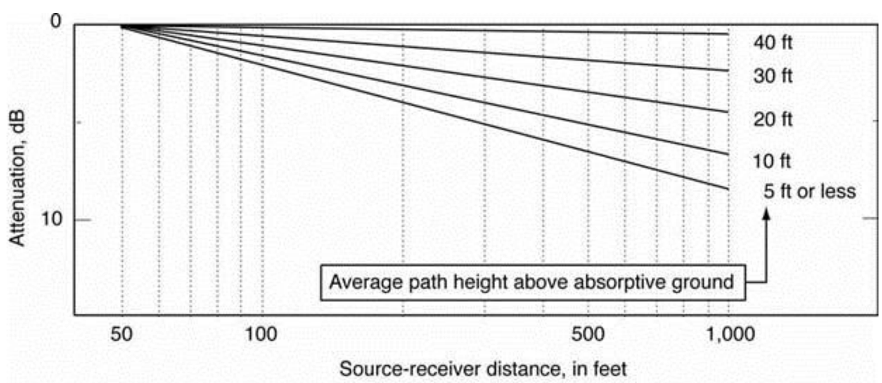

Figure 3-4 Attenuation due to Soft Ground

Shielding

Sound paths are sometimes interrupted by terrain, human-constructed noise barriers, rows of buildings, or other objects. Noise barriers are one of the most effective means of mitigating noise (Section 4.5, Step 7). 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 from view but does not reduce sound levels substantially over short distances). Sound energy reaches the receiver only by bending (diffracting) over the top of the barrier, as shown in Figure 3-5. This diffraction over the barrier reduces the sound level that reaches the receiver. One important consideration in using noise barriers to mitigate noise impacts is safety. Noise barriers, if not designed and sited carefully, can reduce visibility of trains for pedestrians and motorists, leading to less safe conditions. It is important to consult with safety experts when choosing and siting a noise barrier.

Noise barriers for transportation systems are typically used to attenuate noise at the receiver, potentially reducing received sound levels by 5 to 15 dB, depending upon barrier height, length, and distance from both source and receiver. Barriers on structures close to the transportation noise source may provide less attenuation than barriers located farther from the source due to reverberation (multiple reflections) between the barrier and the body of the vehicle or noise source. This reverberation can be offset by increased barrier height and/or acoustical absorption on the source side of the barrier. Further discussion and equations on acoustical absorption and barrier attenuation is provided in Section 4.5.

Source-to-receiver sound paths may not always travel 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 Section 5.

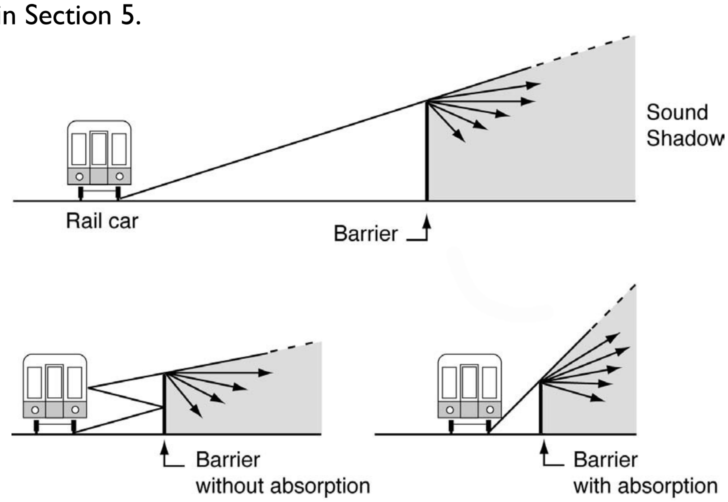

Figure 3-5 Noise Barrier Geometry

3.4 Receiver Response to Transit Noise

This section contains an overview of human receiver response to noise. It serves as background information for the noise impact criteria in Section 4.1.

Noise can interrupt ongoing activities causing community annoyance, especially in residential areas. In general, most residents become highly annoyed when noise interferes considerably with activities such as sleeping, talking, noise-sensitive work, and audio entertainment. In addition, some land uses, such as outdoor concert pavilions, are inherently incompatible with high noise levels.

Annoyance from noise has been investigated and approximate dose-response relationships have been quantified by the U.S. Environmental Protection Agency (EPA).(5) The selection of noise metrics 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, discussed, and refereed by many professionals in acoustics. Basic conclusions of these studies have been adopted by the Federal Interagency Committee on Noise (FICON),[ii] the U.S. Department of Housing and Urban Development (HUD), the American National Standards Institute, and even internationally(6)(7)(8)(9). Conclusions from this seminal EPA work remain scientifically relevant today.

Figure 3-6 contains a synthesis of actual case studies of community reaction to newly introduced sources of noise in a residential urban neighborhood.(10) Plotted horizontally in the figure is the increase in noise from new sources above existing noise levels expressed as Day-Night Sound Levels, L_{dn}, discussed in Appendix B.1.4.5. 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 dB below existing to 25 dB above existing. Note the assumptions included in the graphic are associated with the specific data points from the study. These assumptions are generally appropriate to give context to most transit projects, but community reaction may differ for conditions specific to each project.

In many community attitudinal surveys, transportation noise has been ranked among the greatest causes of community dissatisfaction. A synthesis of many such surveys on annoyance is shown in Figure 3-7.(11)(12) Noise exposure levels are plotted against the percentage of people who are highly annoyed by the particular level of neighborhood noise. As shown in the figure, the percentage of high annoyance is approximately 0 percent at 45 dB, 10 percent around 60 dB, and increases quite rapidly to approximately 70 percent around 85 dB. The scatter about the synthesis line is due to community variation and wording differences in the surveys. An update of the original research containing additional railroad, transit and street traffic noise surveys generally follows the shape of the original response curve shown in Figure 3-7.(12)(13)

As indicated by Figure 3-6 and Figure 3-7, introduction of certain levels of transit noise into a community may have two undesirable effects. First, it may substantially increase noise levels above existing noise levels in a community. This effect is called a relative noise impact. Evaluation of this effect compares new noise levels to the existing levels. Criteria for a relative noise impact evaluation are based upon noise increases above existing levels. Second, newly introduced transit noise may interfere with community activities independent of existing noise levels. For example, it may be too loud to converse or sleep. This effect is called absolute noise impact and is expressed as a fixed level threshold that is not to be exceeded. The fixed level threshold is determined independently of existing noise levels. Relative and absolute noise impacts are discussed in terms of transit noise criteria in Section 4.1, Step 3.

[ii] The Federal Interagency Committee on Aviation Noise (FICAN) is the current version of this group.

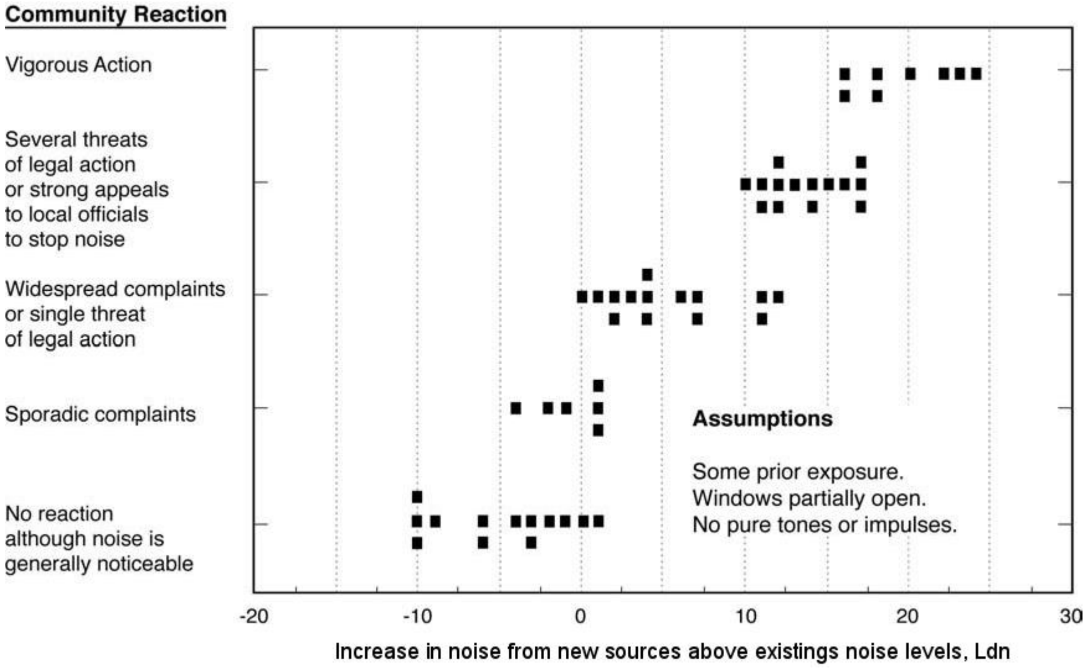

Figure 3-6 Community Reaction to New Noise, Relative to Existing Noise in a Residential Urban Environment

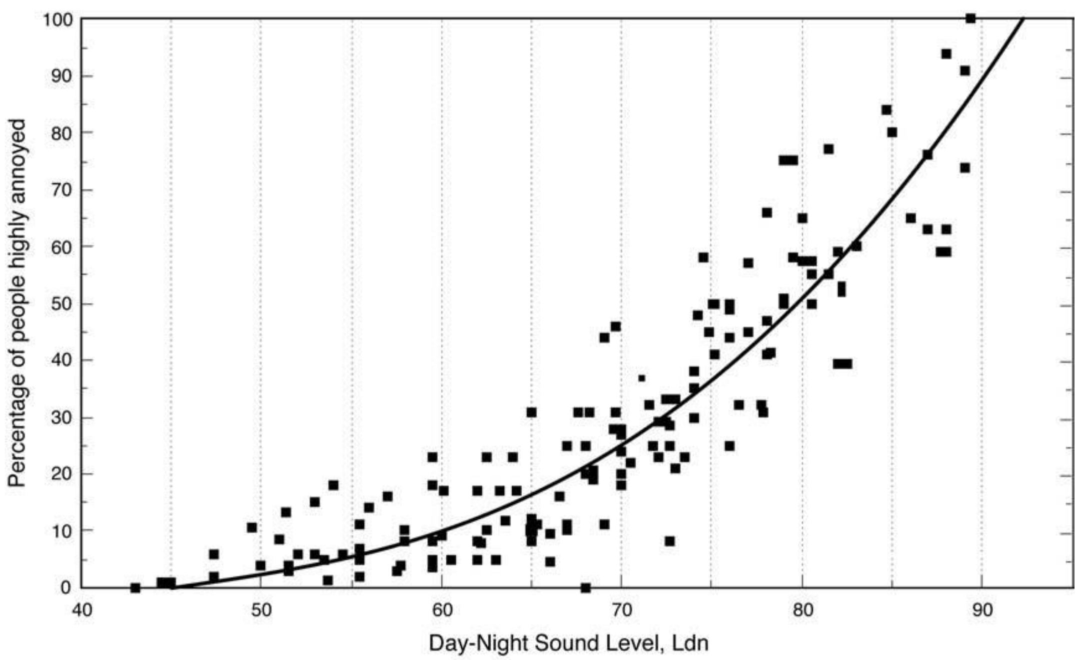

Figure 3-7 Community Annoyance Due to Noise

SECTION

4

Noise Impact Analysis

The FTA noise impact analysis process is a multi-step process used to evaluate the project for potential noise impacts for FTA NEPA approvals. If impact is determined, measures necessary to mitigate adverse impacts must be considered for incorporation into the project.[4] It is recommended that project sponsors develop and formally adopt a policy for determining the need for mitigation for situations that are loosely covered by the impact criteria. Considerations for mitigation policies are included in Section 2.3. The FTA noise impact analysis steps are summarized as follows and are described in the subsequent subsections:

4.1: Determine noise impact criteria.
- **Step 1:** Identify the type of project/dominant noise source (transit or multimodal).
- **Step 2:** Choose land use category for FTA criteria.

4.2: Determine the highest appropriate level of noise analysis for the current stage of project planning or development.

4.3: Evaluate for the potential of impact according to the Noise Screening Procedure.
- **Step 1:** Identify project type.
- **Step 2:** Determine the screening distance.
- **Step 3:** Identify the study area.
- **Step 4:** Locate noise-sensitive land uses.

4.4: Evaluate impact according to the General Noise Assessment and evaluate preliminary mitigation options if impact is found.
- **Step 1:** Identify noise-sensitive receivers.
- **Step 2:** Determine the project noise source reference levels.
- **Step 3:** Estimate project noise exposure by distance.
- **Step 4:** Combine noise exposure from all sources.
- **Step 5**: Measure existing noise exposure.
- **Step 6:** Inventory noise impacts.
- **Step 7:** Determine noise mitigation needs.

4.5: Evaluate for impact according to the Detailed Noise Analysis and evaluate mitigation options if impact is found.
- **Step 1:** Identify noise-sensitive receivers.
- **Step 2:** Determine noise source levels for detailed analysis.
- **Step 3:** Calculate project noise exposure by distance.
- **Step 4:** Combine noise exposure from all sources.
- **Step 5:** Determine existing noise exposure.
- **Step 6:** Assess noise impact.
- **Step 7:** Determine noise mitigation measures.

In addition to analyzing for potential noise impacts, analyze the project for potential vibration impacts according to the process presented in Section 6. After both the noise and vibration analyses have been completed, assess construction noise and vibration according to Section 7 and document findings according to Section 8.

4.1 Determine Noise Impact Criteria

This section describes the procedure for determining the appropriate criteria for assessing project noise impact based on the type of project and project noise source. Project noise is the new noise or change in noise introduced by the project. Noise impact criteria may vary for different segments of the project. Project segments can be portions of a project with similar characteristics.

The procedure to determine the appropriate impact criteria is described in this section and shown more simply as a flow chart in Figure 4-1. If there is uncertainty in how to determine the appropriate criteria, contact the FTA Regional office.

The selected criteria are used in the analysis procedures discussed in Sections 4.3, 4.4, and 4.5 to identify potential impacts and the level of impact.

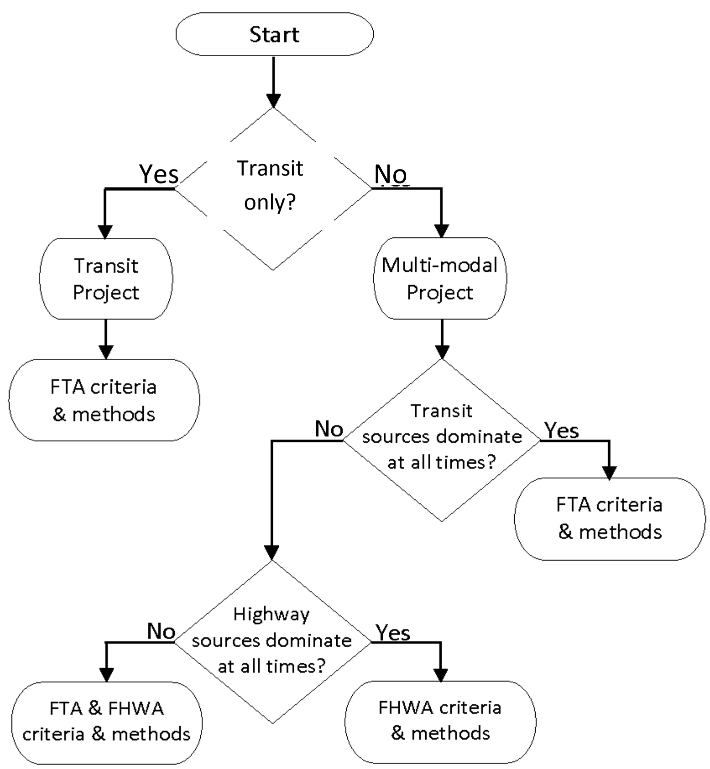

Figure 4-1 Noise Impact Criteria Flow Chart by Project Segment

Step 1: Identify Project Type

Identify the type of project as transit, multimodal (transit and highway), or other multimodal according to the dominant noise source.

Option A: Transit Project (Transit Noise Only) – The transit project category includes all transit projects where the project noise is exclusively due to new transit sources, no changes are made to the highway or to existing highway noise barriers, and the existing noise levels generated by roadway sources will not change because of the project. For these transit projects, FTA is the lead agency conducting the environmental review in cooperation with the transit agency.

Typical examples of transit projects include:

- RRT, LRT, commuter rail, and AGT
- Rail projects built within an existing highway or railroad corridor that do not alter the existing noise levels generated by roadway sources
- Bus facility projects with operations on local streets and highways used to access the facility, where the project does not include roadway construction or modification that changes roadway capacity substantially
- Fixed facilities including storage and maintenance yards, passenger stations and terminals, parking facilities, and substations
- Portions of transit projects not adjacent to highway corridors

FTA impact criteria are appropriate for transit projects, proceed to Step 2.

Option B: Multimodal Project (Transit and Highway Noise) – In this manual, "multimodal" refers to projects that include changes to both transit and highway components, resulting in project noise comprised of both highway and transit noise sources.

Typical examples of multimodal projects include:

- New highway construction providing general-purpose lanes as well as dedicated bus and high occupancy vehicle (HOV) lanes
- Rail transit projects that involve changes to the highway travel lanes or existing highway noise barriers

Evaluate multimodal projects for impact according to the project noise source by project segment. FHWA's noise assessment methods are used to inform FTA's NEPA evaluation only for segments where highway noise levels change due to the transit project. These projects are not necessarily subject to FHWA's procedures at 23 CFR part 772 (*see call out box below*). For segments of the project outside the highway corridor, use FTA's criteria and methods. Use Table 4-1 to determine multimodal project noise.

Once the project noise source(s) is identified**,** determine the appropriate assessment method according to Table 4-2.

Note that a separate noise analysis may be required for FHWA approval of a multimodal project pursuant to 23 CFR part 772. For these projects, it is important to work with FHWA early in the environmental review process to determine how a noise assessment will be completed where FHWA approval is needed for the project.

The determination of whether a project is subject to FHWA procedures at 23 CFR part 772 depends upon the specific circumstances of a project. A proposed transit project that would share an existing highway ROW is not necessarily a FHWA-defined multimodal project. A transit project that meets all three of the following criteria is not considered a multimodal project subject to 23 CFR part 772:

- FTA is the lead agency in the NEPA process and FHWA's limited participation is as a cooperating agency.
- The main transportation purpose of the project, as stated in the purpose and need statement of the environmental document, is transit-related and not highway-related.
- No Federal-aid highway funds are being used to fund the project.

Table 4-1 Multimodal Project Noise Factors

Factor	Description
Volume of Traffic	Major freeways and interstate highways often carry large volumes of traffic throughout the day and night such that the highway noise dominates at all times. Transit noise in this case may be unimportant by comparison, but must still be evaluated using FTA's noise criteria for a potential impact.
Traffic Patterns	Some highways and arterials serve primarily as commuter routes such that nighttime traffic diminishes considerably, while transit systems continue to operate well into the late hours. Here the dominant noise source at times of maximum sensitivity may be transit.
Type of Traffic	Some highways and arterials may serve commuters during the daytime hours, but provide access to business centers by trucks at night. In this case, the roadway noise would likely continue to dominate.
Alignment Configuration	Elevation of the transit mode in the median or beside a busy highway may result in transit noise contributing more noise to nearby neighborhoods than a highway that may be partially shielded by rows of buildings adjacent to the ROW. In this case, both transit and highway noise may be considered dominant.

Table 4-2 Multimodal Project Assessment Methods

Dominant Noise Source	Assessment Method
Transit, at All Times	Use FTA criteria and methods. *Proceed to Step 2.*
Highway, at All Times	Use FHWA criteria and methods to inform FTA's NEPA evaluation. *Contact FHWA directly for assistance using FHWA noise analysis methods and FHWA noise impact criteria.*
Transit and Highway at Different Times	Use both the FHWA and FTA methods to determine if one, both, or neither method determines impact due to the project noise for these segments. Note that the project noise includes both highway and transit sources associated with the project. Both methods are used because the FTA methods consider nighttime sensitivity while the FHWA methods consider the peak traffic hour. *Proceed to Step 2 for FTA criteria. Contact FHWA directly for assistance using FHWA noise analysis methods and FHWA noise impact criteria.*

Option C: Other Multimodal Projects – For projects with components from other modes, contact the FTA Regional office. Additional information on high-speed rail vibration and noise can be found in the Federal Railroad Administration (FRA) "High-Speed Ground Transportation Noise and Vibration Impact Assessment" guidance manual.[14]

Step 2: Choose Land Use Category for FTA Criteria

Determine the appropriate noise-sensitive land use category for the project segment using Table 4-3 and the descriptions below then, proceed to Step 3. FTA criteria are presented by land use.

Table 4-3 Land Use Categories and Metrics for Transit Noise Impact Criteria

Land Use Category	Land Use Type	Noise Metric, dBA	Description of Land Use Category
1	High Sensitivity	Outdoor $L_{eq(1hr)}$*	Land where quiet is an essential element of its intended purpose. Example land uses include preserved land for serenity and quiet, outdoor amphitheaters and concert pavilions, and national historic landmarks with considerable outdoor use. Recording studios and concert halls are also included in this category.
2	Residential	Outdoor L_{dn}	This category is applicable all residential land use and buildings where people normally sleep, such as hotels and hospitals.
3	Institutional	Outdoor $L_{eq(1hr)}$*	This category is applicable to institutional land uses with primarily daytime and evening use. Example land uses include schools, libraries, theaters, and churches where it is important to avoid interference with such activities as speech, meditation, and concentration on reading material. Places for meditation or study associated with cemeteries, monuments, museums, campgrounds, and recreational facilities are also included in this category.

* $L_{eq(1hr)}$ for the loudest hour of project-related activity during hours of noise sensitivity.

Noise-sensitive land use categories are described in in order of sensitivity. Most commercial or industrial uses are not considered noise-sensitive because activities within these buildings are generally compatible with higher noise levels. Business can be considered noise-sensitive if low noise levels are an important part of operations, such as sound and motion picture recording studios.

For residential land use (category 2), apply the noise criteria at the nearest façade of the occupied portion of the building, e.g., not at a garage or porch. The residential criteria should be applied at locations with nighttime sensitivity. For major noise-sensitive outdoor use at non-residential locations, apply the noise criteria at the point of noise-sensitive use nearest the noise source.

Land use categories are evaluated using noise metrics that reflect the noise-sensitive time of day:

- **Categories 1 and 3** – The noise metric, $L_{eq(1hr)}$ is used for all category 1 and 3 land uses where nighttime sensitivity is not a factor. Category 3 land uses are considered less noise-sensitive than category 1 land uses. For transit analyses, $L_{eq(1hr)}$ is computed for the noisiest hour of transit-related activity during which human activities occur at the noise-sensitive location. See Appendix B.1.4.4 for more information on this metric.

- **Category 2** – The noise metric L_{dn} is a used for all category 2 land uses where nighttime sensitivity is a factor. This noise metric includes a 10-dB penalty for nighttime noise. See Appendix B.1.4.5 for more information on this metric.

Land Use Categories: Special Cases

Historic sites, parks, indoor-only land use, and undeveloped land require special consideration. In addition to NEPA, noise impacts may need to be considered under other environmental laws such as Section 106(15) or Section 4(f).(16) Indoor-only use and undeveloped land should be evaluated on a case-by-case basis to determine noise sensitivity based on how each facility is used or the reason it is protected under the applicable requirement.

Historic Sites – Section 106 requires Federal agencies to evaluate potential effects from projects on historic properties. Per the regulations at 36 CFR part 800,(17) historic properties are defined as any prehistoric or historic district, site, building, structure, or object included in, or eligible for the National Register of Historic Places (NRHP). An adverse effect determination under Section 106 is made when a project may alter, directly or indirectly, any of the characteristics of a historic property that qualify the property for inclusion in the National Register in a manner that would diminish the integrity of the property's location, design, setting, materials, workmanship, feeling, or association.

Under FTA environmental reviews, some structures may be evaluated as noise-sensitive resources per this noise manual and evaluated as historic properties under Section 106. However, because this manual and Section 106 regulations have different criteria for effect, identifying a severe noise impact for a structure under this manual does not necessarily mean there would be an adverse effect under Section 106. It is important to thoroughly document the characteristics of historic properties that qualify for inclusion in the NRHP for evaluation of effect under Section 106.

If a property, for example, is listed on the NRHP under criterion C because the structure possesses high artistic values, but lacks integrity of setting, feeling, or association, it is unlikely that a change in the noise environment would affect the features that qualify the property for listing or eligibility for inclusion in the NRHP.

In the assessment of effects on historic properties, consideration should be given to not just the proposed transit project, but any associated mitigation measures with the transit project. For example, if a transit project would involve noise walls or berms as mitigation, the effect of those structures on the visual setting may need to be considered in a Section 106 analysis.

Parks – Most parks used primarily for active recreation such as sports complexes and bike or running paths are not considered noise-sensitive.

However, some parks (even some in dense urban areas) are primarily used for passive recreation such as reading, conversation, or meditation. These places, which may be valued as havens from the noise and rapid pace of everyday city life, are treated as noise-sensitive, and are included in land use category 3. Consult the state or local agency with jurisdiction over the park on questions about how the park is used, and visit the park to observe its use, if possible.

Indoor-Only Use – The land use categories described in this section correspond with noise impact criteria that provide protection for both outdoor and indoor land uses. For locations where noise impact will be evaluated but there is no outdoor land use such as apartment buildings, hotels or upper levels of multi-story buildings, indoor criteria can be used. In these cases, the criterion for indoor noise levels from project sources is a L_{dn} of 45 dBA.(18) This criterion is consistent with the Federal Aviation Administration (FAA). See Section 4.5 for more information on how indoor criteria apply to noise mitigation consideration.

Undeveloped Land – Undeveloped land may also need to be considered for noise impact assessment and mitigation if plans are under way to develop the land for noise-sensitive use. The policy for considering such land for assessment and mitigation should be determined on a project-specific basis by the project sponsor in consultation with the FTA Regional office.

Step 3: Determine Appropriate FTA Criteria Presentation

FTA criteria for noise impact were developed specifically for transit noise sources operating on fixed-guideways or at fixed facilities in urban areas. These criteria are based on well-documented research on human response to community noise and represent a reasonable balance between community benefit and project costs. These criteria do not reflect specific community attitudinal factors. See Appendix C for additional background information on the development of FTA noise criteria.

The criteria specify a comparison of future project noise with existing noise. Note that projections of future noise exposure without the project (no-build scenario) are not included in this analysis. The criteria also consider land use which is an important factor that reflects noise sensitivity based on activity and time period of concern. The criteria are defined with the expectation that communities already exposed to high levels of noise can only tolerate a small increase. In contrast, if the existing noise levels are low, it is reasonable to allow a greater change in the community noise.

The levels of impact are described in Table 4-4. The criteria at which the levels of impact occur are presented in two ways depending on the relationship of project and existing noise sources.

If the project noise source is a new source of transit noise in the community, such as a new project in an area currently without transit, use the criteria as presented in Option A. If the project noise adds to or changes existing transit noise in the community, use the criteria as presented in Option B.

Table 4-4 Levels of Impact

Level of Impact	Description
No Impact	Project-generated noise is not likely to cause community annoyance. Noise projections in this range are considered acceptable by FTA and mitigation is not required.
Moderate Impact	Project-generated noise in this range is considered to cause impact at the threshold of measurable annoyance. Moderate impacts serve as an alert to project planners for potential adverse impacts and complaints from the community. Mitigation should be considered at this level of impact based on project specifics and details concerning the affected properties.
Severe Impact	Project-generated noise in this range is likely to cause a high level of community annoyance. The project sponsor should first evaluate alternative locations/alignments to determine whether it is feasible to avoid severe impacts altogether. In densely populated urban areas, evaluation of alternative locations may reveal a trade-off of affected groups, particularly for surface rail alignments. Projects that are characterized as point sources rather than line sources often present greater opportunity for selecting alternative sites. This guidance manual and FTA's environmental impact regulations both encourage project sites which are compatible with surrounding development when possible. If it is not practical to avoid severe impacts by changing the location of the project, mitigation measures must be considered.

Option A: Project Noise Impact Criteria Presentation – The impact criteria presentation for evaluating existing noise independently to project noise is presented in this option.

The noise levels at which impacts occur are presented in Figure 4-2 and Table 4-5. Equations for the impact criteria are presented in Appendix C. If impact is determined, measures necessary to mitigate impacts are to be considered for incorporation into the project.[3]

Figure 4-2 presents the existing noise exposure on the horizontal axis and project noise on the vertical axis. Category 1 and 2 land uses have the same criteria for project noise and are on the primary vertical axis. Category 3 land use criteria are presented on the secondary vertical axis. Note that project noise for category 1 and 3 land uses is expressed as $L_{eq(1hr)}$, whereas project noise for category 2 land use is expressed as L_{dn}. Also, note that project noise criteria are 5 dB higher for category 3 land uses in Figure 4-2 since these types of land use are less noise-sensitive than those in categories 1 and 2.

Note that for projects in locations with existing noise levels below 55 dBA, the project noise exposure is allowed some increase over the existing noise exposure before it is considered to cause impact. For category 1 and 2 land uses, the maximum project noise level to be considered to cause no impact is 65 dBA ($L_{eq(1hr)}$ or L_{dn}) regardless of the existing noise. Note that no impact at 65 dBA aligns with other Federal agencies in that a L_{dn} of 65 dBA is a standard limit for an acceptable living environment among some Federal agencies.[19] [20] Project noise levels above the top curve are considered to cause severe impact. The upper limit of the severe impact range is 75 dBA for category 1 and 2 land uses. The upper limit of 75 dBA is associated with an unacceptable living environment. Project noise between the two curves is considered to have moderate impact on the community.

The criteria are also tabulated in Table 4-5. Figure 4-2 and the equations that correspond with this figure in Appendix C are the precise definition of the criteria. The values in Table 4-5 can be used for illustrative purposes and should only be used if all numbers are rounded up to the nearest decibel.

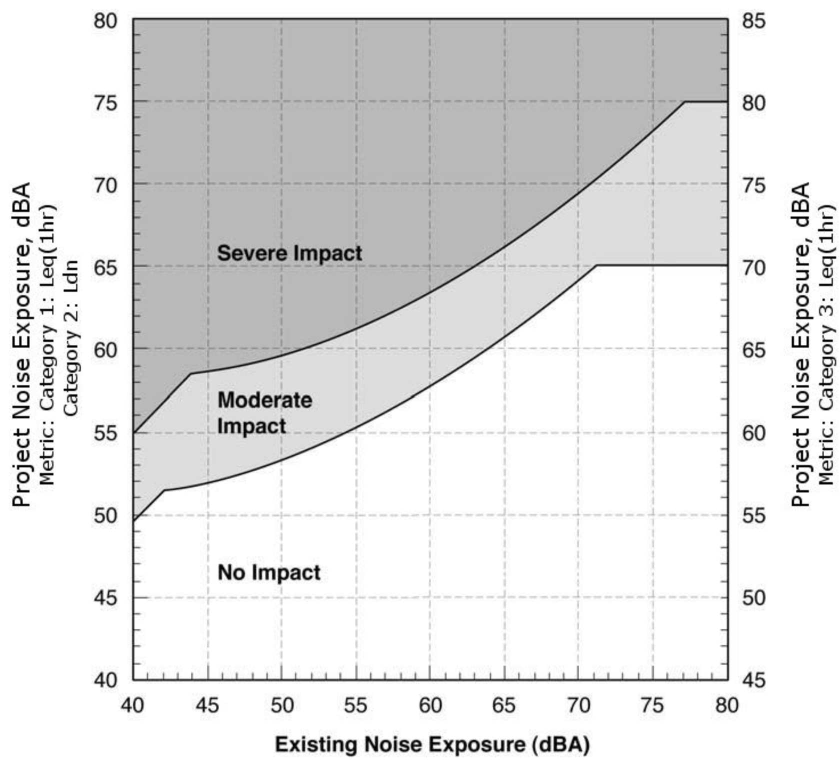

Figure 4-2 Noise Impact Criteria for Transit Projects

Table 4-5 Noise Levels Defining Impact for Transit Projects

Existing Noise Exposure, dBA	Project Noise Impact Exposure, dBA					
	Category 1 ($L_{eq(1hr)}$) or 2 (L_{dn}) Sites			Category 3 Sites ($L_{eq(1hr)}$)		
$L_{eq(1hr)}$ or L_{dn}	No Impact	Moderate Impact	Severe Impact	No Impact	Moderate 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

Option B: Cumulative Noise Impact Criteria Presentation

The impact criteria presentation for evaluating existing noise to project noise cumulatively is presented in this option.

In certain cases, the cumulative form of the noise criteria shown in Figure 4-3 can be used. These cases involve projects where changes are proposed to an existing transit system, as opposed to a new project in an area previously without transit. Such changes might include operations of a new type of vehicle, modifications of track alignments within existing transit corridors, or changes in facilities that dominate existing noise levels. In these cases, the existing noise sources change because of the project, and so it is not possible to define project noise separately from existing noise. An example would be a commuter rail corridor where the existing noise along the alignment is dominated by diesel locomotive-hauled trains, and where the project involves electrification with the resulting replacement of some of the diesel-powered locomotives with electric trains operating at increased frequency of service and higher speeds on the same tracks. In this case, the existing noise can be determined and a new future noise can be calculated, but it is not possible to describe what constitutes the "project noise." For example, if the existing noise dominated by trains was measured to be an L_{dn} of 63 dBA at a particular location, and the new combination of diesel and electric trains is projected to be an L_{dn} of 65 dBA, the change in the noise exposure due to the project would be 2 dB. Referring to Figure 4-3, a 2-dB increase with an existing noise exposure of 63 dBA would be rated as a moderate impact. Normally the project noise is added to the existing noise to come up with a new cumulative noise, but in this case, the existing noise was dominated by a source that changed due to the project, so it would be incorrect to add the project noise to the existing noise. Consequently, the existing noise determined by measurement is compared with a new calculated future noise, but a description of what constitutes the actual project is complex.

Another example would be a rail corridor where a track is added and grade crossings are closed, potentially resulting in a change in train location and horn operation. Here the "project noise" results from moving some trains closer to some receivers, away from others, and elimination of horns. In this case, the change in noise level is more readily determined than the noise from the actual project elements. In all cases, Figures 4-3 and 4-4 for changes in a transit system results in the same assessment of impact as Figure 4-2 for development of transit facilities in a new area.

The noise impact criteria in Figure 4-3 and Figure 4-4 are presented as an increase in cumulative noise level between the existing and project conditions. The horizontal axis represents the existing noise exposure and the vertical axis is the increase in cumulative noise level due to the transit project. Note that noise exposure is expressed as $L_{eq(1hr)}$ for category 1 and 3 land uses and L_{dn} for category 2 land use. Since $L_{eq(1hr)}$ and L_{dn} are measures of total acoustic energy, any new noise sources in a community will cause an increase, even if the new source level is the same or less than the existing noise level (refer to decibel addition in Appendix B). As shown in Figure 4-3, the criterion for moderate impact is a noise exposure increase of 10 dB for an existing noise exposure level of 42 dBA or less, but only a 1-dB increase when the existing noise exposure is 70 dBA.

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 exposure which is less than the existing noise exposure can still cause impact. This is clearer from the examples listed in Table 4-6 which indicate the level of transit noise allowed for different existing levels of exposure. Any increase greater than shown in the table will cause moderate impact.

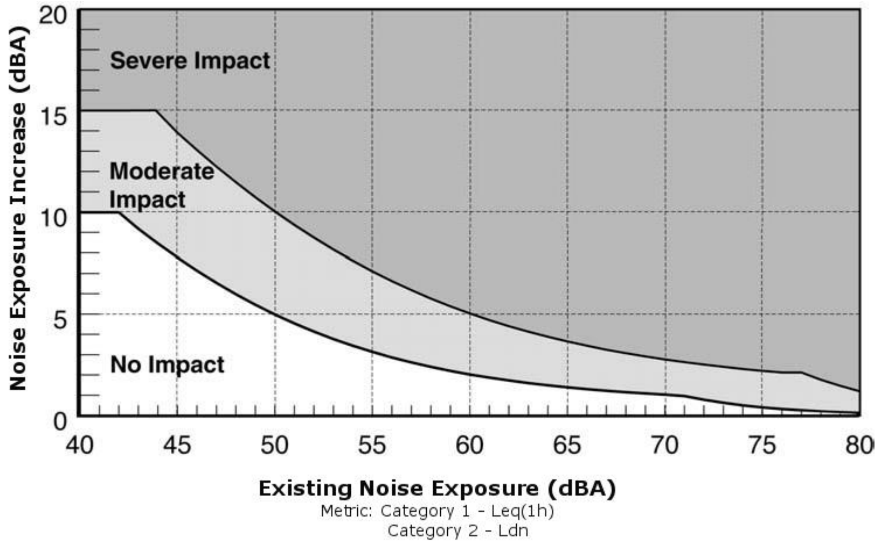

Figure 4-3 Increase in Cumulative Noise Levels Allowed by Criteria (Land Use Cat. 1 & 2)

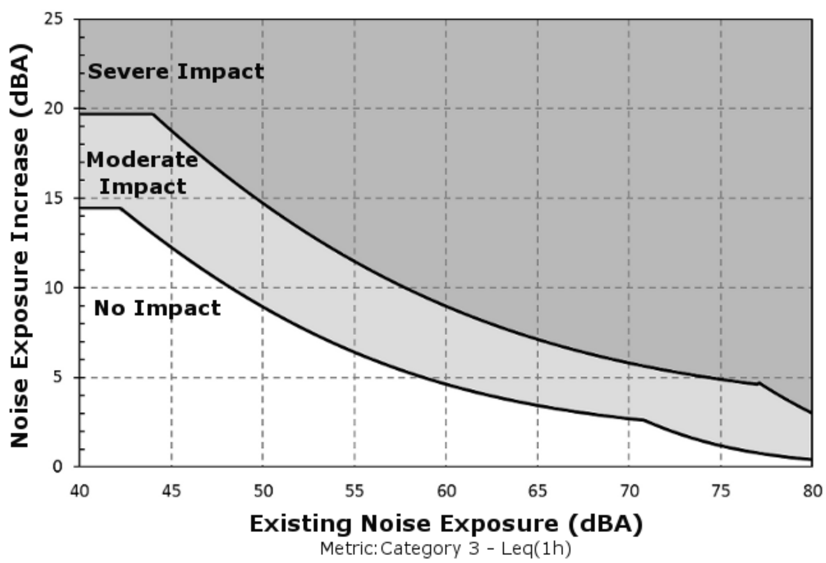

Figure 4-4 Increase in Cumulative Noise Levels Allowed by Criteria (Land Use Cat. 3)

This table shows that as the existing noise exposure increases from 45 dBA to 75 dBA, the allowed project noise exposure increases from 51 dBA to 65 dBA. However, the allowed increase in the cumulative noise level decreases from 7 dB to 0 dB (rounded to the nearest whole decibel). The justification for this is that people already exposed to high levels of noise should be expected to tolerate only a small increase in the amount of noise in their community. In contrast, if the existing noise levels are quite low, it is reasonable to allow a greater change in the community noise for the equivalent difference in annoyance.

Note that Table 4-6 was developed for illustrative purposes and the official criteria are included in Figure 4-3 and Figure 4-4 and the associated equations.

Table 4-6 Noise Impact Criteria: Effect on Cumulative Noise Exposure

L_{dn} or $L_{eq(1hr)}$ in dBA (rounded to nearest whole decibel)			
Existing Noise Exposure	**Allowable Project Noise Exposure Before Moderate Impact**	**Allowable Combined Total Noise Exposure**	**Allowable Noise Exposure Increase Before Moderate Impact**
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

4.2 Determine Noise Analysis Level

There are three levels of analysis to evaluate noise on a transit project based on the type and scale of the project, stage of project development, and environmental setting. These levels, described below, are the Noise Screening Procedure, the General Noise Assessment and the Detailed Noise Analysis.

The Noise Screening Procedure, conducted first, defines the study area of any subsequent noise impact assessment. Where there is potential for noise impact, the General Noise Assessment and Detailed Noise Analysis procedures are used to determine the extent and severity of impact. In some cases, a General Noise Assessment may be all that is needed. However, if the proposed project is near 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.

Conduct the noise screening procedure and then determine the appropriate noise analysis option.

Noise Screening Procedure – The Noise Screening Procedure is a simplified method of identifying study area receivers or locations where a project may have the potential for noise impacts from transit projects. This procedure accounts for impact criteria, the type of project, and noise-sensitive land uses. If no noise-sensitive land uses or receivers are present in the analysis area, then no further noise assessment is needed. If noise-sensitive receivers are identified, then proceed to conduct a General Assessment and/or a Detailed Assessment.

The Noise Screening Procedure steps are provided in Section 4.3.

General Noise Assessment – The General Noise Assessment is used to examine potentially impacted areas identified in the screening step by examining the location and estimated severity of noise impacts. This procedure considers noise source and land use information likely to be available at an early stage in the project development process. Estimates are made of project noise levels and of existing noise conditions to model the location of a noise impact contour that defines the outer limit of an impact corridor or area. This modeling method uses transit-specific noise and adjustment data (in tabular and graphical form) for the noise computations.

For many smaller projects, this assessment may be sufficient to define impacts and determine whether noise mitigation is necessary. The procedure can be used in conjunction with established highway noise prediction procedures to compare highway, transit, and multimodal alternatives. If an assessment is needed to inform the decision on transit mode and general alignment in a corridor, the General Noise Assessment procedures should be used, and not the Detailed Noise Analysis, which requires more detailed information.

The General Noise Assessment procedure is provided in Section 4.4. FTA has also developed an Excel spreadsheet to more simply conduct the General Noise Assessment. It is on FTA's website at http://www.fta.dot.gov/12347_2233.html.

Detailed Noise Analysis – The Detailed Noise Analysis procedure is a comprehensive assessment method that produces the most accurate estimates of noise impacts for a proposed project. It is important to recognize that use of the Detailed Noise Analysis methods will not provide more accurate results than the General Noise Assessment unless more detailed and case-specific input data are used.

The project must be defined to the extent that location, alignment, transit mode, 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) are determined. A detailed Noise Analysis is often accomplished at the development of the final environmental impact statement (FEIS), record of decision (ROD), or combined FEIS/ROD in the NEPA process, when the preferred alternative is undergoing refinements to mitigate its adverse impacts. However, these project details may not be available until the final design phase, requiring that the detail noise analysis be conducted after the NEPA process is complete. However, it is recommended that the detailed analysis be conducted earlier for controversial projects or projects with highly noise-sensitive sites close to tracks.

A Detailed Noise Analysis may be warranted as part of the development of an environmental assessment (EA) if there are potentially severe impacts due to the proximity of noise-sensitive land uses.

In some cases, decisions on appropriate noise mitigation measures can be made based on the results of the General Noise Assessment. But if costly measures may be needed, it is generally recommended that a Detailed Noise Analysis be conducted to verify the need and design of the noise mitigation. The Detailed Noise Analysis is always appropriate under two sets of circumstances:

- For a major transit project with likely noise impacts after the preferred alternative has been selected.
- For any other transit project where potentially severe impacts are identified at an early stage.

Noise impacts may occur for relatively minor transit projects when the project is near noise-sensitive sites, particularly residences. In this case, completing a Detailed Noise Analysis is recommended. Some examples include:

- A terminal or station sited adjacent to a residential neighborhood
- A maintenance facility located near a school
- A storage yard adjacent to residences
- An electric substation located adjacent to a hospital

The Detailed Noise Analysis procedure is provided in Section 4.5.

4.3 Evaluate Impact: Noise Screening Procedure

Identify the potential for impact using the Noise Screening Procedure described below.

Step 1: Identify Project Type

Identify the project type using Table 4-7 and confirm the assumptions in Table 4-8 are appropriate for the project.

The noise screening procedure is intended to be conservative to broadly capture the potential for impact with minimal effort. To make the procedure conservative, the project system must be assumed to be operating under relatively high-capacity conditions, which would produce more noise than normal operating conditions. In addition, the assumptions in Table 4-8 were made using the lowest threshold of impact (50 dBA) from the criteria curves in Figure 4-2. Clarification can be obtained from FTA on special cases that are not represented in this section.

If the assumptions in Table 4-8 are not appropriate for the project, make adjustments to the screening distances in Table 4-8 according to the methodology in Section 4.4 or the FTA spreadsheet model.

Step 2: Determine the Screening Distance

Determine the appropriate screening distance considering the type of project and shielding from intervening buildings.

2a. Determine the appropriate screening distance column in Table 4-7.

> **Option A: Buildings in the Sound Paths –** Use the screening distances in the "Intervening Buildings" column.
>
> **Option B: Buildings Not in the Sound Paths –** Use the distances in the "Unobstructed" column.

2b. Adjust these distances according to the methodology in Section 4.4, or the FTA spreadsheet model, if the assumptions in Table 4-8 are not appropriate for the project. The appropriate screening distance is where the project noise reaches 50 dBA for the appropriate metric. If the assumptions in Table 4-8 are not appropriate for a commuter rail grade crossing project where horns and warning bells are used, use the FRA horn noise model available from the FRA website to develop the screening distance distance (49 CFR § 222).[21]

Step 3: Identify Study Area

Apply the screening distances as follows to identify the study area. The study area is intended to be sufficiently large to encompass all potentially impacted locations.

Option A: Fixed Guideway Transit Sources – Apply the screening distance from the guideway centerline.

Option B: Highway/Transit Sources (e.g., Bus) – Apply the screening distance from the nearest ROW line on both sides of a highway or access road.

Option C: Small Stationary Facilities – Apply the screening distance from the center of the noise-generating activity.

Option D: Stationary Facility Spread Over a Large Area – Apply the screening distance from the outer boundary of the proposed project site.

Step 4: Locate Noise-Sensitive Land Uses

Locate all noise-sensitive land uses within the study area using Table 4-3.

See Section 4.1 for more information on noise-sensitive land uses. Include all categories of noise-sensitive land uses in this step.

If no noise-sensitive land uses are identified, no further noise analysis is needed. If one or more of the noise-sensitive land uses are in the study area, proceed to Section 4.4 and complete a General Noise Assessment.

Table 4-7 Screening Distance for Noise Assessments

Project Systems		Screening Distance, ft*	
		Unobstructed	Intervening Buildings
Fixed-Guideway Systems			
Commuter Rail Mainline		750	375
Commuter Rail Station	With Horn Blowing	1,600	1,200
	Without Horn Blowing	250	200
Commuter Rail Road Crossing with Horns and Bells		1,600	1,200
RRT		700	350
RRT Station		200	100
LRT		350	175
Streetcar		200	100
Access Roads to Stations		100	50
Low and Intermediate Capacity Transit	Steel Wheel	125	50
	Rubber Tire	90	40
	Monorail	175	70
Yards and Shops		1000	650
Parking Facilities		125	75
Access Roads to Parking		100	50
Ancillary Facilities: Ventilation Shafts		200	100
Ancillary Facilities: Power Substations		250	125
Bus Systems			
Busway		500	250
Bus Rapid Transit (BRT) on exclusive roadway		200	100
Bus Facilities	Access Roads	100	50
	Transit Mall	225	150
	Transit Center	225	150
	Storage & Maintenance	350	225
	Park & Ride Lots w/Buses	225	150
Ferry Boat Terminals		300	150

*Measured from centerline of guideway for fixed-guideway sources, from the ROW on both sides of the roadway for highway/transit sources, from the center of noise-generating activity for stationary sources, or from the outer boundary of the proposed project site for fixed facilities spread out over a large area.

Table 4-8 Assumptions for Screening Distances for Noise Assessments

Type of Project		Operations	Speeds*	Metric**
Fixed-Guideway Systems				
Commuter Rail Mainline		66 day /12 night; 1 loco, 6 cars	55 mph	L_{dn}
Commuter Rail Station	With Horn Blowing	22 day / 4 night	N/A	L_{dn}
	Without Horn Blowing	22 day / 4 night	N/A	L_{dn}
Commuter Rail-Highway Crossing with Horns and Bells		22 day / 4 night	55 mph	L_{dn}
RRT		220 day / 24 night; 6-car trains	50 mph	L_{dn}
RRT Station		220 day / 24 night	20 mph	L_{dn}
LRT		150 day / 18 night; 2 artic veh.	35 mph	L_{dn}
Streetcar		150 day / 18 night	25 mph	L_{dn}
Access Roads to Stations		1000 cars, 12 buses	35 mph	$L_{eq(1hr)}$
Low and Intermediate Capacity Transit	Steel Wheel	220 day / 24 night	30 mph	L_{dn}
	Rubber Tire	220 day / 24 night	30 mph	L_{dn}
	Monorail	220 day / 24 night	30 mph	L_{dn}
Yards and Shops		20 train movements	N/A	$L_{eq(1hr)}$
Parking Facilities		1000 cars	N/A	$L_{eq(1hr)}$
Access Roads to Parking		1000 cars	35 mph	$L_{eq(1hr)}$
Ancillary Facilities: Ventilation Shafts		Rapid Transit in Subway	50 mph	L_{dn}
Ancillary Facilities: Power Substations		Sealed shed, air conditioned	N / A	L_{dn}
Bus Systems				
Busway		30 buses, 120 automobiles	50 mph	$L_{eq(1hr)}$
BRT on exclusive roadway		30 buses	35 mph	$L_{eq(1hr)}$
Bus Facilities	Access Roads	1000 cars	35 mph	$L_{eq(1hr)}$
	Transit Mall	20 buses	N/A	$L_{eq(1hr)}$
	Transit Center	20 buses	N/A	$L_{eq(1hr)}$
	Storage & Maintenance	30 buses	N/A	$L_{eq(1hr)}$
	Park & Ride Lots w/Buses	1000 cars, 12 buses	N/A	$L_{eq(1hr)}$
Ferry Boat Terminals		8 boats with horns used in normal docking cycle	N/A	$L_{eq(1hr)}$

*N/A = not applicable
**$L_{eq(1hr)}$ = the loudest hour of project related activity during hours of noise sensitivity.

4.4 Evaluate Impact: General Noise Assessment

The General Noise Assessment should be completed after the Noise Screening Procedure (Section 4.3), through which noise-sensitive receivers have been identified. This can be completed either by using the General Noise Assessment Procedure described below or using the FTA General Noise Assessment Spreadsheet found on the following FTA website: http://www.fta.dot.gov/12347_2233.html.

Assumptions are used throughout the General Noise Assessment. If the listed assumptions are not appropriate for the project and good engineering judgement cannot be used by following the General Noise Assessment procedure, proceed to a Detailed Noise Analysis or consult with the FTA Regional office.

Major steps in the General Noise Assessment procedure and recommended workflow are shown in Figure 4-5 and listed below. Four examples of General Noise Assessments are given at the end of this section. Many of these concepts are explained in greater detail in the context of a Detailed Noise Analysis in Section 4.5.

Step 1: Identify Noise-Sensitive Receivers – Identify noise-sensitive receivers (Section 4.3) and their proximity to the project and major noise sources.

Step 2: Determine Project Noise Source Reference Levels – Determine the project noise sources and reference levels. Then, estimate the project noise exposure at the reference distance of 50 ft considering operational characteristics with preliminary estimations of the effect of mitigation.

Step 3: Estimate Project Noise Exposure by Distance – Estimate project noise exposure at distances beyond 50 ft considering propagation characteristics using a simplified procedure.

Step 4: Combine Noise Exposure from All Sources – Combine all sources associated with the project to predict the total project noise at the receivers.

Step 5: Measure Existing Noise Exposure – Measure the existing noise or estimate the existing noise exposure using a simplified procedure.

Step 6: Inventory Impacts

> **Option A:** Tabulate the change in noise (existing vs. estimated project noise) at each noise-sensitive receiver or cluster, identifying all moderate and severe impacts.
>
> **Option B:** Take inventory of noise-sensitive receivers that fall within the moderate and severe noise contours.

Step 7: Determine Noise Mitigation Needs – Evaluate the need for mitigation and repeat the General Noise Assessment with proposed mitigation.

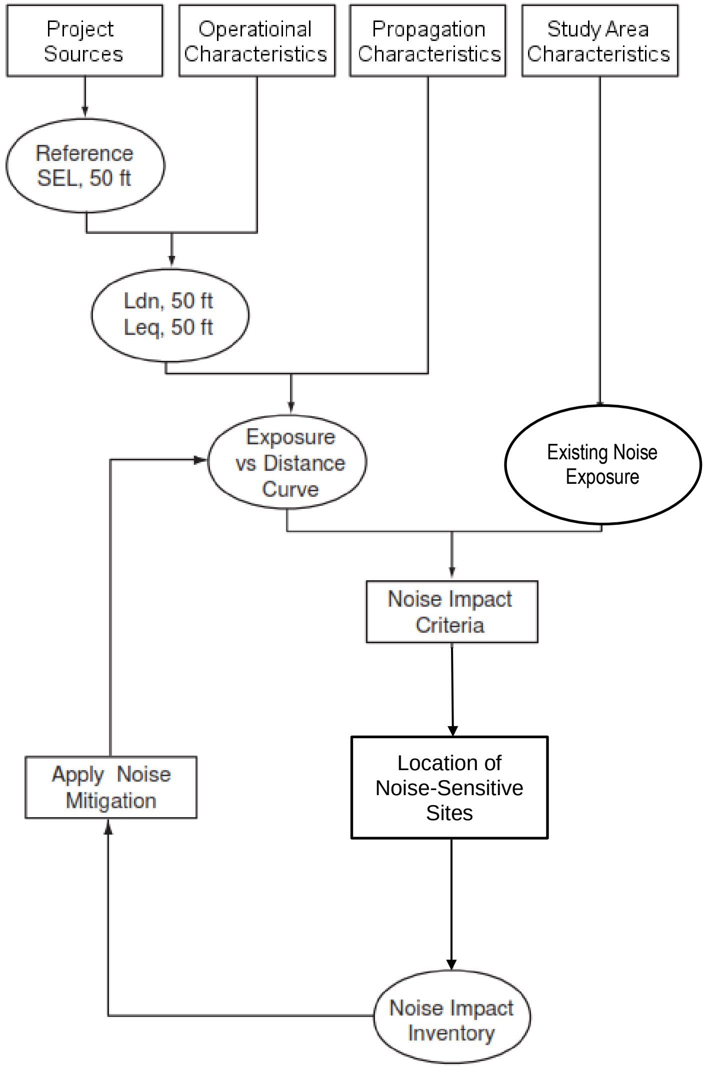

Figure 4-5 Procedure for General Noise Assessment

Step 1: Identify Noise-Sensitive Receivers

Determine the proximity of noise-sensitive land uses identified in Section 4.3 to the project and to the nearest major roadways and railroad lines.

1a. When necessary, use windshield surveys or detailed land use maps to confirm the location of noise-sensitive land uses.

1b. For land uses more than 1,000 ft from major roadways or railroad mainlines, obtain an estimate of the population density in the immediate area, expressed in people per square mile. Distances to roadways or railroads, or population density, will be used later to estimate the existing noise level. Coordinate with the Metropolitan Planning Organization (MPO) for population densities at an appropriate level of detail.

Step 2: Determine Project Noise Source Reference Levels

Determine the general source reference level for each project noise source.

Classify all project noise sources as fixed-guideway transit, highway/transit, or stationary facility and determine the source reference levels. 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.

Option A: Fixed-guideway Transit Sources – For this manual, fixed-guideway transit sources include commuter rail, RRT, LRT, streetcar, AGT, monorail, and magnetically levitated vehicles (maglev). For commuter railroads and LRT systems, the crossing of streets and highways at-grade is likely, and in that case, warning devices should be included in the assessment. At an early project stage, the information available for a General Noise Assessment 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 ROW. Therefore, use conservative estimates (e.g., maximum (expected) design speeds and operations at design capacities) to estimate worst-case noise levels.

First choose the appropriate fixed-guideway transit source reference level and then predict the noise exposure at 50 ft in terms of $L_{eq(1hr)}$ and L_{dn}.

A.i. Choose the reference source noise levels 50 ft from the track for one vehicle in terms of Sound Exposure Level (SEL) using Table 4-9. See Appendix B for a detailed explanation of SEL. Note that the SEL reference speed is 50 mph, unless otherwise noted.

Table 4-9 Reference SEL's 50 ft from Track and at 50 mph, One Vehicle

Source	Type	Reference Conditions	Reference SEL (SEL_{ref}), dBA
Commuter Rail, At-Grade	*Locomotives*	Diesel-electric, 3000 hp, throttle 5	92
		Electric	90
	Diesel Multiple Unit (DMU)	Diesel-powered, 1200 hp	85
	Horns	Within ¼ mile of grade crossing	110
	Cars	Ballast, welded rail	82
Rail Transit and Streetcars at 50 mph		At-grade, ballast, welded rail	82
Rail Transit and Streetcars at 25 mph		At-grade, ballast, welded rail	76
Transit whistles / warning devices		Within 1/8 mile of grade crossing	93
AGT	*Steel Wheel*	Aerial, concrete, welded rail	80
	Rubber Tire	Aerial, concrete guideway	78
Monorail		Aerial straddle beam	82
Maglev		Aerial, open guideway	72

A.ii. Collect the following data:

- Number of train passbys during the day (7 a.m. to 10 p.m.) and night (10 p.m. to 7 a.m.) for category 2 land uses
- Maximum number of train passbys during hours that category 1 or category 3 land uses are normally in use (typically the peak hour train volume)
- Number of vehicles per train for each time period for category 2 land uses (if this number varies during the day or night, take the average)
- Maximum number of vehicles per train during hours that category 1 or category 3 land uses are normally in use (typically the peak hour train volume)
- Train speed in mph (maximum expected)
- Guideway configuration
- Location of highway and street grade crossings, if any
- If this process is repeated to estimate the effect of proposed noise mitigation, include the noise barrier location

A.iii. Calculate the noise exposure at 50 ft in terms of $L_{eq(1hr)}$:

- Calculate $L_{eq(1hr)}$ for each source using the appropriate equations in Table 4-10.
- Compute $L_{eq(1hr).Combo}$ using Eq. 4-6. It may be necessary to compute the combined totals with and without warning horns. Some neighborhoods along the corridor may be exposed to horn noise, but some may not.

A.iv. Calculate the noise exposure at 50 ft in terms of L_{dn}:

- If the project noise will affect any residential receivers, calculate the L_{dn} using the combined $L_{eq(1hr)}$ for both the daytime and nighttime periods separately, using the appropriate equations in Table 4-10.
- It may be necessary to calculate L_{dn} with and without warning horns, as in the previous step.

Note that the equations in Table 4-10 include terms to account for a difference in speed from the 50 mph reference speed and a numerical adjustment to account for the one-hour time period for this metric. For more information on the numerical adjustment to represent the time period of interest, see Appendix B.1.4.4.

Table 4-10 presents an estimate of the noise reduction potentially provided by wayside noise barriers that can be used when assessing mitigation options in a General Noise Assessment. If impact is determined during the General Noise Assessment, repeat the procedure and include proposed mitigation according to Section 4.4, Step 7. See Section 4.5, Step 7 for a complete description of the benefits resulting from various noise mitigation measures that can be evaluated with a Detailed Noise Analysis.

Table 4-10 Computation of Noise Exposure at 50 ft for Fixed-Guideway General Noise Assessment

Locomotives* $L_{eq(1hr)}$ at 50 ft	$L_{eq.Loco(1hr)} = SEL_{ref} + 10\,log(N_{Loco}) + Klog(\frac{S}{50}) + 10\,log(V) - 35.6$	**Eq. 4-1**
Locomotive Warning Horns** $L_{eq(1hr)}$ at 50 ft	$L_{eq.LHorns(1hr)} = SEL_{ref} + 10\,log(V) - 35.6$	**Eq. 4-2**
Rail Vehicles† $L_{eq(1hr)}$ at 50 ft	$L_{eq.RCars(1hr)} = SEL_{ref} + 10\,log(N_{Cars}) + 20\log(\frac{S}{50}) + 10\,log(V) - 35.6 + Adj_{track}$	**Eq. 4-3**
Streetcars (25 mph or slower) $L_{eq(1hr)}$ at 50 ft	$L_{eq.SCars(1hr)} = SEL_{ref} + 10\,log(N_{Cars}) + 2\log(\frac{S}{25}) + 10\,log(V) - 35.6 + Adj_{track}$	**Eq. 4-4**
Transit Warning Horns $L_{eq(1hr)}$ at 50 ft	$L_{eq.THorns(1hr)} = SEL_{ref} - 10\,log(\frac{S}{50}) + 10\,log(V) - 35.6$	**Eq. 4-5**
Combined Locomotive and transit†† $L_{eq(1hr)}$ at 50 ft	$L_{eq.Combo(1hr)} = 10\log(10^{(L_{eq.Loco(1hr)}/10)} + 10^{(L_{eq.RCars(1hr)}/10)} + 10^{(L_{eq.SCars(1hr)}/10)} + 10^{(L_{eq.LHorns(1hr)}/10)} + 10^{(L_{eq.THorns(1hr)}/10)}$	**Eq. 4-6**
Daytime L_d at 50 ft	$L_d = L_{eq(1hr)}$ where V = V_d, N_{Loco} = N_d (loco events), and N_{Cars} = N_d (car events)	**Eq. 4-7**
Nighttime L_n at 50 ft	$L_n = L_{eq(1hr)}$ where V = V_n, N_{Loco} = N_d (loco events), and N_{Cars} = N_d (car events)	**Eq. 4-8**
Day/Night L_{dn} at 50 ft	$L_{dn} = 10log(15 \times 10^{(L_d/10)} + 9 \times 10^{((L_n+10)/10)}) - 13.8$	**Eq. 4-9**

N_{Loco} = average number of locomotives per train

K = constant
- -10 for passenger diesel
- 0 for DMUs
- +10 for electric

S = train speed, mph

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

N_{Cars} = average number of cars per train

Adj_{track} = constant
- +5 for jointed track or for a crossover within 300 ft
- +4 for aerial structure with slab track (except AGT and monorail)
- +3 for embedded track on grade
- -5 if a noise barrier blocks the line of sight

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

$$= \frac{number\ of\ trains, 7\ a.m.\ to\ 10\ p.m.}{15}$$

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

$$= \frac{number\ of\ trains, 10\ p.m.\ to\ 7 a.m.}{9}$$

N_d = average hourly number of events that occur during daytime (7 a.m. to 10 p.m.)

$$= \frac{number\ of\ events\ between\ 7\ a.m.\ to\ 10\ p.m.}{15}$$

N_n = average hourly number of events that occur during nighttime (10 p.m. to 7 a.m.)

$$= \frac{number\ of\ events\ between\ 10\ p.m.\ to\ 7\ a.m.}{9}$$

* Assumes a diesel locomotive power rating at approximately 3000 hp.
** Based on FRA's horn noise model (http://www.fra.dot.gov/eLib/Details/L04091).
† Includes all commuter rail cars, transit cars, streetcars above 25 mph, AGT and monorail.
† † Only include appropriate terms.

Option B: 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 buses, commuter vanpools and carpools. Use the instructions below to estimate source noise levels for projects that involve these types of vehicles and are using FTA's environmental review procedures. At an early project stage, the information available for a General Noise Assessment includes:

- 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 ROW; therefore, use of conservative estimates (e.g., maximum (expected) design speeds and operations at design capacities) to estimate worst-case noise impact levels is recommended. The procedure is consistent with FHWA's highway noise prediction method. The reference SEL levels in Table 4-11 correspond to FHWA's source emission levels and speed coefficients for buses and automobiles.[22]

B.i. Using Table 4-11, choose the appropriate reference source noise levels 50 ft from the roadway in terms of SEL. Note that the SEL reference speed is 50 mph, unless otherwise noted.

Table 4-11 Source Reference Levels at 50 ft from Roadway, 50 mph

Source*	Reference SEL, dBA
Automobiles and Vans	74
Buses (diesel-powered)	82
Buses (electric)	80
Buses (hybrid)	83**

* Assumes normal roadway surface conditions.
** For hybrid buses, determine Reference SEL on a case-by-case basis because they vary, and data are scarce.

B.ii. Collect the following data:

- Number of vehicle passbys during the day (7 a.m. to 10 p.m.) and night (10 p.m. to 7 a.m.) for each vehicle type in Table 4-11, if a category 2 land use is present
- Number of vehicle passbys during hours that category 1 or category 3 land uses are normally in use, each vehicle type in Table 4-11
- Speed (maximum expected)
- Transitway configuration (with or without noise barrier)

B.iii. Calculate the noise exposure at 50 ft in terms of $L_{eq(1hr)}$. Calculate $L_{eq(1hr)}$ for each source using the appropriate equations in Table 4-12.

B.iv. Calculate the noise exposure at 50 ft in terms of L_{dn}. If the project noise will affect any residential receivers, calculate the L_{dn} using the combined $L_{eq(1hr)}$ for both the daytime and nighttime periods separately, using the appropriate equations in Table 4-12.

Note that the equations in Table 4-12 include terms to account for a speed other than the 50 mph reference speed and a numerical adjustment to account for the one-hour time period for this metric. For more information on the numerical adjustment to represent the time period of interest, see Appendix B.1.4.4.

Table 4-12 presents an estimate of noise reduction potentially provided by wayside noise barriers. This is considered illustrative given that barriers are the most common noise mitigation measure. See Section 4.5, Step 7 for a complete description of the benefits resulting from noise mitigation. If impact is determined during the General Noise Assessment without mitigation, repeat the procedure and include proposed mitigation.

Table 4-12 Computation of $L_{eq(1hr)}$ and L_{dn} at 50 ft for Highway/Transit General Noise Assessment

$L_{eq(1hr)}$ at 50 ft	$L_{eq(1hr)} = SEL_{ref} + 10\,log(V) + C_S log(\frac{S}{50}) - 35.6$	**Eq. 4-10**
Daytime L_d at 50 ft	$L_d = L_{Aeq(1hr)}$ where V = V_d	**Eq. 4-11**
Nighttime L_n at 50 ft	$L_n = L_{Aeq(1hr)}$ where V = V_n	**Eq. 4-12**
L_{dn} at 50 ft	$L_{dn} = 10log(15 \times 10^{(L_d/10)} + 9 \times 10^{((L_n+10)/10)}) - 13.8$	**Eq. 4-13**
Barrier Adjustment	= -5 for noise barriers	
V	= hourly volume of vehicles, vehicles per hour	
C_s	= Speed constant 15 for diesel buses 28 for electric buses 21 for hybrid buses[23] 30 for automobile and van pools	
S	= average vehicle speed, mph	
V_d	= average hourly daytime volume of vehicles, vehicles per hour $= \frac{total\ number\ of\ vehicles, 7\ a.m.\ to\ 10\ p.m.}{15}$	
V_n	= average hourly nighttime volume of vehicles, vehicles per hour $= \frac{total\ number\ of\ vehicles, 10\ p.m.\ to\ 7\ a.m.}{9}$	

Option C: Stationary Sources – Stationary sources include fixed transit system facilities. New transit facilities undergo a site review for best location that considers 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, ferry 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. Noise from access roads is treated according to the procedures described in the Highway/Transit Sources category. In a General Noise Assessment, only the prominent features of each fixed facility are considered in the noise analysis.

C.i. For small facilities, using Table 4-13, determine the reference source noise levels 50 ft from the center of the site in terms of SEL. The source reference levels given in the table are based on measurements for the peak hour of operation of a typical stationary source of the noted type and size.

A large facility, such as a rail yard, is spread out over considerable area with various noise sources with different noise levels depending on the layout of the facility. Specifying a single reference SEL for the facility at 50 ft from the center of the site could be misleading if all of these different noise sources are not represented. Therefore, the reference distance should be the equivalent distance of 50 ft, which is determined by estimating the noise levels from the center of the site at a distance far enough to capture all noise sources and projecting back to 50 ft from the center of the site. This approach allows for a conservative estimate of noise for all surrounding areas and the equivalent noise can be considered as 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 (e.g., the dock in the case of ferry boat operations) instead of the center of the site.

Table 4-13 Source Reference Levels at 50 ft 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)	109	1 train with diesel locomotive idling for 1 hour
Crossing signals	109	3600 second duration
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
Ferry Terminal		
Ferry boat (no fog horn sounded)	97	4 ferry boat landings in 1 hour
Ferry boat (fog horn sounded)	100	
Parking Garage	92	1000-car capacity in peak activity hour
Park & Ride Lot	101	12 buses, 1000 cars in peak activity hour

C.ii. Collect the following data:

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

C.iii. Calculate $L_{eq(1hr)}$ at 50 ft. Calculate $L_{eq(1hr)}$ for each source using the appropriate equations in Table 4-14.

C.iv. Calculate L_{dn} at 50 ft. If the project noise will affect any residential receivers, calculate the L_{dn} using the combined $L_{eq(1hr)}$ for both the daytime and nighttime periods separately, using the appropriate equations in Table 4-14.

The equations in Table 4-14 include a numerical adjustment to account for the one-hour time period for this metric. See Appendix B.1.4.4 for more information on the numerical adjustment.

Table 4-14 presents an estimate of noise reduction potentially provided by noise barriers at the property line. Only approximate locations and lengths for barrier or other noise mitigation measures are developed during a General Noise Assessment to provide a preliminary indication of the costs and benefits of mitigation. A Detailed Noise Analysis of the preferred alternative is usually warranted following the General Noise Assessment (if it predicts any impacts) to verify impacts and design the mitigation.

Table 4-14 Computation of $L_{eq(1hr)}$ and L_{dn} at 50 ft for Stationary Source General Noise Assessment*

$L_{eq(1hr)}$ at 50 ft	$L_{eq(1hr)} = SEL_{ref} + C_N - 35.6$	**Eq. 4-14**
Daytime L_d at 50 ft	$L_d = 10\log((\frac{1}{15}) \sum_{7am-10pm} 10^{(L_{Aeq(1hr)}/10)})$	**Eq. 4-15**
Nighttime L_n at 50 ft	$L_n = 10\log((\frac{1}{9}) \sum_{10pm-7am} 10^{(L_{Aeq(1hr)}/10)})$	**Eq. 4-16**
L_{dn} at 50 ft	$L_{dn} = 10\log(15 \times 10^{(L_d/10)} + 9 \times 10^{((L_n+10)/10)}) - 13.8$	**Eq. 4-17**
Barrier Adjustment	= -5 for noise barrier at property line	
Volume Adjustment	$= C_N$ $= 10\log(\frac{N_T}{20})$ Rail yards and shops $= 10\log(N_T)$ Layover tracks $= 10\log(\frac{N_B}{100})$ Bus storage yard $= 10\log(\frac{N_B}{200} + \frac{N_S}{60})$ Bus operating facility $= 10\log(\frac{N_B}{20})$ Bus transit center $= 10\log(\frac{N_F}{4})$ Ferry terminal $= 10\log(\frac{N_A}{1000})$ Parking garage $= 10\log(\frac{N_A}{2000} + \frac{N_B}{24})$ Park & ride lot $= 10\log(\frac{E}{3600})$ Crossing signals N_T = average number of trains per hour during the day (7AM to 10PM) or night (10PM to 7AM) N_B = average number of buses per hour during the day or night N_F = average number of ferry boat landings per hour during the day or night N_S = average number of buses serviced and cleaned per hour during the day or night N_A = average number of automobiles per hour during the day or night E = average hourly duration of events, sec during the day or night	

* If any of these numbers is zero, omit that term.

Step 3: Estimate Project Noise Exposure by Distance

Estimate the project noise exposure for locations beyond the reference distance, such as for noise-sensitive land uses.

In the previous step, noise exposure at the reference distance of 50 ft was calculated for the various noise sources. This step describes how to estimate the project noise exposure beyond (or, if needed, closer than) the reference distance, such as at noise-sensitive land uses locations. This procedure estimates the source's noise exposure as a function of distance. Adjustments are provided to account for shielding attenuation from rows of buildings.

3a. Select the appropriate distance correction curve (Fixed-Guideway & Highway or Stationary) from Figure 4-6. The Fixed-Guideway & Highway curve refers to line sources while the Stationary curve is refers to point sources. The distance correction factor ($C_{distance}$) is 0 dB at 50 ft.

3b. Choose a distance other than 50 ft, such as the distance to a receiver. Determine the correction factor using Figure 4-6 or calculate using the equations in Table 4-15.[iii] For distances beyond 1,000 ft, the equations in Table 4-15 can be used; however, ground effects have an upper limit and atmospheric conditions may affect propagation characteristics. More detailed calculation methods may be required to account for those effects beyond 1,000 ft.

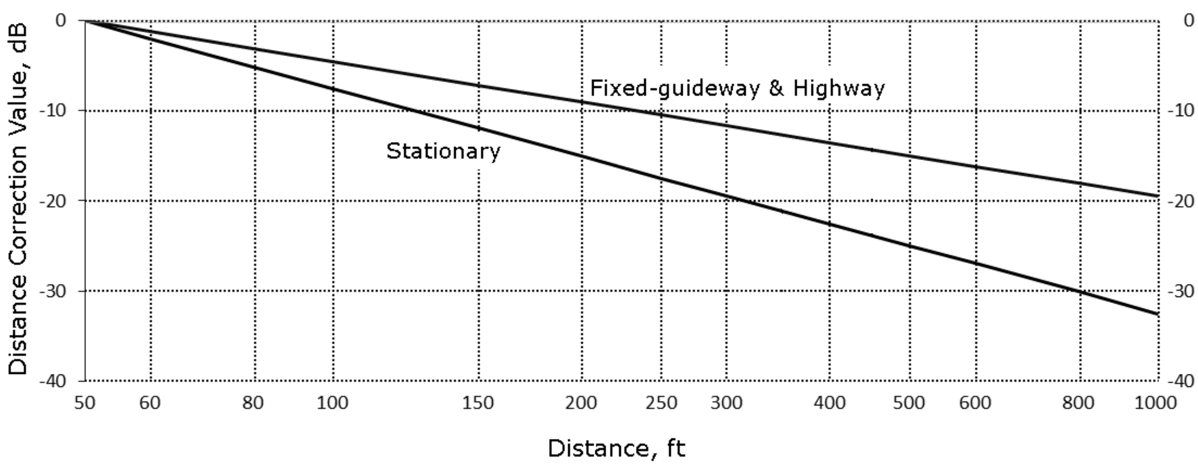

Figure 4-6 Curves for Estimating Exposure vs. Distance in General Noise Assessment

[iii] Note that the curves and equations assume acoustically soft ground beyond a distance of 50 ft. See Table 4-27 for more detailed calculation of ground attenuation.

Table 4-15 Distance Correction Factor Equations for General Noise Assessment

Source	Equation	
Stationary Sources	$C_{distance} = -25\log(\frac{D}{50})$	**Eq. 4-18**
Fixed-guideway and Highway	$C_{distance} = -15\log(\frac{D}{50})$	**Eq. 4-19**
D = distance, ft		

3c. Apply the distance correction ($C_{distance}$) to the project noise exposure at 50 ft (Section 4.4, Step 2) using the following equation:

$$L_{distance} = L_{50} + C_{distance} \quad \textbf{Eq. 4-20}$$

where:

$L_{distance}$ = L_{dn} or $L_{eq(1hr)}$ at the new distance in feet
L_{50} = L_{dn} or $L_{eq(1hr)}$ at 50 ft

3d. Repeat Step 3c for each source-receiver distance from the project. A noise exposure vs. distance curve can be created, if desired, by calculating the noise exposure for all distances of interest and plotting a curve. This curve can be used to assist in determining 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 to assess the potential benefits from mitigation measures.

For second row receivers and beyond, it is necessary to account for shielding attenuation from rows of intervening buildings. Without accounting for shielding, impacts may be substantially overestimated. Use the following general rules to account for 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.

Step 4: Combine Noise Exposure from All Sources

Combine all sources to predict the total project noise at the receivers using the equations in Table 4-16, once propagation adjustments have been made for the noise exposure from each source separately (fixed-guideway, highway/transit, and stationary).

Table 4-16 Computing Total Noise Exposure

Total $L_{eq(t)}$ from all sources for the hour of interest:	$L_{eq.total(1hr)} = 10\log(\sum_{all\ sources} 10^{L_{eq}/10})$	**Eq. 4-21**
Total L_{dn} from all sources	$L_{dn.total} = 10\log(\sum_{all\ sources} 10^{L_{dn}/10})$	**Eq. 4-22**

Step 5: Estimate Existing Noise Exposure

Measure the existing noise or estimate the existing noise exposure using a simplified procedure.

Existing noise in the project vicinity must be quantified and compared to the project noise to determine the potential noise impact. It is generally recommended to measure existing noise, especially at locations known to be noise-sensitive, but if measurement results are not available then they must be estimated. In the Detailed Noise Analysis, the existing noise exposure is usually based on noise measurements at representative locations in the community.

It is not necessary or 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. Because 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 D and Appendix E, respectively.

Changes to Existing Transit

For projects that propose changes to an existing transit system, such as a rehabilitation project, the project noise can include changes to the existing noise because of the project, and so it is not possible to define project noise separately. For these projects, refer to Section 4.1, Step 3 – Option B, on using the cumulative noise criteria.

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 4-17, where a neighborhood's existing noise exposure is based on proximity to nearby major roadways or railroads, or on population density. For areas near major airports, published aircraft noise contours can also be used to estimate the existing noise exposure. The process is as follows:

5a. Obtain scaled mapping and aerial photographs showing the project location and alternatives. A scale of 1 inch = 200 or 400 ft 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 ft from the center of the alignment or property center, depending on whether the project is a line source (fixed guideway/ roadway) or a stationary facility. These data are commonly available from local transit agencies and a number of publicly available online tools.

5b. Estimate the existing noise exposure by estimating the noise from major roads and railroad lines or by population density. First, evaluate the site's proximity to major roads and railroad lines including those that are included in the project. If these noise sources are far enough away that ambient noise is dominated by local streets and community activities, estimate the existing noise based on population density. To choose the appropriate existing noise exposure, compare noise levels from each of the three categories—Roadways, Railroads, and Population Density—and select the lowest level. In case of a lightly used railroad (one train per day or less) select the Population Density category. Existing noise levels are presented in Table 4-17. Refer to Section 4.1, Step 3 – Option B, on using the cumulative noise criteria for projects that propose changes to an existing transit system, such as a rehabilitation project.

Option A: Roadways – Major roadways are separated into two categories for a general noise assessment. Roadways that cannot be described by these two categories are not considered major roadways and would use the Population Density method described below. The roadway categories are as follows:

- Interstate highway—roadways with 4 or more lanes that allow trucks
- Other roadway—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 in Table 4-17 are based on data for light to moderate traffic on typical highways and parkways using FHWA highway noise prediction procedures. Where a range of distances is given, the noise exposure estimates are given at the larger distance (note that the traffic noise at the smaller distance is underestimated). 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:

$$D_{GM} = \sqrt{(D_N)(D_F)} \qquad \textbf{Eq. 4-23}$$

where:

D_{GM} = distance to the geometric mean in feet
D_N = distance to the nearest lane centerline in feet
D_F = distance to the farthest lane centerline in feet

Option B: Railroad Lines – 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 $L_{eq(1hr)}$ only during certain hours of the day, and these hours may vary from day to day. Therefore, to avoid underestimating noise impact when using $L_{eq(1hr)}$, it is recommended that sites near rail lines are estimated based on nearby roadways or population density unless very specific train information is available.

Option C: Population Density – In areas away from major roadways, noise from local streets or in neighborhoods is estimated using a relationship determined during a research program by EPA.[24] 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:

$$L_{dn} = 22 + 10\log(p) \qquad \textbf{Eq. 4-24}$$

where:

L_{dn} = in dBA
p = population density in people per square mile

In areas near major airports, published noise contours can be used to estimate the existing noise exposure. The L_{dn} from such contours should be applied if greater than the estimates of existing noise from other sources at a given location.

Table 4-17 Estimating Existing Noise Exposure for General Noise Assessment

Dominant Existing Noise Source	Distance from Major Noise Source, ft*	Population Density, people per sq. mi.	*Noise Exposure Estimates* L_{eq} Day	L_{eq} Evening	L_{eq} Night	L_{dn}
Interstate Highway**	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
Other Roadway†	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
Railway††	10–30		--	--	--	75
	30–60		--	--	--	70
	60–120		--	--	--	65
	120–240		--	--	--	60
	240–500		--	--	--	55
	500–800		--	--	--	50
	800 and up		--	--	--	45
Population		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

* Distances do not include shielding from intervening rows of buildings. Generally, for estimating shielding attenuation in populated areas, assume 1 row of buildings every 100 ft, 4.5 dB for the first row, and 1.5 dB for every subsequent row up to a maximum of 10 dB attenuation.
** Roadways with 4 or more lanes that permit trucks, with traffic at 60 mph.
† 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.
†† Main line railroad corridors typically carrying 5-10 trains per day at speeds of 30-40 mph.

Step 6: Inventory Noise Impacts

Inventory the potential noise impacts either by comparing the project and existing noise at each noise-sensitive land use or by developing noise impact contours.

Use land use information and assumptions for shielding attenuation from rows of buildings. 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. If the objective is to compare major alignment options, it may not be necessary to identify every different type of noise-sensitive land use. The inventory may include a subset of land uses, including residential and public institutional uses.

Option A is the preferred method as it quantifies the noise impact at each noise-sensitive land use indicating the severity of the impact. Option B may be useful for comparing and narrowing down major alignment options with numerous noise-sensitive land uses.

Option A: Compare existing noise to project noise at each noise-sensitive land use.

A1. Tabulate each individual noise-sensitive land use building and site within the identified screening distance (Section 4.3).

A2. Determine for each noise-sensitive land use the existing noise (Section 4.4, Step 5), the project noise (Section 4.4, Step 3) and the resulting change in noise.

A3. Designate each noise-sensitive land use with either a no, moderate, or severe noise impact based on the criteria in Section 4.1.

A4. Identify all moderate and severe impacts on a project map.

Option B: Develop noise impact contours.

B1. Determine the noise level thresholds at which the project noise would cause moderate and severe impacts using the estimated existing noise exposure from Section 4.4, Step 5 and the noise impact criteria in Figure 4-2.

B2. Determine the distances from the project boundary to the two impact levels using the noise exposure vs. distance curves or equations in Section 4.4, Step 3.

B3. Plot points on a project land use map that correspond to the distances determined in Section 4.4, Step 3. Continue this process for all areas surrounding the project. Connect the plotted points to represent the noise impact contours.

B4. Tabulate all noise-sensitive land use buildings and sites that lie between the impact contours and the project boundary. For residential buildings, an estimate of the number of dwelling units is satisfactory.

B5. Prepare summary tables showing the number of buildings (and estimated dwelling units, if available) within both impact categories.

Specific decibel level noise contours, for example, 65 dBA, can also be plotted if desired. The distances can be determined using the procedure in Section 4.4, Step 3 by substituting the desired decibel level for the impact threshold.

Locations of points will change with respect to the project boundary as the existing ambient exposure changes, the project source levels change, and as shielding effects change. It is recommended to plot points close together to draw a smooth curve. For a General Noise Assessment, the contours may be drawn through buildings and 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. Example 4-1 and Example 4-4 describe the development of noise contours with illustrations.

Step 7: Determine Noise Mitigation Needs

Apply estimates of the noise reduction from proposed mitigation measures (Section 4.4, Step 2), where the assessment shows either severe or moderate impact, and repeat the tabulation of noise impacts.

Note that noise barriers are the only form of mitigation available in a General Noise Assessment. The other mitigation measures are available for a Detailed Noise Analysis. The approximate noise barrier lengths and locations developed in a General Noise Assessment provide a preliminary basis for evaluating the costs and benefits of impact mitigation. This evaluation will provide a conservative estimate of the effect of the mitigation on the identified impacts.

In general, it is recommended to complete a Detailed Noise Analysis for final mitigation measures. However, if impact is identified through a General Noise Assessment and can be mitigated to a level of no impact using the noise reduction estimates included in the General Noise Assessment, a Detailed Noise Analysis may not be needed. Mitigation assumed in the assessment used for the NEPA evaluation must be included in the project as a commitment. Consult with the FTA Regional office to determine if a Detailed Noise Analysis is required for final mitigation measures.

The following examples illustrate how to complete general noise assessments for varying project types including commuter rail, highway/transit, BRT system, and a transit center.

Example 4-1 General Noise Assessment – Commuter Rail

General Noise Assessment for a Commuter Rail System in an Existing Abandoned Railroad Right-of-Way

The following example illustrates the General Noise Assessment procedure for a new fixed-guideway project. The hypothetical project is a commuter rail system to be built within the abandoned ROW of a railroad. The example covers a segment of the corridor that passes through a densely developed area with population density of 25,000 people per square mile in mixed single- and multi-family residential land uses as shown in Figure 4-7. The example is presented in two parts: first, a segment where the rail line is grade-separated and a horn is not sounded; and second, an at-grade street-rail crossing where the horn is sounded.

Assumptions

- **Project Corridor**
  Existing population density is 25,000 people per square mile.
- **Commuter Rail System**
  Commuter train with one locomotive and a three-car consist on a double-track at-grade system with welded rail. Trains operate with 20-minute headways during peak hours and 1-hour headways during off-peak. Speeds are approximately 40 mph along the corridor.

Operating Schedule

	Period	Headway (minutes) Inbound	Headway (minutes) Outbound	Trains per hour Inbound	Trains per hour Outbound	Trains per hour Total	Period Total
Daytime	7 a.m. – 8 a.m.	20	20	3	3	6	6
	8 a.m. – 4 p.m.	60	60	1	1	2	16
	4 p.m. – 6 p.m.	20	20	3	3	6	12
	6 p.m. – 10 p.m.	60	60	1	1	2	8
Nighttime	10 p.m. – 11 p.m.	60	60	1	1	2	2
	11 p.m. – 5 a.m.	--	--	--	--	--	--
	5 a.m. – 6 a.m.	60	60	1	1	2	2
	6 a.m. – 7 a.m.	20	20	1	1	2	2

Part 1: Grade-Separated Street Crossing

Determine Project Source Reference Levels at 50 ft

Classify the noise source: Fixed-Guideway Transit
Determine noise source reference level from Table 4-9:
Locomotive: 92 dBA
Cars: 82 dBA

Estimate Project Noise Exposure at 50 ft

Determine average hourly daytime and nighttime volumes of train traffic.

Daytime (7 a.m. – 10 p.m.)

$$V_d = \frac{42\ trains}{15\ hours} = 2.8\ trains/hour$$

Nighttime (10 p.m. – 7 a.m.)

$$V_n = \frac{6\ trains}{9\ hours} = 0.7\ trains/hour$$

Use Eq. 4-1 and Eq. 4-3 to calculate the daytime $L_{eq(1hr)}$ at 50 ft for the locomotives and rail cars.

$$\begin{aligned} L_{d.Locos} &= SEL_{ref} + 10log(N_{Locos}) + Klog(\frac{S}{50}) + 10log(V_d) - 35.6 \\ &= 92 + 10log(1) - 10log(\frac{40}{50}) + 10log(2.8) - 35.6 \\ &= 61.8\ dB\text{A at 50 ft} \end{aligned}$$

$$\begin{aligned} L_{d.RCars} &= SEL_{ref} + 10log(N_{Cars}) + 20log(\frac{S}{50}) + 10log(V_d) - 35.6 \\ &= 82 + 10log(3) + 20log(\frac{40}{50}) + 10log(2.8) - 35.6 \\ &= 53.7\ dB\text{A at 50 ft} \end{aligned}$$

Calculate the total daytime L_d for the locomotive and rail cars using Eq. 4-7.

$$\begin{aligned} L_{d.Combo} &= 10log(10^{L_{d.Loco}/10} + 10^{L_{d.RCars}/10}) \\ &= 10log(10^{61.8/10} + 10^{53.7/10}) \\ &= 62.4\ dBA\text{ at 50 ft} \end{aligned}$$

Calculate the nighttime $L_{eq(1hr)}$ at 50 ft for the locomotives and rail cars.

$$L_{n.Locos} = SEL_{ref} + 10\log(N_{Locos}) + K\log(\frac{S}{50}) + 10\log(V_n) - 35.6$$
$$= 92 + 10\log(1) - 10\log(\frac{40}{50}) + 10\log(0.7) - 35.6$$
$$= 55.8\ dBA \text{ at 50 ft}$$

$$L_{n.RCars} = SEL_{ref} + 10\log(N_{Cars}) + 20\log(\frac{S}{50}) + 10\log(V_n) - 35.6$$
$$= 82 + 10\log(3) + 20\log(\frac{40}{50}) + 10\log(0.7) - 35.6$$
$$= 47.7\ dBA \text{ at 50 ft}$$

Calculate the total nighttime L_n for the locomotive and rail cars using Eq. 4-8.

$$L_{n.Combo} = 10log(10^{L_{n.Locos}/10} + 10^{L_{n.RCars}/10})$$
$$= 10log(10^{55.8/10} + 10^{47.7/10})$$
$$= 56.4\ dBA \text{ at 50 ft}$$

Calculate L_{dn} at 50 ft for the project using Eq. 4-9.

$$L_{dn.Combo} = 10log\ (15 \times 10^{(L_{d.Combo}/10)} + 9 \times 10^{((L_{n.Combo}+10)/10)}) - 13.8$$

Estimate Existing Noise Exposure

Estimate existing noise at noise-sensitive sites. Since the existing alignment is on an abandoned railroad, the dominant existing noise source can be described by a generalized noise level to characterize a large area. Use Table 4-17 and population density of 25,000 people per square mile to determine the existing noise level. Unobstructed residences range from 100 to 200 ft from the rail line.

According to Table 4-17: L_{dn} = 60 dBA

Determine Noise Level and Distance for the Onset Of Impact

Determine the noise level for the onset of moderate and severe impact using Figure 4-2 and the existing noise level of 60 dBA. Note that this project is land use category 2 and the appropriate metric is L_{dn}.

Existing Noise L_{dn}	Onset of Moderate Impact L_{dn}	Onset of Severe Impact L_{dn}
60 dBA	58 dBA	64 Dba

Determine the distance from the project noise sources to the noise impact contours using the fixed-guideway curve in Figure 4-6 (or the equations in Table 4-15) and the project impact thresholds obtained above. The project noise level at 50 ft is approximately 64 dBA.

Moderate impact (58 dBA)

$$58 - 64 = -6\ dB$$

According to Figure 4-6, the distance correction is approximately -6 dB at 120 ft.
Severe Impact (64 dBA)

$$64 - 64 = 0\ dB$$

According to Figure 4-6, the distance correction is less than 0 dB at approximately 51 ft.

Project Level L_{dn}	Onset of Moderate Impact Distance	Onset of Severe Impact Distance
64 dBA	120 ft	51 ft

Develop Noise Impact Contours

Draw contours for each affected land use, based on the above table and its distance from the rail line (Figure 4-7). Note that the impact distances listed are in terms of distance to the centerline of the Commuter Rail corridor.

Inventory of Noise Impact

There are six residential buildings within the contours defining moderate impact (shaded in Figure 4-7).

Noise Mitigation

The procedure is repeated assuming a noise barrier to be placed at the railroad ROW line. The barrier serves to reduce project noise from the commuter rail by at least 5 dB. Note that the barrier does not affect the project criteria to be used in determining impact, and the same existing noise levels (as the case without a barrier) are used to determine these thresholds.

In this example, the noise barrier decreases the distance to moderate impact from 120 to 60 ft and eliminates all residential noise impact for this segment of the project area.

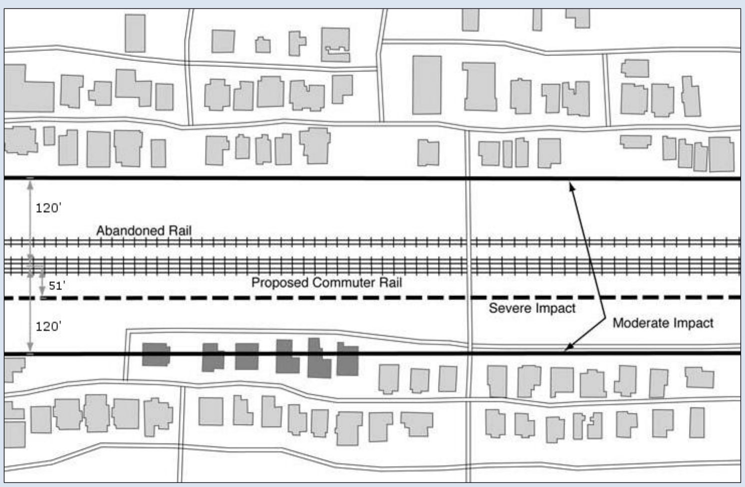

Figure 4-7 Noise Impacts of Hypothetical Commuter Rail

Part 2: At-Grade Crossing with Horn Blowing

Now consider the case of an active street crossing of the commuter railroad tracks. The General Noise Assessment method includes source reference levels for horns on moving trains and warning bells (crossing signals) at the street crossing. According to Table 4-9, the horn noise applies to track segments within ¼ mile of the grade crossing.

Estimate Project Noise Exposure at 50 ft

Using the train volumes from Part 1 and the information in Table 4-9 and Table 4-10, determine the day and nighttime $L_{eq(1hr)}$ from sounding the horns at 50 ft.

$$
\begin{aligned}
L_{d.LHorns} &= SEL_{ref} + 10\log(V_d) - 35.6 \\
&= 110 + 10\log(2.8) - 35.6 \\
&= 78.9\ dB\text{A}
\end{aligned}
$$

$$L_{n.LHorns} = SEL_{ref} + 10\log(V_n) - 35.6$$
$$= 110 + 10\log(0.7) - 35.6$$
$$= 72.9\ dBA$$

Calculate the L_{dn} at 50 ft from train horns using Eq. 4-9 :

$$L_{dn.LHorns} = 10\log(15 \times 10^{\left(L_{d.LHorns}/10\right)} + 9 \times 10^{\left((L_{n.LHorns}+10)/10\right)})\text{-}13.8$$
$$= 81\ dBA$$

At-grade street crossings will have warning bells, typically sounding for 20 seconds for every train passby. The total daytime and nighttime durations are as follows:

E_d = average daytime hourly duration
=20 seconds X 2.8 trains/hour = 56 seconds/hour
E_n = average nighttime hourly duration
=20 seconds X 0.7 trains/hour = 14 seconds/hour

From Table 4-14:

$$L_{d.WBell} = SEL_{ref} + 10\log(\frac{E_d}{3600}) - 35.6$$
$$= 109 + 10\log(\frac{56}{3600}) - 35.6$$
$$= 55.3\ dBA$$

$$L_{n.WBell} = SEL_{ref} + 10\log(\frac{E_n}{3600}) - 35.6$$
$$= 109 + 10\log(\frac{14}{3600}) - 35.6$$
$$= 49.3\ dBA$$

Calculate L_{dn} at 50 ft. from the warning bells using Eq. 4-17:

$$L_{dn.WBell} = 10\log(15 \times 10^{\left(L_{d.WBell}/10\right)} + 9 \times 10^{\left((L_{n.WBell}+10)/10\right)})\text{-}13.8$$
$$= 57.3\ dBA$$

Compared to horn blowing, the crossing signal warning bell noise is negligible, but still must be included in the evaluation.

Estimate Existing Noise Exposure

From Part 1, the existing noise level is 60 dBA.

Determine Noise Level and Distance for the Onset Of Impact

As in Part 1, the existing noise level (60 dBA) is used to determine the onset of moderate and severe impacts:

Existing Noise L_{dn}	Onset of Moderate Impact L_{dn}	Onset of Severe Impact L_{dn}
60 dBA	58 dBA	64 dBA

Determine the distance from the project noise sources to the impact contours using the fixed-guideway curve in Figure 4-6 (or the equations in Table 4-15) and the project impact thresholds obtained above. The project noise at 50 ft is approximately 81 dBA. However, there are at least two intervening rows of buildings, which will provide 6 dB (4.5 dB for the first row and 1.5 dB for the second row) of shielding.

Moderate impact (58 dBA)

$$58 - (81 - 6) = -17\ dB$$

According to Figure 4-6, the distance correction is approximately -17 dB at 715 ft.

Severe Impact (64 dBA)

$$64 - (81 - 6) = -11\ dB$$

According to Figure 4-6, the distance correction is approximately -11 dB at 265 ft.

Project Level L_{dn}	Onset of Moderate Impact Distance	Onset of Severe Impact Distance
81 dBA	715 ft	265 ft

Draw Noise Impact Contours

Contours can be drawn as in Part 1 for ¼ mile on either side of the grade crossing.

Example 4-2 General Noise Assessment – Highway/Transit

General Noise Assessment Example of Highway/Transit Corridor Projects

This example illustrates a highway/transit project where the highway noise dominates and the FHWA assessment methods should be used to inform the FTA process according to the impact criteria in Section 4.1.

Case 1: Highway Dominates

A new LRT system is planned for the median of a major highway that carries heavy traffic both day and night. The noise levels at the first row of houses along the highway were measured during peak hour, mid-day and nighttime with hourly $L_{eq(1hr)}$ readings of 65 dBA, 63 dBA, and 60 dBA, respectively. The LRT tracks will be 125 ft from the first row of houses. The LRT operations during peak hour will be 4-car trains at 45 mph, with 5-minute headways in both directions. Nighttime service decreases to 2-car trains and 20 minute headways.

FTA is providing a share of the funding for the LRT project, but the State DOT and the FHWA are co-lead agencies because the median requires considerable preparation for the tracks, including replacing bridge piers of street crossings and moving some highway lanes.

Assumptions

SEL_{ref} = 82 dBA
Nd = 4 cars per train
Nn = 2 cars per train
S = 45 mph
V_d = 24 trains per hour
V_n = 6 trains per hour

Estimate Project Noise Exposure at 50 ft

Use Table 4-9 and Table 4-10 to determine the peak hour $L_{eq(1hr)}$ for the rail vehicles.

Use Eq. 4-3 to calculate the LRT peak-hour noise level.

$$\begin{aligned} L_{d.RCars}(h) &= SEL_{ref} + 10\,log(N_{cars}) + 20\log(\tfrac{S}{50}) + 10\,log(V) - 35.6 \\ &= 82 + 10\,log(4) + 20\log(\frac{45}{50}) + 10\,log(24) - 35.6 \\ &= 65 \text{ dBA at 50 ft} \end{aligned}$$

Use Eq. 4-3 to calculate the LRT late evening hourly noise level.

$$L_{n.RCars}(h) = SEL_{ref} + 10\,log(N_{cars}) + 20\log(\tfrac{S}{50}) + 10\,log(V) - 35.6$$

$$= 82 + 10\,log(2) + 20\log(\frac{45}{50}) + 10\,log(6) - 35.6$$

= 56 dBA at 50 ft

Estimate Project Noise Exposure at 125 ft

Since the LRT tracks will be 125 ft from the first row of houses, use Figure 4-6 to determine the level at 125 ft.

At 125 ft, the distance correction is 5 dB.

Peak hour:

$$65 - 5 = \ 60\ dBA\ at\ 125\ ft$$

Night hourly:

$$56 - 5 = \ 51\ dBA\ at\ 125\ ft$$

In this case, the highway dominates the noise environment in the area both day and night, by 5 dB during peak hour and 9 dB at night. According to Section 4.1 and Table 4-2, use the FHWA assessment methods.

Example 4-3 General Noise Assessment – BRT System

General Noise Assessment for a BRT System in an Existing Railroad Right-of-Way

This example for a simple BRT project illustrates using the FTA procedures for a new BRT corridor planned in an existing abandoned railroad ROW.

Assumptions

SEL_{ref}	= 82 for buses
S	= 25 mph
V_d	= (344 buses) / (15 hours) = 22.9 buses per hour
V_n	= (116 buses) / (9 hours) = 12.9 buses per hour

Estimate Project Noise Exposure

Use the information and equations in Table 4-12 to calculate the daytime and nighttime $L_{eq(1hr)}$ at 50 ft.

C_S = 15 for buses

$$L_{d.Bus} = \ SEL_{ref} + 10\,log(V_d) + C_S\log(\frac{S}{50}) - 35.6$$

$$= \ 82 + 10\,log(22.9) + 15log(\frac{25}{50}) - 35.6$$

= 55 dBA at 50 ft

$$L_{n.Bus} = \ SEL_{ref} + 10\,log(V_n) + C_S\log(\frac{S}{50}) - 35.6$$

$$= 82 + 10\,log(12.9) + 15log(\frac{25}{50}) - 35.6$$

= 53 dBA at 50 ft

Calculate L_{dn} at 50 ft for the project using Eq. 4-13.

$$L_{dn.Bus} = \ 10\log(15 \times 10^{(L_{d.Bus}/10)} + 9 \times 10^{((L_{n.Bus}+10)/10)}) - 13.8$$

= 60 dBA at 50 ft

Estimate Existing Noise Exposure

The surrounding area is residential with 2,500 people per square mile starting approximately 100 ft away from the proposed alignment. Determine the existing noise using Table 4-17.

L_{dn} = 50 dBA

Determine Noise Level and dIstance for the Onset of Impact

Determine the noise level for the onset of moderate and severe impact using Figure 4-2 and the existing noise level of 50 dBA. Note that this project is land use category 2 and the appropriate metric is L_{dn}.

Existing Noise L_{dn}	Onset of Moderate Impact L_{dn}	Onset of Severe Impact L_{dn}
50 dBA	54 dBA	59 dBA

Determine the distance to the noise impact contours using the fixed-guideway & highway curve in Figure 4-6 (or the equations in Table 4-15) and the project impact thresholds obtained above. The project noise level at 50 ft is approximately 60 dBA.

Moderate impact (54 dBA)

$$54 - 60 = -6\ dB$$

According to Figure 4-6, the distance correction is approximately -6 dB at 125 ft.

Severe Impact (59 dBA)

$$59 - 60 = -1\ dB$$

According to Figure 4-6, the distance correction is less than -1 dB at approximately 60 ft.

Project Level L_{dn}	Onset of Moderate Impact Distance	Onset of Severe Impact Distance
60 dBA	125 ft	60 ft

Inventory of Noise Impact

Since there are residential land uses approximately 100 ft away from the proposed alignment and the onset of moderate impact is at 125 ft, there are possible moderate impacts to the residences.

Noise Mitigation

A barrier is proposed for mitigation between the BRT system and the residences. The analysis is repeated and results in a predicted new project level of 55 dBA and the following impact distances:

Mitigated Project Level L_{dn}	Onset of Moderate Impact Distance	Onset of Severe Impact Distance
55 dBA	60 ft	N/A

With a noise barrier in place between the BRT system and the residences, it is predicted that the onset of moderate impact would occur approximately 60 ft away from the BRT system. Since the residential area begins approximately 100 ft away from the BRT system, which is beyond the distance of moderate impact (60 ft), a noise barrier would provide the appropriate noise mitigation for the predicted moderate impact. The onset of severe impact is listed as N/A because with a noise barrier, the severe impact criterion is not exceeded by the project.

Example 4-4 General Noise Assessment – Transit Center

General Noise Assessment for a Transit Center

The following example illustrates the procedure for performing a General Noise Assessment for a stationary source. 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 4-8.

Assume that the Noise Screening Procedure has already been done for this project and the nearest residence has been identified approximately 140 ft from the center of the proposed transit center. Recall that if any residential or other noise-sensitive land use is identified within 150 ft of a transit center during the Noise Screening Procedure, additional analysis is required.

Assumptions

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

- **Population Density**
  12 houses per block, single family homes, 3 people per family.
  - Block area 78,750 square ft.
  - Population density = 9,750 people/square mile.

- **Bus Traffic**

Period	Hours	Buses per Hour
Peak, Morning	7 a.m.–9 a.m.	30
Peak, Afternoon	4 p.m.–6 p.m.	30
Mid-day	9 a.m.–4 p.m.	15
Evening	6 p.m.–10 p.m.	12
Early Morning (Night)	6 a.m.–7 a.m.	15
Late Night	10 p.m.–1 a.m.	4

Estimate Project Noise Exposure at 50 ft

Determine the hourly volume of buses during day and night.

Daytime (7 a.m. – 10 p.m.)

$$V_d = \frac{273\ buses}{15\ hours} = 18.2\ buses/hour$$

Nighttime (10 p.m. – 7 a.m.)

$$V_n = \frac{27\ buses}{9\ hours} = 3\ buses/hour$$

Calculate the daytime and nighttime $L_{eq(1hr)}$ at 50 ft for the bus transit center using the reference levels in Table 4-13 and the equations in Table 4-14.

$$\begin{aligned} L_{d.BTCenter} &= SEL_{ref} + C_N - 35.6 \\ &= 101 + 10\log\left(\frac{18.2}{20}\right) - 35.6 \\ &= 65\ dBA \text{ at 50 ft} \end{aligned}$$

$$L_{n.BTCenter} = SEL_{ref} + C_N - 35.6$$

$$= 101 + 10\log(\frac{3}{20}) - 35.6$$
$$= 57\ dBA \text{ at 50 ft}$$

Calculate L_{dn} at 50 ft for the project using Eq. 4-17.

$$L_{dn.BTCenter} = 10\log(15 \times 10^{(L_{d.BTCenter}/10)} + 9 \times 10^{((L_{n.BTCenter}+10)/10)}) - 13.8$$
$$= 66\ dBA \text{ at 50 ft}$$

Estimate Existing Noise Exposure

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

Roadway Noise Estimate – The traffic on Main Street qualifies this street for the Other Roadway category in Table 4-17. According to the map, the nearest residence is 275 ft from the edge of Main Street. The table shows existing L_{dn} = 55 dBA at this distance for representative busy city street traffic.
Population Density Noise Estimate – Noise from local streets is estimated from the population density of 9,750 people/square mile. Table 4-17 confirms that the L_{dn} is approximately 55 dBA.

In this example, the existing noise level by both the roadway and population density estimates are the same, but that is not always the case. If the levels are different, use the lower noise level. The existing noise level associated with the residential neighborhood in this example is L_{dn} = 55 dBA.

Determine Noise Level and Distance for the Onset of Impact

Determine the noise level for the onset of moderate and severe impact using Figure 4-2 and the existing noise level of 55 dBA. Note that this project is land use category 2 and the appropriate metric is L_{dn}.

Existing Noise L_{dn}	Onset of Moderate Impact L_{dn}	Onset of Severe Impact L_{dn}
55 dBA	56 dBA	62 dBA

Determine the distances from the center of the property to the noise impact contours using the stationary curve in Figure 4-6. The project noise level at 50 ft is 66 dBA.

<u>Moderate impact (56 dBA)</u>

$$56 - 66 = -10\ dB$$

According to Figure 4-6, the distance correction is approximately -10 dB at 125 ft.

<u>Severe impact (62 dBA)</u>

$$62 - 66 = -4\ dB$$

According to Figure 4-6, the distance correction is -4 dB at approximately 70 ft.

Project Noise L_{dn}	Onset of Moderate Impact Distance	Onset of Severe Impact Distance
66 dBA	125 ft	70 ft

Draw Noise Impact Contours

Draw lines at 70 ft and 125 ft from the center of the property of the proposed transit center. These lines represent the noise impact contours. (Note that in Figure 4-8 the severe impact contour is not drawn for clarity. The contour is just within the dashed line representing the moderate impact contour after mitigation).

Inventory of Noise Impact

Within, or touching, the contour defining moderate impact are three residential buildings (shaded in Figure 4-8). No residences are within the severe impact contour.

Noise Mitigation

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 ft high partially enclosing the transit center, sufficient to screen the residences but not the commercial block facing Main Street. According to Table 4-14, the approximate noise barrier effect is -5 dB. Repeating the procedure above, the noise barrier will reduce the moderate impact contour to 80 ft and the severe impact contour to 45 ft (note that at 50 ft the distance correction is 0), which in this example eliminates all potential impacts on the residences.

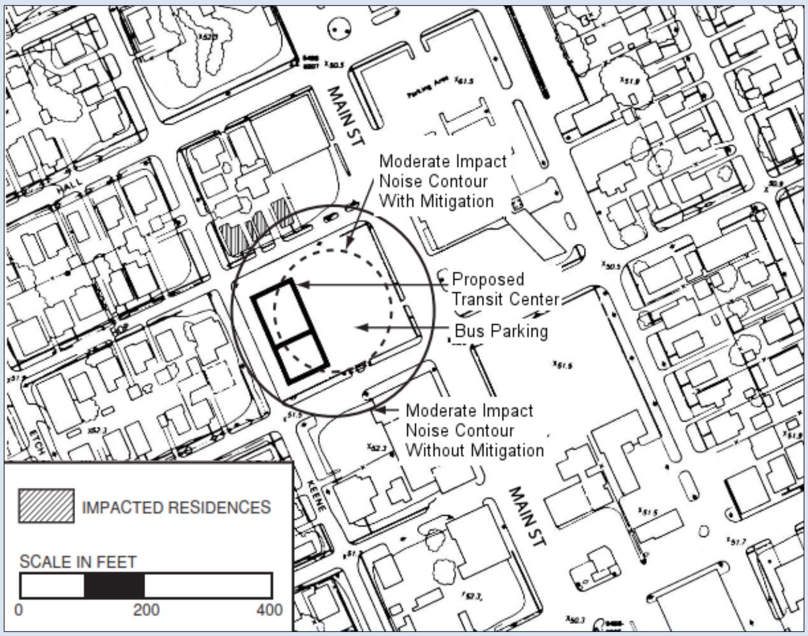

Figure 4-8 Example of Project for General Noise Assessment: Siting of Transit Center in Mixed Commercial/Residential Area

4.5 Evaluate Impact: Detailed Noise Analysis

Evaluate for impact using the Detailed Noise Analysis procedure in this section, if appropriate. For guidelines on when the Detailed Noise Analysis is appropriate, review Section 4.2.

The steps in the Detailed Noise Analysis (Figure 4-9) parallel the steps in the General Noise Assessment, though the Detailed Noise Analysis employs equations for computations rather than graphs or tables. Each step in the Detailed Noise Analysis is more refined in the prediction of project noise and subsequent evaluation of mitigation measures. Noise projections from the project must be determined for each receiver.

- **Step 1: Identify Noise-Sensitive Receivers**
  Identify the noise-sensitive receivers of interest in the impact analysis study, including clustering noise-sensitive areas. This identification is usually based

on the Screening Procedure and General Noise Assessment previously conducted.

- **Step 2: Determine Project Noise Source Reference Levels**
  Determine the project noise sources and reference levels. Then, estimate the project noise exposure at the reference distance of 50 ft, considering operational characteristics. When appropriate, measurements may be used to determine noise source reference levels.

- **Step 3: Determine Propagation Characteristics**
  Estimate project noise exposure as a function of distance, accounting for shielding and propagation along the path.

- **Step 4: Combine Noise Exposure from All Sources**
  Combine all sources to predict the total project noise at receivers.

- **Step 5: Determine Existing Noise Exposure**
  Determine the existing noise exposure. Measurements are used to determine the existing noise exposure. When measurements are unavailable, a simplified procedure to estimate existing noise exposure may be used with a clear justification to and approval by the FTA Regional office.

- **Step 6: Assess Noise Impact**
  Assess the noise impact at each receiver of interest using separate procedures for transit only and multimodal transportation projects.

- **Step 7: Determine Noise Mitigation Measures**
  Evaluate the need for mitigation and repeat the Detailed Noise Analysis with proposed mitigation.

When situations arise that are not explicitly covered in the Detailed Noise Analysis, professional judgment, in consultation with the FTA Regional office, may be used to extend these methods to cover these unique cases, when appropriate. Appendix G provides information on developing and using non-standard modeling procedures.

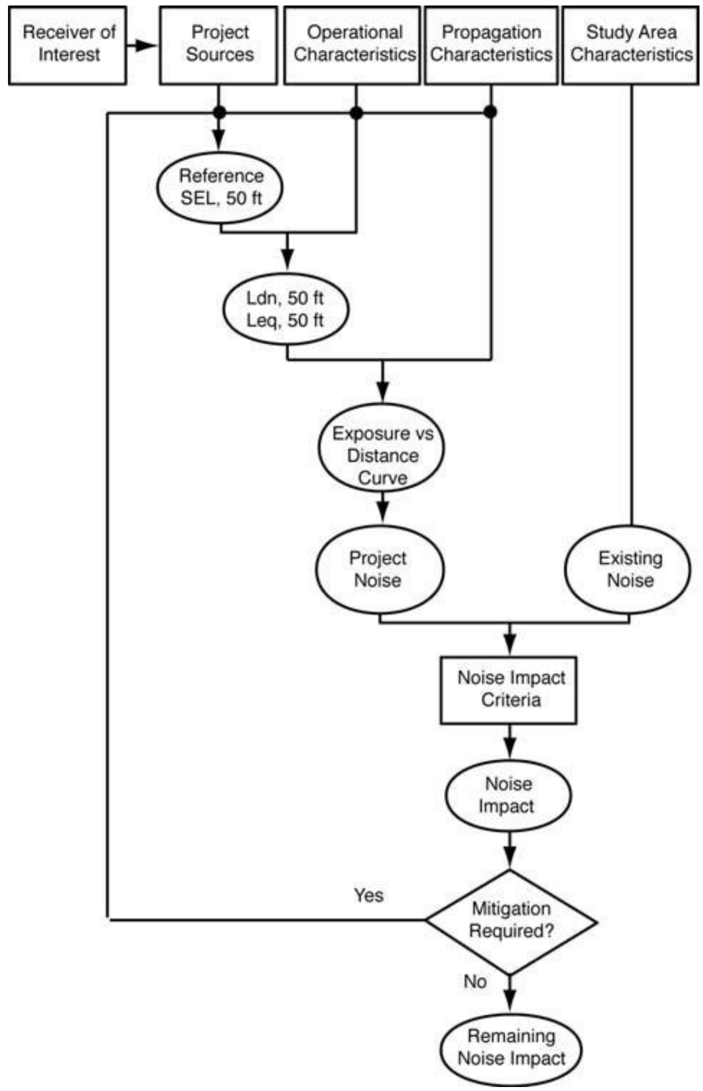

Figure 4-9 Procedure for Detailed Noise Analysis

Step 1: Identify Noise-Sensitive Receivers

Select the noise-sensitive receivers of interest, the number of which will depend upon the land use in the vicinity of the proposed project and the extent of the study area defined by the Noise Screening Procedure in Section 4.3 and the results of the General Noise Assessment in Section 4.4.

The steps in identifying the noise-sensitive receivers of interest, both the number of receivers needed and their locations, shown in Figure 4-10, include:

- **1a.** Identify all noise-sensitive land uses.
- **1b.** Select individual receivers of interest.
- **1c.** Cluster residential neighborhoods and other large noise-sensitive areas.

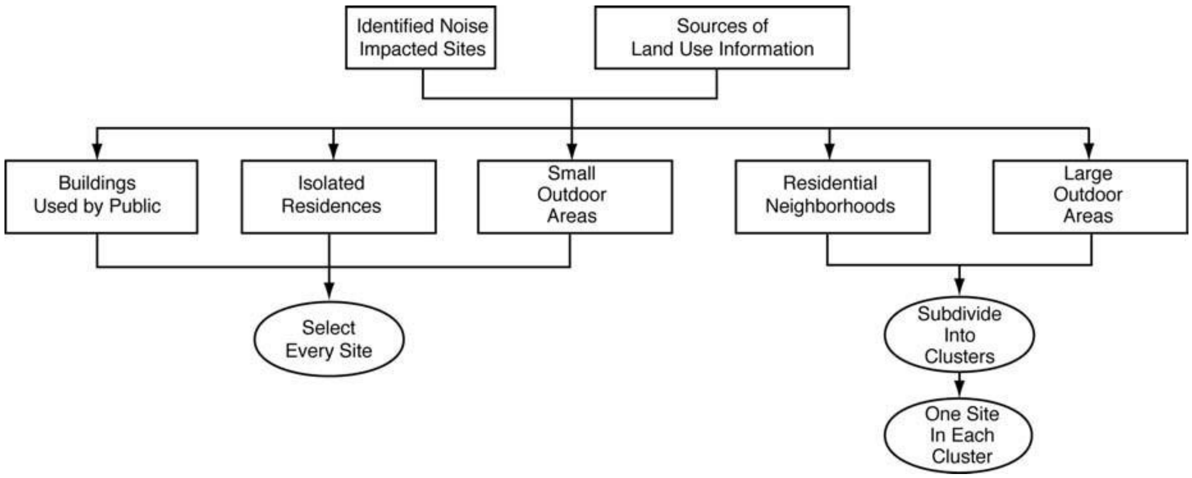

Figure 4-10 Guide to Selecting Noise-Sensitive Receivers of Interest

1a. Identify all noise-sensitive land uses where impact is identified by the General Noise Assessment in Section 4.4. If a General Noise Assessment has not been done, include all noise-sensitive sites according to the Noise Screening Procedure in Section 4.3. In areas where ambient noise is low, include land uses that are farther from the proposed project than for areas with higher ambient levels.

Recommended materials and methods that can assist in locating noise-sensitive land uses near 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. But they can provide broad guidance and may suggest residential pockets hidden within otherwise commercial zones. Of more use are project-specific maps that provide building-by-building detail on the land near the proposed project.

- **Road and town maps** can supplement other maps, are generally more up-to-date, and may be of larger scale.

- **Aerial photographs,** when current, especially those of 400-ft scale or better, 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,** in which the corridor is driven and land uses are annotated on base maps, may be used for definitive identification of noise-sensitive sites. 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. In addition, maps and aerial photos typically reveal only horizontal distances, not vertical distances. Houses on a hill overlooking the project may need a barrier of unacceptable height for its attenuation to be effective, and the greater vertical distance between source and receiver may eliminate the impact entirely. The windshield survey would reveal where vertical contour maps or other means may be needed so that vertical distances can be determined**.**

- **Geographic Information Systems (GIS)** provides electronic mapping needed for identifying noise-sensitive land uses. GIS data may include land parcels, building structures, aerial photography, and project-specific information. These data may be obtained during the project study or from local or regional agencies that store and maintain GIS data. Using electronic GIS data has advantages over paper mapping with respect to automating the process of identifying noise-sensitive land uses and accurately being able to determine their distances to the project alignment

Table 4-18 contains three types of *land uses of interest* and provides guidelines as to when receivers should be analyzed individually and when they can be clustered.

Table 4-18 Land Uses of Interest

Land Uses	Specific Use	Selecting Receivers
Residences	Isolated single family residences Neighborhoods (single and 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 (closest to the project noise source and at an intermediate distance from the predominant sources of existing noise) in each cluster (i.e., Balance the distance between the receiver and the new noise source and the receiver and the existing noise source). Multiple clusters in one location may be needed to fully characterize the area.
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.
Outdoor noise-sensitive areas	Certain parks Historic sites used for interpretation Amphitheaters Passive recreation areas Cemeteries Other outdoor noise-sensitive areas	For relatively small noise-sensitive areas, select noise-sensitive sites as separate receivers of interest. For relatively large areas (e.g. a cemetery, etc.), cluster by proximity to project noise sources, proximity to ambient-noise sources, and location along project line. Choose one receiver of interest (closest to the project noise source and at an intermediate distance from the predominant sources of existing noise) in each cluster.

1b. Select the following types of noise-sensitive receivers within the noise study area, per Table 4-18, to be evaluated as individual receivers:

- Every major noise-sensitive public building
- Every isolated residence
- Every relatively small outdoor noise-sensitive area

Use judgment to avoid analyzing noise where such analysis is obviously not needed. Areas that are considered particularly noise-sensitive by the community, but do not meet the criteria in Table 4-3, should be considered on a case-by-case basis as discussed in Section 4.1.

1c. 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. Subdivide all such neighborhoods/areas into clusters of approximately uniform noise, each containing a collection of noise-sensitive sites. Strive to obtain uniformity of both project noise and ambient noise using the following guidelines:

- In general, project noise reduces (drops off) with distance from the project. For this reason, project noise uniformity requires nearly equal distances between the project noise source and all sites within the cluster. Clusters are typically shaped as long narrow strips parallel to the transit corridor and/or circling project point sources such as maintenance facilities. It is suggested to cluster sites where the project noise varies over a range of 5 dB or less.

- Note that noise drops off approximately 3 dB per doubling of distance for line sources and approximately 6 dB per doubling of distance for point sources over open terrain. This reduction in noise will occur over a shorter distance in areas containing obstacles blocking the path of sound propagation, such as rows of buildings.

- Ambient noise usually drops off from non-project sources in the same manner as 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 manufacturing facilities. It is suggested to cluster sites where the ambient noise varies over a range of 5 dB or less. Ambient noise levels may be difficult to judge without measurements. In areas without predominant sources of noise, like highways, ambient noise can be considered to vary with population density, which is often uniform along the corridor. In situations where ambient noise tends to be uniform, the clusters can encompass relatively large areas.

After defining clusters, select one representative receiver in each cluster. It is recommended to choose the receiver closest to the project noise source and at an intermediate distance from the predominant sources of existing noise. See Appendix D for additional guidance and examples on clustering receivers, as well as an example.

Assess each identified cluster representative and individual noise-sensitive receiver of interest using the Detailed Noise Analysis as presented in the following steps.

Step 2: Determine Project Noise Source Reference Levels

Identify the major project noise sources near the noise-sensitive receivers of interest, group them by source type, and determine reference levels to compute project noise at 50 ft, as shown in Figure 4-11.

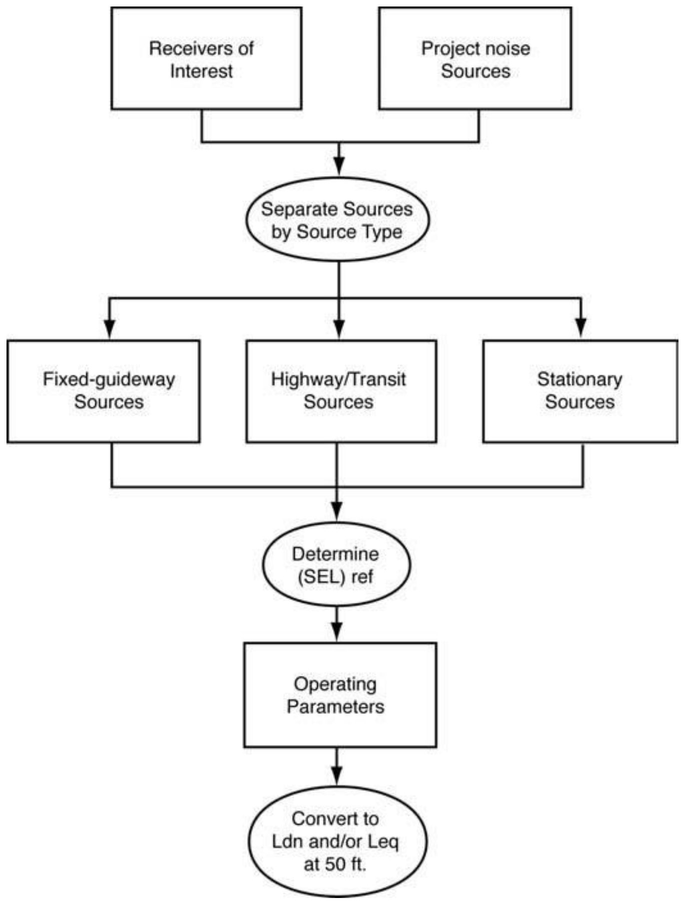

Figure 4-11 Flow Diagram for Determining Project Noise at 50 ft

2a. Identify the major project noise sources near receivers of interest according to Table 4-19. The right-hand column of the table indicates if each source is considered as a major contributor to the overall noise impact. Note that some noise sources can create high noise levels but are not indicated as major contributors. 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.

Table 4-19 Sources of Transit Noise

Project Type	Source Type	Actual Source	Major?
Commuter Rail Light Rail Streetcars RRT	Fixed-Guideway	Locomotive and rail car passbys Horns and whistles Crossing signals Crossovers/switches Squeal on tight curves Track-maintenance equipment	Yes Yes Yes Yes Yes No
	Stationary	Substations Chiller plants	Yes No
Busways Bus Transit Malls	Highway/Transit	Bus passbys Buses parking	Yes No
	Stationary	Buses idling	Yes
AGT Monorail	Fixed-Guideway	Vehicle passbys	Yes
	Miscellaneous	Line equipment	No
Terminals Stations Transit Centers	Fixed-Guideway	Locomotive and rail car passbys Crossovers/switches Squeal on tight curves	Yes Yes Yes
	Highway/Transit	Bus passbys Buses parking Automobile passbys	Yes No No
	Stationary	Locomotives idling Buses idling Ferry boats landing, idling, and departing at dock HVAC equipment Cooling towers P/A systems	Yes Yes Yes No No No
Park-and-Ride Lots	Highway/Transit	Bus passbys Buses idling Automobile passbys	Yes Yes 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 Locomotives idling Squeal on tight curves Horns, warning signals, coupling/ uncoupling, auxiliary equipment, crossovers/ switches, brake squeal, and air release	Yes Yes Yes Yes
	Highway/Transit	Bus passbys	Yes
	Stationary	Buses idling Yard/shop activities Car washes HVAC Equipment P/A Systems	Yes No No No No

2b. Separate the major noise sources by source type: fixed-guideway transit, highway/transit or stationary facility. Note that a major fixed-guideway system will usually have stationary facilities associated with it, and that a stationary facility may have highway/transit elements associated with it. Then use the instructions in the following source type options below to:

2c. Determine the source reference levels for the all project noise sources. Each source reference level pertains to reference operating conditions for stationary sources or one vehicle passby under reference operating conditions.

These reference levels should incorporate source-noise mitigation only if such mitigation will be considered for incorporation into the system specifications. 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. If special features that result in noise reductions are included in any of the predictions, the Federal environmental documents must include a commitment by the project sponsor to adopt such treatments before the project is approved for construction. For example, if the specifications include vehicle noise limits that may not be exceeded, 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.

2d. Convert the source reference level to noise exposure in terms of $L_{eq(1hr)}$ or L_{dn} under project operating conditions using the appropriate equations depending upon the type of source. The noise exposure is determined at the reference distance of 50 ft.

Option A. Fixed-guideway Sources – Compute project noise at 50 ft for fixed-guideway sources as identified in the second column of Table 4-19.

A.i. Reference SEL Levels

Determine the reference SEL at 50 ft for each major fixed-guideway noise source, either by measurement according to Appendix F or by referencing Table 4-20. The table provides guidance on which method is preferred for each source type. The "NO" designation implies that the source levels given in the table are appropriate to use in the analysis, and the "YES" designation implies that measurements are preferred over the data given in the table. In general, measurements are preferred for source types that vary considerably from project to project, including any emerging technology sources. The data in the table are adequate for source types that do not vary considerably from project to project.

For sources where measurements are preferred, refer to Appendix F for guidance on measurement procedures and methods for conversion of these measurements to the reference conditions of Table 4-20. 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 using the equations in Appendix F. This is only appropriate when there is a firm commitment to adopt the noise specifications in the vehicle procurement documents during the engineering phase and to adhere to the specifications throughout the procurement, delivery, and testing of the vehicles.

Approximate L_{max} values are provided in the table for general user information. As discussed in Appendix B.1.4.2, L_{max} is not used directly in the evaluation of noise impact.

Table 4-20 Source Reference SELs at 50 ft: Fixed-Guideway Sources at 50 mph

Source	Reference SEL, dBA	Approximate L_{max}, dBA	Prefer Measurements? *
Rail cars	82	80	No
Streetcars**	76	74	No
Locomotives – diesel	92	88	No
Locomotives – electric	90	86	No
Diesel multiple unit (DMU)	85	81	Yes
Agt – steel wheel	80	78	Yes
Agt – rubber tire	78	75	Yes
Monorail	82	80	Yes
Maglev	72	70	Yes
Transit car horns (emergency)	93	90	No
Transit car whistles	81	78	No
Locomotive horns			
At-grade crossing	113	110	No
From crossing to 1/8 mile	†	110	No
From 1/8 mile to 1/4 mile	110	110	No

* "No" implies that the source levels given in the table are appropriate to use in the analysis and "Yes" implies that measurements are preferred over the data given in the table.
** The reference speed for streetcars is 25 mph. For streetcar speeds above 25 mph, use the "Rail Cars" reference level and 50 mph for the reference speed.
† Use the following equation for locomotive horns from crossing to 1/8 mile:

$$SEL_{Ref} = 113 - 3 \times \left(\frac{D_P}{660}\right)$$

where:
D_P= distance from grade crossing parallel to tracks

A.ii. Estimate Noise Exposure at 50 ft – Use the reference SELs in Table 4-20, operating conditions, and the equations in Table 4-21 to predict the noise exposure at 50 ft expressed in terms of $L_{eq(1hr)}$ and L_{dn}. Follow the steps below:

1. **Identify operating conditions** – Trains with different numbers of cars or operating conditions produce different noise exposure levels and should be converted from SEL to L_{dn} separately. Use the following guidelines to determine if sources should be converted separately. These differences 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).

2. **Establish relevant time periods** – For each of these source types and conditions, determine the relevant time periods for all receivers that may be affected by this source.
   - For residential receivers, the time periods of interest for computation of L_{dn} are: daytime (7 a.m. to 10 p.m.) and nighttime (10 p.m. to 7 a.m.).
   - If the source will affect non-residential receivers, the time period of interest is the loudest hour of project-related activity during hours of noise sensitivity. 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.
   - Number of rail cars in the train (if this number varies during the day, take the average for the daytime and nighttime periods separately for category 2 land uses, and use the maximum number during the period of interest for category 1 or 3 land uses).
   - Number of locomotives in the train, if any.
   - Train speed, in miles per hour (maximum expected).
   - Average throttle setting of the train's locomotive(s) for diesel-powered locomotives and DMU's only.[iv] If this input is not available, assume a throttle setting of 8 for locations where the vehicle would accelerate and 5 for all other locations.[25]
   - For residential receivers of interest:
     - Average hourly train volume during daytime hours (the total number of train passbys between 7 a.m. and 10 p.m., divided by 15 hours);
     - Average hourly train volume during nighttime hours (the total number of train passbys between 10 p.m. and 7 a.m., divided by 9 hours);
   - For non-residential receivers of interest, number of events that occur during each hour of interest in trains per hour; and
   - Track type (continuously welded or jointed) and profile (at-grade or elevated).

4. **Calculate $L_{eq(1hr)}$ at 50 ft**
   - Calculate $L_{eq(1hr)}$ using the appropriate equations in Table 4-21 for each hour of interest.
   - Compute the combined $L_{eq(1hr)}$. It may be necessary to compute the combined totals with and without the warning horns; some neighborhoods along the corridor may be exposed to the horn noise and some may not.

5. **Calculate L_{dn} at 50 ft**
   - If the project noise will affect any residential receivers, calculate the L_{dn} using the combined day $L_{eq(1hr)}$ and the combined night $L_{eq(1hr)}$.
   - It may be necessary to calculate L_{dn} with and without the warning horns, as above.

[iv] Omit this term if not applicable from the equation in Table 4-21 for other vehicle types.

Note that the equations in Table 4-21 include terms to account for a difference in speed from the reference speed of 50 mph and a numerical adjustment to account for the one-hour time period for this metric. For more information on the numerical adjustment to represent the time period of interest, see Appendix B.1.4.4.

Table 4-21 Computation of $L_{eq(1hr)}$ and L_{dn} at 50 ft: Fixed-Guideway Sources

Locomotives* $L_{eq(1hr)}$ at 50 ft	$L_{eq.Loco(1hr)} = SEL_{ref} + 10\,log(N_{Loco}) + C_T + Klog(\frac{S}{50}) + 10\,log(V) - 35.6$	**Eq. 4-25**
Locomotive Warning Horns** $L_{eq(1hr)}$ at 50 ft	$L_{eq.LHorns(1hr)} = SEL_{ref} + 10\,log(V) - 35.6$	**Eq. 4-26**
Rail Vehicles† $L_{eq(1hr)}$ at 50 ft	$L_{eq.RCars(1hr)} = SEL_{ref} + 10\,log(N_{Cars}) + 20\log(\frac{S}{50}) + 10\,log(V) - 35.6 + Adj_{track}$	**Eq. 4-27**
Streetcar (25 mph or slower) $L_{eq(1hr)}$ at 50 ft	$L_{eq.SCars(1hr)} = SEL_{ref} + 10\,log(N_{Cars}) + 2\log(\frac{S}{25}) + 10\,log(V) - 35.6 + Adj_{track}$	**Eq. 4-28**
Transit Warning Horns** $L_{eq(1hr)}$ at 50 ft	$L_{eq.THorns(1hr)} = SEL_{ref} - 10\,log(\frac{S}{50}) + 10\,log(V) - 35.6$	**Eq. 4-29**
Combined Locomotive and transit†† $L_{eq(1hr)}$ at 50 ft	$L_{eq.Combo(1hr)} = 10\log(10^{(L_{eq.Loco(1hr)}/10)} + 10^{(L_{eq.RCars(1hr)}/10)} + 10^{(L_{eq.SCars(1hr)}/10)} + 10^{(L_{eq.LHorns(1hr)}/10)} + 10^{(L_{eq.THorns(1hr)}/10)}$	**Eq. 4-30**
Daytime L_d at 50 ft	$L_d = L_{eq(1hr)}$ where V = V_d, N_{Loco} = N_d (loco events), and N_{Cars} = N_d (car events)	**Eq. 4-31**
Nighttime L_n at 50 ft	$L_n = L_{eq(1hr)}$ where V = V_n, and N_{Loco} = N_d (loco events), and N_{Cars} = N_d (car events)	**Eq. 4-32**
Day/Night L_{dn} at 50 ft	$L_{dn} = 10\log(15 \times 10^{(L_d/10)} + 9 \times 10^{((L_n+10)/10)}) - 13.8$	**Eq. 4-33**

N_{Loco} = average number of locomotives per train

C_T $= 0\ for\ T < 6$
$2(T-5)\ for\ T \geq 6$
where
T = average throttle setting for diesel-powered locomotives and DMUs only

K = -10 for passenger diesel
0 for DMUs‡
+10 for electric

N_{Cars} = average number of cars per train

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

S = train speed, mph

Adj_{track} = constant
+5 for jointed track or for a crossover within 300 ft
+4 for aerial structure with slab track (except AGT and monorail)
+3 for embedded track on grade

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

$$= \frac{number\ of\ trains, 7\ a.m.\ to\ 10\ p.m.}{15}$$

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

$$= \frac{number\ of\ trains, 10\ p.m.\ to\ 7 a.m.}{9}$$

N_d = average hourly number of events that occur during daytime (7 a.m. to 10 p.m.)

$$= \frac{number\ of\ events\ between\ 7\ a.m.\ to\ 10\ p.m.}{15}$$

N_n = average hourly number of events that occur during nighttime (10 p.m. to 7 a.m.)

$$= \frac{number\ of\ events\ between\ 10\ p.m.\ to\ 7\ a.m.}{9}$$

* Assumes a diesel locomotive power rating at approximately 3000 hp ** Based on FRA's horn noise model (www.fra.dot.gov/Elib/Document/2681
† Includes all commuter rail cars, transit cars, streetcars above 25 mph, AGT and monorail. †† Only include appropriate terms.
‡ Because of the wide range of vehicle types that qualify as a DMU, measurements are preferred for the reference level and speed coefficient. If no measurements are conducted, use the reference level in Table 4-20 and a speed coefficient of 0.

Example 4-5 Detailed Noise Analysis – Fixed Guideway Noise Sources

Computation of $L_{eq(1hr)}$ and L_{dn} at 50 ft for Fixed-Guideway Source

A commuter train with 1 diesel locomotive and 6 cars will pass close to a residential area at a grade crossing. The track is jointed.

Assumptions

SEL_{ref} = 92 for diesel locomotives
= 82 for rail cars
= 113 for locomotive warning horns at-grade crossing
N_{Cars} = 6
N_{Loco} = 1
S = 43 mph
T = 8
$V_d = 40\ trains/15\ hours = 2.667\ trains\ per\ hour$
$V_n = 2\ trains/9\ hours = 0.222\ trains\ per\ hour$

Use the equations in Table 4-21 to determine the daytime $L_{eq(1hr)}$ for each source and the combined daytime $L_{eq(1hr)}$ at 50 ft.

$$L_{d.Locs(1hr)} = SEL_{ref} + 10\,log(N_{Loco}) + C_T + Klog(\frac{S}{50}) + 10\,log(V_d) - 35.6$$
$$= 92 + 10\,log(1) + 6 + (-10)log(\frac{43}{50}) + 10\,log(2.667) - 35.6$$
$$= 67.3\ dBA \text{ at 50 ft}$$

$$L_{d.RCars(1hr)} = SEL_{ref} + 10\,log(N_{Cars}) + 20log\left(\frac{S}{50}\right) + 10\,log(V_d) - 35.6 + Adj_{track}$$
$$= 82 + 10\,log(6) + 20log\left(\frac{43}{50}\right) + 10\,log(2.667) - 35.6 + 5$$
$$= 62.1\ dBA \text{ at 50 ft}$$

$$L_{d.LHorn(1hr)} = SEL_{ref} + 10\,log(V_d) - 35.6$$
$$= 113 + 10\,log(2.667) - 35.6$$
$$= 81.7\ dBA \text{ at 50 ft}$$

$L_{d.Combo(1hr)}$ With horn:
$$= 10log\left[10^{\left(L_{d.Locos(1hr)}/10\right)} + 10^{\left(L_{d.RCars(1hr)}/10\right)} + 10^{\left(L_{d.LHorn(1hr)}/10\right)}\right]$$
$= 81.9\ dBA$ in neighborhoods where the horn is sounded

Without horn:
$$= 10log\left[10^{\left(L_{d.Locos(1hr)}/10\right)} + 10^{\left(L_{d.RCars(1hr)}/10\right)}\right]$$
$= 68.4\ dBA$ in neighborhoods where the horn is not sounded

Use the same equations as above to determine the nighttime $L_{eq(1hr)}$ at 50 ft. Use V_n instead of V_d.

$L_{n.Locos(1hr)}$ = 56.5 for locomotives
$L_{n.RCars(1hr)}$ = 51.3 for cars
$L_{n.LHorn(1hr)}$ = 70.9 for horns
$L_{n.Combo(1hr)}$ = 71.1 in neighborhoods where the horn is sounded
= 57.6 in neighborhoods where the horn is not sounded

Calculate the L_{dn} with and without horns.

$$L_{dn.Combo} = 10log\left[15 \times 10^{\left(L_{d.Combo}/10\right)} + 9 \times 10^{\left((L_{n.Combo}+10)/10\right)}\right] - 13.8$$

With horn: = 81.6 at 50 ft in neighborhoods where horns are sounded
Without horn: = 68.1 at 50 ft in neighborhoods where horns are not sounded

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

Option B. Highway/Transit Sources – Compute project noise at 50 ft for highway/transit noise sources as identified in the second column of Table 4-19. Use the instructions below to estimate source noise levels for projects following FTA's procedures that involve highway vehicles.

This method is based on the original FHWA highway noise prediction model, with updated noise emission levels.(26) The vehicle equations are applicable to speeds typical of freely-flowing traffic on city streets and access roads.

B.i. Reference SEL Levels – Determine the reference SEL at 50 ft for each major highway/transit source, either by measurement according to Appendix F or by using Table 4-22.(v) The table provides guidance on which method is preferred for each source type. "NO" implies that the source levels given in the table are appropriate to use in the analysis, and "YES" implies that measurements are preferred over the data given in the table. For sources where measurements are preferred, refer to Appendix F for guidance on measurement procedures and methods for conversion of measurement data to the reference conditions in Table 4-20.

Approximate L_{max} values are provided in the table for general user information. As discussed in Appendix B.1.4.2, L_{max} is not used directly in the evaluation of noise impact.

Table 4-22 Source Reference SELs at 50 ft: Highway/Transit Sources at 50 mph

Source	Reference SEL, dBA	Approximate L_{max}, dBA	Prefer Measurements?*
Automobiles	74	70	No
Buses (diesel)	82	79	No
Buses (electric trolleybus)	80	77	No
Buses (hybrid)**	83	80	Yes

* "No" implies that the source levels given in the table are appropriate to use in the analysis and "Yes" implies that measurements are preferred over the data given in the table.
** Hybrid bus with full-time diesel engine and electric drive motors.

v Idling buses are considered stationary sources.

B.ii. Noise Exposure at 50 ft – Use the reference SELs in Table 4-22, operating conditions, and the equations in Table 4-23 to predict the noise exposure at 50 ft expressed in terms of $L_{eq(1hr)}$ and L_{dn}. Follow the steps below:

1. **Identify operating conditions** – Noise emission from most transit buses is not dependent upon whether the buses are accelerating or cruising. However, accelerating suburban buses are substantially louder than cruising suburban buses. For this reason, suburban buses require separate calculation along roadway stretches where they are accelerating. Separate calculation is also needed for all highway/transit vehicles at different speeds, since speed affects noise emissions. Use the following guidelines to determine if sources should be calculated separately. These differences 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}); or
   - 15 percent change in vehicle speed.

2. **Establish relevant time periods** – For each of these source types and conditions, determine the relevant time periods for all receivers that may be affected by this source.
   - For residential receivers, the time periods of interest for computation of L_{dn} are: daytime (7 a.m. to 10 p.m.) and nighttime (10 p.m. to 7 a.m.).
   - If the source will affect non-residential receivers, the time period of interest is the loudest hour of project related activity during hours of noise sensitivity. 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 the vehicle types of concern
   - Average running speed in miles per hour
   - For residential receivers of interest:
     - Average hourly vehicle volume during daytime hours (total number of vehicle passbys between 7 a.m. and 10 p.m., divided by 15).
     - Average hourly vehicle volume during nighttime hours (total number of vehicle passbys between 10 p.m. and 7 a.m., divided by 9).
   - For non-residential receivers of interest, number of events that occur during each hour of interest, in vehicles per hour

4. **Calculate $L_{eq(1hr)}$ at 50 ft – Calculate $L_{eq(1hr)}$ using the appropriate** equations in Table 4-23 for each hour of interest.

5. **Calculate L_{dn} at 50 ft –** If the project noise will affect any residential receivers, calculate the L_{dn} using the day $L_{eq(1hr)}$ and night $L_{eq(1hr)}$.

Note that the equations in Table 4-23 include terms to account for a difference in speed from the reference speed of 50 mph and a numerical adjustment to account for the one-hour time period for this metric. For more information on the numerical adjustment to represent the time period of interest, see Appendix B.1.4.4.

Table 4-23 Computation of $L_{eq(1hr)}$ and L_{dn} at 50 ft: Highway/Transit Sources

$L_{eq(1hr)}$ at 50 ft	$L_{eq(1hr)} = SEL_{ref} + 10\,log(V) + C_{emissions} - 10\log(\frac{S}{50}) - 35.6$	**Eq. 4-34**
Daytime L_d at 50 ft	$L_d = L_{eq(1hr)}$ where V = V_d	**Eq. 4-35**
Nighttime L_n at 50 ft	$L_n = L_{eq(1hr)}$ where V = V_n	**Eq. 4-36**
L_{dn} at 50 ft	$L_{dn} = 10log(15 \times 10^{\left(L_d/10\right)} + 9 \times 10^{\left((L_n+10)/10\right)}) - 13.8$	**Eq. 4-37**
Adjustments	= -3 for automobiles, open-graded asphalt = +3 for automobiles, grooved pavement	
V	= average hourly volume of vehicles, vehicles per hour	
$C_{emissions}$	= $25\log(\frac{S}{50})$ for buses $31\log(\frac{S}{50})$ for hybrid buses [23] 1.6 for accelerating 3-axle commuter buses $40\log(\frac{S}{50})$ for automobiles	
S	= average vehicle speed, mph (distance divided by time, excluding stop time at red lights)	
V_d	= average hourly daytime volume of vehicles of this type, vehicles per hour $= \frac{total\ vehicle\ volume, 7\ a.m.\ to\ 10\ p.m.}{15}$	
V_n	= average hourly nighttime volume of vehicles, vehicles per hour $= \frac{total\ vehicle\ volume, 10\ p.m.\ to\ 7\ a.m.}{9}$	

Example 4-6 Detailed Noise Analysis – Highway Transit Noise Sources

Computation of $L_{eq(1hr)}$ and L_{dn} at 50 ft for Highway/Transit Source

A bus route with city buses will pass close to a school that is in session from 8 a.m. to 4 p.m. on weekdays. Within this time period, the hour of greatest activity for this bus route is 8 a.m. to 9 a.m.

Assumptions

SEL_{ref} = 82 dBA

S = 40 mph

V = 30 buses per hour

Use the equations in Table 4-23 to determine the hourly $L_{eq(1hr)}$ at 50 ft.

$$L_{d.Bus} = SEL_{ref} + 10\,log(V) + C_{emissions} - 10\log(\frac{S}{50}) - 35.6$$

$$= 82 + 10\,log(30) + 6 + 25 \times log(\frac{40}{50}) - 10\log(\frac{40}{50}) - 35.6$$

$= 59.7\ dBA$ at 50 ft

This same bus also passes close to a residential area with the following operating conditions:

$$V_d = 200\ buses/15\ hours = 13.33\ buses\ per\ hour$$
$$V_n = 20\ buses/9\ hours = 2.22\ buses\ per\ hour$$

Calculate the daytime and nighttime $L_{eq(1hr)}$ at 50 ft.

$$L_{d.Bus} = 82 + 10\,log(13.33) + 6 + 25 \times log(\frac{40}{50}) - 10\log(\frac{40}{50}) - 35.6$$
$$= 56.2\ dBA \text{ at 50 ft}$$

$$L_{n.Bus} = 82 + 10\,log(2.22) + 6 + 25 \times log(\frac{40}{50}) - 10\log(\frac{40}{50}) - 35.6$$
$$= 48.4\ dBA \text{ at 50 ft}$$

Calculate L_{dn} at 50 ft.

$$L_{dn.Bus} = 10log(15 \times 10^{\left(L_{d.Bus}/_{10}\right)} + 9 \times 10^{\left((L_{n.Bus}+10)/_{10}\right)}) - 13.8$$
$$= 57.2\ dBA \text{ at 50 ft}$$

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

Option C. Stationary Sources – Compute project noise at 50 ft for stationary sources as identified in the second column of Table 4-19.

C.i. Determine Reference SEL Levels – Determine the reference SEL at 50 ft for each major stationary source, either by measurement according to Appendix F or by using Table 4-24. The table provides guidance on which method is preferred for each source type. "NO" implies that the source levels given in the table are appropriate to use in the analysis, and "YES" implies that measurements are preferred over the data given in the table. In general, measurements are preferred for source types that vary considerably from project to project. For example, curve squeal is highly variable depending on weather conditions, curve radius, and train speed. The data in the table are adequate for source types that do not vary considerably from project to project (crossing signals, for example). For sources where measurements are preferred, refer to Appendix F for guidance on measurement procedures and methods for conversion of these measurements to the reference conditions of Table 4-24.

Layover facilities and transit centers can be the sources of low-frequency noise from idling diesel engines. Sounds with considerable low-frequency components can cause greater annoyance than would be expected based on their A-weighted levels. Low-frequency sounds often cause windows and walls to vibrate resulting in secondary effects in buildings such as rattling of dishes in cupboards and wall-mounted pictures. The reference levels in Table 4-24 are adjusted to take increased annoyance into account. For a Detailed Noise Analysis at locations where such idling takes place for an extended period, use the method described in ANSI Standard S12.9-Part 4, Annex D.(27)

Approximate L_{max} values are provided in the table for general user information. As discussed in Appendix B.1.4.2, L_{max} is not used directly in the evaluation of noise impact.

Table 4-24 Source Reference SELs at 50 ft: Stationary Sources

Source	Reference SEL, dBA	Approximate L_{max}, dBA	Prefer Measurements?*
Auxiliary Equipment	101	65	Yes
Locomotive Idling	109	73	No
Rail Transit Idling	106	70	No
Buses Idling	111	75	No
Ferry Boat Landing**, Idling, and Departing	91	78	No
Ferry Boat Fog Horn	90	84	No
Track Curve Squeal	136	100	Yes
Car Washes	111	75	Yes
Crossing Signals	109	73	No
Substations	99	63	No

* "No" implies that the source levels given in the table are appropriate to use in the analysis, and "YES" implies that measurements are preferred over the data given in the table.

**Ferry boat landings are included in the stationary source category because the noise from the landing remains in one area even though the boats move in and out.

C.ii. Estimate Noise Exposure at 50 ft – Use the reference SELs in Table 4-24, operating conditions, and the equations in Table 4-25 to predict the noise exposure at 50 ft expressed in terms of $L_{eq(1hr)}$ and L_{dn}. Follow the steps below:

1. **Identify operating conditions** – Identify actual source durations and numbers of events. Sources with different operating conditions should be converted from SEL to L_{dn} separately. Use the following guidelines to determine if sources should be converted separately. These differences in operating conditions will produce an approximate 2-dB change in noise exposure:
   - 40 percent change in event duration (e.g., from 30 to 42 minutes), or
   - 40 percent change in number of events per hour (e.g., from 10 to 14 events per hour).

2. **Establish relevant time periods** – For each of these source types and conditions, determine the relevant time periods for all receivers that may be affected by this source.
   - For residential receivers, the time periods of interest for computation of L_{dn} are: daytime (7 a.m. to 10 p.m.) and nighttime (10 p.m. to 7 a.m.).
   - If the source will affect non-residential receivers, the time period of interest is the loudest hour of project related activity during hours of noise sensitivity. 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 each relevant source
   - Average duration of one event, in seconds
   - For residential receivers of interest:
     - Average number of events per hour that occur during the daytime (the total number of events between 7 a.m. and 10 p.m., divided by 15).

- Average number of events per hour that occur during the nighttime (the total number of events between 10 p.m. and 7 a.m., divided by 9).
- For non-residential receivers of interest, number of events that occur during each hour of interest in events per hour

4. **Calculate $L_{eq(1hr)}$ at 50 ft** – Calculate $L_{eq(1hr)}$ using the appropriate equations in Table 4-25 for each hour of interest.

5. **Calculate L_{dn} at 50 ft** – If the project noise will affect any residential receivers, calculate the L_{dn} using the day $L_{eq(1hr)}$ and night $L_{eq(1hr)}$.

Note that the equations in Table 4-25 include a numerical adjustment to account for the one-hour time period for this metric. For more information on the numerical adjustment to represent the time period of interest, see Appendix B.1.4.4.

Table 4-25 Computation of $L_{eq(1hr)}$ and L_{dn} at 50 ft: Stationary Sources

$L_{eq(1hr)}$ at 50 ft	$L_{eq(1hr)} = SEL_{ref} + 10\,log(N) + 10\log(\frac{E}{3600}) - 35.6$	**Eq. 4-38**
Daytime L_d at 50 ft	$L_d = L_{eq(1hr)}$ where N = N_d	**Eq. 4-39**
Nighttime L_n at 50 ft	$L_n = L_{eq(1hr)}$ where N = N_n	**Eq. 4-40**
L_{dn} at 50 ft	$L_{dn} = 10\log(15 \times 10^{\left(L_d/10\right)} + 9 \times 10^{\left((L_n+10)/10\right)}) - 13.8$	**Eq. 4-41**

N = number of events of this type that occur during one-hour

E* = duration of one event, sec

N_d = average hourly number of events that occur during daytime (7 a.m. to 10 p.m.)

$$= \frac{number\ of\ events\ between\ 7\ a.m.\ to\ 10\ p.m.}{15}$$

N_n = average hourly number of events that occur during nighttime (10 p.m. to 7 a.m.)

$$= \frac{number\ of\ events\ between\ 10\ p.m.\ to\ 7\ a.m.}{9}$$

*Omit the term containing E for ferry boat, and fog horn noise sources.

Example 4-7 Detailed Noise Analysis – Stationary Noise Sources

Computation of $L_{eq(1hr)}$ and L_{dn} at 50 ft for Stationary Sources

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

Assumptions

SEL_{ref} = 109 dBA
E = 25 seconds (counting both cycles of the signal)
N = 22

Use the equations in Table 4-25 to determine the hourly $L_{eq(1hr)}$ at 50 ft.

$$L_{d.Cross} = SEL_{ref} + 10log(N) + 10log\left(\frac{E}{3600}\right) - 35.6$$
$$= 109 + 10log(22) + 10log(\frac{25}{3600}) - 35.6$$
$$= 65.2\ dBA \text{ at 50 ft}$$

This same signal crossing lies close to a residential area with the following operating conditions:

N_d = $200\ /15\ hours = 13.3\ events\ per\ hour$
N_n =$12\ /9\ hours = 1.33\ events\ per\ hour$

Calculate the daytime and nighttime $L_{eq(1hr)}$ at 50 ft.

$$L_{d.Cross} = 109 + 10log(13.3) + 10log(\frac{25}{3600}) - 35.6$$
$$= 63.1\ dBA \text{ at 50 ft}$$
$$L_{n.Cross} = 109 + 10log(1.33) + 10log(\frac{25}{3600}) - 35.6$$
$$= 53.1\ dBA \text{ at 50 ft}$$

Calculate L_{dn} at 50 ft.

$$L_{dn} = 10log(15 \times 10^{\left(L_{d.Cross}/10\right)} + 9 \times 10^{\left((L_{n.Cross}+10)/10\right)}) - 13.8$$
$$= 63.1\ dBA \text{ at 50 ft}$$

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

Step 3: Determine Propagation Characteristics

Determine the combined propagation characteristics between each source and receiver of interest.

3a. Calculate project noise exposure as a function of distance. *Calculate the project noise exposure at distances other than 50 ft, such as at receiver locations, as a function of distance accounting for shielding and ground effects along the path.* See Example 4-8 below.

1. Determine the topography of the ground within the transit corridor using the figures in Table 4-26 as a guide. It is not necessary to represent the transit corridor with an extreme number of changes in topography. Often, several typical sections will suffice throughout the transit corridor.

2. Use the equations in Table 4-26 to determine ground factor (G) based on the effective path height (Heff) for each identified terrain feature. Standard source heights are included at the bottom of the table. Assume receiver heights of 5 ft for both outdoor receivers and first-floor receivers. Note that larger ground factors correspond to larger amounts of ground attenuation with increasing distance from the source. For acoustically "hard" (e.g., non-absorptive) ground conditions, G should be taken to be zero.

3. Determine the distance correction factor using the ground factor and another distance, such as the distance to a receiver, and the equations in Table 4-27.

4. Apply the distance correction ($C_{distance}$) to the project noise exposure at 50 ft (Section 4.5, Step 2) using the following equation:

$$L_{distance} = L_{50ft} + C_{distance}$$ **Eq. 4-42**

where:

$L_{distance}$ = L_{dn} or $L_{Aeq(1hr)}$ at the new distance, ft

L_{50ft} = L_{dn} or $L_{Aeq(1hr)}$ at 50 ft

5. Plot noise exposure as a function of distance if desired.

Table 4-26 Ground Factor G, for Ground Attenuation

Ground Factor

Soft Ground:

$$G = \begin{cases} 0.66, & H_{eff} \leq 5 \\ 0.75(1 - \frac{H_{eff}}{42}), & 5 < H_{eff} < 42 \\ 0, & H_{eff} \geq 42 \end{cases}$$

Eq. 4-43

H_{eff} = sum of average path heights on either side of the barrier, see below.

Hard Ground: $G = 0$

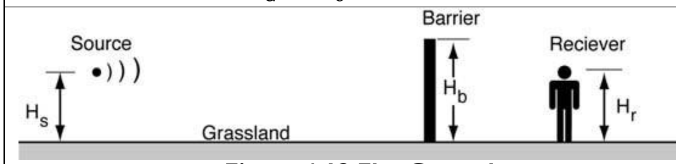

Figure 4-12 Flat Ground

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

Eq. 4-44

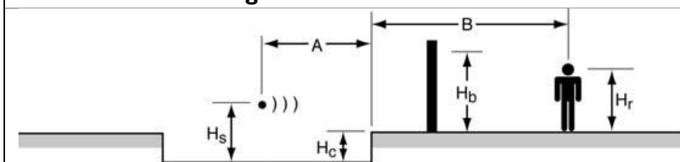

Figure 4-13 Source in Shallow Cut

$$H_{eff} = \frac{H_s + 2H_b + H_c + H_r}{2} \quad for\ B \leq \frac{A}{2}$$

Use **Eq. 4-44** $\quad for\ B > \frac{A}{2}$

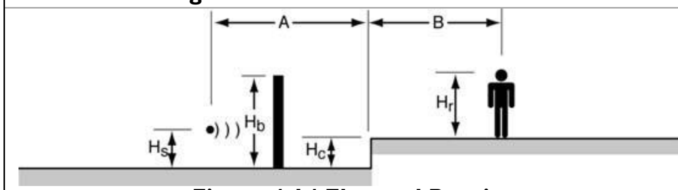

Figure 4-14 Elevated Receiver

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

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

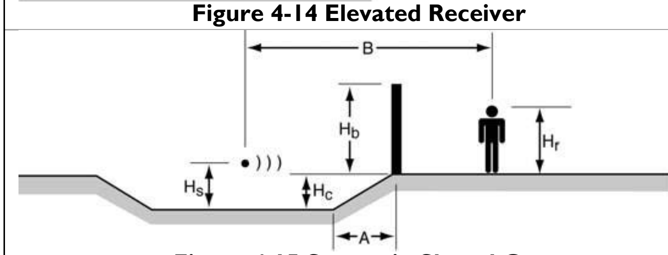

Figure 4-15 Source in Sloped Cut

Use **Eq. 4-44** $\quad for\ A \leq \frac{B}{2}$

$$H_{eff} = \frac{H_s + 2H_b + H_c + H_r}{2} \quad for\ A > \frac{B}{2}$$

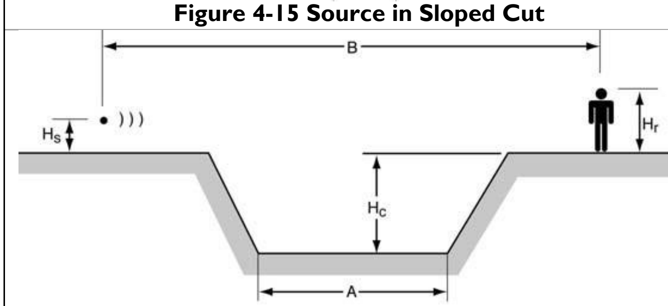

Figure 4-16 Source and Receiver Separated by Trench

$$H_{eff} = \frac{H_s + H_r}{2} \quad for\ A \leq \frac{B}{2}$$

$$H_{eff} = \frac{H_s + 2H_c + H_r}{2} \quad for\ A > \frac{B}{2}$$

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

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

Table 4-27 Distance Correction Factor Equations for Detailed Noise Analysis

Source	Equation*	
Stationary Sources	$C_{distance} = -20\log(\frac{D}{50}) - 10G\log(\frac{D}{50})$	**Eq. 4-45**
Fixed-guideway rail car passbys	$C_{distance} = -10\log(\frac{D}{50}) - 10G\log(\frac{D}{42})$	**Eq. 4-46**
Fixed-guideway locomotive and rubber-tired vehicle passbys, highway vehicle passbys and horns	$C_{distance} = -10\log(\frac{D}{50}) - 10G\log(\frac{D}{29})$	**Eq. 4-47**
$D =$ distance, ft $G =$ ground factor, see Table 4-26		

*These equations assume the distance between the source and receiver is approximately 300 ft or less. At longer distances, ground effects have an upper limit and atmospheric conditions may affect propagation characteristics. Therefore, more detailed calculation methods may be required to account for those effects.

Example 4-8: Detailed Noise Analysis – Exposure vs. Distance Curve

Exposure vs. Distance Curve for Fixed-Guideway Source

Plot an exposure vs. distance curve for a diesel-electric commuter train that does not sound the horn in this area.

Assumptions

The terrain is flat grassland without a noise barrier.

$L_{eq.Loco}\ (8-9am)$ = 72 dBA at 50 ft

$L_{dn.Loco}$ = 68 dBA at 50 ft

H_r = 5 ft

H_b = 0 ft (for a “no noise barrier” case)

H_s = 8 ft (for a diesel-electric commuter train)

Calculate H_{eff} using the equations in Table 4-26.

$$H_{eff} = \frac{H_s + 2H_b + H_r}{2} = \frac{8+0+5}{2} = 6.5 \text{ ft}$$

Determine the ground factor using Eq. 4-43.

$$G = 0.75(1 - \frac{H_{eff}}{42}) = 0.63$$

Use Eq. 4-45 to determine noise vs. exposure equations for $L_{d.loco}$ and $L_{dn.loco}$.

$$L_{eq.Loco} = 72 - 10\log(\tfrac{D}{50}) - 6.3\log(\tfrac{D}{42})$$

$$L_{dn.Loco} = 68 - 10\log(\tfrac{D}{50}) - 6.3\log(\tfrac{D}{42})$$

Plot the two equations (see example in Figure 4-17). From these curves, the noise levels due to this train operation can be determined for a receiver of interest at any distance without shielding.

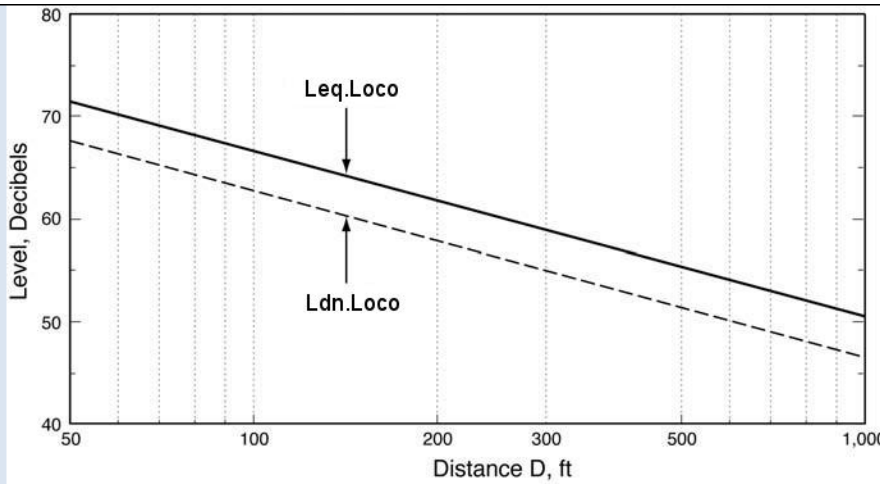

Figure 4-17 Example Exposure vs. Distance Curves

3b. Calculate the attenuation due to shielding for each distance of interest from Step 3a, using the following equation and Tables 4-26 through 4-30 and as illustrated in Example 4-9. If the conditions described in the tables are not met, the attenuation due to shielding is considered zero. Shielding can be due to intervening noise barriers, terrain features, rows of buildings, and dense tree zones.

$$A_{shielding} = \max\{IL_{barrier}\ or\ A_{buildings}\ or\ A_{trees}\} \qquad \textbf{Eq. 4-48}$$

where:

$IL_{barrier}$ = barrier insertion loss, see Table 4-28

$A_{buildings}$ = attenuation due to buildings, see Table 4-29

A_{trees} = attenuation due to trees, see Table 4-30

Table 4-28 Barrier Insertion Loss

Barrier Insertion Loss	$IL_{barrier} = \max\{0 \text{ or } (A_{barrier} - 10(G_{NB} - G_B)\log(\frac{D}{50}))\}$	**Eq. 4-49**
$A_{barrier}$	$= \min\{12\ or\ [5.3\log(P) + 6.7]\}$	For non-absorptive transit barriers within 5 ft of the rail
	$= \min\{15\ or\ (5.3\log(P) + 9.7)\}$	For absorptive transit barriers within 5 ft of the rail
	$= \min\{15 \text{or} (20\log(\frac{2.51\sqrt{P}}{\tanh(4.46\sqrt{P})}) + 5)\}$	For all other barriers, and for protrusion of terrain above the line of sight
P	= path length difference, ft (see figure 4-18)*	
D	= closest distance between the receiver and the source, ft	
G_{NB}	= ground factor G computed without barrier (see Table 4-26)	
G_B	= ground factor G computed with barrier (see Table 4-26)	

* If the source height (exhaust outlet) for diesel-electric locomotives is not available, assume 15 ft.

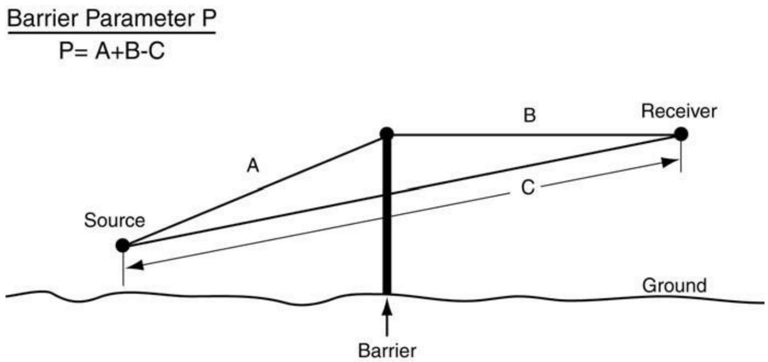

Figure 4-18 Noise Barrier Parameter "P"

Table 4-29 Attenuation due to Buildings

Condition	Equation	
Gaps in the row of buildings constitute less than 35% of the length of the row	$A_{buildings} = \min\{10\ or\ [1.5\ (R-1)+5]\}$	**Eq. 4-50**
Gaps in the row of buildings constitute 35 to 65% of the length of the row	$A_{buildings} = \min\{10\ or\ [1.5\ (R-1)+3]\}$	**Eq. 4-51**
Gaps in the row of buildings constitute more than 65% of the length of the row	$A_{buildings} = 0$	
R = number of rows of houses that intervene between the source and receiver		

Table 4-30 Attenuation due to Trees

Condition	Equation	
At least 100 ft of trees intervene between the source and receiver with no clear line-of-sight between source and receiver, and the trees extend 15 ft or more above the line-of-sight	$A_{trees} = \min\left\{10\ or\ \frac{W}{20}\right\}\ where\ W \geq 100ft$ $= 0\ where\ W < 100ft$	**Eq. 4-52**
W = width of tree zone along the line-of-site between the source and receiver in feet		

Example 4-9: Detailed Noise Analysis – Shielding

Computation of Shielding

The following features are between the rail corridor and a receiver of interest. Calculate the attenuation due to shielding.

1. A 15-foot high noise barrier is 40 ft from the closest track and 130 ft from the receiver
2. A dense tree zone 100 ft thick that extends 15 ft above the line-of-sight

Assumptions

H_s = 8 ft
H_r = 5 ft

Barrier dimensions

A = 40.61 ft
B = 130.38 ft
C = 170.03 ft

Barrier

Calculate H_{eff} with and without the barrier using the equations in Table 4-26.

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

$$= \frac{8+0+5}{2}$$

= 6.5 ft

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

$$= \frac{8+15+5}{2}$$

= 21.5 ft

Determine the ground factor with and without the barrier using Eq. 4-43.

$$G_{NoBarrier} = 0.75(1 - \frac{H_{eff}}{42})$$

$$= 0.63$$

$$G_{Barrier} = 0.75(1 - \frac{H_{eff}}{42})$$

$$= 0.37$$

Calculate the barrier insertion loss using Table 4-28 and Figure 4-18.

$$P = A + B - C$$

$= 0.96$ ft

$$A_{barrier} = \min\{15 \text{or} (20 \log(\frac{2.51\sqrt{P}}{\tanh\left(4.46\sqrt{P}\right)}) + 5)\}$$

= 12.8 dB

= min { $15\ or\ 12.8\}$

= 12.8 dB

$$IL_{barrier} = \max\{0 \text{ or } (A_{barrier} - 10(G_{NoBarrier} - G_{Barrier}) \log(\frac{D}{50}))\}$$

$$= 12.8 - 10(0.63 - 0.37) \log(\frac{170}{50})$$

= 11.4 dB

Trees

Determine the attenuation due to trees using Table 4-30.

$$A_{trees} = \min\{10\ or\ \frac{W}{20}\}$$

$= 5$ dB

Total Shielding

The total shielding is the maximum of the barrier and tree zone shielding, 11.4 dB.

$$A_{shielding} = \max\{IL_{barrier}\ or\ A_{buildings}\ or\ A_{trees}\}$$

$$= \max\{11.4\ or\ 0\ or\ 5\}$$

= 11.4 dB

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

3c. Combine the two propagation characteristics.
Combine the results from Steps 3a and 3b to determine the noise at the receiver considering the propagation characteristics of distance and shielding by applying the distance correction and attenuation due to shielding to the project noise exposure level at 50 ft.

The equations in Table 4-31 combine the equations in Steps 3a and 3b.

Table 4-31 Calculate L_{dn} or $L_{eq(1hr)}$

Source	Equation*	
Stationary Sources	$L_{DistShield} = L - 20\log(\frac{D}{50}) - 10G\log(\frac{D}{50}) - A_{shielding}$	**Eq. 4-53**
Fixed-guideway rail car passbys	$L_{DistShield} = L - 10\log(\frac{D}{50}) - 10G\log(\frac{D}{42}) - A_{shielding}$	**Eq. 4-54**
Fixed-guideway locomotive and rubber-tired vehicle passbys, highway vehicle passbys and horns	$L_{DistShield} = L - 10\log(\frac{D}{50}) - 10G\log(\frac{D}{29}) - A_{shielding}$	**Eq. 4-55**
L = L_{dn} or L_{eq} D = distance, ft G = ground factor, see Section 4.5, Step 3a $A_{shielding}$ = attenuation due to shielding, see Section 4.5, Step 3b.		

*These equations assume the distance between the source and receiver is approximately 300 ft or less. At longer distances, ground effects have an upper limit and atmospheric conditions may affect propagation characteristics. Therefore, more detailed calculation methods may be required to account for those effects.[28, 29]

Step 4: Combine Noise Exposure from All Sources

Combine all sources to predict the total project noise at the receivers using the equations in Table 4-32 after propagation adjustments have been made for the noise exposure from each source separately.

Table 4-32 Computing Total Noise Exposure

Total $L_{eq(1hr)}$ from all sources for the hour of interest:	$L_{eq.total(1hr)} = 10\log(\sum_{all\ sources} 10^{L_{Aeq(1hr)}/10})$	**Eq. 4-56**
Total L_{dn} from all sources	$L_{dn.total} = 10\log(\sum_{all\ sources} 10^{L_{dn}/10})$	**Eq. 4-57**

Example 4-10 Detailed Noise Analysis – Combine Sources

Computation of Total Exposure from Combined Sources

Combine the noise exposure from the commuter train and light rail system to estimate the total noise exposure at the receiver.

Assumptions
A commuter train operation produces the following levels at a receiver of interest:

$L_{eq.Commuter}$ = 72 dBA
$L_{dn.Commuter}$ = 68 dBA

A light rail system produces the following levels at the same receiver:

$L_{eq.LightRail}$ = 69 dBA

$L_{dn.LightRail}$ = 70 dBA

No other project sources affect this receiver.

Calculate the total noise exposure at the receiver using the equations in Table 4-32.

$$L_{eq.total} = 10\log(10^{(72/10)} + 10^{(69/10)})$$
$$= 73.8 \text{ dBA}$$
$$L_{dn.total} = 10\log(10^{(68/10)} + 10^{(70/10)})$$
$$= 72.1 \text{ dBA}$$

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

Step 5: Determine Existing Noise Exposure

Choose the appropriate method for characterizing noise and then determine the existing noise at each identified noise-sensitive receiver. The existing noise is needed to determine the noise impact according to the criteria described in Section 4.1, Step 2. Recall that impact is assessed based on a comparison of the existing ambient noise exposure and the additional noise exposure that will be caused by the project. The existing noise exposure must be estimated for all receivers of interest identified in Section 4.5, Step 1.

For a Detailed Noise Analysis, it is recommended to measure existing noise at each receiver of interest identified in Section 4.5, Step 1, for the most precise assessment of existing noise and conclusions concerning noise impact. However, measurements are expensive, often thwarted by weather, and take considerable time in the field. If taking measurements at each identified receiver is not possible, other less precise methods are available. Different methods may be used at different receivers along the project. However, it is important to recognize the correlation between the precision of measurements and the confidence in the impact assessment. Especially in a Detailed Noise Analysis, avoid using less precise methods of measuring existing noise just for the sake of convenience or expediency. The use of less precise methods must be clearly justified.

Option A. Noise Exposure Measurements – Full one-hour measurements are the most appropriate way to determine ambient noise exposure for non-residential receivers with the level of precision expected in a Detailed Noise Analysis**.** For residential receivers, full 24-hour measurements are more appropriate. These full-duration measurements are preferred over other methods of characterizing existing noise where time and study funds allow.

Follow the procedures below for these full-duration ambient noise exposure measurements:

Ai. Non-residential land uses – Measure a full hour $L_{eq(1hr)}$ at the receiver of interest on at least two non-successive weekdays (generally between noon on Monday and noon on Friday). Select the hour of the day when the maximum project activity is expected to occur.

A.ii. Residential land uses – Measure a full 24-hour L_{dn} at the receiver of interest for a single weekday (generally between noon on Monday and noon on Friday).

A.iii. Microphone position – The location of the microphone at the receiver depends upon the proposed location of the transit noise source, so use good technical judgment in positioning the measurement microphone. If, for example, a new rail line will be in front of the house, do not locate the microphone in the backyard behind the house where the line of sight between the noise source and receiver is obstructed. Figure 4-19 illustrates recommended measurement positions for various locations of the project, with respect to the house and the existing source of ambient noise.

A.iv. Measurement guidelines – Undertake all measurements in accordance with good engineering practice following guidelines given in ASTM and ANSI standards.(30)(31)

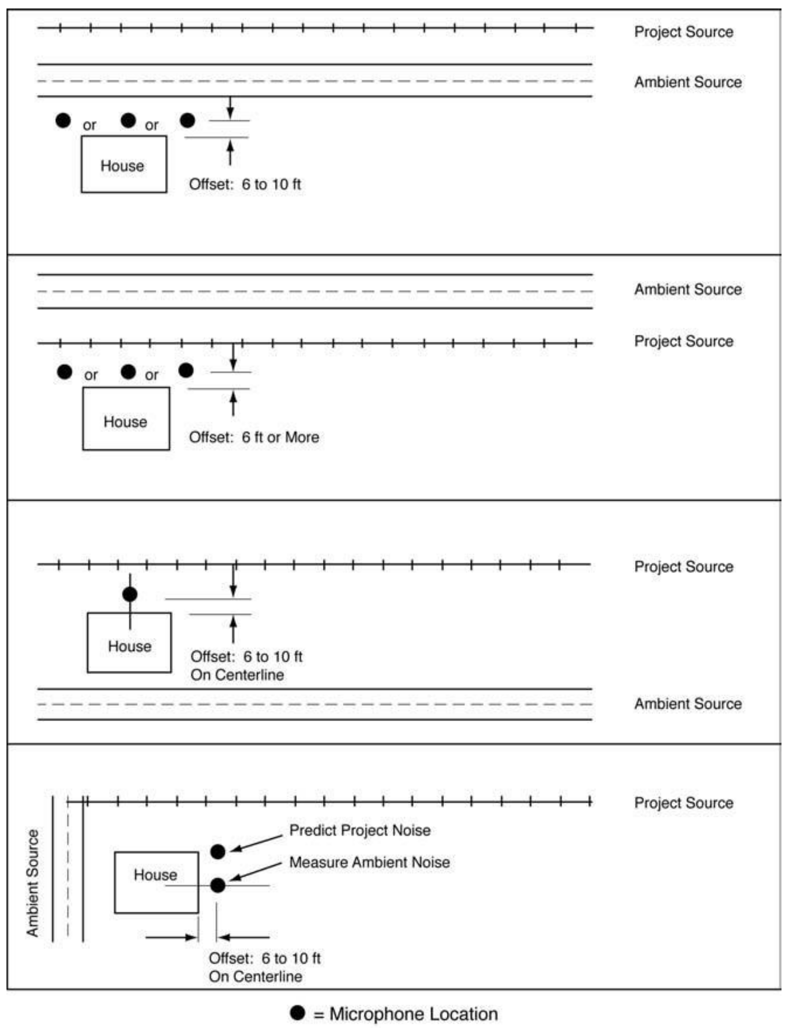

Figure 4-19 Recommended Microphone Locations for Existing Noise Measurements

Option B. Noise Exposure Computations from Partial Measurements – Often, measurements can be made at some of the receivers of interest and used to estimate noise exposure at nearby receivers. In other situations, several $L_{eq(1hr)}$ measurements can be taken at a receiver and then the L_{dn} computed from these. Both options require experience and knowledge of acoustics to select representative measurement sites. If using this method to compute an Ldn, a minimum time period of one hour should be used for each measurement period. It is unacceptable to extrapolate a one hour measurement from a shorter measurement period.

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. Residential neighborhoods with otherwise similar homes may have greatly varying noise environments. For example, one area of the neighborhood may be located where the ambient noise is clearly due to highway traffic. A second area toward the interior of the neighborhood may have highway noise as a factor, but also include other noise sources from the community. A third area located deep into the residential area could 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:

- 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 to use their experience and judgment in fully utilizing the measurements in their computations. This does necessitate a conservative estimate (underestimate) of existing noise to account for reduced precision from partial data as compared to full noise measurements.

Those without a background in acoustics are encouraged to use the procedures in Appendix E to compute existing noise from partial measurements. These methods include a factor to conservatively estimate (underestimate) existing noise to account for reduced precision from partial data as compared to full noise measurements.

Option C. Estimating Existing Noise Exposure – The least precise way to determine noise exposure is to estimate it from a table. This method is often used for the General Noise Assessment, but it is not recommended for a Detailed Noise Analysis. It can be used, however, in the absence of better data for locations where roadways or railroads are the predominant ambient noise source. Table 4-17 presents these existing levels. The levels in Table 4-17 are conservative and underestimate existing noise to account for reduced precision compared to full noise measurements. If a simplified procedure to estimate existing noise exposure is chosen it must be clearly justified and receive approval by the FTA Regional office.

While measurements are considered the most precise method, there is one situation where it may be more accurate to estimate rather than measure the existing noise exposure, which is in areas near major airports where aircraft noise is dominant. Because airport noise is highly variable based on weather conditions and corresponding runway usage, it is preferable in such cases to base the existing noise exposure on published aircraft noise contours in terms of Annual Average L_{dn}.

Step 6: Assess Noise Impact

Assess noise impact at each receiver of interest identified in Section 4.5, Step 1 using the noise impact criteria in Section 4.1 and the procedures in this step. Choose the appropriate noise impact assessment procedure for a transit project or multimodal project.

Option A. Transit Projects – For transit projects, noise impact is assessed at each receiver of interest using the criteria for transit projects described in Section 4.1. The noise impact assessment procedure is as follows:

A.i. Tabulate existing ambient noise exposure (rounded to the nearest whole decibel) at all receivers identified Section 4.5, Step 1. In cases where large residential buildings are exposed to noise on one side only, the receivers on that side are included in the analysis.

A.ii. Tabulate project noise exposure at these receivers from Section 4.5, Step 4.

A.iii. Determine the level of noise impact (no impact, moderate impact, or severe impact) according to Section 4.1.

A.iv. Document the results in noise-assessment inventory tables. Include the following 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, moderate impact, or severe impact)
- A sum of the total number of receivers and numbers of dwelling units predicted to experience moderate impact or severe impact

A.v. Illustrate the areas of moderate impact and severe impact. Two methods of displaying impact are labeling and contouring.

- In a Detailed Noise Analysis, the most accurate indication of impact is to label each impacted building or cluster identified in the inventory table.
- A less precise illustration of impacted areas is a plot of project noise contours on the maps or aerial photographs, along with shaded impact areas. Use the procedures in Section 4.4, Step 6 and the levels from Section 4.5, Step 2 to develop these contours.

Note that it is difficult to position noise contours in urban areas due to shielding, terrain features, and other propagation anomalies. If noise contours are used, they should be considered illustrative rather than definitive. If desired to conform to 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 dBA.

A.vi. Including information on 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 moderate impact and severe impact.

Option B. Multimodal Projects – For multimodal projects, project noise comprised of both highway and transit noise sources that are assessed according to the FTA noise impact criteria (see Table 4-2), use the procedure in Option A above. For multimodal projects that require FHWA's noise assessment methods to inform FTA's evaluation (see Section 4.1, Step 1 - Option B), follow the FHWA guidance.(32) In general, the appropriate calculation method is to use the current version of FHWA's Traffic Noise Model (TNM).(22) TNM is a state-of-the-art computer program used for predicting noise impacts near highways.

TNM allows for a detailed assessment at each receiver of interest by separately calculating the noise contribution of each roadway segment. For each roadway segment, the noise from each vehicle type is computed from reference noise levels, adjusted for:

- Vehicle volume
- Vehicle speed
- Grade
- Roadway segment length
- Source-to-receiver distance

Further adjustments needed to accurately model the sound propagation from source to receiver include:

- Shielding provided by rows of buildings,
- Effects of different ground types,
- Source and receiver elevations, and
- Effect of any intervening noise barriers.

TNM sums the noise contributions of each vehicle type for a given roadway segment at the receiver. TNM then repeats this process for all roadway segments, summing their contributions to generate the predicted noise level at each receiver.

Step 7: Determine Noise Mitigation Measures

Evaluate alternative mitigation measures where the Detailed Noise Analysis shows either severe or moderate impact, and it is not feasible to change the alignment or location of the project to avoid impact. Project noise that is found to cause no impact does not generally require any mitigation.

Mitigation of noise impact from transit projects may involve treatments at the three fundamental components of the noise problem: at the noise source, along the source-to-receiver propagation path, or 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 at the receiver. After mitigation options have been determined, repeat the project noise computations including the adopted mitigation and reassess the remaining noise impact.

Approximate costs for noise control measures are documented in a report from the Transit Cooperative Research Program (TCRP)[(33)] and are also presented in this section. These costs reflect the noise mitigation costs available in 1997 (unless otherwise noted), which are the most recent data available as of this publication, and should only be used as representative estimates when considering noise mitigation options. Current noise mitigation costs should be researched before decisions on noise mitigation options are finalized, and then they should be documented according to Section 8.

7a. Evaluate Source Treatments – The most effective noise mitigation treatments are applied at the noise source. This is the preferred approach to mitigation when possible. Common source treatments and their estimated acoustical effectiveness are included in Table 4-33 and described below. It is important to note that the values below are estimates and should be applied with good engineering judgement. It also important to note that these mitigation measures should not be applied as a reduction in the reference SEL values for a vehicle that already incorporates that measure as a feature, such as vehicle skirts. Measurements to determine the reference SEL source level are required in those instances.

Table 4-33 Transit Noise Mitigation Measures – Source Treatments

Mitigation Measure		Effectiveness
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
Quiet Fan Design and Fan Placement*		Varied
Preventative Maintenance on Rail Systems*		Varied
Resurfacing Roads**		10 dB
Guideway Support for Buses**		10 dB
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		6-10 dB
Quiet Zones*		Reduces occurrence of horn noise

†FTA does not normally accept operational restrictions as a noise mitigation measure – see below.
* Applies to rail projects only.
** Applies to bus projects only.

- **Stringent Vehicle and Equipment Noise Specifications**
  - **Vehicles** – Among the most effective noise mitigation treatments is noise control 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 considering the noise reduction benefits and costs.

    Effective enforcement includes penalties for non-compliance with the specifications. The noise mitigation achieved by source treatment is dependent on the quality of installation and maintenance. Vehicles failing to meet the noise specification could result in complaints from the public and require additional noise mitigation measures applied along the path or at receivers.

  - **Stationary sources** – Stringent but achievable noise specifications for stationary sources are also an effective approach for mitigating noise impacts. Typical equipment includes fixed plant equipment such as transformers and mechanical equipment, as well as grade-crossing signals. For example, it may be possible to reduce noise impact from grade-crossing signals in some areas by specifying equipment that sets the level of the warning signal lower in locations where ambient noise is lower to minimize the signal noise in the direction of noise-sensitive receivers.

- **Operational Restrictions** – Changes in operations that can mitigate noise include the lowering of speed, the reduction of nighttime (10 p.m. to 7 a.m.) operations, and reduction of warning horns and signals.

  - **Speed reduction** – Because noise from most transit vehicles is dependent 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 $L_{eq(1hr)}$ and L_{dn} (Table 4-21) results in a 6-dB reduction when reducing the speed to half of the original speed.

    Although there are tangible benefits from speed reductions during the most noise-sensitive time periods, FTA does not ordinarily accept speed reduction as a noise mitigation measure for two important reasons: speed reduction is unenforceable and negated if vehicle operators do not adhere to established policies, and it is contrary to the purpose of the transit investment by FTA, which is to move as many people as possible as efficiently and safely as possible.

  - **Reduction of nighttime operations** – Complete elimination of nighttime operations has a strong effect on reducing the L_{dn}, because nighttime noise is increased by 10 dB when calculating L_{dn}. But restrictions on operations are usually not feasible because of service demands. FTA generally does not pursue restrictions on operations as a noise reduction measure. However, if early morning idling can be curtailed to the minimum necessary, however, this can have a measurable effect on L_{dn}.

While there are tangible benefits from limits on operations during the most noise-sensitive time periods, FTA does not recommend limits on operations as a way to reduce noise impacts because it is contrary to the purpose of the transit investment by FTA which is to move as many people as possible as efficiently and safely as possible.

 - **Reduction of warning horns and signals** – Minimizing or eliminating horns and other warning signals at gate crossings can reduce noise impact for light rail and commuter rail systems. Although these mitigation options are limited by safety considerations, they can be effective in the right circumstances. For examples, see quiet zones below and wayside horns in Step 7b.

- **Wheel Treatments (Rail)** – A major source of noise from steel-wheel and steel-rail systems is the wheel/rail interaction that can produce three distinctive sounds: roar, impact, and squeal (as discussed in Section 3.2). 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 spot on the wheels. Squeal occurs when a steel-wheel tread or its flange rubs across the rail, resulting in resonant vibrations in the wheel that creates a screeching sound. Various wheel designs and other mitigation measures exist to reduce the noise from each of these three mechanisms.

  - **Resilient wheels** – Resilient wheels are effective in eliminating wheel squeal on tight turns with reductions of 10 to 20 dB in the high-frequency range where squeal noise occurs. Rolling noise is also slightly reduced with resilient wheels and typically achieves a 2-dB reduction on tangent track. The costs for resilient wheels are approximately $2000 to $3000 per wheel, as compared to about $400 to $700 for standard steel wheels.[(vi)]

  - **Damped wheels** – Damped wheels, like resilient wheels, are effective in eliminating wheel squeal on tight turns with reductions of 5 to 15 dB in the high-frequency range where squeal occurs. Rolling noise is also slightly reduced by approximately 2 dB on tangent track. This treatment involves attaching vibration absorbers to standard steel wheels. The costs for damped wheels add approximately $500 to $1000 to the normal $700 for each steel wheel.

[vi] Assumes 8 wheels per vehicle.

- **Vehicle Treatments** – 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. The mitigation options for these systems include:

  - **Quiet fan design and placement** – Fan noise can be reduced by installation 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 considerable difference in the noise radiated to the wayside or to patrons on the station platforms.

  - **Vehicle skirts and undercar absorption** – 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 dB 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 dB of mitigation. By carrying their own noise barriers, vehicles with these features can provide cost-effective noise reduction. The cost for vehicle skirts will add approximately $5000 to $10000 per vehicle. Undercar absorption will add approximately $3500 per vehicle, assuming that 50% of the underside of the floor is treated.

- **Preventative Maintenance (Rail)** – Preventative maintenance is the best strategy to minimize rail and wheel deterioration. While these are not mitigation measures in the traditional sense and should not be included as mitigation in an environmental document, they can help to keep both noise and vibration levels at a "like-new" level or reduce both noise and vibration in systems with deferred maintenance. This can be accompanied by considerable life cost benefits for the transit system.

  - **Spin-slide control systems** – Similar to anti-locking brake systems (ABS) on automobiles, spin-slide control systems reduce the incidence of wheel flats, a major contributor of impact noise. Trains with smooth wheel treads can be up to 20 dB 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. The cost of slip-slide control may be incorporated in the new vehicle costs, but may be between $5,000 and $10,000 per vehicle with a maintenance cost of $200 per year.

- **Wheel truing** – 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. As a guideline, it is recommended that wheel sets match within approximately ±0.01 inch and all wheels on the same truck should match within ±0.02 inches to minimize damage and wear to wheels and rails.(34) A wheel truing machine costs approximately $1 million, including associated maintenance materials and labor costs. The TCRP report estimates a system with 700 vehicles would incur a yearly cost of $300,000 to $400,000 for a wheel truing program.

  It is recommended to install wheel-flat detector systems to identify vehicles that are most in need of wheel truing. These systems are becoming more common on railroads and intercity passenger systems, but are relatively rare on transit systems.

- **Rail grinding** – The smoothness of the running surface is critical in the mitigation of noise from a moving vehicle. Mill scale grinding before commencement of pre-revenue service train operations is critical. Experience shows that grinding new rails after approximately 3 months of train operations and scheduling routine grinding at approximate intervals of 2 years in the problem areas would minimize noise problems related to corrugation in most cases. Grinding with small machines when the corrugation depth is still small is a reasonable approach. As a guideline, it is recommended to spot-grind at locations where corrugation occurs before corrugation grows to 0.02 inches (32).

  Periodic rail grinding can result in a net savings per year on wheel and rail wear. Most transit systems contract out rail grinding, although some of the larger systems make the investment of approximately $1 million for the equipment and do their own grinding. Contractors typically charge a fixed amount per day for the equipment on site, plus an amount per pass-mile (one pass of the grinding machine for one mile). Typical rail grinding cost would be approximately $7,000 to $10,000 per pass-mile.

- **Wheel and rail profile matching** – It is important to consider the wheel and rail profile compatibility when truing wheels and grinding rails. If the profiles do not match, the benefits of this kind of preventative maintenance will not be achieved.

  It is equally important to consider initial wheel and rail profile compatibility. Work with track designers and vehicle suppliers early in the design process to ensure wheel and rail profile compatibility. Profiles should be defined during the design phase and should be in place when system opens.[32] The cost of wheel and rail profile matching may be incorporated in the new vehicle and new rail costs.

Profile grinding of the rail head in combination with a wheel truing program may be the most practical approach to controlling and reducing noise and vibration where such practices are not normally conducted.

  - **Maintenance program** – Clearly defined maintenance specifications should be developed during design phase of the project. The specifications should define rail and wheel profiles, include detailed guidance for pre-revenue mill scale grinding, address issues related to healthy rail-wheel interface, and include a mechanism for periodic monitoring of wheel and rail condition and verification for compliance.[32] A diligent maintenance program can often resolve or reduce rail noise issues before they occur. Vehicle reconditioning programs should also be developed particularly for components such as suspension system, brakes, wheels, and slip-slide detectors.

- **Guideway Support (Bus)** – The smoothness of the running surface is critical in the mitigation of noise from a moving vehicle.
  - **Resurfacing roads** – Roughness on the guideway can be eliminated by resurfacing roads, thereby reducing noise levels by up to 10 dB.

  - **Bridge expansion joint angles and design** – 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.

- **Turn Radii and Rail Lubrication** – For steel-wheel/steel-rail systems with non-steerable trucks and sharp turns, squeal can typically be eliminated by designing all turn radii to be greater than 1000 ft, or 100 times the truck wheelbase, whichever is less. If this is not possible, squeal can be mitigated by installation of lubricators (though the potential environmental impacts of lubricant application should be factored into this decision).Rail lubricators cost approximately $10,000 - $40,000 per curve.

- **Movable-point and Spring-rail Frogs** – Frogs with spring-loaded mechanisms and frogs with movable points can reduce impact noise near crossovers. According to the TCRP report, a spring frog costs approximately $12,000, twice the cost of a standard frog. A movable point frog involves elaborate signal and control circuitry resulting in higher costs of approximately $200,000.

- **Use of Locomotive Horns at-grade Crossings and Quiet Zones** – In cases where commuter rail operations share tracks or ROW with freight or intercity passenger trains that are part of the general railroad system, the safety rules of the FRA, including the Train Horn Rule, apply.[35] The Train Horn Rule requires that locomotive horns be sounded at public highway grade crossings, although some exceptions are allowed in carefully defined circumstances. Locomotive horns are often a major contributor in projections of adverse noise impact, in the community from proposed commuter rail projects. Since noise barriers are not feasible at highway-rail grade crossings, the establishment of quiet zones could be considered.

Quiet zones can be established in which supplemental safety measures (SSMs) are used in place of the locomotive horn to provide an equivalent level of safety at-grade crossings.[vii] By adopting an approved SSM at each public grade crossing, a quiet zone of at least a half-mile long can be established. These measures are in addition to the standard safety devices required at most public grade crossings (e.g., stop signs, reflectorized crossbucks, flashing lights with gates that do not completely block travel over the tracks). Below are four SSMs that have been predetermined by the FRA to fully compensate for the lack of a locomotive horn:

- **Temporary closure of a public highway-rail grade crossing** – This measure requires closure of the grade crossing for one period each 24 hours, and the closure must occur at the same time each day.
- **Four-quadrant gate system** – This measure involves the installation of at least one gate for each direction of traffic to fully block vehicles from entering the crossing.
- **Gates with medians or channelization devices** – This measure keeps traffic in the proper travel lanes as it approaches the crossing. This denies the driver the option of circumventing the gates by traveling in the opposing lane.
- **One-way street with gates** – This measure consists of one-way streets with gates installed, so that all approaching travel lanes are completely blocked.

In addition to the pre-approved SSMs, the FRA rule also identifies a range of other measures that may be used in establishing a quiet zone. These could include modified SSMs or non-engineering types of measures, such as increased monitoring by law enforcement for grade crossing violations or instituting public education and awareness programs that emphasize the risks associated with grade crossings and applicable requirements. These alternative safety measures (ASMs) require approval by FRA based on a demonstration that public safety would not be compromised by eliminating horn usage.

The lead agency for designating a quiet zone is the local public authority responsible for traffic control and law enforcement on the roads crossing the tracks. To satisfy the FRA regulatory requirements, the public transit agency must work closely with this agency while also coordinating with any freight or passenger railroad operator sharing the ROW. The final environmental document should discuss the main considerations in adopting the quiet zone including: the engineering feasibility, receptiveness of the local public authority, consultation with the railroad, preliminary cost estimates, and evidence of the planning and interagency coordination that has occurred to date. If a quiet zone will be relied on as a mitigation measure, the final environmental document should provide reasonable

[vii] For more information on quiet zones, visit: https://www.fra.dot.gov/Page/P0889.

assurance that any remaining issues can and will be resolved. For more information on documentation requirements see Section 8.

The cost of establishing a quiet zone varies considerably, depending on the number of intersections that must be treated and the specific SSMs, ASMs, or combination of measures that are used. The FRA gives a cost estimate of $15,000 per crossing for installing two 100-foot-long, non-traversable medians that prevent motorists from driving around closed gates. A typical installation of a four-quadrant gate system is in the range of $175,000–$300,000 per crossing.(36) Who pays for the installation of modifications can become a major consideration in a decision to pursue a quiet zone designation, especially in cases where noise from preexisting railroad operations is controversial in the community. In many cases where a quiet zone would mitigate a severe impact caused by the proposed transit project, the costs are covered by the project sponsor and FTA in the same proportion as the overall cost-sharing for the project.

7b. Evaluate Path Treatments – When noise mitigation treatments cannot be applied at the noise source or additional mitigation is required after treating the source, the next preferred placement of noise mitigation is along the noise propagation path between the source and receiver. Common path treatments and their estimated acoustical effectiveness are included in Table 4-34 and described below.

Table 4-34 Transit Noise Mitigation Measures – Path Treatments

Mitigation Measure	Effectiveness
Noise barriers close to vehicles	6-15 dB
Noise barriers at row line	3-15 dB(37)
Alteration of horizontal & vertical alignments	Varied
Wayside horns	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
Vegetation and trees	Varied, see Table 4-30

* Applies to rail projects only.

- **Noise Barriers** – Noise 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 Section 3.3. The necessary height of a barrier depends on the source height and the distance from the source to the barrier, see Table 4-28 and Figure 4-18.
  - **Noise barriers close to vehicles** – Barriers located very close to a rapid transit train, for example, may only need to be approximately 3 to 4 ft above the top of rail to be effective. Standard barriers close to vehicles can provide noise reductions of 6 to 10 dB.
  - **Noise barriers at ROW line –** Barriers on the ROW line or for trains on the far track, the height must be increased to provide equivalent effectiveness to barriers located close to the vehicles. Otherwise, the effectiveness can drop to 3 dB or less, even if the barrier breaks the line-of-sight.

All barrier effectiveness can be increased by as much as 5 dB by applying sound-absorbing material to the inner surface of the barrier. The length of the barrier wall is also important to its effectiveness. The barrier must be long enough to block noise from 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 noise-sensitive locations. The barrier length can be refined in the engineering phase, closely examining the predicted sound level exceedances at specific receivers, site geometries, and the contribution of barrier flanking noise, then adjusting the length as appropriate.

Noise barriers can be made of any outdoor weather-resistant solid material that meets the minimum sound transmission loss required by the project. Materials that are commonly used for noise barriers include 16-gauge steel, 1-inch thick plywood, and any reasonable thickness of concrete. Typically, a surface density of 4 pounds per square foot is required. Areas with strong winds may require more stringent structural requirements. It is critical to seal any gaps between barrier panels and between the barrier and the ground or elevated guideway deck for maximum performance.

Costs for noise barriers (based on highway installations) range from $20 to $25 per square foot of installed noise barrier at-grade with additional cost for design and inspection.(38) Installation on aerial structures could be twice the amount of installation at-grade, especially if the structure has to be strengthened to accommodate the added weight and wind load.

As described in Section 3.3, noise barriers, if not designed and sited carefully, can reduce visibility of trains for pedestrians and motorists, which causes safety concerns. It is important to consult with safety experts in choosing and siting a noise barrier.

- **Alteration of Horizontal and Vertical Alignments** – Transit alignment in a 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.

- **Wayside Horns** – The sounding of a locomotive horn as the train approaches an at-grade intersection produces a very wide noise footprint in the community. Using wayside horns at these intersections instead of the locomotive horn can substantially reduce the noise footprint without compromising safety at the grade crossing.

  A wayside horn does not need to be as loud as a locomotive horn, and the warning sound is focused only on the area where it is needed. These are pole-mounted horns used in conjunction with flashing lights and gates at the intersection, with a separate horn oriented toward each direction of oncoming vehicle traffic. Noise levels in nearby residential and business areas can be reduced substantially with wayside horns, depending on the location with respect to the grade crossing.

A plan to use wayside horns in place of the locomotive horn at public grade crossings must be coordinated with several public and private entities, notably the local agency having responsibility for traffic control and law enforcement on the road crossings, the state agency responsible for railroad safety, any railroads that share the ROW, and FRA. Public notification must also be given. Preliminary cost information from testing programs indicates a wayside horn system at a railroad/highway grade crossing costs approximately $50,000.

- **Buffer Zones** – Because noise levels attenuate with distance, one noise mitigation option is to increase the distance between noise sources and the closest noise-sensitive receivers. This can be accomplished by locating alignments away from noise-sensitive sites. Acquisition of land or purchasing easements for noise buffer zones is an option that may be considered if appropriate for the project.

- **Ground Absorption – Ballast on Guideways** – 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 substantial effect on the propagation of noise to greater distance. 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 dB at-grade and up to 5 dB on an aerial structure.

- **Vegetation and Trees** – In almost all cases, vegetation and trees are ineffective at providing noise mitigation. Vegetation and Trees can provide some mitigation if at least 100 ft of trees intervene between the source and receiver, if no clear line-of-sight exists between the source and receiver, and if the trees extend 15 ft or more above the line-of-sight as described in Section 4.5, Step 3b. This is generally not a recommended form of mitigation to pursue.

7c. Evaluate Receiver Treatments – Consider treatments to the receivers when noise mitigation treatments cannot be applied at the source or along the propagation path, or if combinations of treatments are required. Common receiver treatments and their estimated acoustical effectiveness are included in Table 4-35 and are described in this section.

Table 4-35 Transit Noise Mitigation Measures – Receiver Treatments

Mitigation Measure	Effectiveness
Acquisition of Property Rights for Construction of Noise Barriers	5-10 dB
Building Noise Insulation	5-20 dB

- **Noise Barriers** – In certain cases, it may be possible to acquire limited property rights for the construction of noise 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. See Section 3.3 for more information on noise barriers.

- **Building Insulation** – In cases where noise barriers are not feasible—such as multi-story buildings, buildings very close to the ROW, or grade crossings—the only practical noise mitigation measure may be to provide sound insulation for the buildings. In these cases, the need for mitigation at locations where impact has been identified will depend on the use (outdoor vs. indoor), any existing outdoor to indoor reduction in noise levels, and the feasibility of constructing effective noise barriers for second stories and above.

  Depending on the quality of the original building façade, especially windows and doors, sound insulation treatments can improve the noise reductions from transit noise by 5 to 20 dB. To be considered cost-effective, a treatment should provide a minimum reduction of 5 dB in the interior of the building and meet the L_{dn} 45 dBA interior criterion. For more information, see Section 4.1.

  In many cases, especially in locations with high ambient noise levels, the existing sound insulation of a building may already meet the 45 dBA L_{dn} interior noise criterion. It is recommended that sound insulation testing be conducted to determine if the existing sound insulation is sufficient or what additional measures would be required to meet the interior criterion. Effective treatments include:
  - Caulking and sealing gaps in the building façade; and
  - Installation of new doors and windows that are specially designed to meet acoustical transmission-loss requirements:
    - Exterior doors facing the noise source should be replaced with well-gasketed, solid-core wood doors and well-gasketed storm doors.
    - Acoustical windows are typically made of multiple layers of glass with air spaces between to provide noise reduction. Acoustical performance ratings are published in terms of Sound Transmission Class (STC) for these windows. It is recommended to use a minimum STC rating of 39 on any window exposed to the noise source.

  These treatments are beneficial for heat insulation as well as for sound insulation, but acoustical windows are typically non-operable and central ventilation or air conditioning is needed. Residents' preferences should be considered.

  If needed, additional building sound insulation can be provided by sealing vents and ventilation openings and relocating them to a side of the building away from the noise source. In cases where the noise sources is low-frequency noise from diesel locomotives, it may be necessary to increase the mass of the building façade for wood-frame houses by adding a layer of sheathing to the exterior walls.

Examples of residential sound insulation for rail or highway projects are limited. However, much practical experience with sound insulation of buildings has been gained through grants for noise mitigation to local airport authorities by FAA.

SECTION 5 Transit Vibration

This section presents the basic concepts of transit ground-borne vibration, also referred throughout this manual as simple "vibration," and low-frequency groundborne-noise that sometimes results from vibration. The steps for the screening and assessing of potential vibration impacts of transit projects for FTA NEPA approval are described in the following sections.

The Source-Path-Receiver framework for ground-borne vibration for a rail system illustrated in Figure 5-1 is central to all environmental vibration studies. The train wheels rolling on the rails create vibration energy that is transmitted through the track support system into the transit structure. The vibration of the transit structure excites the adjacent ground, creating vibration waves that propagate through the ground and into nearby buildings creating ground-borne vibration effects that potentially interfere with activities. The vibrating building components may radiate sound, which this manual refers to as ground-borne noise. Airborne noise from transit sources is covered in Sections 2.3–4.5 of this manual. Ground-borne noise refers to the noise generated by ground-borne vibration.

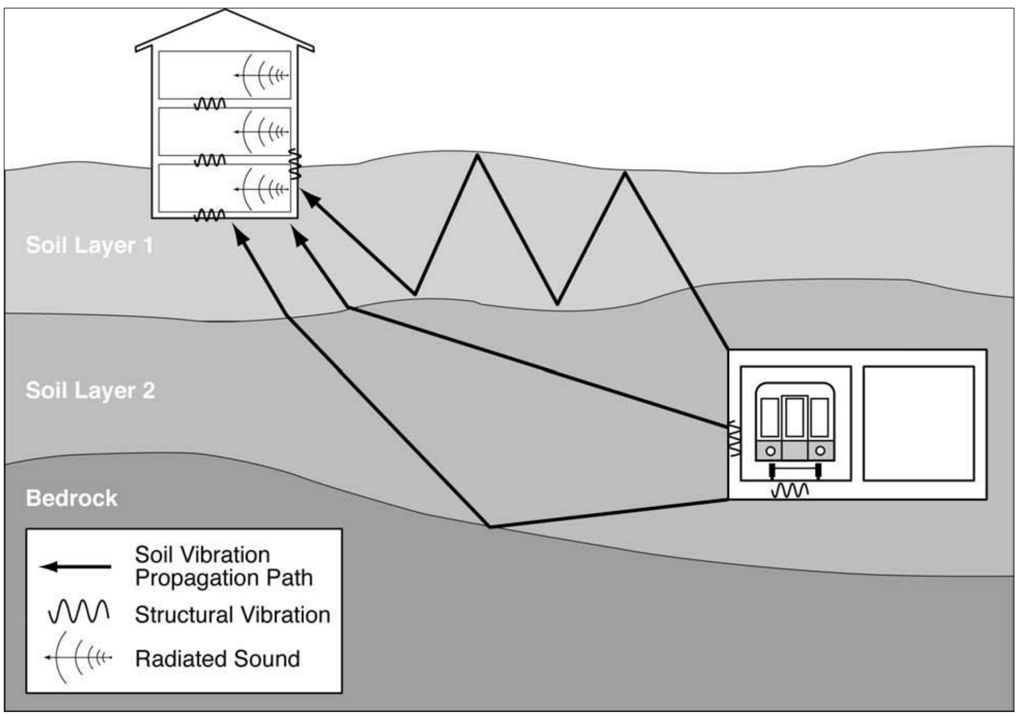

Figure 5-1 Propagation of Ground-Borne Vibration into Buildings

This section contains the following:

- Section 5.1 The ground-borne vibration and noise metrics used in this manual
- Section 5.2 An overview of transit vibration sources

- Section 5.3 An overview of transit vibration paths
- Section 5.4 An overview of receiver factors of transit vibration and a discussion of the technical background for ground-borne noise criteria

5.1 Ground-Borne Vibration and Noise Metrics

Vibration is an oscillatory motion that 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 metrics is zero. Displacement is the most intuitive metric. 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. Most transducers used for measuring ground-borne vibration use either velocity or acceleration. Furthermore, the response of humans, buildings, and equipment to vibration is more accurately described using velocity or acceleration.

This manual uses the metrics outlined in Table 5-1 for transit ground-borne vibration and noise measurements, computations, and assessment. These metrics are consistent with common usage in the United States.

Table 5-1 Ground-borne Vibration and Noise Metrics

Metric	Abbreviation	Definition
Vibration Decibels	VdB	The vibration velocity level in decibel scale.
Peak Particle Velocity	PPV	The peak signal value of an oscillating vibration velocity waveform. Usually expressed in inches/second in the United States.
Root Mean Square	rms	The square root of the arithmetic average of the squared amplitude of the signal.
A-weighted Sound Level	dBA	A-weighted sound levels represent the overall noise at a receiver that is adjusted in frequency to approximate typical human hearing sensitivity. This unit is used to characterize ground-borne noise.

The metrics in the table above are illustrated in Figure 5-2. The components in the figure include:

- **Raw signal** – This curve shows the instantaneous vibration velocity, which fluctuates positively and negatively about the zero point.

- **Peak particle velocity (PPV)** – PPV is the maximum instantaneous positive or negative peak of the vibration signal. PPV is often used in monitoring of construction vibration (such as blasting) since it is related to the stresses that are experienced by buildings and is not used to evaluate human response.

- **Root mean square (rms) velocity** – Because the net average of a vibration signal is zero, the rms amplitude is used to describe smoothed vibration amplitude. The rms of a signal is the square root of the average of the squared amplitude of the signal. The average is typically calculated over a one-second period. The rms amplitude is always less than the PPV(viii) and is always positive. The rms amplitude is used to convey the magnitude of the vibration signal felt by the human body, in inches/second.

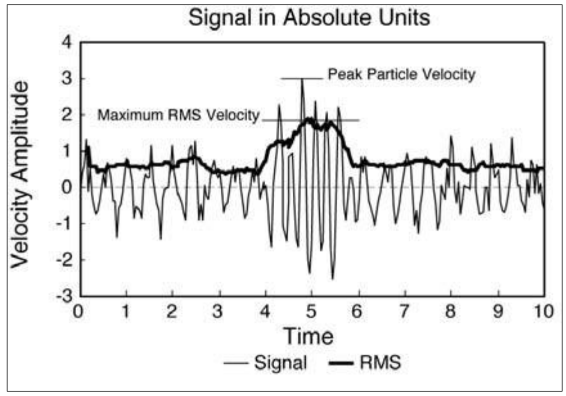

Figure 5-2 Vibration Signal in Absolute Units

The PPV and rms velocity are described in inches per second in the United States and meters per second internationally (with several different reference values). Although it is not universally accepted, vibration is commonly expressed in decibel notation. The decibel scale compresses the range of numbers required to describe vibration.

The graph in Figure 5-3 shows the rms curve from Figure 5-2 expressed in decibels.

Vibration velocity level in decibels is defined as:

$$L_v = 20\log\left(\frac{v}{v_{ref}}\right)$$ **Eq. 5-1**

where:

L_v = velocity level, VdB
v = rms velocity amplitude
v_{ref} = 1 x 10^{-6}in/sec in the USA
= 1 x 10^{-8}m/sec internationally*

*Because of the variations in the reference quantities, it is important to be clear about what reference quantity is being used when specifying velocity levels. All vibration levels in this manual are referenced to 1×10^{-6} inches/second.

viii The ratio of PPV to maximum rms amplitude is defined as the crest factor for the signal. The crest factor is typically greater than 1.41, 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.

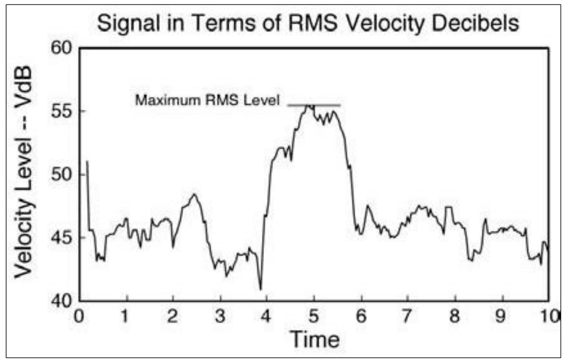

Figure 5-3 Vibration Signal in RMS Velocity Decibels

Ground-borne noise occurs when vibration radiates through a building interior and creates a low-frequency sound, often described as a rumble, as a train passes by. The annoyance potential of ground-borne noise is typically characterized with the A-weighted sound level. Although the A-weighted sound level is typically used to characterize community noise, characterizing low-frequency noise using A-weighting can be challenging because the non-linearity of human hearing causes sounds dominated by low-frequency components to seem louder than broadband sounds (sounds consisting of many frequency components, with no dominant frequencies) 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. Because ground-borne noise sounds louder than broadband noise at the same noise level, the limits for ground-borne noise are lower (i.e., stricter) than would be the case for broadband noise.

5.2 Sources of Transit Ground-borne Vibration and Noise

Ground-borne vibration can be a concern for nearby neighbors of a transit system route or maintenance facility. However, 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. This section discusses common sources of ground-borne vibration and noise.

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 vibration waves that propagate through the ground and create perceptible ground-borne vibration in nearby buildings include construction equipment, steel-wheeled trains, and traffic on rough roads. If the roadway is fairly smooth, the vibration from rubber-tired traffic is rarely perceptible. Building damage due to vibration is also rare for typical transportation projects; but in extreme cases, such as during blasting or pile-driving during construction, vibration could cause damage to buildings.

Figure 5-4 illustrates common vibration sources and the human and structural response to ground-borne vibration ranging from approximately 50 VdB (below perceptibility) to 100 VdB (the threshold of potential damage). The background vibration velocity level in residential areas is usually 50 VdB or lower,[ix] and the threshold of perception for humans is approximately 65 VdB. A vibration level of 85 VdB in a residence can result in strong annoyance.

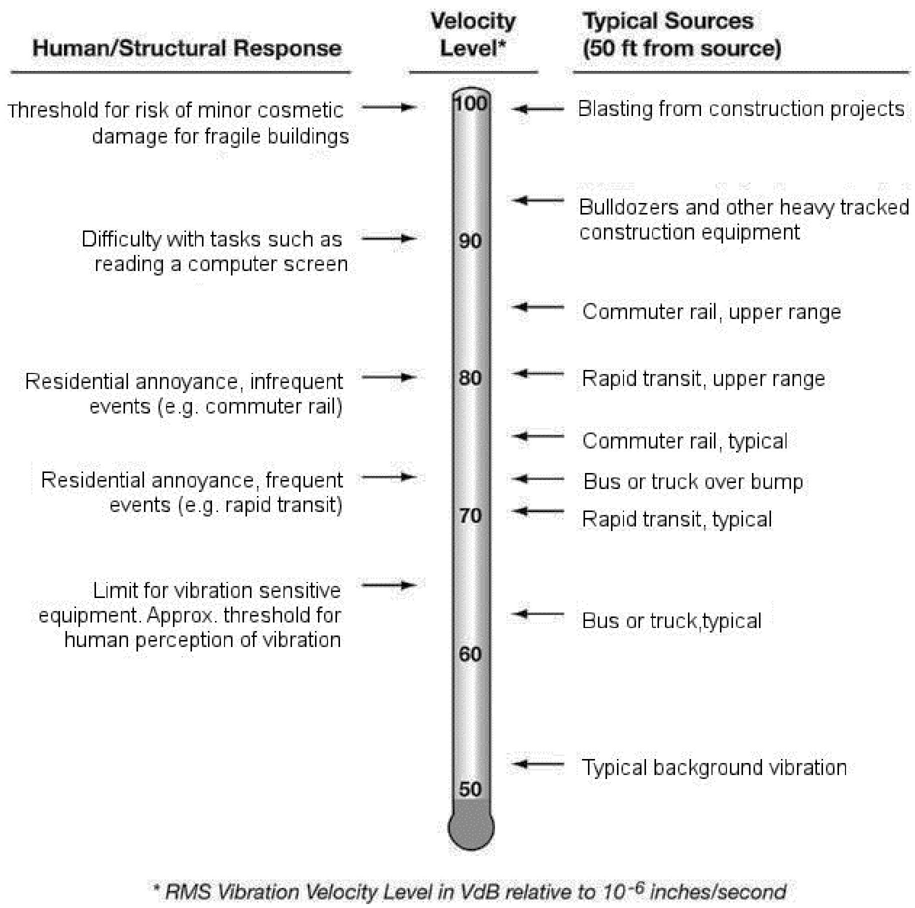

Figure 5-4 Typical Levels of Ground-Borne Vibration

Rapid transit or light rail systems typically generate vibration levels of 70 VdB or more near their tracks, while buses and trucks rarely create vibration that exceeds 70 VdB unless there are bumps due to frequent potholes in the road. Heavy locomotives on diesel commuter rail systems create vibration levels approximately 5 to 10 dB higher than rail transit vehicles.

Vibration from trains is strongly dependent on factors such as how smooth the wheels and rails are, as well as the resonance frequencies of the vehicle suspension system and the track support system. These systems, like all mechanical systems, have resonances that result in increased vibration response at certain frequencies, called natural frequencies. Unusually rough road or track, steel-wheel flats, geologic conditions that promote efficient propagation of vibration, or vehicles with very stiff suspension systems could increase typical

[ix] Background vibration is typically 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 examples of equipment that is highly sensitive to vibration.

vibration levels by approximately 10 VdB. Common factors that contribute to ground-borne vibration and noise at the source are presented in Table 5-2. These factors are discussed in more detail throughout this Section.

Table 5-2 Factors that Influence Levels of Ground-Borne Vibration and Noise at the Source

Category	Factors	Influence
Operations and Vehicles	Speed	Higher speeds result in higher vibration levels. Doubling speed results in a vibration level increase of approximately 4 to 6 dB.
	Vehicle Suspension	Stiff suspension in the vertical direction can increase the effective vibration forces. On transit cars, the primary suspension has the largest effect on vibration levels.
	Wheel Condition and Type	Wheel flats and general wheel roughness are major sources of vibration from steel wheel/steel rail systems. Resilient wheels on rail transit systems can provide some vibration reduction over solid steel wheels, but are usually too stiff to provide substantial reduction. For more information, see Section 6.4, Step 2.
Guideway	Track/Roadway Surface	Rough track or rough roads are often sources of excessive vibration. 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 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.
	Transit Structure	Heavier transit structures typically result in the lower vibration levels. The vibration levels from a lightweight bored tunnel will usually be higher than from a poured concrete box subway.
	Transit System Elevation	A rail system guideway will be either underground (subway), at-grade, or elevated, with substantial differences in the vibration characteristics at each elevation. ▪ Underground: vibration is typically the most important environmental factor of interest. ▪ At-grade: airborne noise is typically the dominant factor, although vibration and noise can be a problem, particularly at interior locations well isolated from exterior noise. ▪ Elevated: it is rare for vibration to be an issue with elevated railways except when guideway supports are located within 50 ft of buildings.

Brief discussions of ground-borne vibration and noise sources for different modes of transit are provided below.

At-Grade Heavy Rail and Light Rail

Ground-borne vibration and noise from urban heavy rail and LRT is common when there is less than 50 ft between the track and building foundations. Local geology and structural details of the building determine if the source of complaints is due to perceptible vibration or audible ground-borne noise. Complaints about ground-borne vibration from surface track are more common than ground-borne noise complaints. A substantial percentage of complaints about both ground-borne vibration and noise correlate with proximity of special track work, rough or corrugated track, or wheel flats. Light rail systems tend to generate fewer complaints than heavy rail due to lower operating speeds.

Commuter and Intercity Passenger Trains

There is the potential for vibration-related issues when new commuter or intercity rail passenger service (including electric multiple units (EMUs) and diesel multiple units (DMUs)) powered by either diesel or electric locomotives is introduced in an urban or suburban area. Commuter and intercity passenger trains have similar characteristics, but commuter trains typically operate on a more frequent schedule. These passenger trains often share track with freight trains, which have different vibration characteristics as discussed below.

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. However, because locomotive suspensions are similar, the maximum vibration levels of local and long-distance freights are similar. Locomotives and rail cars with wheel flats are the sources of the highest vibration levels.

If the transit project does not in any way change the freight service, tracks, etc., then vibration from the freight line would be part of the existing conditions and need to be considered in terms of cumulative impacts (see Section 6.2, Step 3 on how to consider cumulative impacts). If the project results in changes to the freight path, operations, frequency, etc. (e.g., relocating freight tracks within the ROW to make room for the transit tracks) then those potential impacts and mitigation should be evaluated as part of the proposed project. However, note that vibration mitigation is very difficult to implement on tracks where freight trains with heavy axle loads operate.

High-Speed Passenger Trains

Passenger trains travelling at high speeds, 90 to 250 miles per hour, have the potential for creating high levels of ground-borne vibration. Ground-borne vibration should be anticipated as one of the major environmental impacts of any trains travelling at high speeds located in an urban or suburban area.[x] For projects that are specifically high-speed transportation refer to the FRA "High-Speed Ground Transportation Noise and Vibration Impact Assessment" guidance manual.[39]

AGT Systems

AGT systems include a wide range of transportation vehicles that provide local circulation in downtown areas, airports, and theme parks. Because AGT systems normally operate at low speeds, have lightweight vehicles, run on elevated structures, and rarely operate in vibration-sensitive areas, ground-borne vibration problems are very rare.

Subway and At-grade Track

While ground-borne vibration produced from trains operating subway and at-grade track have very different characteristics, they have comparable overall vibration velocity levels. Complaints about ground-borne vibration are often more common near subways than near at-grade track. This is not because

[x] Amtrak trains (branded Acela at the time of publication) on the Northeast Corridor between Boston and Washington, DC, which attain moderate to high speeds in some sections with improved track, fit into this category.

subways create higher vibration levels than at-grade systems, rather because subways are usually located in more densely developed areas in closer proximity to building foundations, and 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.

Streetcars
Complaints about ground-borne vibration from street cars are uncommon given that streetcars typically operate at very low speeds (less than 25 mph).

Buses
Because the rubber tires and suspension systems of buses provide vibration isolation, it is unusual for buses to cause ground-borne vibration or noise problems. For most issues with bus-related vibration, such as rattling of windows, the cause is almost always airborne noise and directly related to running surface conditions such as potholes, bumps, expansion joints, or other discontinuities in the road surface (usually resolved by smoothing the discontinuities).

Buses operating inside buildings will likely cause vibration concerns for other building inhabitants. An example of this situation is a bus transfer station in the same building as commercial office space. Sudden loading of a building slab by a heavy moving vehicle or by vehicles running over lane divider bumps can cause intrusive building vibration.

5.3 Paths of Transit Ground-Borne Vibration and Noise

Vibration travels from the source through the transit structure and excites the adjacent ground, creating vibration waves that propagate through soil layers and rock strata to the foundations of nearby buildings. The vibration then propagates from the foundation throughout the remainder of the building structure. The vibration of the building structure and room surfaces can radiate a low-frequency rumble called ground-borne noise (Figure 5-1).

Soil and subsurface 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. Vibration propagation is more efficient in stiff clay soils. Shallow rock may concentrate the vibration energy close to the surface, resulting in ground-borne vibration problems at large distances from the track. Factors such as soil layers and depth to water table can have substantial effects on the propagation of ground-borne vibration. These factors are summarized in Table 5-3.

Table 5-3 Factors that Influence Levels of Ground-borne Vibration and Noise along Path

Geology Factors	Influence
Soil type	Vibration levels are generally higher in stiff clay-type soil than in loose sandy soil.
Rock layers	Vibration levels are usually 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. Vibration levels do not attenuate as rapidly in rock as in soil.
Soil layering	Soil layering can have a substantial effect on the vibration levels since each stratum can have considerably different dynamic characteristics.
Depth to water table	The presence of the water table may have a substantial effect on vibration, but a definite relationship has not been established.

5.4 Receiver Factors that Influence Ground-Borne Vibration and Noise

Ground-borne vibration is a concern almost exclusively inside buildings. 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, coupling of the building foundation to the soil, and propagation of the vibration through the building. In general, the heavier a building is, the lower the response will be to the incident vibration energy. Common factors that contribute to ground-borne vibration and noise at the receiver are presented in Table 5-4.

Table 5-4 Factors that Influence Levels of Ground-Borne Vibration and Noise at the Receiver

Receiver Building Factors	Influence
Foundation type	The heavier the building foundation, the greater the coupling loss as the vibration propagates from the ground into the building.
Building construction	Each building has different characteristics relative to structure-borne vibration, but, in general, the heavier the building, the lower the levels of vibration. The maximum vibration amplitudes of the floors and walls of a building will often occur at the resonance frequencies of the components of the building.
Acoustical absorption	The more acoustically absorptive materials in the receiver room, the lower the ground-borne noise level. Note that because ground-borne noise usually is a low-frequency phenomenon, it is affected by low-frequency absorption (e.g., below 250 Hz).

5.5 Human Response to Transit Ground-borne Vibration and Noise

This section contains an overview of human receiver response to ground-borne vibration and noise. It serves as background information for the vibration impact criteria in Section 6.2.

The effects of ground-borne vibration can include perceptible movement of floors in buildings, rattling of windows, shaking of items on shelves or hanging on walls, and low-frequency noise (ground-borne noise). Building damage is not a factor for typical transportation projects, but in extreme cases, such as during blasting or pile-driving during construction, vibration could cause damage to buildings. Although the perceptibility threshold is approximately 65 VdB, human response to vibration is not usually substantial unless the vibration exceeds 70 VdB (Figure 5-4). A vibration level that causes annoyance is well below the damage risk threshold for typical buildings (100 VdB).

Ground-borne vibration is almost never a problem 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. Ground-borne noise that accompanies the building vibration is usually perceptible only inside buildings and typically is only an issue at locations with subway or tunnel operations where there is no airborne noise path or for buildings with substantial sound insulation such as a recording studio.

One of the challenges in developing suitable criteria for ground-borne vibration is that there has been relatively little research into human response to vibration and, specifically, human annoyance with building vibration. The American National Standards Institute (ANSI) developed criteria for evaluation of human exposure to vibration in buildings in 1983,[(40)] and the International Organization for Standardization (ISO) adopted similar criteria in 1989[(41)] and revised them in 2003.[(42)] The 2003 version of ISO 2631-2 acknowledges that "human response to vibration in buildings is very complex." It further indicates that the degree of annoyance cannot always be explained by the magnitude of the vibration alone. In some cases, complaints are associated with measured vibration that is lower than the perception threshold. Other phenomena such as ground-borne noise, rattling, visual effects such as movement of hanging objects, and time of day (e.g., late at night) all play some role in the response of individuals. To understand and evaluate human response, which is often measured by complaints, all of these related effects need to be considered.

Figure 5-5 illustrates the relationship between the vibration velocity level measured in 22 homes and the general response of the occupants to the vibration from measurements performed for several transit systems along with subjective ratings by researchers and residents. These data are published in the "State-of-the-Art Review of Ground-borne Noise and Vibration."[(43)] The figure also includes a curve representing the percent of people annoyed by vibration from high-speed trains from a Japanese study for comparison.[(44)]

Both the occupants and the people who performed the measurements agreed that floor vibration in the Distinctly Perceptible range is unacceptable for a residence. The data indicates that residential vibration exceeding 75 VdB is unacceptable for a repetitive vibration source such as rapid transit trains that pass every 5 to 15 minutes. The results from the Japanese study confirm the conclusion that at a vibration velocity level of 75 to 80 VdB, many people will find the vibration annoying. A Transportation Research Board (TRB) study of human response to vibration from 2009 also supports this finding and indicates that incidence of complaints fall rapidly with a level decreasing below 72 VdB.[(42)(45)]

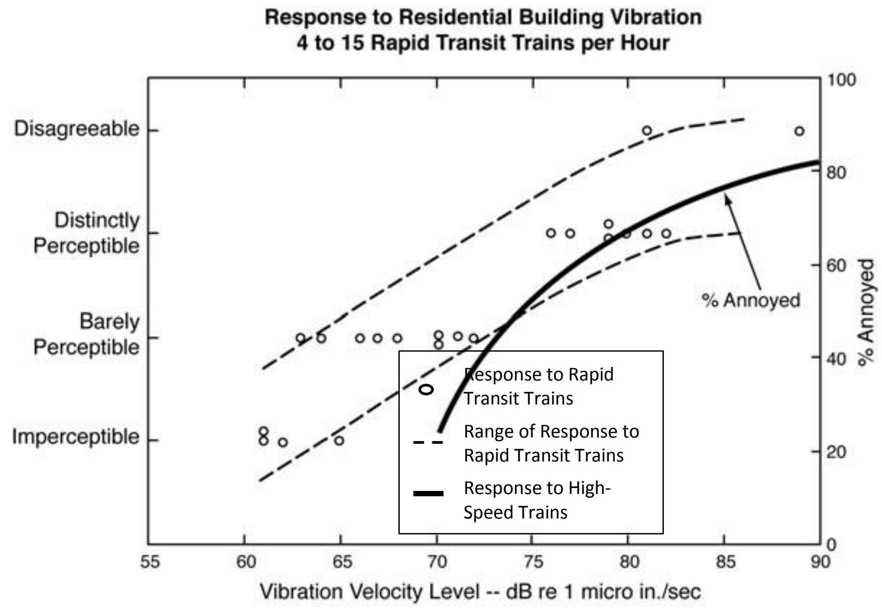

Figure 5-5 Response to Transit-Induced Residential Vibration

Table 5-5 presents the human response to different levels of ground-borne vibration and noise on which the criteria presented in Section 6.2 are based. The vibration level (VdB) is presented with the corresponding frequency assuming that the vibration spectrum peaks at 30 Hz or 60 Hz.[xi] The ground-borne noise levels (dBA) are estimated for the specified vibration velocity with a peak vibration spectrum of 30 Hz (Low Freq) and 60 Hz (Mid Freq). Note that the human response differs for vibration velocity level based on frequency. For example, the noise caused by vibrating structural components may cause annoyance even though the vibration cannot be felt. Alternatively, a low-frequency vibration can cause annoyance while the ground-borne noise level it generates does not.

[xi] The A-weighted level of ground-borne noise can be estimated by applying A-weighting to the vibration velocity spectrum and by subtracting an additional 5 dB for a room with average acoustical absorption. 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 dB lower than the velocity level. If the vibration spectrum peaks at 60 Hz, the A-weighted sound level will be approximately 25 dB lower than the velocity level.

Table 5-5 Human Response to Different Levels of Ground-Borne Vibration and Noise

Vibration Velocity Level	Noise Level		Human Response
	Low Freq*	Mid Freq**	
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 annoying. Low-frequency noise: tolerable for sleeping areas. Mid-frequency noise: excessive in most quiet occupied areas.
85 VdB	45 dBA	60 dBA	Vibration tolerable only if there are an infrequent number of events per day. Low-frequency noise: excessive for sleeping areas. Mid-frequency noise: excessive even for infrequent events for some activities.

*Approximate noise level when vibration spectrum peak is near 30 Hz.
**Approximate noise level when vibration spectrum peak is near 60 Hz.

SECTION

6

Vibration Impact Analysis

The FTA vibration impact analysis process is a multi-step process used to evaluate a project for potential vibration impacts. If impact is determined, measures necessary to mitigate adverse impacts are to be considered for incorporation into the project.[3]

The FTA vibration impact analysis steps are summarized as follows and are described in the following sections:

6.1 Determine vibration analysis level.

6.2 Determine vibration impact criteria.
  Option A: General Vibration Assessment Criteria
  Option B: Vibration Impact Criteria for a Detailed Vibration Analysis

6.3 Evaluate Impact: Vibration Screening Procedure
  Step 1: Classify project vehicles.
  Step 2: Determine project type.
  Step 3: Determine screening distance.
  Step 4: Identify vibration-sensitive land uses.

6.4 Evaluate Impact: General Vibration Assessment.
  Step 1: Select base curve for ground surface vibration level.
  Step 2: Apply adjustments.
  Step 3: Inventory vibration impact.

6.5 Evaluate Impact: Detailed Vibration Analysis
  Step 1: Characterize Existing Vibration
  Step 2: Estimate Vibration Impact
  Step 3: Assess Vibration Impacts
  Step 4: Determine Vibration Mitigation Measures

A similar process for the noise impact analysis is presented in Section 4. After the noise and vibration analyses have been completed, assess construction noise and vibration according to Section 7 and document findings according to Section 8.

6.1 Determine Vibration Analysis Level

There are three levels of analysis to assess the potential ground-borne vibration and noise impacts resulting from a public transportation project. The appropriate level of analysis varies by project based on the type and scale of the project, the stage of project development, and its environmental setting. These three levels are: the Vibration Screening Procedure, the General Vibration Assessment, and the Detailed Vibration Analysis. These levels of vibration analysis mirror the levels of noise analysis discussed in Section 4.2.

The Vibration Screening Procedure, performed first, defines the study area of any subsequent vibration impact assessment. Where there is potential for impact, the General Vibration Assessment and Detailed Vibration Analysis procedures are used to determine the extent and severity of impact. In some cases, a General Vibration Assessment may be all that is needed. However, if the proposed project is near noise-sensitive land uses and it appears at the outset that the impact would be substantial, it is prudent to conduct a Detailed Vibration Analysis.

The methods for analyzing transit vibration are consistent with those described in recognized handbooks and international standards.[46][47]

Conduct the vibration screening procedure and then determine the appropriate vibration analysis option:

Vibration Screening Procedure – The Vibration Screening Procedure is a simplified method of identifying the potential for vibration impact from transit projects. The Vibration Screening Procedure is applicable to all types of transit projects and does not require any specific knowledge about the vibration characteristics of the system or the geology of the area. This procedure uses simplified assumptions and considers the type of project and the presence or absence of vibration-sensitive land uses within a screening distance that has been developed to identify most potential vibration impacts. If no vibration-sensitive land uses are present within the defined screening distance, then no further vibration assessment is necessary.

The Vibration Screening Procedure steps are provided in Section 6.3, Step 1.

General Vibration Assessment – The General Vibration Assessment is used to examine potential impacts to vibration-sensitive land use areas identified in the screening step more closely. It uses generalized information likely to be available at an early stage in the project development process and during the development of most environmental documents.

Vibration levels at receivers are determined by estimating the overall vibration velocity level and A-weighted ground-borne noise levels as a function of distance from the track and applying adjustments to account for factors such as track support systems, vehicle speed, type of building, and track and wheel conditions.

A General Vibration Assessment is sufficient for the environmental review of many projects, including projects that compare transit modal alternatives or relocate a crossover or turnout. The General Vibration Assessment may also be sufficient if it results in a commitment to mitigation that eliminates the vibration impacts, such as a change in transit mode or alignment. However, if impact is identified through the General Vibration Assessment procedures and not mitigated, a Detailed Vibration Analysis of the selected alternative must be completed. Most vibration mitigation measures can only be specified after a Detailed Vibration Analysis has been done.

The General Vibration Assessment procedure is provided in Section 6.3, Step 2.

Detailed Vibration Analysis – The Detailed Vibration Analysis procedure is a comprehensive assessment method that produces the most accurate estimates of vibration impact for a proposed project and is often accomplished during the engineering phase of a project when there are sufficient data identifying potential adverse vibration impacts from the project. However, a Detailed Vibration Analysis may be warranted earlier in the environmental review process if there are potentially severe impacts due to the proximity of vibration-sensitive land uses. This type of assessment requires professionals with experience in performing and interpreting vibration propagation tests.

A Detailed Vibration Analysis may not be necessary for all segments of a project. Generalized prediction curves from the General Vibration Assessment procedures may be sufficient for most of the alignment, and the Detailed Vibration Analysis procedure may only need to be applied to particularly sensitive receivers (Section 6.3). Note that a Detailed Vibration Analysis is typically required when designing special track-support systems such as floating slabs or ballast mats. These and other costly vibration mitigation measures can only be specified after a Detailed Vibration Analysis has been done in the engineering phase of the project.

The Detailed Vibration Analysis procedure is presented in Section 6.3, Step 3.

6.2 Determine Vibration Impact Criteria

Use the FTA criteria presented in this section when conducting a General Vibration Assessment or a Detailed Vibration Assessment. Like noise, the sensitivity to vibration varies by land use type, and the criteria represent these sensitivities. These criteria are based on national and international standards,[(38)(39)(48)] as well as experience on human response to building vibration. See Section 5.5 for additional background information on the development of FTA vibration criteria. The criteria for environmental impact from ground-borne vibration and noise are based on the maximum root-mean-square (rms) vibration velocity levels for repeated events of the same source.

Determine the appropriate criteria based on the level of analysis (Section 6.1). The impact criteria for the General Vibration Assessment are presented in Option A, and the impact criteria for the Detailed Vibration Analysis are presented in Option B.

Option A: General Vibration Assessment Criteria

Determine the land use according to Step 1 and the frequency of events according to Step 2. The impact criteria for the General Vibration Analysis are presented in Step 3.

Step 1: Land Use Categories

Determine the appropriate land use category for the receiver of vibration impacts of the project or project segment. Sensitive land use categories for vibration assessment are presented in Table 6-1 in order of sensitivity. Consider indoor use of the buildings when determining land use categories for ground-borne vibration and noise, since impact is experienced indoors.

Table 6-1 Land Use Categories for General Vibration Assessment Impact Criteria

Land Use Category	Land Use Type	Description of Land Use Category
-	Special Buildings	This category includes special-use facilities that are very sensitive to vibration and noise that are not included in the categories below and require special consideration. However, if the building will rarely be occupied when the source of the vibration (e.g., the train) is operating, there is no need to evaluate for impact. Examples of these facilities include concert halls, TV and recording studios, and theaters.
1	High Sensitivity	This category includes buildings where vibration levels, including those below the threshold of human annoyance, would interfere with operations within the building. Examples include buildings where vibration-sensitive research and manufacturing* is conducted, hospitals with vibration-sensitive equipment, and universities conducting physical research operations. The building's degree of sensitivity to vibration is dependent on the specific equipment that will be affected by the vibration. Equipment moderately sensitive to vibration, such as high resolution lithographic equipment, optical microscopes, and electron microscopes with vibration isolation systems are included in this category.** For equipment that is more sensitive, a Detailed Vibration Analysis must be conducted.
2	Residential	This category includes all residential land use and buildings where people normally sleep, such as hotels and hospitals. Transit-generated ground-borne vibration and noise from subways or surface running trains are considered to have a similar effect on receivers.***
3	Institutional	This category includes institutions and offices that have vibration-sensitive equipment and have the potential for activity interference such as schools, churches, doctors' offices. Commercial or industrial locations including office buildings are not included in this category unless there is vibration-sensitive activity or equipment within the building. As with noise, the use of the building determines the vibration sensitivity.

* Manufacturing of computer chips is an example of a vibration-sensitive process.

** Standard optical microscopes can be impacted at vibration levels below the threshold of human annoyance.

*** Even in noisy urban areas, the bedrooms will often be in quiet buildings with effective noise insulation. However, ground-borne vibration and noise are experienced indoors, and building occupants have practically no means to reduce their exposure. Therefore, occupants in noisy urban areas are just as likely to be exposed to ground-borne vibration and noise as those in quiet suburban areas.

- **Ground-borne Vibration** – Locations with equipment that is highly-sensitive to vibration should be included in category 1 or assessed using the Detailed Vibration Analysis procedures (Section 6.3, Step 3) and criteria (Section 6.2, Option B) or specific criteria of the equipment manufacturer.

  Most computer installations or telephone switching equipment is not considered sensitive to vibration. Although the owners of this type of equipment often are concerned with the potential for ground-borne vibration interrupting smooth operation of their equipment, it is rare for computer or other electronic equipment to be particularly sensitive to vibration. This type of equipment is typically designed to operate in common building environments where the equipment may experience occasional disturbances and continuous background vibration caused by other equipment.

- **Ground-borne Noise** – Ground-borne noise is typically only assessed at locations with subway or tunnel operations where there is no airborne noise path, or for buildings with substantial sound insulation such as a recording studio. For typical buildings with at-grade or elevated transit operations, the interior airborne noise levels are often higher than the ground-borne noise levels. For interior rooms or other special cases, ground-borne noise may need to be assessed.

Step 2: Identify Event Frequency

Determine the appropriate frequency of events for the project or project segment.

Community response to vibration correlates with the frequency of events and, intuitively, more frequent events of low vibration levels may evoke the same response as fewer high vibration level events. This effect is accounted for in the ground-borne vibration and noise impact criteria by characterizing projects by frequency of events. Event frequency definitions are presented in Table 6-2.

Table 6-2 Event Frequency Definitions

Category	Definition	Typical Project Types
Frequent Events	More than 70 events per day	Most rapid transit
Occasional Events	30–70 events per day	Most commuter trunk lines
Infrequent Events	Fewer than 30 events per day	Most commuter rail branch lines

Step 3: Apply Impact Criteria by Land Use and Event Frequency

Select the appropriate impact criteria for ground-borne vibration and noise based on the previously identified land use categories and frequency of events. It is also important to consider the time of vibration sensitivity. If the building is not typically occupied when the vibration source (e.g., train) is operating, it is not necessary to consider impact.

The criteria in this section are appropriate for assessing human annoyance or interference with vibration-sensitive equipment for common projects. While not typical, existing conditions, freight train operations, and building damage may require consideration.

- **Existing Conditions** – The criteria in this section do not consider existing conditions. In most cases, the existing environment does not include a substantial number of perceptible ground-borne vibration or noise events. However, existing conditions must be evaluated in some cases, such as for projects located in an existing rail corridor. For criteria considering existing conditions, see Step 3b.

- **Freight Train Operations** – The criteria are primarily based on experience with passenger train operations. Passenger train operations (rapid transit, commuter rail, and intercity passenger railroad) create vibration events that last approximately 10 seconds or less while a typical line-haul freight train event lasts approximately two minutes. This manual is oriented to transit projects. However, situations will occur when freight train operations must be evaluated, such as when freight train tracks are relocated for a transit project within a railroad ROW. Guidelines on applying these criteria to freight train operations are presented in Step 3c.

- **Building Damage** – It is extremely rare for vibration from train operations to cause substantial or even minor cosmetic building damage. However, damage to fragile historic buildings located near the ROW may be of concern. Even in these cases, damage is unlikely except when the track is located very close to the structure. Damage thresholds that apply to these structures are discussed in Section 7.2, Step 4 on Construction Vibration Impacts.

3a. Choose the impact criteria by land use category and event frequency. The criteria for ground-borne vibration and noise land use categories 1-3 are presented in Table 6-3. The criteria are presented in terms of acceptable indoor ground-borne vibration and noise levels. Impact will occur if these levels are exceeded. Criteria for ground-borne vibration are expressed in terms of rms velocity levels in VdB, and criteria for ground-borne noise are expressed in terms of A-weighted sound pressure levels in dBA.

Table 6-3 Indoor Ground-Borne Vibration (GBV) and Ground-Borne Noise (GBN) Impact Criteria for General Vibration Assessment

Land Use Category	GBV Impact Levels (VdB re 1 micro-inch /sec)			GBN Impact Levels (dBA re 20 micro Pascals)		
	Frequent Events	Occasional Events	Infrequent Events	Frequent Events	Occasional Events	Infrequent Events
Category 1: Buildings where vibration would interfere with interior operations.	65 VdB*	65 VdB*	65 VdB*	N/A**	N/A**	N/A**
Category 2: Residences and buildings where people normally sleep.	72 VdB	75 VdB	80 VdB	35 dBA	38 dBA	43 dBA
Category 3: Institutional land uses with primarily daytime use.	75 VdB	78 VdB	83 VdB	40 dBA	43 dBA	48 dBA

* This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. For equipment that is more sensitive, a Detailed Vibration Analysis must be performed.
** Vibration-sensitive equipment is generally not sensitive to ground-borne noise; however, the manufacturer's specifications should be reviewed for acoustic and vibration sensitivity.

The criteria for ground-borne vibration and noise for special land uses are presented in Table 6-4. The criteria are presented in terms of acceptable indoor ground-borne vibration and noise levels. Impact will occur if these levels are exceeded. As for the other land uses, the criteria for ground-borne vibration are expressed in terms of rms velocity levels in VdB, and criteria for ground-borne noise are expressed in terms of sound pressure levels in dBA.

Table 6-4 Indoor 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 (dBA re 20 micro-Pascals)	
	Frequent Events	Occasional or Infrequent Events	Frequent Events	Occasional or Infrequent 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

3b. Consider the presence of existing vibration conditions.
When the project will cause vibration more than 5 dB above the existing vibration, the existing source can be ignored, and the standard vibration criteria in Step 3a are appropriate. When the project will cause vibration less than 5 dB above the existing vibration level, use the instructions presented in this section to determine the appropriate impact criteria for the project. For information on characterizing existing vibration conditions, see Section 6.2, Step 3.

Use Table 6-5 and Figure 6-1 to determine the appropriate impact criteria. Sources of existing vibration are typically longer in duration than the events introduced into the environment due to the project. The frequency of use in the rail corridor is also a factor in characterizing the existing conditions. Both factors are considered in the process of determining appropriate impact criteria in Table 6-5 and Figure 6-1.
Examples of projects considering the existing vibration conditions in Table 6-5 and Figure 6-1 include:

- An automated people mover system planned for a corridor with an existing rapid transit service with 220 trains per day that did not have a significant increase in events from the existing 220 trains per day and that is not 3 dB above the existing vibration level would cause no additional impact.
- Where a new commuter rail line shares a heavily-used corridor with a rapid transit system, the project vibration exceeds the existing vibration level, there is not a significant increase in the number of events, and the project vibration exceeds the existing vibration level by 3 dB or more, the projected vibration levels must be evaluated using the standard impact criteria to determine impact.
- If a new transit project will use an existing railroad ROW and the location of existing railroad tracks are shifted, existing vibration can be substantial. The track relocation and reconstruction can result in lower vibration levels that would benefit the receivers and not introduce any adverse impact. However, if the track relocation causes higher vibration levels at vibration-sensitive receivers, then the projected vibration levels must be evaluated using the standard impact criteria to determine impact.

Table 6-5 Impact Criteria Considering Existing Conditions

<table>
<tr><th>Category</th><th>Number of Operations
(At present – without project)</th><th>Criteria</th></tr>
<tr><td>Heavily Used</td><td>More than 12 trains per day</td><td>Use the standard vibration criteria in Section 6.2, Step 3a for the following scenarios:
The existing vibration does not exceed the standard vibration criteria.
The existing vibration exceeds the standard vibration criteria and there is a significant increase in events.*
The existing vibration exceeds the standard vibration criteria, and the project vibration is 3 dB or more above the existing vibration.
The project has no impact if the existing vibration exceeds the standard vibration criteria, the number of events does not increase significantly, and the project vibration does not exceed the existing vibration by 3 dB or more.</td></tr>
<tr><td>Moderately Used</td><td>5 – 12 trains per day</td><td>Use the standard vibration criteria in Section 6.2 Step 3a for the following scenarios:
The existing vibration does not exceed the standard vibration criteria.
The existing vibration exceeds the standard vibration criteria, and the project vibration is not 5 dB or more below the existing vibration.
The project has no impact if the existing vibration exceeds the standard vibration criteria and the project vibration is at least 5 dB below the existing vibration.</td></tr>
<tr><td>Infrequently Used</td><td>Fewer than 5 trains per day</td><td>The standard vibration criteria in Section 6.2, Step 3a apply.</td></tr>
</table>

* Approximately doubling the number of events is required for a significant increase.

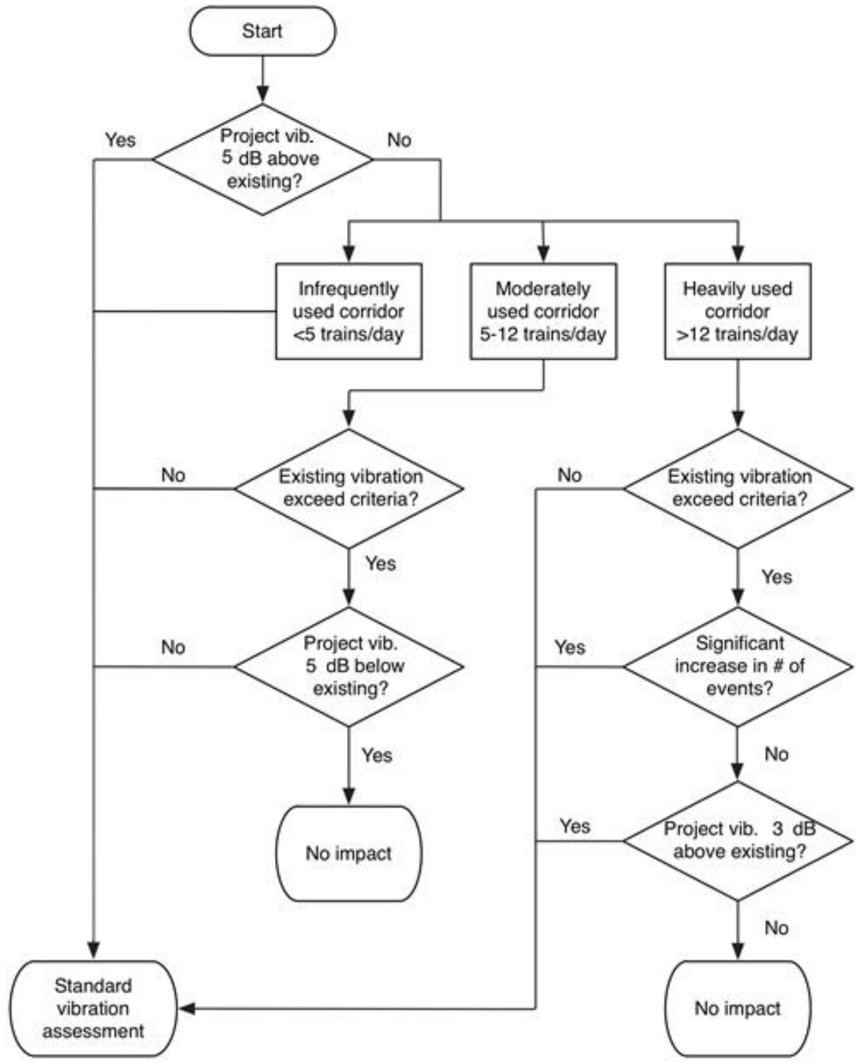

Figure 6-1 Existing Vibration[xii] Criteria Flow Chart

3c. Apply criteria to freight trains if part of the project.

Use the criteria presented in Step 3a to assess the vibration from freight trains in shared ROW scenarios because no specific impact criteria exist for freight railroads. It is important to consider that freight operations occur over substantially greater distances than passenger train operations and have different weight and axle loads.

When assessing vibration from freight train operations, consider the locomotive and rail car vibration separately. Since locomotive vibration lasts for a very short time, it can be characterized by the infrequent events category in Table 6-2. Rail car vibration from a typical line-haul freight train usually lasts for several minutes and can be characterized by the frequent events category in Table 6-2. Note

[xii] Vibration is abbreviated as "vib." in this flowchart.

that locomotives often create vibration levels that are 3 to 8 dB higher than those created by rail cars.

Use good engineering judgment to confirm the approach is reasonable for each project. For example, some spur rail lines carry very little rail traffic (sometimes only one train per week) or have short trains, in which case it may not be necessary to evaluate for impact. If there is uncertainty in how to determine the appropriate criteria, contact the FTA Regional office.

Decisions to relocate freight tracks closer to vibration-sensitive sites should be made with the understanding that increased vibration due to freight rail may not be possible to mitigate. Freight rail vibration may not always be successfully mitigated by the same methods as rail transit systems.

Option B: Vibration Impact Criteria for a Detailed Vibration Analysis

Determine the appropriate impact criteria for ground-borne vibration and ground-borne noise for a Detailed Vibration Analysis.

Step 1: Ground-Borne Vibration

Choose the appropriate criteria based on Figure 6-2 and Table 6-6.

Ground-borne vibration criteria presented in this section are more detailed than in the General Vibration Assessment. The criteria are based on international standards for the effects of vibration on people related to annoyance and interference with activities in buildings(39) as well as industry standards for vibration-sensitive equipment.(46) The criteria in this section are used to assess the potential for interference or annoyance from building response and to determine performance of vibration reduction methods. Note that for highly-sensitive equipment, specific vibration criteria provided by the manufacturer supersede the criteria in this section.

The criteria are presented by category in Figure 6-2 and are defined by international and industry standards.(39)(46) These criteria define limits for acceptable maximum rms vibration velocity level with a one-second averaging time at the floor of the receiving building in terms of a one-third octave band frequency spectrum. Band levels that exceed a particular criterion curve indicate impact; and therefore, mitigation options should be evaluated considering the specific frequency range in which the treatment is most effective. Interpretations of the criteria are presented in Table 6-6.

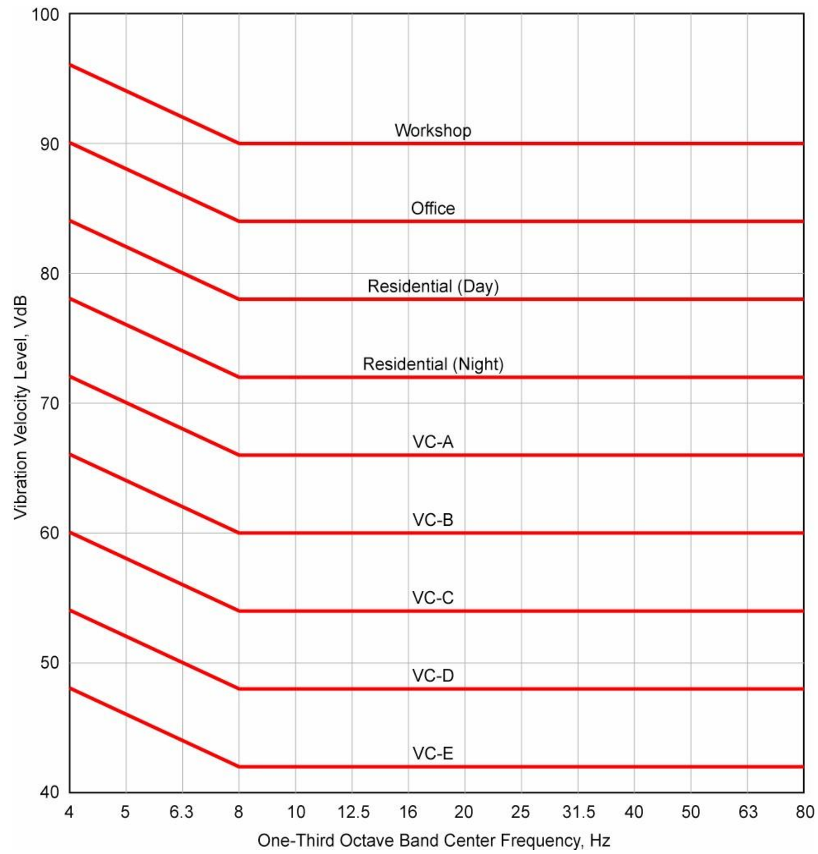

Figure 6-2 Criteria for Detailed Vibration Analysis

Table 6-6 Interpretation of Vibration Criteria for Detailed Vibration Analysis

Criterion Curve	Max Lv,* VdB	Description of Use
Workshop (ISO)	90	Vibration that is distinctly felt. Appropriate for workshops and similar areas not as sensitive to vibration.
Office (ISO)	84	Vibration that can be felt. Appropriate for offices and similar areas not as sensitive to vibration.
Residential Day (ISO)	78	Vibration that is barely felt. Adequate for computer equipment and low-power optical microscopes (up to 20X).
Residential Night, Operating Rooms (ISO)	72	Vibration is not felt, but ground-borne noise may be audible inside quiet rooms. Suitable for medium-power optical microscopes (100X) and other equipment of low sensitivity.
VC-A	66	Adequate for medium- to high-power optical microscopes (400X), microbalances, optical balances, and similar specialized equipment.
VC-B	60	Adequate for high-power optical microscopes (1000X) and inspection and lithography equipment to 3-micron line widths.
VC-C	54	Appropriate for most lithography and inspection equipment to 1-micron detail size.
VC-D	48	Suitable in most instances for the most demanding equipment, including electron microscopes operating to the limits of their capabilities.
VC-E	42	The most demanding criterion for extremely vibration-sensitive equipment.

* As measured in 1/3-octave bands of frequency over the frequency range 8 to 80 Hz.

In addition to the uses described in Table 6-6, the detailed vibration criteria can be applied to the three land use categories presented in Table 6-3.

- For residential land uses (category 2), use the residential night criterion curve in Table 6-6.
- For institutional uses (category 3), use the residential day criterion curve in Table 6-6.
- For category 1, the specific use of the building should be matched to the appropriate criterion curve in Table 6-6.
- For special buildings, such as those found in Table 6-4, either the criteria in Table 6-4 or specific criteria presented by the building operator should be used.

These criteria use a frequency spectrum because vibration-related problems generally occur due to resonances of the structural components of a building or vibration-sensitive equipment. Resonant response is frequency-dependent. A Detailed Vibration Analysis can provide an assessment that identifies potential problems resulting from resonances.

The detailed vibration criteria are based on generic cases when people are standing or equipment is mounted on the floor in a conventional manner. Consequently, the criteria are less stringent at very low frequencies below 8 Hz. Where special vibration isolation has been provided in the form of pneumatic isolators, the resonant frequency of the isolation system is very low. Consequently, in this special case, the curves may be extended flat at lower frequencies.

Step 2: Ground-borne Noise

Ground-borne noise impacts are assessed based on criteria for human annoyance and activity interference. The Detailed Vibration Analysis procedure provides vibration spectra inside a building. To evaluate ground-borne noise, convert these vibration spectra to sound pressure level spectra in the occupied spaces using the method described in Section 6.5 and compare to the criteria as follows:

- For residential buildings, use the criteria presented in Table 6-3.
- For special buildings listed in Table 6-4, A-weighted noise may not be sufficient to assess activity interference for a Detailed Vibration Analysis. Each special building may have a unique specification for acceptable noise levels and criteria must be determined on a case-by-case basis. For example, a recording studio may have stringent requirements for allowable noise in each frequency band.

6.3 Evaluate Impact: Vibration Screening Procedure

Determine the potential for impact using the Vibration Screening Procedure by identifying any vibration-sensitive land uses (Table 6-1) within the appropriate screening distance.

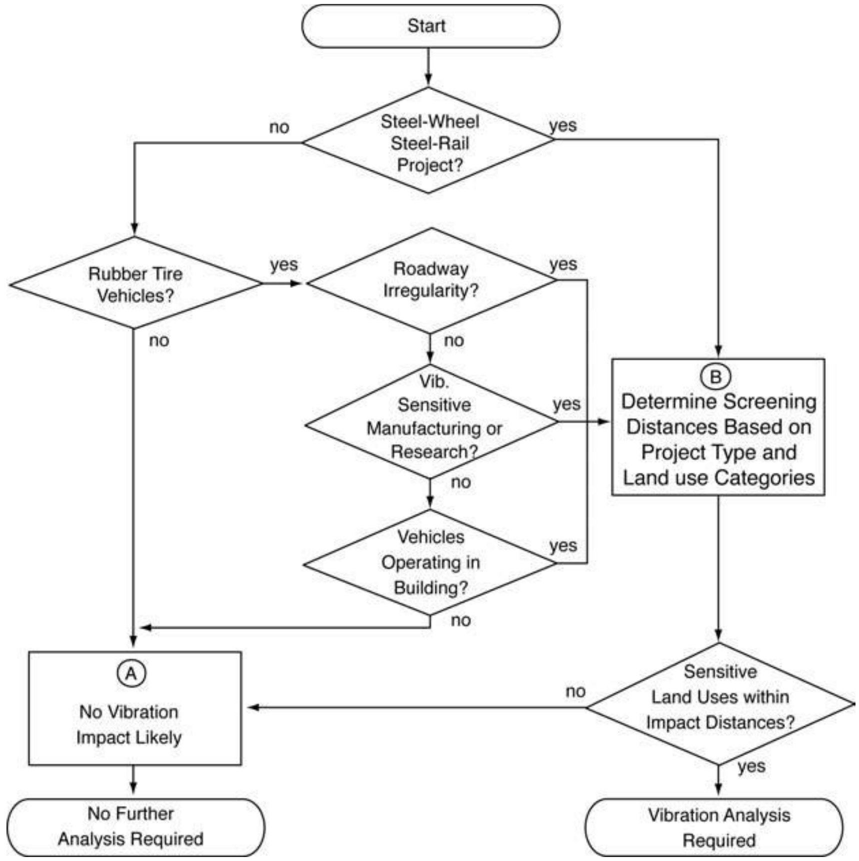

Figure 6-3 Flow Chart of Vibration Screening Process

Step 1: Classify Project Vehicles

Determine the project type and the next step based on the guidelines below.

Option A: No Vehicles – Transit projects that do not involve vehicles do not have potential for vibration impact and do not require further analysis (Box A in Figure 6-3).

Many smaller FTA-funded projects, such as bus terminals, park-and-ride lots, and station rehabilitation are in this category, and do not require further analysis of ground-borne vibration impact. However, if track systems are modified (e.g., tracks moved or switches modified), *proceed to Step 2*.

Option B: Steel-wheeled/Steel-rail Vehicles – Transit projects with steel-wheeled/steel-rail vehicles have potential for vibration impact (Box B in Figure 6-3); *proceed to Step 2*. These rail systems include urban rapid transit, LRT, commuter rail, and steel-wheel intermediate capacity transit (ICT) systems.

Option C: Rubber-tire Vehicles – For projects that involve rubber-tire vehicles and do not meet the following conditions, vibration impact is unlikely, and no further analysis is needed. *Proceed to Step 2* for projects that involve rubber-tire vehicles and meet the following conditions (Box A in Figure 6.3):

- **Roadway irregularity** – Expansion joints, speed bumps, or other design features that result in unevenness in the road surface can result in perceptible ground-borne vibration at distances up to 75 ft away.
- **Operation close to vibration-sensitive buildings** – Buses, trucks, or other heavy vehicles operating close to a vibration-sensitive building (within approximately 100 ft from the property line) may impact vibration-sensitive activities, such as research that uses electron microscopes or manufacturing of computer chips.
- **Vehicles operating within buildings** – Special considerations are often required for shared use facilities where vehicles operate inside or directly underneath buildings such bus stations located inside an office building complex.

Step 2: Determine Project Type

Determine the project type according to Table 6-7.

Table 6-7 Project Types for Vibration Screening Procedure

Project Type Number	Project Type	Description
1	Conventional Commuter Railroad	Both locomotives and passenger vehicles create vibration. For commuter trains, the highest vibration levels are typically created by the locomotives. Electric commuter rail vehicles create levels of ground-borne vibration that are comparable to electric rapid transit vehicles.
2	RRT	Ground-borne vibration impact from rapid transit trains is one of the major environmental issues for new systems. Ground-borne vibration is usually a major concern for subway operations. It is less common for at-grade and elevated rapid transit lines to create intrusive ground-borne vibration and noise since air-borne noise typically dominates.
3	LRT and Streetcars	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, typical vibration levels are usually lower. Steel-wheel/steel-rail AGT is included in either this category or the ICT category depending on the level of service and train speeds.
4	Intermediate Capacity Transit	Because of the low operating speeds of most ICT systems, 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 include diesel buses, electric trolley buses, and rubber-tired people movers. Most projects that do not include steel-wheel trains do not cause vibration impacts.**

*See the screening distances for category 1 land uses in Table 6-8.

****** 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 complaint, the vibration can usually be attributed to irregularities in the road.

Step 3: Determine Screening Distance

Determine the appropriate screening distances based on land use and project type according to Table 6-8.

The distances are based on the criteria presented in Section 6.3, the procedures in Section 6.4 assuming normal vibration propagation, and include a 5-dB factor of safety. Even so, areas with very efficient vibration propagation can have substantially higher vibration levels.

Because of the 5-decibel safety factor, the screening distances will identify most of the potentially impacted areas, even for areas with efficient propagation. However, when there is evidence of efficient propagation, such as previous complaints about existing transit facilities or a history of problems with construction vibration, increase the distances in Table 6-8 by a factor of 1.5.

Table 6-8 Screening Distances for Vibration Assessments

Type of Project	Critical Distance for Land Use Categories* Distance from ROW or Property Line, ft		
	Land Use Cat. 1	Land Use Cat. 2	Land Use Cat. 3
Conventional Commuter Railroad	600	200	120
RRT	600	200	120
LRT and Streetcars	450	150	100
ICT	200	100	50
Bus Projects (if not previously screened out)	100	50	--

*For the Vibration Screening Procedure, evaluate special buildings as follows: Category 1 - concert halls and TV studios, Category 2 - theaters and auditoriums

Step 4: Identify Vibration-Sensitive Land Uses

Identify all vibration-sensitive land uses (Table 6-1) within the chosen screening distance. If no vibration-sensitive land uses are identified, no further vibration analysis is needed. If one or more of the vibration-sensitive land uses are in the screening distance, complete a General Vibration Assessment (Section 6.4) or a Detailed Vibration Analysis (Section 6.5).

6.4 Evaluate Impact: General Vibration Assessment

Evaluate for impact using the General Vibration Assessment procedure if the Vibration Screening Procedure (Section 6.3) identified vibration-sensitive receivers within the screening distance of the transit vibration source.

For guidelines on when the General Vibration Assessment is appropriate, review Section 6.1.

The basic approach for the General Vibration Assessment is to define a curve or set of curves that predicts the overall ground-borne vibration as a function of distance from the source, then apply adjustments to these curves to account for factors such as vehicle speed, geologic conditions, building type, and receiver location within the building. 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.

Step 1: Select Base Curve for Ground Surface Vibration Level

Select a standard vibration curve to represent general vibration characteristics for the source.

The curves presented in Figure 6-4 are based on measurements of ground-borne vibration at representative North American transit systems and can be used to represent vibration characteristics for standard transportation systems in the General Vibration Assessment.

These curves assume typical ground-borne vibration levels, equipment in good condition, and speeds of 50 mph for the rail systems and 30 mph for buses. Adjustments to account for differences in speed and geologic conditions are included in Step 2.

Select a base curve from Figure 6-4 according to the guidelines in Table 6-9. Equations for the curves in Figure 6-4 are included in Table 6-10. Additional considerations for selecting a base curve for systems not included in Table 6-9 are presented below by transit mode.

Table 6-9 Ground Surface Vibration Level Base Curve Descriptions

Curve	Description
Locomotive-Powered Passenger or Freight Curve	Appropriate for vehicles powered by diesel or electric locomotives including intercity passenger trains and commuter rail trains.
Rapid Transit or Light Rail Vehicles Curve	Appropriate for both heavy and light-rail vehicles on at-grade and subway track.
Rubber-Tired Vehicles Curve	Appropriate for rubber-tire vehicles. These types of vehicles rarely create ground-borne vibration problems unless there is a discontinuity or bump in the road that causes the vibration. This curve represents the vibration level for a typical bus operating on smooth roadway.

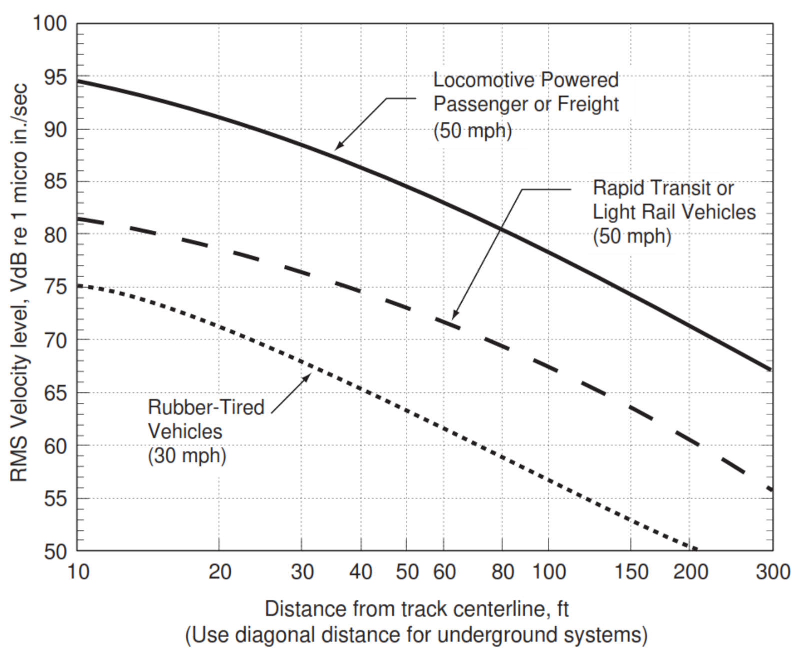

Figure 6-4 Generalized Ground Surface Vibration Curves

Table 6-10 Generalized Ground Surface Vibration Equations

Curve	Equation	
Locomotive Powered Passenger or Freight Curve	$L_v = 92.28 + 14.81\log(D) - 14.17\log(D)^2 + 1.65\log(D)^3$	**Eq. 6-1**
Rapid Transit or Light Rail Vehicles Curve	$L_v = 85.88 - 1.06\log(D) - 2.32\log(D)^2 - 0.87\log(D)^3$	**Eq. 6-2**
Rubber-Tired Vehicles Curve	$L_v = 66.08 + 34.28\log(D) - 30.25\log(D)^2 + 5.40\log(D)^3$	**Eq. 6-3**
L_v = velocity level, VdB D = distance, ft		

Considerations for selecting a base curve for different transit modes include:

- **Intercity passenger trains** – Although intercity passenger trains can be an important source of environmental vibration, it is rare that they are considered for FTA-funded projects unless a new transit mode uses an existing rail alignment. When a new transit line uses an existing rail alignment, changes in the intercity passenger traffic can result in either positive or negative impacts. Use the locomotive-powered passenger or freight curve for intercity passenger trains unless there are specific data available on the ground-borne vibration created by the new train operations.

- **Locomotive-powered commuter rail** – Use the locomotive-powered passenger or freight curve for all commuter rail system powered by either diesel or electric locomotives.

- **Electric multiple unit (EMU)** – Use the rapid transit or light rail vehicles curve for self-powered electric commuter rail trains.

- **Diesel multiple unit (DMU)** – Self-powered DMUs create vibration levels somewhere between rapid transit vehicles and locomotive-powered passenger trains. A vibration curve for DMUs can be estimated by lowering the locomotive-powered passenger or freight curve by 5 dB.

- **Subway heavy rail or light rail** – Use the rapid transit or light rail vehicles curve for subway heavy rail and subway light rail. Although vibrations from subway and at-grade tracks have very different characteristics, the overall vibration velocity levels are comparable. When applied to subways, the rapid transit or light rail vehicles curve 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 light rail** – Use the rapid transit or light rail vehicles curve for at-grade heavy rail or light rail. Heavy rail and LRT vehicles have similar suspension systems and axle loads and create similar levels of ground-borne vibration.

- **Elevated guideways or aerial structures** – Vibration from operations on an elevated structure is typically not an issue unless the guideway is supported by a building or located very close to buildings. Apply the appropriate adjustment for the aerial structures (Section 6.4, Step 2).

- **Streetcars** – Use the rapid transit or light rail vehicles curve for street cars.

- **ICT** – Use the rapid transit or light rail vehicles curve for ICT systems with steel wheels and the rubber-tired vehicles curve for ICT systems with rubber tires.

- **Other vehicle types** – For less common modes such as magnetically-levitated vehicles (maglev), monorail, or AGT, use good engineering judgment to choose a standard curve to best fit the mode or if a new curve needs to be developed, as a function of distance from the track. Examples include:
  - Vibration from a rubber-tire monorail operating on aerial guideway can be approximated using the rubber-tired vehicles curve with the appropriate adjustment for the aerial structure (Section 6.4, Step 2).
  - Most of the data available on the noise and vibration characteristics of maglev vehicles comes from high-speed systems intended for inter-city service. Even though there is no direct contact between the vehicle and the guideway, the dynamic loads on the guideway can generate ground-borne vibration. Measurements on a German high-speed maglev resulted in ground-borne vibrations at 75 mph which is comparable to the base curve for rubber-tired vehicles at 30 mph.[49]

Step 2: Apply Adjustments

Apply project-specific adjustments to the standard vibration curve.

Once the base curve has been selected, use the adjustments in the following instructions to develop project-specific vibration projections at each receiver. All adjustments are given as single numbers to add to, or subtract from, the base level.

Adjustments are separated by source, path, and receiver and include speed, wheel and rail type and condition, type of track support system, type of building foundation, and number of floors above the basement level. Calculate the appropriate adjustments to the base level. An example of the General Vibration Assessment is provided at the end of this Section.

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 adjustments in this section are suitable for generalized evaluation of the vibration impact and vibration mitigation measures because they are based on typical vibration spectra. However, these adjustments are not adequate for detailed evaluations of impact of vibration-sensitive buildings or for detailed specification of mitigation measures.

2a. Apply source adjustments to the base curve using Table 6-11 and the descriptions below to account for the project-specific source characteristics.

Table 6-11 Source Adjustment Factors for Generalized Predictions of GB Vibration and Noise

Source Factor	Adjustment to Propagation Curve			Comment
		Reference Speed		
	Vehicle Speed	50 mph	30 mph	
Speed	60 mph	+1.6 dB	+6.0 dB	Vibration level is approximately proportional to $20\log(speed/speed_{ref})$, see Eq. 6-4.
	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	
Vehicle Parameters (not additive, apply greatest value only)				
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.
Track Conditions (not additive, apply greatest value only)				
Worn or Corrugated Track	+10 dB			Corrugated track is a common problem. Mill scale* on new rail can cause higher vibration levels until the rail has been in use for some time. If there are adjustments for vehicle parameters and the track is worn or corrugated, only include one adjustment.
Special Trackwork within 200 ft	+10 dB (within 100 ft) +5 dB (between 100 and 200 ft)			Wheel impacts at special trackwork will greatly increase vibration levels. The increase will be less at greater distances from the track. Do not include an adjustment for special trackwork more than 200 ft away.
Jointed Track	+5 dB			Jointed track can cause higher vibration levels than welded track.
Uneven Road Surfaces	+5 dB			Rough roads or expansion joints are sources of increased vibration for rubber-tire transit.
Track Treatments (not additive, apply greatest value only)				
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.

*Mill scale on a new rail is a slightly corrugated condition caused by certain steel mill techniques.

In addition to the comments in Table 6-11, use the following guidelines to select the appropriate adjustment factors. Some adjustments in the same category are not cumulative (additive) and only the greatest applicable adjustment should be applied. The adjustments that are not additive are noted in Table 6-11 and in the descriptions below. Note that some adjustments are not additive across multiple categories and are noted in the comments of Table 6-11. For example, the adjustment for a vehicle with stiff primary suspension is 8 dB, and the adjustment for wheel flats is 10 dB. If the vehicle has a stiff primary suspension and has wheel flats, the projected vibration levels should be increased by 10 dB, not 18 dB.

In addition, some vibration control measures are targeted for specific frequency ranges. The shape of the actual vibration spectra should be considered so that an appropriate vibration control measure may be selected.

- **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 dB, and halving train speed will reduce the levels by 6 dB. The adjustments in Table 6-11 have been tabulated for reference vehicle speeds of 30 mph for rubber-tired vehicles and 50 mph for steel-wheel vehicles. Use the following relationship to calculate the adjustments for other speeds.

  $$Adj_{speed}\ (dB) = 20\log\left(\frac{speed}{speed_{ref}}\right) \qquad \textbf{Eq. 6-4}$$

  Variation with speed has been observed to be as low as $15\log\left(\frac{speed}{speed_{ref}}\right)$, but unless specific speed data for vibration for a vehicle has been obtained, use Eq. 6-4.

- **Vehicle Parameters** – 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, a stiff primary suspension (vertical resonance frequency greater than 15 Hz) can result in higher levels of ground-borne vibration than soft primary suspensions. Vehicles, for which the primary suspension consists of rubber or neoprene around the axle bearing, usually have a very stiff primary suspension with a vertical resonance frequency greater than 40 Hz or more.

  Deteriorated wheel condition is another factor that increases vibration levels. It can be assumed that a new system has vehicles with wheels in good condition. When older vehicles are used on new track, it is important to consider the condition of the wheels, and it may be appropriate to include an adjustment for the wheel condition.

  Resilient wheels will reduce vibration levels at frequencies greater than the effective resonance frequency of the wheel. When this resonance frequency is relatively high, greater than 80 Hz, resilient wheels may only have a marginal effect on ground-borne vibration.

The adjustments in this category are not additive; apply the greatest applicable value only.

- **Track Conditions** – 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 assume welded rail in good condition. Jointed rail causes higher vibration levels than welded rail and the increase depends on the condition of the joints.

  Wheel impacts at special trackwork, such as frogs at crossovers, create much higher vibration forces than typical track conditions. Because of the higher vibration levels at special trackwork, crossovers are the principal areas of vibration impact on new systems. Methods of mitigating the vibration impact include modifying the track support system, installing low-impact frogs, or relocating the crossover. 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 5 to 15 dB higher than normal. Mill scale will typically wear away after some time in service, but the track must be ground to remove corrugations or to reduce the roughness from wear.

  Roadway surfaces in the rubber-tired vehicle base curve are assumed to be smooth. Rough washboard surfaces, bumps, or uneven expansion joints are the types of running surface defects that cause increased vibration levels over the smooth road condition.

  The adjustments in this category are not additive; apply the greatest applicable value only. If there are adjustments for vehicle parameters and the track is worn or corrugated, only include one adjustment.

2b. Apply path adjustments to the base curve using Table 6-12 and the descriptions below to account for the project-specific path characteristics.

Table 6-12 Path Adjustment Factors for Generalized Predictions of GB Vibration and Noise

Path Factor	Adjustment to Propagation Curve			Comment
Resiliently Supported Ties (Low-Vibration Track, LVT)	-10 dB			Resiliently supported tie systems have been found to provide very effective control of low-frequency vibration.
Track Structure (not additive, apply greatest value only)				
Type of Transit Structure	Relative to at-grade tie & ballast:			In general, the heavier the structure, the lower the vibration levels. Putting the track in cut may reduce the vibration levels slightly. Rock-based subways generate higher-frequency vibration.
	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	
Ground-borne Propagation Effects				
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.	The positive adjustment accounts for the lower attenuation of vibration in rock compared to soil. It is generally more difficult to excite vibrations in rock than in soil at the source.
		50 ft	+2 dB	
		100 ft	+4 dB	
		150 ft	+6 dB	
		200 ft	+9 dB	
Coupling to building foundation	Wood-Frame Houses		-5 dB	In general, the heavier the building construction, the greater the coupling loss.
	1-2 Story Masonry		-7 dB	
	3-4 Story Masonry		-10 dB	
	Large Masonry on Piles		-10 dB	
	Large Masonry on Spread Footings		-13 dB	
	Foundation in Rock		0 dB	

In addition to the comments in Table 6-12, use the following guidelines to select the appropriate adjustment factors.

- **Track Structure** – The weight and size of a transit structure affects the vibration radiated by that structure. In general, vibration levels are lower for heavier transit structures. Therefore, 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 and damping of the structure and the extra distance that the vibration must travel before it reaches the receiver. Elevated structures in AGT applications are sometimes designed to bear on building elements. This is a special case and may require detailed design considerations.

  The adjustments in this category are not additive; apply the greatest applicable value only.

- **Ground-Borne Propagation Effects – Geologic Conditions** – Although it is known that geologic conditions have a considerable effect on the vibration levels, it is rarely possible to develop more than a general understanding of the vibration propagation characteristics for a General Vibration Assessment. One of the challenges 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).

  Some geologic conditions are repeatedly associated with efficient propagation. Shallow bedrock, less than 30 ft below the surface, is likely to have efficient propagation. Soil type and stiffness are also important factors in determining propagation characteristics. In particular, stiff, clayey soils, consolidated sand, gravel, and glacial till can be 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 conservative approach would be to use the 10-dB adjustment for efficient propagation for areas where efficient propagation is likely. However, this adjustment can greatly overstate the potential for vibration impact where efficient propagation is not present and should be applied using good judgment. 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 reason to suspect efficient propagation conditions, conduct a Detailed Vibration Analysis during the engineering phase and include vibration propagation tests at the areas with potential for efficient propagation.

- **Track Structure and Geologic Conditions** – **Examples**
  - **Subway**
    For a subway, determine if 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 like soil than hard rock. Whether a subway is founded in soil or rock can make a 15-dB difference in the vibration levels.

    When a subway structure is founded in rock, include the following Track Structure and Ground-borne Propagation Effects adjustments from Table 6-12:
    - Type of Transit Structure adjustment: Rock-based – 15 dB
    - Geologic Conditions adjustment: Propagation in rock layer for the appropriate distance.

    This adjustment increases with distance because vibration attenuates more slowly in rock than in the soil used as a basis for the reference curve.

- **At-grade** – When considering at-grade vibration sources, determine if the vibration propagation characteristics are typical or efficient. Efficient vibration propagation results in vibration levels approximately 10 dB higher than typical levels. This more than doubles the potential impact zone for ground-borne vibration.

- **Ground-Borne Propagation Effects – Coupling to Building Foundation** – 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 typical residential structures, 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.

  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 based on building type if there is at least a 10-foot layer of soil between the building foundation and the rock layer.

2c. Apply receiver adjustments to the base curve using Table 6-13 and the descriptions below to account for the project-specific receiver characteristics. The data in Table 6-13 is applicable when the building structural features are known.

For more generic cases that do not have detailed information on individual buildings, use a conservative approach and apply the following adjustments to predict indoor vibration based on the outdoor vibration, instead of using the adjustments in Table 6-13:[(43)(50)]

- Light-weight, wood-frame construction 1st floor: +3 dB
- Light-weight, wood-frame construction 2nd and 3rd floors: +6 dB
- Large buildings: 0 dB
- Small masonry buildings: +3 dB

Table 6-13 Receiver Adjustment Factors for Generalized Predictions of GB Vibration and Noise

Receiver Factor	Adjustment to Propagation Curve		Comment
Floor-to-floor attenuation	1 to 5 floors above grade	-2 dB/floor	This factor accounts for dispersion and attenuation of the vibration energy as it propagates through a building starting with the first suspended floor.*
	5 to 10 floors above grade	-1 dB/floor	
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.

* Floor-to-floor attenuation adjustments for the first floor assume a basement.

In addition to the comments in Table 6-13, use the following guidelines to select the appropriate adjustment factors. Note that receiver adjustments are additive.

- Vibration generally reduces in level as it propagates through a building. As indicated in Table 6-13, a 1- to 2-decibel attenuation per floor is typically appropriate.
- 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. Example: All adjustments for the first floor assuming a basement are: -5 dB for the coupling loss; -2 dB for the propagation from the basement to the first floor; and +6 dB for the floor amplification. The total adjustment in this case is -1 dB.

2d. Apply adjustments to the final adjusted curve using Table 6-14 and the descriptions below to convert ground-borne vibration levels to ground-borne noise levels.

Table 6-14 Conversion to Ground-borne Noise

Conversion to Ground-borne Noise			
Noise Level in dBA	Peak frequency of ground vibration:		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-, mid-, 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.
	Low frequency (<30 Hz)	-50 dB	
	Mid Frequency (peak 30 to 60 Hz)	-35 dB	
	High frequency (>60 Hz)	-20 dB	

Estimate the levels of radiated noise using the average vibration amplitude of the room surfaces (floors, walls, and ceiling), and the total acoustical absorption in the room.

The un-weighted sound pressure level is approximately 5 dB[37][43] less than the vibration velocity level when the velocity level is referenced to $1x10^{-6}$ inches/sec; but for a better estimate, it is necessary to consider general frequency ranges. Since ground-borne noise is A-weighted, the adjustments vary by frequency range, as described below. See Appendix B.1.4.1 for more information on A-weighting.

To select the appropriate adjustment, classify the frequency characteristics according to the guidelines below.

- **Low Frequency (<30 Hz)** – Low-frequency vibration characteristics can be assumed for the following conditions:
  - Subways surrounded by cohesionless sandy soil
  - Vibration isolation track support systems
  - Most surface track

- **Mid Frequency (peak 30 to 60 Hz)** – The mid-frequency vibration characteristic can be assumed for the following conditions:
  - Subways, unless other information indicates that one of the other assumptions is appropriate,
  - Surface track when the soil is very stiff with high clay content

- **High Frequency (>60 Hz)** – High-frequency characteristics can be assumed for the following conditions:
  - Subways with the transit structure founded in rock
  - Subways, when there is very stiff, clayey soil

Step 3: Inventory of Vibration Impact

Take inventory of vibration-sensitive land uses with impact and determine if a Detailed Vibration Analysis is required.

Compare the projected vibration levels, including all appropriate adjustments in Section 6.4, Step 2, to the criteria to determine if impact from ground-borne vibration or noise is likely. Note that for any transit mode, variation in vibration levels under apparently similar conditions is not uncommon. In the General Vibration Assessment, it is preferable to make a conservative assessment of the impact and include buildings that may ultimately not be subject to impact.

The standard curves in Section 6.4, Step 1, represent the upper range of vibration levels from well-maintained systems. Although actual levels fluctuate widely, it is rare that ground-borne vibration will exceed these curves by more than 1 or 2 dB unless there are extenuating circumstances such as wheel- or running-surface defects. However, because actual levels of ground-borne vibration will sometimes differ substantially from the projections, use the following guidelines to interpret vibration impact:

- **Projected vibration is below the impact threshold** – Vibration impact is unlikely, and the environmental document should state this.

- **Projected ground-borne vibration is 0 to 5 dB greater than the impact threshold** – There is a strong chance that actual ground-borne vibration levels will be below the impact threshold. The environmental document should report impact at these locations as exceeding the applicable threshold, present possible mitigation measures and costs, and commit to conducting more detailed studies to refine the vibration impact analysis during the engineering phase. During the Detailed Vibration Analysis, determine appropriate mitigation, if necessary. A site-specific Detailed Vibration Analysis may show that vibration impacts will not occur and control measures are not needed.

- **Projected ground-borne vibration is 5 dB or greater than the impact threshold** – Vibration impact is probable and Detailed Vibration Analysis must be conducted during the engineering phase to determine appropriate vibration control measures. The environmental document should report impact at these locations as exceeding the applicable threshold, present possible mitigation measures and costs, and commit to conducting more detailed studies to refine the vibration impact analysis during the engineering phase. During the Detailed Vibration Analysis, determine appropriate mitigation, if necessary. A site-specific, Detailed Vibration Analysis may show that very costly vibration mitigation must be incorporated into the project to eliminate the impacts.

FTA recommends the reporting of a vibration level as a single value and not as a range, as ranges tend to confuse the interpretation of impact.

Express the results of the General Vibration Assessment in terms of an inventory with the following components:

- Include all vibration-sensitive land uses as identified in the Vibration Screening Procedure.
- Organize the inventory according to the categories described in Table 6-8.
- Include information on potentially feasible mitigation measures to reduce vibration to acceptable levels based on the generalized reduction estimates provided in this section. To be considered feasible, the measure or combination of measures must provide at least a 5-dB reduction of the vibration levels and be reasonable in terms of cost.

These potential mitigation measures are considered preliminary. Final vibration mitigation measures can only be specified after a Detailed Vibration Analysis has been done; see Section 6.5 for more information. Vibration control is frequency-dependent; therefore, specific recommendations of vibration control measures can only be made after evaluating the frequency characteristics of the vibration.

Example 6-1 General Vibration Assessment – LRT

General Vibration Assessment for an LRT project

The hypothetical project is a LRT system that operates at 40 mph on at-grade, ballast and tie track with welded rail. The first floor of houses is at 125 ft from the LRT tracks and there is efficient propagation through the soil. The houses are constructed with wood frames. The houses will be exposed to 260 train passbys per day. Calculate the ground-borne vibration and assess for impact.

Select Base Curve for Ground Surface Vibration

Determine the appropriate base curve and the RMS velocity level (L_v).

According to Table 6-9, the Rapid Transit or Light Rail Vehicles curve is appropriate.

$L_v = 65\ VdB$ at 125 ft for this curve at 50 mph

Apply Adjustments

Apply the appropriate source adjustments using Table 6-11.

$$Source\ Speed\ Adjustment = 20\log\left(\frac{40}{50}\right) = -1.9\ dB$$
$$L_v = 65 - 1.9 = 63.1\ VdB$$

Apply the appropriate path adjustments using Table 6-12.

$$Efficient\ propagation = +10\ dB$$
$$Coupling\ to\ building\ foundation\ (wood\ frame) = -5\ dB$$
$$L_v = 63.1 + 10 - 5 = 68.1\ VdB$$

Apply the appropriate receiver adjustments using Table 6-13.

$$Amplification\ due\ to\ resonance\ of\ floor = +6\ dB$$
$$First\ floor\ attenuation = -2\ dB$$
$$L_v = 68.1 + 6 - 2 = 72.1\ VdB$$

Assess for Impact

Because there are more than 70 events per day, this project is in the Frequent Events category (Table 6-2). For category 2 land uses (residences) with frequent events, the impact criteria is 72 VdB (Table 6-3). Therefore, according to the General Vibration Assessment, there is potential for impact and a Detailed Vibration Analysis should be completed.

6.5 Evaluate Impact: Detailed Vibration Analysis

Evaluate for impact using the Detailed Vibration Analysis procedure, if appropriate (Section 6.1).

The goal of the Detailed Vibration Analysis is to use all available tools to develop accurate projections of potential ground-borne vibration impact and when necessary, to design mitigation measures. A Detailed Vibration Analysis requires developing estimates of the frequency components of the vibration signal, usually in terms of 1/3-octave-band spectra. The analytical techniques for solving vibration problems are complex, and the technology continually advances. Therefore, the approach presented in this section focuses on the key steps for these analyses. The key elements of the Detailed Vibration Analysis procedure and recommended steps are described below.

The methods in this section generally assume a steel-wheel/rail system. The procedures could be adapted to bus systems. However, this is rarely necessary because vibration impact is very infrequent with rubber-tired transit.

In general, when situations arise that are not explicitly covered in the Detailed Vibration Analysis, professional judgment may be used to extend these methods to cover these unique cases, when appropriate. Appendix G provides information on developing and using non-standard modeling procedures.

Step 1: Characterize Existing Vibration Conditions

Conduct measurements to survey and document the existing vibration conditions.

In contrast to noise impact analysis, the existing ambient vibration is not required to assess vibration impact in most cases; but, it is important to document general background vibration in the project corridor. Because the existing environmental vibration is usually below human perception, a limited vibration survey is sufficient even for a Detailed Vibration Analysis.

It is particularly valuable to survey vibration conditions at sensitive locations for the following reasons:

- To obtain valuable information on the true sensitivity of the activity to external vibration and obtain a reference condition under which vibration is not problematic.
- To document that existing vibration levels are above or below the normal threshold of human perception for the existing condition.
- To document levels of vibration created by existing rail lines. If vibration from an existing rail line is higher than the proposed train, there may not be impact even if the standard impact criteria are exceeded.
- To use existing vibration sources to characterize propagation. Existing vibration sources such as freight trains, industrial processes, quarrying operations, or normal traffic can be used to characterize vibration propagation. Carefully designed and performed measurements may eliminate the need for more complex propagation tests. See Appendix G for information on using non-standard modeling procedures.
- To identify the potential for efficient vibration propagation. 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.

Conduct measurements to characterize existing vibration conditions. The goal of most ambient vibration measurements 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(51) can transmit vibration energy into a building, the vertical component typically dominates.

1a. Choose Measurement Locations – Conduct outdoor and/or indoor measurements to characterize existing vibration conditions, as appropriate, for the project. Although ground-borne vibration is almost exclusively a problem inside buildings, it is generally recommended to perform measurements outdoors because equipment inside the building may cause more vibration than exterior sources. Additionally, the building structure and the resonances of the building can have strong effects on the vibration that are difficult to predict. It can also be important to measure and document those indoor sources of vibration. These indoor sources may cause vibration greater than that due to external sources like street traffic or aircraft overflights. When measuring (indoor) floor vibration, take measurements near the center of a floor span where the vibration amplitudes are the highest.

1b. Measurement Considerations

- **Site selection** – Selecting sites for an ambient vibration survey requires good judgment. Sites selected to characterize a transit corridor should be distributed along the entire project where potential for impacts have been identified 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 vibration areas;
  - Measurements along major traffic arterials and highways or freeways to characterize high-ambient vibration areas;
  - Measurements in any area with vibration-sensitive activities; and
  - Measurements at any major existing source of vibration such as railroad lines.

- **Transducer placement** – Place the transducers near the building setback line. For ambient measurements along railroad lines, it is recommended to include:
  - Multiple sites at 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 to locate any switches, bad rail joints, corrugations, or other factors that could be responsible for higher than normal vibration levels. Locations with these kinds of irregularities should be represented in addition to locations with rail in better condition.

- **Transducer mounting methods** – The way a transducer is mounted can affect the measured levels of ground-borne vibration.
  - Straightforward methods of mounting transducers on the ground surface or on pavement are adequate for vertical vibration measurements for the frequencies of concern for ground-borne vibration (less than about 200 Hz).
  - Quick-drying epoxy, clay, or beeswax can be used to mount transducers to smooth paved surfaces or 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.
  - When in doubt, review the specific transducer documentation and discuss additional mounting guidance with the transducer manufacturer.

1c. Existing Vibration Characterization – The appropriate methods of characterizing ambient vibration are dependent on the type of information required for the analysis. Consider the following when characterizing the existing vibration:

- **Ambient vibration** – Ambient vibration is usually characterized with a continuous 10- to 30-minute measurement of vibration. The rms velocity level of the vibration velocity level over the measurement period provides an indication of the average vibration energy. The rms velocity level over the measurement period is typically equivalent to a long averaging time rms level.

- **Specific events** – Characterize specific events such as train passbys by the rms level over the time that the train passes by. If the locomotives produce vibration levels more than 5 dB higher than the passenger or freight cars, obtain a separate rms level for the locomotives. 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}. In some cases, it may be adequate to characterize the train passby using L_{max}, which is simpler to obtain than the rms averaged over the entire train passby.

- **Spectral analysis** – Perform a spectral analysis of vibration propagation data. For example, if vibration transmission of the ground is suspected of having particular frequency characteristics, use 1/3-octave band charts to describe vibration behavior. Narrowband spectra also can be valuable, particularly for identifying discrete frequency components and designing specific mitigation measures.

  Note that it is preferred to characterize existing vibration in terms of the rms velocity level instead of the peak PPV, which is commonly used to monitor construction vibration. As discussed in Section 5.1, rms velocity is considered more appropriate than PPV for describing human response to building vibration.

Step 2: Estimate Vibration Impact

Estimate ground-borne vibration and noise at sites where significant impact is probable and assess for impact.

Predicting ground-borne vibration associated with a transportation project continues to be 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.

The procedure described in this section is based on site-specific tests of vibration propagation. This procedure was developed under a FTA-funded research contract[52] and is recommended for detailed evaluations of ground-borne vibration. Other approaches to a prediction procedure, such as finite element methods, can be used. See Appendix G for information on using non-standard modeling procedures.

Overview of Prediction Procedure – This procedure was developed to allow the use of data collected in one location to accurately predict vibration levels in another site where the geologic conditions may be completely different. The procedure is based on transfer mobility. Transfer mobility is the complex velocity response produced by a point force as a function of frequency. It 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 analyses in this manual focus on transfer mobility magnitude, which is the magnitude for the velocity relative to the force without reference to phase. The transfer mobility level is the level in decibels relative to 1E-6 in/lb-s.

The 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. Force density is the force per root distance along the track in lb/ft$^{1/2}$. The force density can be combined with transfer mobility measurements at vibration-sensitive sites along a new project to develop projections of future ground-borne vibration.

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 as originating from a single point. Therefore, the vibration source must be modeled as a line-source. Consequently, the point transfer mobility must be modified to account for a line-source. The subsequent line-source transfer mobility is given in units of decibels relative to 1e-6 in/s/lb/sqrt(ft).

The prediction procedure considers ground-borne vibration to be divided into several basic components described below and shown in Figure 6-5.

- **Excitation Force (Force Density)** – 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 is the level in decibels of the force density relative to 1 lb/ft$^{1/2}$ and describes the force that excites the soil/rock surrounding the transit structure.

- **Vibration Propagation (Transfer Mobility)** – 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. Rayleigh waves [(49)] are also created and propagate along the ground surface. These Rayleigh waves can be a major carrier of vibration energy. The mathematical modeling of vibration is complicated when there are soil strata with different elastic properties, which is common. As indicated in Figure 6-5, the propagation through the soil/rock is modeled using the transfer mobility, which is usually determined experimentally.

The combination of the force density level and the transfer mobility is used to predict the ground- surface vibration. This is the major difference from the General Vibration Assessment, which generalizes estimates of the ground-borne vibration.

- **Building Vibration** – When the ground vibration excites a building foundation, it sets the building into vibratory motion and vibration waves propagate 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 vibration that can be felt and cause windows and household items to rattle.

- **Audible Noise** – In addition to vibration that can be felt, the vibration of room surfaces radiates low-frequency sound that may be audible. The sound level is affected by the amount of acoustical absorption in the receiver room.

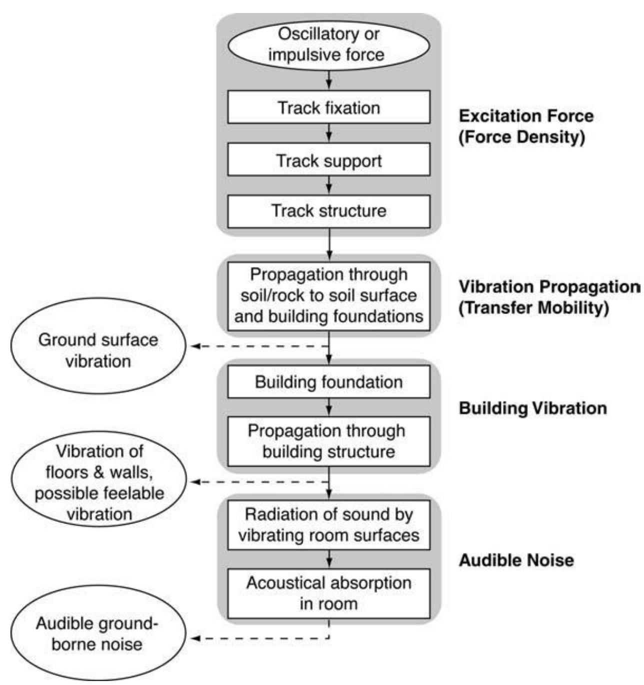

Figure 6-5 Ground-Borne Vibration and Noise Model

A fundamental assumption of the prediction approach outlined in this section 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 one-third octave band spectral levels in decibels with consistent reference values:

$$L_v = FDL + LSTM + C_{build} \quad \textbf{Eq. 6-5}$$

$$L_A = L_v + K_{rad} + K_{A-wt} \quad \textbf{Eq. 6-6}$$

where:

L_v = rms vibration velocity level in VdB

FDL = force density level in dB for a line vibration source such as a train

$LSTM$ = line-source transfer mobility level in dB from the tracks to the sensitive site

C_{build} = adjustments to account for ground-building foundation interaction and attenuation of vibration amplitudes as vibration propagates through buildings

L_A = A-weighted sound level

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 -5 dB can be used for K_{rad} for typical residential rooms when the decibel reference value for L_v is 1 micro in/sec [37][50]

K_{A-wt} = A-weighting adjustment at the 1/3-octave band center frequency

All of the quantities given above are functions of frequency, and the standard approach is to develop projections on a 1/3-octave band basis using the average values for each 1/3-octave band. The end results of the analysis are the 1/3-octave band spectra of the ground-borne vibration and the ground-borne noise.

The spectra are then compared to the vibration criteria for the Detailed Vibration Analysis. The A-weighted ground-borne noise level can be calculated from the vibration spectrum and compared to the criteria. This more detailed approach differs from the General Vibration 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.

The key steps in obtaining quantities for Eq. 6-5 and Eq. 6-6 are presented in the following steps and include:

Step 2a. Estimate force density
Step 2b. Measure the point-source transfer mobility
Step 2c. Estimate line-source transfer mobility
Step 2d. Project ground-borne vibration and ground-borne noise

2a. Estimate Force Density – The estimate of force density can be based on previous measurements or a special test program can be designed to measure the force density at an existing facility.

If no suitable measurements are available, conduct testing 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 a specific site. Review the report

"State-of- the-Art Review: Prediction and Control of Ground-Borne Noise and Vibration from Rail Transit Trains" [41] for examples of appropriate adjustments.

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. To derive force density, the best results are achieved by deriving line-source transfer mobility from a line of impacts. The standard approach is to average the force density from measurements at three or more positions at one site. If feasible, it is recommended to take measurements at more than one site and at multiple speeds.

If no suitable measurements are available, see Steps 2b and 2c for guidelines on obtaining line-source transfer mobility.

The force density for each 1/3-octave band is as follows:

$$FDL = L_v - LSTM \qquad \textbf{Eq. 6-7}$$

where:

FDL	= force density level in dB
L_v	= measured train ground-borne vibration level in VdB
$LSTM$	= line-source transfer mobility level in dB

Figure 6-6 shows example trackbed force densities in decibels relative to 1 lb/(ft)$^{1/2}$. These force densities were developed from measurements of vibration from heavy and LRT vehicles and represent an incoherent line of vibration force equal to the length of transit trains. This figure provides a comparison of the vibration forces from heavy commuter trains and LRT vehicles with different types of primary suspensions, illustrating the range of vibration forces commonly experienced in a transit system. A force density of a vehicle includes the characteristics of its track support system at the measurement site. Adjustments must be applied to the force density to account for differences between the facility where the force density was measured and the new system being analyzed.

Figure 6-7 shows typical force densities for rail transit vehicles at 40 mph on ballast and tie tracks, which are approximately within the tolerances shown in Figure 6-6. The force densities should be applied very carefully for other track types and speeds. The embedded tracks, although considerably stiffer than ballast and tie tracks, are expected to show similar force density levels.[53] The curves in Figure 6-7 should also be applied with caution for newer generations of light rail vehicles as well as vehicles that utilize direct fixation tracks. The preferred approach for vibration predictions would be to perform force density measurements at a system with vehicles and operations that are similar to those of the future project.

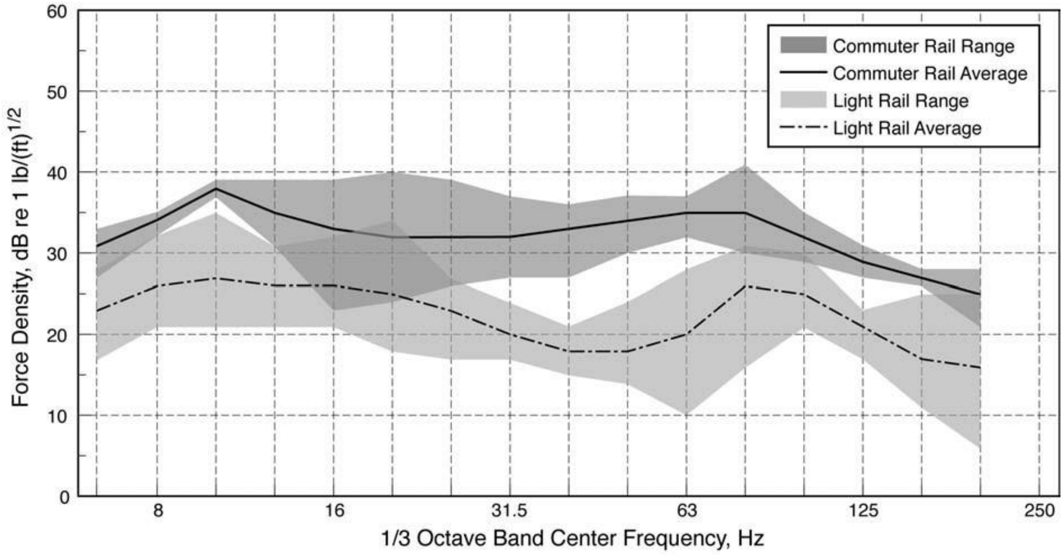

Figure 6-6 Typical Force Densities for Rail Transit Vehicles, 40 mph

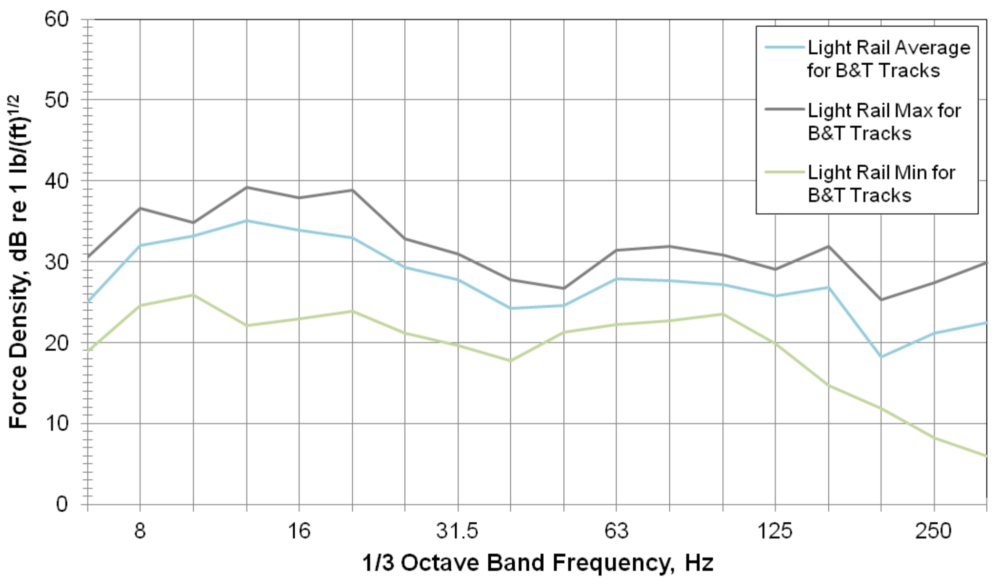

Figure 6-7 Typical Force Densities for LRT Vehicles, 40 mph

2b. Measure Point-Source Transfer Mobility – Using the appropriate instrumentation, measure point-source transfer mobility for sources with short lengths, such as buses or single car vehicles or columns supporting elevated structures. For longer vehicles, see Section 2c for a discussion of measuring line-source transfer mobilities.

The test procedure to measure point-source transfer mobility consists of impacting the ground by dropping a heavy weight and measuring the force into the ground and the response at several distances from the impact. Other excitation sources may include swept sine, sine-dwell, random vibration, and maximum length sequence. The goal of the test is to create vibration pulses that travel from the source to the receiver using the same path that will be taken by the transit system vibration.

Figure 6-8 illustrates the field procedure for measuring both at-grade and subway testing of transfer mobility. A weight is dropped from a height of 3 to 4 ft onto a force transducer. The responses of the force and vibration transducers are recorded on a multichannel 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 recorded data.

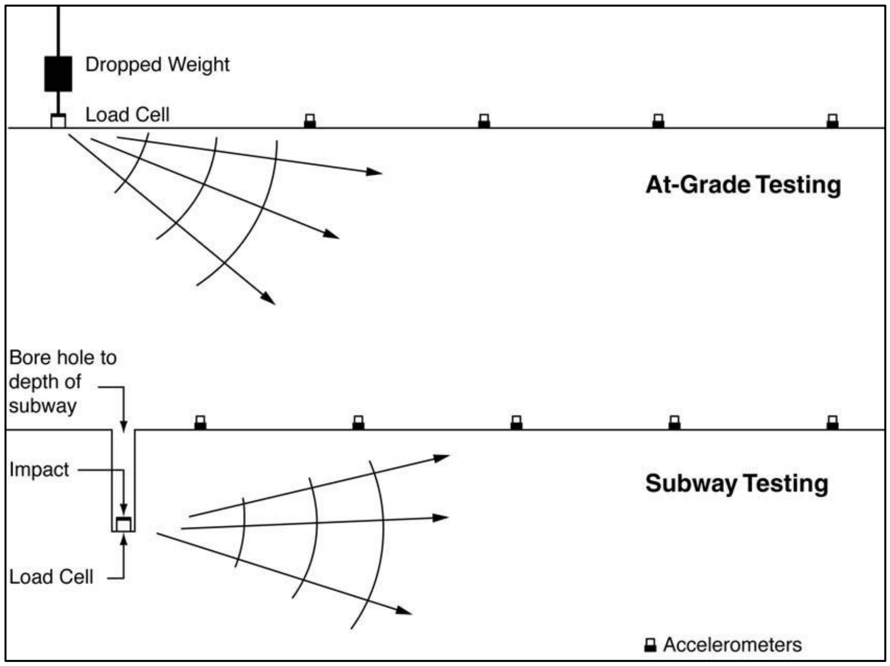

Figure 6-8 Test Configuration for Measuring Transfer Mobility

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 while the bore holes are drilled to allow for the use of 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 is used to excite the ground; typically, a 140-pound weight is dropped 18 inches onto a collar that is attached to the drill string. 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.

Standard signal-processing techniques are used to determine the transfer function (frequency response function) between the exciting force and the resultant ground-borne vibration. Numerical regression methods are used to combine a number of two-point transfer functions into a smooth point-source transfer mobility level that represents the average vibration propagation characteristics of a site as a function of both distance from the source and frequency. The transfer mobility level is usually expressed in terms of a group of 1/3-octave band transfer mobility levels. Figure 6-9 is an example of point-source transfer mobility levels from a series of tests at the Transportation Technology Center in Pueblo, Colorado.(50)(54)(55)(56)(57)

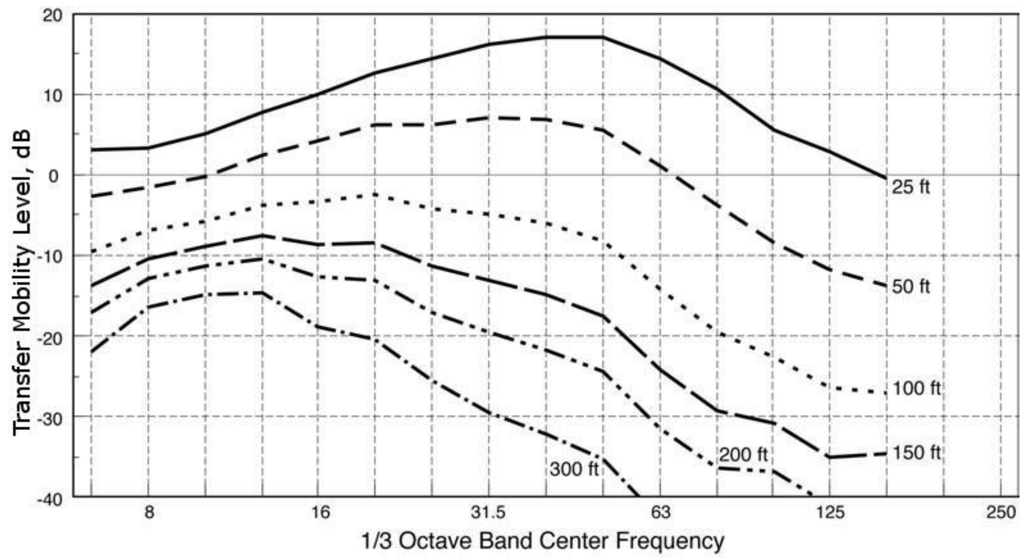

Figure 6-9 Example of Point-Source Transfer Mobility

Instrumentation

Performing a transfer mobility test requires specialized equipment, which is generally available from commercial sources. Typical instrumentation for field-testing and laboratory analysis of transfer mobility is shown in Figure 6-10.

A load cell can be used as the force transducer. The force transducer should be capable of impact loads of 5,000 to 50,000 pounds depending on the hammer used for the impact. For borehole testing, the load cell must be hermetically sealed and capable of being used at the bottom of a 30- to 100-foot-deep hole partially filled with water.

Either accelerometers or geophones can be used as the vibration transducers. Geophones should be carefully mounted so that they are vertical. 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. Data should be acquired with a digital acquisition system with a flat frequency response over the range of 6 to 400 Hz.

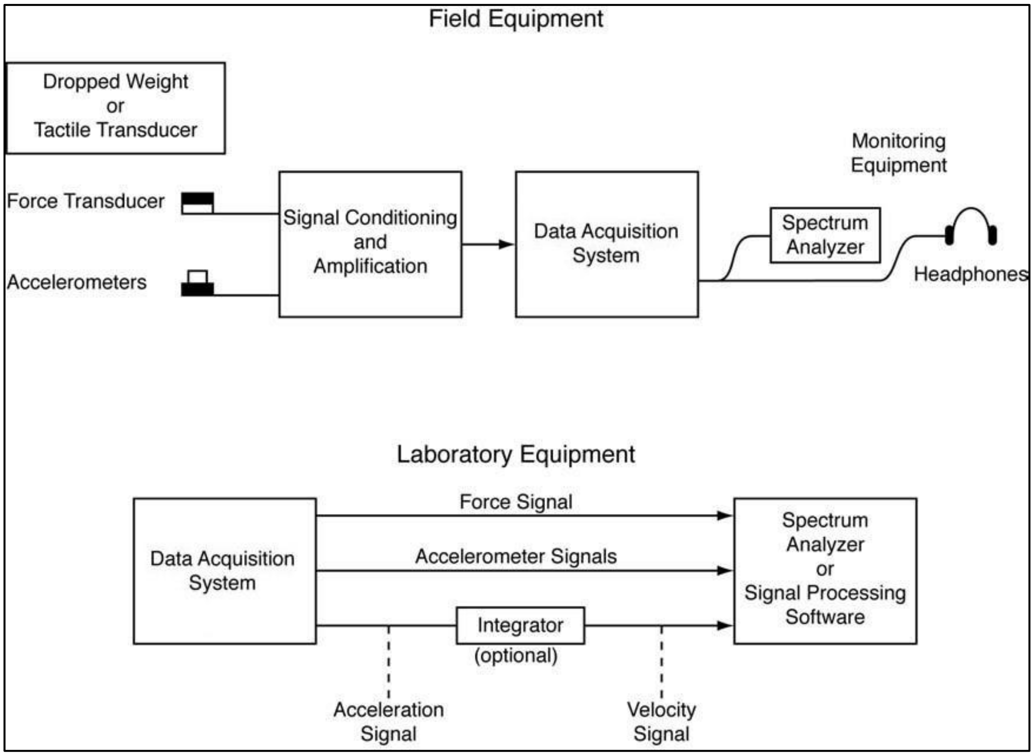

Figure 6-10 Equipment Required for Field Testing and Laboratory Analysis

A narrowband spectrum analyzer or signal-processing software can be used to calculate the transfer function and coherence between the force and vibration data. The analyzer must be capable of capturing impulses from at least two channels to calculate 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. Time averaging of the impulses will provide substantial 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.

Alternative methods of determining transfer mobility may be used, provided that these techniques have been demonstrated to provide the same results as the conventional weight-drop method over the frequency range of 6 Hz to 400 Hz. See Appendix G for information on developing and using non-standard procedures. These methods may include using other impulse-response measurement systems involving the use of shakers or electro-mechanical actuators, stimuli such as sweeps or maximum length sequences (MLS), and various signal processing techniques. A forthcoming ANSI Standard will describe in detail the procedures, methodologies, and reporting requirements for performing ground-borne vibration propagation measurements.

The transfer function can be calculated with either a spectrum analyzer or signal-processing software. Note that transfer functions should include the average of at least 20 impulses. Specialized multi-channel spectrum analyzers have built-in capabilities for computing transfer functions and are computationally efficient. However, signal-processing software can offer more flexibility in analyzing data signals and allows the use of different digital signal processing methods. Typical measurement programs involve acquisition of data in the field and later processing of the information in a laboratory. However, recent advances in instrumentation and signal-processing software allow data to be collected and analyzed while in the field.

2c. Estimate Line-Source Transfer Mobility – Estimate line-source transfer mobility for long sources such as multi-car trains. Line-source transfer mobilities are used to normalize measured vibration velocity levels from train passbys and to obtain force density. Two different approaches can be 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.

Option A: Lines of Transducers – Develop line-source transfer mobility curves from tests using one or more lines of transducers as shown in Figure 6-11 and described below.

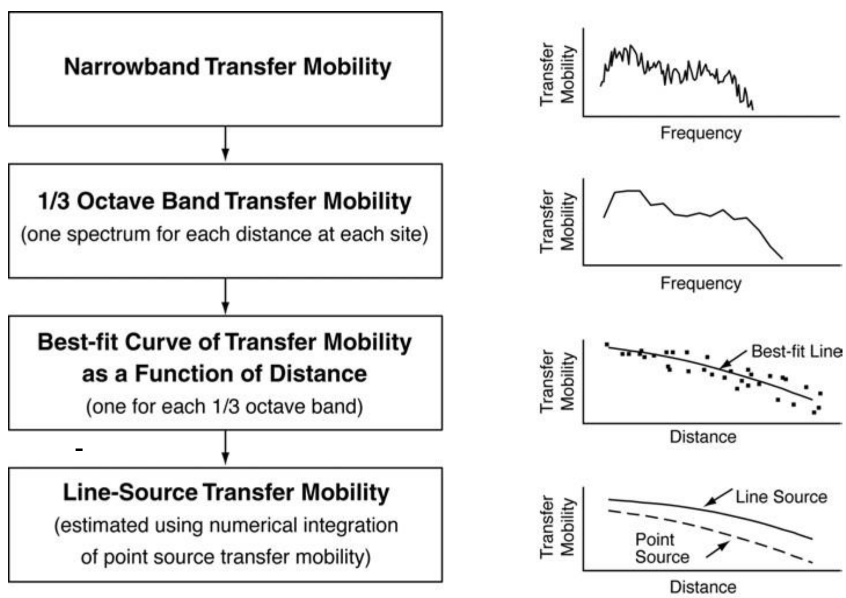

Figure 6-11 Analysis of Transfer Mobility

Ai. Obtain 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, two or more lines should be used to characterize a site if possible. A total of 10 to 20 transducer positions are often used to characterize a site.

Aii. Calculate the equivalent 1/3-octave band transfer functions, generally between 6 and 400 Hz. This reduces each spectrum to 15 numbers. As shown in Figure 6-11, the 1/3-octave band spectrum is much smoother than the narrowband spectrum.

Aiii. 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.

Aiv. Apply the best-fit curve to the vibration sources. The 1/3-octave band best-fit curves can be directly applied to point vibration sources. Buses can usually be considered point-sources, as can columns supporting elevated structures. However, for a line vibration source such as a train, numerical integration must be used to calculate the equivalent line-source transfer mobility. The numerical integration procedures are detailed in the TRB publication: "A Prediction Procedure for Rail Transportation Ground-Borne Noise and Vibration."[50]

Option B: Line of Impulses – This second procedure for estimating line-source transfer mobility is best for detailed assessment of specific vibration paths or specific buildings and is a more direct approach.

Bi. Measure multiple point-source transfer mobilities according to the procedures in Step 2b above. The vibration transducers are placed at specific points of interest and a line of impacts is used. For example, a 150-foot train might be represented by a line of 11 impact positions along the track centerline at 15-foot intervals (Figure 6-12).

Bii. Sum the point-source results using Simpson's rule[xiii] for numerical integration to calculate the line-source transfer mobility.

Figure 6-13 shows an example of line-source transfer mobilities that were derived from the point-source transfer mobilities shown in Figure 6-9.

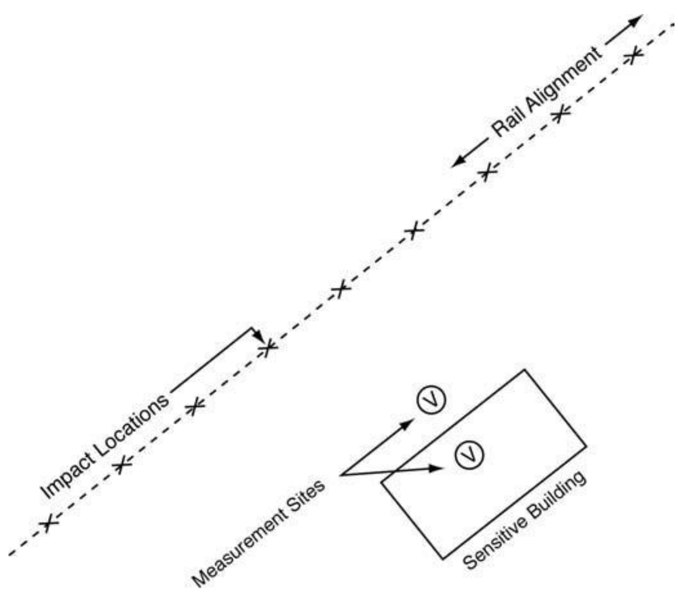

Figure 6-12 Schematic of Transfer Mobility Measurements Using a Line of Impacts

[xiii] Simpson's rule is a method for approximating integrals.

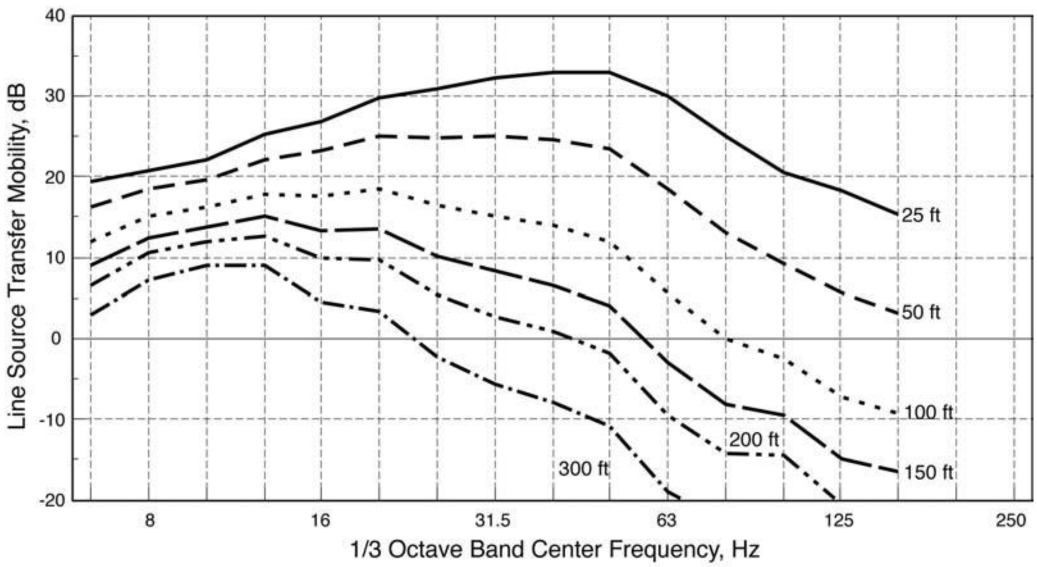

Figure 6-13 Example of Line-source Transfer Mobility

2d. Project Ground-Borne Vibration and Noise – Combine force density and line-source transfer mobility to project ground-borne vibration. Then, apply adjustment factors to estimate the building response to the ground-borne vibration and to estimate the A-weighted sound level inside buildings.

The propagation of vibration from the building foundation to the receiver room is very complex and 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. If the detailed features of the individual buildings are available, the recommended procedure is to estimate the propagation of vibration through a building and the radiation of sound by vibrating building surfaces using simple empirical or theoretical models. The recommended procedures are outlined in the Handbook of Urban Rail Noise and Vibration Control.[(44)] The approach consists of adding the following adjustments to the 1/3-octave band spectrum of the projected ground-borne vibration:

- **Building response or coupling loss** – This adjustment represents the change in the incident ground-borne vibration due to the presence of the building foundation. The adjustments described in the handbook [(44)] are shown in Figure 6-14. Note that the correction is zero when estimating basement floor vibration or vibration of at-grade slabs. Measured values may be used in place of these generic adjustments.

- **Transmission through the building** – The vibration amplitude typically decreases as the vibration energy propagates from the foundation through the remainder of the building. The general assumption is that vibration attenuates by 1 to 2 dB for each floor.

- **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.

- **Floor vibration and ground-borne noise** – 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. The radiation adjustment is -5 dB for typical rooms, [37] [50] which gives:

$$L_A \approx L_V + K_{A-wt} - 5 \qquad \textbf{Eq. 6-8}$$

where:

L_A = A-weighted sound level in a 1/3-octave band
L_v = rms vibration velocity level in that band
K_{A-wt} = A-weighting adjustment at the 1/3-octave band center frequency

The A-weighted levels in the 1/3-octave bands are combined to produce the overall A-weighted sound level.

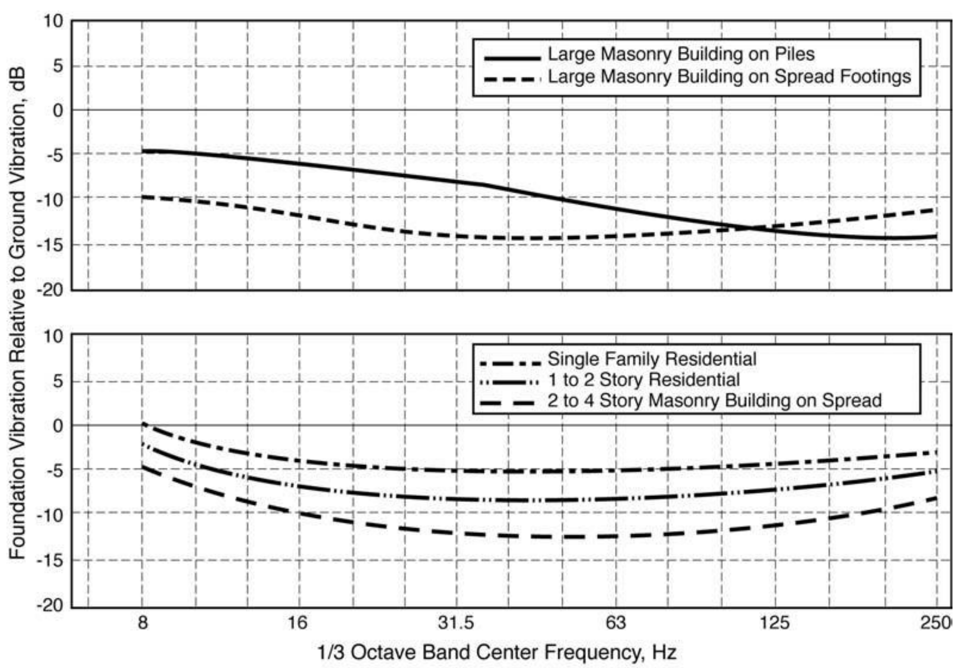

Figure 6-14 Foundation Response for Various Types of Buildings

Where detailed information on the structural features of individual buildings are unavailable and there are no site-specific data on outdoor to indoor propagation characteristics, the preferred approach is to apply a combined factor for the foundation response and the gain from floor resonances. Empirical data based on the TCRP D-12 Project from 34 measurement sites across 5 cities in North

America and other studies suggest that the average change in vibration from outdoor to indoor was 0 dB across all 1/3-octave bands with a standard deviation of approximately 5 to 6 dB in the 31.5 to 63 Hz frequency.(43)(48) Therefore, the recommended approach for predicting indoor vibration based on outdoor data is to use an adjustment of +3 to +6 dB for light-weight, wood-frame construction and use an adjustment of 0 dB for heavier buildings.

However, for buildings with high-vibration sensitivity or where there is concern regarding interference with vibration-sensitive equipment, it is advisable to measure the outdoor-indoor response of the building, using the process described in Section 2b or 2c, to determine the actual response of the foundation and building to vibration.

Step 3: Assess Vibration Impact

Take inventory of vibration-sensitive land uses with impact.

Assess vibration impact at each receiver of interest using the impact criteria in Section 6.3. Note that ground-borne vibration and noise levels that exceeded criteria in the General Vibration Assessment may not cause impact according to the more detailed procedures of the Detailed Vibration Analysis; in which case, mitigation is not required. But if projected levels still exceed the criteria, evaluate vibration mitigation measures using the spectra provided by the Detailed Vibration Analysis.

Step 4: Determine Vibration Mitigation Measures

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.

The purpose of vibration mitigation is to minimize the adverse effects that the project ground-borne vibration and ground-borne noise 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 may be necessary to develop innovative approaches to control the impact. See Appendix G for information on using non-standard methods.

Standard vibration control measures for rail transit systems are discussed in this step. Note that vibration control measures for rail transit systems are not always effective for freight trains.(xiv) Bus systems rarely cause vibration impact, but if impact occurs, roadway roughness or unevenness caused by bumps, pot holes, expansion joints, or driveway transitions are usually the causes. Smoothing the roadway surface is typically the recommended course of action.(xv)

[xiv] The heavy axle loads associated with freight rail are outside the range of applicable design parameters for vibration reduction on lighter rail transit systems. Plans to relocate existing railroad tracks closer to vibration-sensitive sites in order to accommodate a new rail transit line in the ROW must be carefully considered because it may not be possible to mitigate the increased vibration impact from freight trains.

[xv] In cases where a rubber-tired system runs inside a building, such as an airport people mover, vibration control may involve additional measures. Loading and unloading of guideway support beams may generate dynamic forces that transmit into the building structure. Special guideway support systems may be required, similar to the discussion below regarding floating slabs.

Vibration reduction measures incur additional costs to a system. Some of the same treatments for noise mitigation can be considered for vibration mitigation. Costs for noise control measures are documented in a report from the Transit Cooperative Research Program (TCRP).(31) Where applicable to vibration reduction, costs for noise abatement methods from that report are given in the following sections. These costs reflect the noise mitigation costs as of 1997 (unless otherwise noted), and should only be used as representative estimates when considering noise mitigation options. Current noise mitigation costs should be researched before decisions on noise mitigation options are finalized, and then they should be documented according to Section 8.

Mitigation of vibration impacts may involve treatments at the source, along the source-to-receiver propagation path, or at the receiver.

1a. Evaluate Source Treatments – The most effective vibration mitigation treatments are applied at the vibration source. This is the preferred approach to mitigation when possible. Possible source treatments include:

- **Preventative Maintenance** – Effective maintenance programs are essential for controlling ground-borne vibration. Key vibration points are discussed below; see Section 4.5, Step 7 for more detailed information on the benefits of effective maintenance programs on controlling transit noise and vibration. While these are not mitigation measures in the traditional sense, and should not be included as mitigation in an environmental document, they can help to keep both noise and vibration levels at a "like-new" level or reduce both in systems with deferred maintenance.

  - **Rail grinding** is a particularly important practice for vibration mitigation for rail that develops corrugations. The TCRP report notes that periodic rail grinding results in a net savings per year on wheel and rail wear. Most transit systems contract out rail grinding, although some of the larger systems make the investment and do their own grinding. As mentioned in Section 4.5, Step 7, the typical rail grinding cost would be $1000 to $7000 per grinding pass mile, with an additional investment of approximately $1 million for the equipment for a larger transit system to do its own grinding.

  - **Dramatic vibration reduction** results can be achieved by removing wheel flats through **wheel truing**. As mentioned in Section 4.5, Step 7, a wheel truing machine costs approximately $1 million, including associated maintenance, materials, and labor costs. The TCRP report figures a system with 700 vehicles would incur a yearly cost of $300,000 to $400,000 for a wheel truing program.

  - **Profile grinding of the rail head** in combination with a wheel truing program may be the most practical approach to controlling and reducing vibration and noise where such practices are not normally conducted. Profiles should be defined during the design phase and should be in place when system opens.(32) The cost of wheel and rail profile matching may be incorporated in the new vehicle and new rail costs.

Rough wheels or rails can increase vibration levels by as much as 20 dB in extreme cases, negating the effects of even the most effective vibration control measures. Yet, it is rare that vibration control measures (such as those discussed below) will provide more than 15 to 20 dB attenuation. When there are ground-borne vibration impacts 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 considerable vibration reduction. Regular maintenance may replace the need to modify the existing track system, such as through adding floating slabs.

- **Planning and Design of Special Trackwork** – A large percentage of the vibration impact from a new transit facility is often caused by wheel impacts at 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. This may require adjusting the location by several hundred feet provided it will not have an adverse impact on the operation plan for the system. Careful review of crossover and turnout locations during the project development phase is an important step to minimizing potential for vibration impact.

  Another approach is to use special devices (frogs) at turnouts and crossovers that incorporate mechanisms to close the gaps between running rails. Frogs with spring-loaded mechanisms and frogs with movable points can substantially reduce vibration levels near crossovers. According to the TCRP report, a spring frog costs about $12,000, twice the cost of a standard frog. A movable point frog involves elaborate signal and control circuitry resulting in higher costs at approximately $200,000.

- **Vehicle Specifications** – The ideal rail vehicle with respect to minimizing ground-borne vibration should have the following characteristics:
  - Low, unsprung weight
  - Soft primary suspension
  - A minimum of metal-to-metal contact between moving parts of the truck
  - 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, although some have recommended the vertical resonance frequency be less than 8 Hz.

- **Special Track Support Systems** – When the vibration assessment indicates that vibration levels will be excessive, the track support system is typically modified to reduce the vibration levels.

  Floating slabs, resiliently supported ties, high-resilience fasteners, and ballast mats can be used 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 impact is less common for at-grade and elevated track. Note that the cost of these types of vibration control measures is a higher percentage of the overall construction costs for at-grade and elevated track, and exposure to the elements can require substantial design modifications.

  Each major vibration control measure for track support is discussed below. Costs for these treatments are not covered by the TCRP report, but are given as estimates based on transit agency experience.

  - **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, and do provide some vibration reduction compared to 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 may reduce vibration by as much as 5 to 10 dB at frequencies above 30 to 40 Hz. These premium fasteners vary in cost and can be priced competitively when purchased in large quantities.

  - **Ballast mats** – A ballast mat consists of a rubber or other type of elastomer pad that is placed under the ballast. In general, the mat 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 8 to 12 dB attenuation at frequencies above 25 to 30 Hz.[58] Ballast mats are often a good retrofit measure for existing tie-and-ballast track where there is vibration impact. Installed ballast mats cost approximately $180 per track-foot.

  - **Undertie pads** – Undertie pads (resiliently supported concrete ties) consist of a rubber pad mounted on the bottom of a concrete tie directly on the ballast. The pads provide vibration isolation at frequencies above 25 Hz and are easy to install or retrofit. Installed undertie pads cost approximately $260 per track-foot.

- **Resiliently supported ties** – The resiliently supported tie system consists of concrete ties supported by rubber pads resting on top of a slab track or subway invert. The rails are fastened directly to the concrete ties using standard rail clips. Resiliently supported ties provide vibration reduction in between 15 to 40 Hz, which is particularly appropriate for transit systems with vibration impact in the 20 to 30 Hz range. A resiliently supported tie system costs approximately $400 per track-foot.

- **Floating slabs** – Floating slabs can be very effective at controlling ground-borne vibration and noise and consist of a concrete slab supported on resilient elements such as rubber or a similar elastomer. Floating slabs are effective at frequencies greater than their single-degree-of-freedom vertical resonance frequency.

  Floating slabs are among the most expensive vibration control treatments. A typical double-tie floating slab system costs approximately 4 times the cost of ballast and tie per track foot. Examples of floating slabs include:
  - Floating slabs used in Washington, DC; Atlanta, GA; and Boston, MA, were all designed to have a vertical resonance in the 14 to 17 Hz range.
  - A special system referred to as the double-tie system was first used in Toronto. It consists of 5-foot-long slabs with four or more rubber pads under each slab. This system was designed with a resonance frequency in the 12 to 16 Hz rang3.
  - Another special floating slab was used in San Francisco's Bay Area Rapid Transit (BART) system. It uses a discontinuous precast concrete double-tie system with a resonance frequency in the 5 to 10 Hz frequency range.

- **Tire-derived aggregate (TDA)** – TDA (shredded tires) consists of a layer of tire shreds wrapped in geotech fabric placed underneath the ballast on hard packed ground. This is a new, low-cost option that can provide reduction in vibration levels at frequencies above 25 Hz. This mitigation measure has proven to be effective for the Denver Regional Transportation District (RTD) light rail system as well as the Santa Clara Valley Transportation Authority (VTA) light rail system,[59] but the effective life of TDA has not been determined. Installed TDA costs approximately $260 per track-foot.

- **Other 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. But there is little confirmation that any of these approaches will make a substantial change in the vibration levels.

- **Operational Changes** – The most effective 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 include:
    - Use of equipment that generates the lowest vibration levels during the nighttime hours when people are most sensitive to vibration and noise.
    - Adjusting nighttime schedules to minimize movements in the most sensitive hours.

While there are tangible mitigation benefits from speed reductions and limits on operations during the most sensitive time periods, FTA does not generally accept speed reduction as a vibration mitigation measure for two important reasons: (1) speed reduction is unenforceable and negated if vehicle operators do not adhere to established policies, and (2) it is contrary to the purpose of the transit investment by FTA, which is to move as many people as possible as efficiently and safely as possible. FTA does not recommend limits on operations as a way to reduce vibration impacts.

1b. Evaluate Path Treatments – When vibration mitigation treatments cannot be applied at the vibration source or additional mitigation is required after treating the source, the next preferred placement of vibration mitigation is along the vibration propagation path between the source and receiver. Possible path treatments include:

- **Trenches** – Use of trenches to control ground-borne vibration is analogous to controlling airborne noise with noise barriers. This approach has not received much attention in the United States, but trenches could be a practical method for controlling transit vibration from at-grade track. A rule-of-thumb given by Richert and Hall(60) 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, requiring that a trench 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 tested a trench filled with Styrofoam to keep it open and reported successful performance over a period of at least one year. Solid barriers can be constructed with sheet piling or concrete poured into a trench.

- **Buffer Zones** – Expanding the rail ROW can be the most economical method of reducing the vibration impact by simply increasing the distance between the source and receiver. A similar approach is to negotiate a vibration easement from the affected property owners (e.g., a row of single-family homes adjacent to a proposed commuter rail line). There may be legal limitations, however, on the ability of funding agencies to acquire land strictly for the purpose of mitigating vibration (or noise) impact.

1c. Evaluate Receiver Treatments – When vibration mitigation treatments cannot be applied at the source or along the propagation path, or if combinations of treatments are required, treatments to the receivers can be considered as described below.

- **Building Modifications** – In some circumstances, it is practical to modify the affected building to reduce the vibration level. Vibration isolation of buildings 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 and is typically only possible for new construction. Vibration impacts on sensitive laboratory instruments, such as electron microscopes, may be controlled with vibration isolation tables.

  This approach is particularly important for shared-use facilities such as an 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 aside from modification of equipment mounting systems. 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. Alternatively, the equipment mounting systems could be modified or the equipment could be relocated to a different building at far less cost.

SECTION

7

Noise and Vibration during Construction

Construction noise and vibration often generates complaints from the community, even when construction is for a limited timeframe. Public concerns about construction noise and vibration increase considerably with lengthy periods of heavy construction on major projects as well as prevalence of nighttime construction (often scheduled to avoid disrupting workday road and rail traffic). Noise and vibration complaints typically arise from interference with people's activities, especially when the adjacent community has no clear understanding of the extent or duration of the construction. Misunderstandings can arise when the community thinks a contractor is being insensitive, and the contractor believes it is performing the work in compliance with local ordinances. This situation underscores the need for early identification and assessment of potential problem areas.

This section outlines the procedures for assessing noise and vibration impacts during construction. The type of assessment (qualitative or quantitative) and the level of analysis are determined based on the scale of the project and surrounding land uses. In cases where a full quantitative assessment is not warranted, a qualitative assessment of the construction noise and vibration environment can lead to greater understanding and tolerance in the community. For major projects with extended periods of construction at specific locations, a quantitative assessment can aid contractors in making bids by allowing changes in construction approach and including mitigation costs before the construction plans are finalized.

Generally, local noise ordinances are not very useful for evaluating construction noise impact. 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 uses. 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.

Procedures for assessing construction noise are presented in Section 7.1. Procedures for assessing construction vibration are presented in Section 7.2.

7.1 Construction Noise Assessment

Noise impacts from construction may vary greatly depending on the duration and complexity of the project. The key elements of the Construction Noise Assessment procedure and recommended workflow are as follows.

Step 1: Determine Level of Construction Noise Assessment

Step 2: Use a Qualitative Construction Noise Assessment to Estimate Construction Noise

Step 3: Use a Quantitative Construction Noise Assessment to Estimate Construction Noise

Step 4: Assess Construction Noise Impact

Step 5: Determine Construction Noise Mitigation Measures

If there is uncertainty in how to determine the appropriate level of assessment, contact the FTA Regional office.

Step 1: Determine Level of Construction Noise Assessment

Determine the appropriate level of assessment based on the scale and type of the project and depending on the stage of environmental review.

Consider the following factors:
- Scale of the project
- Proximity of noise-sensitive sites to the construction zones
- Number of noise-sensitive receivers in the project area
- Duration of construction activities near noise-sensitive receivers
- Schedule, including the construction days, hours, and time periods
- Method (e.g., cut-and-cover vs. bored tunneling)
- Concern about construction noise expressed in comments by the general public (e.g., through scoping or public meetings)

1a. Determine if an assessment is required – Construction Noise Assessments are not required for many small projects including:
- Installation of safety features like grade-crossing signals;
- Track improvements within the ROW; or
- Erecting small buildings and facilities which are similar in scale to the surrounding development.

For small projects like these, include descriptions in the environmental document of the length of construction, the loudest equipment to be used, the expected truck access routes, the avoidance of nighttime activity, and any other relevant planned construction method.

1b. Determine whether a qualitative or quantitative assessment is required

- **Qualitative Construction Noise Assessment** – Qualitative Construction Noise Assessments may be required for projects with less than a month of construction time in a noise-sensitive area. See Step 2 for more information on Qualitative Construction Noise Assessments.

- **Quantitative Construction Noise Assessments** – Quantitative Construction Noise Assessments may be required for projects with a month or more of construction in noise-sensitive areas or if particularly noisy equipment will be involved. See Step 3 for more information on Quantitative Construction Noise Assessments.

Step 2: Use a Qualitative Construction Noise Assessment to Estimate Construction Noise

Use a qualitative construction noise assessment to estimate construction noise for appropriate projects per Section 7.1, Step 1b.

Provide qualitative descriptions in the environmental document of the following elements:

- Duration of construction (both overall and at specific locations)
- Equipment expected to be used (e.g., noisiest equipment)
- Schedule with limits on times of operation (e.g., daytime use only)
- Monitoring of noise
- Forum for communicating with the public
- Commitments to limit noise levels to certain levels, including any local ordinances that apply
- Consideration of application of noise control treatments used successfully in other projects

Effective community outreach and relations are important for these projects. Disseminate information to the public early regarding the kinds of construction equipment, expected noise levels, and durations to forewarn potentially affected neighbors about the temporary inconvenience. Including a general description of the variation of noise levels during a typical construction day may also be helpful.

Note that the construction criteria in Step 4 do not apply to qualitative assessments.

Step 3: Use a Quantitative Construction Noise Assessment to Estimate Construction Noise

Use a quantitative construction noise assessment to estimate construction noise for appropriate projects per Section 7.1, Step 1b.

For Quantitative Construction Noise Assessments, follow the recommended procedure in this step and include a description of the planned construction methods and any basic measures that have been identified to reduce the potential impact, such as prohibiting the noisiest construction activities during the nighttime, in the environmental document. It may be prudent, however, to defer final decisions on noise control measures until the project and construction plans are defined in greater detail during the engineering phase.

- **Noise Source Levels from Typical Construction Equipment and Operations** – The noise levels generated by construction equipment vary greatly on factors such as the type of equipment, the equipment model, the operation being performed, and the condition of the equipment. Typically, the dominant source of noise from most construction equipment is the engine, often a diesel engine, which usually does not have sufficient muffling. In other cases, such as impact pile-driving or pavement-breaking, noise generated by the process dominates. Construction equipment can be considered to operate in the following two modes for Construction Noise Assessments:

- **Stationary** – 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** – Mobile equipment moves around the construction site with power applied in cyclic fashion (bulldozers, loaders), or to and from the site (trucks). Movement around the site is considered in the construction noise prediction procedure.

Variation in power imposes additional complexity in characterizing the noise source level from mobile equipment. Describe 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 $L_{eq(t)}$ of the operation.

Typical noise levels from representative equipment are included in Table 7-1. The levels are based on an EPA Report,(61) measured data from railroad construction equipment taken during the 1976 Northeast Corridor Improvement Project, the FHWA Roadway Construction Noise Model, and other measured data.

For equipment that is not represented in Table 7-1, measure the noise levels according to the standard procedures for measuring the exterior noise levels for the certification of mobile and stationary construction equipment by the Society of Automotive Engineers.(62)(63)

Table 7-1 Construction Equipment Noise Emission Levels

Equipment	Typical Noise Level 50 ft from Source, dBA
Air Compressor	80
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	82
Grader	85
Impact Wrench	85
Jack Hammer	88
Loader	80
Paver	85
Pile-driver (Impact)	101
Pile-driver (Sonic)	95
Pneumatic Tool	85
Pump	77
Rail Saw	90
Rock Drill	95
Roller	85
Saw	76
Scarifier	83
Scraper	85
Shovel	82
Spike Driver	77
Tie Cutter	84
Tie Handler	80
Tie Inserter	85
Truck	84

3a. Use the metric $L_{eq(t)}$ to assess construction noise. This unit is appropriate because $L_{eq(t)}$ can be used to describe:

- Noise level from operation of each piece of equipment separately, and levels can be combined to represent the noise level from all equipment operating during a given period
- Noise level during an entire phase
- Average noise over all phases of the construction

3b. Use Eq. 7-1 to predict construction noise impact for major transit projects, considering the noise generated by the equipment and noise propagation due to distance. Calculate $L_{eq.equip}$ for all equipment individually, then use decibel addition to sum the $L_{Aeq.equip}$ for all equipment operating during the same time period. See Appendix B.1.1 for information on decibel addition.

$$L_{eq.equip} = L_{emission} + 10\log(Adj_{Usage}) - 20\log(\frac{D}{50}) - 10G\log(\frac{D}{50}) \qquad \textbf{Eq. 7-1}$$

where:

$L_{eq,equip}$ = $L_{eq(t)}$ at a receiver from the operation of a single piece of equipment over a specified time period, dBA
$L_{emission}$ = noise emission level of the particular piece of equipment at the reference distance of 50 ft, dBA
Adj_{Usage} = usage factor to account for the fraction of time that the equipment is in use over the specified time period
D = distance from the receiver to the piece of equipment, ft
G = a constant that accounts for topography and ground effects

Determine the quantities for Eq. 7-1 based on the level of assessment as described below.

- A general assessment of construction noise is warranted for projects in an early assessment stage when the equipment roster and schedule are undefined and only a rough estimate of construction noise levels is practical.
- A detailed analysis of construction noise is warranted when many noise-sensitive sites are adjacent to a construction project or where contractors are faced with stringent local ordinances or heightened public concerns expressed in early outreach efforts.

Complete the appropriate assessment for each phase of construction. 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. As a result of the equipment mix, each phase has its own noise characteristics; some phases have higher continuous noise levels than others, and some have higher impact noise levels than others.

Option A: General Assessment – Determine the quantities for Eq. 7-1 based on the following assumptions for a General Assessment of each phase of construction.

- **Noise emission level ($L_{emission}$)** – Determine the emission level at 50 ft according to noise from typical construction equipment described above and Table 7-1.

- **Usage factor (Adj_{Usage})** – Assume a usage factor of 1. This assumes a time period of one-hour with full power operation. Most construction equipment operates continuously for periods of one-hour or more during the construction period.

  Therefore, $10\log(Adj_{usage}) = 0$ and can be omitted from the equation.

- **Distance (D)** – Assume that all equipment operates at the center of the project, or centerline for guideway or highway construction project.

- **Ground effect (G)** – G = 0 assuming free-field conditions and ignoring ground effects. If ground effects are of specific importance to the assessment, consider using the Detailed Analysis procedure.

Only determine the $L_{eq.equip}$ for the two noisiest pieces of equipment expected to be used in each phase of construction. Then, sum the levels for each phase of construction using decibel addition.

Option B: Detailed Analysis – Determine the quantities for Eq. 7-1 based on the following assumptions for a Detailed Analysis of each phase of construction. Alternatively, for detailed, long-term, and complex construction projects or projects near a particularly sensitive site, the FHWA's Windows-based screening tool, "Roadway Construction Noise Model (RCNM)," can be used for the prediction of construction noise.[64]

- **Noise emission level ($L_{emission}$)** – Measure or certify the noise emission level for each piece of equipment.

- **Usage factor (Adj_{Usage})** – 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 used during a period of time that will affect Adj_{Usage}.

  For example, an 8-hour $L_{eq(t)}$ is determined by making Adj_{Usage} 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 Adj_{Usage} 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. To account for increased sensitivity to nighttime noise, the nighttime noise levels are adjusted by 10 dB in the L_{dn} computation (see Appendix B.1.4.5).

- **Distance (D)** – Determine the location of each piece of equipment during operation and the distance to each receiver.

- **Ground effect (G)** – Use Table 4-26 in Section 4.5, Step 3 to calculate G to account for the site topography, natural and man-made barriers, and ground effects.

  Compute the 8-hour $L_{eq(t)}$ ($L_{eq.equip(8hr)}$) and the 30-day average L_{dn} ($L_{dn.equip(30day)}$) for all equipment expected to be used in each phase of construction separately. Then, sum the levels for each phase of construction using Eq. 4-56 and Eq. 4-57 in Table 4-32.

Step 4: Assess Construction Noise Impact

Compare the predicted noise levels from the Quantitative Construction Noise Assessment with impact criteria to assess impact from construction noise for each phase of construction.

No standardized criteria have been developed for assessing construction noise impact. Consequently, criteria must be developed on a project-specific basis unless local ordinances apply. As stated earlier in this section, local noise ordinances are typically 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 account for 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.

The construction impact guidelines are presented based on the level of quantitative assessment.

Option A: General Assessment – Compare the combined $L_{eq.equip(1hr)}$ for the two noisiest pieces of equipment for each phase of construction determined in Section 7.1, Step 3 to the criteria below. Then, identify locations where the level exceeds the criteria.

Table 7-2 General Assessment Construction Noise Criteria

Land Use	$L_{eq.equip(1hr)}$, dBA	
	Day	Night
Residential	90	80
Commercial	100	100
Industrial	100	100

Option B: Detailed Analysis – Compare the combined $L_{eq.equip(1hr)}$ and the combined $L_{dn.equip(30day)}$ for all equipment for each phase of construction determined in Section 7.1, Step 3 to the criteria below. Then, identify locations where the level exceeds the criteria.

Table 7-3 Detailed Analysis Construction Noise Criteria

Land Use	$L_{eq.equip(8hr)}$, dBA		$L_{dn.equip(30day)}$, dBA
	Day	Night	30-day Average
Residential	80	70	75
Commercial	85	85	80*
Industrial	90	90	85*

*Use a 24-hour $L_{eq(24hr)}$ instead of $L_{dn.equip(30day)}$.

Step 5: Determine Construction Noise Mitigation Measures

Evaluate the need for mitigation and select appropriate mitigation measures.

Where potential impacts have been identified according to Section 7.1, Step 4, evaluate appropriate control measures. Include descriptions of how each affected location will be treated with one or more mitigation measures in the environmental document.

5a. Determine the appropriate approach for construction noise control. Categories of approaches include:

- **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. Select streets with the 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, and loaded vinyl curtains can be draped under elevated structures.

- **Sequence of operations**
  - Combine noisy operations to occur in the same time period. The total noise level produced will not be substantially 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.

- **Alternative construction methods**
  - Avoid impact pile-driving where possible in noise-sensitive areas. Drilled piles or the use of a sonic/vibratory pile driver or push pile driver are quieter alternatives where the geological conditions permit their use.
  - Use specially-quieted equipment, such as quieted and enclosed air compressors and properly-working mufflers on all engines.
  - Select quieter demolition methods. 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.

Include descriptions of how each impacted location will be treated with one or more mitigation measures in the environmental impact assessment when possible.

5b. Describe and commit to a mitigation plan that will be developed later when the information is available to make final decisions (not often available during the project development phase) on all specific mitigation measures. This may be the case for large, complex projects. The objective of the plan should be to minimize construction noise using all reasonable (e.g., cost vs. benefit) and feasible (e.g., possible to construct) means available.

Components of a mitigation plan may include some or all of the following provisions, which should also be specified in construction contracts:

- **Equipment noise emission limits** – Equipment noise limits are absolute noise limits applied to generic classes of equipment at a reference distance (typically 50 ft). The limits should be set no higher than what is reasonably achievable for well-maintained equipment with effective mufflers. Lower limits that require source noise control may be appropriate for certain equipment when needed to minimize community noise impact, if reasonable and feasible. Provisions could also be included to require equipment noise certification testing prior to use on-site.

- **Lot-line construction noise limits** – Lot-line construction noise limits are noise limits that apply at the lot-line of specific noise-sensitive properties. The limits are typically specified in terms of both noise exposure (usually $L_{eq(t)}$ over a 20-30-minute period) and maximum noise level. They should be based on local noise ordinances if applicable, as well as pre-construction baseline noise levels (usually 3 to 5 dB above the baseline).

- **Operational and/or equipment restrictions** – It may be necessary to prohibit or restrict certain construction equipment and activities near residential areas during nighttime hours. This is particularly true for activities that generate tonal, impulsive, or repetitive sounds, such as back-up alarms, hoe ram demolition, and pile-driving.

- **Noise abatement requirements** – In some cases, specifications may be provided for particular noise control treatments based on the results of the design analysis and/or prior commitments made to the public by civic authorities. An example would be the requirement for a temporary noise barrier to shield a particular community area from noisy construction activities.

- **Noise monitoring plan requirements** – Plans can be developed for pre-project noise monitoring to establish baseline noise levels at sensitive locations, as well as for periodic equipment and lot-line noise monitoring during the construction period. The plan should outline the measurement and reporting methods that will be used to demonstrate compliance with the project noise limits.

- **Noise control plan requirements** – For major construction projects, preparation and submission of noise control plans on a periodic basis (e.g., every six months) are generally required. These plans should predict the construction noise at noise-sensitive receiver locations based on the proposed construction equipment and methods. If the analysis predicts that the specified noise limits will be exceeded, the plan should specify the mitigation measures that will be applied and should demonstrate the expected noise reductions these measures will achieve. The objective of this proactive approach is to minimize the likelihood of community noise complaints by ensuring that any necessary mitigation measures are included in the construction plans.

- **Compliance enforcement program** – If construction noise is an issue in the community, it is important that a program be implemented to monitor contractor compliance with the noise control specifications and mitigation plan. It is recommended that this function be performed by a construction management team on behalf of the public agency.

- **Public information and complaint response procedures** – To maintain positive community relations, it is recommended to keep the public informed about the construction plans and efforts to minimize noise, and procedures should be established for prompt response and corrective action to noise complaints during construction.

Most of these provisions are appropriate for large-scale projects, where construction activity will continue for many months, if not years. The linked references contain more information on construction noise for major transportation projects.[60][65]

7.2 Construction Vibration Assessment

Construction activity can result in varying degrees of ground vibration, depending on the equipment and methods employed. Operation of construction equipment causes ground vibrations that spread through the ground and diminish in strength with distance. Buildings founded on the soil near the construction site respond to these vibrations with varying results, ranging from no perceptible effects at the lowest levels, low rumbling sounds and perceptible vibrations at moderate levels, and slight damage at the highest levels.

While ground vibrations from construction activities do not often reach the levels that can damage structures, fragile buildings must receive special consideration. The construction vibration criteria include consideration of the building condition.

The key elements of the Construction Vibration Assessment procedures and recommended workflow are as follows:

Step 1: Determine level of construction vibration assessment

Step 2: Use a qualitative construction vibration assessment

Step 3: Use a quantitative construction vibration assessment

Step 4: Assess construction vibration impact

Step 5: Determine construction vibration mitigation measures

Step 1: Determine Level of Construction Vibration Assessment

Determine the appropriate level of assessment based on the scale and type of the project and the stage of environmental review.

1a. Determine if an assessment is required.
Construction Vibration Assessments are not required for many small projects including:

- Installation of safety features like grade-crossing signals
- Track improvements within the ROW
- Erecting small buildings and facilities, which are similar in scale to the surrounding development

1b. Determine whether a qualitative or quantitative assessment is required.

- **Qualitative Construction Vibration Assessment** – A qualitative construction vibration assessment is appropriate for projects where prolonged annoyance or damage from construction vibration is not expected. For example, equipment that generates little or no ground vibration—such as air compressors, light trucks, and hydraulic loaders—only require qualitative descriptions. See Section 7.2, Step 2 for more information on qualitative construction vibration assessments.

- **Quantitative Construction Vibration Assessment** – A quantitative construction vibration analysis is appropriate for projects where construction vibration may result in building damage or prolonged annoyance. For example, activities such as blasting, pile-driving, vibratory compaction, demolition, and drilling or excavation near sensitive structures require a quantitative analysis. See Section 7.2, Step 3 for more information on quantitative construction vibration assessments.

If there is uncertainty in how to determine the appropriate level of assessment, contact the FTA Regional office.

Step 2: Use a Qualitative Construction Vibration Assessment

Use a qualitative construction vibration assessment to estimate vibration for appropriate projects per Section 7.2, Step 1b.

Provide qualitative descriptions in the environmental document of the following elements:

- Duration of construction (both overall and at specific locations)
- Equipment expected to be used
- Description of how ground-borne vibration will be maintained at an acceptable level

Note that the criteria in Section 7.2, Step 4 do not apply to qualitative assessments.

Step 3: Use a Quantitative Construction Vibration Assessment

Use a quantitative construction vibration assessment to estimate vibration for appropriate projects per Section 7.2, Step 1b.

For quantitative construction vibration assessments, follow the recommended procedure in this step. Vibration source levels from typical construction equipment and operations are provided below, and procedures on how to estimate construction vibration for damage and annoyance are provided in Steps 3a and 3b, respectively.

- **Vibration Source Levels from Construction Equipment** – Table 7-4 presents average source levels in terms of velocity for various types of construction equipment measured under a wide variety of construction activities. The approximate rms vibration velocity levels were calculated from the PPV limits using a crest factor of 4, representing a PPV-rms difference of 12 dB. Note that although the table gives one level for each piece of equipment, there is considerable variation in reported ground vibration levels from construction activities. The data in Table 7-4 provide a reasonable estimate for a wide range of soil conditions.(66)(67)(68)(69)

Table 7-4 Vibration Source Levels for Construction Equipment

Equipment		PPV at 25 ft, in/sec	Approximate Lv* at 25 ft
Pile Driver (impact)	upper range	1.518	112
	typical	0.644	104
Pile Driver (sonic)	upper range	0.734	105
	typical	0.17	93
Clam shovel drop (slurry wall)		0.202	94
Hydromill (slurry wall)	in soil	0.008	66
	in rock	0.017	75
Vibratory Roller		0.21	94
Hoe Ram		0.089	87
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 micro-in/sec

3a. Damage Assessment

Assess for building damage for each piece of equipment individually.

Construction vibration is generally assessed in terms of peak particle velocity (PPV), as described in Section 5.1.

- Determine the vibration source level (PPV_{ref}) for each piece of equipment at a reference distance of 25 ft as described above and in Table 7-4.
- Use Eq. 7-2 to apply the propagation adjustment to the source reference level to account for the distance from the equipment to the receiver. Note that the equation is based on point sources with normal propagation conditions.

$$PPV_{equip} = PPV_{ref} \times (\frac{25}{D})^{1.5} \qquad \textbf{Eq. 7-2}$$

where:

PPV_{equip} = the peak particle velocity of the equipment adjusted for distance, in/sec
PPV_{ref} = the source reference vibration level at 25 ft, in/sec
D = distance from the equipment to the receiver, ft

3b. Annoyance Assessment
Assess for annoyance for each piece of equipment individually. Ground-borne vibration related to human annoyance is related to rms velocity levels, expressed in VdB as described in Section 5.1.

Estimate the vibration level (L_v) using Eq. 7-3.

$$L_{v.distance} = L_{vref} - 30log(\frac{D}{25}) \qquad \textbf{Eq. 7-3}$$

where:

$L_{v.distance}$ = the rms velocity level adjusted for distance, VdB
L_{vref} = the source reference vibration level at 25 ft, VdB
D = distance from the equipment to the receiver, ft

Step 4: Assess Construction Vibration Impact

Compare the predicted vibration levels from the Quantitative Construction Vibration Assessment with impact criteria to assess impact from construction vibration.

Assess potential damage effects from construction vibration for each piece of equipment individually. Note that equipment operating at the same time could increase vibration levels substantially, but predicting any increase could be difficult. The criteria presented in this section should be used during the environmental impact assessment phase to identify problem locations that must be addressed during the engineering phase.

Compare the PPV and approximate L_v for each piece of equipment determined in Section 7.2, Step 3 to the vibration damage criteria in Table 7-5, which is presented by building/structural category, to assess impact.(70)(71) The approximate rms vibration velocity levels were calculated from the PPV limits using a crest factor of 4.

Table 7-5 Construction Vibration Damage Criteria

Building/ Structural Category	PPV, in/sec	Approximate L_v*
I. Reinforced-concrete, steel or timber (no plaster)	0.5	102
II. Engineered concrete and masonry (no plaster)	0.3	98
III. Non-engineered timber and masonry buildings	0.2	94
IV. Buildings extremely susceptible to vibration damage	0.12	90

*RMS velocity in decibels, VdB re 1 micro-in/sec

Compare the L_v determined in Section 7.2, Step 3 to the criteria for the General Vibration Assessment in Section 6.2 to assess annoyance or interference with vibration-sensitive activities due to construction vibration.

Step 5: Determine Construction Vibration Mitigation Measures

Evaluate the need for mitigation and select appropriate mitigation measures where potential human impacts or building damage from construction vibration have been identified according to Section 7.2, Step 4.

5a. Determine the appropriate approach for construction vibration mitigation considering equipment location and processes.

- **Design considerations and project layout**
  - Route heavily-loaded trucks away from residential streets. Select streets with the fewest homes if no alternatives are available.
  - Operate earth-moving equipment on the construction lot as far away from vibration-sensitive sites as possible.

- **Sequence of operations**
  - Phase demolition, earth-moving, and ground-impacting operations so as not to occur in the same time period. Unlike noise, the total vibration level produced could be substantially less when each vibration source operates separately.
  - Avoid nighttime activities. Sensitivity to vibration increases during the nighttime hours in residential neighborhoods.

- **Alternative construction methods**
  - Carefully consider the use of impact pile-driving versus drilled piles or the use of a sonic/vibratory pile driver or push pile driver where those processes might create lower vibration levels if geological conditions permit their use.
    - Pile-driving is one of the greatest sources of vibration associated with equipment used during construction of a project. The source levels in Table 7-4 indicate that sonic pile drivers may provide substantial reduction of vibration levels compared to impact pile drivers. But, 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. Continuous operation at a fixed frequency may, however, be more

noticeable to nearby residents, even at lower vibration levels. Furthermore, the steady-state excitation of the ground may induce a growth in the resonant response of building components. Resonant response may be unacceptable in cases of fragile buildings or vibration-sensitive manufacturing processes. Impact pile drivers, however, produce a high vibration level for a short time (0.2 seconds) with sufficient time between impacts to allow any resonant response to decay.

- Select demolition methods involving little to no 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. Milling generates lower vibration levels than excavation using clam shell or chisel drops.
- Avoid vibratory rollers and packers near sensitive areas.

5b. Describe and commit to a mitigation plan that will be developed and implemented during the engineering and construction phase when the information available during the project development phase will not be sufficient to define specific construction vibration mitigation measures. The objective of the plan should be to minimize construction vibration damage using all reasonable and feasible means available. The plan should include the following components:

- A procedure for establishing threshold and limiting vibration values for potentially affected structures, based on an assessment of each structure's ability to withstand the loads and displacements due to construction vibrations
- A commitment to develop a vibration monitoring plan during the engineering phase and to implement a compliance monitoring program during construction

SECTION

8

Documentation of Noise and Vibration Assessment

The level of required documentation is determined according to the project class of action. Section 2.1 covers the appropriate class of action (EIS, EA, or CE) for different projects. If there is uncertainty in the appropriate level of documentation, contact the FTA Regional office.

The noise and vibration analysis must be articulated to the public in a clear, comprehensive manner for all levels of documentation. The 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.

A separate technical report or memorandum is often prepared as a supplement to the environmental document. A technical report is appropriate in cases when including the data from the assessment would create an unreasonably long environmental document. The details of the analysis are important for establishing the basis for the assessment. Therefore, all details in the technical report should be contained in a well-organized format for easy access to the information.

For large-scale projects, the environmental document should contain a summary of the essential analysis information to provide subject matter context and the analysis findings. For these projects, separate technical reports are usually prepared as supplements to the EIS or EA and referred to in the environmental document. For smaller projects, or projects with minimal noise or vibration impact, all of the technical information may be presented in the environmental document itself or in a technical memorandum. Other projects might have no potential for noise or vibration impacts. For those projects, that environmental documentation should explain that no noise or vibration impacts are expected.

This section provides guidance on presenting the necessary noise and vibration information in the environmental document (Section 8.1) and the associated technical report (Section 8.2).

8.1 Environmental Document

In the environmental document, provide a summary of the comprehensive noise and vibration information from the technical report and emphasize the salient points of the analysis in a format and style that the public can understand. Smaller projects may have all of the technical information contained within the environmental document, so take special care in summarizing the technical details to convey the information adequately.

Step 1: Choose the Information to Include

Choose the appropriate noise and vibration analysis information to include based on the level of environmental review and the associated documentation.

1a. Provide full disclosure of noise and vibration impacts in the environmental document, including identification of locations where impacts cannot be mitigated below the severe impact level. In general, an EIS describes significant impacts and plans to mitigate the impacts. For EAs, completion of the environmental review with a finding of no significant impact (FONSI) may depend on mitigation being considered for incorporation in the proposed project. The way mitigation is presented in the environmental document depends on the type of impact (noise or vibration) and the stage of project development and environmental review. Projects that meet the criteria of a CE may also require the completion of a noise and/or vibration analysis, and the results of such an analysis should be documented in a noise memo or the CE documentation.

1b. Document noise impacts – Typically, airborne noise impacts can be accurately predicted during the environmental review. For projects that focus on a single alternative, noise impacts can be accurately identified in the draft environmental document. If mitigation is anticipated, then mitigation options should be explored in the EA or draft EIS; firm decisions on mitigation can be deferred to the final document. But for all projects, decisions on noise mitigation should be made before the final document is approved.

1c. Document vibration impacts – Predicting vibration impacts accurately is more complex because ground-borne vibration may be strongly influenced by subsurface conditions. The geotechnical studies that reveal these conditions are normally undertaken during the engineering phase, after the environmental review process is complete. Therefore, the final environmental document will usually not be able to state with certainty whether mitigation is needed for ground-borne vibration and noise.

If the engineering phase is conducted at the same time as the final environmental document, report the results of the Detailed Vibration Analysis in the final environmental document. If the engineering phase is conducted after the final environmental document, report the results of the General Vibration Assessment in the final environmental document. If impact is determined, include a commitment in the final document to conduct a Detailed Vibration Analysis during the engineering phase to complete the impact assessment. Also, include a discussion on various control measures that could be used and the likelihood that the criteria could be met through the use of one or more of the measures. It may be possible to state a commitment in the final environmental document to adhere to the impact criteria for the Detailed Vibration Analysis, while deferring the selection of specific vibration control measures until the completion of detailed studies in the engineering phase. When work is conducted after FTA signs its final decision document (i.e., ROD, combined FEIS/ROD, or FONSI), additional documentation, such as a reevaluation of the previous decision, may be necessary. FTA recommends contacting the FTA Regional office directly in these situations.

1d. Describe mitigation measures in the decision document – After the decision document is approved, incorporate the mitigation measures by reference in the actual grant agreements signed by FTA and the project sponsor. The mitigation measures then become contractual conditions that must be adhered to by the project sponsor.

It is typically appropriate to include the following noise and vibration information in the environmental document, as described in Section 8.1:

- The existing conditions (affected environment)
- The direct impacts from operation (environmental consequences)
- The construction impacts (environmental consequences)

Step 2: Organize information in the Environmental Document

Include information in the following sections of the environmental document separating out the noise and vibration information.

2a. Existing Conditions (Affected Environment) – Describe the existing conditions (conditions without the project) in terms of the existing noise and vibration conditions in this section of the document. The primary function of this section is to establish the focus and baseline conditions for the discussion of environmental impacts. Include the following basic information and separate the noise and vibration sections.

- **Description of noise/vibration metrics, effects and typical levels** – Include a targeted summary of relevant information from Section 3 of this manual. This will serve as background for the discussions of noise/vibration levels and characteristics that will follow in later sections. Provide illustrative material to convey typical levels to the public.

- **Inventory of noise/vibration-sensitive sites** – Describe the approach for identifying noise- and vibration-sensitive sites as well as the identified sites and site descriptions. Use sufficient detail to demonstrate completeness. Document these results on a map.

- **Noise/vibration measurements** – Document the basis for selecting measurement sites, including tables of sites coordinated with maps showing locations of sites. Summarize the measurement approach and include the justification for the measurement procedures used.

  Present measurement data in well-organized tables and figures with a summary and interpretation of measured data. Measurements are often included in the table of measurement sites described in the previous paragraph. In some cases, measurements may be supplemented or replaced by collected data relevant to the noise and vibration characteristics of the area. For example, soil information for estimating ground-borne vibration propagation characteristics may be available from other projects in the area.

A summary and interpretation of how the collected data define the project setting is fundamental to this section.

2b. Direct Impacts – Include the following in the discussion on direct impacts due to project operation:

- **Overview of approach** – Provide a targeted summary of relevant information on the assessment procedure for determining noise/vibration impacts as a framework for the following sections.

- **Estimated noise/vibration levels** – Provide a general description of prediction models used to estimate project noise/vibration levels. Describe any distinguishing features unique to the project, such as source levels associated with various technologies.

  Describe the results of the predictions in general terms first, followed by a detailed accounting of predicted noise levels. Supplement this information with tables and illustrate by contours, cross-sections, or shaded mapping. If contours are included in a technical report, it is not necessary to repeat them in this section.

- **Criteria for noise/vibration impact** – Describe the impact criteria for the project in detail and reference the appropriate section in this manual. Include tables listing the criteria levels or the figures included in this manual.

- **Noise/vibration impact assessment** – Present the impact assessment in its own section or combined with the section above.

  Describe the locations, as identified in the screening procedure, where noise/vibration impact is expected to occur without implementation of mitigation measures, based on the screening results, predicted future levels, existing levels, and application of the impact criteria.

  Include inventory tables of impacted noise- and vibration-sensitive sites to quantify the impacts for all noise/vibration-sensitive sites included in the Affected Environment (Existing Conditions) as described in the Existing Conditions section above.

- **Noise/vibration mitigation measures** – Perhaps the greatest difference between the technical report and the environmental document is with mitigation. The technical report discusses mitigation options and recommendations, while the environmental document provides the vehicle for reaching decisions on appropriate mitigation measures.

  Begin this section with a summary of the noise/vibration mitigation measures considered for the impacted locations. Describe the specific measures selected for implementation in detail. Also, include any applicable, specific noise or vibration policies the project sponsor may have in place.

In cases where it is not possible to commit to a specific mitigation measure in the final environmental document, it may be possible to commit to a certain noise/vibration level. For example, the environmental document could include a commitment to meet or exceed the impact criteria specified in Sections 4.1 and 6.2.

- **Unavoidable adverse environmental effects** – If it is projected that adverse noise/vibration impacts will result after all reasonable abatement measures have been incorporated, identify these impacts in this section.

2c. Construction Impacts – Discuss construction impacts in the environmental document's section on construction impacts, if present. If, because of the scale of the project, the environmental document does not have a separate construction impacts section, then the construction impacts should be discussed with the rest of the resource impacts.

When a special section on construction noise/vibration impacts is included in the document, it should be organized according to the comprehensive outline on long-term impacts described above. For projects with relatively minor effects, include a brief summary of impact.

8.2 Technical Report on Noise and Vibration

The technical report is intended to present complete technical data and descriptions in a manner that can be understood by the general public, but is more technical than the information found in the environmental document. All 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.

Include the following major subject headings and key information described below. If both noise and vibration have been assessed, include separate sections for noise and vibration with subsections for key information as described below. Additional details on documentation requirements for the technical report of non-standard procedures and methodologies are included in Appendix G.

- **Overview** – Include a brief description of the project and an overview of the noise/vibration concerns to highlight initial considerations in framing the scope of the study.

- **Inventory of Noise/Vibration-Sensitive Sites** – Describe the approach for identifying noise- and vibration-sensitive sites as well as the identified sites and site descriptions. Use sufficient detail to demonstrate completeness. Document results on a map.

- **Measurements of Existing Noise/Vibration Conditions**
  - Document the basis for selecting measurement sites, including tables of sites coordinated with maps showing locations of sites. Summarize the measurement approach with justification for the measurement procedures used.
  - If the measurement data are used to estimate existing conditions at other locations, include the rationale and the method of estimation. Describe measurement procedures in detail.
  - Include tables of measurement instruments documenting manufacturer, type, serial number, and date of most recent calibration by authorized testing laboratory. Document measurement periods, including the time of day and length of time at each site to demonstrate adequate representation of ambient conditions.
  - Present measurement data in well-organized tables and figures with a summary and interpretation of measured data.

- **Additional Measurements Related to the Project** – Include detailed description of measurements and results for projects that require specialized measurements at noise- and vibration-sensitive sites. Examples include:
  - Outdoor-to-indoor noise level reduction of homes
  - Transmission of vibration into concert halls and recording studios
  - Special source-level characterization

- **Predictions of Noise/Vibration from the Project**
  - Describe the prediction model used to estimate future project conditions and specific data used as input to the models. Reference the appropriate section in this manual. Document any change or extension to the models recommended in this manual, so that the validity of the adjustments can be confirmed. See Appendix G for more information.
  - Describe in detail the modeled scenarios and why the scenarios were chosen.
  - Tabulate computed levels and illustrate by contours, cross-sections, or shaded mapping. Illustrate noise/vibration impacts with base maps at a scale with enough detail to provide reference for the location.

- **Noise/Vibration Criteria**
  - Describe the impact criteria for the project in detail and reference the appropriate section in this manual. Include tables specifying the criteria levels or the figures included in this manual.
  - If construction noise and/or vibration assessments were conducted, include the construction criteria in a separate section with the construction assessment details. See below for more information.

- **Noise/Vibration Impact Assessment**
  - Describe the impact assessment according to the appropriate noise and/or vibration impact assessment sections in this manual.
  - If an alternatives analysis was conducted, present a resulting impact inventory for each alternative mode or alignment in a format that allows comparison among alternatives.
  - Tabulate the inventory according to the different types of affected noise- and vibration-sensitive sites. Present the results of the assessment both before and after mitigation.

- **Noise/Vibration Mitigation**
  - Begin this section with a summary of all treatments considered, including those not carried to final consideration.
  - Consider final candidate mitigation treatments separately and provide a description of the features of the treatment, including costs, expected benefit in reducing impacts, locations where the benefit would be realized, and a discussion of the practicality of alternative treatments.
  - Include enough noise and vibration impact information to allow the project sponsor and FTA to reach decisions on mitigation prior to issuance of an environmental decision document.

- **Construction Noise/Vibration Impacts**
  - Describe criteria adopted for construction noise or vibration if construction noise and/or vibration assessments were conducted.
  - Describe the method used for predicting construction noise or vibration and include inputs to the models such as equipment roster by construction phase, equipment source levels, assumed usage factors, and other assumed site characteristics.
  - Present predicted levels for noise- and vibration-sensitive sites and identify short-term impacts.
  - In cases where construction impacts are identified, discuss feasible abatement methods using enough detail to allow construction contract documents to include mitigation measures.

- **References** – Provide references for all criteria, approaches, and data used in the analyses, as well as other reports related to the project that may be relied on for information, e.g., geotechnical reports.

Appendix A: Glossary of Terms

Terminology used through the manual is defined in this appendix.[(49)(72)]

A-weighting	A standardized filter used to alter the sensitivity of a sound level meter with respect to frequency so that the instrument is less sensitive at low and high frequencies where the human ear is less sensitive. Abbreviated as dBA.
Absolute Noise Impact	Noise that interferes with activities independent of existing noise levels and is expressed as a fixed level threshold.
Accelerometer	A transducer that converts vibratory motion to an electrical signal proportional to the acceleration of that motion.
Ambient	The pre-project background noise or vibration level, which is often used interchangeably with "existing noise" in this manual.
Amplitude	Difference between the extremes of an oscillating signal.
Alignment	The horizontal location of a railroad or transit system as described by curved and tangent track.
At-grade	Tracks on the ground surface.
Automated Guideway Transit (AGT)	Guided steel-wheel or rubber-tired transit passenger vehicles operating singly or in multi-car trains with a fully automated system on fixed-guideways along an exclusive ROW. AGT includes personal rapid transit, group rapid transit, and automated people mover systems.
Auxiliaries	The term applied to a number of separately driven machines, operated by power from the main engine or electric generation. They include the air compressor, radiator fan, traction motor blower, and air conditioning equipment.
Ballast mat	A 2- to 3-inch-thick elastomer mat placed under the normal track ballast on top of a rigid slab or packed sub-grade.
Ballast	Granular material placed on the trackbed for the purpose of holding the track in line and at surface.
Bus Rapid Transit (BRT)	A type of limited-stop bus operation that relies on technology to help speed up the service. Buses can operate on exclusive transitways, high-occupancy-vehicle lanes, expressways, or ordinary streets.
Catenary	On electric railroad and LRT systems, the term describing the overhead conductor that is contacted by the pantograph or trolley, and its support structure.
Commuter rail	Conventional passenger railroad serving areas surrounding an urban center. Most commuter railroads utilize locomotive-hauled coaches, often in push-pull configuration.
Consist	The total number and type of cars, locomotives, or transit vehicles in a trainset.
Continuous welded rail	A number of rails welded together to form unbroken lengths of track without gaps or joints.
Corrugated rail	A rough condition of alternating ridges and grooves which develops on the rail head in service.
Crest factor	The ratio of peak particle velocity to maximum RMS amplitude in an oscillating signal.
Criteria	Plural form of "criterion," the relationship between a measure of exposure (e.g., sound or vibration level) and its corresponding effect.
Cross tie	The transverse member of the track structure to which the rails are spiked or otherwise fastened to provide proper gage and to cushion, distribute, and transmit the stresses of traffic through the ballast to the trackbed.
Crossover	Two turnouts with the track between the frogs arranged to form a continuous passage between two nearby and generally parallel tracks.
Cumulative	The summation of individual sounds into a single total value related to the effect over time.
Cut	A terrain feature typically created to allow for a trackbed to be at a lower level than the surrounding ground.

dB	See Decibel.
dBA	See A-weighting.
Decibel	The standard unit of measurement for sound pressure level and vibration level. Technically, a decibel is the unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the logarithm of this ratio. Abbreviated as dB.
DMU	Diesel-powered multiple unit. See Multiple Unit.
DNL	See L_{dn}.
Electrification	A term used to describe the installation of overhead wire or third rail power distribution facilities to enable operation of trains.
Embankment	A bank of earth, rock, or other material constructed above the natural ground surface.
Equivalent level	The level of a steady sound, which, in a stated time period and at a stated location, has the same sound energy as the time-varying sound. Also, written as L_{eq}.
Event	A passby of a vehicle (e.g., train, bus, or car) of any size consist.
Ferry boat	A transit mode comprised of vessels to carry passengers and/or vehicles over a body of water.
Fixed-guideway	A public transportation facility with a separate ROW for the exclusive use of public transportation and other high-occupancy vehicles.
Flange	The vertical projection along the inner rim of a wheel that serves, together with the corresponding projection of the mating wheel of a wheel set, to keep the wheel set on the track.
Floating slab	A special track support system for vibration isolation, consisting of concrete slabs supported on resilient elements, usually rubber or similar elastomer.
Force density	Force density is the force per root distance along the track in $lb/ft^{1/2}$. The force density level is the level in decibels of the force density relative to 1 $lb/ft^{1/2}$ and describes the vehicle force that excites the soil/rock surrounding the transit structure.
Frequency	The number of times that a periodically occurring quantity repeats itself in a specified period. With reference to noise and vibration signals, the number of cycles per second.
Frequency spectrum	Distribution of frequency components of a noise or vibration signal.
Frog	A track structure used at the intersection of two running rails to provide support for wheels and passageways for their flanges, thus permitting wheels on either rail to cross the other.
Gage (of track)	The distance between the rails on a track.
Grade crossing	The point where a rail line and a motor vehicle road intersect at the same vertical elevation.
Guideway	Supporting structure to form a track for rolling or magnetically-levitated vehicles.
Head-End Power (HEP)	A system of furnishing electric power for a complete railway train from a single generating plant in the locomotive.
Heavy rail	See Rail Rapid Transit.
Hertz (Hz)	The unit of acoustic or vibration frequency representing cycles per second.
Hourly average sound level	The time-averaged A-weighted sound level, over a 1-hour period, usually calculated between integral hours. Abbreviated as $L_{(1h)}$.
Hybrid Bus	A rubber-tired vehicle that features a hybrid diesel-electric propulsion system. A diesel engine runs an electric generator that powers the entire vehicle including electric drive motors that deliver power to the wheels.
Idle	The speed at which an engine runs when it is not under load.
Intermediate Capacity Transit (ICT)	A transit system with less capacity than rail rapid transit (RRT), but more capacity than typical bus operations. Examples of ICT include bus rapid transit (BRT), automated guideway transit (AGT), monorails, and trolleys.
Intermodal facility	Junction of two or more modes of transportation where transfers may occur.
Jointed rail	A system of joining rails with steel members designed to unite the abutting ends of contiguous rails.

$L_{(1h)}$	See Hourly Average Sound Level.
L_{dn}	Day-Night Sound Level. The sound exposure level for a 24-hour day calculated by adding the sound exposure level obtained during the daytime (7 a.m. to 10 p.m.) to 10 times the sound exposure level obtained during the nighttime (10 p.m. to 7 a.m.). This unit is used throughout the United States for environmental impact assessment. Also, written as DNL.
$L_{eq(1hr)}$	Equivalent Sound Level. The metric for cumulative noise exposure over a specific time interval is the equivalent sound level
Light Rail Transit (LRT)	A mode of public transit with tracked vehicles in multiple units operating in mixed traffic conditions on streets as well as sections of exclusive ROW. Vehicles are generally powered by electricity from overhead lines.
Locomotive	A self-propelled, non-revenue rail vehicle designed to convert electrical or mechanical energy into tractive effort to haul railway cars. See also Power Unit.
Main line	The principal line or lines of a railway.
Maglev	Magnetically-levitated vehicle; a vehicle or train of vehicles with guidance and propulsion provided by magnetic forces. Support can be provided by either an electrodynamic system wherein a moving vehicle is lifted by magnetic forces induced in the guideway or an electromagnetic system wherein the magnetic lifting forces are actively energized in the guideway.
Maximum sound level	The highest exponential-time-average sound level, in decibels, that occurs during a stated time period. Abbreviated as L_{max}. The standardized time periods are 1 second for L_{max}, slow, and 0.125 second for L_{max}, fast.
Metric	Measurement value or a quantitative descriptor used to identify a specific measure of sound level.
Monorail	Guided transit vehicles operating on or suspended from a single rail, beam, or tube.
Multimodal Project	In this manual, the term multimodal project is used to describe a project that includes changes to both transit and highway components in segments of the project.
Multiple Unit (MU)	A term referring to the practice of coupling two or more diesel-powered or electric-powered passenger cars together with provision for controlling the traction motors on all units from a single controller.
Noise	Any disagreeable or undesired sound or other audible disturbance.
Octave band	A standardized division of a frequency spectrum in which the interval between two divisions is a frequency ratio of 2.
One-third octave band	A standardized division of a frequency spectrum in which the octave bands are divided into thirds for more detailed information. The interval between center frequencies is a ratio of 1.25.
Pantograph	A device for collecting current from an overhead conductor (catenary), consisting of a jointed frame held up by springs or compressed air and having a current collector at the top.
Park-and-ride facility	A parking garage and/or lot used for parking passengers' automobiles while they use transit agency facilities and vehicles.
Peak factor	See Crest factor.
Plan-and-profile	Mapping used by transportation planners that shows two-dimensional plan views (x- and y- axes) on the same page as two-dimensional profiles (x- and z-axes) of a road or track.
Peak Particle Velocity (PPV)	The peak signal value of an oscillating vibration velocity waveform. Usually expressed in inches/second in the United States.
Peak-to-Peak (P-P) Value	Of an oscillating quantity, the algebraic difference between the extreme values of the quantity.
Power unit	A self-propelled vehicle, running on rails and having one or more electric motors that drive the wheels and thereby propel the locomotive and train. The motors obtain electrical energy either from a rail laid near, but insulated from, the track rails, or from a wire suspended above the track. Contact with the overhead wire is made by a pantograph mounted on top of the unit.
Project segment	Portions of a project with similar characteristics.

Pure tone	Sound of a single frequency.
Radius of curvature	A measure of the severity of a curve in a track structure based on the length of the radius of a circle that would be formed if the curve were continued.
Rail	A rolled steel shape, commonly a T-section, designed to be laid end to end in two parallel lines on cross ties or other suitable supports to form a track for railway rolling stock.
Rail Rapid Transit (RRT)	Often called "Heavy Rail Transit." A mode of public transit with tracked vehicles in multiple units operating in exclusive rights-of-way. Trains are generally powered by electricity from a third rail alongside the track.
Receiver	A stationary far-field position at which noise or vibration levels are specified.
Relative Noise Impact	Noise increase above existing levels.
Resonance frequency	The phenomenon that occurs in a structure under conditions of forced vibration such that any change in frequency of excitation results in a decrease in response.
Right-of-Way	Abbreviated as ROW. Lands or rights used or held for railroad or transit operation.
Root Mean Square (rms)	The square root of the mean-square value of an oscillating waveform, where the mean-square value is obtained by squaring the value of amplitudes at each instant of time and then averaging these values over the sample time.
RMS Velocity Level (LV)	See Vibration Velocity Level.
SEL	See Sound Exposure Level.
Sound Exposure Level	The level of sound accumulated over a given time interval or event. Technically, the sound exposure level is the level of the time-integrated mean square A-weighted sound for a stated time interval or event, with a reference time of one second. Abbreviated as SEL.
Sound	A physical disturbance in a medium that is capable of being detected by the human ear.
Spectrum	See Frequency Spectrum.
Sub-ballast	Any material of a superior character, which is spread on the finished subgrade of the roadbed and below the top-ballast, to provide better drainage, prevent upheaval by frost, and better distribute the load over the roadbed.
Subgrade	The finished surface of the roadbed below the ballast and track.
Suburban bus	A bus similar to an intercity bus with high-backed seats but no luggage compartment, often used in express mode to city centers from suburban locations.
Switch	A track structure used to divert rolling stock from one track to another.
Tangent track	Track without curvature.
Track	An assembly of rail, ties, and fastenings over which cars, locomotives, and trains are moved.
Traction motor	A specially designed direct current series-wound motor mounted on the trucks of locomotives and self-propelled cars to drive the axles.
Trainset	A group of coupled cars including at least one power unit.
Transducer	Device designed to receive an input signal of a given kind (motion, pressure, heat, etc.) and to provide an output signal of a different kind (electrical voltage, amperage, etc.) in such a manner that desired characteristics of the input signal appear in the output signal for measurement purposes.
Transfer mobility	Transfer mobility is the complex velocity response produced by a point force as a function of frequency and represents the relationship between a vibration source that excites the ground and the resulting vibration of the ground surface.
Transit center	A fixed location where passengers interchange from one route or vehicle to another.
Trolley bus	A rubber-tired, electrically-powered bus operating on city streets drawing power from overhead lines.
Truck	The complete assembly of parts including wheels, axles, bearings, side frames, bolster, brake rigging, springs, and all associated connecting components, the function of which is to provide support, mobility, and guidance to a railroad car or locomotive.
Trunk line	See Mainline. The mainline of a commuter railroad where the branch line traffic is combined.

Turnout	An arrangement of a switch and a frog with closure rails, by means of which rolling stock may be diverted from one track to another.
VdB	See Vibration Velocity Level.
Vibration Velocity Level (LV)	Ten times the common logarithm of the ratio of the square of the amplitude of the RMS vibration velocity to the square of the amplitude of the reference RMS vibration velocity. The reference velocity in the United States is one micro-inch per second. Abbreviated as VdB.
Vibration	An oscillation wherein the quantity is a parameter that defines the motion of a mechanical system.
Wheel flat	A localized flat area on a steel wheel of a rail vehicle, usually caused by skidding on steel rails, causing a discontinuity in the wheel radius.
Wheel squeal	The noise produced by wheel-rail interaction, particularly on curves where the radius of curvature is smaller than allowed by the separation of the axles in a wheel set.

Additional, relevant acoustic terminology and formulas are defined in ANSI S1.1-1994 (49).

Appendix B: Fundamentals of Noise

Noise is generally considered to be unwanted sound. Sound is what we hear when our ears are exposed to small pressure fluctuations in the air. There are many ways in which pressure fluctuations are generated, but typically they are caused by vibrating movement of a solid object. This manual uses the terms noise and sound interchangeably because there is no physical difference between them. Noise can be described in terms of three variables: amplitude (loud or soft); frequency (pitch); and time pattern (variability).

B.1 Amplitude

The loudness of a sound is described by the sound wave's amplitude of pressure fluctuations above and below atmospheric pressure. Pressure is measured in Pascals. The mean value of the positive and negative pressure fluctuations is the static atmospheric pressure and is not a useful metric of sound. However, the effective magnitude of the sound pressure in a sound wave can be expressed by the rms of the oscillating pressure. See Figure B-1 for an illustration of the rms pressure.

The rms pressure is calculated according to Eq. B-1. The values of sound pressure are squared and time-averaged to smooth out variations. The rms pressure is the square root of this time-averaged value.

$$P_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} P_i^2} \qquad \textbf{Eq. B-1}$$

where:

P_{rms} = sound pressure
P_i = individual sound pressure
N = number of samples
$i = 1$ = index of summation

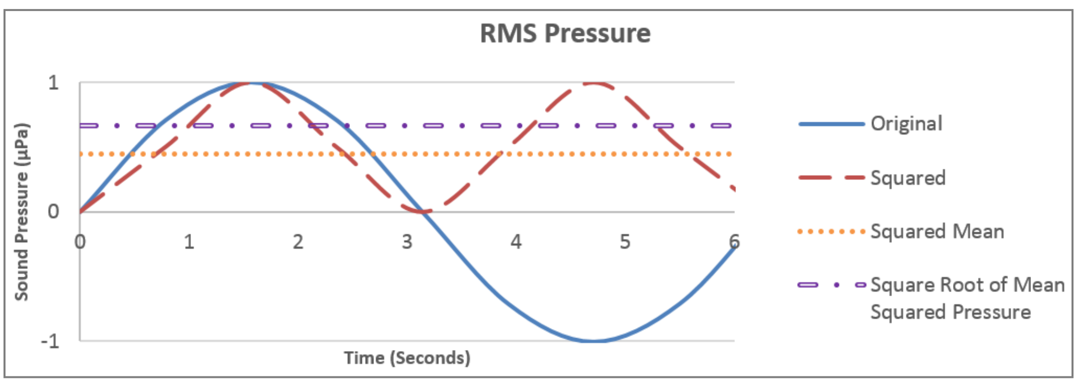

Figure B-1 RMS Pressure Illustration

Most humans with typical or average hearing can perceive sounds ranging from approximately 20 microPascals to 20 million microPascals or more. Because of the difficulty in dealing with such an extreme range of numbers, acousticians use a logarithmic scale to describe sound levels. Acousticians use a compressed scale based on logarithms of the ratios of the sound energy contained in the wave related to the square of sound pressures instead of the sound pressures themselves, resulting in the "sound pressure level" in decibels (dB). The 'B' in dB is always capitalized because the unit is named after Alexander Graham Bell, a leading 19th century innovator in communication.

Sound pressure level (L_p) is defined as:

$$L_p = 10log_{10}(\frac{p_{rms}^2}{p_{ref}^2}); or$$

$$L_p = 20log_{10}(\frac{P_{rms}}{P_{ref}})\ dB \qquad \textbf{Eq. B-2}$$

where

L_P = sound pressure level, dB
P_{rms} = RMS sound pressure
P_{ref} = 20 microPascals

Inserting the range of sound pressure values mentioned above into Eq. B-2 results in a typical quietest sound at 20 microPascals at 0 dB. A typical loudest sound of 20 million microPascals is 120 dB.

B.1.1 Decibel Addition

The combination of two or more sound pressure levels at a single location requires decibel addition, which is the addition of logarithmic quantities of sound energy (P^2_{rms}).

To add sound energy from multiple, unique sources, add the sound energy as shown Eq. B-3.

$$L_p = 10log_{10}(\frac{{P_1}^2 + {P_2}^2 + \cdots + {P_n}^2}{P_{ref}^2}) \qquad \textbf{Eq. B-3}$$

where

L_P = sound pressure level, dB
$P_1, P_{2,} P_n$ = individual source RMS sound pressures to add
P_{ref} = 20 microPascals

A doubling of identical sound sources results in a 3-dB increase, as shown mathematically below.

$$L_p = 10log_{10}(2\frac{p_{rms}^2}{p_{ref}^2})$$

$$= 10log_{10}(\frac{p_{rms}^2}{p_{ref}^2}) + 10log_{10}(2)$$

$$= 10log_{10}(\frac{p_{rms}^2}{p_{ref}^2}) + 3$$

To add decibel levels (instead of sound energy) use the following equation:

$$L_p = 10log_{10}(\sum_{i=1}^{N} 10^{(L_i/10)})$$

where

L_p = sound pressure level, dB
N = number of samples
i = index of summation
L_i = individual sound pressure levels, dB
L_P = sound pressure level, dB
L_1, L_2, L_n = individual source sound pressure levels to add

The equation above can be rewritten as follows:

$$L_p = 10log_{10}(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} + \cdots + 10^{\frac{L_n}{10}}) \qquad \textbf{Eq. B-4}$$

where

L_1, L_2, L_n = individual source sound pressure levels to add

Decibel addition can be quickly approximated using Figure B-2.

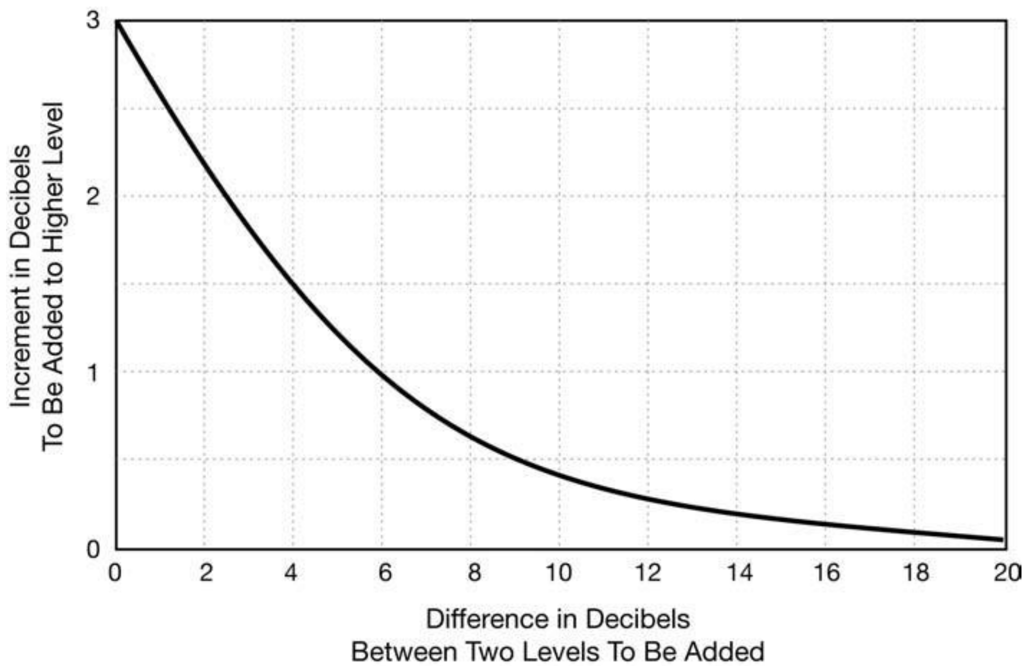

Figure B-2 Graph for Approximate Decibel Addition

Example B-1 Decibel Addition – Identical Buses

Decibel Addition

What is the combined sound pressure level of two identical buses if the noise from one bus resulted in a sound pressure level of 70 dB?

Since a doubling of identical sound sources results in a 3-dB increase:

$$\begin{aligned} L_p &= 70 + 3 \\ &= 73\ dB \end{aligned}$$

Example B-2 Decibel Addition – Two Sources

Decibel Addition

What is the combined sound pressure level of 64 dB and 60 dB?

Using Eq. B-4:

$$\begin{aligned} L_p &= 10log_{10}(10^{64/10} + 10^{60/10}) \\ &= 65.5\ dB \end{aligned}$$

Using Figure B-2:
The x-axis values represent the difference between the two sound levels, 64 and 60 dB. The difference between the sound levels in this example is 4. The point on the curve corresponding to 4 on the x-axis is 1.5. The y-axis values represent the increment that is added to the higher level.

$$\begin{aligned} L_p &= 64 + 1.5 \\ &= 65.5\ dB \end{aligned}$$

B.1.2 Frequency

Sound is a fluctuation of air pressure. The number of times the fluctuation occurs in one second is called its frequency. In acoustics, frequency is quantified in cycles per second, or Hertz (Hz). The hearing for a typical human covers the frequency range from 20 Hz to 20,000 Hz.

Some sounds, like whistles, are associated with a single frequency; this type of sound is called a pure tone. However, most often, noise is made up of many frequencies, called a spectrum. Analyzing a noise spectrum allows for identification of dominant frequency ranges and can assist in identifying noise sources. Often a frequency spectrum is divided into standardized frequency bands for analysis. Most commonly, the frequency bands for transit analyses are octave bands (where the interval between two divisions is a frequency ratio of 2) and one-third octave bands (where the interval between center frequencies is a ratio of 1.25).(73)

If the spectrum associated with a transit noise source is dominated by many low-frequency components, the noise will have a characteristic like the rumble of thunder; this is often associated with noise from a subway. Mid-range frequencies are often associated with wheel/rail noise, and high frequencies may be associated with wheel squeal due to sharp curves on a track.

The spectrum in Figure B-3 illustrates the full range of acoustical frequencies that can occur near a transit system. In this example, the noise spectrum was measured near a train on an elevated steel structure with a sharp curve.

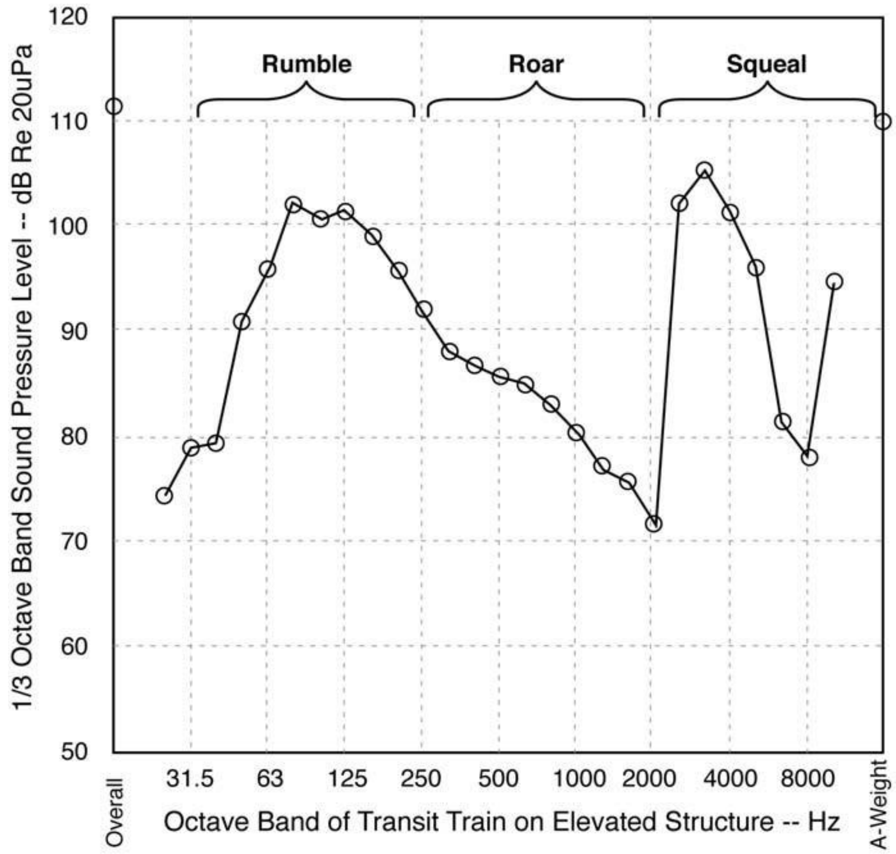

Figure B-3 Noise Spectrum of Transit Train on Curve and Elevated Structure

The human auditory system does not respond equally to all frequencies of sound. For sounds normally heard in our environment, low frequencies below 250 Hz and frequencies above 10,000 Hz are generally considered less audible than the frequencies in between. This is because our ears are less sensitive in those areas. To better represent human hearing, frequency response functions were developed to characterize the way people respond to different frequencies. These are referred to as A-, B-, and C-weighted curves and represent human auditory response to normal, very loud, and extremely loud sound levels, respectively. Environmental noise is generally considered to be in the normal sound level range; and, therefore, the A-weighted sound level is considered best to represent the human response.

The A-weighting curve is shown in Figure B-4. This curve illustrates that sounds at 50 Hz would have to be amplified by 30 dB to be perceived as loud as a sound at 1000 Hz at normal sound levels.

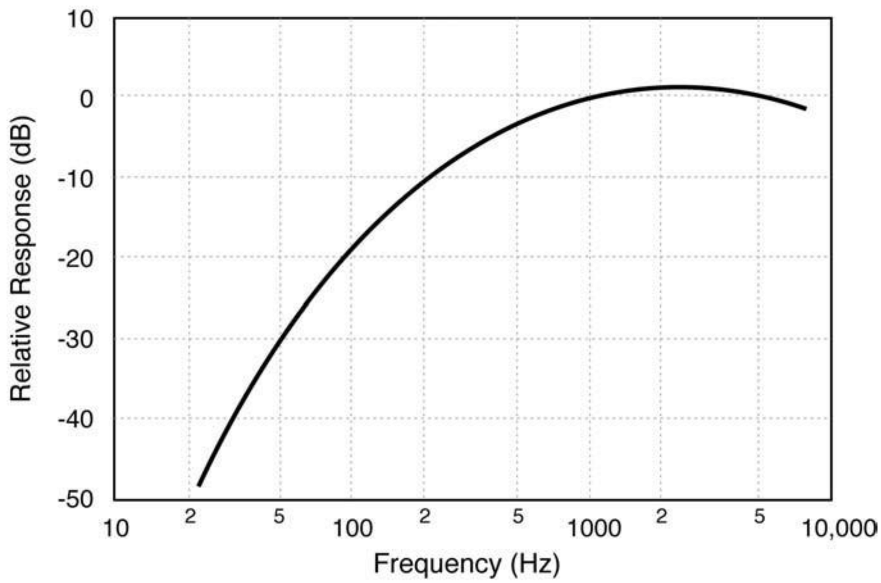

Figure B-4 A-Weighting Curve

Low frequencies have longer wavelengths of sound (cycles are less frequent) and, conversely, high frequencies have shorter wavelengths (cycles are more frequent). The size of the wavelength in feet is dependent on frequency and speed of sound as follows:

$$f\lambda = c \qquad \textbf{Eq. B-5}$$

where

f = frequency in cycles per second, Hz
λ = wavelength, ft
c = speed of sound, ft/sec

The speed of sound in air varies with temperature; but at standard conditions, it is approximately 1000 ft per second. Therefore, at standard conditions, a frequency of 1000 Hz has a wavelength of 1 foot and a frequency of 50 Hz has a wavelength of 20 ft. The scale of these waves explains, in part, the reason humans perceive sounds of 1000 Hz better than those of 50 Hz. A wavelength of 1 foot is similar to the size of a person's head; whereas, a wavelength of 20 ft is similar to dimensions associated with a house, which is why low-frequency sounds (such as those from an idling locomotive) are sometimes not attenuated by walls and windows of a home. These sounds transmit indoors with relatively little reduction in strength.

B.1.3 Time Pattern

The third important characteristic of noise is its variation in time. Environmental noise is considered to be a combination of all outdoor noise sources. When combined, sources such as distant traffic, wind in trees, and distant industrial or farming activities often 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 over time as natural forces change or as human activity follows its daily cycle. In addition to this low-level, slowly varying background noise, a succession of identifiable noisy events of relatively brief duration may be added. These events may include single-vehicle passbys, aircraft flyovers, screeching of brakes, and other short-term events, which all cause the noise level to substantially fluctuate from moment to moment.

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

B.1.4 Noise Metrics

The noise metrics referred to in this manual are described in the sections below.

B.1.4.1 A-weighted Sound Level: The Basic Noise Unit

The basic noise unit for transit noise is the A-weighted sound level and is described in ANSI S1.1-1994 (49). It describes the noise level at the receiver at any moment in time and can be read directly from noise-monitoring equipment when frequency weighting is set to A-weighting. Figure B-5 shows examples of typical A-weighted sound levels for both transit and non-transit sources, ranging from approximately 30 dBA (very quiet) to 90 dBA (very loud).

The unit dBA denotes the decibel level is A-weighted. The letter "A" indicates that the sound has been filtered to reduce the strength of very low and very high-frequency sounds to emulate the human response to sound levels as described in Appendix B.1.2. This allows for events that are out of the range of human hearing, such as high-frequency dog whistles and low-frequency seismic disturbances, to be filtered out. On average, each A-weighted sound level increase of 10 dB corresponds to an approximate doubling of subjective loudness.

A-weighted sound levels are adopted as the basic noise unit for transit noise impact assessments because they:

- Can be measured easily,
- Approximate the human ear's sensitivity to sounds of different frequencies,
- Match attitudinal-survey tests of annoyance better than other basic units,
- Have been in use since the early 1930s, and
- Are endorsed as the proper basic unit for environmental noise by most agencies concerned with community noise throughout the world.

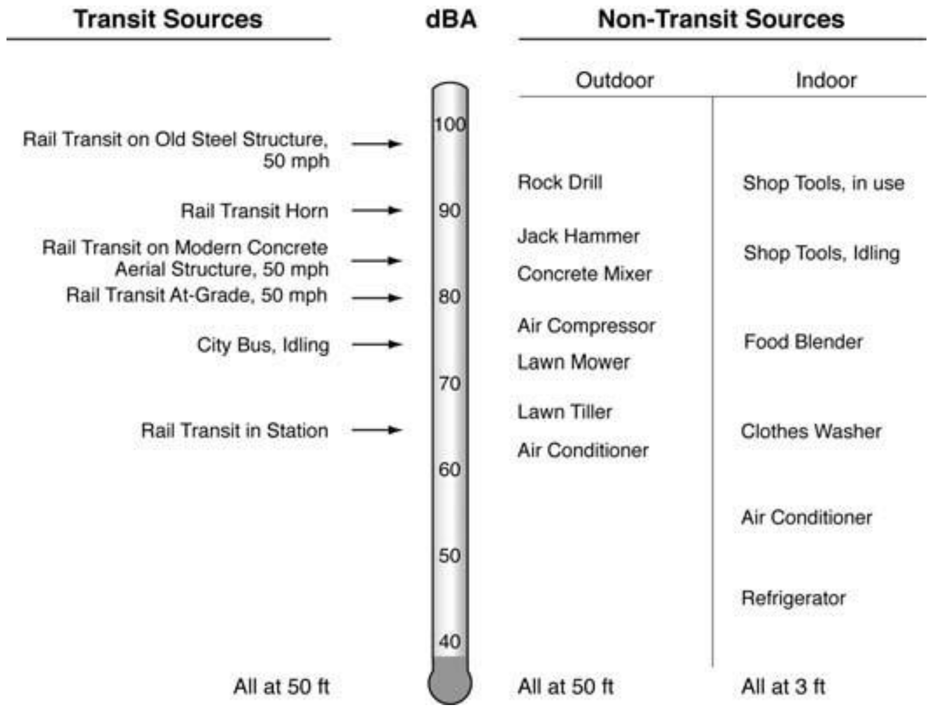

Figure B-5 Typical A-weighted Sound Levels

B.1.4.2 Maximum Sound 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 sound level, (49) abbreviated here as L_{max}. L_{max} is illustrated in Figure B-6 where time is plotted horizontally, and A-weighted sound level is plotted vertically.

Although L_{max} is commonly used in vehicle-noise specifications,[xvi] it is not used for transit environmental noise impact assessment. L_{max} does not include the number and duration of transit events, which are important for assessing people's reactions to noise. It also cannot be normalized to a one-hour or 24-hour cumulative measure of impact, and therefore, is not conducive to comparison among different transportation modes. For example, cumulative noise metrics commonly used in highway noise assessments are $L_{eq(1hr)}$ and L_{10}, the noise level exceeded for 10 percent of the peak hour.

[xvi] 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 time weighting set to "fast." However, for tests of continuous or stationary transit sources, it is usually more appropriate to use the "slow" setting. When set to "slow," sound level meters ignore some of the very-transient fluctuations, which are negligible when assessing the overall noise level.

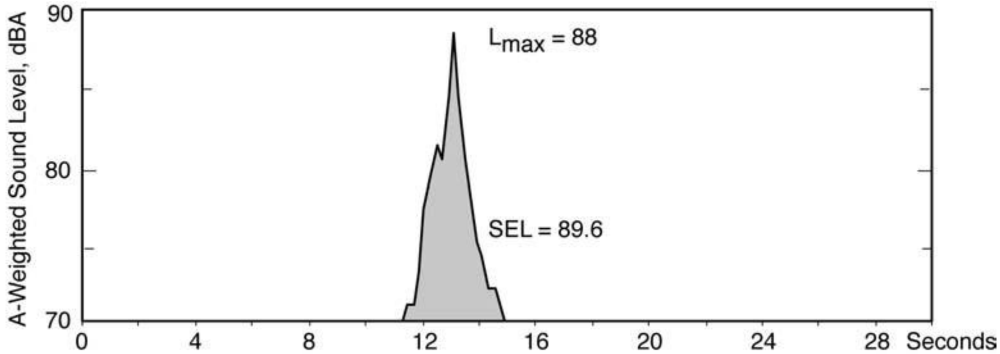

Figure B-6 Typical Transit-Vehicle Passby

B.1.4.3 Sound Exposure Level (SEL): Exposure from a Single Noise Event

Sound exposure level, abbreviated here as SEL, is the cumulative noise exposure from a single noise event, normalized to one second (49). SEL contains the same overall sound energy as the actual varying sound energy during the event. It is the primary metric for the measurement of transit vehicle noise emissions and an intermediate metric in the measurement and calculation of both $L_{eq(1hr)}$ and L_{dn}. The SEL metric is A-weighted and is expressed in the unit dBA.

This concept is illustrated in Figure B-6 and Figure B-7 where the shaded regions are the sound exposure during and event. The example in Figure B-6 is a transit-vehicle passby and Figure B-7 is an example of a fixed-transit facility as a transit bus is started, warmed up, and then driven away. For this event, the noise exposure is large due to duration of the event.

SEL is an A-weighted cumulative measure that is referenced to one second. Louder events have greater SELs than quieter events, and events of longer duration have greater SELs than shorter events. This is generally consistent with community response to noise. Noise events of longer duration are considered more disruptive than events of shorter duration with equal maximum A-weighted sound levels.

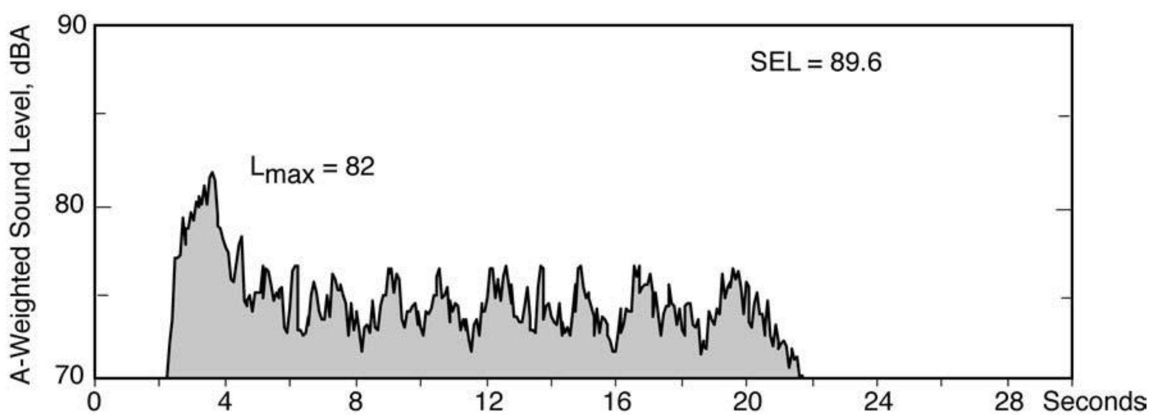

Figure B-7 Typical Fixed-Facility Noise Event

Conceptually, the sound exposure level can be expressed as:

$$SEL = 10log_{10}(\frac{Total\ sound\ energy}{during\ the\ event})$$

Mathematically, the sound exposure level is computed as follows:

$$SEL = 10log_{10}(\sum_{i=1}^{N} 10^{(L_i/10)}) \qquad \textbf{Eq. B-6}$$

where

SEL = Sound exposure level, dBA
N = number of samples
i = index of summation
L_i = individual A-weighted sound level, dBA

The events shown in Figure B-6 and Figure B-7 are compared graphically in Figure B-8 using a logarithmic vertical scale. The shaded zones in these figures indicate noise exposure over time. The actual event shows the noise exposure over the time of the event, and the equivalent SEL shows the total noise exposure normalized to one second. Note that events 1 and 2 in Figure B-8 have different time periods and noise levels throughout the event, but the same resulting SEL.

SEL is used in transit noise analyses because it:

1. Accounts for both the duration and amplitude of an event,
2. Allows a uniform assessment method for both transit-vehicle passbys and fixed-facility noise events, and
3. Can be used to calculate the one-hour and 24-hour cumulative metrics for comparison across different transportation modes.

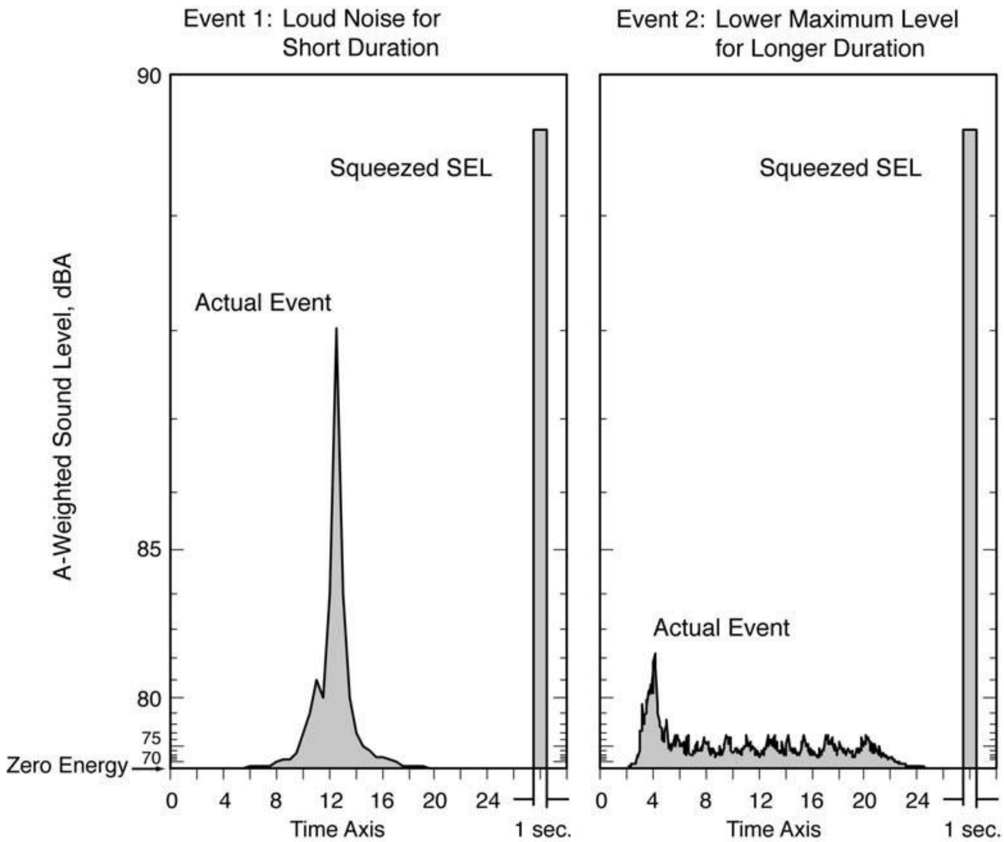

Figure B-8 An Energy View of Noise Events

B.1.4.4 Equivalent Sound Level ($L_{eq(t)}$)

The metric for cumulative noise exposure over a specific time interval is the equivalent sound level (49). It is a single decibel value that accounts for total sound energy from all sound levels over a specified time interval (or time period). The time period associated with the equivalent sound level metric can vary for different types of analyses. This metric is abbreviated as $L_{eq(t)}$, where "t" is the duration of the time period. $L_{eq(t)}$ represents a hypothetical constant sound level and contains the same overall sound energy as the actual varying sound energy during the time period "t". For most transit noise analyses, an A-weighted, hourly equivalent sound level is used, abbreviated here as $L_{eq(1hr)}$. $L_{eq(1hr)}$ is expressed in the unit, dBA.

Figure B-9 shows examples of typical unmitigated hourly $L_{eq(1hr)}$'s, both for transit and non-transit sources ranging from 40 (quiet) to 80 dB (loud). Note that these $L_{eq(1hr)}$'s depend upon both the number of events during the hour as well as each event's duration, which is affected by vehicle speed. For example, doubling the number of events during the hour will increase the $L_{eq(1hr)}$ by 3 decibels, as will doubling the duration of each individual event.

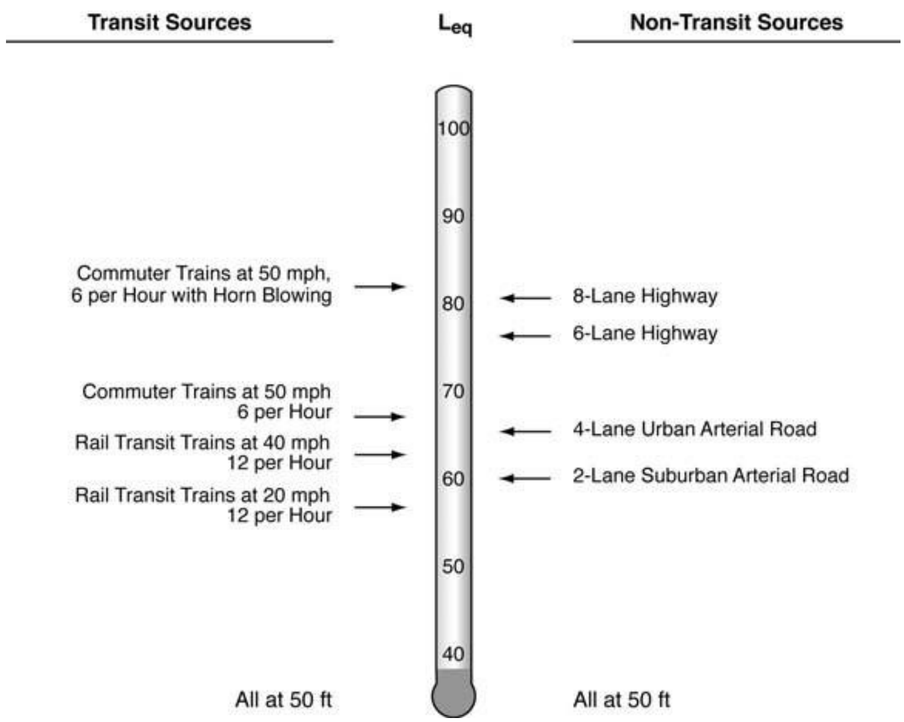

Figure B-9 Typical Hourly $L_{eq(1hr)}$'s

An example of sound levels over time for a single noise event such as a train passing on nearby tracks is illustrated in the top frame of Figure B-10. 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 equivalent sound level is shown for three different time periods Figure B-10. The area under the curve in this top frame is the noise that reaches the receiver (noise exposure) over this five-minute period. The center frame of the figure shows sound levels over the one-hour period, including the five-minute period from the top frame. The area under the curve represents the noise exposure for one hour. The bottom frame shows sound levels over a full 24-hour period and is discussed in Appendix B.1.4.5.

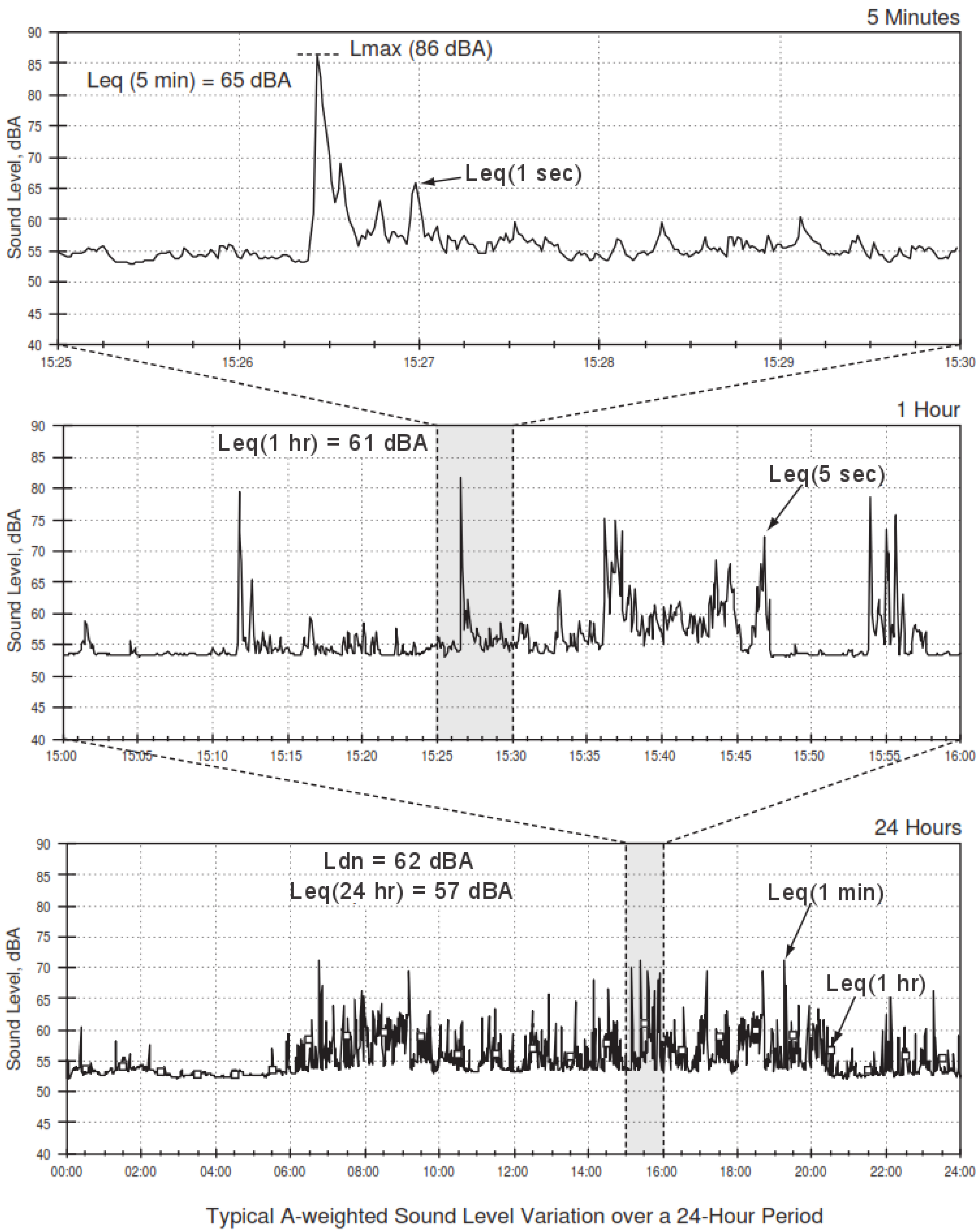

Figure B-10 Example A-weighted Sound Level Time Histories

Conceptually, the equivalent sound level can be expressed as:

$$L_{eq}(t) = 10log_{10}(\frac{Total\ Sound\ Energy}{Time\ Period})$$

Mathematically, the equation is as follows:

$$L_{eq}(t) = 10log_{10}(\frac{1}{T}\sum_{i=1}^{N} 10^{(L_i/10)})$$

where

$L_{eq(t)}$ = equivalent sound level of time period "t", dBA
T = time period, sec (3600 for an hourly $L_{eq(1hr)}$)
N = number of samples, sec (3600 for an hourly $L_{eq(1hr)}$)
i = index of summation
L_i = individual A-weighted sound level, dBA

The equation above can be rewritten as follows for a one-hour time period:

$$L_{eq}(1h) = 10log_{10}[Total\ Sound\ Energy\ in\ 1\ hr] - 35.6$$ **Eq. B-7**

where

35.6 = numerical adjustment for a time period of 1 hour ($10log_{10}(t)$)

The sound energy is totaled over a full hour (3600 seconds) and is accumulated for all noise events during that hour. When computing the equivalent sound level for a time period other than one hour, T is modified in the equation to the duration of the time period in seconds. The numerical adjustment (35.6) accounts for time period of interest, in this case, one hour.

An alternate way for computing $L_{eq(1hr)}$ for a series of transit-noise events using sound exposure levels can be expressed conceptually as follows:

$$L_{eq}(1h) = 10log_{10}(\begin{matrix}Energy\ Sum\ of\\ all\ SELs\end{matrix}) - 35.6$$

Mathematically, the equation is as follows:

$$L_{eq}(t) = 10log_{10}(\frac{1}{T}\sum_{i=1}^{N} 10^{(SEL_i/10)})$$ **Eq. B-8**

where

$L_{eq(t)}$ = equivalent sound level of time period "t", dBA
T = time period, sec (3600 for an hourly $L_{eq(1hr)}$)
N = number of sample, sec (3600 for an hourly $L_{eq(1hr)}$)
i = index of summation
SEL = individual sound exposure level, dBA

Hourly $L_{eq(1hr)}$ is adopted as the measure of cumulative noise impact for non-residential land uses (those not involving sleep) because $L_{eq(1hr)}$:

- Correlates well with speech interference in conversation and on the telephone – as well as interruption of TV, radio, and music enjoyment;
- Increases with the duration of transit events;
- Accounts for the number of transit events over the hour, which is also important to people's reactions; and

- Is used by the Federal Highway Administration in assessing highway-traffic noise impact.(Thus, this noise metric can be used for directly comparing and contrasting highway, transit, and multimodal alternatives).

B.1.4.5 Day-Night Sound Level (L_{dn}): 24-Hour Exposure from All Events

The metric for cumulative 24-hour exposure is the Day-Night Sound Level, (49) abbreviated here as L_{dn}. It is a single, A-weighted decibel value that accounts for total sound energy from all sound sources over 24 hours and is expressed in the unit, dBA. Events between 10 p.m. and 7 a.m. are increased by 10 dB to account for people's greater nighttime sensitivity to noise.

Figure B-11 shows examples of typical L_{dn}'s, both for transit and non-transit sources, ranging from 50 to 80 dB, where 50 is considered a quiet 24-hour period and 80 a loud 24-hour period. Note that these L_{dn}'s depend upon the number of events during day and night separately, including each event's duration, which is affected by vehicle speed.

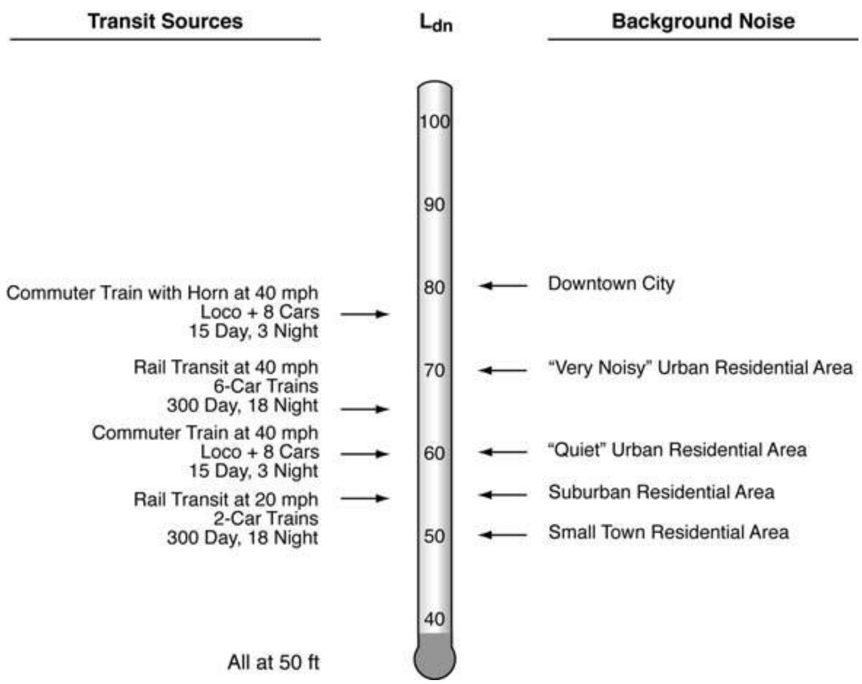

Figure B- 11 Typical L_{dn}'s

An example of sound level variation over 24 hours is visualized in the bottom frame of Figure B-10. The area under the curve represents the receiver's noise exposure over the 24 hours. Note that some vehicle passbys occur at night, when the background noise is typically lower and the 10 dB adjustment is applied.

Conceptually, the day-night level can be expressed as:

$$L_{dn} = 10log_{10}(\frac{Total\ Sound\ Energy_{Day}}{Time\ Period_{Day}\ (seconds)} + \frac{n_{adj,n} \times Total\ Sound\ Energy_{Night}}{Time\ Period_{Night}\ (seconds)})$$

Mathematically, the equation is as follows:

$$L_{dn} = 10log_{10}(\frac{1}{T_d}\sum_{i=1}^{N} t_i \times 10^{(L_{d,i}/10)} + \frac{1}{T_n}\sum_{j=1}^{M} t_j \times 10^{((L_{n,j}+n_{adj,n})/10)}) \qquad \textbf{Eq. B-9}$$

where

L_{dn}	= cumulative 24-hour exposure (day-night sound level), dBA
T_d	= time period during the daytime, between 7 a.m. and 10 p.m. sec (54,000)
N	= number of samples during the daytime (54,000)
i	= index of summation
t_i	= time interval of measurements in seconds (1)
$L_{d,i}$	= individual A-weighted sound level during the daytime, dBA
T_n	= time period during the nighttime, between 10 p.m. and 7 p.m. sec (32,400)
M	= number of samples during the nighttime (32,400)
j	= index of summation
t_j	= time interval of measurements, sec (1)
$L_{n,j}$	= individual A-weighted sound level during the nighttime, dBA
$n_{adj,n}$	= nighttime noise adjustment (10 dB)

The equation above can be rewritten as follows:

$$L_{dn} = 10log_{10}\left[\left(15 * Total\ Sound\ Energy_{Day}\right) + \left(9 * n_{adj,n} * \ Total\ Sound\ Energy_{Night}\right)\right] - 49.4$$

The sound energy is totaled over a full 24 hours, and the sound energy is accumulated from all noise events during that time period. The numerical adjustment (49.4) accounts for time period of interest, in this case, 24 hours.

An alternative way of computing L_{dn} from twenty-four hourly $L_{eq(1hr)}$'s can be expressed conceptually as follows:

$$L_{dn} = 10log_{10}(\frac{\substack{Energy\ sum\ of \\ daytime, hourly\ Leqs} + (n_{adj,n} * \substack{Energy\ sum\ of \\ nighttime, hourly\ Leqs})}{Time\ period\ (seconds)})$$

The equation above can be rewritten as:

$$L_{dn} = 10log_{10}(\frac{\substack{Energy\ sum\ of \\ daytime, hourly\ Leqs} + (n_{adj,n} * \substack{Energy\ sum\ of \\ nighttime, hourly\ Leqs})}{(\frac{86400}{3600})})$$

The equation above can be reduced further and rewritten as:

$$L_{dn} = 10log_{10}(\substack{Energy\ sum\ of \\ daytime, hourly\ Leqs} + \ (n_{adj,n} * \substack{Energy\ sum\ of \\ nighttime, hourly\ Leqs})) - 13.8 \qquad \textbf{Eq. B-10}$$

L_{dn} due to a series of transit-noise events can also be computed in terms of SEL. The equation below assumes that transit noise dominates the 24-hour noise environment, where nighttime SELs are increased by 10 dB before totaling:

$$L_{dn} = 10log_{10}(\genfrac{}{}{0pt}{}{Energy\ sum\ of}{all\ daytime\ SELs} + (n_{adj,n} * \genfrac{}{}{0pt}{}{Energy\ sum\ of}{all\ nighttime\ SELs})) - 49.4 \qquad \textbf{Eq. B-11}$$

L_{dn} is adopted as the measure of cumulative noise impact for residential land uses (those involving sleep), because it:

- Correlates well with the results of attitudinal surveys of residential noise impact
- Increases with the duration of transit events
- Accounts for the number of transit events over the full twenty-four hours
- Accounts for the increased sensitivity to noise at night, when most people are asleep
- Allows composite measurements to capture all sources of community noise combined
- Allow quantitative comparison of transit noise with other community noises
- Is the designated metric of choice of other Federal agencies (e.g., HUD, FAA, and EPA) and has wide international acceptance

Appendix C: Background for Transit Noise Impact Criteria

The noise criteria presented in Section 4.1 of this manual have been developed based on well-documented criteria and research on human response to community noise. The primary goals in developing the noise criteria were to ensure that the impact limits are firmly founded in scientific studies, realistically based on noise levels associated with new transit projects, and represent a reasonable balance between community benefit and project costs. This appendix provides background information on the development of these criteria.

C.1 Relevant Literature

The following is an annotated list of the documents that are particularly relevant to the noise impact criteria:

1. **U.S. EPA's "Levels Document"**[74]
   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. **Committee on Hearing, Bioacoustics and Biomechanics (CHABA) Working Group 69, "Guidelines for Preparing Environmental Impact Statements on Noise"**[75]
   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 Transportation Association (APTA) Guidelines for Design of Rapid Transit Facilities**[76]
   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; but the metric used in the APTA Guidelines is not appropriate for environmental assessment purposes.

   The APTA Guidelines criteria are in terms of L_{max} for conventional RRT 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 RRT operations with 5 to 10 minute headways. Therefore, the APTA criteria are questionable for assessing the noise impact of other transit modes that 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**[77]
   In 1978, Theodore J. Schultz, an internationally known acoustical scientist, synthesized the results of a large number of social surveys concerning annoyance due to transportation noise. A group of these surveys were remarkably consistent, 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 3-7) 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% when L_{dn} is approximately 90 dBA. Most importantly, 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. For example, 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, confirming the shape of the original Schultz curve [(12)].

5. **HUD's Standards**[(19)]
HUD 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 acceptability standards define 65 dB (L_{dn}) as the threshold for a normally unacceptable living environment (moderate impact for FTA) and 75 dB (L_{dn}) as the threshold for an unacceptable living environment (severe impact for FTA).

C.2 Basis for Noise Impact Criteria Curves

The lower curve in Figure 4-2 represents the onset of moderate impact and 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."[(72)]
- The conclusion by EPA and others that a 5 dB increase in L_{dn} or $L_{eq(1hr)}$ is the minimum required for a change in community reaction.
- The research concludes 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 (Figure 3-7).

The increase in noise level from an existing ambient level of 50 dBA to a cumulative level of 55 dBA because of a project is found to cause minimal impact, with 2% of people highly annoyed, as described in the bullets above. This is considered the lowest threshold where impact starts to occur. Therefore, for an existing ambient noise level of 50 dBA, the curve representing the onset of moderate impact is at 53 dBA, the combination of which yields a cumulative level of 55 dBA by decibel addition. The remainder of the lower curve in Figure 4-2 was determined from the annoyance curve (Figure 3-7) by allowing a fixed 2% increase in annoyance at other levels of existing ambient noise. As cumulative noise increases, the increment to attain the same 2% increase in highly annoyed people is smaller. 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 a 2% increase of highly annoyed people at an existing ambient noise level of 70 dBA.

The upper curve in Figure 4-2 represents the onset of severe impact based on a total noise level, corresponding to a higher degree of impact. The severe noise impact curve is based on the following considerations:

- HUD defines an L_{dn} of 65 as the onset of a normally unacceptable noise zone (moderate impact for FTA) in its environmental noise standards [(19)]. FAA considers that residential land uses are not compatible with noise environments where L_{dn} is greater than 65 dBA (20).

- An increase of 5 dB in L_{dn} or $L_{eq(t)}$ is commonly assumed as the minimum required increase for a change in community reaction.
- The research concludes that an increase of 5 dB in L_{dn} or $L_{eq(t)}$ represents a 6.5% increase in the number of people highly annoyed (Figure 3-7).

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 the level at which severe impact starts to occur with a 6.5% increase in the number of people highly annoyed as described in the bullets above. Therefore, for an existing ambient noise level of 60 dBA, the curve representing the onset of severe impact is at 63 dBA, the combination of which yields a cumulative level of 65 dBA by decibel addition. The remainder of the upper curve in Figure 4-2 was determined from the annoyance curve (Figure 3-7) by allowing a fixed increase of 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, moderate impact for land use categories 1 and 2 is considered to occur whenever the transit L_{dn} equals or exceeds 65 dBA, and severe impact occurs whenever the transit 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 approximately 45 dBA). This is a conservative limit that reflects the lack of social survey data on people's reactions to noise at such low ambient levels. Like the FHWA approach in assessing the relative impact of a highway project, the transit noise criteria include limits on noise increase of 10 dB and 15 dB for moderate impact and severe impact, respectively, relative to the existing noise level.

Note 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 dB 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 4-2. Aside from active parks, which are clearly less sensitive to noise than category 1 and 2 sites, category 3 sites include primarily indoor activities. Therefore, the criteria account for some noise reduction from the building structure.

C.3 Equations for Noise Impact Criteria Curves

The equations for the noise impact criteria curves shown in Figure 4-2 are included in this section. These equations may be useful when performing the noise assessment methodology using spreadsheets, computer programs, or other analysis tools. Otherwise, such mathematical detail is generally not necessary to implement the criteria, and direct use of Figure 4-2 is adequate and less time-consuming.

A total of four continuous curves are included in the criteria, creating two threshold curves for moderate and severe impact for category 1 and 2, and two curves for category 3 (See Table C-1). 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, each one is defined by a set of three discrete equations. These equations are approximately continuous at the transition points. The following is a description of the three equations:

- 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 limited to 10 dB and 15 dB for moderate 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 Appendix C.2. This curve is a third-order, polynomial approximation derived from the Schultz curve(75) and covers the range of noise exposure encountered in most populated areas. This curve is used for determining noise impact in most cases for transit projects.
- The third equation 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, the absolute limit is 65 dBA for moderate impact and 70 dBA for severe impact. For land use category 3, the absolute limit is 75 dBA for moderate impact and 80 dBA for severe impact.

Table C-1 Threshold of Moderate and Severe Impacts

Threshold of Moderate Impact

Category 1 and 2

$$L_p = \begin{cases} 11.450 + 0.953L_E, & L_E < 42 \\ 71.662 - 1.164L_E + 0.018{L_E}^2 - 4.088 \times 10^{-5}{L_E}^3, & 42 \leq L_E \leq 71 \\ 65, & L_E > 71 \end{cases} \quad \textbf{Eq. C- 12}$$

Category 3

$$L_p = \begin{cases} 16.450 + 0.953L_E, & L_E < 42 \\ 76.662 - 1.164L_E + 0.018{L_E}^2 - 4.088 \times 10^{-5}{L_E}^3, & 42 \leq L_E \leq 71 \\ 70, & L_E > 71 \end{cases} \quad \textbf{Eq. C- 13}$$

Threshold of Severe Impact

Category 1 and 2

$$L_p = \begin{cases} 17.322 + 0.940L_E, & L_E < 44 \\ 96.725 - 1.992L_E + 3.02 \times 10^{-2}{L_E}^2 - 1.043 \times 10^{-4}{L_E}^3, & 44 \leq L_E \leq 77 \\ 75, & L_E > 77 \end{cases} \quad \textbf{Eq. C- 14}$$

Category 3

$$L_p = \begin{cases} 22.322 + 0.940L_E, & L_E < 44 \\ 101.725 - 1.992L_E + 3.02 \times 10^{-2}{L_E}^2 - 1.043 \times 10^{-4}{L_E}^3, & 44 \leq L_E \leq 77 \\ 80, & L_E > 77 \end{cases} \quad \textbf{Eq. C- 15}$$

L_E = the existing noise exposure in terms of L_{dn} or $L_{eq(1hr)}$
L_p = the project noise exposure which determines impact in terms of L_{dn} or $L_{eq(1hr)}$)

Appendix D: Clustering Receivers of Interest

This appendix supplements the information in Section 4.5 on clustering receivers of interest.

The general approach to selecting noise-sensitive receivers in the study area is included in Section 4.5, Step 1. General guidelines are as follows:

- Select the following types of receivers to evaluate individually:
  - Every major noise-sensitive public building
  - Every isolated residence
  - Every relatively small outdoor noise-sensitive area
- Residential neighborhoods and relatively large outdoor noise-sensitive areas can often be clustered and represented by a single receiver.

Clustering similar receivers reduces the number of computations needed later, especially for large-scale projects where a greater number of noise-sensitive sites may be affected. For this approach to be effective, it is essential that the representative receiver accurately represents the noise environment of the cluster.

The major steps in clustering receivers include:

1. First, cluster receivers according to approximately equal exposure to the primary project noise source. These areas typically run parallel to a linear project or circle major stationary sources relative to the proposed project.
2. Next, cluster receivers according to major sources of ambient noise. These areas typically run parallel to or encircle major sources of ambient noise.
3. Then, cluster receivers according to changes in the project layout or operations along the corridor.
4. Finally, select a representative receiver for each cluster.

The major steps are expanded below and include instructions on how to draw cluster boundaries on a map.

1. **Boundaries along the proposed project** – Draw cluster boundaries along the proposed project as described below to separate clusters based on distance from the project. Draw these cluster boundaries for the project sources listed as major in Table 4-19.

   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 ft, 50 ft, 100 ft, 200 ft, 400 ft, and 800 ft. For linear sources, such as a rail line, draw these boundaries as lines parallel to the proposed ROW line. For 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 Noise Screening Procedure in Section 4.3 or the General Noise Assessment of Section 4.4.

- **Remaining project sources** – Repeat the process for the primary project source for all other project listed as major in Table 4-19, such as substations and crossing signals. If several project sources are located approximately together, only consider one source, since the others would produce approximately the same boundary.

  It is good practice to optimize the number of clusters for a project to simplify the procedure.

Where rows of buildings parallel the transit corridor:

- Ensure 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 3 and 4
- Add cluster boundaries between these rows if not already included.

2. **Boundaries along sources of ambient noise** – Draw cluster boundaries along all major sources of ambient noise based upon distance from these sources, as described below.
   - Draw cluster boundaries along all interstates and major roadway arterials at the following distances from the near edge of the roadway: 0 ft, 100 ft, 200 ft, and 500 ft.
   - Draw cluster boundaries along all other roadways that have state or county numbering at 0 ft and 100 ft from the near edge of the roadway.
   - For all major industrial sources of noise, draw cluster boundaries that encircle the source at the following distances from the near property line of the source: 0 ft, 100 ft, 200 ft, and 400 ft.

3. **Boundaries based on changes in project layout or operations** – Further subdivision is needed to account for changes in project noise where proposed project layout or operating conditions change considerably along the corridor. 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 approximately 100 ft are moved closer together
   - Approximately where speed and/or throttle are reduced when approaching stations and where steady service speed is reached after departing stations
   - Approximately 200 ft 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 including 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 considerably, such as up and down the line from tight curves where wheels may squeal

4. **Selection of a representative receiver from each cluster** – Determine a representative receiver for each cluster boundary drawn in the steps above.
   - **Residential clusters**
     Select a representative receiver within the cluster at the house closest to the proposed project. If this receiver is not the clear choice, select the receiver furthest from major sources of ambient noise.
   - **Outdoor noise-sensitive clusters (e.g., urban park or amphitheater)**

Select a representative receiver within the cluster at the closest point of active noise-sensitive use. If this receiver is not the clear choice, select the receiver farther from major sources of ambient noise.

Note that some clusters may fall between areas with receivers of interest. This could occur when operational changes or track layouts change in an open, undeveloped area. Retain these clusters. Do not merge them with adjacent clusters. Do not select a representative receiver of interest from them.

Example D-1 Clustering Receivers

Receivers of Interest and Clustering Receivers

In this hypothetical situation, a new rail transit line, labeled "new rail line" in Figure D-1, is proposed along a major urban street with commercial land use. A residential area is located adjacent to the commercial strip, located approximately one-half block from the proposed transit alignment. A major arterial, labeled "highway," crosses the alignment.

Cluster Receivers Along the Primary Project Source

Primary Project Source

The primary project source in this example is the new rail line. Boundaries are first drawn at distances of 0 ft from the right-of- way line (edge of the street in this example), 50 ft, 100 ft, 200 ft, 400 ft, and 800 ft, (Figure D-1). Distances are 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, but 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.

Rows of Buildings Parallel to the Transit Corridor

This example includes rows of buildings parallel to the transit corridor. The first set of boundary 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.

Cluster Receivers Along the Primary Project Source

The roadway arterial (labeled "highway") is the only major source of ambient noise shown.

Cluster boundaries are drawn at 0 ft, 100 ft, 200 ft and 500 ft from the near edge of the roadway on both sides. These lines are shown with distances labeled at the side of the figure.

Select a Representative Receiver from Each Cluster

Representative receivers are shown as filled circles in Figure D-1. Note that the receivers labeled with "REC" are primarily for use in Appendix E.

Locate receiver, "REC 3". Note that this cluster is located at the outer edge of influence from the major source ("highway") where local street traffic is the dominant source for ambient noise (in practice, this 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."

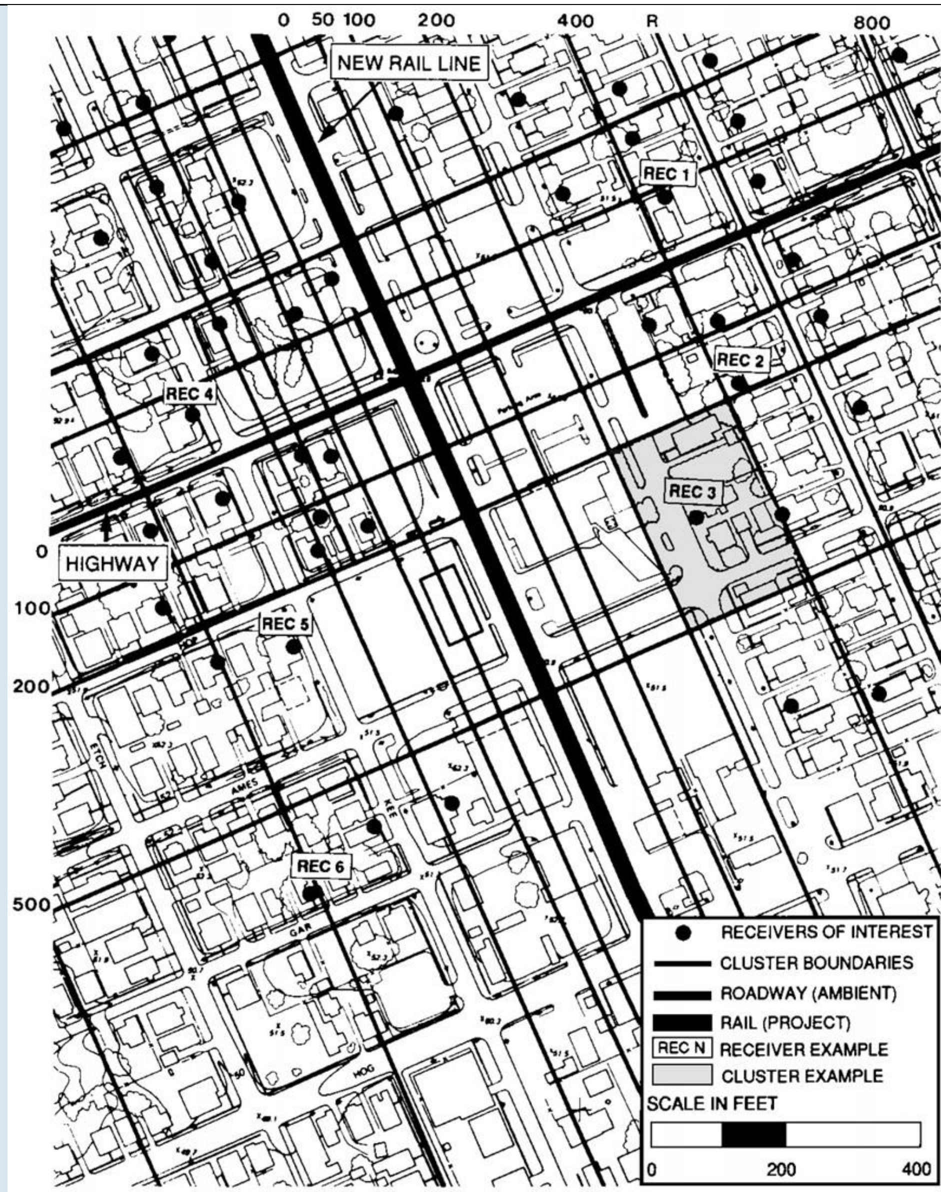

Figure D-1 Example of Receiver Map Showing Cluster Boundaries

Appendix E: Determining Existing Noise

Different options of determining existing noise, including full measurement, computation from partial measurements, and tabular look-up, are described in Section 4.5, Step 5. This appendix provides additional details associated with each method and examples of when each method could be used.

Additional details on the methods for estimating existing noise are provided below:

Option 1: $L_{eq(1hr)}$ measurement (non-residential) – Full one-hour measurements are recommended to determine existing noise for non-residential receivers of interest. These measurements are preferred over all other options and will accurately represent the $L_{eq(1hr)}$. The following procedures apply to these full-duration measurements:

- Measure $L_{eq(1hr)}$ at the receiver of interest during a typical hour of use on two non-successive days. Choose the hour in which maximum project activity will occur. The $L_{eq(1hr)}$ will be accurately represented using this method. Typically, measuring between noon Monday and noon Friday is recommended, but weekend days may be more appropriate for places of worship.
- Position the measurement microphone for all sites as shown in Figure 4-19, considering relative orientation of project and ambient sources. Position the microphone in a location that is somewhat shielded from the ambient source to measure the ambient noise at these locations at the quietest area on the property.
- Conduct all measurements in accordance with good engineering practice.

Option 2: L_{dn} measurement (residential) – Full 24-hour measurements are recommended to determine ambient noise for residential receivers of interest. These measurements are preferred over all other options and will accurately represent the L_{dn}. The following procedures apply to these full-duration measurements:

- Measure a full 24-hour L_{dn} at the receiver of interest for a single weekday (generally between noon Monday and noon Friday).
- Position the measurement microphone for all sites as shown in Figure 4-19 considering relative orientation of project and ambient sources. Position the microphone in a location that is somewhat shielded from the ambient source to measure the ambient noise at these locations at the quietest area on the property.
- Conduct all measurements in accordance with good engineering practice.

Option 3: L_{dn} computation of L_{dn} from 3 partial $L_{eq(1hr)}$ measurements (residential) – An alternative way to determine L_{dn} is to measure $L_{eq(1hr)}$ for three typical hours of the day, then compute the L_{dn} from these three $L_{eq(1hr)}$ measurements. This method is less precise than its full-duration measurement. The following procedures apply to this partial-duration measurement method for L_{dn}:

- Measure the $L_{eq(1hr)}$ during each of the following time periods:
  - During peak-hour roadway traffic
  - Midday, between the morning and afternoon roadway-traffic peak hours
  - During late night between midnight and 5 a.m.
- Position the measurement microphone for all sites as shown in Figure 4-19 considering relative orientation of project and ambient sources. Position the microphone in a location that is somewhat shielded from the ambient source to measure the ambient noise at these locations at the quietest area on the property.
- Conduct all measurements in accordance with good engineering practice.
- Compute the L_{dn} using the equation below

$$L_{dn} \approx 10\log(3 \times 10^{\frac{L_{eq.peakhour} - 2}{10}} + 12 \times 10^{\frac{L_{eq.midday} - 2}{10}} + 9 \times 10^{\frac{L_{eq.latenight} + 8}{10}}) - 13.8 \qquad \textbf{Eq. E-1}$$

The resulting L_{dn} will be slightly underestimated due to the adjustment to the measured levels in these equations. This underestimation is intended to compensate for the reduced precision of the computed L_{dn}. If using this method, a minimum time duration of one hour should be used for each measurement period in computing an Ldn.

Option 4: Computation of L_{dn} from 1 partial $L_{eq(1hr)}$ measurement (residential) – L_{dn} can also be determined by measuring $L_{eq(1hr)}$ for one hour of the day, and then computing L_{dn} from the $L_{eq(1hr)}$. This method is less precise than computing L_{dn} from 3 $L_{eq(1hr)}$ measurements. This method may be useful for projects with are many sites assessed by the General Noise Assessment. This method may also be appropriate when determining if a particular receiver of interest represents a cluster in a Detailed Noise Analysis. The following procedures apply to this partial-duration measurement option for L_{dn}:

- Measure the $L_{eq(1hr)}$ for the loudest hour of project-related activity during hours of noise sensitivity. If this hour is not selected, other hours may be used with the understanding that the estimate is less precise.
- Position the measurement microphone for all sites as shown in Figure 4-19, considering relative orientation of project and ambient sources. Position the microphone in a location that is somewhat shielded from the ambient source to measure the ambient noise at these locations at the quietest area on the property.
- Conduct all measurements in accordance with good engineering practice.
- Convert the measured hourly $L_{eq(1hr)}$ to L_{dn} with the appropriate equation below.

For measurements between 7 a.m. and 7 p.m.:

$$L_{dn} \approx L_{eq} - 2 \qquad \textbf{Eq. E-2}$$

For measurements between 7 p.m. and 10 p.m.:

$$L_{dn} \approx L_{eq} + 3 \qquad \textbf{Eq. E-3}$$

For measurements between 10 p.m. and 7 a.m.:

$$L_{dn} \approx L_{eq} + 8 \qquad \textbf{Eq. E-4}$$

The resulting L_{dn} will be moderately underestimated due to the use of the adjustment constants in these equations. This underestimation is intended to compensate for the reduced precision of the computed L_{dn}. If using this method, a minimum time duration of one hour should be used for each measurement period in computing an Ldn.

Option 5: Computation of $L_{eq(1hr)}$ or L_{dn} from $L_{eq(1hr)}$ or L_{dn} of a comparable site (all land uses) – Computing $L_{eq(1hr)}$ or L_{dn} from the $L_{eq(1hr)}$ or L_{dn} of a comparable site where the ambient noise is dominated by the same source that is comparable in precision to Option 4. This method can be used to characterize noise in several neighborhoods by using a single representative receiver. It is critical 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, the existing measurements can be used to reduce the amount of project noise monitoring. The following procedures apply to this method of determining of ambient noise:

- Choose another receiver that is comparable to the receiver (CompRec) of interest with the following:
  - The same source of dominant ambient noise

  - The ambient level of the comparable receiver was measured according to 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 by noise barriers, terrain, rows of buildings, or dense tree zones
- Determine the following from a plan or aerial photograph:
  - The distance ($D_{CompRec}$) from the comparable receiver to the near edge of the ambient source
  - The distance (D_{Rec}) from this receiver of interest to the near edge of the ambient source
- Determine the number of rows of buildings (N) that intervene between the receiver of interest and the ambient source.
- Compute the ambient level at the receiver of interest (Rec) with the appropriate equation below

If roadway sources dominate:

$$L_{Rec} \approx L_{CompRec} - 15\log(\frac{D_{Rec}}{D_{CompRec}}) - 3N \quad \textbf{Eq. E-5}$$

If other sources dominate:

$$L_{Rec} \approx L_{CompRec} - 25\log(\frac{D_{Rec}}{D_{CompRec}}) - 3N \quad \textbf{Eq. E-6}$$

The resulting L_{Rec} will be moderately underestimated. This underestimation is intended to compensate for the reduced precision of the computed L_{dn}.

Option 6: Estimation of L_{dn} by table look-up (all land uses) – The least precise way to determine the ambient noise is to estimate the level using a table. A tabular look-up can be used to establish baseline conditions for a General Noise Assessment if a noise measurement cannot be made. This method should not be used for a Detailed Noise Analysis. The following instruction applies to this method of determining of ambient noise:

Estimate either the $L_{eq(1hr)}$ or the L_{dn} using Table 4-17 based on distance from major roadways, rail lines, or upon population densities. In general, these tabulated values are substantially underestimated.

The underestimation is intended to compensate for the reduced precision of the estimated ambients.

Examples – Examples of when each method of determining existing noise may be appropriate are provided below using the example from Appendix D. Existing noise at the receivers labeled "REC" in Figure D-1 could be estimated as follows:

- **Option 1: $L_{eq(1hr)}$ measurement** – Existing noise at REC 1 is due to the highway at the side of this church. $L_{eq(1hr)}$ can be measured during a typical church hour.
- **Option 2: L_{dn} measurement –** Existing noise at the residence REC 2 is due to a combination of the highway and local streets. L_{dn} can be measured for a full 24-hours.
- **Option 3: L_{dn} computation of L_{dn} from 3 partial $L_{eq(1hr)}$ measurements** – Existing noise at the residence REC 3 is due to the street in front of this residence. L_{dn} can be computed from three $L_{eq(1hr)}$ measurements.

- **Option 4: Computation of L_{dn} from 1 partial $L_{eq(1hr)}$ measurement** – Existing noise at the residence REC 4 is due to the highway. Because the highway has a predictable diurnal pattern, L_{dn} can be computed from one $L_{eq(1hr)}$ measurement.
- **Option 5: Computation of L_{dn} from L_{dn} of a comparable site** – Existing noise at the residence REC 5 is due to Kee Street. REC 3 is also affected by local street traffic and is a comparable distance from the highway. L_{dn} for REC 5 can be computed based on the L_{dn} at REC-3.
- **Option 6: Estimation of L_{dn} by table look-up** – Existing noise at the residence REC 6 is due to local traffic. L_{dn} can be estimated by tables based on population density along this corridor.

Appendix F: Computing Source 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 Section 4.5, Step 2 indicate measurements are preferred, data are not available for the source of interest, or more precise data are required than available in the table.

Close-by source measurements for vehicle passbys may capture either the vehicle's sound exposure level (SEL) or maximum noise level (L_{max}). Both metrics can be measured directly by commonly available sound level meters. While the L_{max} metric is not used for transit noise impact assessments, it can be used to compute SEL source reference levels. L_{max} measurements are often available from transit-equipment manufacturers and some transit system equipment specifications may limit close-by L_{max} levels.

Close-by source measurements for stationary sources capture the source's SEL over one source event, where the event duration may be chosen based on measurement convenience. The duration will factor out of the computation when the measured value is converted to reference operating conditions.

This manual does not specify elaborate methods for undertaking the close-by source measurements, but rather, provides general processes. It is required that all measurements conform to good engineering practice, guided by the standards of the American National Standards Institute and other such organizations (27, 28, 29).

This appendix presents information according to noise source as follows:

- Appendix F.1: Highway and rail vehicle passbys for vehicles of the same type
- Appendix F.2: Stationary sources
- Appendix F.3: L_{max} for single train passbys (for trains of mixed consists)

F. 1 Highway and Rail Vehicle Passbys

This section provides information on appropriate conditions for vehicle passby measurements, instructions on converting measurements made under non-reference conditions to source reference levels, and examples of these computations.

The following conditions are required for vehicle passbys, in addition to good engineering practice:

- Measured vehicles must be representative of project vehicles in all aspects, including representative acceleration and speed conditions for buses.
- Track must be relatively free of corrugations and train wheels relatively free of flats, unless these conditions are typical of the proposed project.
- Road surfaces must be smooth and dry, unless these conditions are typical of the proposed project.
- Perpendicular distance between the measurement position and the source's centerline must be 100 ft or less.
- Vehicle speed must be 30 mph 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.

When close-by source measurements are made under non-reference conditions, use the instructions below and the equations in Table F-1 to convert the measured values to source reference levels. For rail vehicles, measure/convert a group of locomotives or a group of cars separately. This computation requires that all measured vehicles be of the same type. For trains of mixed consists, see Appendix F.3.

SEL measured for a highway-vehicle passby, or a passby of a group of identical rail vehicles

- 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}, using Eq. F-1.

L_{max} 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}, using either Eq. F-2 or Eq. F-3, as appropriate, for locomotives or rail cars.

L_{max} 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, SELref, using Eq. F-4.

Table F-1 Conversion to Source Reference Levels at 50 ft – Highway and Rail Sources

Measured	Source	Equation	
SEL	Vehicle passby	$SEL_{ref} = SEL_{meas} + 10\log(\frac{S_{meas}}{50}) + 10log(\frac{D_{meas}}{50}) + C_{consist} + C_{emissions}$	**Eq. F-1**
L_{max}	Rail-vehicle passby, locomotives only	$SEL_{ref} = L_{Amax} + 10\log(\frac{L_{meas}}{50}) + 10\log(\frac{D_{meas}}{50}) - 10\log(2 \propto) + C_{consist}$ $+C_{emissions} + 3.3$	**Eq. F-2**
	Rail-vehicle passby, cars only	$SEL_{ref} = L_{Amax} + 10\log(\frac{L_{meas}}{50}) + 10\log(\frac{D_{meas}}{50}) - 10\log\ [2 \propto + \sin(2 \propto)]$ $+C_{consist} + C_{emissions} + 3.3$	**Eq. F-3**
	Highway-vehicle passby	$SEL_{ref} = L_{Amax} + 20\log(\frac{D_{meas}}{50}) + C_{emissions} + 3.3$	**Eq. F-4**

S_{meas} = speed of measured vehicle(s), mph

D_{meas} = closest distance between measurement position and source, ft

$C_{consist}$ = 0 for buses and automobiles
$-10\log(N_{Cars})$ for locomotives and rail cars
where N is the number of locomotives or rail cars in the measured group

$C_{emissions}$ = 0 for T < 6 for locomotives
-2 (T-5) for T ≥ 6
where T is average throttle setting of measured diesel – electric locomotive(s)

$-30\log(\frac{S_{meas}}{50})$ for rail cars

$-25\log(\frac{S_{meas}}{50})$ for buses

$-38.1\log(\frac{S_{meas}}{50})$ for automobiles

E_{meas} = event duration of measurement, sec

L_{meas} = total length of measured group of locomotives *or* rail cars, ft

$\propto$ = arctan$(\frac{L_{meas}}{2D_{meas}})$, rad

Example F-1 Calculate SEL_{ref} – Locomotives

Computation of SEL_{ref} from SEL Measurement of Fixed-guideway Source

SEL was measured for a passby of two diesel-powered locomotives with the following conditions:

SEL_{meas} = 90 dBA
N_{Cars} = 2
T = 6
S_{meas} = 55 mph
D_{meas} = 65 ft

Compute the source reference level using Eq. F-1.

$$SEL_{ref} = SEL_{meas} + 10\log(\frac{S_{meas}}{50}) + 10log(\frac{D_{meas}}{50}) + C_{consist} + C_{emissions}$$

$$= 90 + 10\log\left(\frac{55}{50}\right) + 10\log\left(\frac{65}{50}\right) - 10\log(2) + (-2(6-5))$$

= 86.5 dBA

Example F-2 Calculate SEL_{ref} – Rail Cars

Computation of SEL_{ref} from L_{max} Measurement of Fixed-Guideway Source

L_{max} was measured for a passby of a 4-car consist of 70-ft long rail cars with the following conditions:

L_{max} = 90 dBA
N_{Cars} = 4
S_{meas} = 70 mph
D_{meas} = 65 ft
L_{meas} = 280 ft
$\propto$ = 1.14

Compute the source reference level using Eq. F-3.

$$SEL_{ref} = L_{Amax} + 10\log(\frac{L_{meas}}{50}) + 10\log(\frac{D_{meas}}{50}) - 10\log\,[2\propto + \sin(2\propto)] + C_{consist} + C_{emissions} + 3.3$$

$$= 90 + 10\log(\frac{280}{50}) + 10\log(\frac{65}{50}) - 10\log\,[2(1.14) + \sin(2(1.14))] - 10\log(4) - 30\log(\frac{70}{50}) + 3.3$$

= 86.7 dBA

Example F-3 Calculate SEL_{ref} – Bus

Computation of SEL_{ref} from L_{max} Measurement of Highway Vehicle Source

L_{max} was measured for a bus with the following conditions:

L_{max} = 78 dBA
D_{meas} = 80 ft
S_{meas} = 40 mph

Compute the source reference level using Eq. F-4

$$SEL_{ref} = L_{max} + 20\log(\frac{D_{meas}}{50}) + C_{emissions} + 3.3$$
$$= 78 + 20\log(\frac{80}{50}) - 25\log(\frac{40}{50}) + 3.3$$
= 87.8 dBA

F.2 Stationary Sources

This section provides information on appropriate conditions for stationary source measurements, instructions on converting measurements made under non-reference conditions to source reference levels, and an example of this type of computation.

The following conditions are required for stationary sources, 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, and the distance to the closest source component must be 200 ft or less.

$$\frac{Distance\ to\ the\ farthest\ source\ component}{Distance\ to\ the\ closest\ source\ component}$$

  If both conditions cannot simultaneously be met, separate close-by measurements of individual components of this source must be made, for which these distance conditions can be met.

- The following ratio must be 2 or less:

$$\frac{Lateral\ length\ of\ the\ source\ area}{Distance\ to\ the\ closest\ source\ component}$$

  The lateral length of the source area is measured perpendicular to the general line-of-sight between source and measurement positions.

  If this condition cannot be met, then make separate close-by measurements 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 close-by source measurements are made under non-reference conditions, use the instructions below and the equation in Table F- 2 to convert the measured values to source reference levels.

SEL was measured for a stationary noise source

- 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, SELref using Eq. F- 5.

Table F-2 Conversion to Source Reference Levels at 50 ft - Stationary Sources

Measured	Source	Equation
SEL	Stationary noise source	$SEL_{ref} = SEL_{meas} - 10\log(\frac{E_{meas}}{3600}) + 20\log(\frac{D_{meas}}{50})$ **Eq. F- 5**
S_{meas} = speed of measured vehicle(s), in miles per hour E_{meas} = event duration of measurement, in seconds D_{meas} = closest distance between measurement position and source, in feet		

Example F-4 Calculate SEL_{ref} – Signal Crossing

Computation of SEL_{ref} from SEL Measurement of Stationary Source

SEL was measured for a signal crossing with the following conditions:

SEL_{meas} = 70 dBA
E_{meas} = 10 sec
D_{meas} = 65 ft

Compute the source reference level using Eq. F-5.

$$SEL_{ref} = SEL_{meas} - 10\log(\frac{E_{meas}}{3600}) + 20\log(\frac{D_{meas}}{50})$$

$$= 70 - 10\log(\frac{10}{3600}) + 20\log(\frac{65}{50})$$

= 97.8 dBA

F.3 L_{max} for Single Train Passby

This section provides procedures for the computation of L_{max} for a single train passby. This procedure can be used to characterize trains of mixed consists using L_{max}. Follow the instructions below.

- Collect the following input information:
  - SEL_{ref}, from Section 4.5, specific to both the locomotive type and car type of the train
  - N_{loco}, the number of locomotives in the train
  - N_{cars}, the number of cars in the train
  - L_{loco}, the total length of the train's locomotive(s), in feet (or N_{loco} 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

- Use the equations in Table F-3 to compute the following:
  - $L_{max.loco}$ for the locomotive(s) using Eq. F-6

- $L_{max.cars}$ for the rail car(s) using the Eq. F-7
- $L_{max.total}$, the larger L_{max} from the locomotives(s) and rail car(s) is the L_{max} for the total train passby, see Eq. F- 8.

Table F-3 Conversion to Lmax at the Receiver, for a Single Train Passby

Source	Equation	
Locomotives	$L_{max.Loco} = SEL_{locos} + 10log\left(\frac{S}{50}\right) - 10log\left(\frac{L}{50}\right) + 10\log(2\propto) - 3.3$	**Eq. F-6**
Rail Cars	$L_{max.Rcars} = SEL_{Rcars} + 10log\left(\frac{S}{50}\right) - 10log\left(\frac{L}{50}\right) + 10\log(2\propto + \sin(2\propto)) - 3.3$	**Eq. F-7**
Total Train	$L_{max.total} = max(L_{max.Loco}\ or\ L_{max.RCars})$	**Eq. F-8**

L = total length of measured group of locomotive(s) or rail car(s), ft

S = vehicle speed, mph

$\propto$ = arctan $\left(\frac{L}{2D}\right)$, rad

D = closest distance between receiver and source, ft

Example F-5 Calculate L_{max} – Train Passby

Computation of L_{max} for Train Passby

Calculate the L_{max} of commuter train at receiver of interest according to the following conditions:

SEL_{ref} = 92 dBA for locomotives
= 82 dBA for rail cars
N_{Loco} = 1
N_{Cars} = 6
S = 43 miles per hour
D = 125 ft
$\propto_{locos}$ = 0.27
$\propto_{cars}$ = 1.03

The locomotive and rail cars each have a unit length (L) of 70 ft.

Determine the total length of the locomotive and rail cars.

L_{Loco} = 70 ft
L_{cars} = 420 ft

Compute L_{max} for the locomotive using Eq. F-6:

$$L_{max.Loco} = SEL_{loco} + 10log\left(\frac{S}{50}\right) - 10log\left(\frac{L}{50}\right) + 10\log(2 \propto) - 3.3$$

$$= 92 + 10log\left(\frac{43}{50}\right) - 10log\left(\frac{70}{50}\right) + 10\log(2 \times 0.27) - 3.3$$

= 84.0 dBA

Compute L_{max} for the rail cars using Eq. F-7:

$$L_{max.Rcars} = SEL_{Rcars} + 10log\left(\frac{S}{50}\right) - 10log\left(\frac{L}{50}\right) + 10\log(2 \propto + \sin(2 \propto)) - 3.3$$

$$= 82 + 10log\left(\frac{43}{50}\right) - 10log\left(\frac{420}{50}\right) + 10\log((2 \times 1.03) + \sin(2 \times 1.03)) - 3.3$$

= 73.5 dBA

Find the total L_{max} for the train passby using Eq. F-8.

$$L_{max.total} = max(L_{max.Loco}\ or\ L_{max.Rcars})$$

=84.0 dBA

Appendix G: Non-Standard Modeling Procedures and Methodology

This manual provides guidance for preparing and reviewing the noise and vibration sections of environmental documents, as well as FTA-approved methods and procedures to determine the level of noise and vibration impact resulting from most federally-funded transit projects. Situations may arise, however, that are not explicitly covered in this manual. Professional judgment may be used to extend the basic methods to cover these cases, when appropriate. It is important to note that each project is unique and must be evaluated on a case-by-case basis. This appendix provides procedures for the use of non-standard noise and vibration modeling procedures and methodologies on public transportation projects.

Submittal Procedure – The procedure for using non-standard modeling procedures and methodology is as follows:

1. The transit project manager should contact the FTA Regional office to discuss the proposed methods and/or data not described in this manual prior to use of the non-standard approach.
2. The non-standard methodology should be documented according to the guidelines below as part of the technical report described in Section 8.2.

Examples of Methods that Require Communication and Documentation – The following noise and vibration analysis methods and data require communication with the FTA Regional office and documentation:

- Non-standard transit noise and vibration modeling and analysis methods not described in this manual (including non-standard adjustments, computations, and assumptions). This includes modifications to standard FTA noise and vibration methods.
- Non-standard transit noise and vibration reference data not described in this manual (including measured data, substitution data, data at non-standard reference distances and/or speeds, new transit noise sources, and transit noise sources operating in non-standard conditions).
- Non-standard transit noise and vibration impact criteria not described in this manual, including the maximum sound pressure level metric.
- Non-standard methods of evaluating construction noise, including non-standard construction noise impact criteria.
- Other noise modeling tools besides the FTA Noise Impact Assessment Spreadsheet or Traffic Noise Model (TNM®) for highway noise modeling, such as the development of a finite element method model.
- Any transit noise and vibration analysis that involves an impact area or noise source that is controversial.

Documentation Guidelines – The use of non-standard noise and vibration analysis methods or data requires the following documentation components in a technical memorandum attached to the environmental document:

- **Background**
  Briefly describe the transit project for which non-default methods or data are needed. State the dominant noise sources, type of analysis, and the impact criteria. Include any additional relevant information.

- **Statement of Benefit**
  Briefly describe the benefit of the non-default noise and vibration methods or data to the transit project. Describe the appropriateness of the non-default methods or data, as well as why the standard method or data are insufficient or problematic.

- **Non-standard Data Description**
  Describe the non-standard noise or vibration data in detail. Include source type, manufacturer, reference conditions (speed, distance, and operational conditions), name of data supplier, and a date associated with data development/measurement. For measured noise or vibration data, provide corresponding data documentation (such as a data measurement or a development report). For substitution data, a comparison between the non-standard data and corresponding standard data should be provided. Furthermore, if outside sources recommend the use of the non-standard data (such as a technical society, a standards organization, or a vehicle manufacturer), references for those recommendations should be included.

- **Non-standard Methods Description**
  Describe the non-standard noise or vibration analysis method in detail. This should include a detailed description and derivation of the method (including data used in the development of the method), a description of the usage of the method, and a comparison between the non-standard method and the corresponding standard method in the context of the transit analysis. If the method has been validated against measurement data, a description of that validation analysis should be provided. If the method is derived from another source (such as a different transportation noise or vibration method), provide corresponding documentation for that source. A description of how the method is conservative (for example, estimating the worst-case scenario) or some discussion on the probability of exceeding the predicted level should be provided. Furthermore, if outside sources recommend the use of the non-standard method (such as a technical society or standards organization), references for those recommendations should be included.

- **Non-standard Tools Description**
  Describe in detail any non-standard noise or vibration models that have not been explicitly recommended in this manual. This should include a detailed description of the tool (including data used, the computations implemented in the tool, any modifications or adjustments to the tool or the corresponding data, and the usage of the tool), a description of the validation of the tool (including reference documentation and validation analyses), and a comparison between the non-standard tool and the equivalent standard tool in the context of the transit analysis. Quantitative comparisons, such as the standard deviation of the non-standard tool and an estimate of the least mean square of differences between the standard and non-standard tools, should be provided and explained. A description of how the method is conservative (for example, estimating the worst-case scenario) or some discussion on the probability of exceeding the predicted level should be provided. If outside sources recommend the use of the non-standard tool (such as a technical society or standards organization), references for those recommendations should be included.

ENDNOTES

1 Regulations for Implementing the Procedural Provisions of the National Environmental Policy Act, Council on Environmental Quality, 40 CFR parts 1500-1508, 1978.

2 National Environmental Policy Act of 1969, United States Congress, 42 U.S.C §4331, 1969.

3 U.S. Department of Transportation, Federal Transit Administration and Federal Highway Administration, "Environmental Impact and Related Procedures," Final Rule, 52 *Federal Register* 32646-32669, January 2014 (23 CFR part 771).

4 U.S. Department of Transportation, Federal Transit Administration and Federal Highway Administration, "Planning Assistance and Standards." Final Rule, 58 *Federal Register* 58064, June 2014 (23 CFR part 450).

5 U.S. Environmental Protection Agency, "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," Report No. 550/9-74-004, Washington DC, March 1974.

6 Federal Interagency Committee on Urban Noise, "Guidelines for Considering Noise in Land Use Planning and Control," Environmental Protection Agency, the Department of Transportation, the Department of Housing and Urban Development, the Department of Defense, and the Veterans Administration, Washington DC, June 1980.

7 U.S. Department of Housing and Urban Development, "Environmental Criteria and Standards of the Department of Housing and Urban Development," Final Rule, 44 *Federal Register* 40861, Washington DC, 12 July 1979 (24 CFR part 51).

8 American National Standards Institute, "Compatible Land Use With Respect to Noise," Standard S3.23-1980, New York NY, May 1980.

9 American National Standards Institute, "Quantities and Procedures for Description and Measurement of Environmental Sound," ANSI S12.9-1998/Part 5, New York. NY, January 1998.

10 T. J. Schultz, "Noise Rating Criteria for Elevated Rapid Transit Structures," U.S. Department of Transportation, Report No. UMTA-MA-06-0099-79-3, Washington DC, May 1979.

11 T. J. Schultz, "Synthesis of Social Surveys on Noise Annoyance," *Journal of the Acoustical Society of America*, Vol. 63, No. 8, August 1978.

12 S. Fidell, D.S. Barber, 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.

13 S. Fidel, "The Schultz Curve 25-years Later: A Research Perspective," *Journal of the Acoustical Society of America*, Vol. 114, No. 6, Pt. 1, December 2003.

14 "High-Speed Ground Transportation Noise and Vibration Impact Assessment", DOT/FRA/ORD-12/15, U.S. Department of Transportation Federal Railroad Administration, 2012.

15 National Historic Preservation Act, Section 106; P.L. 89-665, 15 October 1966.

16 The Department of Transportation Act of 1966, Section 4(f); P.L. 89-670, 15 October 1966.

17 U.S. Department of Transportation, Federal Transit Administration and Federal Highway Administration, "Protection of Historic Properties." Final Rule, 65 *Federal Register* 77725, July 2013 (36 CFR 800).

[18] "Eligibility and Justification Requirements for Noise Insulation Projects," Program Guidance Letter 12-09, November 2012. https://www.faa.gov/airports/aip/guidance_letters/historical_guidance_letters/media/aip-pgl-2012-09-noise-insulation.pdf.

[19] U.S. Department of Housing and Urban Development, "Environmental Criteria and Standards", Vol. 12, July 1979; amended by 49 *Federal Register* 880, 6 January 1984 (24CFR part 51).

[20] U.S. Department of Transportation, Federal Aviation Administration, "Federal Aviation Regulations Part 150: Airport Noise Compatibility Planning," January 1981.

[21] U.S. Department of Transportation, Federal Railroad Administration, "Use of Locomotive Horns at Public Highway-Rail Grade Crossings." Final Rule, 70 *Federal Register* 21844, October 2013 (49 CFR 222).

[22] U.S. Department of Transportation, Federal Highway Administration, "FHWA Traffic Noise Model User's Guide," Report No. FHWA-PD-96-009, Washington, DC, January 1998. Also, "FHWA Traffic Noise Model User's Guide (Version 2.5 Addendum)," April 2004.

[23] J.C. Ross, C.E. Hanson, R.V. Hartz, "Houston Southeast Corridor Environmental Impact Statement BRT Noise and Vibration Assessment," technical memorandum prepared by Harris Miller Miller & Hanson for Metropolitan Transit Authority of Harris County Houston, Texas, September 20, 2005.

[24] U.S. Environmental Protection Agency, "Population Distribution of the United States as a Function of Outdoor Noise Level," Report No. 550/9-74-009, June 1974.

[25] T. M. Johnson, "The Importance of Vehicle Throttle Setting Information for Rail Transit Noise Impact Assessments," *Proc. Inter-Noise 2012*, New York, NY, August 2012.

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

[27] American National Standards Institute, "American National Standard Quantities and Procedures for Description and Measurement of Environmental Sound, Part 4: Noise Assessment and Prediction of Long-term Community Response," ANSI 12.9-1996, New York, 1996.

[28] C. Harris, "Handbook of Acoustical Measurements and Noise Control."

[29] International Organization for Standardization "Acoustics -- Attenuation of sound during propagation outdoors -- Part 2: General method of calculation." ISO 9613-2.

[30] American Society for Testing and Materials, "Standard Guide for Measurement of Outdoor A-weighted Sound Levels," E 1014-84, Philadelphia, 1984.

[31] American National Standards Institute, "Method for the Measurement of Sound Pressure Levels," ANSI S1. 13-1971(R1976), New York, 1971.

[32] U.S. Department of Transportation, Federal Highway Administration, "Measurement of Highway-Related Noise," FHWA-PD-96-046, May 1996.

[33] J.T. Nelson, "Wheel/Rail Noise Control Manual," Transportation Cooperative Research Report No. 23, Transportation Research Board, Washington, DC, 1997.

[34] "Challenges in Maintaining Quiet Streetcar and Light Rail Systems," Session No. 409, Transportation Research Board Annual Meeting, Washington DC, January 2014.

[35] U.S. Department of Transportation, Federal Railroad Administration, "Use of Locomotive Horns at Highway-Rail Grade Crossing," Final Rule, 70 *Federal Register* 21844, April 27, 2005 (49 CFR 222).

[36] "Interim Final Rule for the Use of Locomotive Horns at Highway-Rail Grade Crossings," Federal Railroad Administration, Final Environmental Impact Statement, December 2003.

[37] T.A. Busch, R.E. Nugent, "A Reduced-Scale Railway Noise Barrier's Insertion Loss and Absorption Coefficients: Comparison of Field Measurements and Predictions," *Journal of Sound and Vibration*, 749-759, October 2003.

[38] U.S. Department of Transportation, Federal Highway Administration, "Highway Noise Barrier Design Package," August 2000.

[39] "High-Speed Ground Transportation Noise and Vibration Impact Assessment," DOT/FRA/ORD-12/15, U.S. Department of Transportation Federal Railroad Administration, 2012.

[40] American National Standards Institute, "Guide to Evaluation of Human Exposure to Vibration in Buildings," ANSI S3.29-1983 (ASA 48-1983).

[41] International Organization for Standardization, "Evaluation of Human Exposure to Whole-Body Vibration, Part 2: Continuous and Shock-Induced Vibrations in Buildings (1-80Hz)," ISO-2631-2, 1989.

[42] International Organization for Standardization, "Mechanical Vibration and Shock: Evaluation of Human Exposure to Whole Body Vibration: Part 2 – Vibration in Buildings (1 to 80 Hz)," ISO-2631-2, 2003.

[43] J. T. Nelson, H. J. Saurenman, "State-of-the-Art Review: Prediction and Control of Ground-borne Noise and Vibration from Rail Transit Trains," U.S. Department of Transportation, Urban Mass Transportation Administration, Report No. UMTA-MA-06-0049-83-4, DOT-TSC-UMTA-83-3, December 1983.

[44] Y. Tokita, "Vibration Pollution Problems in Japan," Inter-Noise 75, Sendai, Japan, 1975. (pp. 465-472)

[45] J. A. Zapfe, H. Saurenman, S. Fidell, "Ground-Borne Noise and Vibration in Buildings Caused by Rail Transit," Transportation Research Board, Final Report for TCRP Project D-12, December 2009.

[46] J.T. Nelson, H.J. Saurenman, G.P. Wilson, "Handbook of Urban Rail Noise and Vibration Control," prepared under contract to U.S./DOT Transportation Systems Center, Report No. UMTA-MA-06-0099-82-2, February 1982.

[47] International Organization for Standardization, "Mechanical Vibration – Ground-borne Noise and Vibration Arising from Rail Systems," ISO/FDIS 14837-1:2005.

[48] Institute of Environmental Sciences and Technology, "Considerations in Clean Room Design," RR-CC012. 3, 2015.

[49] U.S. Department of Transportation, Volpe National Transportation Systems Center, "Vibration Characteristics of the Transrapid TR08 Maglev System," Report No. DOT-VNTSC-FRA-02-06, March 2002.

[50] S. McKenna, "A Study of Build Amplification from Ground-Borne Vibration," Noise-Con 2011, Portland, Oregon, July 25-27, 2011.

[51] American National Standards Institute, "Acoustical Terminology," ANSI S1.1-1994.

[52] J.T. Nelson, H.J. Saurenman, "A Prediction Procedure for Rail Transportation Ground-Borne Noise and Vibration," *Transportation Research Record,* 1143, August 1988.

53 J. T. Nelson, "Tri-Met Track Vibration Isolation Tests," Final Report for Portland Tri-Met, October 1998.

54 J.T. Nelson, H.J. Saurenman, "Ground-Borne Vibration Tests with MARTA C-Car," report prepared for Metropolitan Atlanta Rapid Transit Authority, November 16, 1981.

55 H.J. Saurenman, "Preliminary Results of Ground-Borne Vibration Tests with BRRT/Miami Vehicle," technical memorandum prepared for US DOT/Transportation Systems Center, contract DOT-TSC-1796, 8 February1983.

56 H.J. Saurenman, "Ground-borne Vibration Tests with NFTA Prototype Vehicle at the Transportation Test Center," technical memorandum prepared for Transportation Test Center, Project No. P-83-C-01078, 3 August 1983.

57 H.J. Saurenman, "Noise and Vibration Tests with Portland Tri-Met Prototype Vehicle at the Transportation Test Center," technical memorandum prepared for Transportation Test Center, Project No. P-83-C-02649, 26 March 1984.

58 R.A. Carman, D.L. Watry, "Measured Vibration Reduction Performance of Ballast Mat Installation for Light Rail Vehicles on Embedded Track," APTA, 1997 Rapid Transit Conference of the APTA, V. 3-Way & Structures and Construction (1997-8).

59 D.A. Towers, "Evaluation of the Ground-Borne Vibration Reduction Properties of Tire Derived Aggregate Installed on the Denver RTD Light Rail System," Harris Miller Miller and Hanson Inc., 2012.

60 F. E. Richert, J. R. Hall, *Vibrations of Soils and Foundations*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1970.

61 U.S. Environmental Protection Agency, "Noise from Construction Equipment and Operations, Building Equipment and Home Appliances," NTID300.1, 31 December 1971.

62 Society of Automotive Engineers, "Exterior Sound Level Measurement Procedure for Powered Mobile Construction Equipment," SAE Recommended Practice J88a, 1976.

63 Society of Automotive Engineers, "Sound Levels for Engine Powered Equipment," SAE Standard J952b, 1976.

64 U.S. Department of Transportation, Federal Highway Administration, "FHWA Roadway Construction Noise Model User's Guide," FHWA-HEP-05-054, January 2006. Available at http://www.fhwa.dot.gov/environment/noise/construction_noise/rcnm/.

65 E. Thalheimer, "Construction noise control program and mitigation strategy at the Central Artery/Tunnel Project," Noise Control Eng. J. 48(5), September–October 2000, 157-165).

66 U.S. Department of Transportation, Federal Highway Administration. "Highway Construction Noise Handbook," FHWA-HEP-06-015, August 2006.

67 D.J. Martin, "Ground Vibrations from Impact Pile Driving during Road Construction," Supplementary Report 544, United Kingdom Department of the Environment, Department of Transport, Transport and Road Research Laboratory, 1980.

68 J.F. Wiss, "Vibrations during Construction Operations," *Journal of Construction Division, Proc. American Society of Civil Engineers*, 100, No. CO3, 239-246, September 1974.

69 J.F. Wiss, "Damage Effects of Pile Driving Vibrations," *Highway Research Record*, No. 155, Highway Research Board, 1967.

[70] D.A. Towers, "Ground-borne Vibration from Slurry Wall Trench Excavation for the Central Artery/Tunnel Project Using Hydromill Technology," *Proc. InterNoise 95*, Newport Beach, CA, July 1995.

[71] Swiss Consultants for Road Construction Association, "Effects of Vibration on Construction," VSS-SN640-312a, Zurich, Switzerland, April 1992.

[72] American Public Transportation Association, *Public Transportation Factbook*, 55th Edition, March 2004.

[73] American National Standards Institute, "Preferred Frequencies, Frequency Levels and Band Numbers for Acoustical Measurements," ANSI S1.6-1984 (R2006).

[74] 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 No. 550/9-74-004, March 1974.

[75] 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.

[76] American Public Transit Association, "Noise and Vibration," 1981 Guidelines for Design of Rapid Transit Facilities, Section 2.7, 1981.

[77] T.J. Schultz, "Synthesis of Social Surveys on Noise Annoyance*," Journal of the Acoustical Society of America*, Vol. 64, No. 2, August 1978, 377-405.

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