High-Speed Ground Transportation Noise and Vibration Impact Assessment

U. S. Department
of Transportation
Federal Railroad Administration

December 1998

Office of Railroad Development
Washington, D.C. 20590

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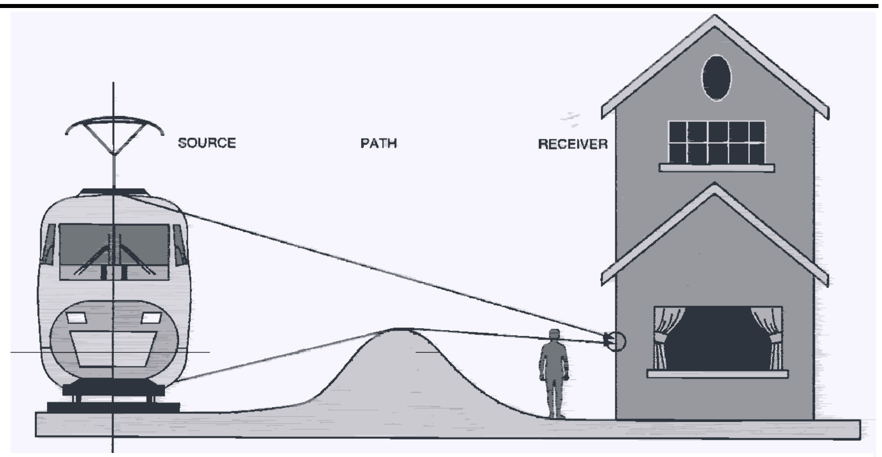

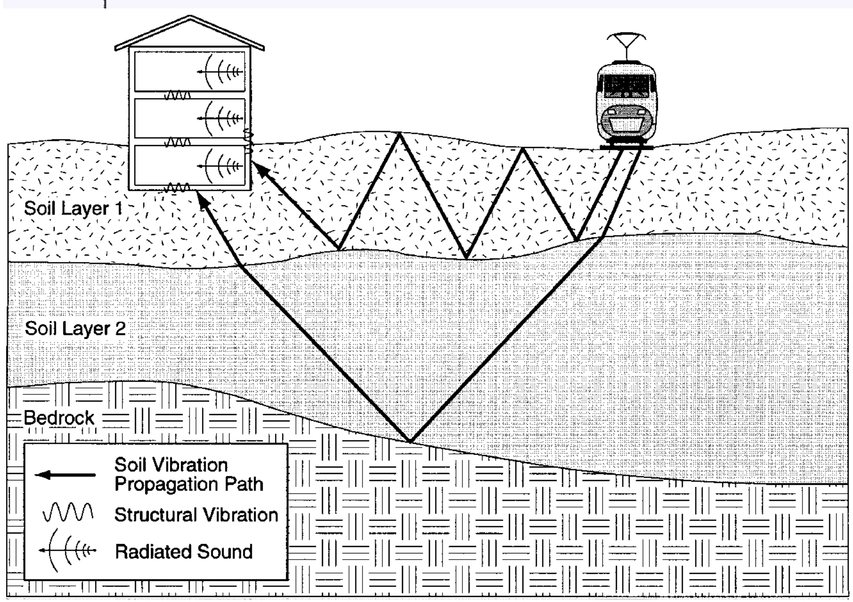

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Chapter 1

INTRODUCTION

1.1 PURPOSE

This manual provides procedures for the assessment of potential noise and vibration impacts resulting from proposed high-speed ground transportation (HSGT) projects, including high-speed rail using traditional steel-wheel on steel-rail technology and magnetically levitated (maglev) systems[1]. This document reflects the result of research conducted for the Federal Railroad Administration (FRA) and is presented as part of FRA's efforts to promote the consideration of HSGT as a transportation option in those intercity corridors where it has the potential to be a cost effective and environmentally sound component of the intermodal transportation system. The National Environmental Policy Act and related statutes, regulations and orders (NEPA) mandate consideration of potential impacts on the human and natural environment as part of the decision making process when Federal agencies evaluate proposals to fund or otherwise approve major actions. Most states have similar environmental review requirements.

Experience during previous environmental impact reviews of high-speed rail projects has shown that possible increases in noise and vibration are frequently among the potential impacts of most concern to residents in the vicinity of the proposed project. As the interest in HSGT grows and environmental review of HSGT projects are initiated in several locations across the country, it becomes clear to FRA that there is a need to provide a standardized set of procedures for the evaluation of noise and vibration impacts. There is also a need to provide guidance to promoters and designers of HSGT projects on ways in which the design of those projects can incorporate measures that address these concerns. And there is a need for

[1]For brevity, this manual uses the terms "high speed ground transportation" and "high speed rail" interchangeably, both referring to high speed guided intercity transportation.

providing a means through which public agency reviewers of projects can determine where and to what extent the public benefits of HSGT justify investment in impact mitigation. This manual attempts to fulfill these needs.

1.2 ORGANIZATION OF THE MANUAL

This manual is divided into two parts, noise and vibration. Each part has a parallel organization, which addresses the following topics:

Topic	Noise	Vibration
Basic Concepts	Chapter 2	Chapter 6
Criteria	Chapter 3	Chapter 7
Initial Evaluation	Chapter 4	Chapter 8
Detailed Analysis	Chapter 5	Chapter 9
Construction Noise/Vibration	Chapter 10.1	Chapter 10.2
Documentation	Chapter 11	Chapter 11

Appendices

A. Background for Noise Concepts
B. Existing Noise Determination
C. Noise Source Reference Level Determination
D. Glossary of Terms

Chapter 2

BASICS OF HIGH-SPEED RAIL NOISE

Noise from high-speed rail systems is similar to noise from other rail systems except for a few unique features resulting from the higher speeds of travel. The rail systems defined as "high-speed" are primarily steel wheeled, both electrically powered and fossil fueled, capable of maximum speeds of 125 mph and greater. Noise characteristics of these trains vary considerably as speed increases. Consequently, this manual sub-divides these systems into three categories:

- “high-speed,” with a maximum speed between 125 and 150 mph,
- “very high-speed,” with a maximum speed between 200 and 250 mph, and
- “maglev,” magnetically levitated and powered systems representing the upper range of speed performance up to 300 mph, although no such systems currently operate in revenue service.[1]

Because ancillary sources are not unique to high speed ground transportation systems, noise from electrical substations, maintenance facilities, yards, and stations, are not addressed in this manual. These noise sources are substantially the same for any type of rail system and do not have characteristics specific to high-speed rail systems. Noise and vibration from lower speed trains are also not addressed. The methods described in the corresponding transit noise manual from Federal Transit Administration are applicable.[2]

This chapter discusses the basic concepts of high-speed rail noise to provide background for the

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[1]Noise from maglev in this manual is based principally on research and test track data from the German TransRapid System, currently under development.

[2]U.S. Department of Transportation, Federal Transit Administration, “Transit Noise and Vibration Impact Assessment," Final Report, DOT-T-95-16, April 1995.

assessment procedures presented in Chapters 4 and 5. Noise from a ground transportation system is often expressed in terms of a Source-Path-Receiver framework. This framework is sketched in Figure 2-1 and is central to all environmental noise studies. Each project **source** generates close-by noise levels, which depend upon the type of source and its operating characteristics. Then, along the propagation **path** between all sources and receivers, noise levels are reduced (attenuated) by distance, intervening obstacles, and other factors. Finally, at each **receiver**, noise combines from all sources and may interfere with receiver activities.

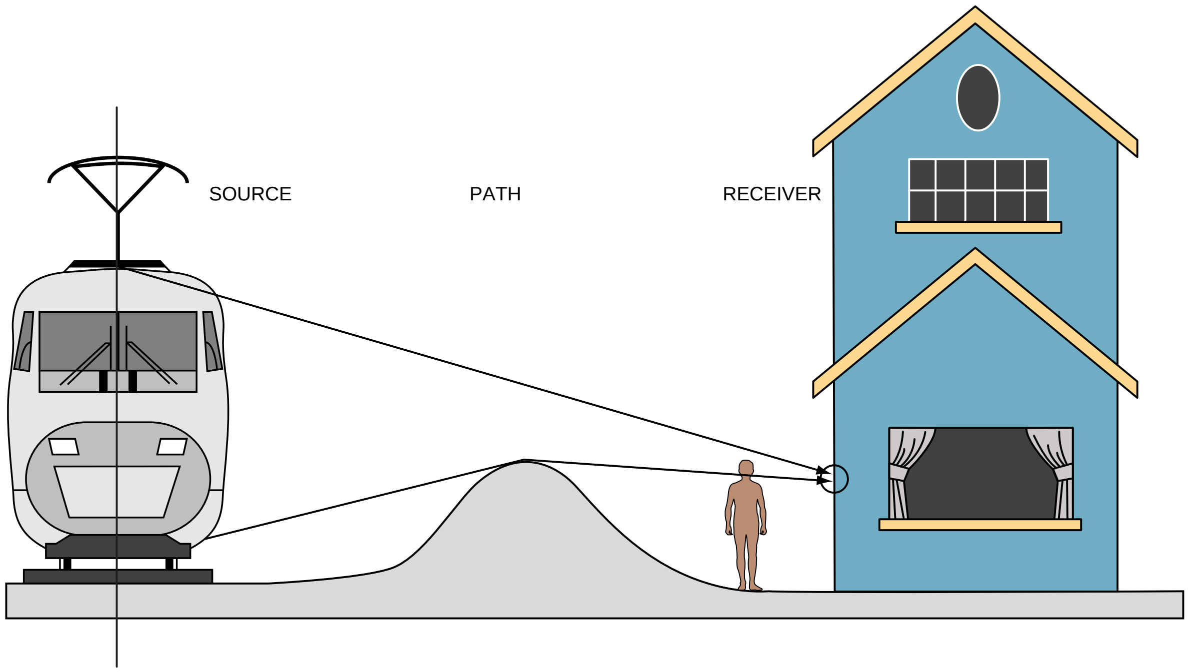

Figure 2-1 The Source-Path-Receiver Framework

This chapter emphasizes the **sources** of noise from high-speed trains and, to a lesser extent, the **path** component, which includes aspects such as sound attenuation with increasing distance from the source, excess attenuation due to atmospheric absorption and ground effects, and acoustic shielding by terrain, sound barriers, or intervening buildings.

In brief, this chapter contains:

- a summary of the **noise descriptors** used in this manual for high-speed rail noise (Section 2.1);
- an overview of noise **sources**, including a list of major sources specific to high-speed rail systems and discussion of noise-generation mechanisms (Section 2.2);
- an overview of noise **paths**, with a discussion of the various attenuating mechanisms on the path between source and receiver (Section 2.3);

- a summary of the theoretical **models** used to predict high-speed rail noise, in addition to actual measurement data from existing high-speed rail systems (Section 2.4).

2.1 NOISE DESCRIPTORS

The universal descriptor used for environmental noise is the A-weighted sound level. It describes the level of noise measured at a receiver at any moment in time and is read directly from noise-monitoring equipment, with the weighting switch set on "A." Typical A-weighted sound levels for high-speed rail and other sources are shown in Figure 2-2. The high-speed rail sources are described further in Section 2.4.

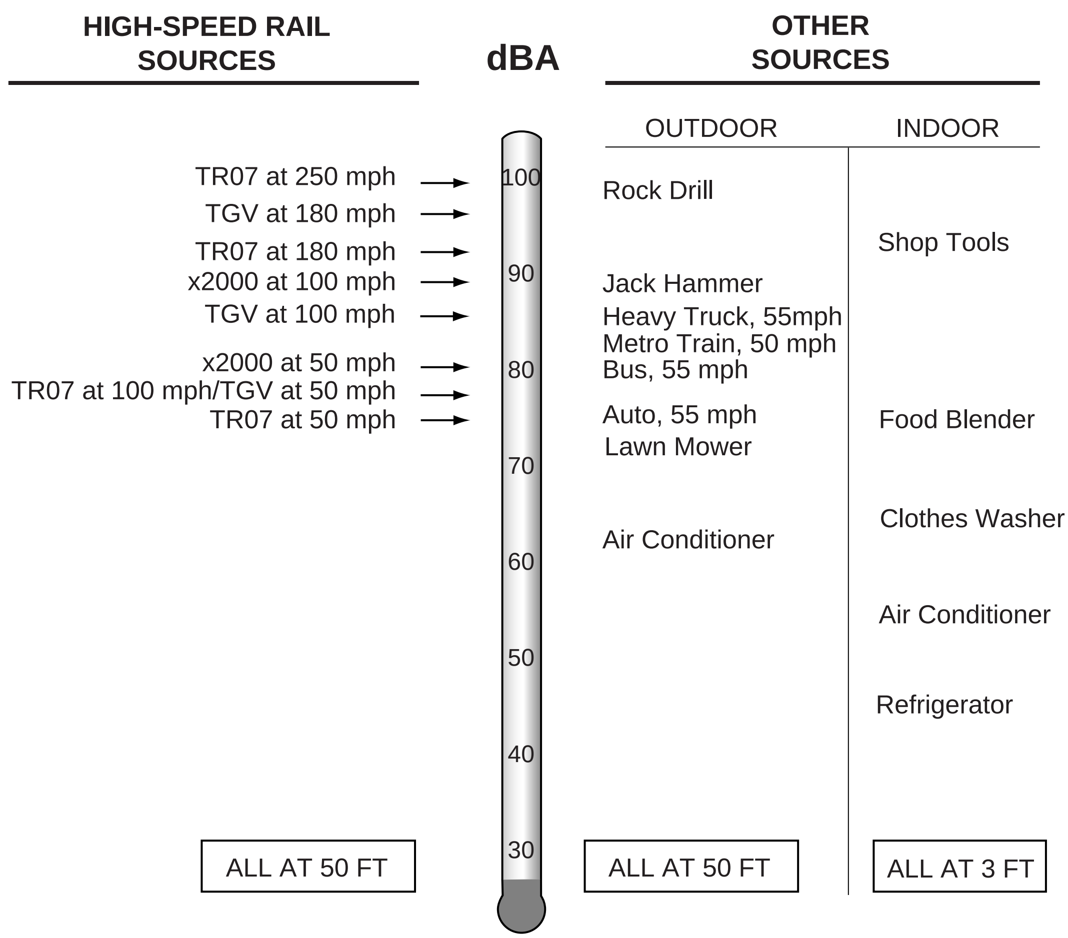

Figure 2-2 Typical A-Weighted Sound Levels

As shown in Figure 2-2, typical A-weighted sound levels range from the 40s to the 90s, where 40 is very quiet and 90 is very loud. The scale in the figure is labeled "dBA" to denote the way A-weighted sound levels are typically written. The letters "dB" stand for "decibels" and refer to the general strength of the noise. The letter "A" indicates that the sound has been filtered to reduce the strength of very low and very high-frequency sounds, much as the human ear does. Without this A-weighting, noise monitoring equipment would respond to events people cannot hear, such as high-frequency dog whistles and low-frequency seismic disturbances. On the average, each A-weighted sound level increase of 10 decibels corresponds to an approximate doubling of subjective loudness. Definitions of acoustical terms are given in Appendix D. Additional information on noise and its measurement can be obtained from textbooks and handbooks on acoustics.

2.1.1 Standard U.S. Noise Descriptors

This manual uses the following single-number descriptors, all based on the A-weighted sound level as the fundamental unit, for environmental noise measurements, computations, and assessment:

The **Maximum Level (L_{max})** during a single noise event. There are two standard ways of obtaining the L_{max}, one using the "fast" response setting on the sound level meter, or $L_{max,f}$ (obtained by using a 0.125 second averaging time), and the other using the "slow" setting, or $L_{max,slow}$ (obtained by using a 1 second averaging time). $L_{max,fast}$ can occur arbitrarily and is usually caused by a single component on a moving train, often a defective component such as a flat spot on a wheel. As a result, inspectors from the Federal Railroad Administration use $L_{max,fast}$ to identify excessively noisy locomotives and rail cars during enforcement of Railroad Noise Emission Compliance Regulations.[3] $L_{max,slow}$, with its greater averaging time, tends to de-emphasize the effects of non-representative impacts and impulses and is generally better correlated with the Sound Exposure Level (SEL), defined below, which is the basis of impact assessment. Thus, $L_{max,slow}$ is typically used for modeling train noise mathematically. In general, however, the L_{max} descriptor in either form is not recommended for noise impact assessment. Because it is used in vehicle-noise specifications and commonly measured for individual vehicles, equations are included in Appendix C to convert between $L_{max,slow}$ and the cumulative descriptors described below.

The **Sound Exposure Level (SEL)** describes a receiver's cumulative noise exposure from a single noise event. It is represented by the total A-weighted sound energy during the event, normalized to a one-second interval. It is the primary descriptor of high-speed rail vehicle noise emissions and an intermediate value in the calculation of both L_{eq} and L_{dn} (defined below).

The **Hourly Equivalent Sound Level [L_{eq}(h)]** describes a receiver's cumulative noise exposure from all events over a one-hour period. The underlying metric for calculating L_{eq}(h) is SEL. L_{eq}(h) is used in this manual to assess noise for non-residential land uses. For assessment, L_{eq} is computed for the loudest operating hour during the hours of noise-sensitive activity.

The **Day-Night Sound Level (L_{dn} or DNL)** describes a receiver's cumulative noise exposure from all events over a 24-hour period. The basic unit used in calculating L_{dn} is the L_{eq}(h) for each one-

[3]U.S. Department of Transportation, Federal Railroad Administration, "Railroad Noise Emission Compliance Regulations," Final Rule, 48 Federal Register 56756 - 56761; December 23, 1983 (23 Code of Federal Regulations 210).

hour period. It may be thought of as a noise exposure, totaled after increasing all nighttime A-Levels (between 10 p.m. and 7 a.m.) by 10 decibels. Every noise event during the 24-hour period increases this exposure, louder events more than quieter events, and events that are of longer duration more than briefer events. In this manual, L_{dn} is used to assess noise for residential land uses. Typical community L_{dn}s range from about 50 to 70 dBA, where 50 represents a quiet noise environment and 70 is a noisy one.

Detailed definitions and mathematical representations of all of these noise descriptors are presented in Appendix A.

2.1.2 Other Noise Descriptors

Noise from high-speed rail systems is often measured, reported or referred to in terms of other descriptors used primarily in Europe and Japan. These descriptors are slightly different in their mathematical definitions from the U.S. descriptors listed above. To avoid confusion with the descriptors used in this manual, Table 2-1 provides a partial list of these descriptors and a brief definition of each. Mathematical definitions to assist the user to translate data to the descriptors in this manual are provided in Appendix A.

Table 2-1 Summary of International Rail Noise Descriptors

Metric	Abbreviation(s)	Country	Definition
A-weighted Passby Level	$L_{aeq,P}$ or $L_{p,p}$	Germany, France	Equivalent A-weighted sound-pressure level, energy-averaged over the time of passby (train length).
	L_{max}(mean)	Scandinavia	
One-Hour L_{eq}	$L_{aeq,1h}$ or $L_{p,1h}$	Germany, France	Sound-pressure level, energy-averaged over one hour.
Average A-weighted Maximum Level	L_{Amax}	Japan	Power-averaged "slow" maximum level ($L_{max,s}$) of 20 consecutive train passbys.
Sound Exposure Level	L_{AE}	Japan	Power-averaged value of sound exposure within 10 dB of L_{Amax}, sampled at a time interval of 5/3 sec.

2.1.3 The L_{max}-SEL Relationship

To help the reader gain a preliminary understanding of high-speed rail noise descriptors and the interrelationships among descriptors, the following discussion illustrates how SEL, the fundamental descriptor used in calculating noise exposure, relates to L_{max}. Both descriptors characterize a single noise event; however, they do not always correlate with each other.

The L_{max} for a typical high-speed train passby is identified in Figure 2-3, where time is plotted horizontally and A-weighted sound level is plotted vertically. The event shown represents a measured time signature of a TGV passby at 180 mph at 83 feet (25 meters).

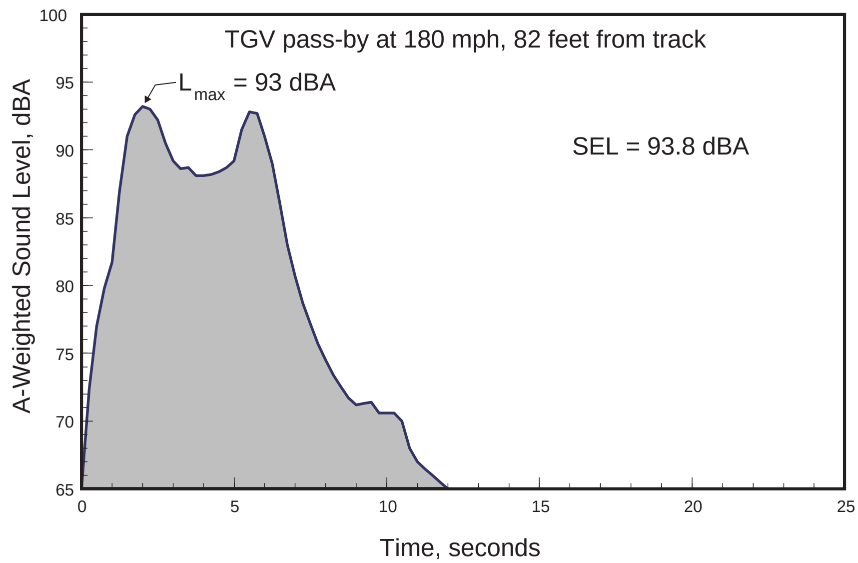

Figure 2-3 Typical High-Speed Train Passby

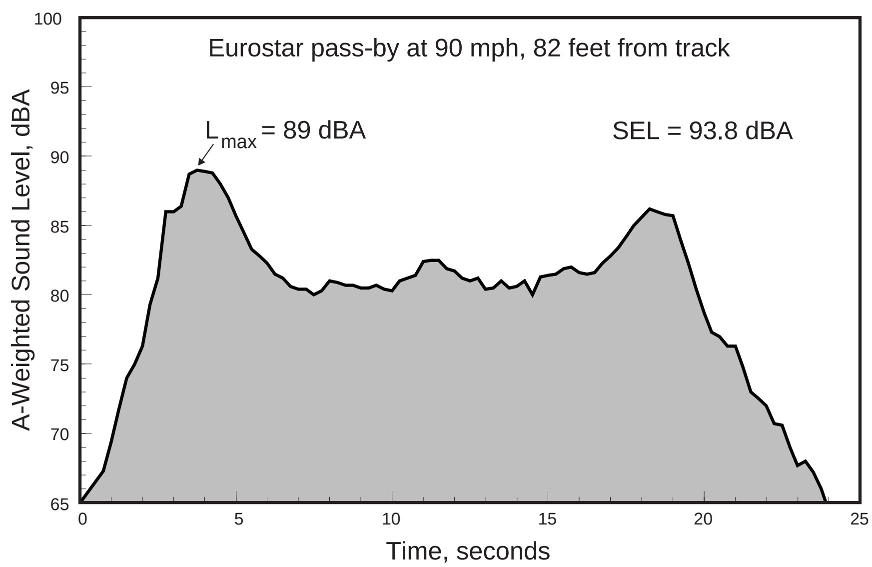

Figure 2-4 Typical Longer-Duration High-Speed Train Event

The noise exposure that occurred during a high-speed train passby, is shaded in Figure 2-3. This exposure represents the total amount of sound energy that enters the receiver's ears (or the measurement microphone) during the passby. A noise event of longer duration, a Eurostar train passby at 90 mph, is shown in Figure 2-4. For this event, the noise exposure is large due to *duration*. Since the Eurostar train is nearly two times as long as the standard TGV trains, both the added length and slower speed contribute to the increased duration of the Eurostar event. Compared with the event in Figure 2-3, the L_{max} is 4 dBA lower, but the measured SELs are the same.

The time histories in Figures 2-3 and 2-4, but with a stretched vertical scale are repeated in Figure 2-5. The stretched scale corresponds to a linear scale of sound pressure, or energy, at any moment in time. Mathematically, sound energy is proportional to 10 raised to the (L/10) power, that is, $10^{(L/10)}$. The stretched vertical scale represents noise exposure as energy exposures. Only when plotted at this stretched scale do the shaded zones properly correspond to the noise exposures that underlie the SEL. The shaded zones in the two frames have equal areas, corresponding to equal noise exposures for these two very different noise events.

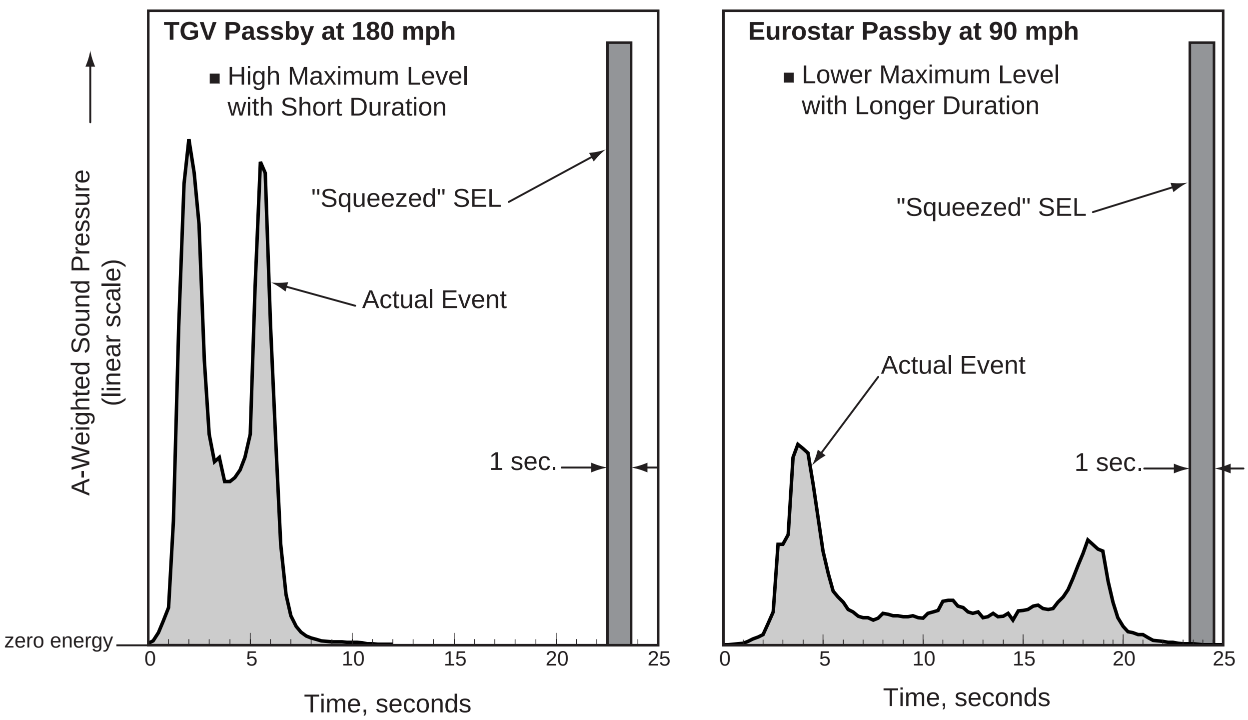

Figure 2-5 An "Energy" View of Noise Events

Each frame of the figure also contains a tall, thin shaded zone of one-second duration. This tall zone is the way to envision SELs. In the tall zone, the original shaded zone has been squeezed shorter and shorter in time, while retaining the same area. As its duration is squeezed, its height increases to keep the area constant. If a noise exposure shading is squeezed to a duration of one second, its height will then equal its SEL value; mathematically, its area is now $10^{(L/10)}$ times one second. Note that the resulting height of the squeezed zone depends both upon the L_{max} and the duration of the event – that is, upon the total area under the original, time-varying A-weighted sound level.

2.1.4 Onset Rate

An important characteristic of the noise from high-speed rail systems is the **onset rate** of the sound signature. Onset rate is the average rate of change of increasing sound pressure level in decibels per second (dB/sec) during a single noise event. The rapid approach of a high-speed train is accompanied by a sudden increase in noise for a receiver near the tracks. Researchers report that sounds of approaching vehicles carry a sense of convergence and cause greater annoyance than receding sounds.[4] Moreover, sounds with fast onset rates are more annoying than sounds with less rapid variation or steady noise with the same maximum noise level.[5] Research by the U.S. Air Force on the effect of onset rate on aircraft noise annoyance shows that people are increasingly annoyed by sudden sounds with onset rates greater than about 15 dB per second (dB/sec), as described more fully in Appendix A.[6,7] Onset rates of greater than 15 dB/sec occur for receivers within 60 feet of a 150 mph train, and occur at greater distances for trains at higher speeds. Measured onset rates for a steel wheel train (ICE) and a maglev train (TR 07) are shown plotted for the ratio of speed to distance in Figure 2-6. The plot shows that onset rate:

- increases as speed increases for a given distance, and
- decreases as distance increases for a given speed.

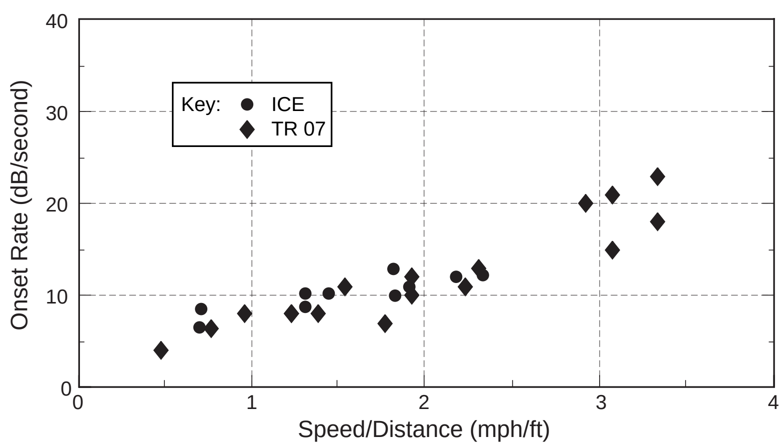

Figure 2-6 Measured High-Speed Rail Onset Rates

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[4]G. Rosinger, D. W. Nixon and H.E. von Gierke, "Quantification of the Noisiness of 'Approaching' and 'Receding' Sounds," J. Acoust. Soc. Am., 48, pp. 843-853, October 1970.

[5]K. Plotkin, L.C. Sutherland, J.A. Molino, "Environmental Noise Assessment for Military Aircraft Training Routes: Volume 2: Recommended Noise Metric." Wyle Laboratories Report WR 86-21 prepared for Wright-Patterson Air Force Base AAMRL/BBE, April 1987.

[6]K.J. Plotkin, K. W. Bradley, J.A. Molino, K.G. Helbing, D.A. Fisher. "The Effect of Onset Rate on Aircraft Noise Annoyance, Vol. 1: Laboratory Experiments," US Air Force Systems Command, Report Number AL-TR-1992-0093, May 1992.

[7]E. Stusnick, K.A. Bradley, J.A. Molino, and G. deMiranda. "The Effect of Onset Rate on Aircraft Noise Annoyance, Vol. 2: Rented Home Experiment." US Air Force Materiel Command, Report Number AL/OE-TR-1993-0170, October 1992.

Although the measured onset rates in Figure 2-6 do not exceed about 25 dB/sec at normal measurement distances, actual onset rates can rise to greater values close to the tracks. When onset rates exceed about 30 dB/sec people tend to be startled, or surprised by the sudden onset of the sound. **Startle** as an added factor in annoyance is discussed in Appendix A-4. The onset rate of 30 dB/sec is used as the basis for establishing distances within which startle is likely to occur and serves as added information in the impact assessment methods presented in Chapters 4 and 5.

2.2 SOURCES OF HIGH-SPEED RAIL NOISE

The total wayside noise generated by a high-speed train passby consists of several individual noise-generating mechanisms, each with its own characteristics of source location, strength, frequency content, directivity, and speed dependence. These noise sources can be generalized into three major regimes:[8]

Regime I. propulsion or machinery noise,

Regime II. mechanical noise resulting from wheel/rail interactions and/or guideway vibrations, and

Regime III. aerodynamic noise resulting from airflow moving past the train.

For a conventional train with a maximum speed of up to about 125 mph, propulsion and mechanical noise are sufficient to describe the total wayside noise. The aerodynamic noise component begins to be an important factor when the train speed exceeds about 160 mph.

The significance of these different regimes is that, for a given train, there are three distinct speed ranges in which only one sound source dominates the total noise level. The dependence of the A-weighted sound level on vehicle speed (S) for a typical high-speed train is illustrated in Figure 2-7. A qualitative indication of the maximum sound level during a passby is plotted vertically in this figure. The three speed regimes are labeled "I," "II," and "III," each corresponding to the dominant sound source in the regime, or propulsion, mechanical, and aerodynamic noise, respectively. The speed at which the dominant sound source changes from one to another is called an acoustical transition speed (v_t). The transition from propulsion noise to mechanical noise occurs at the lower acoustical transition speed (v_{t1}), and the transition from mechanical to aerodynamic noise occurs at the upper acoustical transition speed (v_{t2}).

The various noise sources for a steel-wheeled high-speed tracked system and maglev system are illustrated in Figures 2-8 and 2-9 respectively. These sources differ in where they originate on the train and in what frequency range they dominate.

[8]B. Barsikow and B. Müller, “Wayside noise generated by the German high-speed transport systems, ICE and Transrapid,” 72nd Annual Meeting of the Transportation Research Board, Washington, D.C., 1993.

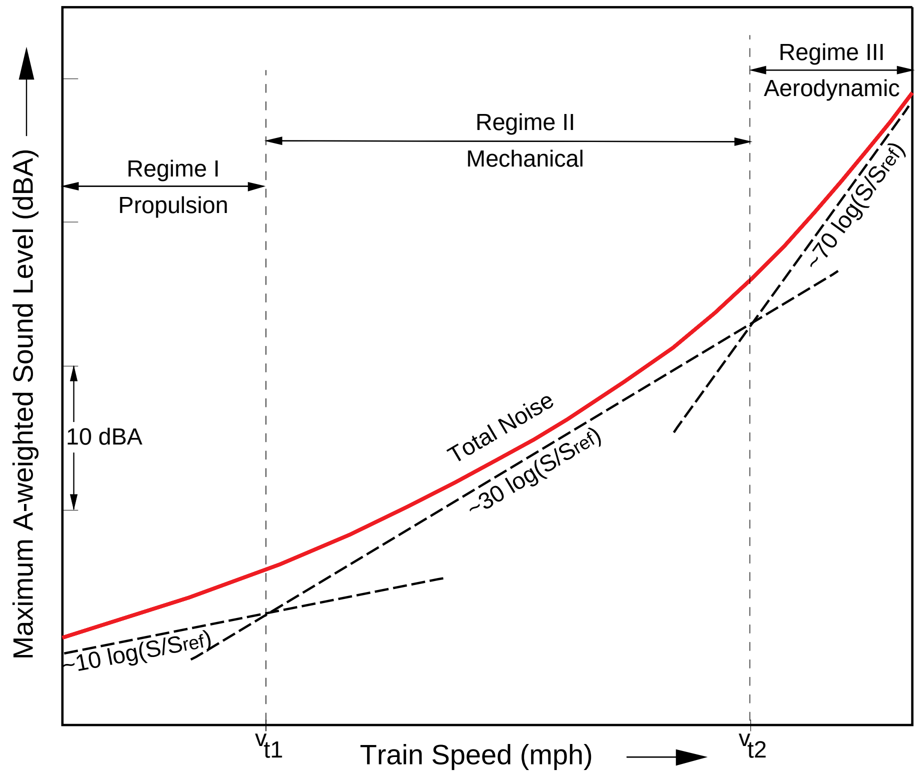

Figure 2-7 Generalized Sound Level Dependence on Speed

2.2.1 Regime I: Propulsion Sources

Steel-Wheeled Trains. At low speeds, Regime I, propulsion mechanisms, or machinery and auxiliary equipment that provide power to the train are the predominant sound sources. Most high-speed trains are electrically powered; the propulsion noise sources are, depending on the technology, associated with electric traction motors or electromagnets, control units, and associated cooling fans (see Figure 2-8). Fans can be a major source of noise; on conventional steel-wheeled trains fans are usually located near the top of the power units, about 10 feet above the rails. Fan noise tends to dominate the noise spectrum in the frequency bands near 1000 Hz. External cooling fan noise tends to be constant with respect to train speed, which makes fans the dominant noise when a train is stopped in a station.

Maglev Trains. Noise from the propulsion magnets in a maglev system is a result of induced vibration from magnetic forces. One source of vibration is oscillating magnetostriction, which also causes the characteristic hum sometimes heard from electrical transformers and which is likely to be tonal in character (see Figure 2-9). Sound at the magnetic pole-passing frequency is another effect of magnetic traction; the interaction of the moving vehicle and the stationary magnetic poles at a uniform spacing causes a tonal sound that varies uniformly with velocity. These forces are located at the magnet gaps between the vehicle and the guideway. Propulsion noise in general has a relatively weak speed dependence, typically following a relationship of ten times the logarithm of speed.

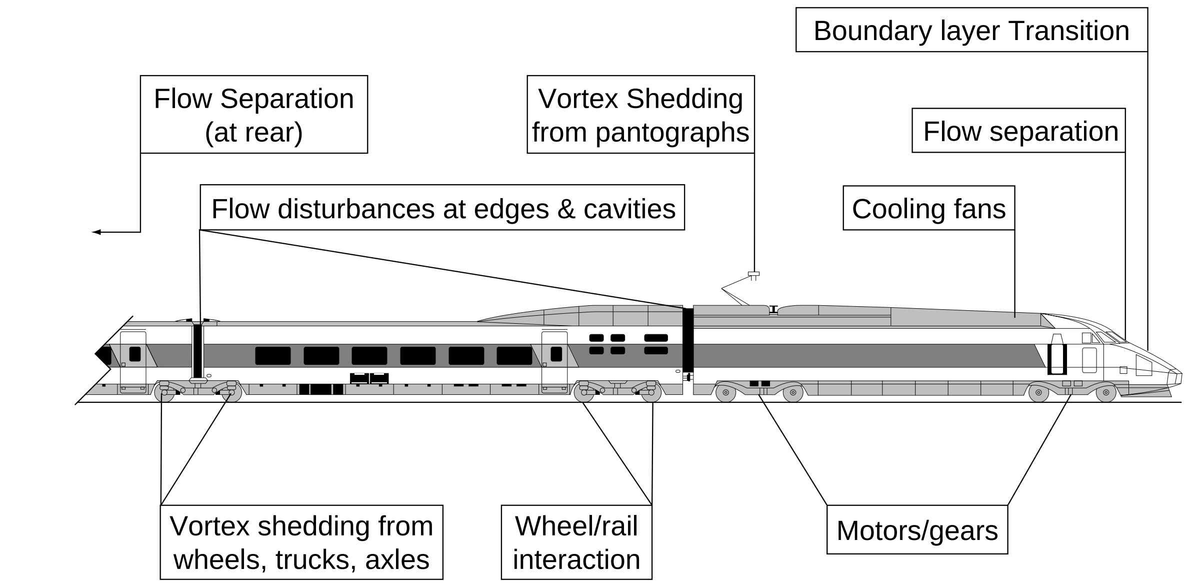

Figure 2-8 Noise Sources on a Steel-Wheeled High-Speed Rail System

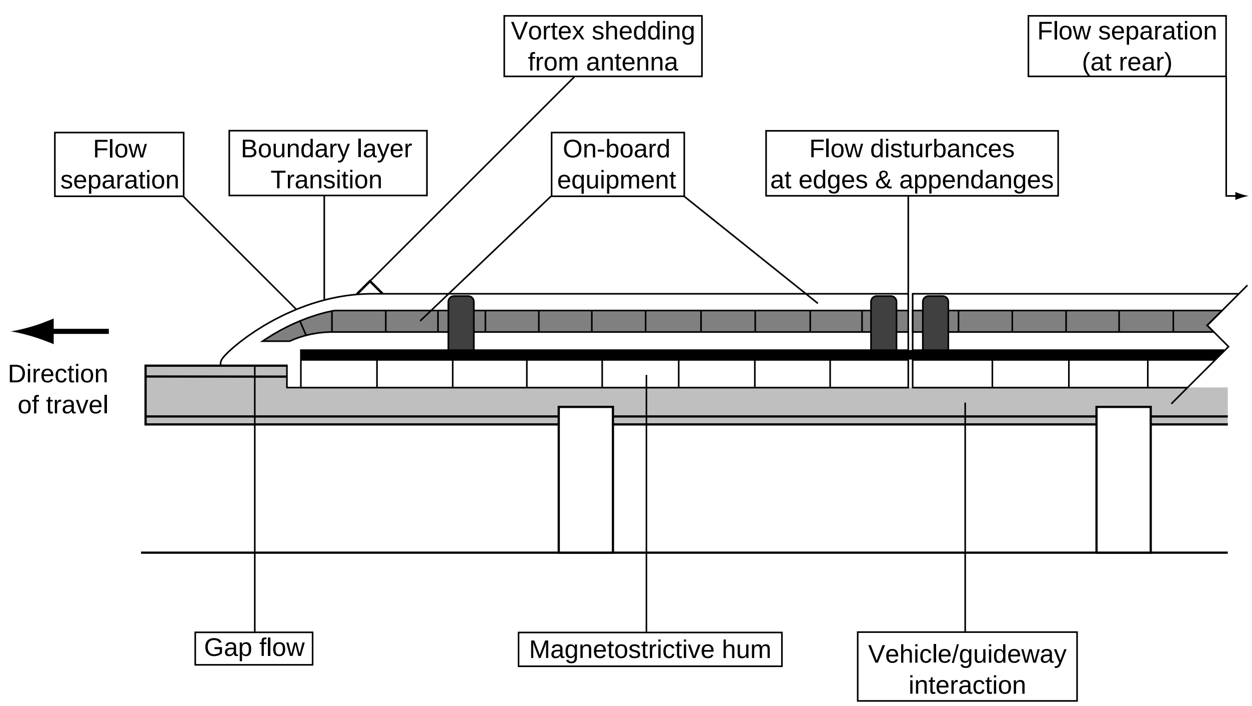

Figure 2-9 Noise Sources on a Maglev System

2.2.2 Regime II: Mechanical/Structural Sources

Steel-Wheeled Trains. The effects of wheel-rail interaction of high-speed trains, guideway structural vibrations, and vehicle-body vibrations fall into the category of mechanical noise sources. These sources tend to dominate the total noise level at intermediate speeds (Regime II), and cover the widest of the three speed regimes. For steel-wheeled trains, wheel-rail interaction is the source of the rolling noise radiated by steel wheels and rails caused by small roughness elements in the running surfaces. This noise source is close to the trackbed with an effective height of about 2 feet above the rails. The spectrum for rolling noise peaks in the 2 kHz to 4 kHz frequency range, and it increases more rapidly with speed than does propulsion noise, typically following the relationship of 30 times the logarithm of train speed. Wheel-rail noise typically dominates the A-weighted sound level at speeds up to about 160 mph.

Maglev Trains. Maglev technology is not free from mechanical/structural noise sources despite the lack of physical contact with the guideway. The maglev analogies to wheel-rail noise from a steel-wheeled train are noise from wheels rolling on guideway support surfaces at low speeds for electrodynamic (EDS) systems, which require forward motion up to a certain speed before lift can occur, and noise from magnetic pole-passing. Sound also is radiated by guideway vibrations and vehicle body vibrations. Both of these sources tend to radiate sounds at relatively low acoustical frequencies; fundamental resonance frequencies of guideway support beams are generally below 10 Hz, with radiation from box beam panels up to about 80 Hz. Vehicle body vibrations depend on the details of body panel construction; they can result in substantial sound radiation throughout the audible range. For maglev systems, the combination of all mechanical sources results in an increase of noise approximately 30 times the logarithm of speed.

2.2.3 Regime III: Aerodynamic Sources

Propulsion and rolling noise are generally sufficient to describe the total noise up to speeds of about 160 mph for steel-wheeled trains. Above this speed, however, aerodynamic noise sources tend to dominate the radiated noise levels. These sources begin to generate significant noise at speeds of about 180 mph, depending on the magnitude of the mechanical/structural noise. For maglev, this transition occurs at a lower speed due to low levels of mechanical noise.

Steel-Wheeled Trains. Aerodynamic noise is generated from high-velocity airflow over the train. For a conventional steel-wheeled train, the components of aerodynamic noise are generated by unsteady flow separations at the front and rear of the train and on structural elements of the train (mainly in the regions encompassing the trucks, the pantograph, inter-coach gaps, and discontinuities along the surface), and a turbulent boundary layer generated over the entire surface of the train.

Maglev Trains. For a maglev vehicle, aerodynamic noise sources include the flow separation on the front and rear ends, vortex shedding from the antennae, flow interactions in the gap between the vehicle and guideway, the wake generated at the trailing end, and the turbulent boundary layer.

Aerodynamic sources generally radiate sound in the frequency bands below 500 Hz, generally described as a rumbling sound. Aerodynamic noise level increases with train speed much more rapidly than does propulsion or rolling noise, with typical governing relationships of 60 to 70 times the logarithm of speed.

2.3 SOUND PROPAGATION PATH

This section contains a qualitative overview of noise-path characteristics from source to receiver, including attenuation along these paths. Sound paths from source to receiver are predominantly air-borne. Along these paths, sound reduces with distance due to (1) **divergence**, (2) **absorption/diffusion**, and (3) **shielding**. The general equation for the prediction of the A-weighted sound level at various distances from the track can be expressed as follows:

$$L_A = L_A(ref) + C_d + C_a + C_g + C_b$$

where: $L_A(ref)$ = a known A-weighted sound level at some reference distance *ref* from the source
C_d = adjustment factor for attenuation due to divergence
C_a = adjustment factor for excess attenuation due to atmospheric absorption
C_g = adjustment factor for excess attenuation from ground absorption
C_b = adjustment factor for excess attenuation due to obstacles such as barriers, berms, and buildings.

In nearly all cases, the adjustment factors are negative numbers due to the nature of the reference conditions. Each of these adjustment factors are discussed in Sections 2.3.1-2.3.3 in terms of their mechanisms of sound attenuation. Specific equations for computing noise-level attenuations along source-receiver paths are presented in Chapters 4 and 5. Sometimes a portion of the source-to-receiver path is not through the air, but rather through the ground or through structural components of the receiver's building. Ground-borne and structure-borne noise propagation are discussed in Chapter 6.

2.3.1 Divergence

Sound levels naturally attenuate with distance. Such attenuation, technically called "divergence," depends upon source configuration and source-emission characteristics. Divergence is shown graphically for point sources and line sources separately in terms of how they attenuate with distance in Figure 2-10. The divergence adjustment factor, C_d, for the receiver is plotted vertically relative to the sound level 50 feet from the source. As shown, the sound level attenuates with increasing distance due to the geometric spreading of sound energy.

For sources grouped closely together (called point sources), attenuation with distance is large: 6 decibels per doubling of distance. Most individual noise sources on a moving high-speed rail vehicle radiate sound as point sources. When many point sources are arrayed in a line, all radiating sound at the same time so any one source is not distinguishable, the arrangement is called a line source. For line sources, divergence with distance is less: 3 decibels per doubling of distance for L_{eq} and L_{dn}, and 3 to 6 decibels per doubling of distance for L_{max}. A train passing along a track or guideway can be considered a line source. In Figure 2-10, the line source curve separates into three separate lines for L_{max}, with the point of departure depending on the length of the line source. For example, close to a short train, it behaves like a line source; far away, it behaves as a point source. The curves shown in Figure 2-10 are for illustrative purposes only, and the exact equations for these curves given Chapter 5 should be used for quantitative analyses.

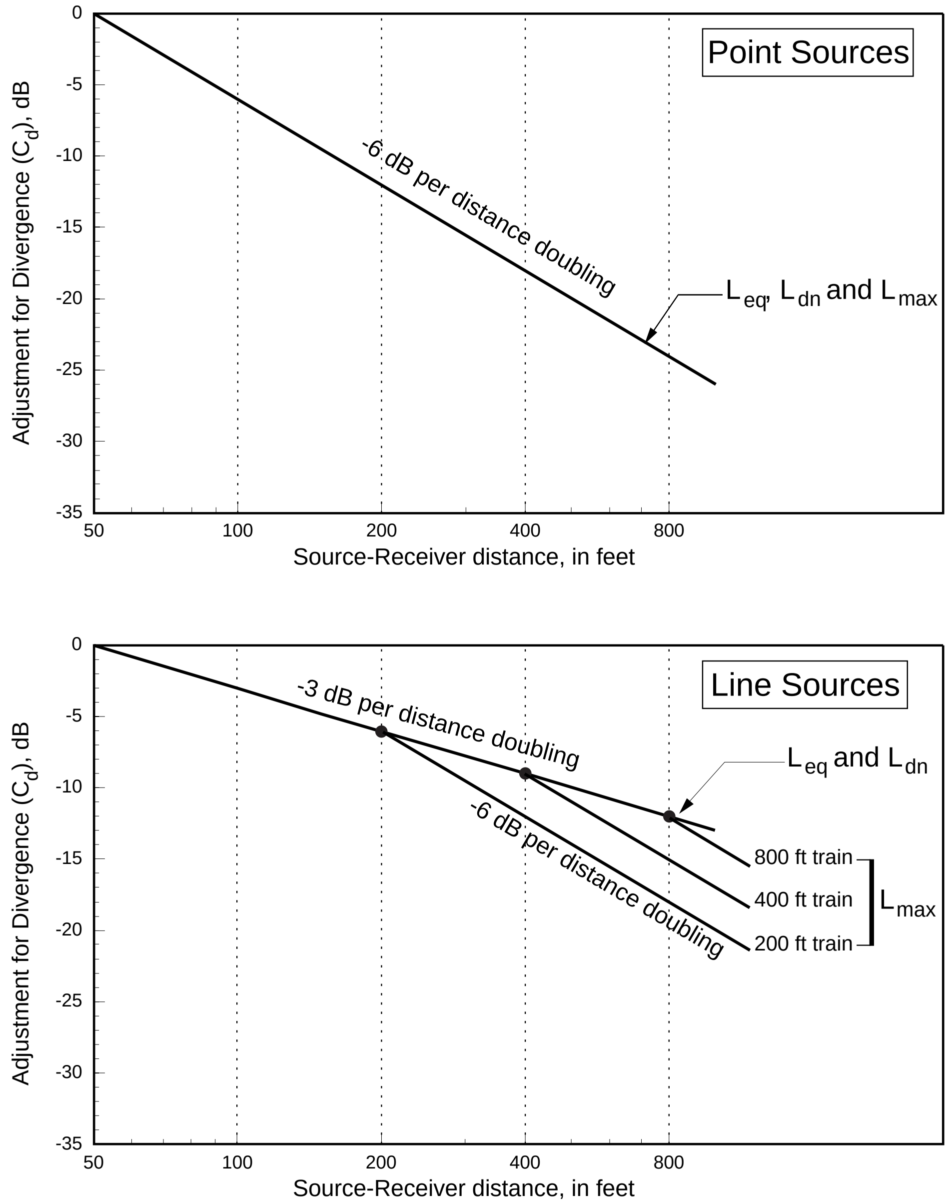

Figure 2-10 Attenuation due to Distance (Divergence)

Some sound sources, such as warning bells, radiate sound energy nearly uniformly in all directions. These are called nondirectional, or monopole, sources. For train noise, however, the rolling noise from wheel-rail interactions, as well as some types of aerodynamic noise, is complicated because the sources do not radiate sound equally well in all directions. This unequal radiation is known as **source directivity**, which is a measure of the variation in a source's radiation with direction. Studies have shown that wheel-rail noise can be modeled by representing the source as a line source (or continuous row of point sources) with dipole directivity.[9] A dipole radiation pattern has also been observed in the turbulent boundary layer near the sides of a train.[10] Typically, a dipole source radiates a directivity pattern such that the sound pressure is proportional to the cosine of the angle between the source orientation and the receiver. Consequently, wheel-rail noise is propagated more efficiently to either side of a moving train than in front, above or behind it.

2.3.2 Absorption/Diffusion

In addition to attenuating because of geometric spreading of the sound energy, sound levels are further attenuated when sound paths lie close to absorptive or "soft" ground, such as freshly plowed or vegetation-covered areas. This additional attenuation, which can be 5 decibels or more within a few hundred feet is illustrated graphically in Figure 2-11. In this figure the adjustment factor, C_g, is plotted vertically as a function of distance. At very large distances, wind and temperature gradients can alter the ground attenuation shown here; such variable atmospheric effects generally influence noise levels well beyond the range of typical railway noise impact and are not included in this manual. Equations for the curves in Figure 2-11 are presented in Chapter 5.

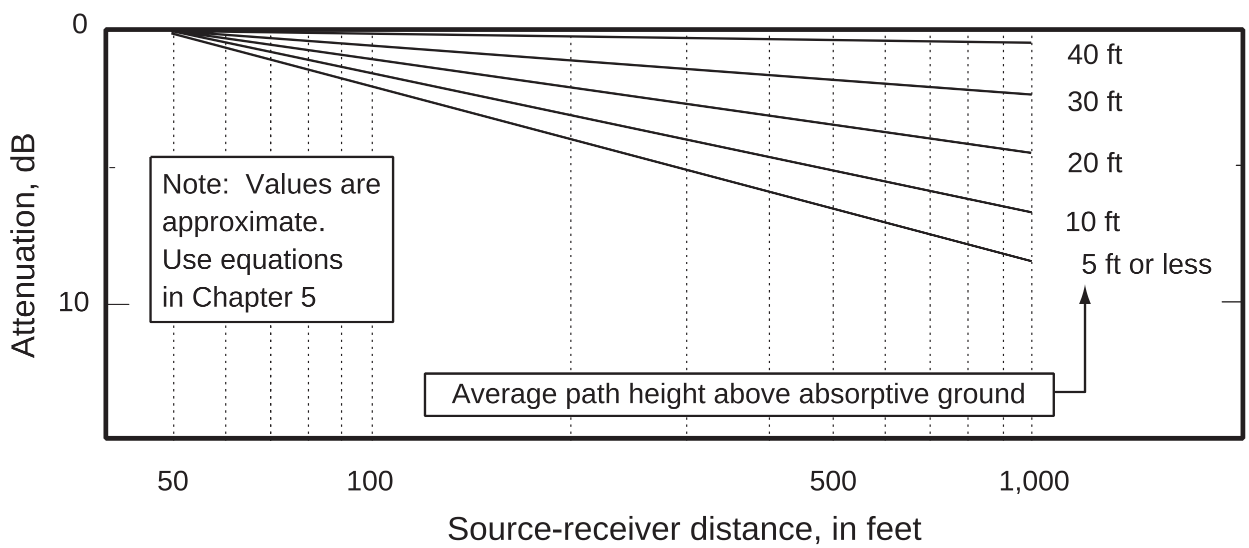

Figure 2-11 Attenuation due to Soft (Sound-Absorptive) Ground

[9] E.J. Rathe, "Railway noise propagation," J. Sound Vib. 51, 371-388 (1977).

[10] W.F. King, "On the boundary layer contribution to wayside noise generated by high-speed tracked vehicles," Inter-Noise '94 Proceedings (1994), pp.175-180.

2.3.3 Shielding

Sound paths are sometimes interrupted by noise barriers, by terrain, by rows of buildings, or by vegetation. Noise barriers, usually the most effective means of mitigating noise in sensitive areas, are the most important of these path interruptions. A noise barrier reduces sound levels at a receiver by breaking the direct path between source and receiver with a solid wall; vegetation, in contrast, hides the source but does not reduce sound levels significantly. Sound energy reaches the receiver only by bending (diffracting) over the top of the barrier, as shown in Figure 2-12. This diffraction reduces the sound level at the receiver.

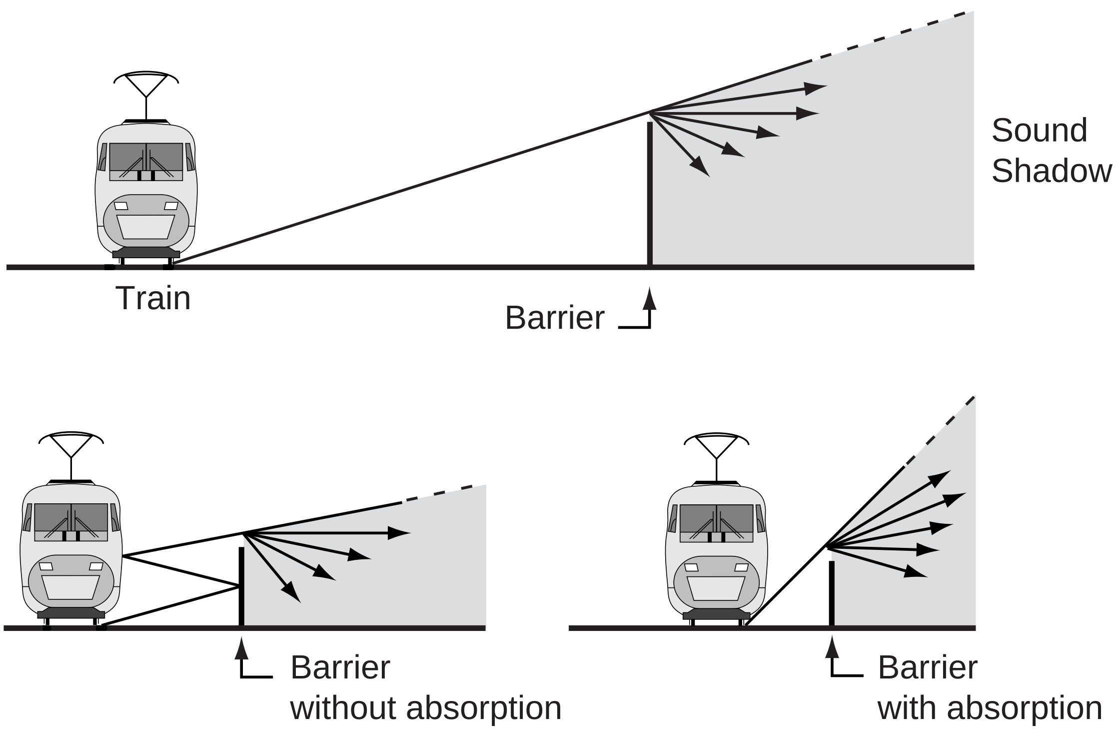

Figure 2-12 Noise Barrier Geometry

Noise barriers for transportation systems typically attenuate noise at the receiver by 5 to 15 dBA (which corresponds to an adjustment factor C_b range of -5 to -15 dBA), depending upon receiver and source height, barrier height, length, and distance from both source and receiver. The attenuation of noise by a barrier also is frequency dependent, i.e., all other factors being the same, the higher the frequency of the noise, the greater the barrier attenuation. As discussed in Section 2.2, the peak frequencies and source heights of high-speed rail noise vary according to the dominant noise source in a particular speed regime. In general, aerodynamic noise has lower peak frequencies than does wheel-rail noise, which means that a barrier is less effective at attenuating aerodynamic noise. In addition, aerodynamic noise sources tend to be located higher up on the train than wheel-rail noise sources. As a result, a noise barrier high enough to shield aerodynamic noise will be relatively expensive compared to a barrier for controlling wheel-rail noise, since it must extend 15 feet or more above the top of rail. For operating speeds up to about 160 mph, a barrier high enough to shield wheel-rail and other lower car body sound sources would normally provide sufficient sound attenuation.

Barriers on structure, very close to the source, provide less attenuation than predicted using standard barrier attenuation formulae, due to reverberation (multiple reflections) between the barrier and the body of the train. This reverberation can be offset by increased barrier height, which is easy to obtain for such close barriers, and/or the use of acoustically absorptive material on the source side of the barrier. These concepts are illustrated in Figure 2-12. Acoustical absorption is included as a mitigation option in Chapter 5. Equations for barrier attenuation, as well as equations for other sound-path interruptions, also are presented in Chapter 5.

2.4 MATHEMATICAL MODEL OF HIGH-SPEED RAIL NOISE

The development of the high-speed rail noise prediction model consists of two distinct parts: (1) identification of sources, and (2) modeling of the outdoor sound propagation. Part (1) involves the identification and localization of sound sources specific to high-speed rail, and is based solely on empirical data. Section 2.4.1 presents an overview of the available data used to quantify these sources. Part (2) involves the application of sound propagation theory to account for characteristics of the noise path. Section 2.4.2 provides a summary of the mathematical models used to predict sound levels at specific locations.

2.4.1 Identification of Sources

Most of the data used to develop the high-speed rail noise model are taken from measurements of revenue service high-speed train operations in Europe.[11] These measurements of electrically powered trains include the TGV and Eurostar trains in France, the X2000 tilt train in Sweden, and the Pendolino tilt train in Italy. The purpose of the measurement program is to document wayside noise levels from representative European high-speed trainsets, with the specific objective of developing a prediction model for high-speed rail noise. In addition, an existing database of noise measurements from the U.S. Northeast Corridor (NEC) Electrification Project [12], the National Maglev Initiative (NMI) Project [13], and various other sources, provide supplementary data on ICE (Germany), TGV, X2000, RTL-2 (gas-turbine powered), and TR07 (German maglev trainsets).

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[11]Measurements were conducted by Harris Miller Miller & Hanson Inc., in April and May, 1995, as part of the methodology development effort for this manual.

[12]U.S. Department of Transportation, Federal Railroad Administration, Northeast Corridor Improvement Project Electrification -New Haven,CT to Boston, MA: Final Environmental Impact Statement/Report, Volume II: Technical Studies , Chapter 4. Noise and Vibration. DOT/FRA/RDV-94/01-B, DOT-VNTSC-FRA-94-6, Final Report October 1994.

[13]U.S. Department of Transportation, Federal Railroad Administration, Noise from High Speed Maglev Systems, DOT/FRA/NMI-92/18, January 1993.

As an overview of the available data, measured noise levels from the various high-speed trainsets are plotted over a range of speeds in Figures 2-13 and 2-14. A graph of $L_{max,slow}$ as a function of train speed, normalized to a reference distance of 100 feet is shown in Figure 2-13. Figure 2-14 shows the noise level plotted in terms of SEL, with the data normalized to a reference distance of 100 feet and a reference train length of 740 feet. Data from the following test programs are represented in these figures:

- Revenue service operations in Europe. Data from the European measurement program conducted in France, Italy and Sweden referred to above are plotted as individual data points in the graphs. Each data point represents a large quantity of data averaged over similar speed events. Sites were selected to cover a relatively wide speed range. They include operations of the TGV and Eurostar in France, Pendolino in Italy, and X2000 in Sweden.
- Maglev test track in Germany. TR07 noise curve is based on regression analysis of data obtained from tests on a prototype maglev vehicle (TransRapid TR07) at the maglev test track in Emsland, Germany.
- Trainset demonstrations on NEC. Curves of noise level versus speed generated by the noise model recently developed as part of the NEC Electrification Project are included.[14] These curves are based on measurements conducted on the Northeast Corridor as part of demonstration testing of several newer-technology trainsets (including the German ICE, Swedish X2000, and the U.S./French RTL-2 Turboliner) in the U.S. The curves are plotted up to the actual maximum speed obtained for each trainset during testing, even though the maximum allowable speed may be higher.

The results in Figures 2-13 and 2-14 indicate that the European steel-wheeled train measurement data generally fall within the range of the train noise curves developed for the NEC Project. The results also suggest that:

- The TGV trains tested in Europe have noise emissions similar to the ICE and RTL-2 trains tested in the U.S.
- Wayside noise levels for the X2000 and Pendolino trains averaged about 5 decibels higher than other trains measured, with noise emissions similar to the X2000 train tested in the U.S.
- Data for the Eurostar trains showed the greatest variation, with noise levels scattered over the range for other trains.

Maglev noise levels are consistently low relative to the steel-wheeled trains, but it is clear that as speeds reach the upper limits there is less difference between the steel-wheeled and maglev technologies in the level of noise generated as the aerodynamic component becomes significant.

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[14] Because the NEC noise models were developed with less detailed consideration of noise subsources and propagation effects, they do not necessarily yield identical results as computed using the more updated models presented in Chapters 4 and 5 of this manual.

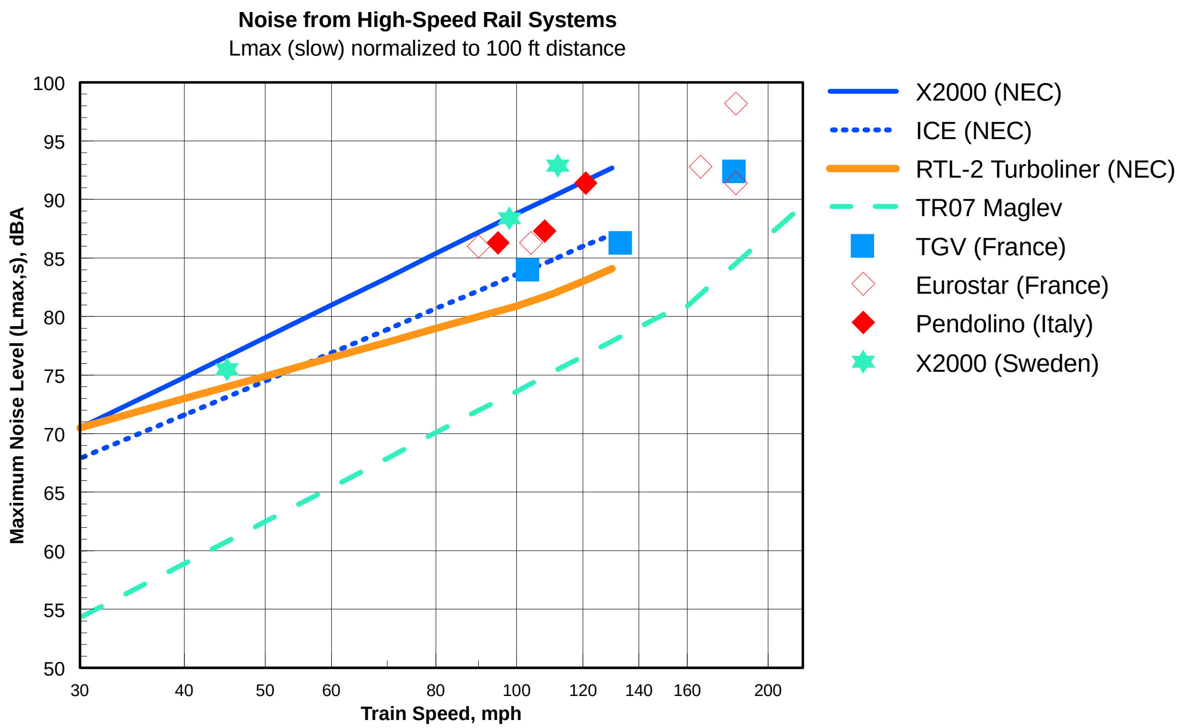


Figure 2-13 Measured Values of $L_{max,s}$ vs Speed from High-Speed Rail Systems

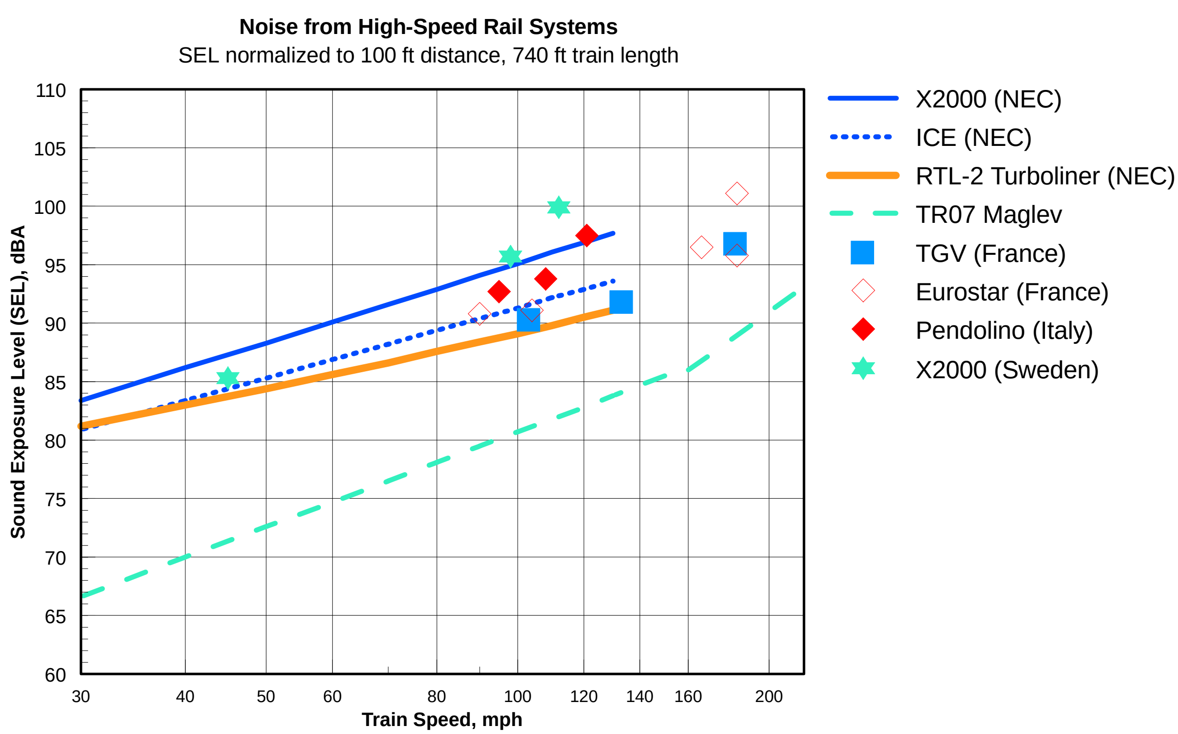


Figure 2-14 Measured Values of SEL vs Speed from High-Speed Rail Systems

2.4.2 Basic Equations

The general approach used to model noise from high-speed trains considers each noise source from a train passby separately as a moving line source of given length, height, speed dependence, and directivity pattern. The standard model for noise from wheel-rail interactions is an incoherent dipole line source.[9] Most other sources, such as propulsion and aeroacoustic mechanisms, can be modeled as having simple monopole directivity.[15,16]

Since the noise impact criteria are based on noise exposure metrics L_{eq} and L_{dn}, the noise computations are based on a reference SEL for each source corresponding to a set of reference operating conditions. Since L_{max} is often the quantity that is measured or provided in vehicle noise specifications, it is important to understand the relationship between L_{max} and SEL. The following equations based on Rathe's model[9] can be used to relate SEL to L_{max} under reference conditions:

$$SEL = L_{max} + 10\log\left(\frac{len}{v}\right) - 10\log\{2\alpha + \sin(2\alpha)\} + 3.3 \qquad \text{for dipole sources}$$

$$SEL = L_{max} + 10\log\left(\frac{len}{v}\right) - 10\log(2\alpha) + 3.3 \qquad \text{for monopole sources}$$

where:

L_{max} = reference $L_{max,s}$ under reference conditions (v_{ref}, y_{ref}), dBA,
len = reference source length, feet,
v = reference train speed, mph,
$\alpha = \tan^{-1}\left(\frac{len}{2y}\right)$, radians, and
y = reference observer distance from track centerline, feet.

Reference conditions are given in tables in Chapters 4 and 5. The following equation is then used to adjust a reference SEL to other operating conditions at the reference distance *y*:

$$SEL = SEL_{ref} + 10\log\left(\frac{len}{len_{ref}}\right) + K\log\left(\frac{v}{v_{ref}}\right)$$

[15] The radiating parts of aerodynamic noise such as the pantograph and the turbulent boundary layer near the wall can originate from dipole-like sources. However, because of the turbulent nature of the sound-generating mechanisms, the directions of the axes of dipoles are likely to vary in time and position, resulting in a more or less randomly radiating chaos of fluctuating dipoles. Thus, the global directivity pattern of a train is more appropriately modeled as a monopole, even though the sources may be dipoles locally.

[16] J.D. van der Toorn, H. Hendriks, T.C. van den Dool, "Measuring TGV source strength with SYNTACAN," J. Sound Vib. 193(1), 1996, p. 113-121.

where:

$$\begin{aligned} len &= \text{source length, feet,} \\ K &= \text{speed coefficient, and} \\ v &= \text{train speed, mph.} \end{aligned}$$

SEL and L_{max} are descriptors of noise levels from a single train passby. The following equations are used to predict noise exposure in terms of the cumulative metrics L_{eq}(h) and L_{dn}, and to adjust for divergence and the effects of the propagation path:

$$L_{eq}(h) = SEL + 10\log(V) + C_d + C_g + C_b - 35.6$$

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

where:

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

C_d = correction for divergence (distance attenuation), dB

C_g = correction for ground attenuation, dB

C_b = correction for excess shielding due to barriers or berms, dB

$L_{eq}(day)$ = daytime L_{eq}, or energy-average $L_{eq}(h)$ during daytime hours (7 a.m. to 10 p.m.)

$L_{eq}(night)$ = nighttime L_{eq}, or energy-average $L_{eq}(h)$ during nighttime hours (10 p.m. to 7 a.m.)

Methods for calculating the correction factors C_d, C_g, and C_s are based on source type, receiver distance, and cross-sectional geometry are presented in Chapters 4 and 5.

Chapter 3

NOISE IMPACT CRITERIA

The criteria used in evaluating noise impacts from high-speed rail are based on maintaining a noise environment considered acceptable for land uses where noise may have an effect. These criteria take into account the unusual noise characteristics of high-speed rail operations, including the effects of startle on humans, livestock, and wildlife to the extent that these effects are known.

The noise impact criteria for high-speed rail facilities are presented in Section 3.1. These criteria are adapted from criteria developed by the Federal Transit Administration for rail noise sources operating on fixed guideways or at fixed facilities.[1] The criterion for the onset of **impact** varies according to the existing noise level and the predicted project noise level, and it is determined by the minimum measurable change in community reaction. The corresponding criterion for **severe impact** also varies according to the existing noise level as well as the project noise level, but it is determined by the change in community reaction between an acceptable and an unacceptable noise environment. Guidelines for the application of the criteria are included in Section 3.2, and background material on the development of the criteria is included in Appendix A.

3.1 NOISE IMPACT CRITERIA FOR HIGH SPEED RAIL PROJECTS

The noise impact criteria for high-speed rail projects are shown in graphs and tables in this section. The equations used to define these criteria are included in Appendix A. The criteria apply to high-speed rail

[1] U.S. Department of Transportation, Federal Transit Administration. "Transit Noise and Vibration Impact Assessment," Final Report, DOT-T-95-16, April 1995.

operations as well as to fixed facilities such as storage and maintenance yards, passenger stations and terminals, parking facilities, and substations.

3.1.1 Basis of Noise Impact Criteria

The noise impact criteria for human annoyance, presented in Figure 3-1 and Table 3-1, are based on comparison of the existing outdoor noise levels and the future outdoor noise levels from a proposed high-speed rail project. They incorporate both absolute criteria, which consider activity interference caused by the high-speed rail project alone, and relative criteria, which consider annoyance due to the change in the noise environment caused by the project. These criteria were developed to apply to a wide variety of surface transportation modes, to recognize the heightened community annoyance caused by late-night or early-morning operations, and to respond to the varying sensitivities of communities to projects under different background noise conditions.

The noise criteria and descriptors for human annoyance depend on land use, as defined in Table 3-2. Further guidance on the definition of land use, the selection of the appropriate noise metric, and the application of these criteria are given in Section 3.2, with more detailed guidelines provided in Chapters 4 and 5.

Noise effects on livestock and wildlife also have been considered. There are no established criteria relating high-speed rail noise and animal behavior. However, some characteristics of high-speed rail noise are similar to low overflights of aircraft, and researchers generally agree that high noise levels from aircraft overflights can have a disturbing effect on both domestic livestock and wildlife. Some animals get used to noise exposure, while some do not. Documented effects range from simply taking notice and changing body position to taking flight in panic. Whether these responses represent a threat to survival of animals remains unclear, although panic flight may result in injuries to animals in rough terrain or in predation of unprotected eggs of birds. A limited amount of quantitative noise data relating actual levels to effects provides enough information to develop a screening procedure to identify areas where noise from high speed rail operations could affect domestic and wild animals. The basis for the screening is shown in Table 3-3. A summary of recent literature related to noise effects on livestock and wildlife is included in Appendix A.

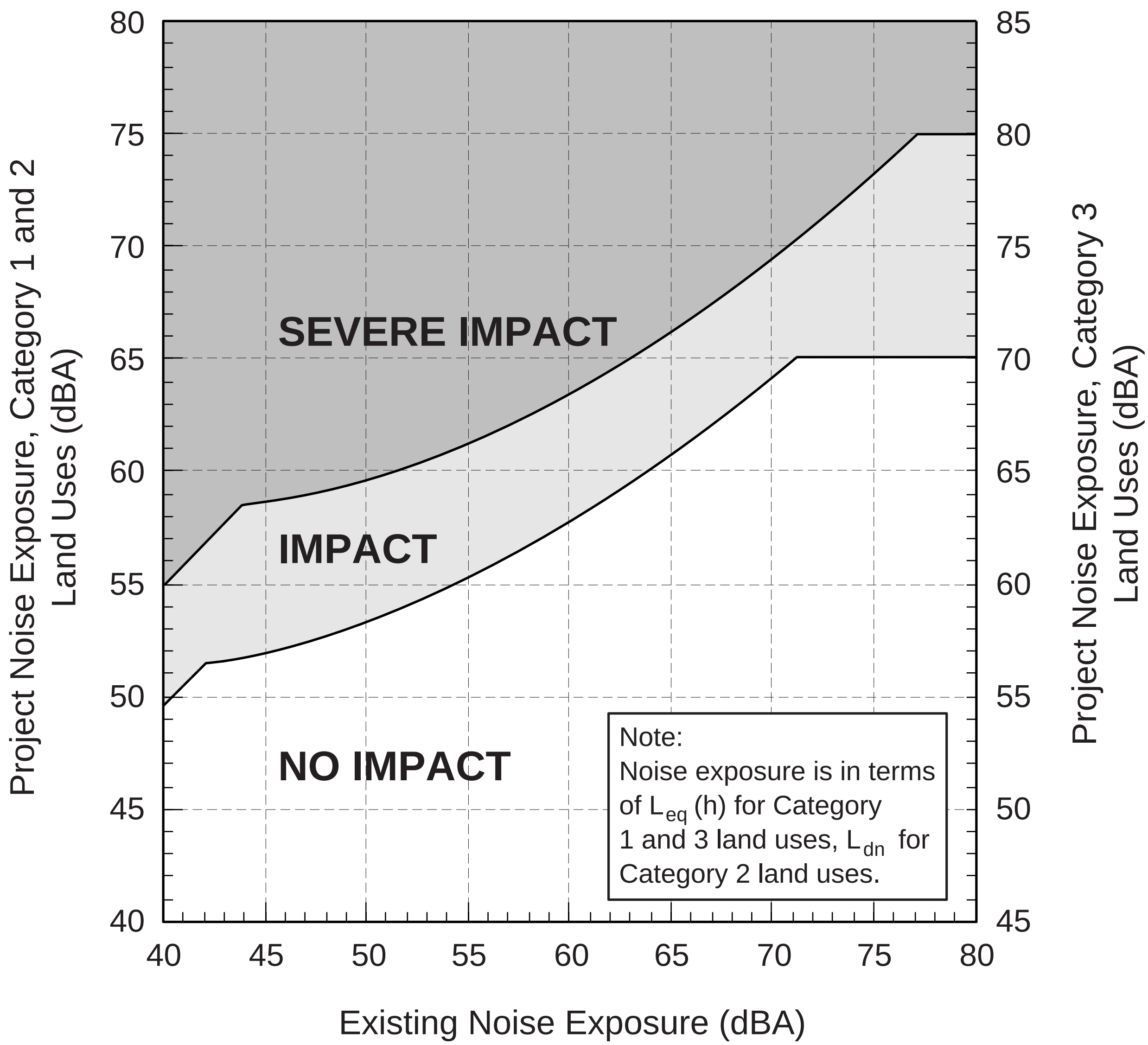


Figure 3-1 Noise Impact Criteria for High Speed Rail Projects

Table 3-1 Noise Levels Defining Impact for High Speed Rail Projects

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

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

Table 3-2 Land Use Categories and Metrics for High Speed Rail Noise Impact Criteria

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

* Onset-rate adjusted sound levels (L_{eq}, L_{dn}) are to be used where applicable.
** L_{eq} for the noisiest hour of transit-related activity during hours of noise sensitivity.

Table 3-3 Interim Criteria for High Speed Rail Noise Effects on Animals

Animal Category	Class	Noise Metric	Noise Level (dBA)
Domestic	Mammals (Livestock)	SEL	100
	Birds (Poultry)	SEL	100
Wild	Mammals	SEL	100
	Birds	SEL	100

3.1.2 Definitions of Levels of Impact

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

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

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

As the existing level of ambient noise increases, the allowable level of project noise increases, but the total allowable increase in community noise exposure is reduced. This reduction accounts for the unexpected result -- project noise exposure levels that are less than the existing noise exposure can still cause impact. The examples in Table 3-4 more clearly illustrate the levels of project noise and existing levels of exposure that result in crossing the threshold of impact.

Table 3-4 Noise Impact Criteria: Effect on Cumulative Noise Exposure

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

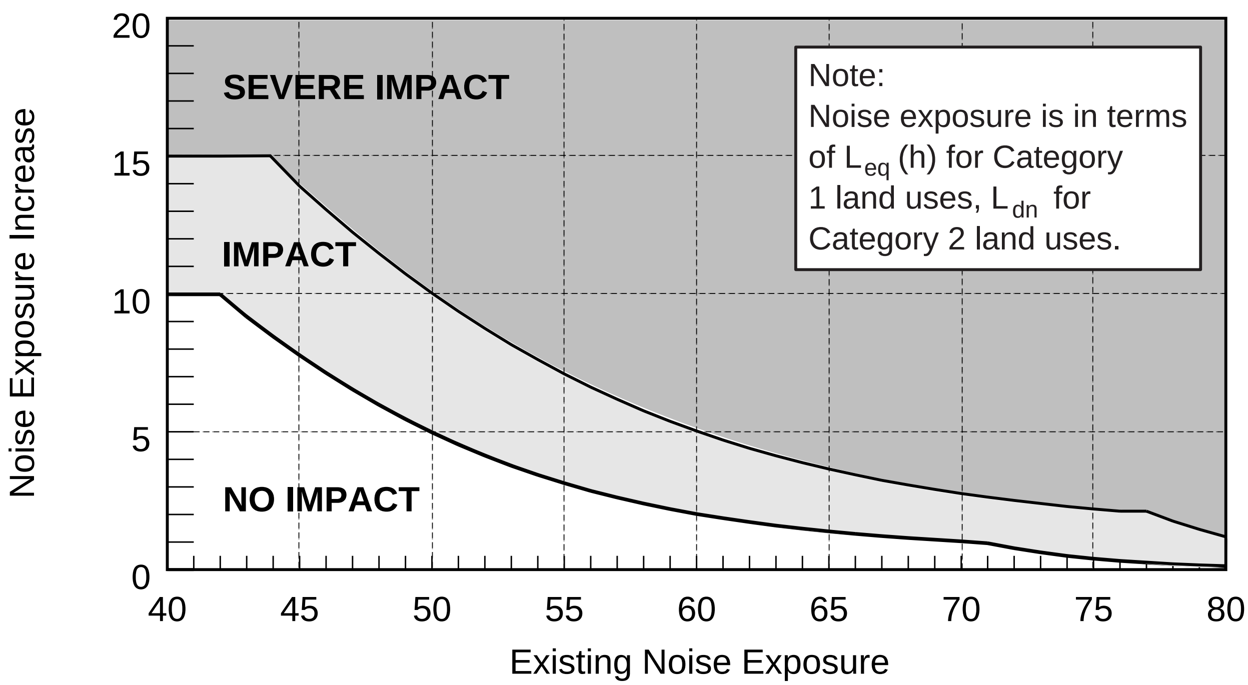


Figure 3-2 Increase in Cumulative Noise Levels Allowed by Criteria (Land Use Cat. 1 & 2)

Any increase in allowable noise exposure greater than shown in Table 3-4 will cause impact. 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 dBA to 0 dBA (rounded to the nearest whole decibel). The justification for this decrease is that people already exposed to high levels of noise will notice and be annoyed even by only a small increase in the amount of noise in their community. In contrast, if the existing noise levels are quite low, a greater change in the community noise will be required for the equivalent level of annoyance. It should be noted that these annoyance levels are based on general community reactions to noise at varying levels that have been documented in scientific literature and do not account for specific community attitudinal factors that may exist.

3.2 APPLICATION OF NOISE IMPACT CRITERIA

This section provides practical guidance on interpretation of the land use categories and application of the impact criteria.

3.2.1 Noise-Sensitive Land Uses

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

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

Historically significant sites are treated as noise-sensitive depending on the land use activities. Sites of national significance with considerable outdoor use required for site interpretation would be in Category 1. Historical sites that are currently used as residences would be in Category 2. Historic buildings with indoor use of an interpretive nature involving meditation and study fall into Category 3. Category 3 sites include museums, significant birthplaces, and buildings in which significant historical events occurred.

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

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

3.2.2 Considerations in Applying the Noise Impact Criteria

The procedure for assessing Impact is to determine the existing noise exposure and the predicted project noise exposure at a given site, in terms of either L_{dn} or $L_{eq}(h)$ as appropriate, and to plot these levels on Figure 3-1. In locations very near the right-of-way, the “onset-rate adjusted sound level” may be used (Figure 4-2). The location of the plotted point in the three impact ranges is an indication of the magnitude of the impact. For simplicity, noise impact also can be determined by using Table 3-1, rounding all noise level values to the nearest whole decibel before using the table. This level of precision is sufficient for determining the degree of noise impact at specific locations and should be adequate for most applications. However, a more precise determination of noise impact may be appropriate in some situations, such as estimating the distance from the project to which noise impact extends. In such cases, more precise noise limits can be determined using the criteria equations provided in Appendix A.

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

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

Application of criteria for livestock and wildlife provides information on the exposed area in which noise could have an effect, even if the consequences of those effects are not fully known. Researchers have observed both behavioral and physiological effects with the approximate single event sound levels listed in Table 3-3. The noise descriptors used by the researchers are not always well defined, but the best descriptor for a single event that incorporates both level and duration is the Sound Exposure Level (SEL). Procedures for calculating SEL for varying distances from high speed train passbys are described in Chapters 4 and 5. Criteria are not yet fully developed to the point where dose-response relationships can be fully described for different animal species. However, the assessment is based on the assumption that impact occurs when a noise event is sufficiently loud to generate an observable effect in domestic livestock or wildlife. The term “wildlife” is assumed to include all endangered species until species-specific information can be developed.

3.2.3 Mitigation Policy Considerations

FRA’s traditional approach to abatement of noise sources from high speed rail systems is embodied in its Railroad Noise Emission Compliance Regulation.[2] Rather than specific environmental regulations, the compliance regulation is intended to enforce the “Noise Emission Standards for Transportation Equipment: Interstate Rail Carriers” promulgated by the U.S. Environmental Protection Agency.[3] These Standards limit the amount of noise emitted from power cars and rail cars under stationary and moving conditions. In addition, the National Environmental Policy Act (NEPA) establishes a broad mandate for federal agencies to incorporate environmental protection and enhancement measures into the programs and

[2]U.S. Department of Transportation, Federal Railroad Administration,”Railroad Noise Emission Compliance Regulations,” Final Rule, 48 Federal Register 56756- 56761; December 23, 1983 (23 Code of Federal Regulations 210).

[3]U.S. Environmental Protection Agency, “Noise Emission Standards for Transportation Equipment: Interstate Rail Carriers,” 40 Code of Federal Regulations 201, July 1, 1984.

projects they help promote, approve and/or finance.[4] FRA strongly encourages noise abatement on high speed rail projects where noise impacts, and certainly where severe noise impacts are identified according to methods of this manual.

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

Chapter 4

INITIAL NOISE EVALUATION

This chapter contains procedures for an initial evaluation of potential noise impacts from a high-speed rail project. The goals of an initial noise evaluation are to identify the potential for impacts and to determine their order of magnitude, so that a more detailed analysis can be done where significant impacts are found in later phases of the design processes. The initial evaluation includes two parts: a preliminary screening of the project corridor to identify areas of potential impact, and a general noise assessment. The Screening Procedure is described in Section 4.1 and the General Assessment procedures are described in Section 4.2. An example of an initial noise evaluation appears at the end of this chapter. The initial evaluation results in an inventory of buildings where noise impact could occur and where noise mitigation measures, such as noise barriers, may be needed. In this regard, the method is designed to overstate the potential impact. This information is useful for comparing alternatives and selecting those with the least potential for noise impacts.

Noise from high-speed trains passing near noise-sensitive receptors is the focus of an initial evaluation. Except for special cases, other ancillary project noise sources, such as electrical sub-stations, roadway traffic near passenger stations, and maintenance facilities generally should not be considered at this stage of planning. Usually, a lack of detail on the design and placement of these types of noise sources precludes a meaningful noise assessment.

The screening procedure of the initial evaluation is based on the type of technology and the type of area the alignment is passing through. The screening procedure identifies whether impacts are likely to occur, but it does not attempt to predict noise exposure at specific receptors or to estimate the mitigation requirements. The screening procedure is appropriate for very early phases of a project when the design is still at a conceptual stage.

The General Assessment portion of the initial evaluation is based on noise source and land use information likely to be available at early stages in the project development process. The General Assessment includes estimating source level for the high-speed rail technology being considered, estimating existing noise exposure using a simplified procedure, determining noise impact based on the criteria given in Chapter 3, and preparing an inventory of the potential impacts and mitigation requirements. At the comparatively early planning stage, the General Assessment can help establish the most promising corridor locations.

4.1 NOISE SCREENING PROCEDURE

The Screening Procedure is based on very general assumptions and can be applied in the early phases of a project before specific project elements have been defined. The screening distances appropriate for the project are used to define the study area for any subsequent noise impact assessment. Distances for project types are listed in Table 4-1. When there are noise-sensitive receptors within the screening distance, impact is possible, and as the project definition evolves, the procedures for General (this chapter) and Detailed (Chapter 5) Noise Assessments are used to determine the extent and severity of impact.

The Screening Procedure indicates whether any noise-sensitive receivers are close enough to the proposed alignments for noise impact to be possible, and it identifies locations where the project has little possibility of noise impact. Screening can be useful when making a broad-brush comparison of potential impacts for different corridors. Screening also can be used to select the corridors that will be studied in more detail and to define the study area of any subsequent noise impact assessment. This selection can be a key element of a noise impact study since high-speed rail corridors may extend over hundreds of miles. Where no noise-sensitive land uses are within the screening distance, no further noise assessment is necessary. This approach allows the noise analysis to focus on locations where impacts are likely.

The Screening Procedure takes account of the noise impact criteria, the type of project, and noise-sensitive land uses. For screening purposes, all noise-sensitive land uses are considered to be in a single category. The distances given in Table 4-1 delineate a project’s noise study area. The areas defined by the screening distances are sufficiently large to encompass all potential impacts. The distances were developed using typical noise emissions of high-speed trains, but with the maximum number of operations and speeds of a given project type and the lowest applicable impact threshold from Chapter 3 to obtain worst case conditions. This approach gives a conservative estimate of impact. With the greater refinement in the general and detailed procedures, the noise impact distances should always be less than the screening distances listed in Table 4-1.

The Screening Procedure is applicable to high-speed rail projects using both steel-wheeled and maglev technologies. Screening distances by the type of corridor or alignment involved, either shared with an existing rail or highway corridor or newly built through undeveloped land, are listed in Table 4-1.

The steps for the Screening Procedure are:

Step 1. **Project Setting**. Determine the type of project corridor, and ambient noise environment, and locate them on Table 4-1. For many high-speed rail projects, the corridor can vary from one type to another, both in alignment characteristics and ambient environment, over the length of the project corridor. These variations should be identified and included when screening an entire project corridor.

Step 2. **Technology**. Determine the appropriate column (steel-wheel on steel rail or maglev) under Screening Distance in Table 4-1. Apply this distance from the guideway centerline.

Step 3. **Study Area Characteristics**. Within the distance noted above, locate any of the noise-sensitive land uses listed in Table 3-2.

Step 4. **Assessment**. If it is determined that none of the listed land uses are within the distances noted in Table 4-1, then no further noise analysis is needed. On the other hand, if one or more of the noise-sensitive land uses are within the screening distances noted in Table 4-1, then the project will require further analysis using the General Noise Assessment procedures described in the following sections.

Table 4-1 Screening Distances for Noise Assessments

Type of Project Corridor	Ambient Type	Screening Distance† for Project Type (feet)	
		Steel-Wheeled	Maglev
Shared with Existing Rail Line	Urban/Noisy Suburban	450	200
	Quiet Suburban/Rural	900	300
Shared with Existing Highway	Urban/Noisy Suburban	450	125
	Quiet Suburban/Rural	700	125
New Corridor (previously undeveloped land)	Urban/Noisy Suburban	450	200
	Quiet Suburban/Rural	900	350

† Measured from centerline of guideway or rail corridor

4.2 GENERAL NOISE ASSESSMENT

The General Noise Assessment determines the potential for noise impact by applying simplified models to estimate train noise and existing ambient noise, and then comparing the results with the impact criteria in Chapter 3. The procedure involves noise predictions commensurate with the level of detail of available data in the early stages of major investment planning. For projects in preliminary stages of planning, a general assessment may be all that is needed to evaluate noise impacts and to propose mitigation measures. The General Assessment also can be used to compare alternatives, such as locations of alignments or candidate high-speed transportation modes (steel-wheeled versus maglev technology), and can provide the appropriate level of detail about noise impacts for a corridor or sub-area study.

The general noise assessment procedure starts with determining the project noise level at a reference distance for the various project alternatives. This reference noise source level differs depending on the type of high-speed vehicle chosen for the project. The noise generated by each vehicle depends on the source characteristics described in Chapter 2. The reference noise source level is then used to compute noise exposure, accounting for anticipated operating conditions based on information about the project. At an early project stage, the information available may include:

- candidate technology or vehicle type,
- guideway variations,
- hours of operation,
- headways,
- design speed, and
- alternative alignments.

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

The steps in the general noise assessment are described in detail in the following sections and are summarized below:

Step 1. Source Levels

- Place the alternative under study into one of three categories: steel-wheeled electric-powered, steel-wheeled fossil fuel-powered, or maglev.
- Determine the source reference level, which pertains to a typical passby of the project vehicle in a given speed range under reference operating conditions. *Use Table 4-2. The noise descriptor, SEL, used to define the reference level is discussed in Chapter 2. If L_{max} is available from source measurements or specifications, a conversion to SEL is necessary. Use the method described in Appendix C.*

Step 2. Project Operating Conditions

- Convert the source reference level to noise exposure in terms of L_{eq}(h) or L_{dn} at the reference distance of 50 feet under anticipated project operating conditions. *Use the appropriate equations contained in Table 4-4, depending upon the type of source.*

- Correct the noise exposure to account for vertical terrain effects, such as embankments and trenches. *Use the method described in Section 4.2.2.*

Step 3. Propagation Characteristics

- Draw a noise exposure-versus-distance curve for this source, which will show the project noise exposure as a function of distance, ignoring shielding. *Use the method described in Section 4.2.3.*
- Estimate the reduction in noise level to account for shielding attenuation from rows of buildings. *Use the general rule given at the bottom of Table 4-5. It is important to include adjustments for shielding attenuation from rows of buildings; omitting them can result in unrealistically high estimates of noise impact.*
- Draw an adjusted exposure-versus-distance curve.
- Identify noise-sensitive locations very close to the tracks where receivers may be startled by rapid onset rates of noise from high-speed trains. *The distance defining a potential startle zone is identified in Section 4.2.3.*

Step 4. Study Area Characteristics

- Estimate the existing noise exposure for areas adjacent to the project. *Use the methods described in Section 4.2.4.*

Step 5. Noise Impact Estimation

- Locate the distance at which project noise exposure results in impact corresponding to the estimated existing noise exposure, on a point-by-point basis. *Use the impact criteria from Chapter 3.*

- Connect the points to obtain a contour line around the project, which signifies the outer limits of impact.

Alternatively, when it is desired to compare different technologies:

- Determine contours corresponding to specific noise levels from the exposure-vs.-distance curves (for example, 60 dBA, 65 dBA, 70 dBA contours).

Step 6. Noise Impact Inventory

- Tabulate noise-sensitive land uses within the specific contours.

Step 7. Noise Mitigation

- Estimate the noise reduction that would be achieved with mitigation in the community areas where potential for impact has been identified.

- Repeat the tabulation of noise impacts after mitigation has been applied.

4.2.1 Noise Source Levels for General Assessment

The procedure starts with establishing the noise source levels, expressed in terms of SEL under reference conditions of speed, distance, and length. These quantities are given in Table 4-2 for the two general categories of high-speed trains: steel-wheeled (including both electric-and fossil fuel-powered locomotives) and maglev trains.

Reference SELs for each type of high-speed rail vehicle are given in Table 4-2 for the three speed regimes corresponding to propulsion, mechanical, and aerodynamic noise sources dominating the overall wayside noise. The speed regimes were discussed in Chapter 2. These speed regimes are defined by transition speeds, S_{t1} and S_{t2}, as well as speed-dependency coefficients K, which represent the slopes of the SEL versus speed curve in each regime. These parameters are included in Table 4-2. For each speed regime, the table also lists the reference SEL, reference speed, and reference length. These parameters are used in the equations of Table 4-4 to predict the noise exposure at 50 feet. A reference distance of 50 feet is used to minimize propagation effects.

Table 4-2 Reference Parameters at 50 feet from Track/Guideway

Reference Quantity	Abbreviation	Speed Regime	Vehicle Type		
			Steel-Wheeled		Maglev
			Electric	Fossil Fuel	
Reference SEL	SEL_{ref}	I	89 dBA	87 dBA	72 dBA
		II	93 dBA	94 dBA	73 dBA
		III	99 dBA	n/a	78 dBA
Speed Coefficient	K	I	3	5	2
		II	17	16	17
		III	47	n/a	50
Reference Speed	S_{ref}	I	20 mph	20 mph	20 mph
		II	90 mph	90 mph	60 mph
		III	180 mph	n/a	120 mph
Reference Length	len_{ref}	I	73 feet	73 feet	82 feet
		II	634 feet	634 feet	82 feet
		III	73 feet	n/a	82 feet
Transition Speed	S_{t1}	I → II	60 mph	60 mph	60 mph
	S_{t2}	II → III	170 mph	n/a	120 mph

A generalized plot of SEL as a function of speed, with each of the three speed regimes identified is shown in Figure 4-1. This plot illustrates use of several of the parameters listed in Table 4-2 in each of the three speed regimes. It differs from Figure 2-7 in that it plots SEL, not L_{max}, versus speed and represents the relationship as three discrete straight-line segments to approximate the smooth curve. The general equation relating SEL to speed for each speed regime at the reference distance (50 feet) is defined as:

$$SEL = SEL_{ref} + K \log\left(\frac{S}{S_{ref}}\right)$$

where S = train speed in miles per hour, and all other quantities are defined by the reference parameters given in Table 4-2. As indicated in Figure 4-1, the speed coefficient K represents the "slope" of the line in each speed regime.

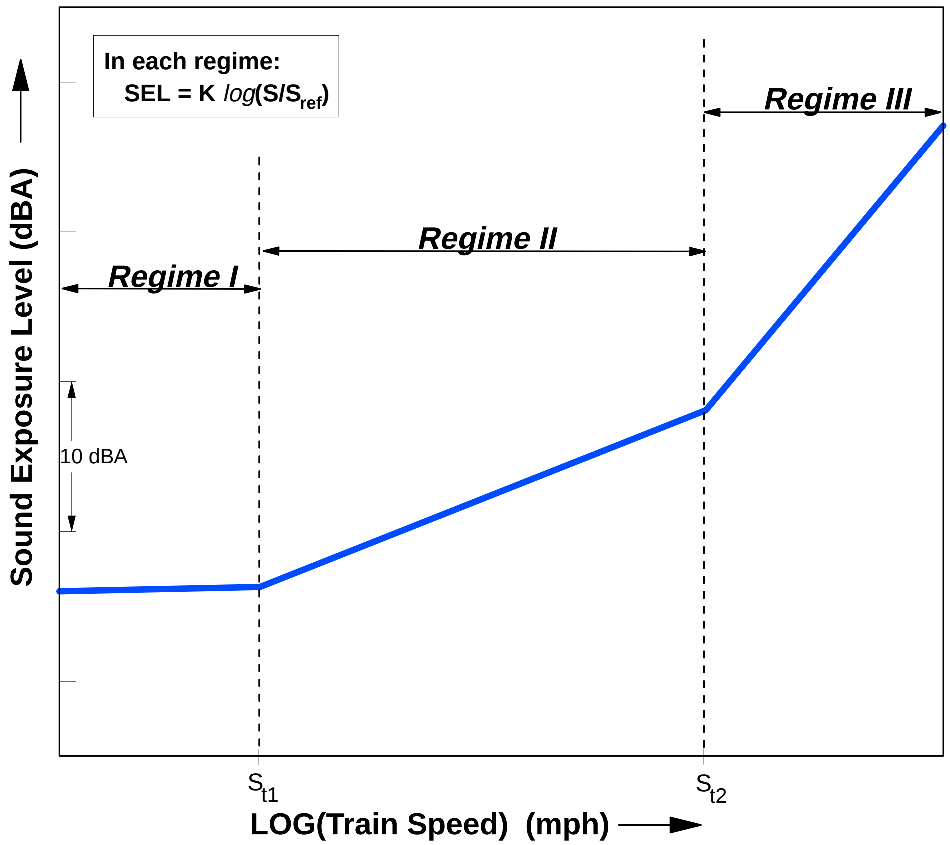


Figure 4-1 Generalized SEL vs Speed for a High-Speed Train Passby

4.2.2 Project Operating Conditions

After determining the reference level for the candidate high-speed rail technology, the next step is to determine noise exposure at 50 feet under project operating conditions and expressed in terms of L_{dn} and $L_{eq}(h)$. The additional data needed include:

- number of train passbys during daytime hours (defined as 7 a.m. to 10 p.m.) and nighttime hours (defined as 10 p.m. to 7 a.m.),

- maximum number of train passbys during hours that Category 1 or Category 3 land uses are normally in use (usually the peak-hour train volume),
- number and unit length of locomotives (power cars) and passenger coaches per train,
- speed (maximum expected), and
- guideway configuration.

Shielding. Attenuation from various types of shielding including noise barriers, also should be accounted for at this step of the process. Shielding attenuation depends primarily on geometrical factors relating the noise source, receiver, and intervening terrain or structures. The approximate noise reduction provided from the shielding effects of track layout such as trenches and embankments, as well as from "negative" shielding (i.e., noise increase) for elevated structures are provided in Table 4-3 . These noise reductions are given in terms of a correction factor, C_s, to be added to the reference SEL.

If noise mitigation is determined necessary at the end of the first pass of the General Assessment, Table 4-3 also gives the nominal noise reduction achieved by a 10-foot high wayside noise barrier, the most common mitigation measure for railway noise.

The equations necessary for calculating these quantities based on the reference SEL, adjusted to account for operating conditions, and the parameters listed here are listed in Table 4-4.

4.2.3 Propagation Characteristics

The process described in the Section 4.2.2 results in estimates of noise exposure at 50 feet for the proposed project. This section describes the procedure used to estimate the project noise exposure at other distances, resulting in a noise exposure versus distance relationship sufficient for use in a general assessment. The procedure is as follows:

1. Noise Exposure at 50 feet. Determine the L_{dn} or L_{eq} at 50 feet for the appropriate vehicle type using the equations in Table 4-4.

2. Attenuation with Distance. Adjust for the distance to the receiver using the equation:

$$L_{dn}\ (\text{or } L_{eq})\Big|_{\text{at distance, } d} = L_{dn}\ (\text{or } L_{eq})\Big|_{\text{at 50 feet}} - 15\log\left(\frac{d}{50}\right)$$

where d is the perpendicular distance from the receiver to the track centerline in feet. This equation gives an approximate relationship between noise exposure and distance that can be used to determine the noise impact contour for the first row of unobstructed buildings. This relationship can be plotted to display noise from both unmitigated and mitigated conditions to assess the benefits from mitigation measures.

Table 4-3 Shielding Corrections for Track Geometry

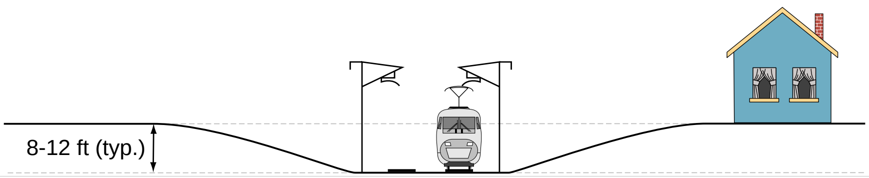
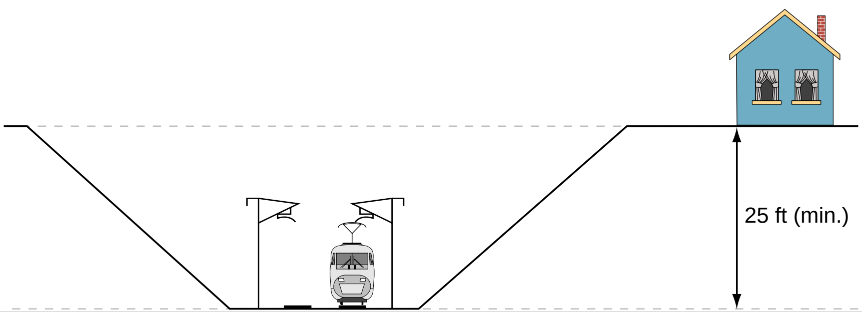
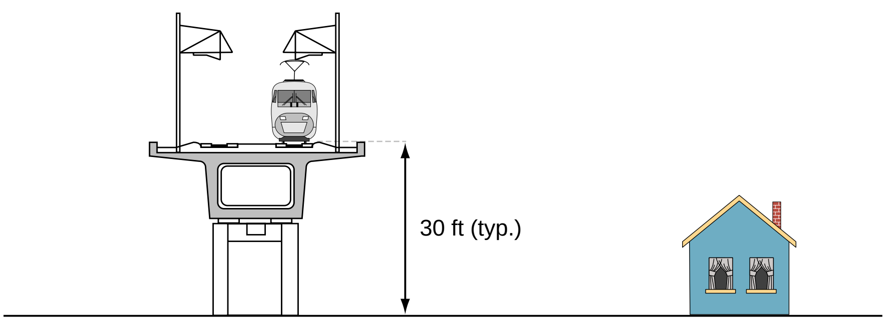
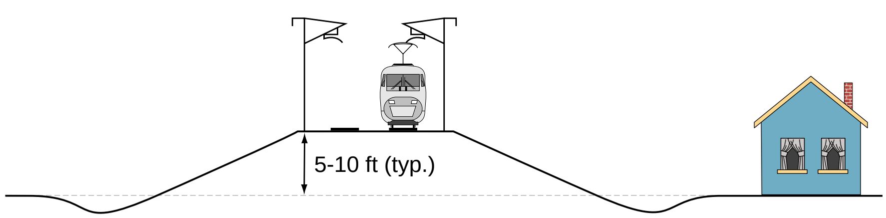
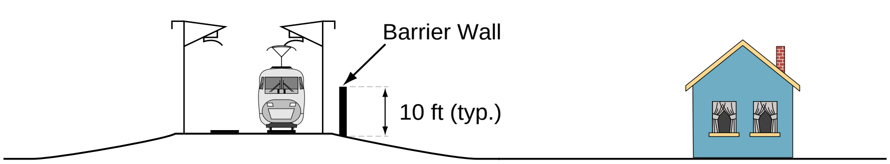
CASE	Speed Regime	Shielding Correction (C_s)
1) Tracks in Shallow Cut 	I	0 dBA
	II	–10 dBA
	III	–3 dBA
2) Tracks in Deep Trench or Cut 	I	–10 dBA
	II	–15 dBA
	III	–10 dBA
3) Tracks on Aerial Structure 	I	+4 dBA
	II	+4 dBA
	III	+2 dBA
4) Tracks on Embankment 	I	0 dBA
	II	–5 dBA
	III	0 dBA
5) Noise Barrier 	I	0 dBA
	II	–10 dBA
	III	–5 dBA

Table 4-4 Computation of Noise Exposure at 50 feet for General Assessment

Quantity	Equation
SEL at 50 ft:	$SEL = SEL_{ref} + K \log\left(\frac{S}{S_{ref}}\right) + 10 \log\left(\frac{len}{len_{ref}}\right)$
Hourly L_{eq} at 50 ft:	$L_{eq}(h) = SEL + 10 \log V + C_s - 35.6$
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = L_{eq}(h)\Big\rvert_{V = V_d}$
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = L_{eq}(h)\Big\rvert_{V = V_n}$
L_{dn} at 50 ft:	$L_{dn} = 10 \log\left[15 * 10^{\left(L_{eq}(day)/10\right)} + 9 * 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$

$$len = \begin{cases} \text{total length of power unit(s), ft} \rightarrow & \text{in Speed Regime I} \\ \text{total train length, ft} \rightarrow & \text{in Speed Regime II} \\ \text{total train length, ft} \rightarrow & \text{in Speed Regime III} \end{cases}$$

S = train speed, in miles per hour

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

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

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

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

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

3. Shielding from Rows of Buildings. Account for shielding attenuation from rows of intervening buildings for second row receivers and beyond. Without accounting for shielding, impacts may be substantially over-estimated. Use the following general rules to determine the effect of shielding from intervening rows of buildings:

- Assign 3 dB of shielding attenuation for the *first* row of intervening buildings only. (Attenuation means a subtraction from the sound level.)
- Assign 1.5 dB of shielding attenuation for each subsequent row, up to a maximum total attenuation of 10 dB.

Startle Effects

As discussed in Chapter 2, there is considerable evidence that increased annoyance is likely to occur for train noise events with rapid onset rates. The relationship of speed and distance to define locations where the onset rate for high speed rail operations may cause startle, assuming open flat terrain with unobstructed view of the tracks in both directions is shown in Figure 4-2. The potential for startle for the most part is confined to an area very close to the tracks. For example, Figure 4-2 shows that 150 mph high-speed rail operations would have the potential for startle within 32 feet of the track centerline.

For the purposes of a General Noise Assessment, it is necessary only to identify noise-sensitive locations where startle may be an additional annoyance. The speed information contained in Figure 4-2 should be used to determine the distance within which startle could occur. Any noise-sensitive land use within that distance should be identified as a candidate for annoyance by startle.

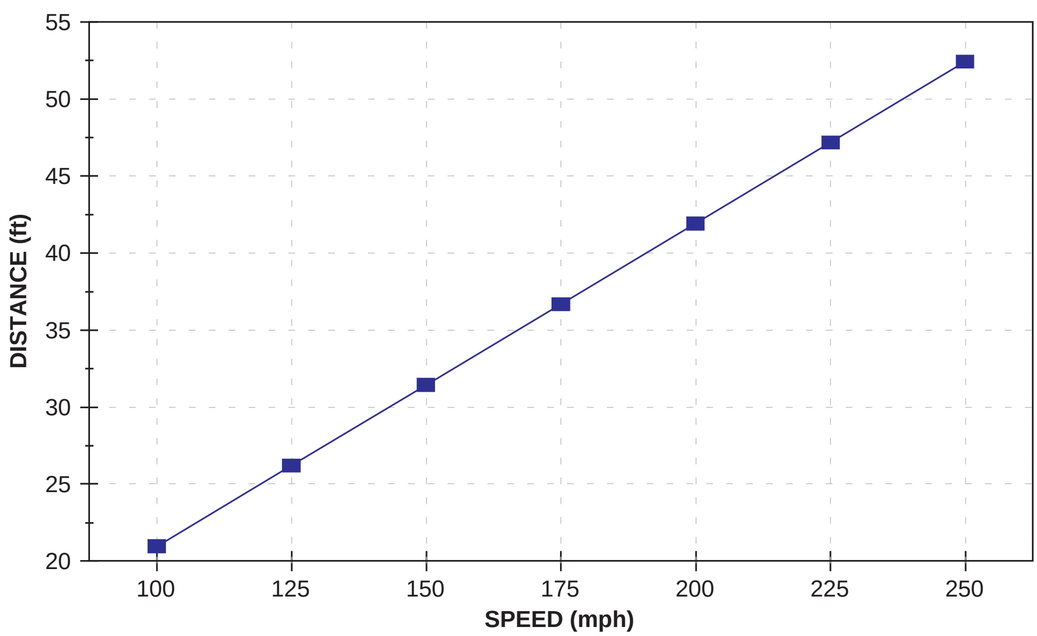


Figure 4-2 Distance from Tracks within which Startle Can Occur for HSR

4.2.4 Study Area Characteristics

The impact criteria described in Chapter 3 base the threshold of impact on estimates of existing noise exposure in the vicinity of the project. Impact is assessed using a combination of the existing noise exposure and the additional noise exposure that will be caused by the project. The Detailed Analysis procedures presented in Chapter 5 base the existing noise exposure on noise measurements at representative locations in the community. It is generally a good idea to base all estimates of existing noise on measurements, especially at locations known to be noise-sensitive. However, measurements are not always possible at the general assessment stage. This section gives procedures for estimating existing noise in the project study area from general data available early in project planning. The procedure uses Table 4-5, where a neighborhood's existing noise exposure is based on proximity to nearby major roadways or railroads or on population density. The process is as follows:

1. Mapping: Obtain scaled mapping and aerial photographs showing the project location and alternatives. A scale of 1 inch = 200 or 400 feet is appropriate for the accuracy needed in the noise assessment. The size of the base map should be sufficient to show distances of at least 1,000 feet from the center of the alignment.

2. Sensitive Receivers: Review the maps, together with land use information, to determine the proximity of the noise-sensitive land uses to the project and to the nearest major roadways and railroad lines. When necessary, windshield surveys or more detailed land use maps may confirm the location of sensitive receivers. For land uses more than 1,000 feet from major roadways or railroad mainlines (see definitions in Table 4-5), obtain an estimate of the population density in the immediate area, expressed in people per square mile.

3. Existing Noise Exposure: Use Table 4-5 to estimate existing noise exposure. Existing noise exposure is estimated by first looking at a site's proximity to major roads and railroad lines. If the site is located far enough from any major "linear" sources so that ambient noise is dominated by local streets and community activities, then the estimate should be based on population density alone. If the site is within about 1,000 feet of a major linear source, an estimate of the noise exposure from that source should be made based on generalized assumptions. Compare the noise levels from each of the three categories (roadways, railroads, and population density) and select the highest level to estimate the current exposure. In all cases, the noise levels are underestimated to provide a conservative impact assessment.

   Major roadways are separated into two categories: interstates, or roadways with four or more lanes that allow trucks; and "others," parkways without trucks and city streets with the equivalent of 75 or more heavy trucks per hour or 300 or more medium trucks per hour. The estimated roadway noise levels are based on data for light to moderate traffic on typical highways and parkways using the FHWA[1] highway noise prediction model. Where a range of distances is given, the predictions are made at the outer limit, thereby underestimating the traffic noise at the inner distance. For highway noise, distances are measured from the centerline of the near lane for roadways with two

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

lanes, while for roadways with more than two lanes the distance is measured from the geometric mean of the roadway, computed as follows:

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

where:

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

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

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

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

where p = population density in people per square mile.

4. Measurements to estimate existing noise from a shared rail transit corridor: If the proposed high-speed rail project corridor is to be shared with an existing rail transit corridor (rapid transit, commuter rail, etc.), the methods described in Steps 1 through 3 are not adequate to characterize existing noise exposure accurately. Since existing noise exposure is a strong function of distance from the existing rail corridor, general estimates such as those presented in Table 4-5 are difficult to make, given the high variability in the operational characteristics of transit systems. In such cases, noise measurements at representative locations along the corridor are essential to estimate existing noise accurately.

The procedure for the Detailed Noise Analysis (Chapter 5) recommends that these measurements be supplemented and/or substantiated through noise prediction methods developed specifically for

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

different transit modes. These methods are provided in the guidance manual published by US Department of Transportation, Federal Transit Administration.[3]

4.2.5 Noise Impact Estimation

It is often desirable to draw noise impact contours on land use maps to aid the impact inventory. Once the contours are on the map, the potential noise impacts can be estimated by counting the buildings inside the contours. The process is as follows:

1. Project versus Existing Noise Exposure. Identify the noise-sensitive neighborhoods and buildings and estimate existing noise exposure following the procedures described in Section 4.2.4. Use the estimate of existing noise exposure and the noise impact criteria in Figure 3-1 to determine how much additional noise exposure would need to be created by the project before there would be Impact or Severe Impact.

2. Noise Impact Contours. Determine the distances from the project boundary to the two impact levels using the noise exposure-versus-distance relationships from Section 4.2.2. Plot points on the land use map corresponding to those distances in the neighborhood under study. Continue this process for all areas surrounding the project. Connect the plotted points by lines to represent the noise impact contours.

3. Noise Exposure Contours. Alternatively, if it is desired to plot specific noise contours at, for example, 65 dBA, the distances also can be determined directly from the approach described in Section 4.2.2. Again, plot the points associated with a given noise level on the land use map and connect by lines to represent that contour.

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

4.2.6 Noise Impact Inventory

The next step in the General Assessment is to develop an inventory of noise-sensitive land uses that are within the impact contours. Use land use information and the noise impact contours developed in Section 4.2.5 to count buildings within the impact contours. In some cases it may be necessary to supplement the land use information or to determine the number of dwelling units within a multi-family building with a visual survey.

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[3] US Department of Transportation, Federal Transit Administration, Transit Noise and Vibration Impact Assessment, Report No. DOT-T-95-16, April 1995.

Table 4-5 Estimating Existing Noise Exposure for General Assessment

Distance from Major Noise Source[1] (feet)			Population Density (people per sq mile)	Noise Exposure Estimates (dBA)			
Interstate Highways[2]	**Other Roadways[3]**	**Railroad Lines[4]**		**L_{eq} Day**	**L_{eq} Evening**	**L_{eq} Night**	**L_{dn}**
10 - 49				75	70	65	75
50 - 99				70	65	60	70
100 - 199				65	60	55	65
200 - 399				60	55	50	60
400 - 799				55	50	45	55
800 and up				50	45	40	50
	10 - 49			70	65	60	70
	50 - 99			65	60	55	65
	100 - 199			60	55	50	60
	200 - 399			55	50	45	55
	400 and up			50	45	40	50
		10 - 29		--	--	--	75
		30 - 59		--	--	--	70
		60 - 119		--	--	--	65
		120 - 239		--	--	--	60
		240 - 499		--	--	--	55
		500 - 799		--	--	--	50
		800 and up		--	--	--	45
			1 - 99	35	30	25	35
			100 - 299	40	35	30	40
			300 - 999	45	40	35	45
			1,000 - 2,999	50	45	40	50
			3,000 - 9,999	55	50	45	55
			10,000 - 29,999	60	55	50	60
			30,000 and up	65	60	55	65

Notes:

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

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

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

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

The steps for developing the inventory are:

1. Construct tables for all the noise-sensitive land uses identified in the three land-use categories from Chapter 3.

2. For each alternative, tabulate buildings and sites that lie within the impact contours. For residential buildings, estimate either the number of buildings or number of dwelling units. Other pertinent information, such as existing noise levels, corridor segment delineations and expected train speed also may be useful in tabulating the impacts. An example table is shown in Table 4-6.

3. Prepare summary tables showing the number of buildings and dwelling units within each impact zone for each alternative. Utilize the summary table to compare the alternatives, including those with and without noise mitigation measures.

4. Determine the possible need for mitigation based on the degree of impact and appropriate policy considerations.

Table 4-6 Sample Noise Impact Inventory Table

Alignment: 1
Scenario: HS-Electric

Corridor Segment			Existing Ldn (dBA)	Avg Train Speed (mph)	Distance to Contour (ft)		Impact Inventory without mitigation (Number of Buildings)					
Description	Milepost				Impact	Severe Impact	Impact			Severe Impact		
	From	To					SF	MF	Inst	SF	MF	Inst
Downtown Area	0.0	4.6	70	50	45	25	0	2	0	0	0	0
Inside I-95	4.6	5.7	65	80	70	40	6	1	0	0	0	0
To Route 100	5.7	9.5	65	100	80	45	12	0	0	2	0	0
To Pleasant St	9.5	12.0	65	60	60	30	1	0	0	0	0	0
Smithtown Station	12.0	12.2	60	25	40	20	0	0	0	0	0	0
Lakeville mountains	12.2	20.8	55	80	80	40	1	0	0	0	0	0
Central Valley	20.8	26.9	60	110	100	55	7	0	0	4	0	0
To Rt 66 crossing	26.9	33.4	60	125	110	65	6	0	1	2	0	0
I-84 corridor	33.4	41.6	65	140	125	75	14	0	1	5	0	1
To South St	41.6	44.2	65	80	70	40	2	0	0	1	0	0
Business District	44.2	46.2	65	55	60	30	0	1	0	0	0	0
Springfield Station	46.2	46.4	65	25	40	20	0	0	0	0	0	0

SF: Single-Family Residential Inst: Institutional (schools, churches, hospitals)
MF: Multi-Family Residential

4.2.7 Noise Mitigation Requirements

The final step of the General Assessment is to estimate the noise mitigation measures required to minimize the number of impacts. The primary noise control treatment for steel-wheeled high-speed rail systems is the installation of wayside noise barriers.[4] The approximate noise barrier lengths and locations developed in a general assessment will provide a preliminary basis for evaluating the costs and benefits of impact mitigation. This section provides guidelines for making order-of-magnitude cost estimates for noise barriers based on the length of barrier required. A more complete description of

[4] Due to the unique characteristics of maglev systems, noise control considerations are likely to be made at the outset as an integral part of the system design. Retrofitting a maglev system for noise mitigation measures such as sound barriers is likely to incur great costs. Such design options as building sidewalls into the guideway structure, using a concrete rather than a steel guideway, and minimizing structural vibrations of the guideway and vehicle through design are noise control measures that can be taken as a baseline condition. As a result, it may not be applicable to estimate preliminary mitigation without more detailed information on system design.

noise mitigation, with consideration given to other available mitigation treatments applied at the source, path, or receiver, and the benefits resulting from each is provided in Chapter 5.

Train noise barriers need to be high enough to effectively block the line of sight between the noise source and the receiver. The dominant source of train noise over most operating speeds for steel-wheeled high-speed rail, as with conventional rail systems, is wheel-rail interaction. To shield this noise effectively, relatively low barriers located close to the track are usually sufficient. A barrier with its top edge 6 to 8 feet above the top of rail at the right-of-way line usually achieves effective shielding. A barrier at this height above the top of rail can reduce wheel-rail noise by 8 to 10 dBA.

The attenuation of sound by a barrier is frequency dependent; all other things being equal, the higher the frequency of the noise, the greater the barrier attenuation. Because the sound energy for aerodynamic sound sources is in the low frequencies (below 500 Hz) these sources are inherently difficult to shield with a barrier. Further, because the sound level due to aerodynamic sources increases rapidly with increasing speed, a standard 8-foot barrier is less effective at high speeds, where aerodynamic sources dominate the overall sound level.

A relatively low barrier will not shield sound sources located high above the guideway, since such sources would protrude above the top of the barrier. This noise includes noise from propulsion sources, such as cooling fans, as well as aerodynamic noise generated at the upper part of the train. A description of these sources is presented in Chapter 2.

The following steps can be applied in making a preliminary estimate of the noise mitigation measures that might be required following an initial evaluation of noise impact:

1. Barrier Height. Assume an average noise barrier height of 8 feet as a cost-effective mitigation measure for high-speed rail noise impact. If shielding noise from higher noise sources (such as propulsion units) or protecting higher floors of residences is required, assume a 16-foot-high barrier.

2. Barrier Length. In addition to height, determine the length of noise barriers needed to extend far enough to each side of the affected receiver so that train noise from beyond the ends of the barrier does not significantly degrade its acoustical performance. As a rule, the barrier should be long enough to shield the entire train length for an angle of at least 60 degrees in either direction.

3. Barrier Cost. Make a mitigation cost estimate based on the average height and length, assuming a unit cost of $20 per square foot. Use this cost to perform a cost-benefit analysis, if required.

4. Barrier Effectiveness. Assume a net barrier attenuation of 5 dBA for an 8 foot-high barrier, and 8 dBA for a 16-foot-high barrier. These attenuations are applicable to both L_{eq} and L_{dn}. Reassess impact with mitigation based on these reductions using the methods in this chapter.

It is important to note that the barrier estimates made in the initial evaluation are preliminary. Detailed barrier designs should be developed during the final engineering phase of the project. Some of the factors to be addressed during the final engineering phase are the structural, aesthetic, and acoustical feasibility of the barriers, as well as their cost effectiveness with respect to their acoustical benefits. The barriers should be constructed if they are found to be practical and prudent.

Examples 4-1 and 4-2 provide two examples of noise analyses utilizing the procedures presented in this chapter. Example 4-1 illustrates the Initial Noise Evaluation procedure for a representative high-speed rail project alternatives analysis, including both the Noise Screening and General Assessment. The source reference levels used in the analysis are taken directly from Table 4-2, since it is assumed that at this stage measurements or specifications of the equipment are unknown. Example 4-2 demonstrates the conversion of a measured or specified L_{max} to the appropriate source reference level in SEL for use in the General Assessment procedure, using the methods presented in Appendix C.

Example 4-1. Initial Noise Evaluation Comparing Two High-Speed Rail Alignments

This example illustrates the initial noise evaluation procedure for a hypothetical high-speed rail project. The project involves an alternatives analysis of a proposed steel-wheeled high-speed rail system to serve a 200-mile intercity corridor. Two alignment options are available, characterized by the following typical corridor segments:

Alignment Alternative 1: A direct route through primarily undeveloped, rural areas with farmland and scattered residences within 1,000 feet of the corridor. The track would be welded rail on ballast and concrete ties at-grade, designed for a maximum speed of 160 mph.

Alignment Alternative 2: Along the median of a busy multi-lane interstate highway (typical vehicle speeds of 60 to 70 mph during freely flowing conditions), passing through a densely developed area with mixed residential and commercial land use. The alignment would be fully grade-separated, with welded rail on aerial structure (direct-fixation track on concrete slab), and with a maximum design speed of 160 mph. An example of a typical corridor segment is illustrated by the plan map in Figure 4-3. The closest unobstructed residences are 80 to 200 feet from the median centerline.

Assumptions

The assumptions for the project are the same for both alignment alternatives and are as follows:

- **Proposed System:** Steel-wheeled electrically powered high-speed train consisting of two power cars (one on each end) and 10 passenger coaches. Unit length of each power car is 73 feet, unit length of each passenger coach is 63 feet.
- **Proposed Service:** Total of 57 trains per day operating between 6:00 a.m. to 11:00 p.m.. Headways are 20 minutes during daytime hours (7 a.m. to 10 p.m.) the day, 20 minutes during nighttime hours (10 p.m. to 12 a.m., 5 a.m. to 7 a.m.) This service results in the following average hourly volumes:

V_D = 3 trains/hour
V_N = 1.33 trains/hour

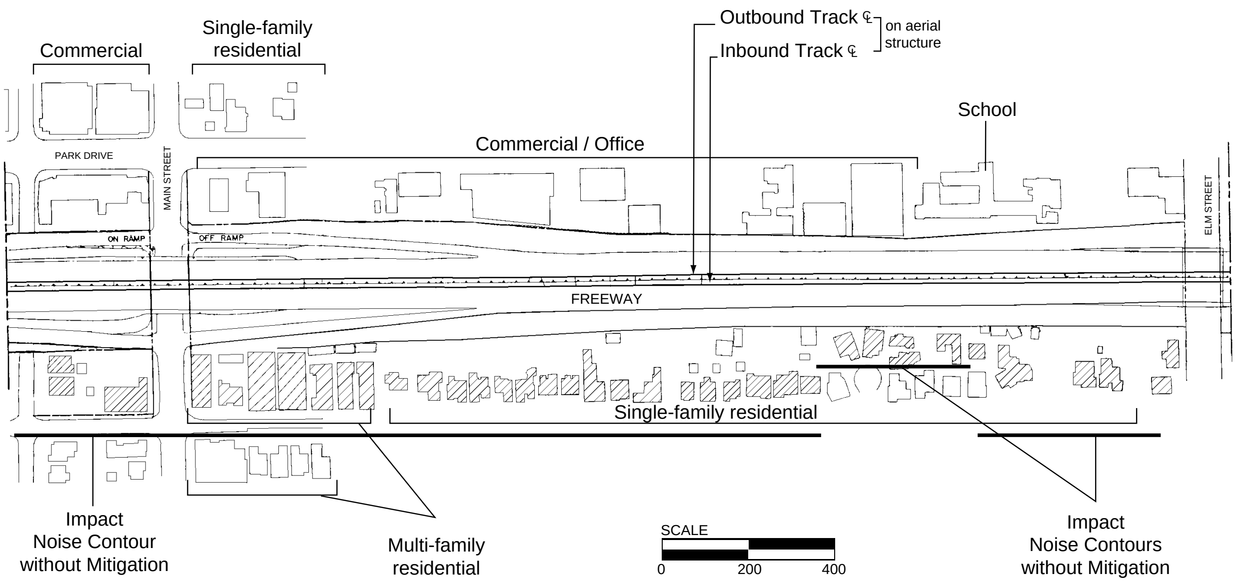

Figure 4-3. Typical Corridor Segment for Example 4-1, Alignment Alternative 2

Procedure

For steel-wheeled systems, the screening procedure (Table 4-1) calls for additional analysis for noise-sensitive land use within 450 feet of a shared corridor-type right-of-way, and 900 feet of a new corridor through undeveloped land, thereby requiring further noise analysis for both alternatives. The procedure is summarized as follows:

Determination of Noise Exposure at 50 feet

1. Determine reference SEL at 50 feet and parameters for proposed system
Table 4-2 indicates that the maximum design speed of 180 mph puts the system in speed regime III (aerodynamic). Thus, the following parameters are applied:

SEL_{ref} = 93 dBA
K = 17
S_{ref} = 90 mph
len_{ref} = 634 feet

The actual source length is defined in Table 4-4 as the total train length, which is calculated as:

len = power cars + coaches = 776 feet

Using the first equation in Table 4-4, adjust to SEL at 50 feet for actual operating conditions,

$$
\begin{aligned}
SEL &= SEL_{ref} + K\log(S/S_{ref}) + 10\log(len/len_{ref}) \\
&= 93 + 17\log(160/90) + 10\log(776/634) \\
&= 98.1 \text{ dBA, or } 98 \text{ dBA (rounded).}
\end{aligned}
$$

2. Calculate $L_{eq}(h)$ and L_{dn} at 50 feet, adjusting for track geometry
For Alignment 1, the track is at-grade so there is no shielding adjustment for track geometry, i.e., $C_s = 0$. Thus, using the equations in Table 4-4,

$$
\begin{aligned}
L_{eq}(day) &= SEL + 10\log(V_d) + C_s - 35.6 \\
&= 93 + 10\log(3) + 0 - 35.6 = 67.3 \text{ dBA} \\
L_{eq}(night) &= SEL + 10\log(V_n) + C_s - 35.6 \\
&= 98 + 10\log(1.33) + 0 - 35.6 = 63.8 \text{ dBA}
\end{aligned}
$$

and, L_{dn} = 70.9 dBA, or 71 dBA (rounded)

For Alignment 2, speed regime III, Table 4-3 indicates that C_s = +2 dBA for aerial structure. Thus,

$$
\begin{aligned}
L_{eq}(day) &= 98 + 10\log(3) + 2 - 35.6 = 69.3 \text{ dBA} \\
L_{eq}(night) &= 98 + 10\log(1.33) + 2 - 35.6 = 65.8 \text{ dBA}
\end{aligned}
$$

and, L_{dn} = 72.9 dBA, or 73 dBA (rounded)

Estimate Propagation of Project Noise Exposure with Distance

3. Apply Noise Exposure-Versus-Distance Relationship
Using the method described in Section 4.2.3, the distance correction equation is applied to the project L_{dn} at 50 feet. A resulting curve of L_{dn} versus distance is obtained for each alignment option, as shown in Figure 4-4.

Estimate Existing Noise Exposure

4. Estimate existing noise at noise-sensitive sites
For Alignment 1, there are no major roadways or rail lines contributing to the existing ambient noise. Thus, the existing noise exposure should be estimated based on population density. For a predominantly rural area, a population density of 300-1000 people/square mile can be assumed, yielding an ambient L_{dn} of **45 dBA** (from Table 4-5). From Figure 3-1, the corresponding project noise exposure L_{dn}s causing impact for Category 2 land uses (residential) are 52 dBA and 59 dBA, for Impact and Severe Impact, respectively.

For Alignment 2, the highway (the dominant noise source) is a major linear source from which noise attenuates rapidly with distance. Thus, it would be inaccurate in this case to assign a single "generalized" noise level to characterize a large area, as for Alignment 1. The existing noise exposure should be estimated as a function of distance from the highway on a site-specific basis.

From Figure 4-3, unobstructed residences range from 80 to 200 feet from the highway. Based on the information in Table 4-5 the L_{dn} is 70 dBA for residences closer than 100 feet from a major interstate highway, and 65 dBA for residences between 100 and 200 feet.

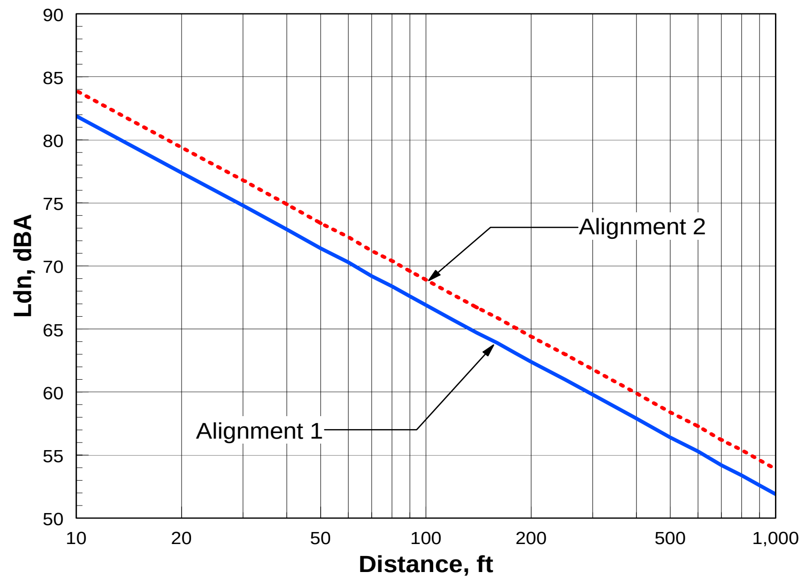

Figure 4-4. Project Noise Exposure vs Distance for Example 4-1

Applying the impact criteria curves in Figure 3-1, the project noise levels that cause impact for Alignment 2 are listed in the following table:

Distance to Highway	Existing Noise, L_{dn}	Project L_{dn} Criterion	
		Onset of Impact	**Onset of Severe Impact**
50 - 99 ft	70 dBA	64 dBA	69 dB
100 - 200 ft	65 dBA	61 dBA	66 dB

Even though the criteria allow for a higher project L_{dn} for Alignment 2 than for Alignment 1 due to the higher existing noise environment, the net allowable increase is less for Alignment 2 (1 to 4 dB) than for Alignment 1 (8 to 14 dB).

Noise Impact Contours

5. Determine Distances to Impact and Severe Impact
Distance-to-impact contours for each alignment are determined by extrapolating along the curves in Figure 4-4 and the project impact thresholds defined in Step 4. The results are summarized as follows for the residences and school:

Alternative	Distance	Existing Noise, L_{dn}	Distance to Noise Impact Threshold, feet	
			Impact	**Severe Impact**
Alignment 1	1000 ft	45 dBA	980	330
Alignment 2	50 - 99 ft	70 dBA	200	90
	100 - 200 ft	65 dBA	330	150

6. Draw Noise Impact Contours
Draw contours for each affected residence based on the distances given in the table in Step 5. The impact distances are defined in terms of distance from the project corridor centerline.

For Alignment 2, the Impact contours are shown in Figure 4-3. The Severe Impact contours do not go beyond the edge of the highway and are thus omitted for simplicity. The impact noise contours are drawn at the two different distances, 200 feet and 350 feet, resulting from the change in existing noise based on distance to the highway. 38 residential buildings are located within the contours defining Impact (shaded in Figure 4-3).

7. Estimate Startle Effects/Wildlife
For either alignment, the distance within which startle could occur is the same. Using a speed of 160 mph in Figure 4-2 results in a distance of approximately 33 feet within which a person could be startled by a high-speed train. None of the buildings in Alignment 2 is within that distance.

The distance within which wildlife could be disturbed also should be evaluated. According to Table 3-3, whenever the SEL exceeds 100 dBA there is a potential for effects on animals. Using Alignment 1 as a likely example, the SEL at 50 feet is 98 dBA. Using the propagation equation given in Section 4.2.3 with SEL in place of L_{eq} (which is valid since both are sound energy descriptors), the distance "d" becomes 37 feet for SEL = 100 dBA. Consequently, wildlife could be disturbed within 37 feet of the tracks in Alignment 1.

End of Example 4-1

Example 4-2. Conversion of Specified L_{max} to Source Reference Level in SEL

In the previous example, Alignment 2 is chosen as the preferred project alternative. The proposed system is modeled on a European high-speed electric trainset with the following noise performance:

L_{max} = 86 dBA, measured at a distance of 82 ft from track centerline and a speed of 100 mph,

which puts us in **Regime II** for the General Assessment.

The steps to convert L_{max} to the equivalent source reference levels for use in the General Assessment, instead of the tabulated value in Table 4-2, are as follows:

1. Convert to SEL under specified conditions
The parameters needed to evaluate the third equation in Table C-2 of Appendix C are:

len = 776 feet,

S = 100 mph,

d = 82 feet, and

$$\alpha = \arctan\left(\frac{len}{2d}\right) = 1.36$$

Substituting into this equation we get SEL at the specified distance and speed:

$$SEL = 86 + 10\log\left(\frac{776}{100}\right) - 10\log(2\times1.36) + 3.3 = 93.9 \text{ dBA, or } 94 \text{ dBA (rounded)}$$

2. Normalize to reference conditions of Table 4-2
Use the fourth equation in Table C-2 to normalize the SEL to the appropriate reference parameters in Table 4-2, for comparison with the tabulated level. The following values are required from Table 4-2:

K = 17,
S_{ref} = 90 mph, and
len_{ref} = 634 feet.

Evaluating the fourth equation in Table C-2 yields:

$$SEL_{ref} = SEL + K\log\left(\frac{S_{ref}}{S}\right) + 10\log\left(\frac{len_{ref}}{len}\right) - 15\log\left(\frac{50}{d}\right)$$

SEL_{ref} = 95.4 dBA, or 95 dBA (rounded).

Thus, this value of SEL_{ref}, based on the specified L_{max}, is 2 dBA higher than the tabulated value, 93 dBA, in Table 4-2 for a steel-wheeled electric train in this speed regime.

End of Example 4-2

Chapter 5

DETAILED NOISE ANALYSIS

Procedures for performing a comprehensive assessment of noise impact for proposed high-speed rail projects are presented in this chapter. The Detailed Noise Analysis allows site-specific noise predictions and mitigation evaluations. Considerably more precision can be achieved with the Detailed Noise Analysis than is possible with the General Assessment described in Chapter 4. While the General Assessment involves the use of generalized, overall noise source levels and simplified noise projection models, a Detailed Noise Analysis considers the noise from each subsource component, with each component defined in terms of a noise-generating mechanism (e.g., propulsion, wheel-rail, aerodynamic), reference noise level, location along the train, and speed dependency. The Detailed Noise Analysis also uses more precise methods to estimate adjustments for horizontal and vertical geometry, ground absorption, and shielding. Although the Detailed Noise Analysis procedures present all the information needed to predict noise and assess impact under "normal" circumstances, sometimes it will be appropriate to adapt the procedures using practical engineering judgement to reflect a project’s specific design parameters.

The Detailed Noise Analysis is appropriate for assessing noise impacts for high-speed rail projects after the preferred alignment and candidate high-speed rail technologies have been selected. At this point the preliminary engineering has been initiated and the preparation of an environmental document (usually an Environmental Impact Statement) has begun. Information required to perform a Detailed Noise Analysis includes type of vehicle equipment to be used, train schedules, speed profiles, plan and profiles of guideways, locations of access roads, and landform topography, including adjacent terrain and building features.

Equations, rather than graphs or tables of numbers, are used in these procedures as the primary mode of computation to allow the use of spreadsheets and/or programmable calculators. These equations and their supporting text have been streamlined in this chapter to provide a concise view of the Detailed Noise Analysis. Background information on noise concepts and the basics of high-speed rail noise are presented in Chapter 2 and Appendix A.

The steps in performing the Detailed Analysis parallel the steps for the General Noise Assessment, although more refined procedures are used to predict project noise and evaluate mitigation measures. The steps are outlined below.

Existing Conditions

Step 1. **Noise Sensitive Receivers**. Guided by the information in Section 5.1.1, identify noise-sensitive receivers. The number of receivers will depend upon the land use in the vicinity of the proposed project and the extent of the study area defined by the screening procedure described in Chapter 4. An initial evaluation (using the procedures presented in Chapter 4) will provide a good indication of the extent of potential impacts.

Step 2. **Existing Noise Exposure**. Estimate the existing noise exposure at each noise sensitive receiver or cluster of receivers using the methods presented in Section 5.1.2.

Projections of High-Speed Rail Noise

Step 3. **Source Reference Levels**. Determine the technology applicable to the project: steel-wheeled high-speed (electric or fossil fuel), steel-wheeled very high-speed, or maglev. For each noise subsource, determine noise exposure in terms of SEL under reference operating conditions. These reference levels should incorporate source-noise mitigation that will be incorporated into the system specifications.

Step 4. **Project Operating Conditions**. Adjust the subsource reference SELs to the anticipated operating conditions of the project (i.e., train consist and speed).

Step 5. **Propagation of Noise to Receivers**. Develop an SEL-versus-distance relationship for each subsource that includes the effects of shielding along the path, as well as any propagation-path mitigation that will be included in the project.

Step 6. **Total Noise Exposure**. Determine total SEL at each receiver by combining the levels from all subsources. Use the SEL to calculate total noise exposure [L_{dn} or L_{eq} (h)] using project operating parameters, including train schedule, speed, and length.

Step 7. **Maximum Noise Level for Train Passbys**. (optional) If determining compliance with vehicle noise limits, project specifications or comparison with measured noise levels is desired, calculate the L_{max} using equations provided in Appendix C.

Noise Impact Assessment

Step 8. **Noise Impact Assessment**. Assess noise impact at each receiver or cluster of receivers using the criteria described in Chapter 3. If a geographic information system (GIS) database is available, incorporating the noise projections and the impact assessment into the GIS database can be an effective means of identifying and displaying where noise impact is expected to occur and comparing the relative impacts for different alternatives. While a conceptual approach for GIS implementation is provided, the details of this process are beyond the scope of this document.

Mitigation of Noise Impact

Step 9. **Mitigation of Noise Impact**. Where the assessment shows impact, evaluate alternative mitigation measures; then loop back to Step 3, modify the project noise computations, and reassess the remaining noise impact. The locations where noise mitigation is needed and any residual impacts with mitigation also can be effectively displayed with GIS databases.

5.1 EXISTING CONDITIONS

5.1.1 Step 1: Noise Sensitive Receivers

The basic steps in identifying noise sensitive receptors are:

- Identify all noise-sensitive land uses.
- Find individual receivers, such as isolated residences and schools.
- Group residential neighborhoods into "clusters" that have similar levels of existing noise and would have similar levels of project noise.

The steps in identifying noise sensitive receivers, both the number of receivers needed and their locations, are shown in Figure 5-1.

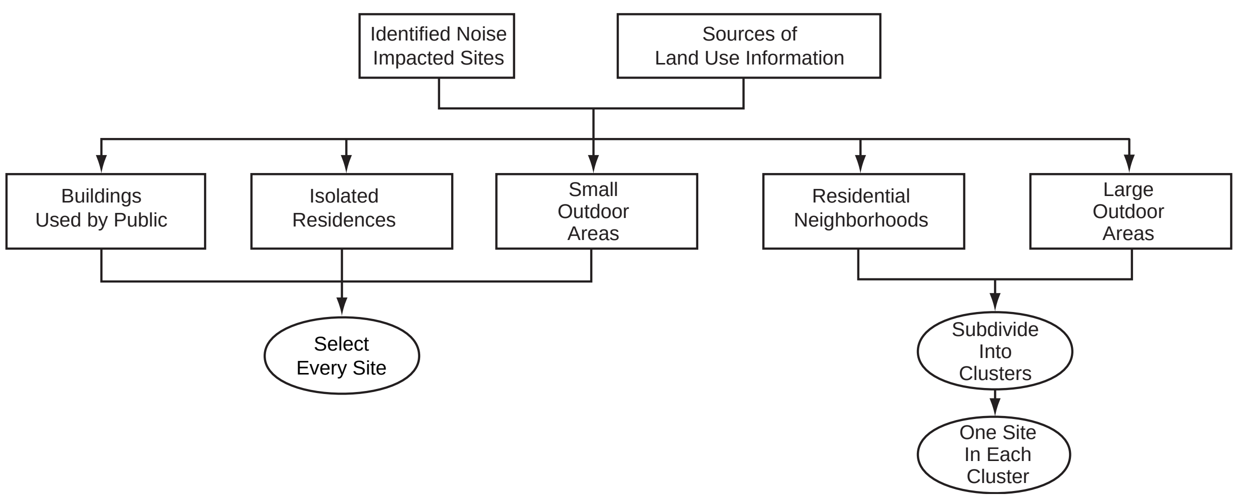

Figure 5-1 Guide to Selecting Receivers of Interest

Identify Noise-Sensitive Land Uses

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

Three categories of land most likely to be affected by noise from high-speed rail projects are listed in Table 5-1. If noise impact was identified at other types of buildings/areas with noise-sensitive use by the general noise assessment, these types also should be identified.

Table 5-1 Noise-Sensitive Land Uses

Land Uses	Specific Use	Selecting Receivers
Outdoor noise-sensitive areas	• Parks • Historic sites used for interpretation • Amphitheaters • Recreation areas • Playgrounds • Cemeteries	• Select each noise-sensitive site
Residences	• Single family residences • Multi-family residences (apartment buildings, duplexes, etc.)	• Select each isolated residence • For residential areas with uniform noise levels, cluster as described in text
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	• Select each noise-sensitive building

Sources of information that can be helpful in locating noise-sensitive land uses in the vicinity of the proposed project include:

- **Land use maps** prepared by regional or local planning agencies or by the project staff. Particularly useful are project-specific maps (track plans, right-of-way plan and profile), which provide building-by-building detail for land uses bordering the project.
- **USGS maps** prepared by the United States Geological Survey, generally at 2,000-foot scale. These maps show individual buildings except in highly urbanized areas, and generally show the location of all schools and places of worship, plus many other public-use buildings. The topographic contours on these maps can be useful for estimating acoustical shielding.

- **Road and town maps**. These maps can supplement the USGS maps. They are generally more up-to-date and may be of larger scale.
- **Aerial photographs,** especially those of 400-foot or smaller scale. When current, aerial photos are valuable in locating potential noise-sensitive land uses close to the proposed project and for determining the distances between receivers and the project alignment.
- **Windshield survey** of the corridor. Definitive identification of noise-sensitive sites often requires driving the corridor and annotating land uses on base maps. Driving the corridor may be the only way to identify new construction, to confirm land uses very close to the project boundary, and to identify site characteristics such as topography and terrain features that are not readily apparent from maps.

Selecting Individual Receivers

Typically, major noise-sensitive public buildings, isolated residences, and relatively small outdoor noise-sensitive areas will be selected as individual receivers. Some judgement in selection is required to avoid a noise analysis where it is obviously not needed. For example, many roadside motels are not particularly sensitive to noise from outdoors. On the other hand, buildings and outdoor areas that the community considers to be particularly noise sensitive must be included. Isolated residences that are particularly close to the project should certainly be included, while those at some distance may often be omitted or clustered together with other land uses, as described in the next section.

Relatively small outdoor noise-sensitive areas should be evaluated using judgement and common sense. For example, playgrounds can often be omitted unless they directly abut the proposed project since noise sensitivity in active playgrounds is generally low.

Clustering Noise-Sensitive Land Uses

Residential neighborhoods and relatively large outdoor noise-sensitive areas often can be clustered, simplifying the analysis without compromising accuracy. These neighborhoods/areas should be subdivided into clusters of approximately uniform noise, each containing a collection of noise-sensitive sites. Uniformity of both project noise and ambient noise should be attained, guided by these receiver-to-source distance considerations:

- In general, project noise drops off with distance from the project. For this reason, project noise uniformity requires nearly equal distances between the project noise source and all points within the cluster. Such clusters will usually be shaped as narrow strips parallel to the rail corridor. Clusters within which the noise exposure will vary over a range of 2 decibels or less are suggested. The fact that noise exposure from rail operations drops off approximately 3 to 4.5 decibels per doubling of distance from the tracks, assuming propagation over open terrain, should be used as guidance. The drop-off will be faster when rows of buildings, terrain, or other obstacles offer acoustical shielding.

- 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 a manufacturing facility. Clusters within which the ambient noise will vary over a range of 3 to 5 decibels or less are recommended, though this may be hard to judge without measurements.

After defining the cluster, one receiver should be selected as representative of the cluster. Generally the receiver closest to the project and at an intermediate distance from the predominant sources of existing noise should be selected.

5.1.2 Step 2: Existing Noise Exposure

In estimating existing noise exposure, one must first decide whether, and how thorough, a noise survey will be performed. Some noise monitoring should be performed unless extenuating circumstances make measurements impractical. Project schedule, bad weather, and limited budget are typical reasons that measurements may not be possible. The most common approach is to use measurements at representative sites to characterize existing noise. When measurements are not possible, the existing noise exposure can be estimated using Table 4-5 in Chapter 4. A penalty for using the convenient tabular estimates is a built-in conservatism in the projections. That is, the projections under-predict the ambient noise somewhat, and thereby over-predict relative noise impact.

Guidelines for noise measurements to characterize existing noise exposure for both residential and non-residential land uses include:

- For non-residential land uses, measure for 30 to 60 minutes at the receiver, preferably on at least two nonsuccessive weekdays (generally between Monday morning and Friday afternoon). Select the hour of the day when the project activity is expected to be at a maximum.
- For residential land uses, measure for a full 24 hours at the receiver for one or more weekday periods (generally between Monday morning and Friday afternoon).
- Use judgement in positioning the measurement microphone. Location of the microphone at the receiver depends upon the proposed location of the high-speed rail alignment. If, for example, a new rail line will be in front of the house, do not locate the microphone in the back yard. Recommended measurement positions corresponding to various locations of the project source are illustrated in Figure 5-2.
- Undertake all measurements in accordance with good engineering practice, following guidelines contained in ASTM and ANSI Standards.[1,2]

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[1]American Society for Testing and Materials, "Standard Guide for Measurement of Outdoor A-Weighted Sound Levels," E 1014-84, Philadelphia, 1984.

[2]American National Standards Institute, "Method for the Measurement of Sound Pressure Levels," ANSI S1.13-1971 (R1976), New York, 1971.

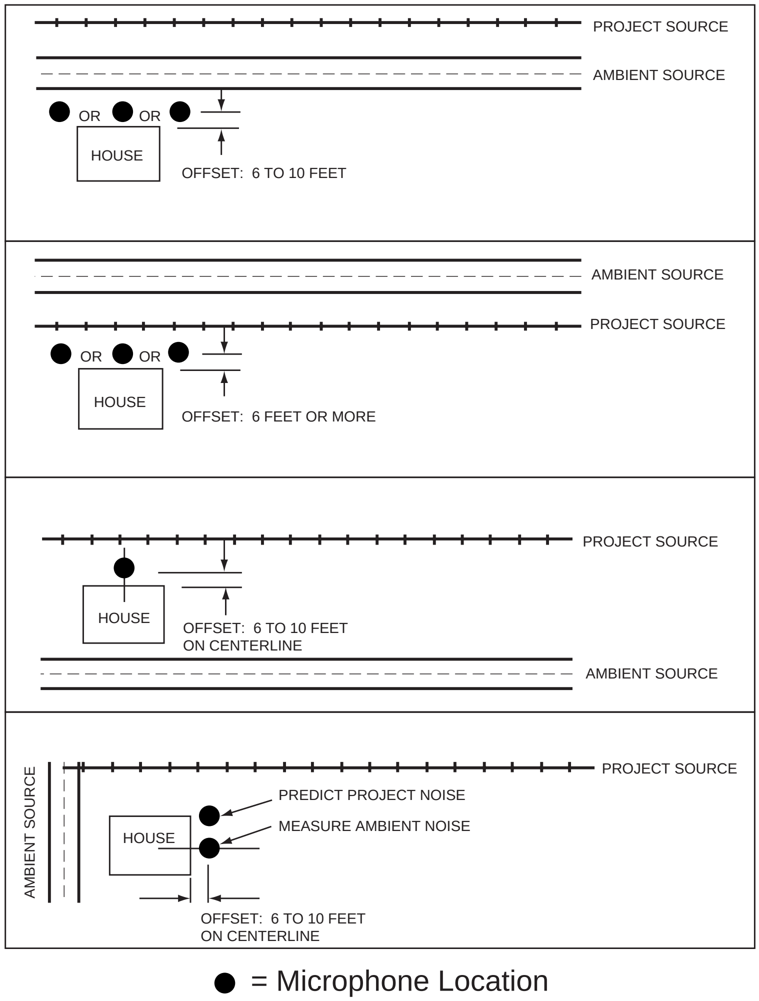


Figure 5-2 Recommended Microphone Locations for Existing Noise Measurements

Measurements made at representative receivers often are used to estimate noise exposure at other similar receivers. In other situations, several hourly L_{eq} measurements at a receiver can be used to estimate L_{dn}. Both of these options require the intuition gained from experience and a knowledge of acoustics to select representative measurement sites.

Measurements at one receiver can be used to represent the noise environment at other sites, but only when proximity to major noise sources is similar among the sites. For example, a residential neighborhood with otherwise similar homes may have greatly varying noise environments. One part of the neighborhood may be located where the ambient noise is clearly due to highway traffic. A second part, toward the interior of the neighborhood, may have highway noise as a factor, but also will receive a significant contribution from other community noise. In a third part of the neighborhood, located deep in the residential area, local street traffic and other community activities could 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.

Representative measurement sites typically can be used to estimate noise levels at other sites 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, and
- 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 judgement in fully utilizing the measurements in their computations. On the other hand, people lacking a background in acoustics should use the procedures in Appendix B to accomplish this same aim. The procedures contained in Appendix B are an attempt to systematize such computations from partial measurements. As a safety factor, these procedures underestimate ambient noise to account for reduced precision compared with full noise measurements.

5.2 PROJECTIONS OF HIGH-SPEED RAIL NOISE

Once receivers have been selected, projections of noise from high-speed trains can be developed for each receiver. The subsequent steps in the computation procedure, described in detail in Sections 5.2.1 through 5.2.5, are:

Step 3. **Source Reference Levels**. Establish the type of system for the proposed high-speed rail project. Determine the reference SEL, length, and speed relationship for each noise subsource on the train.

Step 4. **Project Operating Conditions**. Adjust each subsource SEL to the operating conditions of the project (consist and speed).

Step 5. **Propagation of Noise to Receivers**. Estimate the propagation effects of geometric spreading, ground attenuation, and shielding for each subsource SEL to develop an SEL-versus-distance relationship. Compute an overall, combined SEL from all subsources for a single train passby as a function of distance.

Step 6. **Total Noise Exposure**. Use the project’s operating parameters to calculate overall noise exposure at each receiver from the combined SEL.

Step 7. **Maximum Noise Level for Train Passbys**. If necessary, calculate the maximum noise Level (L_{max}) from a single train passby. L_{max} is not used in the assessment of noise impact, but may be useful for comparisons with measurement data or project specifications.

5.2.1 Step 3: Source Reference Levels

The wayside noise level generated by a high-speed train passby depends primarily on system design and its operating conditions. The SEL used to describe a given system under a fixed set of operating conditions (speed, consist, track configuration) at a reference distance is called the **source reference level.** Since a number of high-speed rail systems are in existence worldwide, with design variations ranging from the type of propulsion mechanism to the car body shape, it is necessary to develop a set of generalized source reference levels for use in the prediction model established in this manual. A review of available data resulted in grouping all existing high-speed rail systems into the following five categories:

- ***High-Speed, Steel-Wheeled Electric***
  Electric-powered, locomotive-hauled trains with maximum operating speeds of 125 to 150 mph,

- ***High-Speed, Steel-Wheeled Fossil Fuel***
  Fossil fuel-powered, locomotive-hauled trains with maximum operating speeds of 125 to 150 mph,

- ***High-Speed, Steel-Wheeled EMU***
  Electric-powered multiple unit (EMU) trains with maximum operating speeds of 125 to 150 mph,

- ***Very High-Speed, Steel-Wheeled Electric***
  Electric-powered, locomotive-hauled trains with maximum operating speed of 200 to 250 mph, and

- ***Maglev***
  Magnetically-levitated trains with maximum operating speed of 250 mph and up.

Once the appropriate system category is selected, the first action in the detailed noise prediction procedure for high-speed train passbys is to establish the source reference level and the corresponding reference conditions for that category. Depending on the system category, this source reference level can be broken down into two or more *subsources* as described in Chapter 2. These subsources relate directly to the various location-specific noise-generating mechanisms on the train, and can be categorized into one of the following three component categories:

- propulsion,
- mechanical, or
- aerodynamic noise.

The relevant subsources and their nominal noise reference levels to be used in computing noise exposure for each of the five system categories are listed in Table 5-2. In this table, the reference SEL for each subsource is given for the reference distance of 50 feet from the track centerline. Also given in the table are the definition and reference value of the associated length of each subsource; for example, wheel-rail noise is associated with the entire train length, while propulsion noise originates only from the power cars. The subsource length is an important parameter, since SEL is an energy descriptor and for a train is always defined normalized to some reference length. The subsource heights, expressed in terms of the height above the rails (or guideway), are also listed in Table 5-2 and are used in evaluating shielding and other propagation effects as described in Section 5.2.3.

The levels in Table 5-2 are based on the results of the background measurement and research program that preceded the preparation of this manual. That program has resulted in an extensive database of noise data on most existing high-speed rail systems, ensuring that Table 5-2 is reasonably accurate for the existing technologies. However, when specific equipment has been selected for a project, it will be more accurate to base the impact assessment on noise measurements of that equipment.[3]

For some projects, source-noise levels will be pre-defined; for example, noise limits are usually included in the specifications for purchase of new vehicles. Compliance with such specifications, almost always defined in terms of L_{max}, can be checked using the equations found in Appendix C. This option is addressed further in Section 5.2.5, accompanied by an example in which noise projections are used to determine compliance with a noise specification given in terms of L_{max}.

[3]As a cautionary note, measurements to obtain reference quantities as in Table 5-2 require special techniques to separate subsource components and are beyond the scope of this manual. If single level measurements are performed, methods for converting these levels to the simplified reference levels used in the General Assessment procedure (Chapter 4) are given in Appendix C.

<table>
<tr><th colspan="10">Table 5-2 Source Reference SELs at 50 feet</th></tr>
<tr><th rowspan="2">System Category and Features [a]</th><th rowspan="2">Example Systems</th><th rowspan="2" colspan="2">Subsource Component</th><th colspan="2">Subsource Parameters</th><th colspan="4">Reference Quantities</th></tr>
<tr><th>Length Definition, len</th><th>Height above rails (ft)</th><th>SEL_{ref} (dBA)</th><th>len_{ref} (ft)</th><th>S_{ref} (mph)</th><th>K</th></tr>
<tr><td rowspan="2">HS ELECTRIC
• Steel-Wheeled
• High-Speed
• Locomotive-Hauled
• Electric Power</td><td rowspan="2">X2000
Talgo (electric)
Amtrak HST</td><td colspan="2">Propulsion</td><td>len_{power}</td><td>10</td><td>86</td><td>73</td><td>20</td><td>15</td></tr>
<tr><td colspan="2">Wheel-rail</td><td>len_{train}</td><td>1</td><td>91</td><td>634</td><td>90</td><td>20</td></tr>
<tr><td rowspan="2">HS FOSSIL FUEL
• Steel-Wheeled
• High-Speed
• Locomotive-Hauled
• Fossil Fuel Power</td><td rowspan="2">RTL-2
Talgo (gas turbine)</td><td colspan="2">Propulsion</td><td>len_{power}</td><td>10</td><td>83</td><td>73</td><td>20</td><td>10</td></tr>
<tr><td colspan="2">Wheel-rail</td><td>len_{train}</td><td>1</td><td>91</td><td>634</td><td>90</td><td>20</td></tr>
<tr><td rowspan="2">HS EMU
• Steel-Wheeled
• High-Speed
• Electric Multiple Units (EMU)</td><td rowspan="2">Pendolino
IC-T</td><td colspan="2">Propulsion</td><td>len_{power}</td><td>10</td><td>86</td><td>73</td><td>20</td><td>1</td></tr>
<tr><td colspan="2">Wheel-rail</td><td>len_{train}</td><td>1</td><td>91</td><td>634</td><td>90</td><td>20</td></tr>
<tr><td rowspan="5">VHS ELECTRIC
• Steel-Wheeled
• Very High-Speed
• Locomotive-Hauled
• Electric Power</td><td rowspan="5">TGV
Eurostar
ICE
Shinkansen</td><td colspan="2">Propulsion</td><td>len_{power}</td><td>12</td><td>86</td><td>73</td><td>20</td><td>0</td></tr>
<tr><td colspan="2">Wheel-rail</td><td>len_{train}</td><td>1</td><td>91</td><td>634</td><td>90</td><td>20</td></tr>
<tr><td rowspan="3">AERO</td><td>Train Nose</td><td>len_{power}</td><td>10</td><td>89</td><td>73</td><td>180</td><td>60</td></tr>
<tr><td>Wheel Region</td><td>len_{train}</td><td>5</td><td>89</td><td>634</td><td>180</td><td>60</td></tr>
<tr><td>Pantograph</td><td>[b]</td><td>15</td><td>86</td><td>–</td><td>180</td><td>60</td></tr>
<tr><td rowspan="4">MAGLEV</td><td rowspan="4">TR07</td><td colspan="2">Propulsion</td><td>len_{train}</td><td>0</td><td>72</td><td>82</td><td>20</td><td>3</td></tr>
<tr><td colspan="2">Guideway/Structural</td><td>len_{train}</td><td>-5</td><td>73</td><td>82</td><td>60</td><td>17</td></tr>
<tr><td rowspan="2">AERO</td><td>Train Nose</td><td>len_{power}</td><td>5</td><td>78</td><td>20</td><td>120</td><td>50</td></tr>
<tr><td>TBL [c]</td><td>len_{train}</td><td>10</td><td>78</td><td>82</td><td>120</td><td>50</td></tr>
</table>

[a] ***HS*** *(High-Speed)* = maximum speed 125-150 mph
VHS *(Very High-Speed)* = maximum speed 200-250 mph
MAGLEV = maximum speed 250 mph and up

[b] originates as a point source (no length)

[c] Turbulent Boundary Layer

5.2.2 Step 4: Project Operating Conditions

Since the source reference levels given in Table 5-2 are for a specific train length and speed, they must be normalized to reflect the actual operating conditions of the project. In other words, trains whose consists are different from the reference consists assumed in Table 5-2 require conversion since they will produce different noise exposure. The same is true for trains at speeds other than those listed in Table 5-2. As guidance, a 40 percent change in the number of power cars or coaches per train, *or* a 15 percent change in train speed, will produce an approximate 2-decibel change in noise exposure.

Once the appropriate system category and reference quantities are established, the following input parameters are required to adjust each reference SEL to the appropriate operating conditions:

- number of passenger cars in the train, N_{cars},
- number of power units in the train, N_{power},
- length of one passenger car, $ulen_{car}$,
- length of one power unit, $ulen_{power}$, and
- train speed in miles per hour, S.

The following equation should be used to adjust each "*n*th " subsource SEL to the operating conditions identified above:

$$SEL_n = (SEL_{ref})_n + 10\log\left(\frac{len}{len_{ref}}\right)_n + K\log\left(\frac{S}{S_{ref}}\right)_n$$

The consist adjustment in the above equation is reflected in the "10 log(len/len_{ref})" term, where *len* represents the subsource length (len_{power}, len_{train}) specified in Table 5-2. These variables are defined as:

$len_{power} = N_{power} \times ulen_{power}$, and

$len_{train} = (N_{power} \times ulen_{power}) + (N_{cars} \times ulen_{car})$.

The speed adjustment is given by the "$K \log(S/S_{ref})$" term, using the appropriate value for K in Table 5-2.

5.2.3 Step 5: Propagation of Noise to Receivers

Propagation characteristics must now be considered in order to compute the noise exposure at specific receivers, using the project SEL at 50 feet for each subsource as the basis for calculation. The sequence in this process are as follows:

- Determine the propagation characteristics between each subsource and the receiver.
- Develop an SEL-distance relationship for each subsource.
- Add a final adjustment using the appropriate shielding term based on intervening barriers and/or terrain features between subsource and receiver.

The steps required to carry out this sequence, resulting in calculation of a specific noise exposure-versus-distance relationship for each noise subsource, are described below:

1. Set up cross-sectional geometries: Draw several approximate topographic sections, each perpendicular to the path of moving sources or radially outward from point sources, similar to those shown in Figure 5-3. Draw separate sections, if necessary, to account for significant changes in topography and/or track geometry. Use judgement to reasonably limit the number of cross sections required. Fewer than ten "typical" sections throughout the project corridor will usually suffice.

2. Estimate Ground Effects:[4] For each topographic cross section, use the relationships illustrated in Figure 5-3 to determine the **effective path height, H_{eff}**, and from it the **ground factor, G, for the wheel-rail and propulsion noise subsources only**. For aerodynamic noise subsources, ground absorption has little attenuating effect and can be disregarded.

   Larger values of G mean larger amounts of ground attenuation with increasing distance from the source. As shown in Figure 5-3, H_{eff} depends upon subsource heights, which are defined in terms of height above rails in Table 5-2, and upon receiver heights, which is usually taken as 5 feet above ground for both outdoor receivers and first floor receivers.

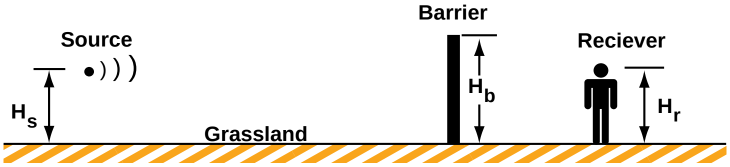
   Because of the different effective source heights for the wheel-rail and propulsion noise subsources, each will have a different H_{eff} and therefore ground factor. For acoustically "hard" (i.e., nonabsorptive) ground conditions, and for all aerodynamic noise subsources, G should be taken to be zero. Application of the computations in Figure 5-3 is restricted to topographies for which horizontal distances are much greater than the vertical distances. In cases where the vertical distance, such as the elevation of the source or receiver, is of the same order of magnitude as any of the horizontal distances, G can be taken as zero if the line of sight is unbroken. Otherwise use the shielding method described in the next step.

3. Estimate Shielding due to Terrain and Noise Barriers: If the line of sight between subsource and receiver is unbroken, calculation of the ground factor (G) alone is sufficient to describe the attenuation of noise with increasing distance. However, if shielding between source and receiver in the form of intervening noise barriers and/or terrain features due to natural topography or to track geometry (e.g., track in cut or on embankment) breaks the line of sight, an additional attenuation must be included in the calculation of propagation effects.

   Equations for computing the attenuation due to shielding ($A_{shielding}$) are provided in Table 5-3 for the basic cross-sectional geometry shown in the figure at the bottom of the table. This fundamental source-barrier-receiver geometry can also be used to model the barrier effect of terrain features that protrude above the line of sight, such as the edge of a deep cut, an embankment, or an earth berm. Examples of application of the shielding model are shown in Figure 5-4.

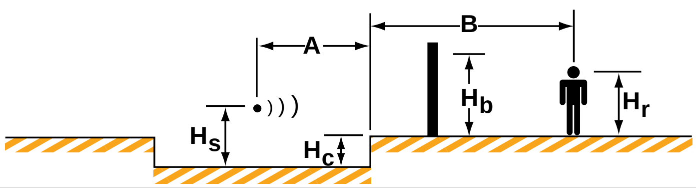
[4] Ontario Ministry of Environment, "ORNAMENT: Ontario Road Noise Analysis Method for Environment and Transportation," November 1988.

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



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

Example 1: Source in shallow cut

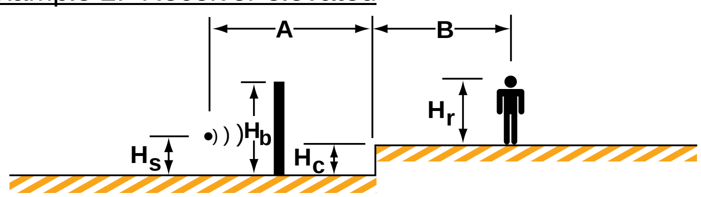


For $B < A/2$,

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

* Otherwise use Equation (1)

Example 2: Receiver elevated



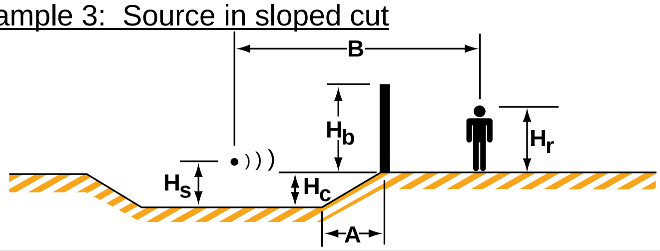
For $H_b > H_c$,

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

For $H_b < H_c$,

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

Example 3: Source in sloped cut

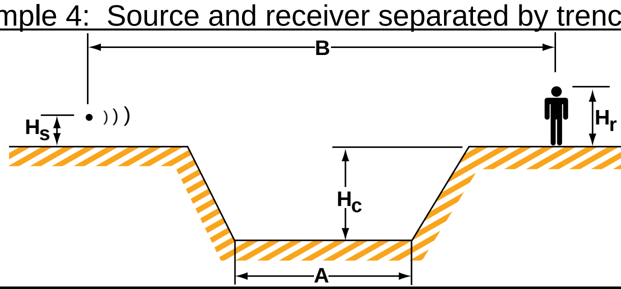


For $A < B/2$,
use Equation (1)

For $A > B/2$,

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

Example 4: Source and receiver separated by trench



For $A > B/2$,

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

For $A < B/2$,

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

Ground Factor

For soft ground:

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

For hard ground:

$$G = 0$$

Notes:

- Values for Sub-Source Heights (H_s) are given in Table 5-2.
- Equations for H_{eff} remain valid even when H_b=0.

Figure 5-3 Computation of Ground Factor G for Ground Attenuation

Table 5-3 Computation of Shielding: Barriers and Terrain

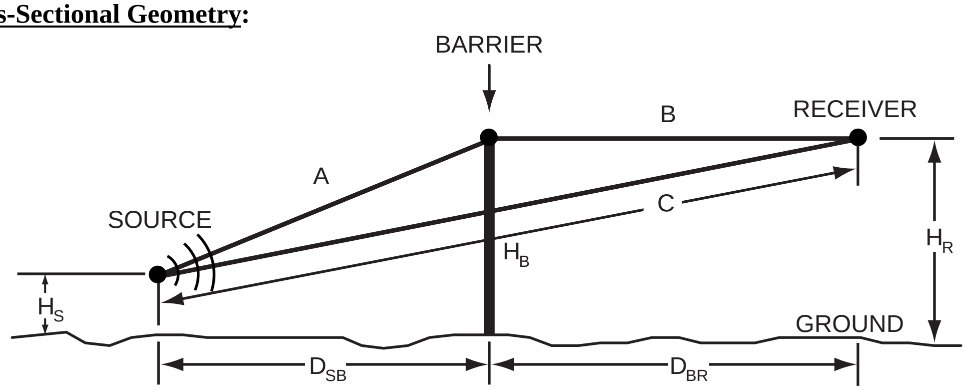
Subsource Type	Equation for Barrier Attenuation
PROPULSION	$A_{barrier} = \min\left\{ 15 \text{ or } \left[20\log\left(\dfrac{2.51\sqrt{P}}{\tanh\left[4.46\sqrt{P}\right]} \right) + 5 \right] \right\}$
WHEEL-RAIL	$A_{barrier} = \min\left\{ 20 \text{ or } \left[20\log\left(\dfrac{3.54\sqrt{P}}{\tanh\left[6.27\sqrt{P}\right]} \right) + 5 \right] \right\}$
AERODYNAMIC	$A_{barrier} = \min\left\{ 15 \text{ or } \left[20\log\left(\dfrac{1.25\sqrt{P}}{\tanh\left[2.22\sqrt{P}\right]} \right) + 5 \right] \right\}$

Barrier Insertion Loss:

$$A_{shielding} = IL_{barrier} = A_{barrier} - 10\left(G_{NB} - G_B\right)\log\left(\frac{D}{50}\right)$$

D	=	closest distance between the receiver and the source, in feet
P	=	path length difference, in feet (see figure below)
G_{NB}	=	Ground factor G computed *without barrier* (see Figure 5-3)
G_B	=	Ground factor G computed *with barrier* (see Figure 5-3)

Basic Cross-Sectional Geometry:



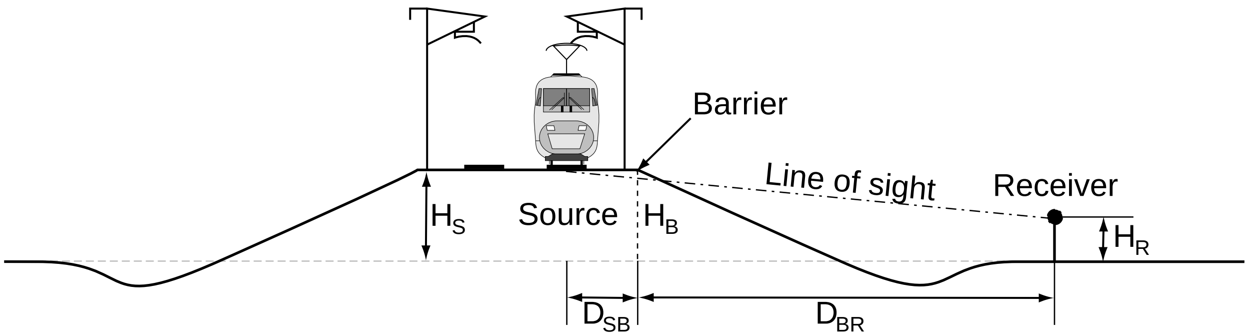
$$P = A + B - C$$

$$A = \sqrt{D_{SB}^{\,2} + \left(H_B - H_S\right)^2}$$

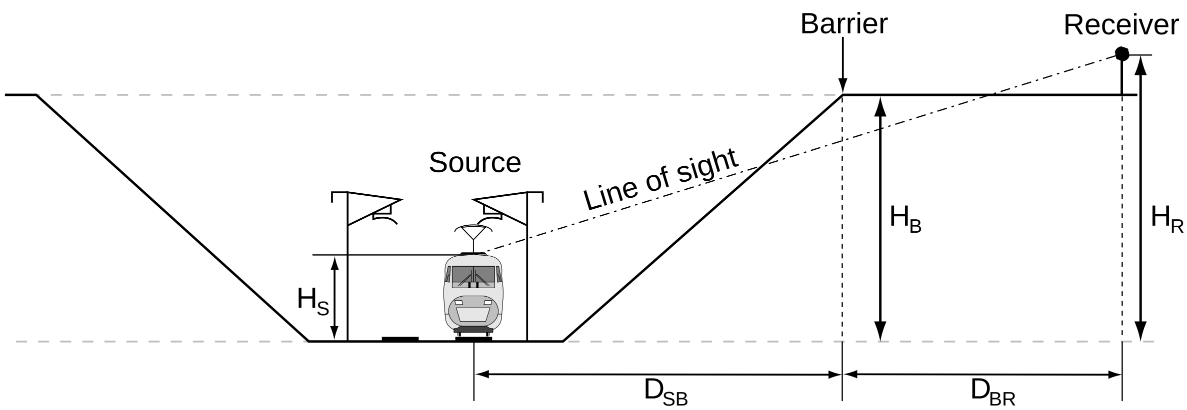
$$B = \sqrt{D_{BR}^{\,2} + \left(H_B - H_R\right)^2}$$

$$C = \sqrt{\left(D_{SB} + D_{BR}\right)^2 + \left(H_S - H_R\right)^2}$$

(a) Barrier Geometry for Edge of Embankment:



(b) Barrier Geometry for Depressed Tracks:



(c) Barrier Geometry for Earth Berm:

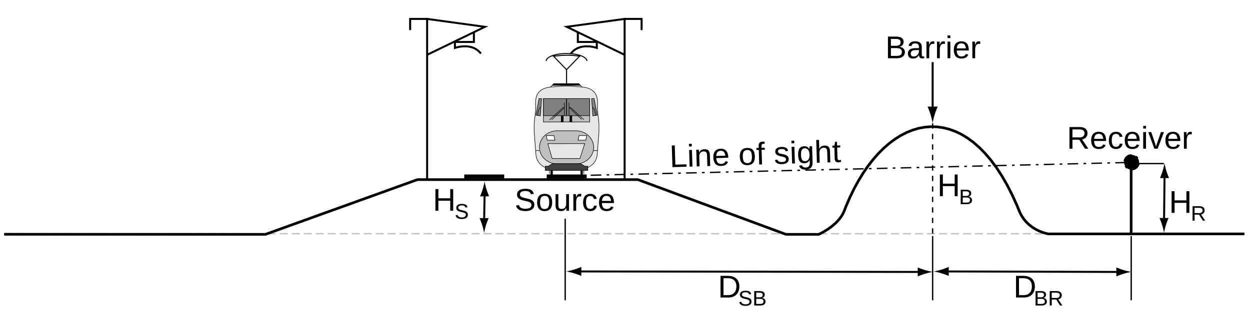


Figure 5-4 Barrier Geometry Models of Terrain for Computation of Shielding

4. Calculate SEL versus Distance: For each subsource SEL at 50 feet developed earlier in the analysis, plot a noise exposure-versus-distance curve, with SEL represented on the vertical axis and distance on the horizontal axis, by evaluating one of the following equations over a range of distances D:

$$SEL = SEL\big|_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{42}\right) - A_{shielding} \qquad \text{for wheel-rail subsources}$$

$$= SEL\big|_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{29}\right) - A_{shielding} \qquad \text{for propulsion subsources}$$

$$= SEL\big|_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - A_{shielding} \qquad \text{for aerodynamic subsources.}$$

5.2.4 Step 6: Cumulative Noise Exposure

The procedures followed in Step 5 (Section 5.2.3) result in calculation of subsource SELs as a function of distance from the project corridor. The next step is to combine the subsources to yield a total SEL value for a train passby and convert from SEL to a measure of cumulative noise exposure based on a specific operating schedule. As guidance, a 40 percent change in either the number of trains per hour or the number of trains per day will produce an approximate 2-decibel change in cumulative noise exposure (L_{eq} or L_{dn}). The procedure is as follows:

1. Total Passby SEL: Calculate the total passby SEL by combining the subsource SELs obtained following Step 4 (Section 5.2.2), using the third equation in Table 5-4. The equations for subsource SEL at 50 feet and at distance *D* are repeated in Table 5-4 for clarity and to illustrate the continuity of the procedure.

2. Noise-Sensitive Hours: Determine the relevant time periods for all receivers that may be affected by the project. For residential receivers, the two time periods of interest for computation of L_{dn} are: daytime (7:00 a.m. to 10:00 p.m.) and nighttime (10:00 p.m. to 7:00 a.m.). For non-residential receivers, choose the loudest project hour during noise-sensitive activity. Several different hours may be of interest for non-residential receivers, depending on the hours the facility is used.

3. Train Operations: Determine number of trains per hour.

   For residential receivers:

   > V_d, the average hourly daytime (7 a.m. to 10 p.m.) train volume, and
   > V_n, the average hourly nighttime (10 p.m. to 7 a.m.) train volume.

   For non-residential receivers:

   > V, the hourly train volume for each hour of interest.

4. Hourly L_{eq}: Compute $L_{eq(h)}$ using the fourth equation in Table 5-4 for each hour of interest.

5. Day-Night Sound Level (L_{dn}): If the project noise will affect any residential receivers, compute the total train L_{dn} using the last three equations in Table 5-4.

Table 5-4 Computation of L_{eq} and L_{dn}

Quantity	Equation
n	
Subsource SEL at 50 ft:	$SEL_n = (SEL_{ref})_n + 10\log\left(\frac{len}{len_{ref}}\right)_n + K\log\left(\frac{S}{S_{ref}}\right)$
Subsource SEL at distance D:	$SEL_n = \begin{cases} SEL_n\Big\vert_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{42}\right) - A_{shielding} & \text{for Wheel/Rail Subsources} \\ SEL_n\Big\vert_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{29}\right) - A_{shielding} & \text{for Propulsion Subsources} \\ SEL_n\Big\vert_{\text{at 50 ft}} - 10\log\left(\frac{D}{50}\right) - A_{shielding} & \text{for Aerodynamic Subsources} \end{cases}$
***N* Subsources**:	
Total SEL for train passby:	$SEL = 10\log\left(\sum_{i=1}^{N} 10^{SEL_i/10}\right)$
Hourly Leq:	$L_{eq}(h) = SEL + 10\log(V) - 35.6 - A_{excess}$
Daytime L_{eq}:	$L_{eq}(day) = L_{eq}(h)\Big\vert_{V=V_d}$
Nighttime L_{eq}:	$L_{eq}(night) = L_{eq}(h)\Big\vert_{V=V_n}$
L_{dn}:	$L_{dn} = 10\log\left[15\cdot 10^{L_{eq}(day)/10} + 9\cdot 10^{(L_{eq}(night)+10)/10}\right] - 13.8$

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

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

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

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

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

† See Section 5.2.2 for definition of terms

6. Excess Shielding: If necessary, adjust for excess shielding. At this point, excess shielding (A_{excess}) that is site-specific and not directly related to the vertical geometry of the source relative to the receiver (as computed in Step 5) can be applied to the overall noise exposure. Such excess shielding can be caused by intervening rows of buildings, dense tree zones, and any other obstruction between the source and the receiver. The attenuations are applied to *overall* L_{eq} and L_{dn} and not to the individual subsource contributions. Equations for computing these attenuations are given in Table 5-5.

Table 5-5 Computation of Excess Shielding: Rows of Buildings and Dense Tree Zones

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

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

An example of application of Steps 1 through 6 of the Detailed Noise Analysis procedure for a hypothetical proposed high-speed rail project follows.

Example 5-1. Detailed Noise Projection Procedure

Consider the following system:

Proposed Equipment: The project will use a steel-wheeled electric train with 2 power cars (one on each end) and 8 passenger coaches. The maximum design speed will be 180 mph, placing it in the "Very High-Speed" category in Table 5-2. The locomotives are 73 feet long each, and the cars are each 61 feet long.

Proposed Service: Hours of revenue service from 5:00 a.m. to midnight. Hourly volumes are:

Daytime (7 a.m. to 10 p.m.):

V_d = 4 trains/hour

Nighttime (10 p.m. to 12 p.m., 5 a.m. to 7 a.m.):

V_n = 1 train/hour

In the corridor segment of concern, the train will pass through a shallow cut with sloped walls, and we are concerned with the sound exposure at a 5-foot receiver standing 80 feet from the edge of the cut (200 feet from the centerline of the near track).

The geometry is illustrated in case 3 of Figure 5-3, with the following parameter values:

A = 105 feet
B = 200 feet
H_r = 5 feet
H_c = 49 feet
H_b = 0 feet, and
H_s = subsource heights as given in Table 5-2 for Very High-Speed trains.

1. Calculate the ground factor, G, for the wheel-rail and propulsion subsources using the equations in Figure 5-3:

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

$$= \frac{(1) + (2\times0) + (49) + (5)}{2} = 27.5 \text{ for wheel-rail}$$

and, $$H_{eff} = \frac{(12) + (2\times0) + (49) + (5)}{2} = 33 \text{ for propulsion.}$$

Using the equation for G, again from Figure 5-3,

$$G = .75\left(1 - \frac{H_{eff}}{42}\right)$$

$$= .75\left(1 - \frac{27.5}{42}\right) = .26 \text{ for wheel-rail}$$

and, $$= .75\left(1 - \frac{33}{42}\right) = .16 \text{ for propulsion.}$$

2. Since the line of sight between the receiver and the source may be broken by the cut (see Figure 5-4(b)), determine the shielding due to the terrain. Using the geometry from Table 5-3, with the barrier height represented by the height of the cut,

D_{SB} = 120 feet,
D_{BR} = 80 feet,
H_R = 54 feet (receiver height + height of cut),
H_B = 49 feet, and
H_S = heights of wheel-rail, propulsion, and aerodynamic subsources from Table 5-2.

Use these values to obtain the lengths A, B, C, and P in Table 5-3:

	Propulsion	Wheel-Rail	Train Nose	Wheel Region	Pantograph
A	125.6	129.2	126.2	127.8	124.7
B	80.2	80.2	80.2	80.2	80.2
C	204.4	206.9	204.8	205.9	203.8
P	1.4	2.5	1.6	2.1	1.1

Insert the path length difference, P, into the equations for Barrier Attenuation from Table 5-3, which yields:

$A_{barrier,propulsion}$ = 14.4,
$A_{barrier,wheel\text{-}rail}$ = 20.0,
$A_{barrier,train\ nose}$ = 8.9,
$A_{barrier,wheel\ region}$ = 10.1, and
$A_{barrier,pantograph}$ = 7.6.

Solve for the insertion loss using the fourth equation in Table 5-3. Because this system does not have a man-made barrier, set G_{NB} and G_B=0. This yields:

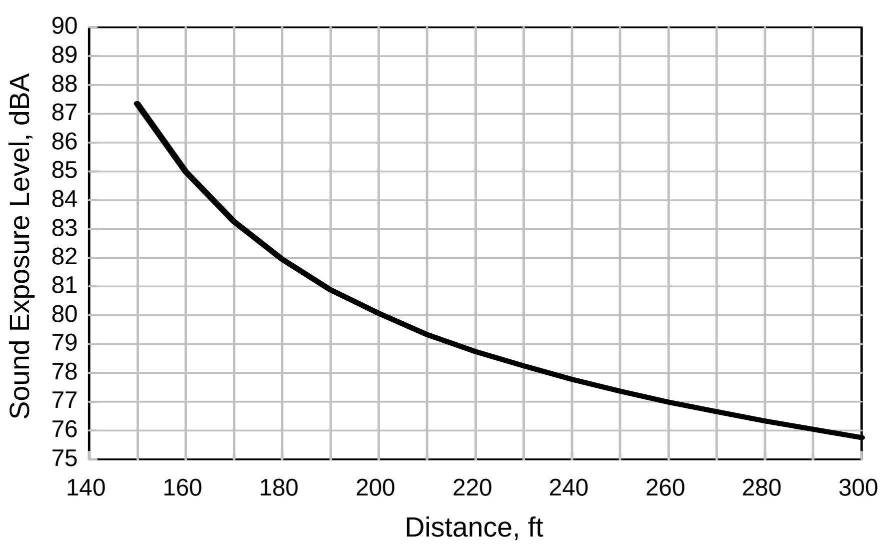
$A_{shielding,propulsion}$ = 14.4,
$A_{shielding,wheel\text{-}rail}$ = 20.0,
$A_{shielding,train\ noise}$ = 8.9,
$A_{shielding,wheel\ region}$ = 10.1, and
$A_{shielding,pantograph}$ = 7.6.

3. To calculate the noise exposure as a function of distance, normalize the reference quantities in Table 5-2 to the actual operating conditions of the proposed system, using the method from Section 5.2.2. This results in the following subsource SELs:

Propulsion = 89 dBA,
Wheel-rail = 97 dBA,
Train nose = 92 dBA,
Wheel region = 89 dBA, and
Pantograph = 86 dBA.

Using these values, evaluate the equations in section 5.2.3 at a distance of 200 feet at each subsource. Add the subsource SELs together to obtain the total SEL exposure. A plot of the total SEL versus distance for this example is given below. At 200 feet, the sound exposure level at the receiver will be about 80 dBA.

SEL vs. Distance
Train in Cut



4. Using the L_{eq} and L_{dn} equations in Table 5-4, compute the cumulative noise exposure at the receiver:

L_{eq}(day) = 51 dBA,
L_{eq}(night) = 45 dBA, and
L_{dn} = 52 dBA.

End of Example 5-1

5.2.5 Step 7: Maximum Noise Level for Train Passbys

Noise impact assessment in this manual is based on either L_{dn} or L_{eq}; therefore, normally it is not necessary to determine and tabulate the maximum levels (L_{max}). However, often it is desirable to include estimates of L_{max} since:

- it is representative of what people hear at any particular instant;
- it is straightforward to measure with a standard sound level meter;
- noise limits in vehicle specifications are usually in terms of L_{max}; and
- because L_{max} represents the sound level heard during a transportation vehicle passby, people can related this metric with other environmental noises, such as an aircraft flyover or a truck passby.

Although L_{max} is not used in this manual as a basis for assessing noise impact, when used in conjunction with L_{eq}(h) or L_{dn} it can provide a more complete description of the noise effects of a proposed project. L_{max} also may be necessary in determining compliance with the project noise limits. Equations for computing L_{max} from SEL and also for estimating a single reference SEL (for use in the General Assessment method presented in Chapter 4) from a specified or measured value of L_{max} are given in Appendix C. Application of these equations is illustrated in Example 5-2.

Example 5-2. Calculation of L_{max} using Detailed Noise Analysis Procedure

This example demonstrates how to compute L_{max} combining the methods described in Chapter 5 and the equations given in Appendix C. The segment in question will utilize an electric locomotive-hauled train with a maximum design speed of 150 mph, which places it in the "high speed" category of Table 5-2. The land abutting the rail corridor is flat with no shielding, and the tracks are on a 3-foot high embankment. The receiver is assumed to be 5 feet high, and the noise specification requires L_{max} at a distance of 50 feet away from the centerline of the tracks. The trainset is made up 2 power units (one at each end of the set) and 10 passenger coaches. The parameters for this train are,

$SEL_{ref,propulsion}$ = 86 dBA,

$SEL_{ref,wheel\text{-}rail}$ = 91 dBA,

N_{locos} = 2,

N_{cars} = 10,

L_{locos} = 73 feet,

L_{cars} = 61 feet,

$L_{total,locos}$ = 146 feet,

$L_{total,cars}$ = 610 feet,

S= 150 mph, and

D= 50 feet.

The SELs for each subsource must be computed for the proposed consist and speed using the methods described in section 5.2. Then, L_{max} from each subsource can be calculated using the equations in Appendix C. The highest subsource L_{max} is used in the noise specification for this trainset.

First, the effective path heights must be calculated to determine the ground attenuation. As shown in Figure 5-3, the effective ground height is

$$H_{eff} = (H_s+2H_b+H_r)/2$$

so H_{eff} = 4.5 for the wheel-rail subsource, and
H_{eff} = 9 for the propulsion subsource.

This corresponds to

G = .66 for the wheel-rail subsource, and
G = .59 for the propulsion subsource.

The reference parameters given in Table 5-2 must now be adjusted to actual speed and distance conditions by using the equations from section 5.2.2. It should be noted that for cases where the locomotives are located on opposite ends of the train, they should be treated separately; the equations in Section 5.2.2 assume the locomotives are in groups. In other words,

$$\begin{aligned} SEL_{propulsion} &= SEL_{ref,propulsion}+10\log(73/73)+15\log(150/20) \\ &= 99.1 \end{aligned}$$

for <u>each</u> power unit, and

$$\begin{aligned} SEL_{wheel/rail} &= SEL_{ref,wheel/rail}+10\log((146+610)/634)+20\log(150/90) \\ &= 96.2 \end{aligned}$$

for the wheel/rail component of the train.

Using the equations in section 5.2.3, the SEL at 50 feet for each power unit is:

$$SEL = SEL_{propulsion} - 10\log\left(\frac{D}{50}\right) - 10G\ \log\left(\frac{D}{29}\right)\text{, which yields}$$

$$SEL = 99.1 - 10\log\left(\frac{50}{50}\right) - 10(.59)\log\left(\frac{50}{29}\right) = 97.7$$

and for the wheel-rail subsource is:

$$SEL = SEL_{wheel/rail} - 10\log\left(\frac{D}{50}\right) - 10G\ \log\left(\frac{D}{42}\right)\text{, which yields}$$

$$SEL = 96.2 - 10\log\left(\frac{50}{50}\right) - 10(.66)\log\left(\frac{50}{42}\right) = 95.7$$

These SELs can now be used in the equations given in Table C-1. First, α corresponding to propulsion and wheel/rail noise must be calculated:

α = arctan (L/2D)
= .63 for propulsion noise and
= 1.4 for wheel/rail noise.

Then,

$L_{max,propulsion}$ = 97.7-10log(73/150)+10log(2×.63)-3.3
= 98.5 dBA, or 99 dBA (rounded)

$L_{max,wheel/rail}$ = 95.7-10log(610/150)+10log[(2×1.44)+sin(2×1.44)]-3.3
= 91.3 dBA, or 91 dBA (rounded).

The total L_{max} is the largest of the two:

$L_{max,total}$ = 99 dBA.

End of Example 5-2

5.3 STEP 8: NOISE IMPACT ASSESSMENT

This section outlines procedures for assessing noise impact using the existing and projected noise results developed using the methodologies described in the previous sections. These procedures can be applied not only to noise impact from high-speed rail operations, including projects built within a highway or railroad corridor, but also to impacts from fixed facilities such as storage and maintenance yards, passenger stations and terminals, parking facilities, and substations.

5.3.1 Assessment Procedure

Noise impact should be assessed at each receiver of interest using the criteria for high-speed rail projects described in Chapter 3 as follows:

1. **Existing Noise Exposure**. Tabulate existing ambient noise exposure (rounded to the nearest whole decibel) at all receivers of interest identified earlier in the analysis.

2. **Project Noise Exposure**. Tabulate project noise exposure at these receivers using the analytical procedures described in this chapter. In the tabulation, account for added annoyance from startle for receivers located within the distances given in Figure 4-2 (Chapter 4).

3. **Noise Impact Criteria**. Determine the level of noise impact (No Impact, Impact or Severe Impact) by comparing the existing and project noise exposure based on the impact criteria in Chapter 3.

4. **Noise Impact Inventory**. Document the results in noise-assessment inventory tables. These tables should include the following types of information:

    - receiver identification and location,
    - land-use description,

- number of noise-sensitive sites represented (usually the number of residential buildings or dwelling units),
- closest distance to the project,
- existing noise exposure,
- project noise exposure,
- level of noise impact (No Impact, Impact or Severe Impact), and
- potential for startle.

In addition, these tables should indicate the total number of receivers predicted to experience Impact or Severe Impact.

5. **Graphical Illustration of Noise Impact**. Illustrate the areas of Impact and Severe Impact on maps or aerial photographs. This illustration could consist of noise impact contours on the maps or aerial photographs, along with the impact areas highlighted. This is done by delineating two impact lines: one between the areas of No Impact and Impact and the second between Impact and Severe Impact. To conform with the practices of another agency (e.g., FHWA, FAA), include several contour lines of constant project noise, such as L_{dn} 65, L_{dn} 70 and L_{dn} 75.

6. **Magnitude of Noise Impact**. Determine the magnitude of the impacts as the basis of the assessment, defined by the two threshold curves delineating onset of Impact and Severe Impact. Interpretation of the two impact regimes is discussed in Chapter 3.

7. **Maximum Noise Level**. Evaluate and tabulate L_{max} at sensitive receivers and locations where SEL exceeds the interim criteria for effects on animals as discussed in Chapter 3.

5.3.2 Example of GIS Implementation

Geographic Information System (GIS) technology can be a useful tool in graphically identifying and displaying noise impacts, as well as simplifying the mapping and inventorying work that is needed to complete the impact assessment. While development of a GIS method was not within the scope of this manual, an example showing a conceptual method of implementing GIS is given in this section.

The GIS example utilizes the parameters of Alignment Alternative 1 in Example 4-1 (Chapter 4). This corridor will use a high-speed electric trainset with a maximum speed of 180 mph, passing through a rural area with scattered residences, as shown in Figure 5-5.

Procedure

The screening procedure calls for further analysis for noise-sensitive land use within 1,000 feet of a new corridor. Using GIS, the procedure is as follows:

Step 1. **Digitize GIS Input Map**. Input a diagram of the project area into the GIS by digitizing a map, using aerial or satellite photography, CAD, or other methods. The GIS will determine grade crossings, embankments and cuts from topographic contours. Environmental features such as dense foliage are selected by choosing the appropriate icon and applying the feature to the map.

Step 2. **Identify the sensitive receivers**. Identify and label all sensitive land uses by address and owner, either manually, or by importing the information from a database. Distances from each receiver to the track will be computed automatically.

Step 3. **Input train parameters**. Obtain train data such as speed, type and number of cars for input to the noise propagation model, which is linked to the GIS. As demonstrated in Example 4-1 (Chapter 4), the onset for impact and severe impact is 990 and 350 feet, respectively. The GIS will automatically calculate the distances for impact and severe impact, and draw the noise contours as shown in Figure 5-5.

Step 4. **Assess impact at specific receivers**. Predictions of noise and vibration levels at specific receivers will also be calculated automatically using the noise contour information obtained. To view statistics for a certain residence, select the residence and a dialog box will appear, providing receiver information including address, owner, and projected noise and vibration levels from high-speed trains.

Step 5. **Input new parameters**. To view the effects of different train configurations and/or speeds, input the new parameters into the GIS and the model will redraw new impact contours and update the noise and vibration levels at each receiver.

Once the receiver and geographic information has been entered into the system, it is possible to change any number of variables, including track position, train configuration, and shielding and receive updated noise and vibration predictions with little effort. Use of GIS technology also allows residents who live near a corridor to see the specific impact that a rail project would have on them.

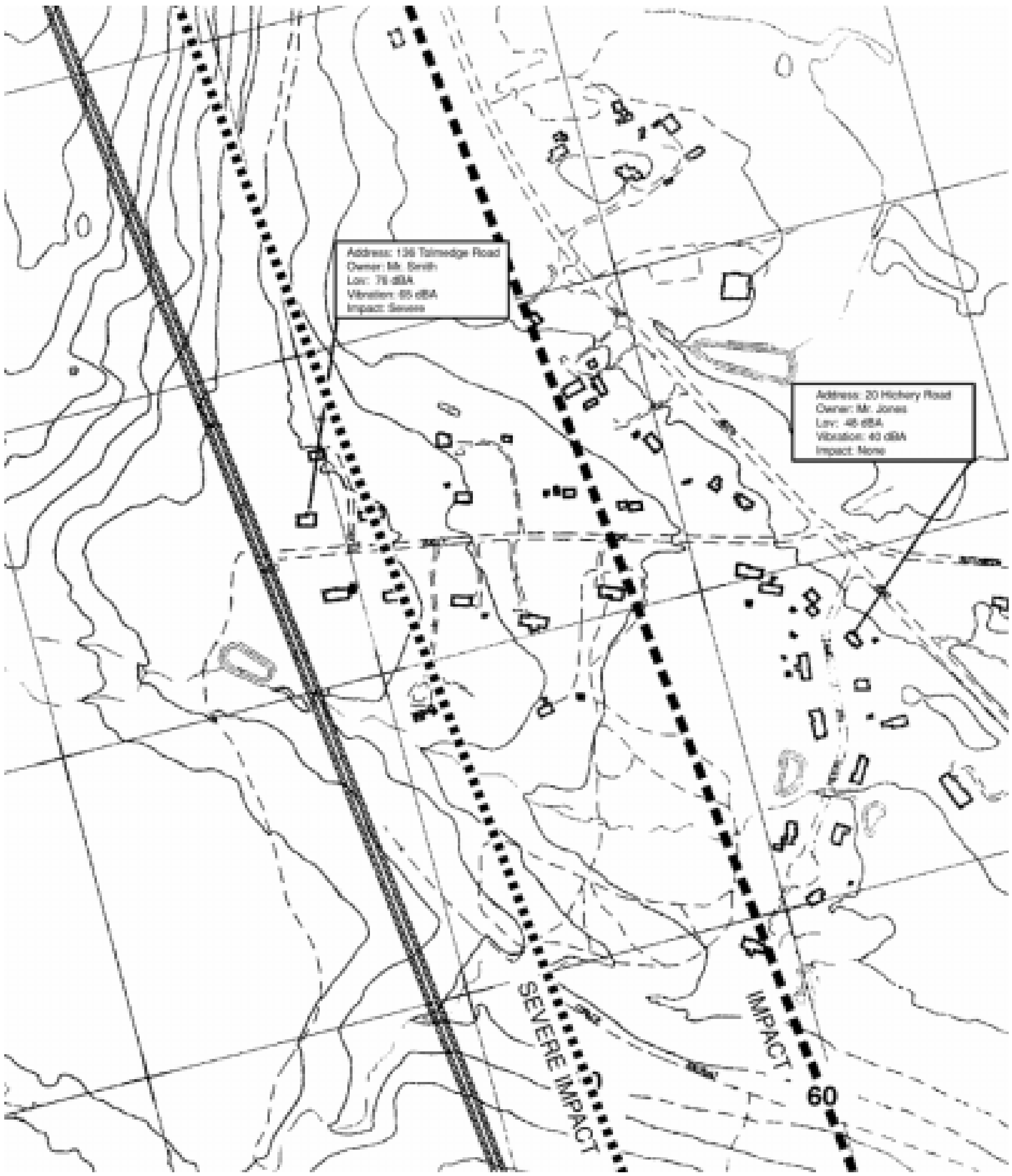


Figure 5-5 Determining Noise Impact using GIS

5.4 MITIGATION OF NOISE IMPACT

This section provides guidance for evaluating noise reduction measures at locations where the noise impact assessment shows either Severe Impact or Impact. In general, mitigation options are chosen from those listed below, and then relevant portions of the project noise are recomputed and reassessed to account for this mitigation. This reassessment provides an accurate prediction of the noise reduction and the resulting net impact of the project, assuming the incorporation of mitigation measures either in the initial project plans by the project proponent, or as a condition imposed by the approving public agency.

The source levels used in this manual are typical of high-speed rail 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 (e.g., wheel skirts, pantograph shrouds). Such measures could further reduce noise impact and warrant consideration by project proponents and public agencies where the Initial Noise Evaluation indicates the potential for extensive areas of severe impact.

Mitigation of noise impact from high-speed rail projects may involve treatments at the three fundamental components of the noise problem: (1) at the noise source, (2) along the source-to-receiver propagation path, or (3) at the receiver. A list of practical noise mitigation measures that should be considered is summarized in Table 5-6. This table is organized according to whether the treatment applies to the source, path, or receiver, and includes estimates of the acoustical effectiveness of each treatment. The treatments are discussed in Sections 5.4.1 through 5.4.3. Note the mitigation treatments are not additive within each group. Professional judgement is required to determine the total effectiveness, but one can usually add the effectiveness of one treatment from each group.

5.4.1 Source Treatments

Vehicle Noise Specifications

Incorporating noise control features during the specification and design of the vehicle is among the most effective noise mitigation treatments. The development and enforcement of stringent but achievable noise specifications by the project sponsor is a major step in controlling noise everywhere on the system. It is important to ensure that noise levels quoted in the specifications are achievable with the application of best available technology during the development of the vehicle and reasonable in light of the noise reduction benefits and costs. Effective enforcement includes imposing significant penalties for noncompliance with the specifications.

Wheel Treatments

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

Various wheel designs and other mitigation measures to reduce the noise from each of these three mechanisms include:

- **Resilient and damped wheels** to reduce rolling noise, but only slightly. A typical reduction is 2 decibels on tangent track. This treatment is more effective in eliminating wheel squeal in tight curves; reductions of 10 to 20 decibels for high frequency squeal noise is typical.
- **Spin-slide control systems,** similar to anti-locking brake systems on automobiles, reduce the incidence of wheel flats (localized flat spots on wheels), a major contributor of impact noise. Trains with smooth wheel treads can be up to 20 decibels quieter than those with wheel flats. To be effective, the anti-locking feature should be in operation during all braking phases, including emergency braking. Wheel flats are more likely to occur during emergency braking than during dynamic braking.
- **Maintenance** of wheels by truing eliminates wheel flats from the treads and restores the wheel profile. An effective maintenance program includes the installation of equipment to detect and correct wheel flats on a continuing basis.

Table 5-6 High Speed Rail Noise Mitigation Measures

Application	Mitigation Measure		Effectiveness
SOURCE	Stringent Vehicle & Equipment Noise Specifications		Varied
	Placement of HVAC systems		Varied
	Sound-Absorptive Duct Lining for Air Intake/Exhaust		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
	Under-car Absorption		5 dB
	Spin-slide control (prevents flats)		**
	Wheel Truing (eliminates wheel flats)		**
	Rail Grinding (eliminates corrugations)		**
	Turn Radii greater than 1000 ft		(Avoids Squeal)
	Rail Lubrication on Sharp Curves		(Reduces Squeal)
	Movable-point Frogs (reduce rail gaps at crossovers)		(Reduces Impact Noise)
	Elimination of all surface discontinuities/edges on Vehicle Body		3-6 dB
	Pantograph cover or shroud		5 dB
PATH	Sound Barriers close to Vehicles		6-10 dB
	Sound Barriers at ROW Line		5-8 dB
	Alteration of Horizontal & Vertical Alignments		Varied
	Acquisition of Buffer Zones		Varied
	Ballast on At-Grade Guideway		3 dB
	Ballast on Aerial Guideway		5 dB
	Resilient Track Support on Aerial Guideway		Varied
RECEIVER	Acquisition of Property Rights for Construction of Sound Barriers		5-10 dB
	Building Noise Insulation		5-20 dB

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

Vehicle Treatments

Vehicle noise mitigation measures are applied to the various mechanical systems associated with propulsion, ventilation, and passenger comfort; these include:

- **Propulsion systems** of high-speed rail vehicles include electric traction motors and fossil fuel turbine engines. Noise from the propulsion system depends on the type of unit and the level of noise mitigation is built into the design.
- **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 problem applies to heat exchangers for electric traction motors and air-conditioning systems. Fan quieting can be accomplished by installation of one of several new designs of quiet, efficient fans. Forced-air cooled electric traction motors can be quieter than self-cooled motors at operating speeds. Placement of fans on the vehicle can make a significant difference in the noise radiated to the wayside or to patrons on the station platforms.

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

Guideway Support

The smoothness of the running surface is critical in the mitigation of noise from a moving vehicle. Due to the high train speeds, smooth rail running surfaces are essential for controlling noise at acceptable levels on high-speed rail systems. Roughness of rail surfaces can be eliminated by grinding rails, thereby reducing noise levels by up to 10 decibels.

Operational Restrictions

Restrictions on operations are not a desirable mitigation option because of service demands. However, in extreme cases they can be a viable option. Two changes in operations that can mitigate noise are decreasing speed in selected, noise-sensitive areas and reducing nighttime (10 p.m. to 7 a.m.) operations. Because noise from high-speed trains depends on speed, a reduction of speed results in lower noise levels. The effect can be considerable. For example, each halving of speed on a steel-wheel/steel-rail system results in a 6 dB reduction in noise exposure (see Table 5-2). Complete elimination of nighttime operations has a strong effect on reducing the L_{dn}, because nighttime noise is increased by 10 decibels when calculating L_{dn}.

It is expected that most new high-speed rail systems will be grade-separated, eliminating the need for grade crossings and their associated noise levels. However, when grade crossings are present in lower-speed track segments, other operational restrictions that can reduce noise impact include minimizing or eliminating horn blowing and other types of audible warning signals. These mitigation options must be compliant with safety regulations and FRA guidelines.

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[5] C.E. Hanson, "Noise Control for Rapid Transit Cars on Elevated Structures," *Journal of Sound and Vibration 87(2)*: 285-294 (1983).

5.4.2 Path Treatments

Sound Barriers

Sound barriers are probably the most common noise mitigation measure used in surface transportation modes. Sound barriers are effective in mitigating noise when they break the line-of-sight between source and receiver. The mechanism of sound shielding is described in Chapter 2. The necessary height of a barrier depends on factors such as the source height and the distance from the source to the barrier. For example, a barrier located very close to the nearest track need only be 3 to 4 feet above the top of rail to effectively reduce wheel-rail noise, providing noise reductions of 6 to 10 decibels. The height of barriers farther away from the adjacent track, such as on the right-of-way line or for trains on the far track, or for screening aerodynamic noise sources, must be increased to provide equivalent effectiveness. Otherwise, the effectiveness of the barrier could drop to 5 decibels or less, even if it breaks the line of sight. Where the barrier is very close to the vehicle or where the vehicles travel between sets of parallel barriers, barrier effectiveness can be increased by as much as 5 decibels by applying sound-absorbing material to the inner surface of the barrier.

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

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

Costs for noise barriers, based on highway installations, range from $15 to $25 per square foot of installed noise barrier at-grade, not counting design and construction inspection costs. The cost of installation on an aerial structure is approximately the same as at-grade, unless the structure has to be strengthened to accommodate the added weight and wind load.

Locating a rail alignment in a reasonably deep cut or trench, as part of a grade separation, can accomplish the same result as installing a noise barrier. The walls of the trench serve the same function as barrier walls in breaking the line-of-sight between source and receiver.

Noise Buffers

Because noise levels attenuate with distance, increasing the distance between noise sources and the closest sensitive receivers can be an effective mitigation measure. This buffer can be accomplished by locating alignments away from sensitive sites. In areas of severe impact, acquiring land or easements for noise buffer zones is an option that may be considered.

Ground Absorption

Propagation of noise over ground is affected by whether the ground surface is absorptive or reflective. Noise from vehicles at-grade is strongly affected by the character of the ground in the immediate vicinity of the vehicle. Guideways for rail systems can be either reflective or absorptive, depending on whether they are concrete or ballast. Ballasted track construction can reduce train noise 3 decibels at-grade and up to 5 decibels on aerial structure.

5.4.3 Receiver Treatments

Sound Barriers

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

Building Insulation

In cases where rights-of-way are restricted, the only practical noise mitigation measure may be to provide sound insulation for the building. The most effective treatments are to caulk and seal gaps in the building envelope and to install windows that are specially designed to meet acoustical transmission-loss requirements. These windows are usually made of multiple layers of glass and are beneficial for heat insulation as well as for sound insulation. Depending on the quality of the original windows, the new windows can provide noise reductions of 5 to 20 decibels. Such windows are usually nonoperable so that central ventilation or air conditioning would be needed. Additional sound insulation, if needed, can be provided by sealing vents and ventilation openings and relocating them to a side of the building away from the noise source.

Chapter 6

GROUND-BORNE VIBRATION CONCEPTS

Noise and vibration are traditionally linked in environmental impact assessments because the two disciplines are perceived to have many physical characteristics in common. For example, noise can be generated by vibration of surfaces. Both involve fluctuating motion: noise is oscillating motion of air and vibration is oscillating motion of structures or the ground. Both are analyzed as wave phenomena: noise is made up of sound waves in air and vibration travels as waves in the ground. Both are measured in decibels. Both are considered sensory effects: noise is related to hearing and vibration is related to feeling. Despite their similarities, however, noise and vibration require entirely different kinds of analyses. The fact that ground-borne vibration travels through a succession of solid media, such as various kinds of soil, rock, building foundation, and building structure, to reach the receiver makes vibration more complicated to measure and to predict than noise.

This chapter provides a general background on ground-borne vibration and summarizes the available data on ground-borne vibration caused by high-speed trains. The focus is on vibration generated by steel-wheel trains.[1] The material presented is based largely on empirical data, since ground-borne vibration is a more complex phenomenon than that of airborne noise. The information contained in this chapter forms the basis of the assessment procedures presented in Chapters 7, 8, and 9.

The effects of ground-borne vibration include perceptible movement of the building floors, rattling of windows, shaking of items on shelves or hanging on walls, and rumbling sounds. In extreme cases, such vibration can damage buildings and other structures. Building damage is not a factor for most surface

[1]Because maglev systems do not touch the guideway except when stationary, the ground-borne vibration forces are much lower than with steel-wheel trains. Although there is some ground-borne vibration generated by the fluctuating magnetic forces, the vibration forces are generally low enough that ground-borne vibration from maglev trains can be ignored.

transportation projects, except during construction when there may be occasional blasting and pile driving. Annoyance from vibration often occurs when the vibration exceeds the threshold of perception by 10 decibels or less. This vibration level is an order of magnitude below the damage threshold for normal buildings.

The basic concepts of ground-borne vibration are illustrated for a high-speed rail system in Figure 6-1. The train wheels rolling on the rails create vibration energy transmitted through the track support system into the trackbed or track structure. The amount of energy that is transmitted into the track structure depends strongly on factors such as how smooth the wheels and rails are and the resonance frequencies of the vehicle suspension system and the track support system.

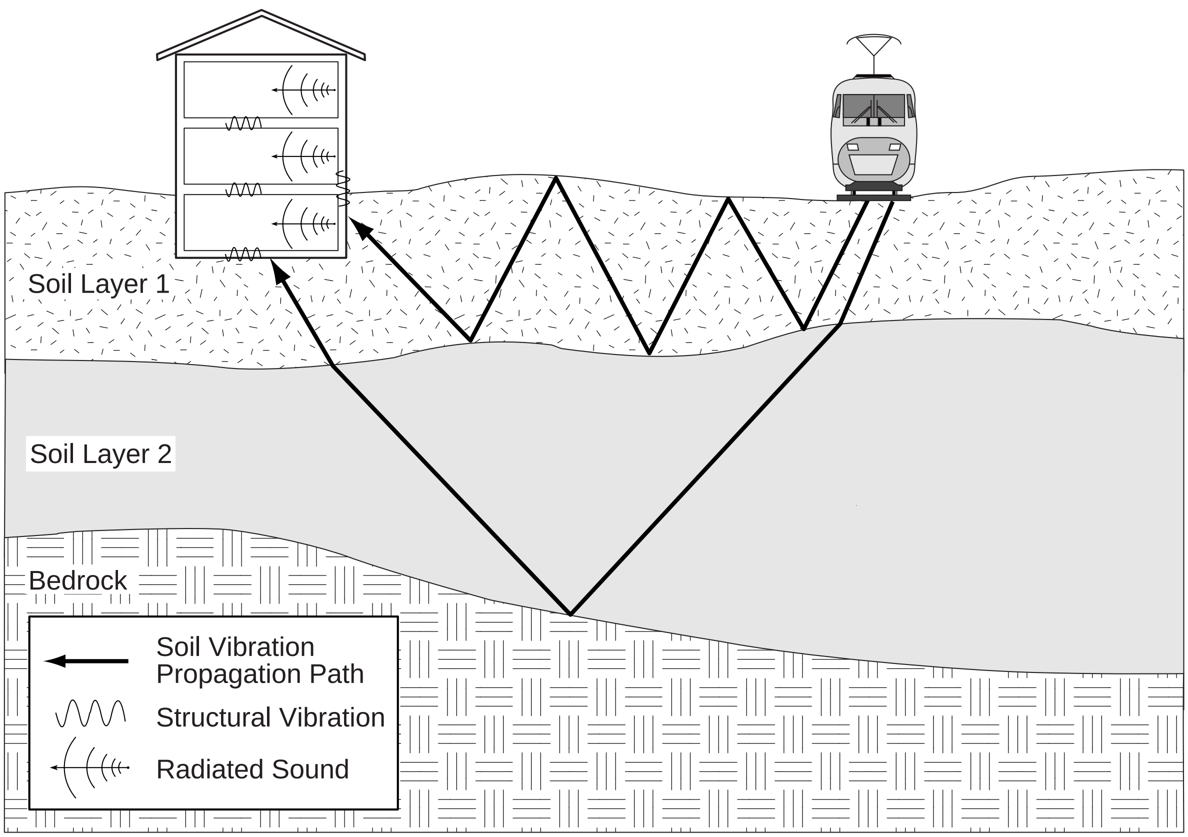

Figure 6-1 Propagation of Ground-Borne Vibrations into Buildings

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

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

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

6.1 DESCRIPTORS OF GROUND-BORNE VIBRATION AND NOISE

6.1.1 Vibratory Motion

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

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

6.1.2 Amplitude Descriptors

Vibration consists of rapidly fluctuating motions with an average motion of zero. The various methods used to quantify vibration amplitude are shown in Figure 6-2. The raw signal is the lighter weight curve in the top graph. This is the instantaneous vibration velocity, which fluctuates about the zero point. The peak particle velocity (PPV) is defined as the maximum instantaneous positive or negative peak of the vibration signal. PPV often is used in monitoring of blasting vibration since it is related to the stresses that are experienced by buildings.

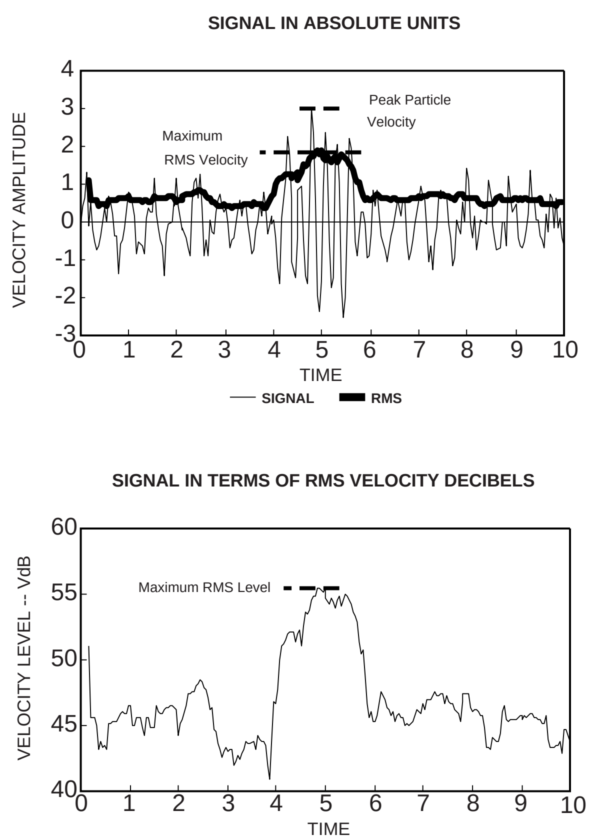

Figure 6-2 Different Methods of Describing a Vibration Signal

Although PPV is appropriate for evaluating the potential of building damage, it is not suitable for evaluating human response. It takes some time for the human body to respond to vibration signals. In a sense, the human body responds to an average vibration amplitude. Because the net average of a vibration signal is zero, the root mean square (RMS) amplitude is used to describe the "smoothed" vibration amplitude. The RMS of a signal is the average of the squared amplitude of the signal. The average is typically calculated over a 1-second period. The RMS amplitude is shown superimposed on the vibration signal in Figure 6-2. The RMS amplitude is always less than the PPV and is always positive.[2]

The PPV and RMS velocities are normally described in inches per second in the U.S. and in meters per second in the rest of the world. Although it is not universally accepted, decibel notation is in common use for vibration. Decibel notation serves to compress the range of numbers required to describe vibration. The bottom graph in Figure 6-2 shows the RMS curve of the top graph expressed in decibels. Vibration velocity level in decibels is defined as:

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

where "L_v" is the velocity level in decibels, "v" is the RMS velocity amplitude, and "v_{ref}" is the reference velocity amplitude. A reference always must be specified whenever a quantity is expressed in terms of decibels. The accepted reference quantities for vibration velocity are $1x10^{-6}$ in./sec in the U.S. and either $1x10^{-8}$ m/sec or $5x10^{-8}$ m/sec in the rest of the world. Because of the variations in the reference quantities, it is important to state clearly the reference quantity being used whenever velocity levels are specified. ***All*** *vibration levels in this manual are referenced to $1x10^{-6}$ in./sec.* Although not a universally accepted notation, the abbreviation "VdB" is used in this document for vibration decibels to reduce the potential for confusion with sound decibels.

A standardized weighted vibration level has been used in Japan to evaluate human response to vibration. This vibration level, often abbreviated VL, is usually referred to as the *weighted acceleration level*. At frequencies greater than 8 Hz, which for all practical purposes is the frequency range of interest for ground-borne vibration:

$$VL \approx L_v - 21$$

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

6.1.3 Ground-Borne Noise

As discussed above, the rumbling sound caused by the vibration of room surfaces is called ground-borne noise. The annoyance potential of ground-borne noise is usually characterized using the A-weighted sound level. Although the A-weighted level is almost the only descriptor for community noise, there are potential problems when characterizing low-frequency noise using A-weighting. This is because of the

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

non-linearity of human hearing, which causes sounds dominated by low-frequency components to seem louder than broadband sounds that have the same A-weighted level. The result is that a ground-borne noise level of 40 dBA sounds louder than 40 dBA broadband airborne noise. This anomaly is accounted for by setting the limits for ground-borne noise lower than would be the case for broadband noise.

6.2 HUMAN PERCEPTION OF GROUND-BORNE VIBRATION AND NOISE

This section gives some general background on human response to different levels of building vibration, thereby establishing the basis for the criteria for ground-borne vibration and noise that are presented in Chapter 7.

6.2.1 Typical Levels of Ground-Borne Vibration and Noise

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

Common vibration sources and the human and structural response to ground-borne vibration are illustrated in Figure 6-3. The range of interest is from approximately 50 VdB to 100 VdB. Background vibration is usually well below the threshold of human perception and is of concern only when the vibration affects very sensitive manufacturing or research equipment, such as electron microscopes and high resolution lithography equipment.

The relationship between ground-borne vibration and ground-borne noise depends on the frequency content of the vibration and the acoustical absorption of the receiving room. The more acoustical absorption in a room, the lower the noise level will be. For a room with average acoustical absorption, the sound pressure level is approximately equal to the average vibration velocity level of the room surfaces.[3] Hence, the A-weighted level of ground-borne noise can be estimated by applying A-weighting to the vibration velocity spectrum. Since the A-weighting at 31.5 Hz is -39.4 dB, if the vibration spectrum peaks at 30 Hz, the A-weighted sound level will be approximately 40 decibels lower than the velocity level. Correspondingly, if the vibration spectrum peaks at 60 Hz, the A-weighted sound level will be about 25 decibels lower than the velocity level.

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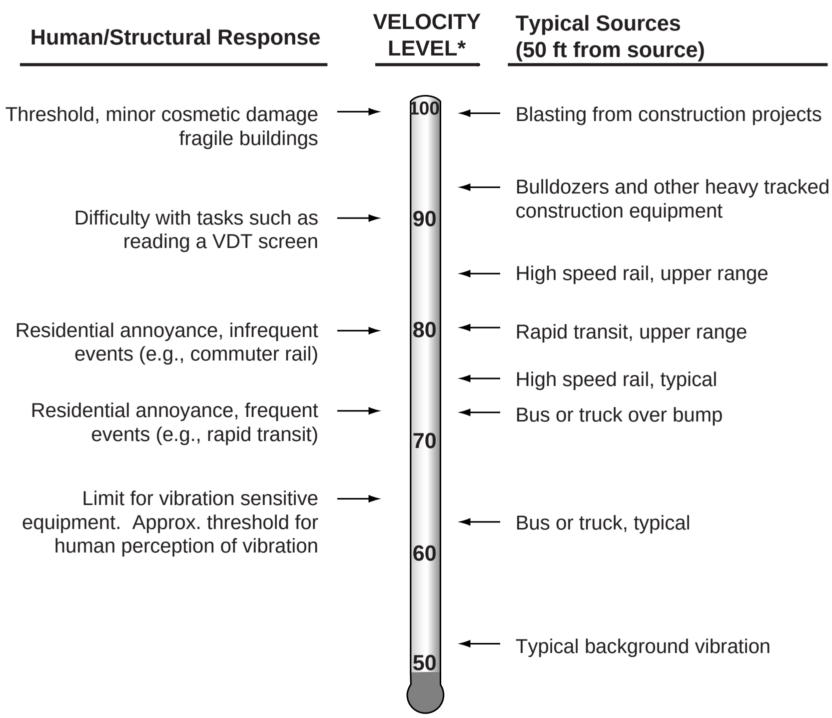
[3]The sound level approximately equals the average vibration velocity level *only* when the velocity level is referenced to 1 micro inch/second. When velocity level is expressed using the international standard of $1x10^{-8}$ m/sec, the sound level is approximately 8 decibels lower than the average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

6.2.2 Quantifying Human Response to Ground-Borne Vibration and Noise

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



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

Figure 6-3 Typical Levels of Ground-Borne Vibration

The relationship between the vibration velocity level measured in 22 homes and the general response of the occupants to vibration from rapid transit trains is illustrated in Figure 6-4. The data points shown were assembled from measurements that had been performed for several transit systems. The subjective ratings are based on the opinion of the person who took the measurements and the response of the occupants. These data were previously published in the "State-of-the-Art Review of Ground-borne Noise and Vibration."[4] Both the occupants and the people who performed the measurements agreed that floor vibration in the "Distinctly Perceptible" category was unacceptable for a residence. The data in Figure 6-4 indicate that residential vibration exceeding 75 VdB is unacceptable if trains are passing every 5 to 15 minutes, as is usually the case with urban transit trains. Additional social survey data is provided by a Japanese study on vibration pollution conducted in 1975.[5] The percent of people annoyed by vibration from high-speed trains in Japan is shown by the "% annoyed" curve in Figure 6-4. Note that the scale corresponding to the percent annoyed is on the right hand axis of the graph. The results of the Japanese study confirm the conclusion that at vibration velocity levels ranging from 75 to 80 VdB, many people will find the vibration annoying.

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[4]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 Number UMTA-MA-06-0049-83-4, DOT-TSC-UMTA-83-3, December 1983.

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

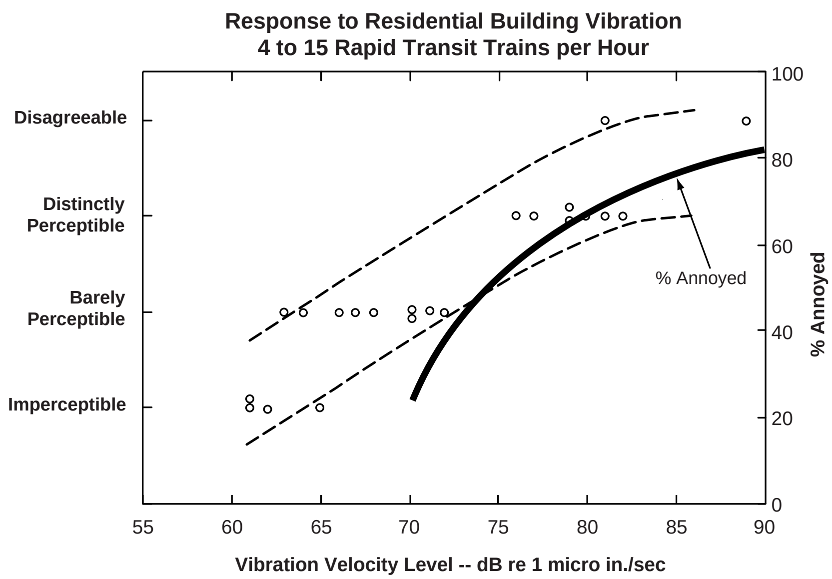

Figure 6-4 Occupant Response to Urban Transit-Induced Residential Vibration

The human response to different levels of ground-borne noise and vibration is described in Table 6-1. The first column lists vibration velocity levels, and the next two columns list the corresponding noise levels assuming that the vibration spectrum peaks at either 30 Hz or 60 Hz. As discussed above, the A-weighted noise level will be approximately 40 dB less than the vibration velocity level if the spectrum peak is around 30 Hz, and 25 dB lower if the spectrum peak is around 60 Hz. However, human response measures illustrate that achieving either the acceptable vibration or acceptable noise levels does not guarantee that the other will be acceptable. The noise caused by vibrating structural components may be very annoying even though the vibration cannot be felt, or the other way around.

Table 6-1 Human Response to Different Levels of Ground-Borne Noise and Vibration

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

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

6.3 FACTORS THAT INFLUENCE GROUND-BORNE VIBRATION AND NOISE

Developing accurate estimates of ground-borne vibration is complicated by the many factors that can influence vibration levels at the receiver position. Factors that have significant effects on the levels of ground-borne vibration are discussed in this section. Some of these factors that are known to have, or are suspected of having, a significant influence on the levels of ground-borne vibration and noise are summarized in Table 6-2. As the table indicates, the physical parameters of the track, trainsets, geology, and receiving building all influence vibration levels. The important physical parameters can be divided into the following four categories:

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

Guideway: The type and condition of the rails, the type of guideway, the rail support system, and the mass and stiffness of the guideway structure can all influence the level of ground-borne vibration. Worn rail and wheel impacts at special trackwork can substantially increase ground-borne vibration. A high-speed rail system guideway will be either in tunnel, open trench, at-grade, or aerial viaduct. It is rare for ground-borne vibration to be a problem with aerial railways, except when guideway supports are located within 50 feet of buildings. Directly radiated airborne noise is usually the dominant problem from guideways at-grade or in cut, although vibration can sometimes be a problem. For tunnels that are under residential areas, however, ground-borne noise and vibration are often among the most significant environmental problems.

Geology: Soil conditions are known to have a strong influence on the levels of ground-borne vibration. Among the most important factors are the stiffness and internal damping of the soil and the depth to bedrock. Experience has shown that vibration propagation is more efficient in clay soils as well as areas with shallow bedrock; the latter condition seems to channel or concentrate the vibration energy close to the surface, resulting in ground-borne vibration problems at large distances from the track. Factors such as layering of the soil and depth to water table can also have significant effects on the propagation of ground-borne vibration.

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

Table 6-2 Factors that Influence Levels of Ground-Borne Vibration and Noise

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

6.4 GROUND-BORNE VIBRATION FROM HIGH-SPEED RAIL SYSTEMS

Available data on ground-borne vibration from high-speed rail systems is primarily from measurements of revenue service operations of the X2000 in Sweden, the Pendolino in Italy, and the TGV and Eurostar trains in France. These data were obtained in May 1995 as part of the data collection task involved in preparing this manual. Vibration measurements were made at two sites in each country, with vibration propagation testing done at the primary site in each country. This measurement program represents one of the first times that detailed ground-borne vibration testing has been carried out in several different countries for high-speed trains operating under normal revenue conditions.

One of the major problems in characterizing ground-borne vibration from trains is that geology has a major influence in vibration levels, and there are no analytical methods of factoring out the effects of geology. This makes it very difficult to compare the levels of ground-borne vibration from different types of trains, unless they are operating on the same track. An experimental method of characterizing vibration propagation characteristics at a specific site that was developed to work around this problem[6] was applied during the tests in Sweden, Italy, and France.

This propagation test procedure basically consists of dropping a weight on the ground and measuring the force of the impact and the vibration pulses at various distances from the impact point. The transfer functions between the vibration pulses and the force impulse are then used to characterize vibration propagation. Assuming a reasonably linear system, these transfer functions define the relationship between any type of exciting force and the resulting ground vibration.

The end result of the propagation test is a measure of the transmissibility of ground vibration, or line source transfer mobility, as a function of distance from the train. Measurements of train vibration and line source transfer mobility at the same site can be used to derive a "force density" function that characterizes the vibration forces of a train independent of the geologic conditions at the site. The test is discussed in greater detail in Chapter 9.

6.4.1 Analysis Procedures

The steps used to analyze the train vibration and ground transfer mobility data to derive force densities were as follows:

1. Transfer mobility and train vibration were expressed in terms of frequency-dependent representations, or frequency spectra.
2. Raw transfer mobility data for *point sources* were combined to approximate *line source* transfer mobility at each test site.

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[6]U.S. Department of Transportation, Federal Transit Administration, Transit Noise and Vibration Impact Assessment, "Chapter 11: Detailed Vibration Analysis," Report DOT-T-95-16, April 1995.

3. Best-fit curves of level vs. distance for each frequency band were obtained using linear regression or other curve-fitting technique, approximate line-source transfer mobility, and train vibration spectra as a function of distance from the source.

4. The difference between the train vibration spectrum and the transfer mobility spectrum at the same distance, or the *force density* spectrum, was calculated. Theoretically the force density should be independent of distance. In practice, however, force density is calculated at each measurement distance, and the average force density is used to characterize each type of trainset. For all of the trainsets, the force densities at the six measurement distances converged to within 3 to 4 decibels of the average.

6.4.2 Trainset Vibration Measurement Results

Vibration velocity measurement results for several different types of high-speed trains are shown in Figure 6-5. Included in Figure 6-5 are results from: 1) the European measurements in May 1995; 2) tests with X2000 equipment on the Northeast Corridor; and 3) measurements of TGV trains in 1991. All of the data points have been normalized to 150 mph. The wide spread in the data is partly due to differences in the equipment and track condition, and partly from differences in geology. To clarify the trends, Figure 6-6 shows best-fit curves for the same data.

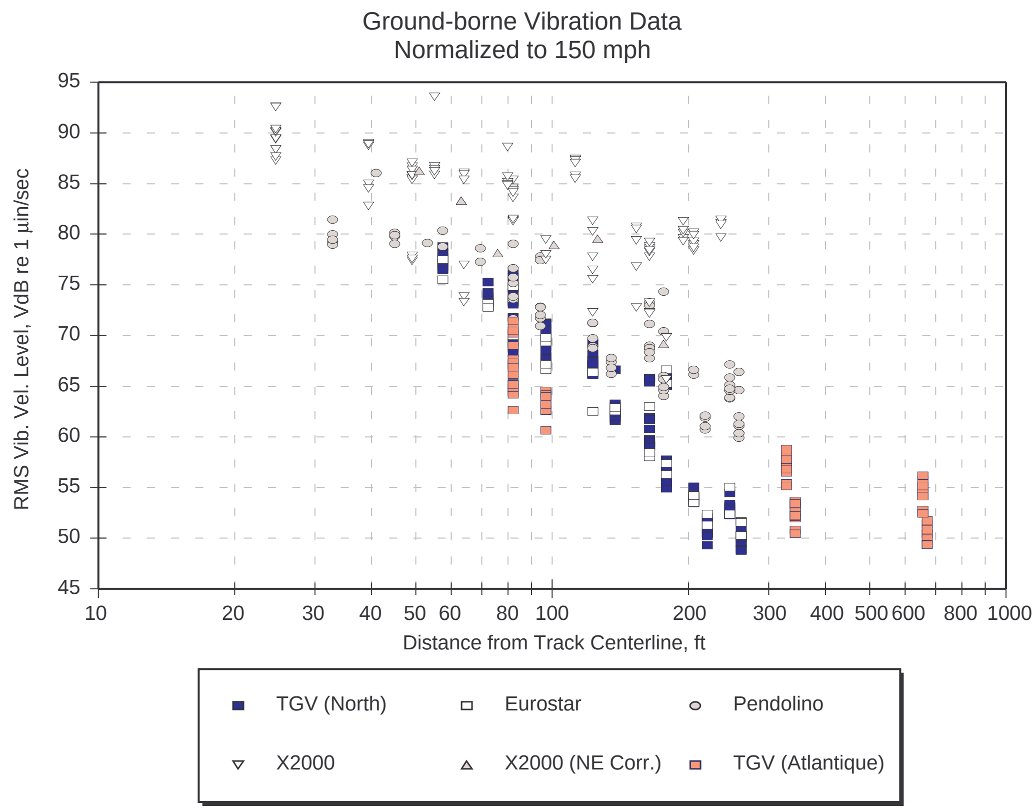


Figure 6-5 Overall Vibration Velocity Level for Different High Speed Trains

Some observations derived from the measurements presented in Figures 6-5 and 6-6 are:

- The TGV and Eurostar trainsets measured along the Nord (North) line in France all had very similar vibration levels. The TGV data measured on the Atlantique line show a distinctly different characteristic.
- The Pendolino trainsets measured in Italy have vibration levels similar to the TGV trainsets operating on the Nord line.
- The X2000 trainsets measured in Sweden show vibration levels much higher than those of the TGV or Pendolino trainsets. However, as discussed later, normalizing the data to a single set of soil conditions indicate that X2000 trainsets actually generate ground-borne vibration forces similar to the other high-speed trains. Consequently, the higher levels appear to be primarily due to the propagation conditions of the ground at the test site in Sweden.
- The test with the X2000 trainset on the Northeast Corridor show relatively high vibration levels. Because propagation tests were not a part of the Northeast Corridor testing, however, it is unknown whether these higher vibration levels were due to geology, track condition, wheel condition, or other factors.

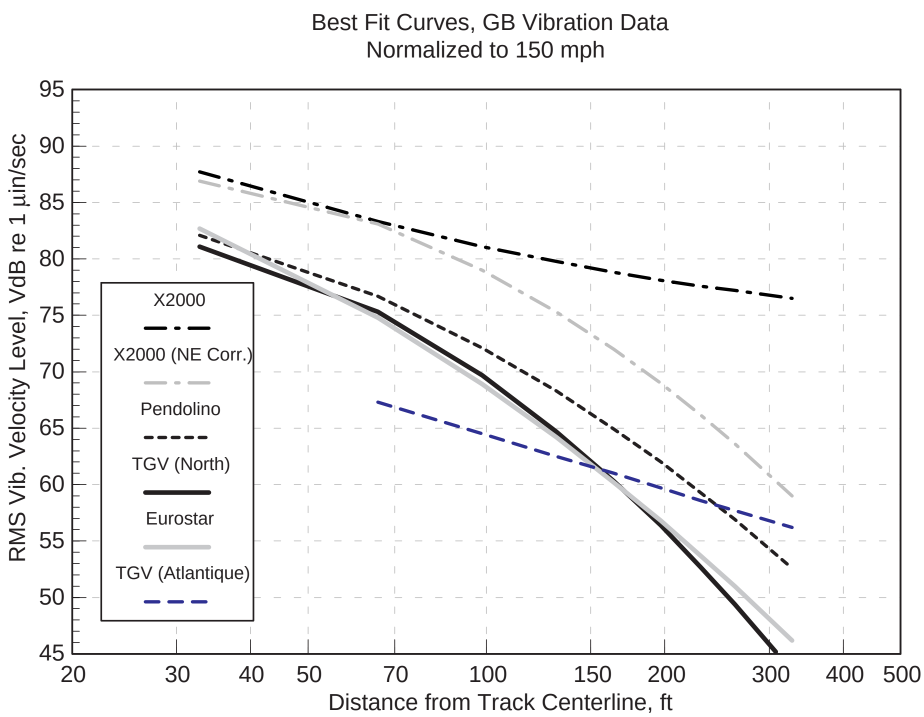


Figure 6-6 Best-Fit Curves of Vibration Velocity Level vs. Distance

A summary of the overall vibration velocity levels of the trainsets measured in Europe, calculated from the smoothed 1/3 octave band spectra, are shown in Figure 6-7. The differences in the vibration levels measured with the different types of trainsets are shown clearly. The X2000 had significantly higher vibration at all distances, with the levels over 30 decibels higher than the TGV trainsets at 100 meters from the tracks.

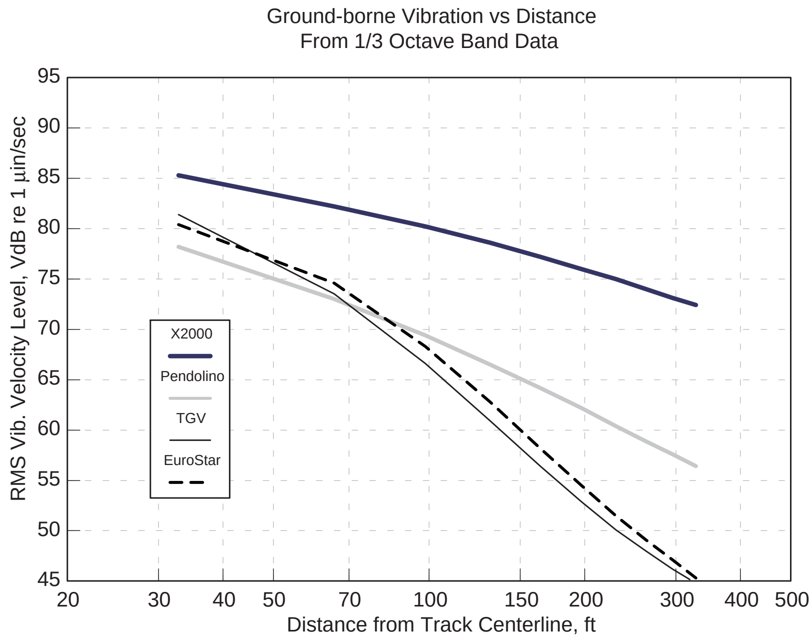


Figure 6-7 Vibration Velocity vs. Distance Calculated from Smoothed 1/3 Octave Bands

Figures 6-5, 6-6, and 6-7 indicate the overall levels of ground-borne vibration as a function of distance, but do not indicate the dominant frequency range in the ground-borne vibration generated by each trainset. Knowing the dominant frequency range helps determine whether the ground-borne vibration is perceived as vibration or audible noise by occupants of buildings near train tracks. The measured vibration velocity in terms of 1/3 octave band levels for the TGV, X2000, and Pendolino trainsets normalized to 150 mph are shown in Figure 6-8. The X2000 measured at the test site in Sweden showed the highest levels of low-frequency vibration below 40 Hz, with the Pendolino data falling between the X2000 and the TGV in this range. In fact, the X2000 vibration levels were higher over the entire frequency spectrum, except at 50 and 63 Hz, where TGV vibration was highest.

As discussed above, much of the difference between the trainsets is likely to be due to geology variations rather than differences in suspension, axle load or wheel conditions of the trainsets. The line source transfer mobility spectra, which indicate the frequency-dependent response characteristics of the ground, for the three different measurement sites are shown in Figure 6-9. It is clear that the transfer mobilities are very different between the three primary sites in France, Italy and Sweden. For example, at 100 Hz the transfer mobility measured at the site in Sweden is 8 decibels higher than the site in France and about 30 decibels higher than the site in Italy. All of the sites were in rural areas where relatively little is known about the specific geology at the test sites. The measurements indicated that these differences in transfer mobility are fairly consistent out to 100 meters from the vibration source.

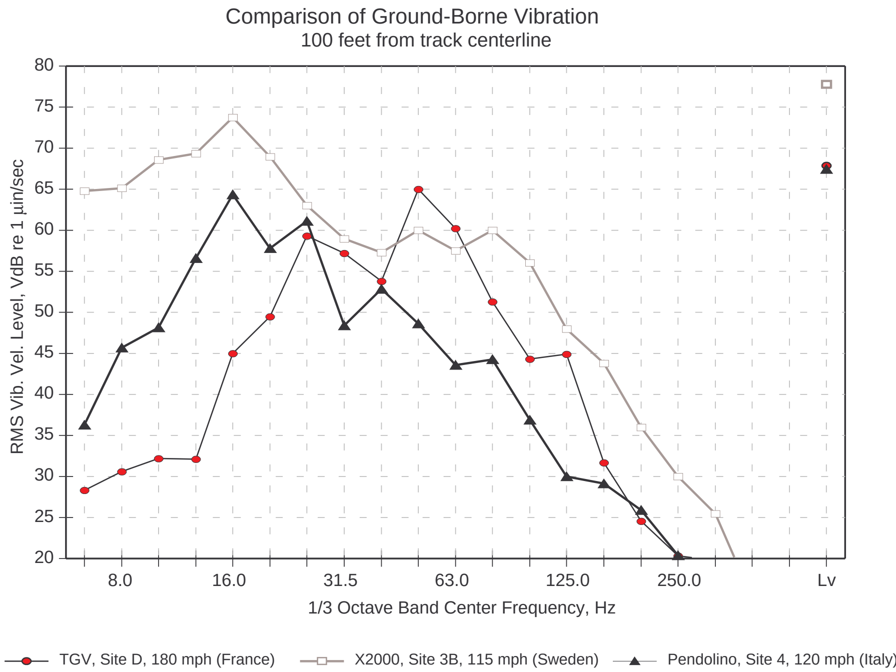


Figure 6-8 Comparison of 1/3 Octave Band Spectra

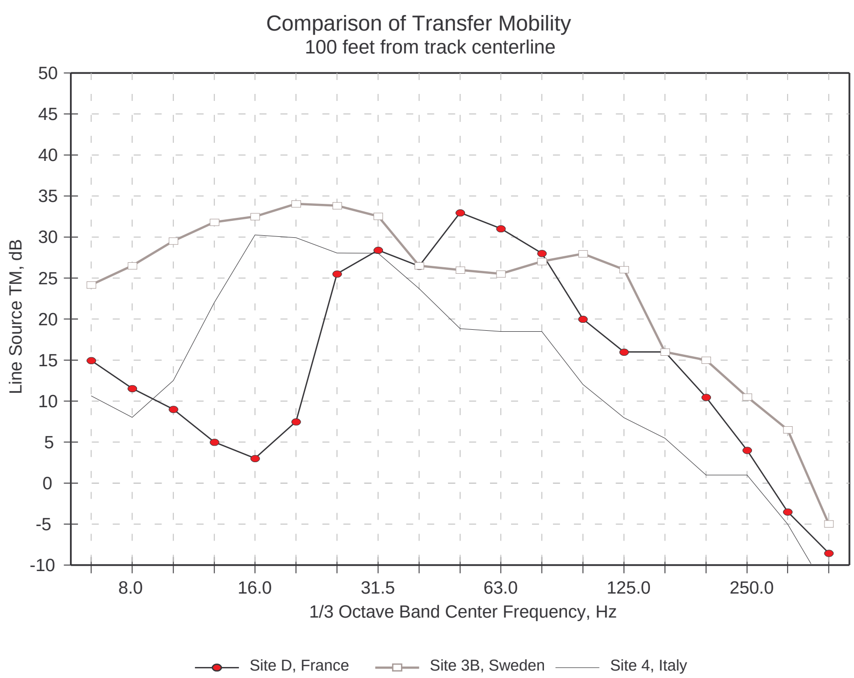


Figure 6-9 Line-Source Transfer Mobility at the Test Sites

The force density functions derived for X2000, Pendolino, TGV, and Eurostar trainsets, all normalized to a speed of 150 mph, are shown in Figure 6-10. The force densities are also very different, but the differences are not as large as the measured ground vibration levels. The TGV and Eurostar force densities are close enough to be considered the same. The X2000 and the Pendolino are surprisingly similar, considering the large difference in the vibration spectra.

The four force density functions can each be combined with the transfer mobility from a single site to approximate what the vibration levels would be if all of the trainsets were operating on the same track at the same location. The resulting overall vibration levels using the transfer mobility from the primary site (Site D) in France are shown in Figure 6-11, and the same results using the transfer mobility from the primary site (Site 3B) in Sweden are shown in Figure 6-12.

Both figures show that using the same transfer mobility, in effect normalizing the ground vibration from the trainsets to one site, substantially reduces the differences in the overall vibration levels. Using the transfer mobility from Sweden, the TGV, Eurostar, and X2000 are all within about 2 decibels, and the Pendolino is 3 to 4 decibels lower. In this case, the range of ground-borne vibration from the different trainsets is limited to a narrow "band" between 75 and 80 VdB at 30 meters from the track. Using the transfer mobility from France, the TGV and Eurostar are 2 to 3 decibels lower than the Pendolino, and the X2000 is about 4 decibels higher than the Pendolino. The levels range from 65 to 73 VdB at 30 meters from the track centerline. The overall conclusion drawn is that all of the trainsets would generate significantly higher ground vibration levels at the Swedish test site than at the French site.

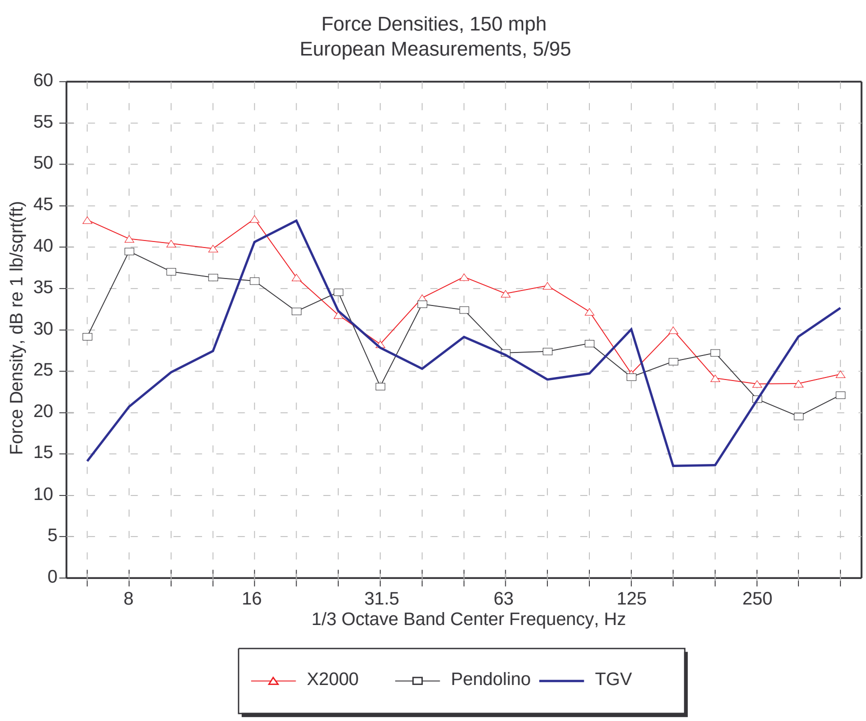
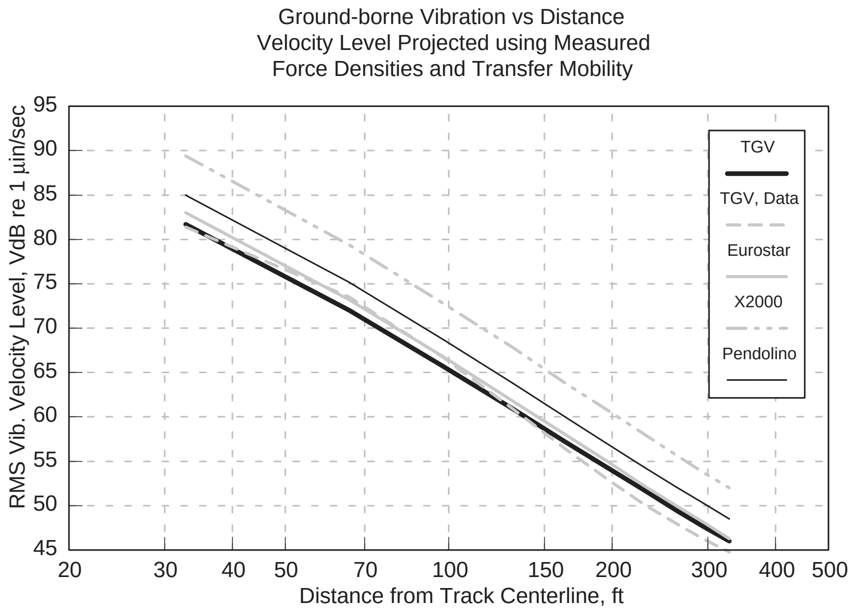
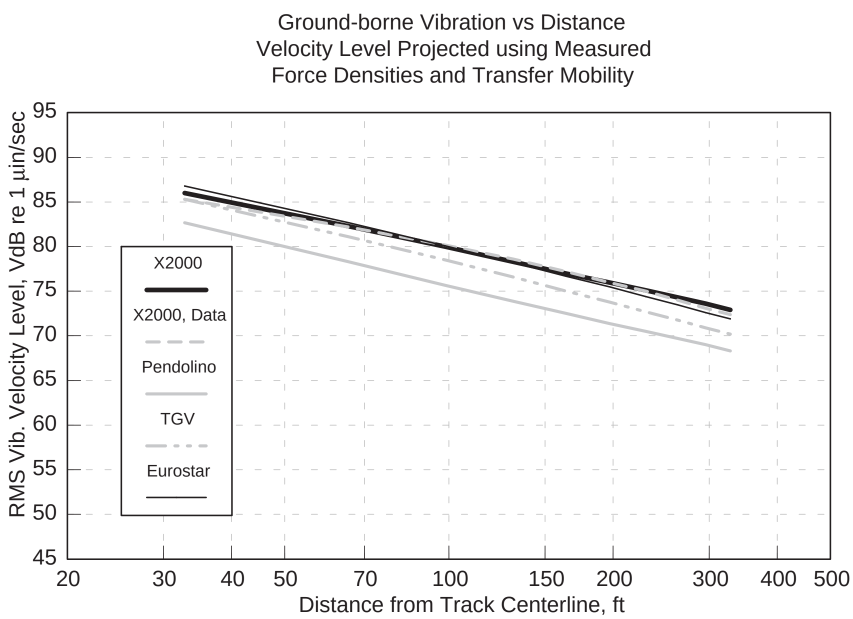


Figure 6-10 Force Density Functions Derived from Measurements



Using transfer mobility from
Site D in France
Train Speed 150 mph

Figure 6-11 Projected Vibration Velocity, Transfer Mobility from Site in France



Using transfer mobility from
Site 3B in Sweden
Train Speed 150 mph

Figure 6-12 Projected Vibration Velocity, Transfer Mobility from Site in Sweden

Finally, to further illustrate the strong effects of the transfer mobility, the results of applying the X2000 force density to the transfer mobility functions at each of the three primary sites are shown in Figure 6-13, in terms of overall vibration level as a function of distance. This shows that close to the track centerline, the projected vibration levels are all relatively high. However, the levels with the transfer mobility from Site 3B in Sweden show considerably slower attenuation with distance than with the other two transfer mobilities due to geological factors.

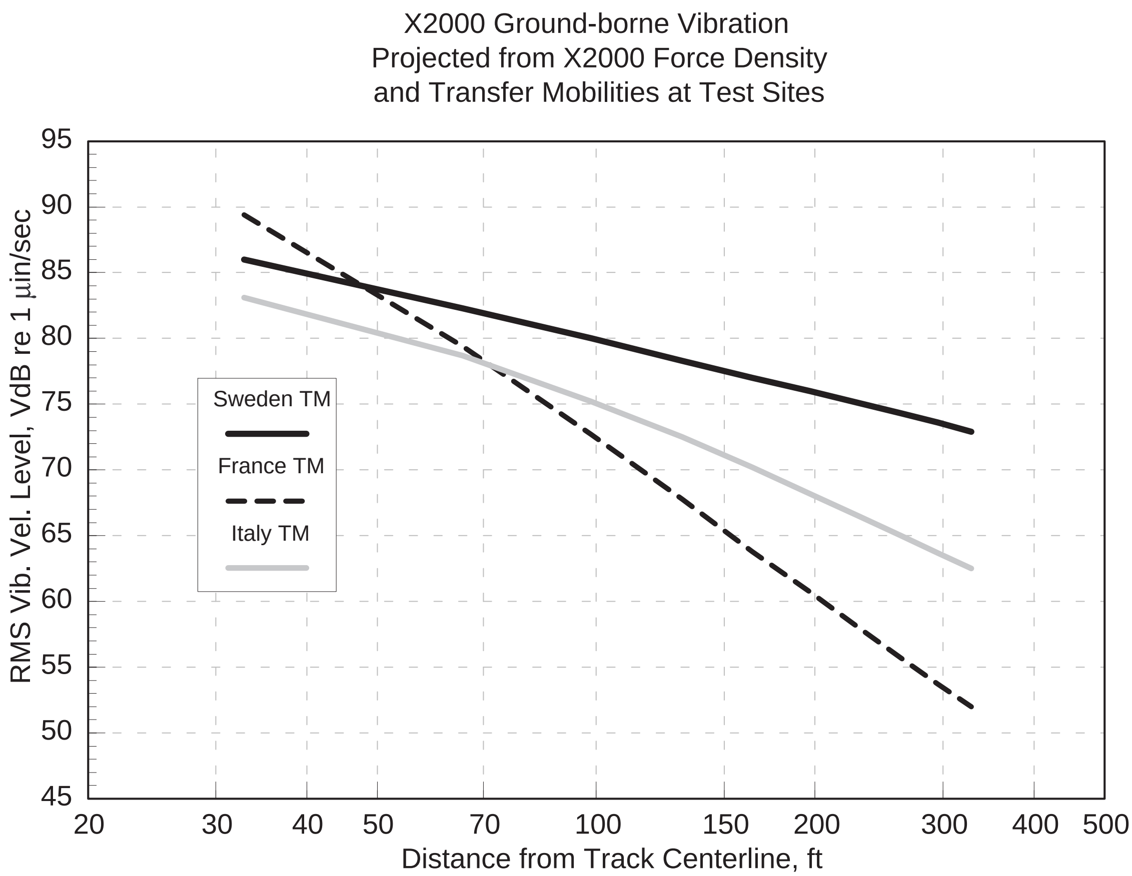


Figure 6-13 Projected Vibration Velocity, X2000 Force Density

Chapter 7

VIBRATION IMPACT CRITERIA

The environmental impacts of vibration from high-speed trains are similar to those of other types of trains. The resulting building vibration can be perceptible and intrusive to building occupants and can cause secondary rattling of windows, items on shelves, and pictures hanging on walls. In addition, the sound reradiated from vibrating room surfaces, referred to as ground-borne noise, often will be audible in the form of a low-frequency rumbling sound.

Because of the relatively rare occurrence of annoyance due to ground-borne vibration and noise, there has been only limited sponsored research of human response to building vibration and structure-borne noise. However, with the construction of new rail rapid transit systems in the past 20 years, considerable knowledge has been gained as to how communities will react to various levels of building vibration. This experience, combined with the available national and international standards,[1,2] represents a good foundation for predicting annoyance from ground-borne noise and vibration in residential areas that would be caused by a high-speed rail project. The criteria for ground-borne vibration and noise included in this chapter are based on the FTA manual *Transit Noise and Vibration Impact Assessment*[3] with only minor modifications.

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

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

[3]U.S. Department of Transportation, Federal Transit Administration, *Transit Noise and Vibration Impact Assessment*, Report Number DOT-T-95-16, April 1995.

The criteria for environmental impact from ground-borne vibration and noise presented in Table 7-1 are based on the maximum levels for a single event. The criteria account for variation in land use as well as the frequency of events, which can differ widely among high-speed rail projects. Most experience is with the community response to ground-borne vibration from rail rapid transit systems with typical headways in the range of 3 to 10 minutes and each vibration event lasting less than 10 seconds. Intuition suggests that with many fewer events each day, as is typical for high-speed rail projects, it should take higher vibration levels to evoke the same community response. Consequently, the criteria distinguish between projects with frequent and infrequent events, where *Frequent Events* are defined as more than 70 events per day. The dividing line between frequent and infrequent events was originally selected in the FTA manual such that most commuter rail projects fall into the infrequent event category. Intercity rail operations are assumed to fall into the infrequent category.

Table 7-1 Ground-Borne Vibration and Noise Impact Criteria

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

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

The criteria are based primarily on experience with passenger train operations, with only limited experience from freight train operations. The difference is that passenger train operations, whether rapid transit, commuter rail, normal, or high-speed intercity, create vibration events that last less than about 10 seconds. A typical line-haul freight train is about 5,000 feet long. At a speed of 30 mph, it takes a 5,000-foot freight train approximately two minutes to pass. Even though the criteria are primarily based on experience with shorter vibration events and this manual is oriented to high-speed rail projects, in some situations potential impacts from freight train ground-borne vibration may need to be evaluated. The prime example is the operation of high-speed trains within an existing freight railroad right-of-way. Some guidelines for applying these criteria to rail corridors with existing freight or passenger trains are given later in this chapter.

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

Vibration Category 1: High Sensitivity – Category 1 includes buildings where it is essential that ambient vibrations be kept very low for the operations within the building. Vibration levels in this category may be well below levels associated with human annoyance. (Concert halls and other special use facilities are covered separately in Table 7-2.) Typical land uses covered by Category 1 are vibration-sensitive research and manufacturing facilities, hospitals with vibration-sensitive equipment, and university research operations. The degree of sensitivity to vibration will depend on the specific equipment that will be affected by the vibration. Equipment such as electron microscopes and high-resolution lithographic equipment can be very sensitive to vibration, and even normal optical microscopes will sometimes be difficult to use when vibration is well below the human annoyance level. Manufacturing of computer chips is an example of a vibration-sensitive process.

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

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

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

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

Some buildings, such as concert halls, television and recording studios, and theaters, can be very sensitive to vibration and noise but do not fit into any of the three categories. Because of the sensitivity of these buildings, they usually warrant special attention during the environmental assessment of a high-speed rail project. Criteria for acceptable levels of ground-borne vibration and noise for various types of special buildings are given in Table 7-2.

Table 7-2 Ground-Borne Vibration and Noise Impact Criteria for Special Buildings

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

Notes:
1. *Frequent Events* is defined as more than 70 vibration events per day.
2. *Infrequent Events* is defined as fewer than 70 vibration events per day.

The criteria related to ground-borne vibration causing human annoyance or interfering with use of vibration-sensitive equipment are listed in Tables 7-1 and 7-2. It is extremely rare for vibration from train operations to cause any sort of building damage, even minor cosmetic damage. However, there is sometimes concern about damage to fragile historic buildings located near the right-of-way. Even in these cases, damage is unlikely except when the track will be very close to the structure. Damage thresholds that apply to these structures are discussed in Chapter 10.

In most cases, except near railroad tracks, the existing environment does not include a significant number of perceptible ground-borne vibration or noise events. However, it is common for high-speed rail projects to use parts of existing rail corridors. The criteria given in Tables 7-1 and 7-2 do not indicate how to account for existing vibration, a common situation for high-speed rail projects using existing rail right-of-ways. Methods of handling representative scenarios include the following:

1. <u>Infrequently used rail corridor</u>: Use the vibration criteria from Tables 7-1 and 7-2 when the existing rail traffic consists of at most one or two trains per day.

2. <u>Moderately used rail corridor</u>: If the existing traffic consists of more than about 10 trains per day with vibration that substantially exceeds the impact criteria, there is no impact as long as the project

vibration levels estimated using the procedures outlined in either Chapter 8 or 9 are at least 5 to 10 decibels less than the existing vibration. Vibration from existing trains could be estimated using the General Assessment procedures in Chapter 8; however, it is usually preferable to measure vibration from existing train traffic.

3. Heavily used rail corridor: If the project will not significantly increase the number of vibration events (less than doubling the number of trains is usually considered not significant), there will not be additional impact unless the project vibration, estimated using the procedures of Chapters 8 or 9, will be higher than the existing vibration. In locations where the new trains will be operating at much higher speeds than the existing rail traffic, it is likely that the high-speed trains will generate substantially higher levels of ground-borne vibration. When the project will cause vibration higher than the existing source, the existing source can be ignored and the vibration criteria in Tables 7-1 and 7-2 applied to the project.

4. Moving existing tracks: Another scenario where existing vibration can be significant is a new high-speed rail line within an existing rail right-of-way that will require shifting the location of existing tracks. Where the track relocation will cause higher vibration levels at sensitive receptors, then the projected vibration levels from both rail systems must be compared to the appropriate impact criterion to determine if there will be impact. Although the impact thresholds given in Tables 7-1 and 7-2 are based on experience with vibration from rail transit systems, they can be applied to freight train vibrations as well. However, locomotive and rail car vibration should be considered separately. Because the locomotive vibration only lasts for a few seconds, the infrequent event limit is appropriate, but for a typical line-haul freight train where the rail car vibration lasts for several minutes, the frequent-event limits should be applied to the rail car vibration. Some judgment must be exercised to make sure that the approach is reasonable. For example, some spur rail lines carry very little rail traffic (sometimes only one train per week) or have short trains, in which case the infrequent limits are appropriate.

Chapter 8

PRELIMINARY VIBRATION ASSESSMENT

Procedures that can be used to develop generalized predictions of ground-borne vibration and noise are described in this chapter. There are three different levels of detail for projecting ground-borne vibration:

Screening – The screening procedure uses a table of distances to determine whether noise-sensitive land uses are close enough to the proposed high-speed rail system for impact from ground-borne vibration to be possible. More detailed analysis is required if any sensitive land uses are within the screening distances. The screening procedure does not require any specific knowledge about the vibration characteristics of the system or the geology of the area.

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

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

The Screening and General Assessment methods are discussed in this chapter. The Detailed Analysis procedure, which is based on measurements to characterize vibration propagation at specific sites, is presented in Chapter 9.

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

The purpose of the General Assessment is to provide a relatively simple method of developing estimates of the overall levels of ground-borne vibration and noise that can be compared to the acceptability criteria given in Chapter 7. For many projects, particularly when comparing alternatives, this level of detail will be sufficient for the environmental assessment. Where potential problems exist, the Detailed Analysis is then undertaken during final design of the selected alternative to define accurately the level of impact and design mitigation measures. A Detailed Analysis usually will be required when designing special track-support systems, such as floating slabs or ballast mats. Detailed Analysis is not usually required if the mitigation measure consists of relocating a crossover or turnout.

8.1 VIBRATION SCREENING PROCEDURE

The screening method is intended to be applied early in a project development before many details on the system have been defined. It allows a quick check to identify whether and where impacts from ground-borne vibration are likely. Screening distances for three different speed ranges and two general types of land use are given in Table 8-1.

Table 8-1 Screening Distances for Vibration Assessments
(applicable to steel-wheel/steel-rail high-speed rail systems)

Land Use	Train Frequency*	Screening Distance, ft		
		Train Speed		
		Less than 100 mph	100 to 200 mph	up to 300 mph
Residential	Frequent	120	220	275
	Infrequent	60	100	140
Institutional	Frequent	100	160	220
	Infrequent	20	70	100

*Frequent = greater than 70 passbys per day.
Infrequent = less than 70 passbys per day.

The screening distances given in Table 8-1 are based on the criteria presented in Chapter 7 and the Generalized Assessment procedures discussed in Section 8.2, assuming "normal" vibration propagation conditions. "Efficient" vibration propagation conditions, characterized by the transmission of ground vibration at low rates of attenuation with distance, can result in substantially higher vibration levels. Efficient propagation has not been assumed in developing the screening distances, since it is a relatively unusual condition and assuming efficient propagation would overestimate the potential for vibration impact. However, by not accounting for the possibility of efficient vibration propagation, some potential impact areas may not be identified in the screening process. When there is evidence of efficient propagation, such as previous complaints about existing rail facilities or a history of problems with construction vibration, the distances in Table 8-1 should be increased by a factor of 2.

8.2 GENERALIZED VIBRATION ASSESSMENT PROCEDURE

The basic approach of the General Assessment procedure is to use a base curve of overall ground-surface vibration as a function of distance from the source, then to apply adjustments to this curve to account for factors such as track support system, train speed, track and wheel condition, building type, and receiver location within the building. This section only considers steel-wheel/steel-rail technology, which, in terms of ground-borne vibration, is no different from existing intercity passenger train and transit trains. For another type of technology, it will be necessary to define an appropriate curve either by extrapolating from existing information or by performing measurements at an existing facility.

8.2.1 Base Curve

The generalized projection curve for steel-wheeled high-speed trains is shown in Figure 8-1. This curve represents typical ground-surface vibration levels assuming equipment in good condition and speeds of 150 mph. The levels must be adjusted to account for factors such as different speeds, equipment, and geologic conditions than those assumed in the figure. The curve in Figure 8-1 is based on the ground-borne vibration measurement data discussed in Section 6.4.

The curve in Figure 8-1 is applicable to high-speed trains both at-grade and in tunnel. The rationale for applying the same curve to these two very different conditions is based on the analysis done for the FTA manual *Transit Noise and Vibration Impact Assessment*.[1] In developing generalized prediction curves for the FTA manual, investigators found that transit trains operating at grade and in tunnel had similar overall vibration levels. This finding was rather surprising because transit trains operating in tunnels tend to generate more vibration complaints than those operating on at-grade track. This tendency is probably due to two factors: (1) tunnels are usually located close to buildings, often directly under them, in densely developed areas, and (2) for at-grade systems, airborne noise from train passbys is usually more noticeable than the ground-borne vibration generated. Although the overall vibration levels from trains operating in tunnel and above grade are similar, there are differences in the frequency spectra of

[1] U.S. Department of Transportation, Federal Transit Administration, *Transit Noise and Vibration Impact Assessment*, Report Number DOT-T-95-16, April, 1995.

the vibration. The ground-borne vibration from trains in tunnels tends to be higher frequency than the vibration from at-grade track, and higher frequencies make the ground-borne noise from tunnels more noticeable in nearby buildings.

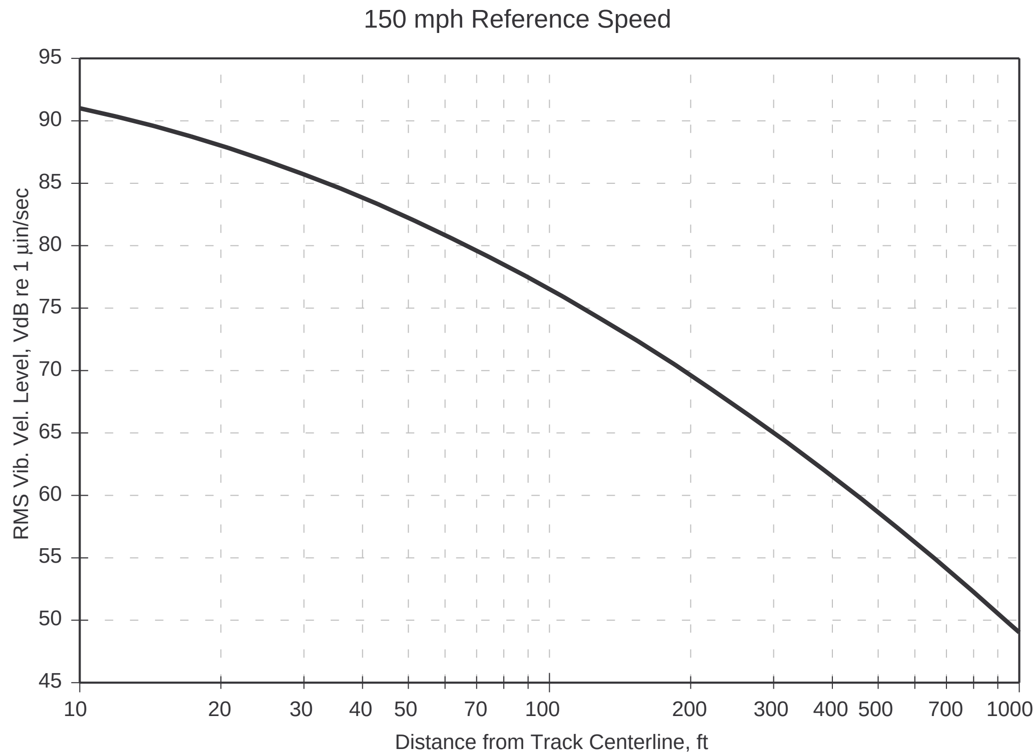

Figure 8-1 Generalized Ground-Borne Vibration Curve

The curve in Figure 8-1 is the same as the curve in the FTA manual (ref. 1) that is applicable to urban transit trains, except that this curve is 10 VdB higher to account for the speed adjustment from 50 mph for urban transit to 150 mph for high-speed rail. This curve represents the high range of the available measurement data of high-speed train ground-borne vibration. Only data from locations known to have unusual vibration propagation conditions were consistently above the curve.

Experience with ground-borne vibration data has shown that, for any specific type of transit mode, a 5 to 10-decibel fluctuation in vibration levels under apparently similar conditions is not uncommon. The curve in Figure 8-1 represents the upper range of the measurement data. Although actual levels fluctuate widely, ground-borne vibration rarely will exceed the curve in Figure 8-1 by more than 1 or 2 decibels unless there are extenuating circumstances, such as rail corrugations, flat spots on wheels, or efficient vibration propagation.

It is not recommended to show projections of normal fluctuation as a "range" of vibration levels. For example, the projected level from Figure 8-1 at a train speed of 150 mph is about 72 VdB, the threshold for acceptable ground-borne vibration for residential land uses, at a distance of 180 feet from the track centerline. If shown as a range to reflect normal fluctuations, the projected level of ground-borne vibration might be given as a range between 67 and to 72 VdB, and the interpretation of whether the projected vibration levels exceed the impact threshold becomes unclear. However, because actual levels of ground-borne vibration will sometimes differ substantially from the projections, some care must be taken when interpreting projections. Some guidelines are given below:

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

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

8.2.2 Adjustment Factors

Once the vibration levels have been projected using the base curve in Figure 8-1, the adjustments listed in Table 8-2 can be used to develop vibration projections for specific receiver positions inside buildings. All of the adjustments are given as numbers to be added to, or subtracted from, the base level. The adjustment parameters are speed, wheel and rail type and condition, type of track support system, type of building foundation, and number of floors above the basement level. Many of these adjustments depend heavily on the frequency spectrum of the vibration source and the frequency dependence of the vibration propagation. The single numbers given are suitable for generalized evaluation of the vibration impact and vibration mitigation measures since they are based on typical vibration spectra. However, the general adjustments are not adequate for detailed evaluations of impact of sensitive buildings or for detailed specification of mitigation measures. Careful consideration of the shape of the actual vibration spectra will avoid selection of an inappropriate vibration control measure, which in some cases could actually cause an increase in the vibration levels.

Table 8-2 Adjustment Factors for Generalized Predictions of Ground-Borne Vibration and Noise

Factors Affecting Vibration Source

Source Factor	Adjustment to Propagation Curve		Comment
Speed	Vehicle Speed	Adjustment (Ref Speed = 150 mph)	Vibration level is approximately proportional to 20*log(speed/speed$_{ref}$). Sometimes the variation with speed has been observed to be as low as 10 to 15 log(speed/speed $_{ref}$).
	300 mph	+6.0 dB	
	200 mph	2.5 dB	
	150 mph	0.0 dB	
	100 mph	-3.5 dB	
	75 mph	-6.0 dB	
Resilient Wheels	0 dB		Resilient wheels do not generally affect ground-borne vibration except at frequencies greater than about 80 Hz.
Worn Wheels or Wheels with Flats	+10 dB		Wheel flats or wheels that are unevenly worn can cause high vibration levels. This problem can be prevented with wheel truing and slip-slide detectors to prevent the wheels from sliding on the track.
Worn or Corrugated Track	+10 dB		If both the wheels and the track are worn, only one adjustment should be used. Corrugated track is a common problem, however, it is difficult to predict the conditions that cause corrugations to occur. Rail grinding can remove rail corrugations.
Crossovers and Other Special Trackwork	+10 dB		Wheel impacts at special trackwork with standard frogs will significantly increase vibration levels. The increase will be less at greater distances from the track. Moveable point frogs mitigate this problem.
Floating Slab Trackbed	Select highest one that applies	-15 dB	The reduction achieved with a floating slab trackbed is strongly dependent on the frequency characteristics of the vibration.
Ballast Mats		-10 dB	Actual reduction is strongly dependent on frequency of vibration.
High Resilience Fasteners		-5 dB	Slab track with track fasteners that are very compliant in the vertical direction can reduce vibration at frequencies greater than 40 Hz.
Resiliently Supported Ties		-10 dB	Resiliently supported tie systems in tunnel have been found to provide very effective control of low-frequency vibration.
Type of Track Structure	Relative to at-grade tie & ballast: Aerial/Viaduct structure Open Cut	 -10 dB 0 dB	The general rule is the heavier the structure, the lower the vibration levels. Putting the track in cut may reduce the vibration levels slightly. Rock-based tunnels will shift vibration to a higher frequency.
	Relative to bored tunnel in soil: Station Cut and Cover Rock-Based	 -5 dB -3 dB -15 dB	

Factors Affecting Vibration Path

Path Factor	Adjustment to Propagation Curve			Comment
Geologic Conditions that Promote Efficient Vibration Propagation	Efficient propagation in soil		+10 dB	Refer to the text for guidance on identifying areas where efficient propagation is possible.
	Propagation in rock layer	**Dist.** 50 ft 100 ft 150 ft 200 ft	**Adjust.** +2 dB +4 dB +6 dB +9 dB	The positive adjustment accounts for the lower attenuation of vibration in rock compared to soil. Because it is more difficult to get vibration energy into rock, propagation through rock usually results in lower vibration than propagation through soil.

Table 8-2 continued . . .		
Factors Affecting Vibration Path		
Path Factor	**Adjustment to Propagation Curve**	**Comment**
Coupling to Building Foundation	Wood Frame -5 dB 1-2 Story Commercial -7 dB 2-4 Story Masonry -10 dB Large Masonry on Piles -10 dB Large Masonry on Spread Footings -13 dB Foundation in Rock 0 dB	The general rule is the heavier the building construction, the greater the coupling loss.
Factors Affecting Vibration Receiver		
Receiver Factor	**Adjustment to Propagation Curve**	**Comment**
Floor-to-floor Attenuation	1 to 5 floors above grade: -2 dB/floor 5 to 10 floors above grade: -1 dB/floor	This factor accounts for dispersion and attenuation of the vibration energy as it propagates through a building.
Amplification due to Resonances of Floors, Walls, and Ceilings	+6 dB	The actual amplification will vary greatly depending on the type of construction. The amplification is lower near the wall-floor and wall-ceiling intersections.
Factors Affecting Ground-borne Noise		
Receiver Factor	**Adjustment to Propagation Curve**	**Comment**
Radiated Sound	Peak frequency of ground vibration: Low frequency (<30 Hz): -50 dB Typical (peak 30 to 60 Hz): -35 dB High frequency (>60 Hz): -20 dB	Use these adjustments to estimate the A-weighted sound level given the average vibration velocity level of the room surfaces. See text for guidelines for selecting low-, typical-, or high-frequency characteristics. Use the high-frequency adjustment for subway tunnels in rock or if the dominant frequencies of the vibration spectrum are known to be 60 Hz or greater.

The following guidelines are used to select the appropriate adjustment factors. Note that the adjustments for wheel and rail condition are not cumulative. When more than one adjustment may apply, the general rule is to apply only the largest adjustment. For example, the adjustment for corrugated rail is 10 decibels and the adjustment for flat spots on wheels is 10 decibels. In an area with both, the projected vibration levels should be increased by 10 decibels, not 20 decibels. Similarly, only one of the vibration mitigation treatments is applied.

Factors Affecting Vibration Source

Train Speed: The levels of ground-borne vibration and noise vary approximately at 20 times the logarithm of speed. This relationship means that doubling train speed will increase the vibration levels approximately 6 decibels and halving train speed will reduce the levels by 6 decibels. The adjustments for 75 to 300 mph using a reference speed of 150 mph are given in Table 8-2. The relationship:

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

should be used to calculate the adjustments for other speeds.

Trainsets: The levels of ground-borne vibration and noise generated by a train passby depend heavily on the trainset’s suspension system, wheel condition, and wheel type. The vehicle suspension consists of springs and dampers that affect the vibration transmitted to the track support system by the wheel/rail interaction. Generally, stiff springs tend to increase the frequency and amplitude of vibrations. Deteriorated wheel condition also will increase vibration levels. It can be assumed that a high-speed rail system will have wheels in good condition. However, when older vehicles will be used on new track, it may be appropriate to include an adjustment for wheel condition. Wheels with flat spots or corrugations can cause vibration levels that are 10 decibels higher than normal. Resilient wheels will reduce vibration levels at frequencies greater than the effective resonance frequency of the wheel. Because this resonance frequency is relatively high, often greater than 80 Hz, resilient wheels usually have only a marginal effect on ground-borne vibration.

Track System and Support: The type of rail (welded or special trackwork), the track support system, and the condition of the rail all affect the vibration generated by the track system. The base curve (Figure 8-1) assumes welded rail in good condition. Jointed rail causes higher vibration levels than welded rail; however, track on new high-speed rail systems virtually always will be welded. The wheel impacts at special trackwork, especially frogs at crossovers, create much higher vibration forces than normally experienced on tangent track. Because of the higher vibration levels at special trackwork, crossovers often are the principal areas of vibration impact on new systems. Special spring- or movable-point frogs are used as a method of mitigating the vibration impact. These special frogs eliminate the gaps in the running rail.

Modifying the track support system is another method of mitigating vibration impact. Special track support systems such as ballast mats, highly resilient track fasteners, resiliently-supported ties, and floating slabs all have been shown to be effective in reducing vibration levels.
The condition of the running surface of the rails can strongly affect vibration levels. Factors such as corrugations, general wear, or mill scale on new track can cause vibration levels that are 5 to 15 decibels higher than normal. Mill scale usually will wear off after some time in service. However, the track must be ground to remove corrugations or to reduce the roughness from wear.

Track Structure: The weight and size of the track structure affects the vibration radiated by that structure. Vibration levels will generally be lower for heavier track structures. Hence, the vibration levels from a cut-and-cover concrete double-box tunnel can be assumed to be lower than the vibration from a lightweight, concrete-lined bored tunnel. Whether or not the tunnel will be founded in bedrock is another factor affecting the radiated vibration. Bedrock is considered to be hard rock. It is usually appropriate to consider soft siltstone and sandstone to be more similar to soil than hard rock. As seen in Table 8-2, whether the tunnel is founded in soil or rock will make up to a 15 decibel difference in the vibration levels. The vibration from aerial structures is lower than from at-grade track because of the mass of the structure and the extra distance that the vibration must travel before it reaches the receiver.

Factors Affecting Vibration Path

Propagation Characteristics: The General Assessment process requires the selection of one general propagation characteristic. When considering at-grade vibration sources, the selection is between "normal" vibration propagation and "efficient" vibration propagation. Efficient vibration propagation results in vibration levels approximately 10 decibels higher than normal vibration propagation, which more than doubles the potential impact zone for ground-borne vibration. One difficulty in identifying the cause of efficient propagation is in determining geologic conditions or special source conditions (e.g., rail corrugations or wheel flat spots) that could cause higher-than-normal vibration levels.

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

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

Coupling-to-Building Foundation: Since annoyance from ground-borne vibration and noise is an indoor phenomenon, the effects of the building structure and its foundation on the vibration propagation path must also be considered. Wood frame buildings, such as the typical residential structure, are more easily excited by ground-borne vibration than heavier buildings. In contrast, large masonry buildings with spread footings have a low response to ground-borne vibration.

Factors Affecting Vibration Receiver

Type of Building and Receiver Location in Building: Vibration generally reduces in level as it propagates through a building. As indicated in Table 8-2, a 1- to 2-decibel attenuation per floor is usually assumed. Resonances of the building structure, particularly the floors, will tend to counteract this attenuation and will cause some amplification of the vibration. Consequently, for a wood-frame structure, the building-related adjustments nearly cancel out. The adjustments for the first floor assuming a basement are: -5 decibels for the coupling loss; -2 decibels for the propagation from the basement to the first floor; and +6 decibels for the floor amplification. The total adjustment is -1 decibel.

Vibration Radiated as Ground-Borne Noise: The levels of radiated noise can be estimated given the average vibration amplitude of the room surfaces (floors, walls and ceiling) and the total acoustical absorption in the room. The average result is that the numerical value of sound-pressure level is approximately equal to that of the vibration velocity level when the velocity level is referenced to

$1x10^{-6}$ in/sec. However, to estimate the A-weighted sound level from the velocity level, it is necessary to have some information about the frequency spectrum. The A-weighting adjustment drops rapidly at low frequencies, reflecting the relative insensitivity of human hearing to low frequencies. For example, A-weighting is -16 dB at 125 Hz, -26 dB at 60 Hz and -40 dB at 30 Hz. Adjustments for vibration depending on whether it has low-frequency, typical or high-frequency characteristics are provided in Table 8-2. Some general guidelines for classifying the frequency characteristics are:

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

A factor that can be particularly complex to address is the effect of vibration propagation through rock. There are three factors from Table 8-2 that need to be included when a tunnel will be founded in rock:

- The -15 decibel adjustment in the "Type of Track Structure" category.
- The adjustment based on the propagation distance in the "Geologic Conditions" category. This positive adjustment increases with distance because vibration attenuates more slowly in rock than in soil.
- The "Coupling to Building" category. When a building foundation is directly on the rock layer, there is no "coupling loss" due to the weight and stiffness of the building. The standard coupling factors should be used if there is at least a 8-foot layer of soil between the building foundation and the rock layer.

8.3 INVENTORY OF VIBRATION IMPACT

The results of the General Assessment are expressed in terms of an inventory of all sensitive land uses where either ground-borne vibration or ground-borne noise from the project exceed the impact thresholds described in Chapter 7. The General Assessment may include a discussion of mitigation measures likely be needed to reduce vibration to acceptable levels at impacted locations.

The purpose of the General Assessment procedure is to develop a reasonably complete inventory of the buildings that may experience ground-borne vibration or ground-borne noise that exceed the impact criteria. At this point, a conservative assessment of the impact is preferred. It is better to include some buildings where ground-borne vibration may be below the impact threshold than to exclude buildings where it may exceed the impact threshold.

The steps for developing the inventory are:

Step 1: Identification of Vibration-sensitive Land Uses

1) Identify all vibration-sensitive land uses within Screening Distance from Table 8-1.
2) Categorize vibration-sensitive land uses according to the categories in Table 7-1.
3) Construct tables of land uses by category.

Step 2: Estimation of Vibration Impact

1) Apply General Assessment procedure to obtain ground-borne vibration and ground-borne noise levels at each sensitive land use identified in Step 1.
2) Compare estimation with impact thresholds in Table 7-1.
3) Identify vibration-sensitive land uses where impact thresholds are exceeded.

Step 3: Preparation of Impact Inventory

1) Prepare summary tables showing the number of buildings in each category impacted by ground-borne vibration and ground-borne noise. This tabluation is done for each alternative.
2) Utilize the summary tables to compare alternatives by the number of buildings impacted.

Step 4: Mitigation of Impact

1) Select appropriate mitigation method from Section 9-4.
2) Re-assess impacts based on application of mitigation measures.

An example of a receiver-specific General Vibration Assessment for a hypothetical high-speed rail project follows. The assumed parameters of the project and receiver are typical of the preliminary planning stage of a project, and it is assumed that no project-specific vibration measurements have been performed.

Example 8-1. General Vibration Assessment of a High-Speed Train Alignment

A high-speed train proposed for a corridor in the Midwest passes through a suburb an average of once an hour. A hospital is located 30 feet from the right-of-way line. The train speed is projected to be 120 mph in this section. The tracks are continuously welded on concrete tie-and-ballast in this at-grade section. The distance from track centerline to the right-of-way is 50 feet. Soil conditions are unknown. Determine if ground-borne vibration and noise from the train will cause impact on the second floor of this three-story brick building.

Step 1: Identification of Vibration-Sensitive Land Use

1) **Category** . A hospital is categorized in "Vibration Category 2: Residential" according to Chapter 7.

2) **Screen**. The "Vibration Screening Procedure" in Section 8.1 shows that for a 120-mph train with "infrequent" service (less than 70 passbys per day), a residential land use within 100 feet should be identified as a potentially affected location. The hospital is located 80 feet from the tracks, well within the screen distance.

Step 2: Estimation of Vibration Impact

1) **Base Curve**. The "Generalized Ground-Borne Vibration Curve" (Figure 8-1) shows a vibration level of 78 VdB at 80 feet for a train at 150 mph.

2) **Adjustments**. Refer to Table 8-2.

2.1 *Speed Adjustment*. Adjustments for speeds other than 150 mph are included in Table 8-2. Unfortunately, 120 mph is not one of the adjustments given. Therefore, the speed correction of 20 log (speed/150) is used.

$$20 \log (120/150) = -1.9 \text{ dB}$$

Round off to -2 dB.

2.2 *Trainsets*. Assume wheels in good condition. No adjustment is applied.

2.3 *Track System*. Assume rails are in good condition. No adjustment.

2.4 *Track Structure*. At-grade tie and ballast is the reference condition. No adjustment is applied.

2.5 *Propagation Characteristics*. Propagation is considered to be normal unless proven otherwise. The soil conditions are unknown, so assume no adjustment.

2.6 *Type of Building and Receiver Location*. The hospital building falls into the category of "2-4 Story Masonry" so the coupling adjustment is -10db. The receiver is on the 2nd floor so the "Floor-to-floor Attenuation" is -2dB. Low-frequency characteristics can be assumed for most surface track, so the "Radiated Sound" adjustment is -50dB to convert the vibration level in VdB to sound level in dBA.

2.7 *Calculation*

i. Ground-Borne Vibration:

Base vibration level	=	78 VdB
Speed adjustment	=	-2 dB
Wheel condition	=	0 dB

Track system	=	0 dB
Track structure	=	0 dB
Propagation	=	0 dB
Foundation coupling	=	-10 dB
Receiver location	=	-2 dB
Floor response	=	+6 dB
Estimated Vibration Level	=	70 VdB

ii. Ground-Borne Noise:

Vibration Level	=	70 VdB
Radiated Sound	=	-50 VdB to dBA adjustment
Estimated Sound Level	=	20 dBA

2.8 *Impact Assessment*. Ground-borne vibration and noise impact criteria are given in Table 7-1. The hospital in this case falls under "Category 2: Residential" land uses exposed to "Infrequent Events." The corresponding threshold for ground-borne vibration impact is 80 VdB and for ground-borne noise impact is 43dBA. Neither threshold is exceeded at the hospital.

End of Example 8-1

Chapter 9

DETAILED VIBRATION ASSESSMENT

The Detailed Assessment approach presented in this chapter provides a means to determine general vibration propagation conditions along a proposed high-speed rail corridor and to develop specific projections for sensitive buildings where vibration impact is predicted by a General Assessment. The goal of the Detailed Assessment is to develop accurate projections of ground-borne vibration using all available tools and, when necessary, to design mitigation measures.

Local geologic conditions can have a very large effect on the impact distances of ground-borne vibration. This effect was dramatically demonstrated by the vibration test results described in Chapter 6. Vibration measurements of the X2000 trains in Sweden indicate that, at the test site, impacts could occur at distances greater than 300 feet from the tracks. In contrast, the tests also showed that the X2000 trains at the TGV test site in France would not cause vibration impacts beyond about 60 feet. The difference appears to be entirely due to the geologic conditions.

Projections using the General Assessment procedures described in Chapter 8 are based on the high range of data from sites that appear to have "normal" geology. This means that the actual levels of ground-borne vibration will usually be 5 VdB or more lower than projections developed using the General Assessment curve and adjustments, and will rarely exceed projections developed using the General Assessment approach. However, an important qualification is that there will be some, apparently rare, conditions where the actual levels of ground-borne vibration will be substantially higher than those projected using the General Assessment procedures.

As indicated above, it can be appropriate to use the Detailed Assessment procedures at several locations along the proposed corridor during the preliminary phases of a high-speed rail project to refine the General Assessment projection curves. A Detailed Assessment is also appropriate during the final design and engineering phases for areas where a General Assessment has indicated the potential for impact.

Procedures for developing detailed assessments of ground-borne vibration are constantly evolving. Analytical techniques for solving vibration problems are complex and the technology continually advances. The material contained in this chapter is not intended to provide the novice with a complete methodology for conducting a Detailed Assessment. Rather, the approach presented focuses on the key steps usually taken by a qualified professional.

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

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

2. *The General Assessment indicates that a proposed high-speed rail project may create vibration impact for a large number of residential buildings adjacent to the alignment. The projections for many of the buildings exceed the impact threshold by less than 5 decibels, which means that more accurate projections may show that vibration levels will be below the impact criterion. If the cost of measures to mitigate vibration would significantly increase project costs, a Detailed Assessment to determine the vibration impact as accurately as possible is warranted.*

3. *A high-speed rail alignment will be close to university research buildings where vibration-sensitive optical instrumentation is used. Vibration from the trains could make it impossible to continue to use the building for this type of research. A Detailed Assessment would determine if it is possible to control the vibration from the trains so that sensitive instrumentation would not be affected.*

A Detailed Vibration Assessment consists of three main steps:

Step 1. Survey Existing Vibration. Although knowledge of the existing levels of ground-borne vibration is not usually required for the assessment of vibration impact, a survey of the existing vibration may be valuable in some instances. Examples include documenting existing background vibration at sensitive buildings, measuring the vibration levels created by sources such as existing rail lines, and, in some cases, characterizing the general background vibration in the project corridor. Characterizing existing vibration conditions is discussed in Section 9.1.

Step 2. Predict Future Vibration and Vibration Impact. All of the available analytical tools should be applied in a Detailed Assessment to develop the best possible estimates of the potential for vibration impact. An approach to projecting ground-borne vibration that consists of measuring vibration propagation characteristics at specific sites is discussed in Section 9.3. The vibration propagation test procedure is described in Section 9.3 and the assessment of vibration impact is discussed in Section 9.1.

Step 3. Develop Mitigation Measures. Controlling the impact from ground-borne vibration requires developing cost-effective measures to reduce the vibration levels. The Detailed Assessment can identify practical vibration control measures that will be effective at the dominant vibration frequencies and compatible with the given trackway structure (aerial, at-grade, subway) and track support system. Vibration mitigation measures are discussed in Section 9.4.

The discussion in this chapter generally assumes vibration analysis of steel-wheel rail systems. The procedures are equally applicable to maglev systems; however, because all available data indicate low levels of ground-borne vibration generated by maglev trains, analysis of ground-borne vibration for a proposed maglev system is generally unnecessary.

9.1 ASSESSMENT OF VIBRATION IMPACT

The purposes of the vibration impact assessment are to inventory all sensitive land uses that may be adversely affected by the ground-borne vibration and noise from a proposed high-speed rail project and to determine the mitigation measures that will be required to eliminate or minimize the impacts. This requires projecting the levels of ground-borne vibration and noise, comparing the projections with the appropriate impact criteria, and developing a list of suitable mitigation measures. The General Assessment is incorporated as an intermediate step in the impact assessment because of its relative simplicity and potential to narrow the areas requiring Detailed Assessment.

The assessment of vibration impact proceeds according to the following steps:

Step 1: Screening. Screen the entire proposed high-speed rail corridor to identify areas where there is the potential for impact from ground-borne vibration. The vibration screening method is described in Chapter 8. If sensitive land uses are not located within the screening distances, it is not necessary to perform any further assessment of ground-borne vibration.

Step 2: Vibration Source Levels. Define a curve of ground-surface vibration level as a function of distance that can be used with the General Assessment. Usually this will mean selecting the generalized curve from Figure 8-1 or adapting measurements from an existing facility.

Step 3: Vibration Propagation Characteristics. Use the General Assessment Procedure to estimate vibration levels for specific buildings or groups of buildings.

Step 4: Study Area Characteristics. In some cases a vibration survey to characterize existing ambient vibration may be necessary. As discussed in Section 9.2, although knowledge of the existing ambient vibration is not generally required to evaluate vibration impact, there are times when a survey of existing conditions is valuable. One common example is when the rail project will be located in an existing rail right-of-way shared by freight trains. Guidelines on the procedure to be used to account for existing vibration that is higher than the impact limit for the project vibration are provided in Chapter 7.

Step 5: Vibration Impact Estimation and Inventory. Compare the projected levels with the impact criteria given in Table 7-1 to determine whether vibration impact is likely. The goal of this step is to develop a reasonably accurate catalog of the buildings that will experience ground-borne vibration or noise levels that exceed the criteria. In the General Assessment, it is best to make a conservative assessment of the impact by including some buildings where the actual vibration ultimately is at or slightly below the impact threshold. Usually it is far easier to control vibration during design and construction rather than to retrofit vibration control measures to solve unanticipated problems that develop once the system is operational. In locations where General Assessment indicates impact, the more refined techniques of Detailed Assessment should be employed.

Step 6: Vibration Mitigation. For areas where the impact criteria may be exceeded, review potential mitigation measures and assemble a list of feasible approaches to vibration control. To be feasible, the measure, or combination of measures, must be capable of providing a significant reduction of the vibration levels, usually at least 4 dB, while being cost effective.

Because vibration control is frequency-dependent, specific recommendations of vibration control measures can be made only after the frequency characteristics of the vibration have been evaluated. Use the Detailed Vibration Assessment to develop specific mitigation recommendations where it is important to estimate the spectrum of ground-borne vibration at potentially affected buildings. This type of assessment is often performed during final design rather than during the environmental assessment stage. Because a Detailed Assessment is more accurate than a General Assessment, there will be cases where the Detailed Assessment will show that the vibration and noise levels will be below the applicable criteria and that mitigation is not required. If the projected levels are still above the limits, the spectra provided by the Detailed Assessment should be used to evaluate mitigation measures.

9.2 CHARACTERIZING EXISTING VIBRATION CONDITIONS

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

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

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

- **Using existing vibration sources to characterize propagation.** Existing vibration sources such as freight trains, industrial processes, quarrying operations, or normal traffic sometimes can be used to characterize vibration propagation. Carefully designed and performed measurements may eliminate the need for more complex propagation tests.
- **Documenting existing levels of general background vibration.** Some measurements of the existing levels of background vibration can be useful simply to document that, as expected, the vibration is below the normal threshold of human perception. Existing vibration in urban and suburban areas is usually due to traffic. If a measurement site has existing vibration approaching the range of human perception (e.g., the maximum vibration velocity levels are greater than about 65 VdB), then this site should be carefully evaluated for the possibility of ground conditions causing "efficient" vibration propagation. Areas with efficient vibration propagation could have vibration problems when the project is built.
- **Documenting vibration from existing rail lines.** Measurements to document the levels of vibration created by existing rail lines can be important in evaluating the impact of the new vibration source and determining vibration propagation characteristics in the area. As discussed in Chapter 7, if vibration from an existing rail line will be higher than that from the high-speed rail trains, there may not be impact even though the normal impact criterion would be exceeded.

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

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

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

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

- sites in quiet residential areas removed from major traffic arterials to characterize low-ambient vibrations,
- sites along major traffic arterials and highways or freeways to characterize high vibration areas,
- sites in any area with vibration-sensitive activities, and
- sites near any significant existing source of vibration such as a railroad line.

The transducers should be located near the building setback line for background vibration measurements. Ambient measurements along railroad lines ideally will include: multiple sites; several distances from the rail line at each site; and 4 to 10 train passbys for each test. Because of the irregular schedule for freight trains and, on many rail lines, 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, the track at each measurement site should be inspected by experienced personnel to locate any switches, bad rail joints, corrugations, or other factors that could be responsible for higher than normal vibration levels.

The appropriate methods of characterizing ambient vibration are dependent on the type of information required for the analysis. Some examples are as follows:

Ambient Vibration: Ambient vibration is usually characterized with a continuous 10- to 30-minute measurement of vibration. The equivalent energy level, or L_{eq}, of the vibration velocity level over the measurement period gives an indication of the average vibration energy. L_{eq} is equivalent to a

[1] J.T. Nelson, H.J. Saurenman, G.P. Wilson, "Metrorail Operational Sound Level Measurements: Ground-Borne Vibration and Noise Levels," prepared by Wilson Ihrig & Associates for Washington Metropolitan Area Transit Authority, December 1979.

[2] T.G. Gutowski, L.E. Wittig, C.L. Dym, "Some Aspects of the Ground Vibration Problem," *Noise Control Engineering*, vol. 10:3, pp 94-101, 1978.

[3] H. Nolle, "High Frequency Ground Vibration Measurements," *Shock and Vibration Bulletin*, vol. 48:4, pp 95-103, 1978.

long averaging time RMS level. Specific events can be characterized by the maximum RMS level (L_{max}) of the event or by performing a statistical analysis of RMS levels over the measurement period. An RMS averaging time of one second should be used for statistical analysis of the vibration level.

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

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

It is preferable that ambient vibration be characterized in terms of the RMS velocity level, not the peak particle velocity (PPV), which is commonly used to monitor construction vibration. As discussed in Chapter 6, RMS velocity level is considered to be better correlated to human response than PPV.

9.3 VIBRATION PREDICTION PROCEDURE

9.3.1 Background

Predicting ground-borne vibration associated with a transportation project is a developing field. Because ground-borne vibration is a complex phenomenon that is difficult to model and predict accurately, most projection procedures that have been used for high-speed rail and other types of rail projects rely on empirical data. Although no single method stands out as the best approach for all situations, the procedure described in this section is one of the most promising because it is based on site-specific tests of vibration propagation. The procedure, which was developed under an FTA (formerly UMTA) research contract,[4] is recommended for detailed evaluations of ground-borne vibration. The same procedure is discussed in Chapter 11 of the FTA manual *Transit Noise and Vibration Impact*

[4]J.T. Nelson, H.J. Saurenman, "A Prediction Procedure for Rail Transportation Ground-Borne Noise and Vibration," Transportation Research Record 1143, National Research Council, Transportation Research Board (Washington, D.C.), August 1988.

Assessment.[5] Other approaches to predicting ground-borne vibration have included pure analytical and pure numerical approaches. Some of these approaches were presented at an international workshop on railway noise.[6]

There is still work to be done before a comprehensive prediction method will be available that can be confidently applied on sensitive projects. The measurements of high-speed rail vibration performed in France, Italy, and Sweden as part of preparation of this manual are discussed in Chapter 6. An important observation from those tests is that vibration from high-speed trains is not caused by mechanisms that are substantially different than vibration from lower speed trains such as rapid transit and light rail trains. This means that procedures for predicting vibration from transit and passenger trains are equally applicable to high-speed trains, following scaling to the appropriate speed. The data show that vibration amplitudes are approximately proportional to $20\times log(\text{speed})$ from 50 mph to over 150 mph.

Perhaps the biggest problem for most prediction approaches is that vibration propagation through the soil and rock layers that are between the source and the receiver is extremely difficult to define. Attenuation along the propagation path is a critical component of any prediction procedure. Even when boreholes are made at regular intervals along a rail alignment, unless the geology is very uniform, they do not uncover geologic variations along the vibration propagation path from the rail line to receiver, which is perpendicular to the tracks. A primary goal of the procedure presented in this section is to characterize vibration propagation with empirical tests. This makes it unnecessary to infer propagation characteristics from standard geologic parameters such as soil classification, wave speed, and density. Experience has shown that the test procedure provides a reasonable estimate of vibration propagation characteristics and that it can identify areas where ground-borne vibration will be higher than normal because of geologic conditions that promote efficient propagation.

9.3.2 Overview of Prediction Procedure using Measured Transfer Mobility

The prediction method described in this section was developed to enable train vibration measurements collected in one city to be used to predict vibration levels in another city where the geologic conditions may be completely different. The procedure uses a special measured function, called *transfer mobility*, which defines the relationship between an exciting force and the resulting vibration velocity at the ground surface. The transfer mobility combines the effects of the media the vibration waves pass through, the types of vibration waves, and all possible paths the vibration can take to go from the source to the receiver.

Transfer mobility is a function of both frequency and distance from the source. The transfer mobility between two points completely defines the composite vibration propagation characteristics between the two points. In most practical cases, receivers are close enough to the train tracks that the vibration

[5] U.S. Department of Transportation, Federal Transit Administration, *Transit Noise and Vibration Impact Assessment*, Report DOT-T-95-16, April 1995.

[6] "The Fifth International Workshop on Railway and Tracked Transit System Noise," Voss, Norway, June 21-24, 1995, (Proceedings published in *Journal of Sound Vibration*, Vol. 193, No. 1, 1996).

cannot be considered to be originating from a single point; the vibration source is more appropriately characterized as a line source. Consequently, the point transfer mobility must be modified to approximate a line source. In the text that follows, TM_{point} is used to indicate the measured point source transfer mobility and TM_{line} is used for the line source transfer mobility derived from TM_{point}. Both are assumed to be in decibels with consistent reference quantities.

Predicting ground-borne vibration at a specific site requires the transfer mobility function for the site and an applicable force density function. The force density function is usually derived from measurements at an existing high-speed rail line. In essence, the force density is the normalized ground-borne vibration with the effects of geology removed. The measured transfer mobility of a site along an existing high-speed rail system can be used to estimate the force density function that is independent of the geology.

The prediction procedure considers ground-borne vibration to be divided into the following components:

1. **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 track structure, such as the railway 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 track structure are usually combined into an equivalent force density level. The force density level describes the force that excites the soil/rock surrounding the track structure.

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

3. **Building Vibration:** When the ground vibration excites a building foundation, it sets the building into motion and starts vibration waves propagating throughout the building structure. The interaction between the ground and the foundation causes some reduction in vibration levels. The amount of reduction depends 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 perceptible vibration and cause annoying rattling of windows and decorative items either hanging on walls or located on shelves.

4. **Audible Noise:** In addition to perceptible vibration, 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.

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

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

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

where:

where:	L_v	=	RMS vibration velocity level in one 1/3 octave band,
	L_A	=	A-weighted sound level in one 1/3 octave band,
	L_F	=	force density for a line vibration source such as a train,
	TM_{line}	=	line source transfer mobility 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,
	K_{rad}	=	adjustment to convert from vibration to sound pressure level, which also for the amount of acoustical absorption inside the room (A value of zero can be used for K_{rad} for typical residential rooms when the decibel reference value for L_v is 1 micro in./sec.[ref. 4]), and
	$K_{A\text{-}wt}$	=	A-weighting adjustment at the 1/3 octave band center frequency.

All of the quantities given above are functions of frequency. The standard approach to dealing with the frequency dependence is to develop projections on a 1/3 octave band basis using the average values for each 1/3 octave band. The end result of the analysis is the 1/3 octave band spectra of the ground-borne vibration and the ground-borne noise. The spectra are then used to calculate overall vibration velocity level and the A-weighted sound level. This is in contrast to the General Assessment procedures, 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.

9.3.3 Measuring Transfer Mobility and Force Density (Vibration Propagation Testing)

The overall purpose of vibration propagation testing is to obtain data that can be used to estimate the following quantities:

1. Point Source Transfer Mobility. This is basically an intermediate quantity that is applicable to point vibration sources. It is a function of both frequency and distance from the source.

2. Line Source Transfer Mobility. The measured point source transfer mobilities are used to estimate an equivalent line source transfer mobility for each test site.

3. Force Density. The force density characterizes the vibration-generating characteristics of the train/track system that will be used. It can be based on previous measurements, or testing can be done at an existing facility to measure the force density. If no suitable measurements are available, testing should be done at a high-speed rail facility with equipment similar to the planned vehicles. Adjustments for factors such as train speed, track support system, and vehicle suspension will

usually be needed to match the force density to the conditions at specific sites. The force density represents an incoherent line of vibration force equal to the length of the trains. The unit of force density is force divided by square root of train length, represented here in decibels relative to 1 lb/(ft)$^{1/2}$.

The basic field procedure for at-grade and tunnel testing of transfer mobility is illustrated in Figure 9-1. The goal of the test is to create vibration pulses that travel from the source through the ground to the receiver, using the same path that will be taken by ground-borne vibration from the train. As shown in Figure 9-1, a weight is dropped from a height of 3 to 4 feet onto a load cell, which is calibrated to measure force. Accelerometers are placed on the ground along a line leading away from the point of force application. The responses of the load cell and accelerometers are recorded on a multichannel tape recorder for subsequent analysis in the laboratory.

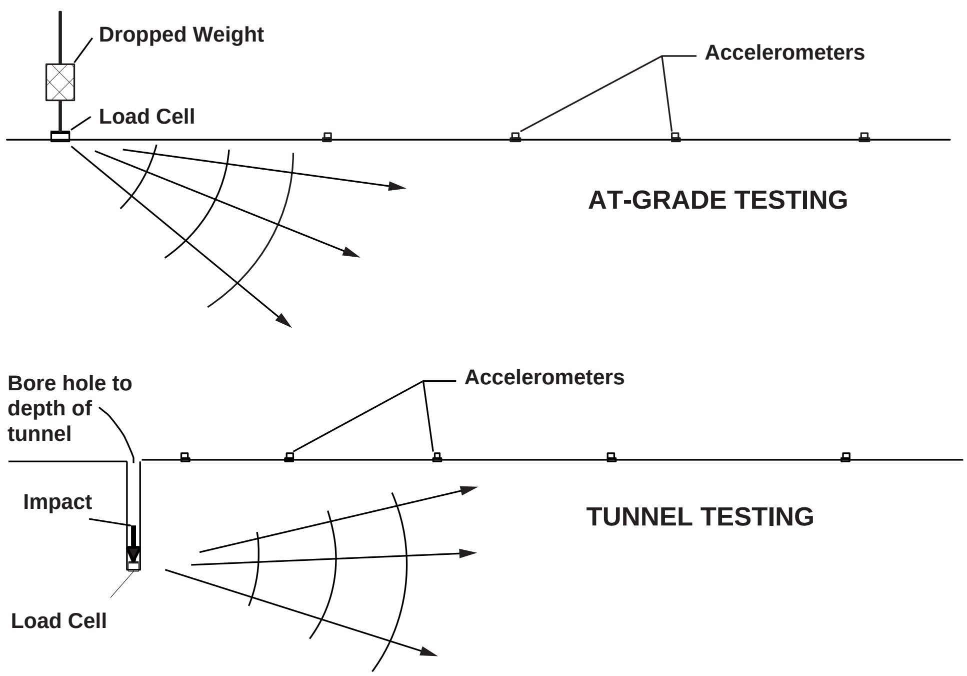

Figure 9-1 Impact Method for Measuring Transfer Mobility

When the procedure is applied to tunnels, the force must be located at the approximate depth of the tunnel. This is done by drilling a bore hole and locating the load cell at the bottom of the hole. The tests are usually performed at the same time that the bore holes are drilled. This allows using the soil-sampling equipment on the drill rig for the transfer mobility testing. The load cell is attached to the bottom of the drill string and lowered to the bottom of the hole. A standard soil sampling hammer, which is usually a 140-lb. weight dropped 18 inches onto a collar attached to the drill string, is used to excite the ground. The load cell must be capable of operating underwater if the water table is near the surface or if a slurry drilling process is used.

Field Procedures

The process of measuring transfer mobility involves impacting the ground and measuring the resulting vibration pulse at various distances from the impact. Two different methods, shown in Figure 9-2, that have been used to estimate equivalent line source transfer mobility from point source transfer mobility are:

1. Lines of transducers: A site is characterized by tests using one or more lines of transducers with the impact at one end of the line. The total length of the line ranges from 150 to 300 feet. Figure 9-2a shows a site being characterized using three lines perpendicular to the rail line. Regression techniques are applied to the 1/3 octave band transfer function data to obtain smooth point-source transfer mobility function curves. Once the point source transfer mobility has been defined, the line source transfer mobility can be calculated using numerical integration techniques (ref. 4). Optimal use of a single borehole can be made by running three or four transducer lines in a radial pattern from each borehole.
2. Lines of impacts: This configuration is shown in Figure 9-2b. One line of transducers is used and the ground is impacted at evenly-spaced intervals along a line perpendicular to the transducer line. Since the impacts represent a train, it is best if the line of impacts can be along the track centerline. When this is not possible, the impact line should parallel the tracks. After the 1/3 octave band point source transfer mobilities are obtained, the equivalent line source transfer mobility is obtained by combining the point source transfer mobilities to approximate a numerical integration. This procedure was used to derive force density functions for X2000, Pendolino, and TGV high speed trains. Recent experience has shown that this approach is more accurate and more repeatable than the first approach. Unfortunately, this approach is usually impractical for tunnels since the ground must be impacted at the bottom of boreholes to approximate propagation from a tunnel structure.

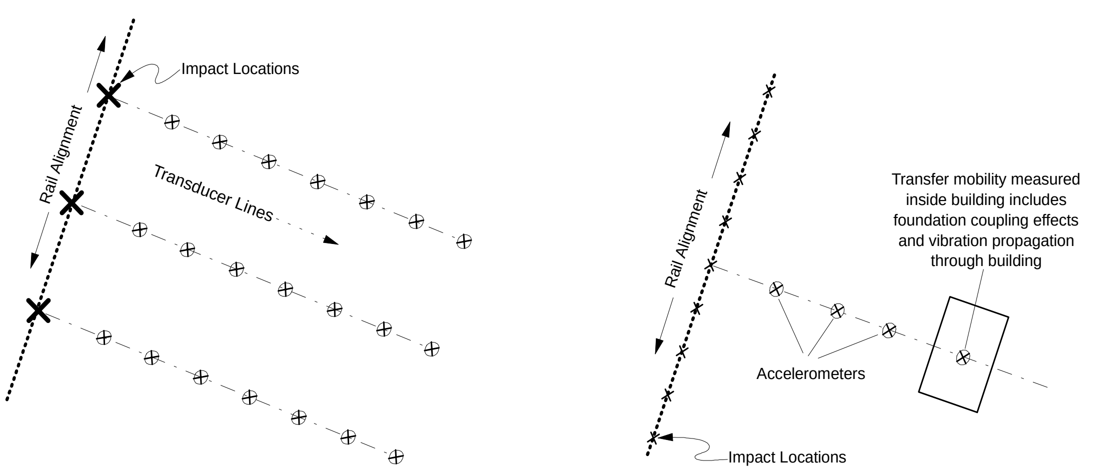

Figure 9.2a Approach 1 for Vibration Propagation Tests **Figure 9.2b Approach 2 for Vibration Propagation Tests**

Figure 9-2 Schematic of Two Approaches for Transfer Mobility Measurements

Instrumentation

Performing a vibration propagation test requires specialized equipment. Most of the equipment is readily available from several commercial sources. Commercially available load cells can be used as the force transducer. For borehole testing, the load cells must be hermetically sealed and capable of sustaining impact forces at the bottom of a 30- to 100-foot deep hole partially filled with water. A typical instrumentation array for field testing and laboratory analysis of transfer mobility is shown in Figure 9-3. The force transducer should be capable of impact loads of 5,000 to 10,000 pounds. Either accelerometers or geophones can be used as the vibration transducers. A requirement is that the transducers with associated amplifiers be capable of accurately measuring levels of 0.0001 inches/sec at 40 Hz and have flat frequency response from 6 Hz to 400 Hz. The tape recorder also must have flat response over the 6 to 400 Hz frequency range. Adequate low-frequency response usually requires either an instrumentation-quality FM recorder or a digital recorder. The response of most normal direct-record tape recorders is inadequate at frequencies below about 30 Hz.

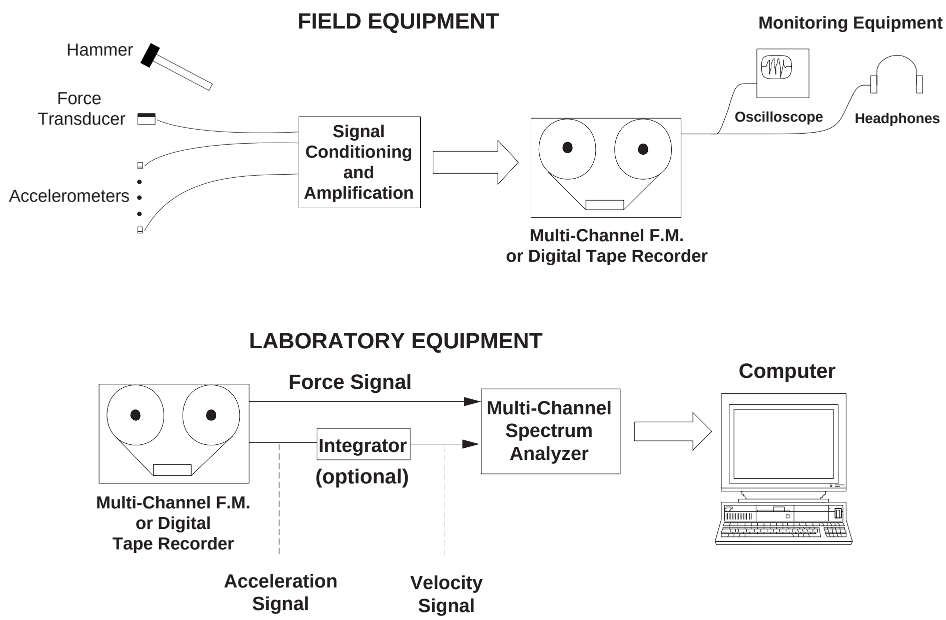

Figure 9-3 Equipment Required for Field Testing and Laboratory Analysis

The narrowband spectrum analyzer is the key element of the laboratory instrumentation. The analyzer must be capable of capturing impulses from at least two channels and calculating the frequency spectrum of the transfer function between the force and vibration channels. All transfer functions should include the average of at least 20 impulses. Averaging more impulses will improve signal enhancement at a rate of 3 dB improvement for each doubling of the number of impacts. Signal enhancement is particularly important when the vibration transducer is more than 100 feet from the impact.

As illustrated in Figure 9-3, the spectrum analyzer usually is interfaced to a computer, which is required to adapt the narrowband transfer function data into a format suitable for evaluating 1/3 octave band transfer mobility. The raw transfer function data usually include several hundred frequency bands. By transforming from narrowband to 1/3 octave band spectra, each spectrum is reduced to 15 to 20 bands. This step reduces the amount of data that must be evaluated to develop the generalized curves. There are specialized multi-channel spectrum analyzers that have built-in capabilities that are sufficient for this data analysis.

Analysis of Transfer Mobility Data

Transfer mobility functions are developed from field measurements in following steps:

Step 1. Analyze the field data to generate narrowband point source transfer mobilities.

Step 2. Calculate 1/3 octave band transfer mobilities at each measurement point from the narrowband results. Because typical spectrum analyzers are not capable of obtaining 1/3 octave band transfer functions, this processing is performed after transferring the data to a computer.

Step 3. Calculate the transfer mobility as a function of distance for each 1/3 octave band.

Step 4. Compute the line source transfer mobility as a function of distance in each 1/3 octave band.

The two field test procedures that have been used to develop estimates of line-source transfer mobility are shown in Figure 9-2. Of the two procedures, the first, involving a single impact point for each line of accelerometers, requires considerably more analysis and professional judgement to develop line source transfer mobility. However, there are some situations where a single impact point is the only practical method to apply.

The steps in developing line-source transfer mobility curves with field data from the first procedure are illustrated in Figure 9-4. The analysis starts with the narrowband transfer function between source and receiver at each measurement position. There should be a minimum of four distances in any test line. Because of the possibility of local variations in propagation characteristics, when feasible, three or more lines should be used to characterize a site. A total of 10 to 20 transducer positions are often used to characterize each site. Assuming that the spectrum analyzer calculates 400 line narrowband transfer functions for each position, a total of 4,000 to 8,000 numbers must be calculated for each site.

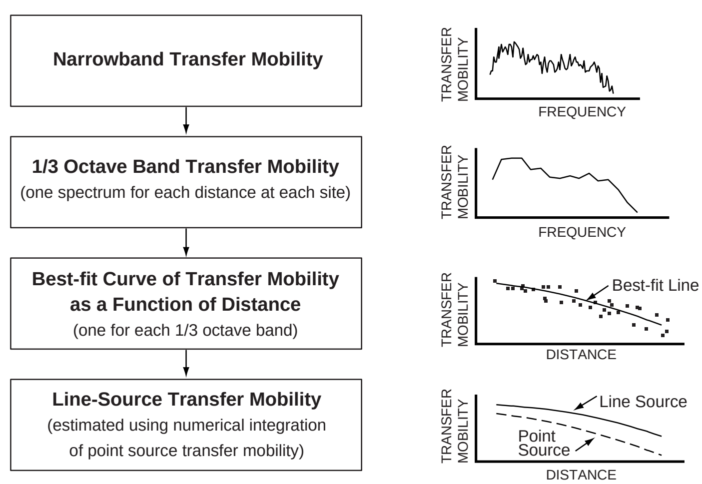

Figure 9-4 Analysis of Transfer Mobility

The next step in the analysis procedure is to calculate the equivalent 1/3 octave band transfer functions. This reduces each spectrum from 400 to 15 numbers. As shown in Figure 9-4, the 1/3 octave band spectrum is much smoother than the narrowband spectrum. The third step is to calculate a best-fit curve of transfer mobility as a function of distance for each 1/3 octave band. When analyzing a specific site, the best-fit curve will be based on 10 to 20 data points. Up to several hundred points could be used to determine average best-fit curves for a number of sites.

The 1/3 octave band best-fit curves can be applied directly to point vibration sources. However, because trains are better represented as line vibration sources, a fourth step is necessary: calculate an equivalent line source transfer mobility using numerical integration.

The analysis involving the second field procedure is slightly different from the first. In this approach, the train is represented by impacts at equally spaced intervals along a line perpendicular to the transducer line. This approach is particularly suited to characterizing a specific building since by placing a transducer inside the building, it is possible to measure line source transfer mobility from the tracks to this point in the building. The resulting transfer mobility combines the vibration path to the building foundation, coupling to the building, and propagation of the vibration energy through the building. This approach can greatly improve the accuracy of projections for that building.

Using the second procedure, a segment of a train can be represented by a line of impact positions along the track centerline at 10- or 20-foot intervals. The 1/3 octave band point source transfer mobilities for each transducer location can then be summed following the trapezoidal rule for numerical integration to directly calculate line-source transfer mobility. The following equation should be used to perform the numerical integration:

$$TM_{line} = 10 \times \log_{10}\left[h \times \left(\frac{10^{\frac{TM_{p_1}}{10}}}{2} + 10^{\frac{TM_{p_2}}{10}} + \ldots + 10^{\frac{TM_{p_{n-1}}}{10}} + \frac{10^{\frac{TM_{p_n}}{10}}}{2} \right) \right]$$

where:

h = impact interval,

TM_{pi} = point source transfer mobility for ith impact location, and

n = last impact location.

This approach is considerably more direct than is possible with lines of vibration transducers. An important feature of this approach is that the impact line usually can be shorter, sometimes much shorter than the train. For example, at a distance of 50 feet from a 600-foot train, most of the vibration energy will come for the part of the train closest to the receiver. In this case, the 600-foot train could be accurately modeled using a 200-foot impact line. Judgment must be used in deciding on an appropriate length for the impact line in balancing accuracy of the results, available test conditions in the field, budget, and time constraints.

Deriving Force Density

Force density is not a quantity that can be measured directly. It must be inferred from measurements of transfer mobility and train vibration at the same site. Using a line of impacts to measure line source transfer mobility (developed using the second transfer mobility test procedure) will give the best force density results. The force density for each 1/3 octave band is then simply:

$$L_F = L_v - TM_{line}$$

where: L_F = force density,
L_V = measured train ground-borne vibration, and
Tm_{line} = line source transfer mobility.

The standard approach is to develop force density from the average of measurements at three or more positions.

Trackbed force densities developed from measurements of the TGV, X2000, and Pendolino trains are shown in Figure 9-5. A "worst case" force density that can be used before any information is available on the type of equipment that will be used for a high-speed rail project also is shown in this figure. Adjustments must be made to the force density to account for differences between the facility where the force density was measured and the new system. Guidance for making these adjustments can be found in a U.S. Department of Transportation report.[7]

9.3.4 Vibration and Structure-Borne Noise in Buildings

The propagation of vibration from the building foundation to the receiver room is a very complex phenomenon, dependent on the specific design of the building. Detailed evaluation of the vibration propagation requires extensive use of numerical procedures, such as finite element modeling. An evaluation this detailed generally is not practical for individual buildings considered in this manual. The propagation of vibration through a building and the radiation of sound by vibrating building surfaces consequently is estimated using simple empirical or theoretical models. The recommended procedures are outlined in the *Handbook of Urban Rail Noise and Vibration Control*[8] The approach consists of adding the following adjustments to the 1/3 octave band spectrum of the projected ground-surface vibration:

1. **Building response or coupling loss**. This represents the change in the incident ground-surface vibration due to the presence of the building foundation. The adjustments in the *Handbook* are shown in Figure 9-6. When estimating basement floor vibration or vibration of at-grade slabs the correction is zero.

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[7]J.T. Nelson, H.J. Saurenman, "State-of-the-Art Review: Prediction and Control of Ground-Borne Noise and Vibration from Rail Transit Trains," Report Number UMTA-MA-06-0049-83-4, U.S. Department of Transportation, Urban Mass Transit Administration, December 1983.

[8]H.J. Saurenman, J.T. Nelson, G.P. Wilson, *Handbook of Urban Rail Noise and Vibration Control*, prepared under contract to US DOT/Transportation Systems Center, Report UMTA-MA-06-0099-82-2, February 1982.

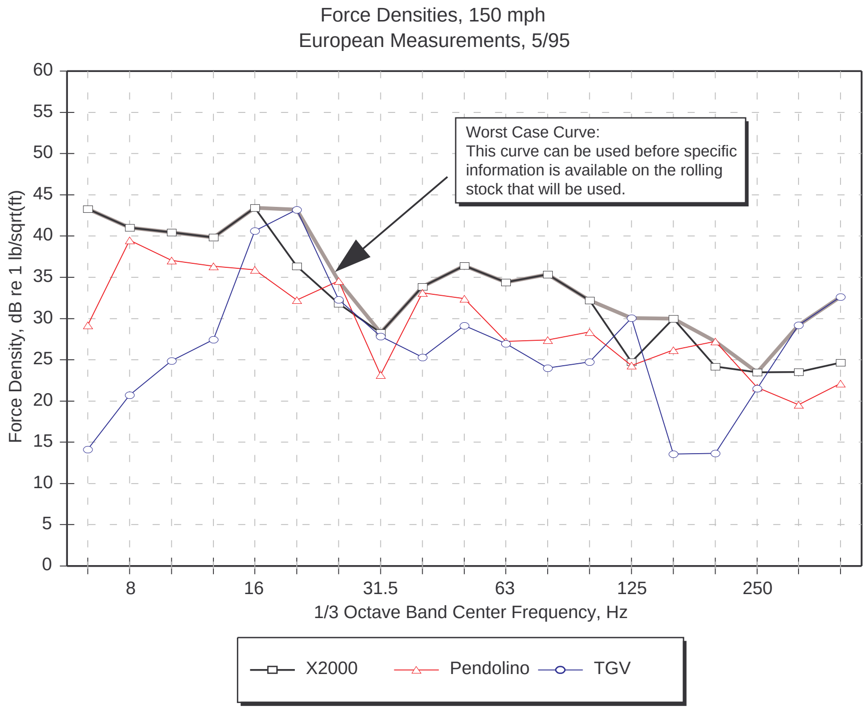

Figure 9-5 Force Densities for High-Speed Trains

2. **Transmission through the building.** The vibration amplitude will decrease as the vibration energy propagates from the foundation through the remainder of the building. The normal assumption is that vibration attenuates by 1 to 2 dB for each floor.

3. **Floor resonances.** Vibration amplitudes will be amplified because of resonances of the floor/ceiling systems. For a typical wood frame residential structure, the fundamental resonance is usually in the 15 to 20 Hz range. Reinforced-concrete slab floors in modern buildings will have fundamental resonance frequencies in the 20 to 30 Hz range. An amplification resulting in a gain of approximately 6 dB should be used in the frequency range of the fundamental resonance.

4. **Radiated 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. As discussed above, the radiation adjustment is zero for typical rooms, which gives:

$$L_A \approx L_v + K_{A\text{-}wt}$$

where: L_A = A-weighted sound level in a 1/3 octave band,
L_v = average RMS vibration velocity level, and
$K_{A\text{-}wt}$ = A-weighting adjustment at the center frequency of the 1/3 octave band.

The A-weighted levels in the 1/3 third octave bands are then combined to give the overall A-weighted sound level.

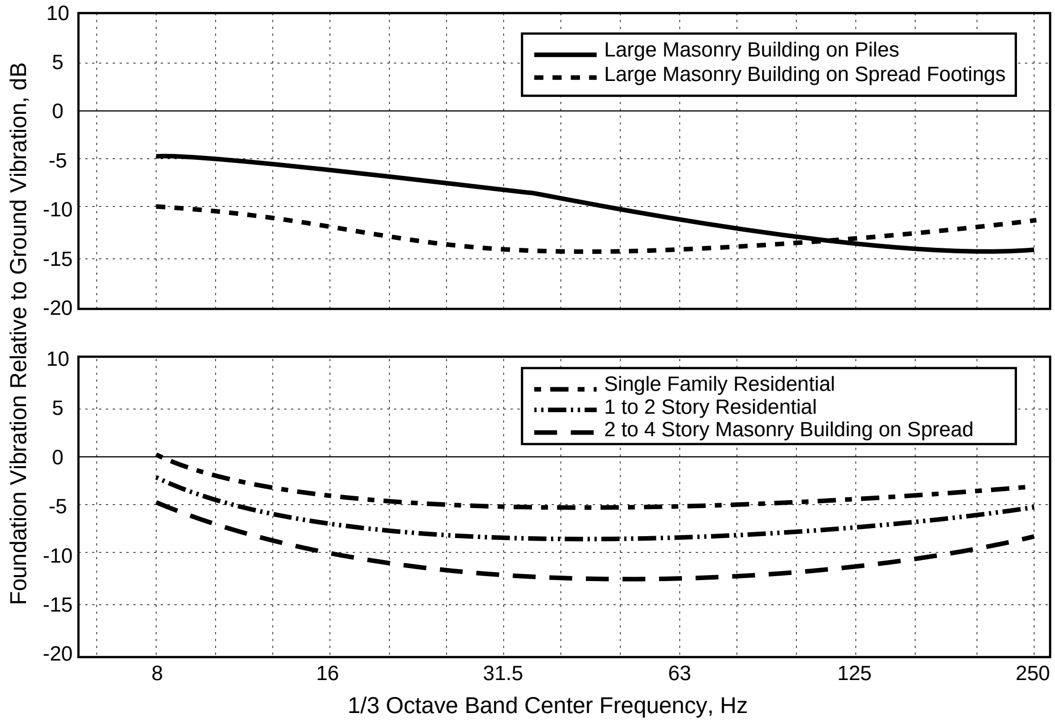

Figure 9-6 Approximate Foundation Response for Various Types of Buildings

9.4 VIBRATION MITIGATION

Mitigation can minimize the adverse effects of project ground-borne vibration on sensitive land uses. Available data indicate that ground-borne vibration from steel-wheel/steel-rail high-speed trains is caused by the same mechanisms as vibration from lower speed trains. Consequently, the approaches to controlling ground-borne vibration from transit systems generally are applicable to high-speed trains.

Because ground-borne vibration is not as common a problem as environmental noise, the mitigation approaches have not been as well defined. In some cases it has been necessary to develop innovative approaches to control the impact. Examples are the floating slab systems that were developed for the Washington, D.C. and Toronto transit systems and wheel-flat detectors that have been used to identify vehicles in need of maintenance.

The importance of adequate wheel and rail maintenance in controlling levels of ground-borne vibration cannot be overemphasized. Problems with rough wheels or rails can increase vibration levels by as much as 20 dB, negating the effects of even the most effective vibration control measures. It is rare that practical vibration control measures will provide more than 15 to 20 dB attenuation. When ground-borne vibration problems are associated with existing rails and rolling stock, often the best control measure is to implement new or improved maintenance procedures. Grinding rough or corrugated rail and implementing wheel truing to restore the wheel surface and contour may reduce vibration more than completely replacing the existing track system with floating slabs.

Assuming that the track and vehicles are in good condition, the options to further reduce ground-borne vibration fit into one of seven categories: (1) maintenance procedures, (2) location and design of special trackwork, (3) vehicle modifications, (4) changes in the track support system, (5) building modifications, (6) adjustments to the vibration transmission path, and (7) operational changes.

Maintenance

As discussed above, effective maintenance programs are essential for keeping ground-borne vibration levels under control. When the wheel and rail surfaces are allowed to degrade, the vibration levels can increase by as much as 20 dB compared to a new or well maintained system. Maintenance procedures that are particularly effective at avoiding increases in ground-borne vibration include:

- Rail grinding on a regular basis, particularly for rail that develops corrugations. Rail condition monitoring systems are available to optimize track conditions.
- Wheel truing to re-contour the wheel, provide a smooth running surface, and remove wheel flats. The most dramatic vibration reduction results from removing wheel flats. However, significant improvements also can be observed simply from smoothing the running surface. Wheel condition monitoring systems are available to optimize wheel conditions.
- Reconditioning vehicles, particularly when components such as suspension system, brakes, and wheels will be improved, and slip-slide detectors will be installed.
- Installing wheel condition monitoring systems to identify those vehicles most in need of wheel truing.

Location and Design of Special Trackwork

Most vibration impact from a new train system is caused by wheel impacts at the special trackwork for turnouts and crossovers. Careful review of crossover and turnout locations during the preliminary engineering stage is an important step in minimizing potential for vibration impact. When feasible, the most effective vibration control measure is to relocate the special trackwork to a less vibration-sensitive area. Sometimes this requires adjusting the location by several hundred feet and will not have a significant adverse impact on the operation plan for the system. Another approach is to install movable-point or spring frogs that eliminate the gaps that occur when standard railbound frogs are used. These special frogs have been shown to significantly reduce vibration levels near crossovers, and they are often specified because of their longer life span under repetitive high-speed conditions.

Vehicle Suspension

The ideal rail vehicle, with respect to minimizing ground-borne vibration, should have a low unsprung weight, a soft primary suspension, a minimum of metal-to-metal contact between moving parts of the truck, and smooth wheels that are perfectly round. A thorough dynamic analysis, including the expected track parameters, should be part of the specifications for any new high-speed trainset.

Special Track Support Systems

When the vibration assessment indicates that vibration levels will be excessive, it is usually the track support system that is modified to reduce the vibration levels. Floating slabs, resiliently supported ties, high resilience fasteners, and ballast mats all have been used to reduce the levels of ground-borne vibration. To be effective, these measures must be optimized for the frequency spectrum of the vibration. These measures have been used successfully on urban transit subway projects, but applications on at-grade and elevated track are rare because: vibration problems are less common for at-grade and elevated track; cost of the vibration control measures is a higher percentage of the construction costs of at-grade and elevated track; and exposure to outdoor weather conditions requires special drainage designs.

The major vibration control measures for track support are discussed below:

- Resilient Fasteners: Resilient fasteners are used to fasten rails to concrete track slabs. Standard resilient fasteners are very stiff in the vertical direction, usually in the range of 200,000 lb/in., although they do provide some vibration reduction. On urban transit systems, special fasteners with vertical stiffness in the range of 40,000 to 75,000 lb/in. have reduced vibration by as much as 5 to 10 dB at frequencies above 30 to 40 Hz.

- Ballast Mats: A ballast mat consists of a rubber or other type of elastomer pad that is placed under the ballast. The mat generally must be placed on a thick concrete or asphalt pad to be effective. It will not be as effective if placed directly on the soil or the sub-ballast. Consequently, most ballast mat applications are in tunnels or bridges. Ballast mats can provide 10 to 15 dB attenuation at frequencies above 25 to 30 Hz. An installation of ballast mat in a tunnel in France near Vouvray in TGV’s Atlantique line prevents vibrations from affecting storage and ageing of wines in a nearby wine cave. Ballast mats are often a good retrofit measure for existing tie-and-ballast track where there are vibration problems.

- Resiliently Supported Ties: A resiliently supported tie system, like the one used in the Channel Tunnel between England and France, consists of concrete ties supported by rubber pads. The rails are fastened directly to the concrete ties using standard rail clips. Some measurement data suggest that resiliently supported ties may reduce low-frequency vibration in the 15 to 40 Hz range, which would make them particularly appropriate for rail systems with vibration problems in the 20 to 30 Hz range. The frequency range over which this type of track support system can affect levels of ground-borne vibration depends on the pad stiffness and the interaction between the pads, ties, and rails.

- Floating Slabs: Floating slabs can be very effective at controlling ground-borne vibration and noise. They basically consist of a concrete slab supported on resilient elements, usually rubber or a similar elastomer. A variant that was first used in Toronto and is generally referred to as the double tie system, consists of 5-foot slabs with four or more rubber pads under each slab. Floating slabs are effective at frequencies greater than their single-degree-of-freedom vertical resonance frequency. The floating slabs used in the Washington DC, Atlanta, and Boston transit systems were all designed to have a vertical resonance in the 14 to 17 Hz range. A special London Transport floating slab that is under the Barbican Redevelopment uses a very heavy design with a resonance frequency in the 5 to 10 Hz frequency range.[9] The primary disadvantage of floating slabs is that they tend to be the most expensive of the track-related vibration control treatments.

- 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, heavier ties, or resilient elements beneath the tracks can be expected to reduce the vibration levels. There also is some indication that vibration levels are lower with wood ties compared to concrete ties. However, there is little confirmation that any of these approaches will make a significant change in the vibration levels. This is unfortunate since modifications to the ballast, rails, or ties are virtually the only options for typical track systems (at-grade, ballast-and-tie) without resorting to a different type of track support system or widening the right-of-way to provide a buffer zone.

Building Modifications

In some circumstances, it is practical to modify an affected building to reduce the vibration levels. Vibration isolation of buildings basically consists of supporting the building foundation on elastomer pads similar to bridge bearing pads. Vibration isolation is seldom an option for existing buildings. However, building vibration isolation can be particularly important for shared-use facilities such as office space above a train station or terminal. When vibration-sensitive equipment such as electron microscopes will be affected by train vibration, specific modifications to the building structure may be the most cost-effective method of controlling the impact. For example, the floor upon which the vibration-sensitive equipment is located could be stiffened and isolated from the remainder of the building.

Trenches

Use of trenches to control ground-borne vibration is analogous to controlling airborne noise with sound barriers. Although this approach has not received much attention in the U.S., a trench can be a practical method for controlling vibration from at-grade track. A rule-of-thumb given by Richert and Hall [10] 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 feet. This means that the trench would have to be approximately 12 feet deep to be effective at 30 Hz.

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[9] P. Grootenhuis, "Floating Track Slab Isolation for Railways," *Journal of Sound and Vibration,* 51:3, pp 443-448, 1977.

[10] F. E. Richert and J. R. Hall, *Vibrations of Soils and Foundations*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1970.

A trench can be an effective vibration barrier if it changes the propagation characteristics of the soil. It can be either open or solid. The Toronto Transit Commission did a test with a trench filled with Styrofoam to keep it open. They reported successful performance over a period of at least one year.[11] Solid barriers can be constructed with sheet piling, rows of drilled shafts filled with either concrete or a mixture of soil and lime,[12] or concrete poured into a trench.

Operational Changes

The most obvious operational change is to reduce the vehicle speed. Reducing the train speed by a factor of two will reduce vibration levels approximately 6 dB. Other operational changes that can be effective in special cases are:

- Use the equipment that generates the lowest vibration levels during the nighttime hours when people are most sensitive to vibration and noise.
- Adjust nighttime schedules to minimize train movements during the most sensitive hours.

While there are tangible benefits from reducing speed and limiting operations during the most sensitive time periods, these measures may not be practical from the standpoint of trip time and service frequency requirements. Furthermore, vibration reduction achieved through operating restrictions requires continuous monitoring and will be negated if the signal system does not enforce compliance with the speed restriction.

Buffer Zones

Expanding the rail right-of-way sometimes will be the most economical method of controlling the vibration impact. A similar approach is to negotiate a vibration easement from the affected property owners.

[11] S. T. Lawrence, "TTC-LRT Trackbed Studies, Ground-borne Vibration Testing, Measurement and Evaluation Program," American Public Transit Association Rapid Transit Conference, San Francisco, CA, 1980.

[12] "The Lime Column Method," Report No. 31, Swedish Geotechnical Institute, Linkoping, Sweden, 1994.

Chapter 10

NOISE AND VIBRATION DURING CONSTRUCTION

This chapter discusses the procedures for assessing the temporary noise and vibration impacts associated with the construction of a new high-speed rail facility. Methods for estimating noise and vibration levels from construction equipment using tabulated source levels, as well as procedures for assessing and mitigating potential noise and vibration impacts are provided. While both construction noise and vibration are included in this chapter, there is generally no overlap between them in the methodology and they are covered in separate sections.

Construction often generates community noise/vibration complaints, despite the limited time frame over which it takes place. Complaints typically arise when construction efforts interfere with people's activities, especially when the community has insufficient information about the extent or duration of the construction. Misunderstandings can occur when the contractor is considered insensitive by the community, even though the contractor believes the construction activities are in compliance with local ordinances. This situation underscores the need for early identification and assessment of potential problem areas. An assessment of the potential for complaints can be made by following procedures outlined in this chapter. That assessment can aid contractors in making bids by allowing changes in construction approach and by including mitigation costs before the construction plans are finalized. Publication of an assessment, including a description of the construction noise and vibration environment, can lead to greater understanding and tolerance in the community.

Control of construction noise and vibration occurs in three areas:

- **Assessment:** The environmental impact assessment identifies the potential problem areas during the construction phase of a project and the environmental assessment document informs the public of the project's construction effects. This information is important for new major infrastructure projects where heavy construction can take place over a lengthy period of time. The procedure for performing a noise assessment is discussed in Section 10.1 and for vibration assessment is discussed in Section 10.2.

- **Construction specifications:** Most large construction projects incorporate noise specifications on construction equipment, but sometimes they must include additional measures to minimize community complaints. Special mitigation measures can be written into the construction documents where they are identified as necessary by the environmental impact assessment. The documents should include realistic specifications that lessen community annoyance without unreasonably constraining the contractors. Typical noise limits on equipment are included in Table 10-1.
- **Compliance verification:** Provide clear direction to field inspectors on conducting and reporting measurements for compliance with noise and vibration specifications in sensitive areas.

10.1 CONSTRUCTION NOISE

The noise levels created by operating construction equipment can vary greatly and depend on factors such as the type of equipment, the specific model, the operation being performed, and the condition of the equipment. The equivalent sound level (L_{eq}) of the construction activity also depends on the fraction of time that the equipment is operated over the time period of construction. This section provides information on typical levels generated by various construction equipment and provides guidance on assessment of noise from construction activities related to rail facilities. The level of noise analysis should be commensurate with the type and scale of the project and with the presence of noise-sensitive land uses in the construction zone.

10.1.1 Noise from Typical Construction Equipment and Operations

The dominant source of noise from most construction equipment is the engine, usually a diesel, without sufficient muffling. In a few cases, such as impact pile driving or pavement breaking, noise generated by the action of the machinery dominates.

For purposes of noise assessment, construction equipment can be considered to operate in two modes, stationary and mobile. Stationary equipment operates in one location for one or more days at a time, with either a fixed-power operation (pumps, generators, compressors) or a variable noise operation (pile drivers, pavement breakers). Noise is assumed to emanate from the point of operation. Mobile equipment moves around the construction site with power applied in cyclic fashion (bulldozers, loaders), or to and from the site (trucks). The movement around the site is handled in the construction noise prediction procedure discussed later in this chapter. Variation in power imposes additional complexity in characterizing the noise source level from a piece of equipment. This variation is handled by describing the noise at a reference distance from the equipment operating at full power and adjusting it based on the duty cycle of the activity to determine the L_{eq} of the operation. Standardized procedures for measuring the exterior noise levels for the certification of mobile and stationary construction equipment have been developed by the Society of Automotive Engineers.[1,2] Typical noise levels generated by representative pieces of equipment are listed in Table 10-1. These levels are based on EPA Reports,[3,4,5] measured data from railroad construction equipment, and other measured data.

Construction activities are characterized by variations in the power expended by equipment, with resulting variation in noise levels over time. Variation in power is expressed in terms of the "usage factor" of the equipment, the percentage of time during the workday that the equipment operates at full power. Time-varying noise levels are converted to a single number (L_{eq}) for each piece of equipment during the operation. Besides having daily variations in activities, major construction projects are accomplished in several different phases. Each phase has a specific equipment mix, depending on the work to be accomplished during that phase.

Each phase also has its own noise characteristics; some will have higher continuous noise levels than others, and some have high-impact noise levels. The purpose of the assessment is to determine not only the levels, but also the duration, of the noise. The L_{eq} of each phase is determined by combining the L_{eq} contributions from each piece of equipment used in that phase. The impact and the consequent noise mitigation approaches depend on the criteria to be used in assessing impact, as discussed in the next section.

10.1.2 Construction Noise Assessment

The level of detail in a construction noise assessment depends on the scale and type of project and the stage of environmental review process. Where the project is a major undertaking (the construction duration is expected to last for more than several months, noisy equipment will be involved, and/or the construction is expected to take place near a noise-sensitive site), then construction noise impacts may be determined in considerable detail, as described in this section. For other projects, the assessment may simply be a description of the equipment to be used, the duration of construction, and any mitigation requirements that will be placed on particularly noisy operations.

[1] Society of Automotive Engineers, "Exterior Sound Level Measurement Procedure for Powered Mobile Construction Equipment," SAE Recommended Practice J88a, 1976.

[2] Society of Automotive Engineers, "Sound Levels for Engine Powered Equipment," SAE Standard J952b, 1976.

[3] U.S. Environmental Protection Agency, "Noise from Construction Equipment and Operations, Building Equipment and Home Appliances," NTID300.1, December 31, 1971.

[4] U.S. Department of Transportation, "Final Environmental Impact Statement, 4(f) Statement; Replacement of Shaw's Cove Bridge and Approaches," FRA-RNC-EIS-80-02-F, September 16, 1981.

[5] William R. Fuller and Ron Brown, "Analysis and Abatement of Highway Construction Noise," EPA 550/9-81-314-A, U.S. Environmental Protection Agency, Office of Noise Abatement and Control and U.S. Department of Transportation, Federal Highway Administration, June 1981.

A construction noise assessment for a major project is performed by comparing the predicted noise levels with criteria established for that type of project. The approach requires an appropriate **descriptor**, a standardized prediction **method**, and a set of recognized **criteria** for assessing the impact.

The descriptor used for construction noise is the L_{eq}. This unit is appropriate for the following reasons:

- It can be used to describe the noise level from operation of each piece of equipment separately and is easily combined to represent the noise level from all equipment operating during a given period.
- It can be used to describe the noise level during an entire phase.
- It can be used to describe the average noise over all phases of the construction.

The recommended method for predicting construction noise impact for major urban transit projects is similar to that suggested by the Federal Highway Administration (FHWA).[6] The FHWA prediction method is used to estimate the construction noise levels associated with the construction of a highway, but it can be used for any transportation project. The method requires:

1. An emission model to determine the noise generated by the equipment at a reference distance.
2. A propagation model that shows how the noise level will vary with distance.
3. A way of summing the noise of each piece of equipment at locations of noise sensitivity.

Table 10-1 Construction Equipment Noise Emission Levels

Equipment	Typical Noise Level (dBA) 50 ft from Source
Air Compressor	81
Backhoe	80
Ballast Equalizer	82
Ballast Tamper	83
Compactor	82
Concrete Mixer	85
Concrete Pump	82
Concrete Vibrator	76
Crane, Derrick	88
Crane, Mobile	83
Dozer	85
Generator	81
Grader	85
Impact Wrench	85
Jack Hammer	88
Loader	85
Paver	89
Pile Driver (Impact)	101
Pile Driver (Sonic)	96
Pneumatic Tool	85
Pump	76
Rail Saw	90
Rock Drill	98
Roller	74
Saw	76
Scarifier	83
Scraper	89
Shovel	82
Spike Driver	77
Tie Cutter	84
Tie Handler	80
Tie Inserter	85
Truck	88

[6] J. A. Reagan and C. A. Grant, "Special Report - Highway Construction Noise: Measurement, Prediction and Mitigation," U.S. Department of Transportation, Federal Highway Administration, 1977.

The first two components of the model are related by the following equation:

$$L_{eq}(equip) = E.L. + 10\log(U.F.) - 20\log\left(\frac{D}{50}\right) - 10\,G\log\left(\frac{D}{50}\right)$$

where:

L_{eq}(equip) = L_{eq} at a receiver resulting from the operation of a single piece of equipment over a specified time period,

E.L. = noise emission level of the particular piece of equipment at the reference distance of 50 feet (taken from Table 10-1),

G = constant that accounts for topography and ground effects (taken from Chapter 6, Figure 6-5),

D = distance from the receiver to the piece of equipment, and

U.F. = usage factor that accounts for the fraction of time that the equipment is in use over the specified time period.

The combination of noise from several pieces of equipment operating during the same time period is obtained from decibel addition of the L_{eq} of each single piece of equipment calculated using this equation.

Major Construction Projects

The assessment of a major construction project can be as detailed as necessary to characterize the construction noise by specifying the various quantities in the equation. For projects in an early assessment stage, when the equipment roster and schedule are undefined, only a rough estimate of construction noise levels is practical.

The following assumptions are adequate for a General Assessment of each phase of construction:

Step 1. **Noise Source Level.** Full power operation for a time period of one hour is assumed because most construction equipment operates continuously for periods of one hour or more at some point in the construction period. Therefore, *U.F.* = 1, and 10 log(*U.F.*) = 0. The emission level at 50 feet, *E.L.*, is taken from Table 10-1. The predictions include only the two noisiest pieces of equipment expected to be used in each construction phase.

Step 2. **Noise Propagation.** Free field conditions are assumed and ground effects are ignored. Consequently, *G* = 0. All pieces of equipment are assumed to operate at the center of the project, or centerline, in the case of a guideway or highway construction project.

A more detailed analysis can be used if warranted, such as when a known noise-sensitive site is adjacent to a construction project or where contractors are faced with stringent local ordinances or specifications as a result of public concern. In such instances, the assessment sequence includes:

Step 1. **Duration of the Construction.** Long-term construction project noise impact is based on a 30-day average L_{dn}, the times of day of construction activity (nighttime noise is penalized by 10 dB in residential areas), and the percentage of time the equipment is to be used during a period of time that will affect *U.F.* For example, an 8-hour L_{eq} is determined by making *U.F.* the percentage of time each individual piece of equipment operates under full power in that period. Similarly, the 30-day average L_{dn} is determined from the *U.F.* expressed by the percentage of time the equipment is used during the daytime hours (7 a.m. to 10 p.m.) and nighttime (10 p.m. to 7 a.m.), separately over a 30-day period. However, to account for increased sensitivity to nighttime noise, the nighttime percentage is multiplied by 10 before performing the computation.

Step 2. **Site topography, natural and constructed barriers, and ground effects.** These features will change the factor *G*. Use Figure 5-3 to calculate *G*.

Step 3. **Refinement of Emission Level.** Measure or certify the emission level of each piece of equipment according to standardized procedures.[7,8] This measurement will refine *E.L.*

Step 4. **Location of Equipment.** Determine the location of each piece of equipment while it is working. The distance factor *D* is therefore specified more exactly.

Step 5. **Total Noise Source Level.** Include all pieces of equipment in the computation of the 8-hour L_{eq} and the 30-day average L_{dn}. The total noise levels are determined using Table 5-5 (Chapter 5).

Minor Construction Projects

Most minor projects need no assessment of construction noise. However, when a construction project over a short period of time occurs in a noise-sensitive area, a qualitative treatment is appropriate. Community relations will be important in this case; early information disseminated to the public about the kinds of equipment, expected noise levels, and durations will help to forewarn potentially affected neighbors about the temporary inconvenience. Helpful information would include a general description of the variation of noise levels during a typical construction day. The General Assessment method described earlier in this section will be sufficient to provide the estimated noise levels. There is no need for a full assessment since the criteria suggested in the following section are not applicable in these cases.

Criteria

No standardized **criteria** have been developed for assessing construction noise impact. Consequently, criteria must be developed on a project-specific basis unless local ordinances apply. Generally, local noise ordinances are not very useful in evaluating construction noise. They usually relate to nuisance and hours of allowed activity and sometimes specify limits in terms of maximum levels, but they are generally not

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[7]Society of Automotive Engineers, "Exterior Sound Level Measurement Procedure for Powered Mobile Construction Equipment," SAE Recommended Practice J88a, 1976.

[8]Society of Automotive Engineers, "Sound Levels for Engine Powered Equipment," SAE Standard J952b, 1976.

practical for assessing the impact of a construction project. Project construction noise criteria should take into account the existing noise environment, the absolute noise levels during construction activities, the duration of the construction, and the adjacent land use. While it is not the purpose of this manual to specify standardized criteria for construction noise impact, the following guidelines can be used as criteria for assessment. They are deliberately conservative because the related assessment method tends to over-predict noise levels. If these criteria are exceeded, the project is likely to face adverse community reaction and steps to mitigate the impact should be evaluated and implemented as necessary.

General Assessment: Identify land uses in the vicinity of the construction project according to residential, commercial, and industrial land use activities. Estimate the combined noise level in one hour from the two noisiest pieces of equipment, assuming they both operate at the same time. Then identify locations where the level exceeds the levels specified in Table 10-2:

Table 10-2 General Assessment Criteria for Construction noise

Land Use	One-hour L_{eq} (dBA)	
	Day	Night
Residential	90	80
Commercial	100	100
Industrial	100	100

Detailed Assessment: Predict the noise level in terms of 8-hour L_{eq} and 30-day averaged L_{dn} and compare to levels specified in Table 10-3:

Table 10-3 Detailed Assessment Criteria for Construction Noise

Land Use	8-hour L_{eq} (dBA)		L_{dn} (dBA)
	Day	Night	30-day Average
Residential	80	70	75[a]
Commercial	85	85	80[b]
Industrial	90	90	85[b]

[a] In urban areas with very high ambient noise levels (L_{dn} > 65 dB), L_{dn} from construction operations should not exceed existing ambient + 10 dB.

[b] Twenty-four-hour L_{eq}, not L_{dn}.

10.1.3 Mitigation of Construction Noise

After using the approach presented in Section 10.1.2 to locate potential impacts from construction noise, the next step is to identify appropriate control measures. The design engineer can implement noise control through layout of the construction site, planning the order of operations, or by choosing less noisy operations. These categories of noise control approaches, with examples of mitigation measures, are given below:

1. Design considerations and project layout:

   - Construct noise barriers, such as temporary walls or piles of excavated material, between noisy activities and noise-sensitive receivers.
   - Route truck traffic away from residential streets, if possible. 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 around clusters of noisy equipment. For example, shields can be used around pavement breakers and loaded vinyl curtains can be draped under elevated structures .

2. Sequence of operations:

   - Combine noisy operations so they occur in the same time period. The total noise level produced will not be significantly greater than the level produced if the operations were performed separately.
   - Avoid nighttime activities. Sensitivity to noise increases during the nighttime hours in residential neighborhoods.

3. Alternative construction methods:

   - Avoid impact pile driving where possible in noise-sensitive areas. Drilled piles or the use of a sonic or vibratory pile driver are quieter alternatives where the geological conditions permit their use.
   - Use specially quieted equipment, such as quieted and enclosed air compressors, and mufflers on all engines.
   - Select quieter demolition methods, where possible. For example, sawing bridge decks into sections that can be loaded onto trucks results in lower cumulative noise levels than impact demolition by pavement breakers.

The environmental assessment should include a description of one or more mitigation approach for each affected location.

10.2 CONSTRUCTION VIBRATION

Construction activity can result in varying degrees of ground vibration, depending on the equipment and methods employed. Operation of construction equipment causes ground vibrations, which spread through the ground and diminish in strength with distance. Buildings founded on the soil in the vicinity of the construction site respond to these vibrations with varying results, ranging from no perceptible effects at the lowest levels, low rumbling sounds and perceptible vibrations at moderate levels, and slight damage at the highest levels. Ground vibrations from construction activities very rarely reach the levels that can damage structures, but they can achieve the audible and perceptible ranges in buildings very close to the site. A possible exception is construction taking place near old, fragile buildings of historical significance where special care must be taken to avoid damage. The construction vibration criteria should include special consideration for fragile historical buildings. The construction activities that typically generate the most severe vibrations are blasting and impact pile driving.

10.2.1 Vibration Source Levels from Construction Equipment

Various types of construction equipment have been measured operating under a wide variety of construction activities, with an average of source levels reported in terms of velocity levels as shown in Table 10-4. Although Table 10-4 gives one level for each piece of equipment, the reported ground vibration levels from construction activities vary considerably. The data provide a reasonable estimate for a wide range of soil conditions.

Since the primary concern with regard to construction vibration is building damage, construction vibration is generally assessed in terms of peak particle velocity (PPV), as defined in Chapter 6. Peak particle velocity is typically a factor of 2 to 6 times greater than root mean square (rms) vibration velocity; a factor of 4 has been used to calculate the approximate rms vibration velocity levels indicated in Table 10-4.

10.2.2 Construction Vibration Assessment

Construction vibration should be assessed in cases where there is a significant potential for impact from construction activities. Such activities include blasting, pile driving, demolition, and drilling or excavation in close proximity to sensitive structures. The recommended procedure for estimating vibration impact from construction activities is as follows:

Step 1. Vibration Source Levels. Select the equipment and associated vibration source levels at the reference distance of 25 feet as shown in Table 10-4.

Step 2. Vibration Propagation. Make the propagation adjustment according to the following formula, based on point sources with normal propagation conditions:

$$PPV_{equip} = PPV_{ref} \times \left(\frac{25}{D}\right)^{1.5}$$

where: PPV_{equip} = the peak particle velocity in in/sec of the equipment adjusted for distance
PPV_{ref} = the reference vibration level in in/sec at 25 feet from Table 10-4, and
D = the distance from the equipment to the receiver.

Step 3. Damage Criterion. Apply the PPV vibration damage threshold criterion of 0.50 in/sec (approximately 102 VdB) for fragile buildings, or 0.12 in/sec (approximately 90 VdB) for extremely fragile historic buildings.[9]

Step 4. Annoyance Criterion. For considerations of annoyance or interference with vibration-sensitive activities, estimate the RMS vibration level L_v at any distance D from the following equation:

$$L_v(D) = L_v(25\text{ ft}) - 20\log\left(\frac{D}{25}\right)$$

Apply the vibration impact criteria in Chapter 7 for vibration-sensitive sites.

Table 10-4 Vibration Source Levels for Construction Equipment
(From measured data.[10,11,12,13])

Equipment		PPV at 25 ft (in/sec)	Approximate L_v[†] at 25 ft
Pile Driver (impact)	upper range	1.518	112
	typical	0.644	104
Pile Driver (vibratory)	upper range	0.734	105
	typical	0.170	93
Clam shovel drop (slurry wall)		0.202	94
Hydromill (slurry wall)	in soil	0.008	66
	in rock	0.017	75
Large bulldozer		0.089	87
Caisson drilling		0.089	87
Loaded trucks		0.076	86
Jackhammer		0.035	79
Small bulldozer		0.003	58

† RMS velocity in decibels (VdB) re 1 μinch/second

[9] Swiss Consultants for Road Construction Association, "Effects of Vibration on Facilities," VSS-SN640-312a, Zurich, Switzerland, April 1992.

[10] 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.

[11] J.F. Wiss, "Vibrations During Construction Operations," Journal of Construction Division, Proc. American Society of Civil Engineers, 100, No. CO3, pp. 239 - 246, September 1974.

[12] J.F. Wiss, "Damage Effects of Pile Driving Vibrations," Highway Research Record, No. 155, Highway Research Board, 1967.

[13] D.A. Towers, "Ground-borne Vibration from Slurry Wall Trench Excavation for the Central Artery/Tunnel Project Using Hydromill Technology," Proceedings of Inter-Noise 95, Newport Beach, CA, July 1995, pp. 227 - 232.

10.2.3 Construction Vibration Mitigation

After using the procedure described in Section 10.2.2 to locate potential impacts (or damage) from construction vibrations, the next step is to identify control measures. Similar to construction noise, mitigation of construction vibration requires consideration of equipment location and processes, as follows:

1. Design considerations and project layout:
   - Route heavily loaded trucks away from residential streets, if possible. Select streets with fewest homes, if no alternatives are available.
   - Operate earthmoving equipment on the construction lot as far away from vibration-sensitive sites as possible.
2. Sequence of operations:
   - Phase demolition, earthmoving, and ground-impacting operations so as not to occur in the same time period. Unlike noise, the total vibration level produced could be significantly less when each vibration source operates separately.
   - Avoid nighttime activities. People are more aware of vibration in their homes during the nighttime hours.
3. Alternative construction methods:
   - Avoid impact pile driving where possible in vibration-sensitive areas. Drilled piles or the use of a sonic or vibratory pile driver causes lower vibration levels where the geological conditions permit their use.
   - Select demolition methods not involving impact, where possible. For example, sawing bridge decks into sections that can be loaded onto trucks results in lower vibration levels than impact demolition by pavement breakers, and milling generates lower vibration levels than excavation using clam shell or chisel drops.
   - Avoid vibratory rollers and packers near sensitive areas.

10.2.4 Special Note on Pile Driving

Pile driving is potentially the greatest source of vibration associated with equipment used during construction of a project. The source levels in Table 10-4 indicate that vibratory pile drivers may provide substantial reduction of vibration levels. However, the additional vibration effects of vibratory pile drivers may limit their use in sensitive locations. A vibratory pile driver operates by continuously shaking the pile at a fixed frequency, literally vibrating it into the ground. However, continuous operation at a fixed frequency may be more noticeable to nearby residents, even at lower vibration levels. Furthermore, the steady-state excitation of the ground may increase resonance response of building components. Resonant response may be unacceptable in cases of fragile historical buildings or vibration-sensitive manufacturing processes. Impact pile drivers, on the other hand, produce a high vibration level for a short time (0.2 seconds) with sufficient time between impacts to allow any resonant response to decay.

Chapter 11

DOCUMENTATION OF NOISE AND VIBRATION ASSESSMENT

To be effective, noise and vibration analyses must be presented to the public in a clear, comprehensive manner. The mass of technical data and information necessary to withstand scrutiny in the environmental review process must be documented in a manner that remains intelligible to the public. Justification for all assumptions used in the analysis, such as selection of representative measurement sites and all baseline conditions, must be presented for review. For large-scale projects, the environmental document normally contains a condensation of essential information to maintain a reasonable size. For these projects, separate technical reports are usually prepared as supplements to the Environmental Impact Statement (EIS) or Environmental Assessment (EA). For smaller projects, or ones with minimal noise or vibration impact, all the technical information may be presented in the environmental document itself. This chapter gives guidance on how the necessary noise and vibration information should be incorporated in the project's environmental documentation.

11.1 THE TECHNICAL REPORT ON NOISE AND VIBRATION

A separate technical report is often prepared as a supplement to the environmental document (EIS or EA). A technical report is appropriate when all of the data cannot be placed in the environmental document. The details of the analysis are important for establishing the basis for the assessment. Consequently, all the details in the technical report should be contained in a well-organized format for easy access to the information. While the technical report is not intended to be a primer on the subject, the technical data and descriptions should be presented in a manner that can be understood by the general public. All the necessary background information should be included in the technical report, including tables, maps, charts, drawings, and references that may be too detailed for the environmental document, but that are important in helping to draw conclusions about the project's noise and vibration impacts and mitigation options.

11.1.1 Organization of Technical Report

The technical report on noise and vibration should contain the following major subject headings, along with the key information content described below. If both noise and vibration have been analyzed, it is generally preferable to separate the noise and vibration sections; as shown in this manual, the approaches to the two topics are quite different.

Overview – This section contains a brief description of the project and an overview of the noise/vibration concerns. It sets forth the initial considerations in framing the scope of the study.

Inventory of Noise and Vibration-Sensitive Sites – The approach for selecting noise/vibration- sensitive sites should be described in sufficient detail to demonstrate completeness. Sites and site descriptions are to be included.

Measurements of Existing Noise and Vibration Conditions – The basis for selecting measurement sites should be documented, along with tables of sites coordinated with maps showing locations of sites. If the measurement data are used to estimate existing conditions at other locations, the rationale and the method should be included. Measurement procedures should be fully described. Tables of measurement instruments should include manufacturer, type, serial number, and date of most recent calibration by authorized testing laboratory. Measurement periods, including time of day and length of time at each site, should be shown to demonstrate adequate representation of the ambient conditions. The measurement data should be presented in well-organized form in tables and figures. A summary and interpretation of measured data should be included.

Special Measurements Related to the Project – Some projects may require specialized measurements at sensitive sites, such as outdoor-to-indoor noise level reduction of homes or transmission of vibrations into concert halls and recording studios. Other projects may need special source level characterization. Full descriptions of the measurements and the results should be included.

Predictions of Noise/Vibration from the Project – The prediction model used for estimating future project conditions should be fully described and referenced. Any changes or extensions to the models recommended in this manual should be fully described so that the validity of the adjustments can be confirmed. Specific data used as input to the models should be listed. Computed levels should be tabulated and illustrated by contours, cross-sections, or shaded mapping. It is important to illustrate noise and vibration impacts with base maps at a scale with enough detail to provide location reference for the reader.

Noise and Vibration Criteria – Impact criteria for the project should be fully described and referenced (refer to Chapters 3 and 8). In addition, any applicable local ordinances should be described. Tables specifying the criteria levels also should be included. If the project involves considerable construction, and a separate construction noise and vibration analysis will be included, then construction criteria should appear in a separate section with its own assessment.

Noise and Vibration Impact Assessment – The impact assessment should be described according to the procedures outlined in this manual. A resulting impact inventory should be presented for each alternative mode or alignment to enable ready comparison among alternatives. The inventory should be tabulated according to the different types of land uses affected. The results of the assessment may be presented both before and after mitigation.

Noise and Vibration Mitigation – The mitigation section of the report should begin with a summary of all treatments considered, even if some are not carried to final consideration. Final candidate mitigation treatments should be considered separately, with description of the features of the treatment, costs, expected benefit in reducing impacts, locations where the benefit would be realized, and discussion of practicality of implementing alternative treatments. Enough information should be included to allow the project sponsor and FRA to reach decisions on mitigation prior to issuance of the final environmental document.

Construction Noise and Vibration Impacts – Criteria adopted for construction noise or vibration should be described, if appropriate. In accordance with Chapter 10, these may be adopted on a project-specific basis. The method used for predicting construction noise or vibration should be described, along with inputs to the models, such as equipment roster by construction phase, equipment source levels, assumed usage factors, and other assumed site characteristics. The predicted levels should be shown for sensitive sites and short-term impacts should be identified. Feasible abatement methods should be discussed in enough detail such that construction contract documents could include mitigation measures.

References – Documentation is an important part of the validation of the technical report. References should be provided for all criteria, approaches and data used in the analyses, including other reports related to the project which may be relied on for information, e.g., geotechnical reports.

11.2 THE ENVIRONMENTAL DOCUMENT

The environmental document typically includes noise and vibration information in three places: a section of the chapter on the affected environment (existing conditions) and two sections in the chapter on environmental consequences (long-term and short-term impacts). The noise and vibration information presented in the environmental document is a summary of the comprehensive information from the technical report, with emphasis on presenting the salient points of the analysis in a format and style that affected property owners and other interested citizens can understand. Smaller projects may have all of the technical information contained within the environmental document; special care should be taken in summarizing technical details to convey the information adequately.

The environmental document provides full disclosure of noise and vibration impacts, including identification of locations where impacts cannot be mitigated satisfactorily. An EIS describes significant impacts and tells what the federal agency intends to do about them. Issuing a Finding of No Significant Impact (FONSI) may depend on mitigation being included. The specific mitigation recommendation in the environmental document depends on the stage of project development and the stage of environmental review. For example, a Draft EIS may discuss different options to mitigate noise or vibration, deferring the final selection of measures to the Final EIS. It may be particularly important to present mitigation options at an early stage, especially if there is a benefit in receiving input from the public on the choices.

The final environmental document (Final EIS or FONSI) can take two approaches to describe any decisions on whether and/or how to mitigate. The document could describe the actual mitigation measures that will be employed, along with the reductions in noise or vibration expected to occur. In this case, the report should include language making it clear that the measures shall be implemented if the project is approved. However, in some cases, mitigation measures may still be under study in the environmental review and will not be selected until the final design stage. In such cases, the final environmental document should express a commitment to mitigate impacts that are verified during final design. Mitigation in these cases can be addressed in the form of a "performance standard" to be met by using one or more of the measures under study.

11.2.1 Organization of Noise and Vibration Sections

Chapter on Affected Environment (Existing Conditions)

This chapter describes the pre-project setting, including the existing noise and vibration conditions, that will likely be affected by one or more of the alternatives. The primary function of this chapter is to establish the focus and baseline conditions for later chapters discussing environmental impacts. Consequently, this chapter is a good place to put basic information on noise and vibration descriptors and effects, as well as for describing the characteristics in the vicinity of the project. Again, it is preferable to separate the noise and vibration sections.

- **Description of Noise and Vibration Descriptors, Effects and Typical Levels:** Information from Chapters 2 and 7 of this manual can be used to provide a background for the discussions of noise/vibration levels and characteristics to follow. Illustrative material to guide the reader in understanding typical levels is helpful.
- **Inventory of Noise and Vibration-Sensitive Sites:** The approach for selecting noise and vibration-sensitive sites should be described in sufficient detail to demonstrate completeness. Sites and site descriptions are to be included.
- **Noise and Vibration Measurements:** A summary of the site selection procedure should be included, along with tables of sites coordinated with maps showing locations of sites. The measurement approach should be summarized, with justification for the measurement procedures used. The measurement data should be presented in well-organized form in tables and figures. To save space, the results are often included with the table of sites described above. In some cases, measurements may be supplemented or replaced by collected data relevant to the noise and vibration characteristics of the area. For example, soils information for estimating ground-borne vibration propagation characteristics may be available from other projects in the area. Fundamental to this section are a summary and interpretation of how the collected data define the project setting.

Chapter on Environmental Consequences.

The section on long-term impacts, the impacts due to operation of the project, should be organized according to the following order:

1. **Overview of Approach.** A summary of the assessment procedure for determining noise and vibration impacts is provided as a framework for the following sections.

2. **Estimated Noise and Vibration Levels.** A general description of prediction models used to estimate project noise/vibration levels should be provided. Any distinguishing features unique to the project, such as source levels associated with various technologies, should be described. The results of the predictions for various alternatives should be described in general terms first, followed by a detailed accounting of predicted noise levels. This information should be supplemented with tables and illustrated by contours, cross-sections or shaded mapping. If contours are included in a technical report, then it is not necessary to repeat them here.

3. **Criteria for Noise and Vibration Impact.** Impact criteria for the project should be fully described and referenced (refer to Chapters 3 and 7). In addition, any applicable local ordinances should be described. Tables listing the criterion levels should be included.

4. **Impact Assessment.** The impact assessment can be a section by itself, or it can be combined with the criteria section. It is important to provide a description of locations where noise and vibration impact is expected to occur without implementation of mitigation measures, based on the predicted future levels, existing levels and the criteria for impact. Inventory tables of impacted land uses should be used to quantify the impacts for comparisons among alternatives. The comprehensive list of noise- and vibration-sensitive sites identified in the Affected Environment chapter should be included in this inventory table.

5. **Noise and Vibration Mitigation.** Perhaps the most significant difference between the technical report and the environmental document is in the area of mitigation. Whereas the technical report discusses options and may make recommendations, the environmental document provides the vehicle for reaching decisions on appropriate mitigation measures, with consideration given to environmental benefits, feasibility, and cost. This section should begin with a summary of all noise and vibration mitigation measures considered for the impacted locations. The specific measures selected for implementation should be fully described. However, for projects where technical details of the mitigation measures cannot be specified at the environmental assessment stage, a commitment is made to the level of abatement; the EIS must demonstrate that mitigation measures under consideration will achieve the necessary reduction. FRA strongly encourages noise abatement for projects where impacts are identified. Reasons for dismissing any abatement measures should also be clearly stated, especially if such non-implementation results in significant adverse effects. The expected benefits for each treatment in reducing impact should be given for each location.

6. **Unavoidable Adverse Environmental Effects.** If it is projected that adverse noise and vibration impacts will result after all reasonable abatement measures have been incorporated, the impacts should be identified in this section.

Impacts During Construction

The environmental document may have a separate section on short-term impacts due to project construction, depending on the scale of the project. For a major project there may be a special section on construction noise and vibration impacts; this section should be organized according to the comprehensive outline described above. For projects with relatively minor effects, a briefer format should be used, with a section included in the chapter on Environmental Consequences.

APPENDIX A
BACKGROUND – NOISE CONCEPTS

A.1 NOISE METRICS

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

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

A.1.1 A-weighted Level: The Basic Noise Unit

As discussed in Chapter 2, the basic noise unit for environmental noise is the A-weighted sound level. It describes the magnitude of noise at a receiver at any moment in time and is read directly from noise-measuring equipment, with the "weighting switch" set on "A." Typical A-weighted sound levels from high-speed rail systems as well as other outdoor and indoor sources are shown in Figure 2-2.

Typical community A-weighted sound levels range from the 30s to the 90s, where 30 is very quiet and 90 is very loud. A-weighted sound level measured in *decibels* is abbreviated "dBA," where the "dB" stands for decibels and refer to the general strength of the noise. The decibel is a unit that can be used to denote the ratio between any two quantities that are proportional to power. When used to describe sound level, the number of decibels is 10 times the logarithm (to the base 10) of the ratio (p^2/p_{ref}^2), where p is the sound pressure (in micropascals) and p_{ref} is a reference pressure (20 micropascals). The letter “A” indicates that the sound has been filtered to reduce the strength of very low and very high-frequency sounds, much as the human ear does. Without this A-weighting, noise-monitoring equipment would respond to events people cannot hear, events such as high-frequency dog whistles and low-frequency seismic disturbances. On the average, each A-weighted sound level increase of 10 decibels corresponds to an approximate doubling of subjective loudness.

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

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

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

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

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

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

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

The following sections illustrate all of these noise descriptors, in turn, and describes their particular application in this manual. Graphic illustrations and mathematical definitions are provided to help the reader understand and see the interrelationships among descriptors.

A.1.2 Maximum Level (L_{max}) During a Single Noise Event

As a train approaches, passes by, and then proceeds into the distance, the A-weighted sound level rises, reaches a maximum, and then fades into the background noise. The maximum A-weighted sound level reached during this passby is called the Maximum Level, abbreviated here as "L_{max}." For noise compliance tests of transient sources, such as moving rail vehicles under controlled conditions with smooth wheel and rail conditions, L_{max} is typically measured with the sound level meter's switch set on "fast," meaning that the sound level is averaged over a period of 0.125 seconds. Another use of L_{max} (fast), abbreviated $L_{max,f}$, is for identifying defective components such as wheel flat spots in a passing train or an excessively noisy car in a long consist of freight cars. However, for tests of continuous or stationary sources, and for describing short-term noise events for the general assessment of noise impact, it is usually more appropriate to use the "slow" setting, where the sound level is averaged over a 1 second period. When set on "slow," sound level meters ignore some of the very-transient fluctuations, which are unimportant to people’s overall assessment of the noise. L_{max} (slow), abbreviated $L_{max,s}$ gives a better representation of sound energy of an event and is therefore more directly related to the sound exposure level (SEL) described in the next subsection.

Measurements reported as L_{max} without designation of “fast” or “slow” meter response often become a source of confusion, which leads to errors in interpretation. Measurements of high-speed trains to obtain reference levels for this manual consistently showed $L_{max,f}$ to be 2 dB higher than $L_{max,s}$. Therefore, in general, if it is important to document the sound level of a very short-term event, less than one second in duration, use the “fast” meter setting; otherwise, use “slow.” The manner in which the L_{max} descriptor fits into the time history of environmental noise is shown in Figure A-1.

A.1.3 SEL: The Cumulative Exposure from a Single Noise Event

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

$$SEL = 10\log\left[\begin{matrix}\text{total sound energy}\\ \text{during the event}\end{matrix}\right]$$

A more specific mathematical definition is:

$$SEL = 10\log\left[\int_{-\infty}^{\infty} 10^{L_A(t)/10}\, dt\right]$$

where $L_A(t)$ represents the time-varying A-weighted sound level during an event. Time base is assumed to be one second.

SEL is used in this manual as the measure of each single high-speed train event because unlike L_{max},

- SEL increases with the duration of a noise event, which is important to people's reaction,
- SEL therefore allows a uniform assessment method for differing high-speed rail technologies, and
- SEL can be used to calculate the one-hour and 24-hour cumulative descriptors discussed below.

A.1.4 Hourly Equivalent Sound Level [$L_{eq}(h)$]

The descriptor for cumulative one-hour exposure is the Hourly Equivalent Sound Level, abbreviated here as "L_{eq}(h)." It is an hourly measure that accounts for the moment-to-moment fluctuations in A-weighted sound levels due to all sound sources during that hour, combined. Sound fluctuation is illustrated in the upper frame of Figure A-1 for a single noise event such as a train passing on nearby tracks. As the train approaches, passes by, and then proceeds into the distance, the A-weighted Sound Level rises, reaches a maximum, and then fades into the background noise. The area under the curve in this upper frame is the receiver's noise exposure over this five-minute period.

The center frame of Figure A-1 shows sound level fluctuations over a one-hour period that includes the five-minute period from the upper frame. The area under the curve represents the noise exposure for one hour. The Hourly Equivalent Sound Level is computed as:

$$L_{eq}(hour) = 10\ \log_{10}\begin{bmatrix}\text{Total sound energy}\\ \text{during one hour}\end{bmatrix} - 35.6$$

or mathematically:

$$L_{eq}(hour) = 10\log_{10}\left[\frac{1}{T}\int_{t_1}^{t_2} 10^{L_A(t)/10}\, dt\right]$$

where the one-hour interval extends from t_1 to t_2, and $T = t_2 - t_1 = 1$ hour. The constant 35.6 is obtained from time normalization: one hour = 3600 seconds, and 10 log 3600 = 35.6.

Sound energy is totaled here over a full hour; thus, it accumulates from all noise events during that hour. Subtraction of 35.6 from the total sound energy during one hour in the first equation converts it into a time average, as does the $1/T$ factor shown in the second equation. In brief, if the actual fluctuating noise were replaced by a constant noise equal to this average value, the receiver would be exposed to the same total noise energy. This type of average value is "equivalent" in that sense to the actual fluctuating noise.

A useful, alternative way of computing L_{eq} due to a series of high speed rail noise events is:

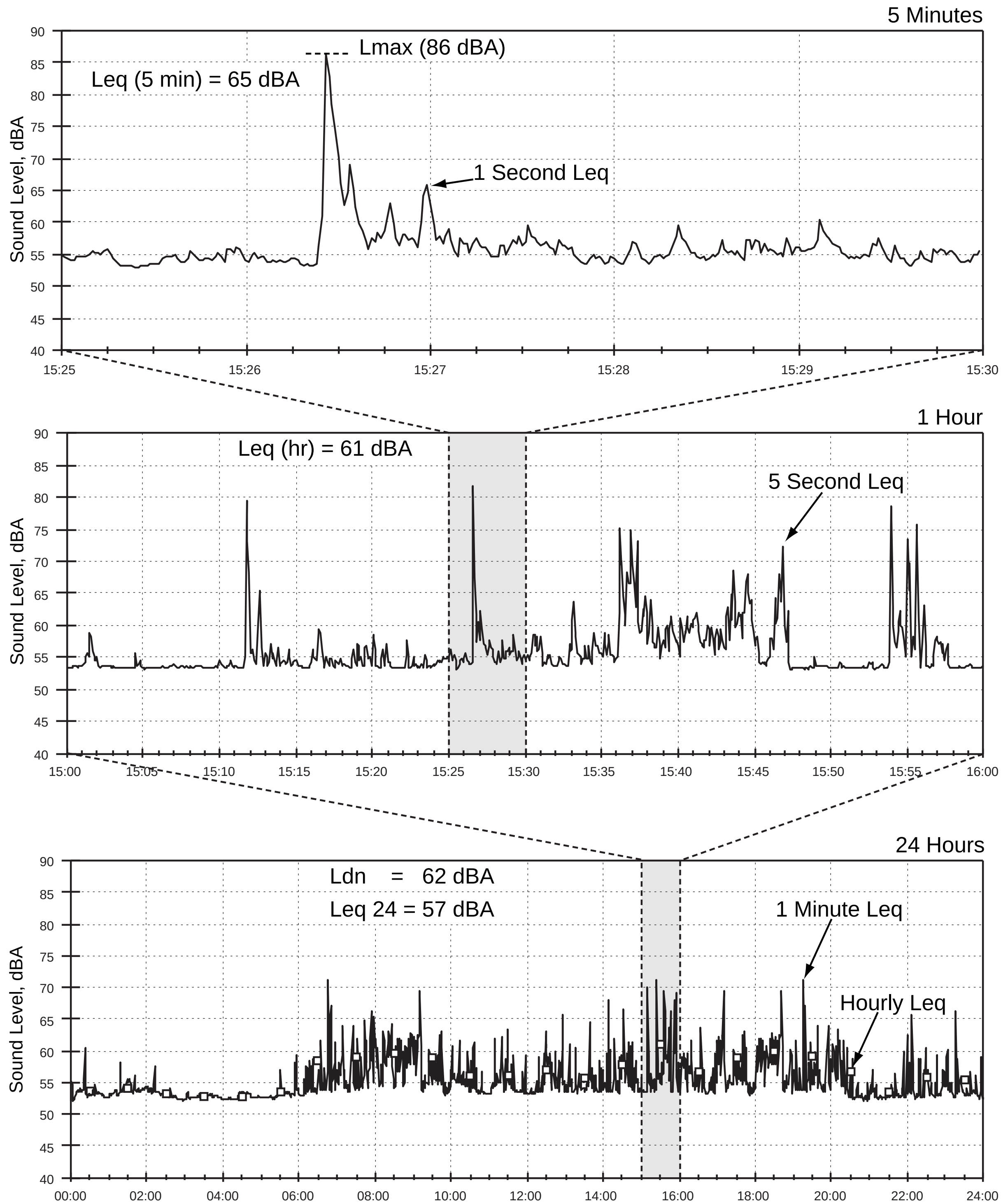
$$L_{eq}(hour) = 10\ \log_{10}\begin{bmatrix}\text{Energy Sum of}\\ \text{all SELs}\end{bmatrix} - 35.6$$

or mathematically:

$$L_{eq}(hour) = 10\log_{10}\left[\frac{1}{T}\sum_i 10^{SEL_i/10}\right]$$

This equation concentrates on the cumulative contribution of individual noise events, and is the fundamental equation incorporated into Chapters 4 and 5.

The bottom frame of Figure A-1 shows the sound level fluctuations over a full 24-hour period. It is discussed in Section A.1.5.



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

Figure A-1 Example A-Weighted Sound Level Time Histories

Typical hourly L_{eq}'s, both for high-speed rail and non-high-speed rail sources, are shown in Figure A-2. These L_{eq}'s depend upon the number of events during the hour and also upon each event's duration, which is affected by speed. Doubling the number of events during the hour will increase the L_{eq} by 3 decibels, as will doubling the duration of each individual event.

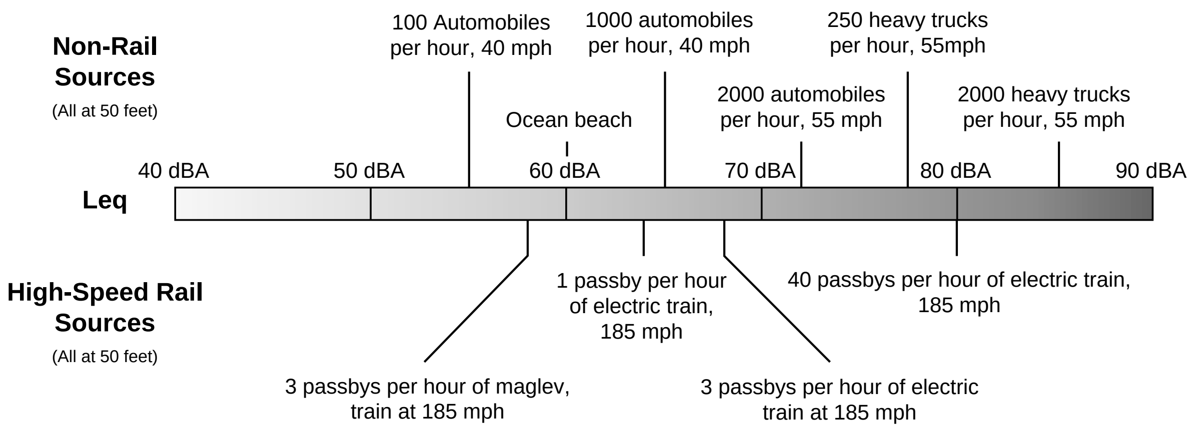


Figure A-2 Typical Hourly L_{eq}'s

Hourly L_{eq} is adopted as the measure of cumulative noise impact for non-residential land uses (those not involving sleep) because:

- L_{eq}'s correlate well with speech interference in conversation and on the telephone – as well as interruption of TV, radio, and music enjoyment,
- L_{eq}'s increase with the duration of events, which is important to people's reaction,
- L_{eq}'s take into account the number of events over the hour, which is also important to people's reaction, and
- L_{eq}'s are used by the Federal Highway Administration in assessing highway-traffic noise impact.

Thus, this noise descriptor can be used to compare and contrast modal alternatives such as highway versus rail. L_{eq} is computed for the loudest facility hour during noise-sensitive activity at each particular non-residential land use.

A.1.5 Day-Night Sound Level (L_{dn}): The Cumulative 24-Hour Exposure from All Events

The descriptor for cumulative 24-hour exposure is the Day-Night Sound Level, abbreviated as "L_{dn}." It is a 24-hour measure that accounts for the moment-to-moment fluctuations in A-Levels due to all sound sources during 24 hours, combined. Such fluctuations are illustrated in the bottom frame of Figure A-1. The area under the curve represents the receiver's noise exposure over a full 24 hours. Some vehicle passbys occur at night in the figure, when the background noise is less. Mathematically, the Day-Night Level is computed as:

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

where nighttime noise (10 p.m. to 7 a.m.) is increased by 10 decibels before totaling. The constant 49.4 is obtained from the time normalization: 24 hours = 86,400 seconds, and 10 log 86,400 = 49.4.

Sound energy is totaled over a full 24 hours; it accumulates from all noise events during that 24 hours. Subtraction of 49.4 from this 24-hour exposure converts it into a type of "average." If the actual fluctuating noise were replaced by a constant noise equal to this average value, the same total noise exposure would enter the receiver's ears.

An alternative way of computing L_{dn} from 24 hourly L_{eq}'s is:

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

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

This is expressed mathematically as:

$$L_{dn} = 10 \log_{10} \left[\frac{\displaystyle\sum_{hour=7am}^{10pm} 10^{L_{eq}(hour)/10} + \sum_{hour=10pm}^{7am} 10^{(L_{eq}(hour)+10)/10}}{24} \right]$$

where:

the 15-hour period from 7:00 am to 10:00 pm is defined as daytime (unweighted), and
the 9-hour period 10:00 pm to 7:00 am is defined as nighttime (with 10-decibel weighting).

L_{dn} due to a series of high-speed train events can also be computed as:

$$L_{dn} = 10 \log_{10} \begin{bmatrix} \text{Energy sum of} \\ \text{all SELs} \end{bmatrix} - 49.4$$

Use of this equation assumes that train noise dominates the 24-hour noise exposure. Here again, nighttime SELs are increased by 10 decibels before totaling. This last equation concentrates upon individual noise events, and is the equation incorporated into Chapters 4 and 5.

Typical L_{dn}'s, both for high-speed rail and conventional transit sources are shown in Figure A-3. As shown in the figure, typical L_{dn}'s range from the 50s to the 70s – where 50 is a quiet 24-hour period and 70 is an extremely noisy one. These L_{dn}'s depend upon the number of events during day and night separately – and also upon each event's duration, which is affected by vehicle speed.

L_{dn} is adopted as the measure of cumulative noise impact for residential land uses (those involving sleep), because:

- L_{dn} correlates well with the results of attitudinal surveys of residential noise impact,
- L_{dn} increases with the duration of transit events, which is important to people's reaction,
- L_{dn} takes into account the number of transit events over the full 24 hours, which is also important to people's reaction,
- L_{dn} takes into account the increased sensitivity to noise at night, when most people are asleep,
- L_{dn} allows composite measurements to capture all sources of community noise combined,
- L_{dn} allows quantitative comparison of transit noise with all other community noises,
- L_{dn} is the designated metric of choice of other Federal agencies such as Federal Transit Administration (FTA), Department of Housing and Urban Development (HUD), Federal Aviation Administration (FAA), and Environmental Protection Agency (EPA), and
- L_{dn} has wide international acceptance.

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

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

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

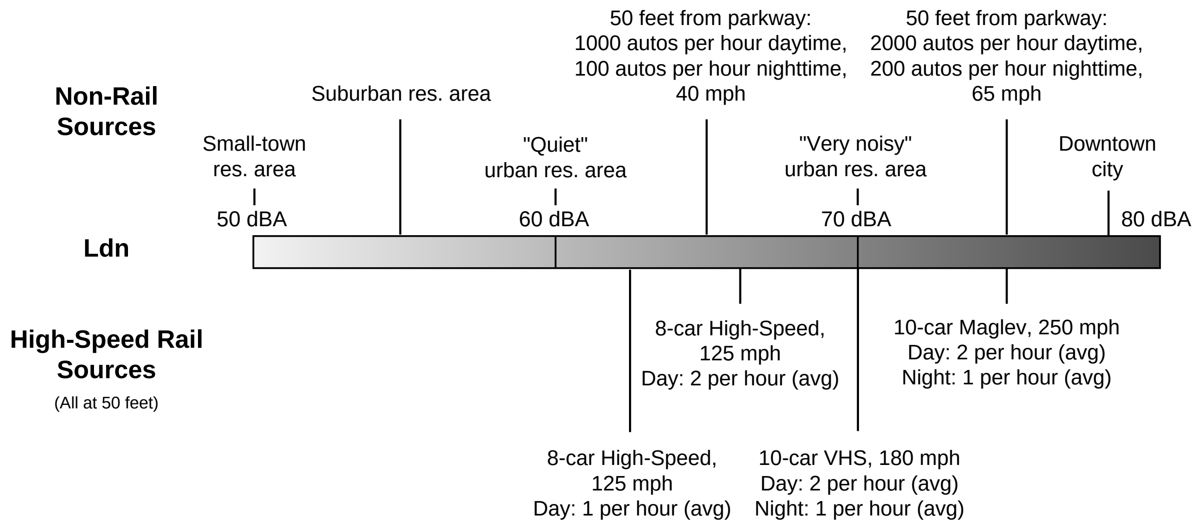


Figure A-3 Typical L_{dn}'s

A.1.6 Other Descriptors

As discussed in Chapter 2, there are a number of international descriptors for transportation noise seldom used in the U.S. The most widely encountered such descriptor, particularly in describing noise from rail systems, is the A-weighted "passby level," or $L_{Aeq,P}$.[1] This descriptor is used to quantify the noise level from a single vehicle passby, and is defined as the A-weighted sound level energy-averaged over the time of the event passby. In a sense, it is like L_{eq}(hour), except that it is evaluated for only a single event and averaged over the event-specific passby time instead of a standardized time period. It is defined mathematically as follows:

$$L_{Aeq,P} = 10\log_{10}\left[\frac{1}{T_p}\int_{t_1}^{t_2} 10^{L_A(t)/10}\,dt\right]$$

where:

> t_1 is the time at the leading edge of the passby,
> t_2 is the time at the trailing edge of the passby, and
> the passby duration $T_p = t_2 - t_1$.

[1] Also sometimes abbreviated $L_{p,p}$ and L_{max}(mean).

In Japan a similar metric is used to describe the noise from train passages, L_{Amax}, and is defined as the power- or energy-average of the "slow" maximum level ($L_{max,s}$) of 20 consecutive train passbys. Mathematically this is expressed as:

$$L_{Amax} = 10\log_{10}\left[\frac{1}{20}\sum_{i=1}^{20} 10^{(L_{max,s})_i/10}\right]$$

A metric known as Sound Exposure Level, but abbreviated L_{AE}, also is used in Japan and has a slightly different definition from the SEL used in this manual. It is defined as the energy-averaged value of the sound exposure, or energy during the event, measured within 10 dB of L_{Amax}, sampled at a time interval of 5/3 seconds. The mathematical expression is:

$$L_{AE} = 10\log_{10}\left[\sum_i \Delta t \cdot 10^{L_{Ai}/10}\right]$$

where Δt = 5/3 seconds.

A.2 RECEIVER RESPONSE TO TRANSPORTATION NOISE

An overview of receiver response to noise is presented in this section. It serves as background information for the noise impact criteria presented in Chapter 3 and for the criteria development process documented in Section A.3.

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

Annoyance to noise has been investigated and approximate exposure-response relationships have been quantified by the Environmental Protection Agency (EPA).[2,3] The selection of noise descriptors in this manual is largely based upon this EPA work. Beginning in the 1970s, EPA undertook a number of research and synthesis studies relating to community noise of all types. Results of these studies have been widely published, and discussed and referenced by many professionals in acoustics. Basic conclusions of these studies have been adopted by the Federal Interagency Committee on Noise, the Department of

[2]Environmental Protection Agency, "Impact Characterization of Noise Including Implications of Identifying and Achieving Levels of Cumulative Noise Exposure," Task group 3, Henning von Gierke, Chairman, Report NTID 73.4, Washington DC, 27 July 1973.

[3]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.

Housing and Urban Development (HUD), the American National Standards Institute, and even internationally.[4,5,6,7] Conclusions from this seminal EPA work remain scientifically valid to this day.

A synthesis of actual case studies of community reaction to newly introduced sources of noise in a residential urban neighborhood is shown in Figure A-4 (ref. 3). The new noise's excess above existing noise levels is shown in Figure A-4. Both the new and existing noise levels are expressed as Day-Night Sound Levels, L_{dn}, discussed in Section A.1.5. The community reaction to this newly introduced noise also is shown in Figure A-4, varying from "No Reaction" to "Vigorous Action," for newly introduced noises averaging from "10 decibels below existing" to "25 decibels above existing." Note that these data points apply only when the stated assumptions are true. For other conditions, the points shift to the right or left somewhat.

In a large number of community attitudinal surveys, transportation noise has been ranked among the most significant causes of community dissatisfaction. A synthesis of many such surveys on annoyance appears in Figure A-5.[8,9] Different neighborhood noise exposures are plotted horizontally. The percentage of people who are *highly annoyed* by their particular level of neighborhood noise is plotted vertically. As shown in the figure, the percentage of high annoyance is approximately 0 at 45 decibels, 10 percent around 60 decibels and increases quite rapidly to approximately 70 percent around 85 decibels. The scatter about the synthesis line is due to variation from community to community and to some wording differences in the various surveys. A recent update of the original research, containing several additional railroad, transit and street traffic noise surveys, confirmed the shape of the original Schultz curve.[10]

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[4]Federal Interagency Committee on Urban Noise, "Guidelines for Considering Noise in Land Use Planning and Control," a joint publication of the 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.

[5]Department of Housing and Urban Development, "Environmental Criteria and Standards of the Department of Housing and Urban Development," 24 Code of Federal Regulations Part 51; 44 Federal Register 40861, Washington DC, 12 July 1979.

[6]American National Standards Institute, "American National Standard: Compatible Land Use With Respect to Noise," Standard S3.23-1980, New York NY, May 1980.

[7]International Standards Organization, "Assessment of Noise with Respect to Community Response," Recommendation R-1996, Geneva, 1971.

[8]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.

[9]T. J. Schultz, "Synthesis of Social Surveys on Noise Annoyance," Journal of the Acoustical Society of America, Vol. 63, No. 8, August 1978.

[10]S. Fidell, D.S. Barber, and T.J. Schultz, "Updating a Dosage-Effect Relationship for the Prevalence of Annoyance Due to General Transportation Noise," Journal of the Acoustical Society of America, Vol. 89, No. 1, January 1991.

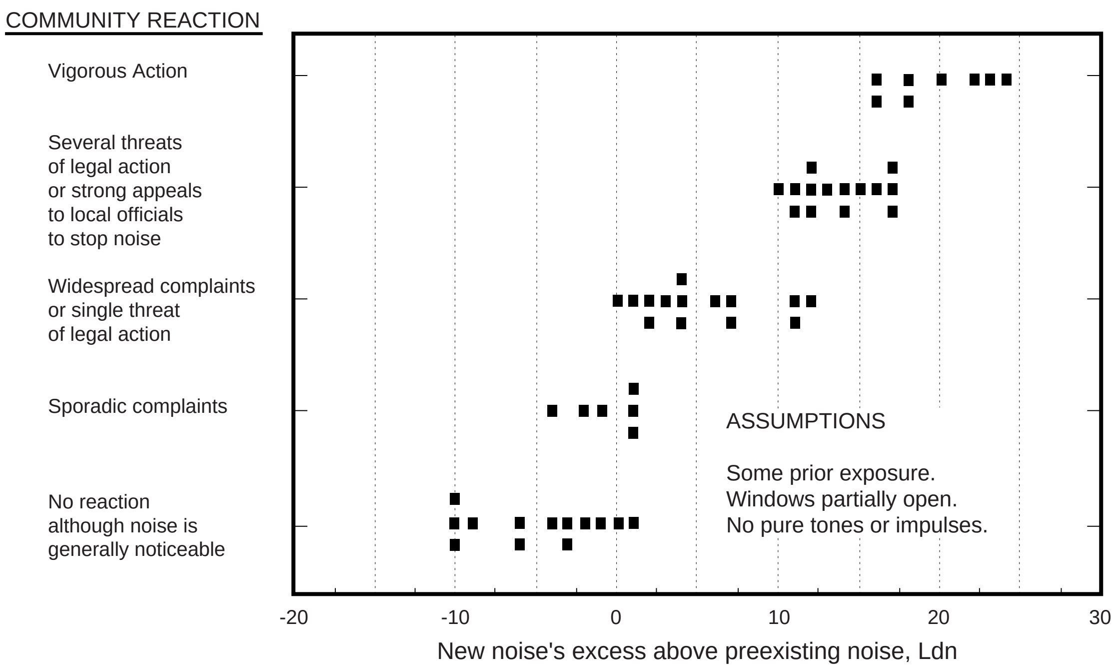

Figure A-4 Community Reaction to New Noise, Relative to Existing Noise in a Residential Urban Environment

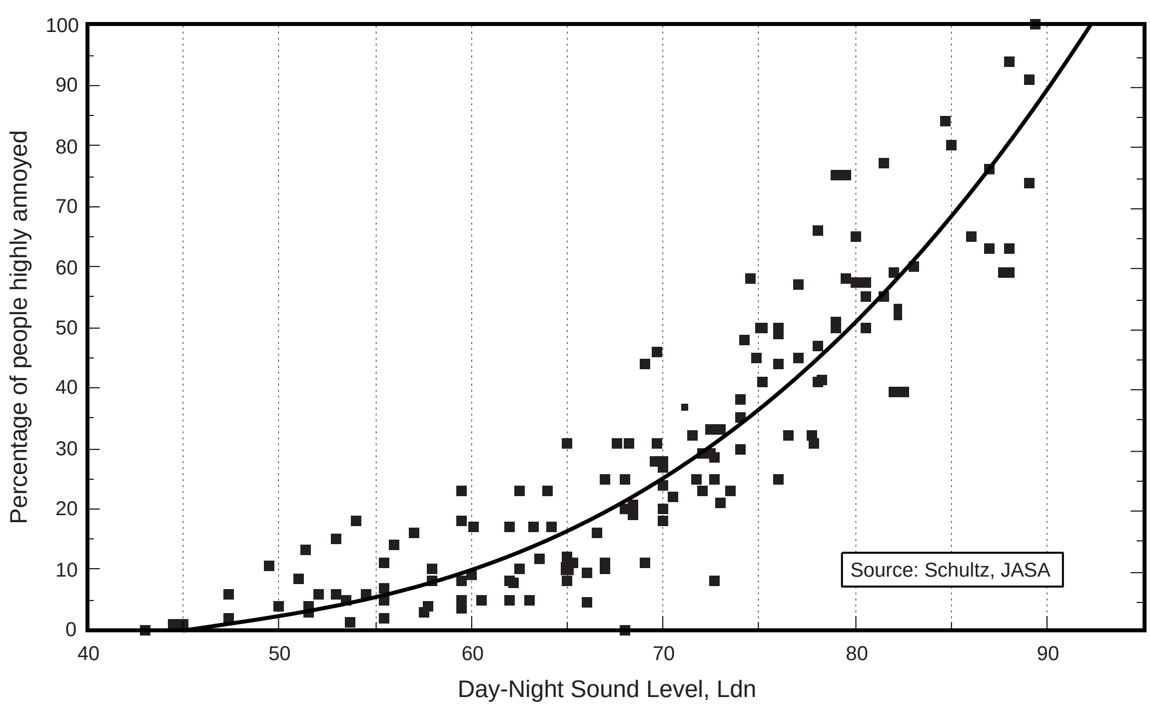

Figure A-5 Community Annoyance Due to Noise

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

A.3 NOISE IMPACT CRITERIA DEVELOPMENT

The noise criteria presented in Chapter 3 of this manual have been developed based on well-documented criteria and research into human response to community noise. The primary goals in developing these noise criteria were to ensure that the impact limits be firmly founded in scientific studies, be realistically based on noise levels associated with high-speed rail projects, and represent a reasonable balance between community benefit and project costs. This section provides the background information.

A.3.1 Relevant Literature

An annotated list of the documents that are particularly relevant to the noise impact criteria follows:

1. US Environmental Protection Agency "Levels Document" (ref. 3): This report identifies noise levels consistent with the protection of public health and welfare against hearing loss, annoyance, and activity interference. It has been used as the basis of numerous community noise standards and ordinances.

2. CHABA Working Group 69, "Guidelines for Preparing Environmental Impact Statements on Noise":[11] 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. "Synthesis of Social Surveys on Noise Annoyance" (ref. 9): In 1978, Theodore J. Schultz, an internationally known acoustical scientist, synthesized the results of a large number of social surveys, each concerning annoyance due to transportation noise. Remarkable consistency was found in a group of these surveys, and the author proposed that their average results be taken as the

[11] 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.

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 A-5) shows that the percent of the population highly annoyed by transportation noise increases from 0 at an L_{dn} of approximately 50 dBA to 100 percent when L_{dn} is about 90 dBA. Most significantly, this curve indicates that for the same increase in L_{dn}, there is a greater increase in the number of people highly annoyed at high noise levels than at low noise levels. In other words, a 5 dB increase at low ambient levels (40 - 50 dB) has less impact than at higher ambient levels (65 - 75 dB). A recent update of the original research, containing several railroad, transit and street traffic noise surveys, confirmed the shape of the original Schultz curve (ref. 10).

4. HUD Standards:[12] The U.S. Department of Housing and Urban Development (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 site acceptability standards define 65 dB (L_{dn}) as the threshold for a normally unacceptable living environment and 75 dB (L_{dn}) as the threshold for an unacceptable living environment.

5. French High Speed Rail Noise Survey:[13] The first comprehensive high-speed rail noise annoyance survey was performed along the route of TGV Atlantique south of Paris. Surveys of residents along the dedicated high-speed rail line were conducted before and after operation of the trains. Results of the study led to recommendations that the noise assessment descriptor be modified to include early morning and nighttime events and that a procedure be developed for noise assessment of multi-modal operations. Both of these objectives are included in the development of criteria for this manual.

A.3.2 Basis for Noise Impact Criteria Curves

The lower curve in Figure 3-1, representing the onset of Impact, is based on the following considerations:

- The EPA finding that a community noise level of L_{dn} less than or equal to 55 dBA is "requisite to protect public health and welfare with an adequate margin of safety" (ref. 2).
- The conclusion by EPA and others that a 5 dB increase in L_{dn} or L_{eq} is the minimum required for a change in community reaction.
- The research finding that there are very few people highly annoyed when the L_{dn} is 50 dBA, and that an increase in L_{dn} from 50 dBA to 55 dBA results in an average of 2 percent more people highly annoyed (see Figure A-5).

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[12] U.S. Department of Housing and Urban Development, "Environmental Criteria and Standards", 24 Code of Federal Regulations Part 51, 12 July 1979; amended by 49 FR 880, 6 January 1984.

[13] J. Lambert, Pl Champelovier, I. Vernet, “Annoyance from high speed train noise: a social survey,” Journal of Sound and Vibration, 193(1), 1996.

Consequently, the change in noise level from an existing ambient level of 50 dBA to a cumulative level of 55 dBA caused by a project is assumed to be a minimal impact. Expressed another way, this is considered to be the lowest threshold where impact starts to occur. Moreover, the 2 percent increment represents the minimum measurable change in community reaction. Thus the curve's hinge point is placed at a project noise level of 53 dBA and an existing ambient noise level of 50 dBA, the combination of which yields a cumulative level of 55 dBA. The remainder of the lower curve in Figure 3-1 was determined from the annoyance curve (Figure A-5) by allowing a fixed 2 percent increase in annoyance at other levels of existing ambient noise. As cumulative noise increases, it takes a smaller and smaller increment to attain the same 2 percent increase in highly annoyed people. While it takes a 5 dB noise increase to cause a 2 percent increase in highly annoyed people at an existing ambient noise level of 50 dB, an increase of only 1 dB causes the 2 percent increase of highly annoyed people at an existing ambient noise level of 70 dB.

The upper curve delineating the onset of Severe Impact was developed in a similar manner, except that it was based on a total noise level corresponding to a higher degree of impact. The Severe Noise Impact curve is based on the following considerations:

- The Department of Housing and Urban Development (HUD) in its environmental noise standards defines an L_{dn} of 65 as the onset of a normally unacceptable noise zone (ref. 7). Moreover, the Federal Aviation Administration (FAA) considers that residential land uses are not compatible with noise environments where L_{dn} is greater than 65 dBA [14].
- The common use of a 5 dBA increase in L_{dn} or L_{eq} as the minimum required for a change in community reaction.
- The research finding that the foregoing step represents a 6.5 percent increase in the number of people highly annoyed (see Figure A-5).

Consequently, the increase in noise level from an existing ambient level of 60 dBA to a cumulative level of 65 dBA caused by a project represents a change from an acceptable noise environment to the threshold of an unacceptable noise environment. This is considered to be the level at which Severe Impact starts to occur. Moreover, the 6.5 percent increment represents the change in community reaction associated with Severe Impact. Thus the upper curve's hinge point is placed at a project noise level of 63 dBA and existing ambient noise level of 60 dBA, the combination of which yields a cumulative level of 65 dBA. The remainder of the upper curve in Figure 3-1 was determined from the annoyance curve (Figure A-5) by fixing the increase in annoyance for all existing ambient noise levels at 6.5 percent.

Both curves incorporate a maximum limit for the high-speed rail project noise in noise-sensitive areas. Independent of existing noise levels, Impact for land use categories 1 and 2 is considered to occur whenever the high-speed rail L_{dn} equals or exceeds 65 dBA and Severe Impact occurs whenever the high-

[14]U.S. Department of Transportation, Federal Aviation Administration, "Federal Aviation Regulations Part 150: Airport Noise Compatibility Planning," January 1981.

speed rail L_{dn} equals or exceeds 75 dBA. These absolute limits are intended to restrict activity interference caused by the project alone.

Both curves also incorporate a maximum limit for cumulative noise increase at low existing noise levels (below about 45 dBA). This is a conservative measure that reflects the lack of social survey data on people's reaction to noise at such low ambient levels. Similar to the FHWA approach in assessing the relative impact of a highway project, the transit noise criteria include caps on noise increases of 10 dBA and 15 dBA for Impact and Severe Impact, respectively, relative to the existing noise level.

Finally, due to the types of land use included in Category 3, the criteria allow the project noise for Category 3 sites to be 5 decibels greater than for Category 1 and Category 2 sites. This difference is reflected by the offset in the vertical scale on the right side of Figure 3-1. With the exception of active parks, which are clearly less sensitive to noise than Category 1 and 2 sites, Category 3 sites include primarily indoor activities and thus the criteria reflect the noise reduction provided by the building structure.

A.3.3 Equations for Noise Impact Criteria Curves

The noise impact criteria can be quantified through the use of mathematical equations that approximate the curves shown in Figure 3-1. These equations may be useful when performing the noise assessment methodology through the use of spreadsheets, computer programs, or other analysis tools. Otherwise, such mathematical detail is generally not necessary to properly implement the criteria, and direct use of Figure 3-1 is likely to be adequate and less time-consuming.

A total of four continuous curves are obtained from the criteria: two threshold curves ("Impact" and "Severe Impact") for Category 1 and 2; and two for Category 3. Note that for each level of impact, the overall curves for Categories 1 and 2 are offset by 5 dBA from Category 3. While each curve is graphically continuous, it is defined by a set of three discrete equations that represent three "regimes" of existing noise exposure. These equations are approximately continuous at the transition points between regimes.

The first equation in each set is a linear relationship, representing the portion of the curve in which the existing noise exposure is low and the allowable increase is capped at 10 dBA and 15 dBA for Impact and Severe Impact, respectively. The second equation in each set represents the impact threshold over the range of existing noise exposure for which a fixed percentage of increase in annoyance is allowed, as described in the previous section. This curve, a third-order polynomial approximation derived from the Schultz curve, covers the range of noise exposure encountered in most populated areas and is used in determining noise impact for most transit projects. Finally, the third equation in each of the four sets represents the absolute limit of project noise imposed by the criteria, for areas with high existing noise exposure. For land use categories 1 and 2, this limit is 65 dBA for Impact and 75 dBA for Severe Impact. For land use category 3, the limit is 70 dBA for Impact and 80 dBA for Severe Impact.

The four sets of equations corresponding to the curves are given below. Each curve represents a threshold of noise impact, with impact indicated for points on or above the curve.

Threshold of Impact:

$$L_P = \begin{cases} 11.450 + 0.953\,L_E & L_E < 42 \\ 71.662 - 1.164\,L_E + 0.018\,L_E^{\,2} - 4.088 \times 10^{-5}\,L_E^{\,3} & 42 \le L_E \le 71 \\ 65 & L_E > 71 \end{cases} \quad \text{Category 1 and 2}$$

$$L_P = \begin{cases} 16.450 + 0.953\,L_E & L_E < 42 \\ 76.662 - 1.164\,L_E + 0.018\,L_E^{\,2} - 4.088 \times 10^{-5}\,L_E^{\,3} & 42 \le L_E \le 71 \\ 70 & L_E > 71 \end{cases} \quad \text{Category 3}$$

Threshold of Severe Impact:

$$L_P = \begin{cases} 17.322 + 0.940\,L_E & L_E < 44 \\ 96.725 - 1.992\,L_E + 3.02 \times 10^{-2}\,L_E^{\,2} - 1.043 \times 10^{-4}\,L_E^{\,3} & 44 \le L_E \le 77 \\ 75 & L_E > 77 \end{cases} \quad \text{Category 1 and 2}$$

$$L_P = \begin{cases} 22.322 + 0.940\,L_E & L_E < 44 \\ 101.725 - 1.992\,L_E + 3.02 \times 10^{-2}\,L_E^{\,2} - 1.043 \times 10^{-4}\,L_E^{\,3} & 44 \le L_E \le 77 \\ 80 & L_E > 77 \end{cases} \quad \text{Category 3}$$

where:

L_E is the existing noise exposure in terms of L_{dn} or L_{eq}(h), and
L_P is the project noise exposure which determines impact, also in terms of L_{dn} or L_{eq}(h).

A.4 STARTLE EFFECTS FROM RAPID ONSET RATES

Researchers report that sounds of approaching vehicles with rapidly rising sound signatures carry a sense of convergence and cause greater annoyance than receding sounds.[15]

A.4.1 High-Speed Rail Noise Signatures

The presence of a high-speed rail system in close proximity to homes may result in a new noise unlike other existing sources of community noise. The sound signature at a position close to a high-speed train passby is characterized by sudden onset of high noise levels for a short duration. A typical example is shown in Figure A-6, where the sound rises rapidly at 15 dB per second and falls again within approximately five seconds. Shorter trains, such as the two-car test train of the German TransRapid TR07, can have even faster onset rates and shorter durations.

[15] G. Rosinger, D.W. Nixon, and H.E. vonGierke. "Quantification of the Noisiness of 'Approaching' and 'Receding' Sounds," J.Acoust. Soc. Am., 48, pp.843-853, October 1970.

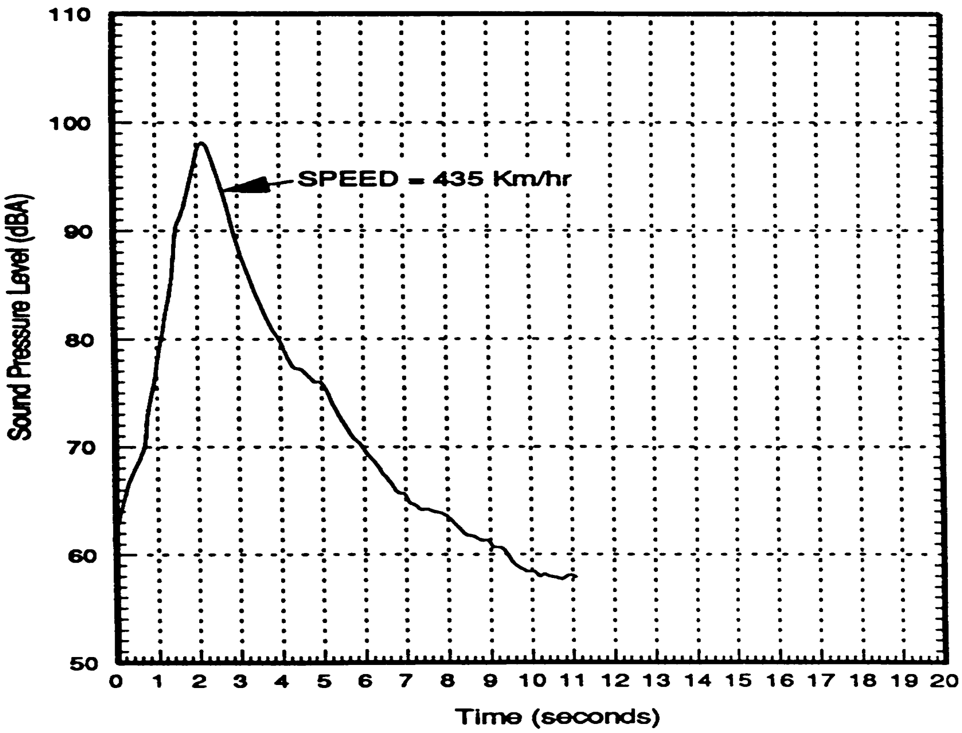

Figure A-6 Time History of A-weighted Sound Level of Maglev at 25 m

The onset rate is related to the rate of approach of a moving vehicle. More correctly, it is related to the rate at which the vector distance between the sound source and the receiver diminishes. Both speed and distance figure into the process. Measured onset rates from two high-speed rail systems are plotted in Figure 2-6.

A.4.2 Research on Startle Effects

When the onset of sound is very sudden, people tend to be **startled**, or surprised, especially when they are not expecting it. Researchers have proposed various adjustments to account for the increased annoyance of fast-rising sound events. The most recent study into the added annoyance from rapid onset rates has been conducted in three parts by the US Air Force in connection with low-altitude military test flights.[16] The initial literature review resulted in an interim metric whereby an "onset rate-adjusted SEL" was used in noise impact analyses where such operations were conducted. The interim adjustment was an addition to the SEL of the passby, starting with 0 dB for onset rates up to 15 dB/sec, ramping up to a maximum of 5 dB for onset rates of 30 dB/sec and higher. Laboratory tests using simulated sound and people hired for the occasion followed, resulting in a revised adjustment. Finally, psychoacoustic tests were conducted in a real home environment with hired test subjects and the currently recommended adjustment was

[16]E. Stusnick, K. Bradley. "The Effect of Onset Rate on Aircraft Noise Annoyance." USAF Report AL/OE-TR-1993-0170, October 1992.

developed. Again, the adjustment is 0 dB up to an onset rate of 15 dB/sec, but the ramp extends to an addition of 11 dB at an onset rate of 150 dB/sec, with the relationship:

$$\text{Adjustment to SEL} = 11 \log (\text{onset rate}) - 12.9, \text{ in decibels}$$

where:

$$15 \text{ dB/sec} < \text{onset rate} < 150 \text{ dB/sec.}$$

A.4.3 Startle Effects Applied to High-Speed Rail Impact Assessment

The interim metric adopted by US Air Force after the first stage of its study was cited as the basis for the suggested adjustment for noise from high-speed maglev operations in a report prepared for the Federal Railroad Administration-sponsored National Maglev Initiative (NMI).[17] The recommended adjustment at that time was to add 5 dB to SEL whenever the onset rate from a maglev passby exceeded 15 dB/sec. Since data are available to show onset rates as a function of speed divided by distance, it was possible to develop a curve defining the relationship between speed and distance within which the onset rate exceeds 15 dB/sec for a maglev train. The proposed onset rate adjustment was recommended for assessment of noise impact from maglev trains.

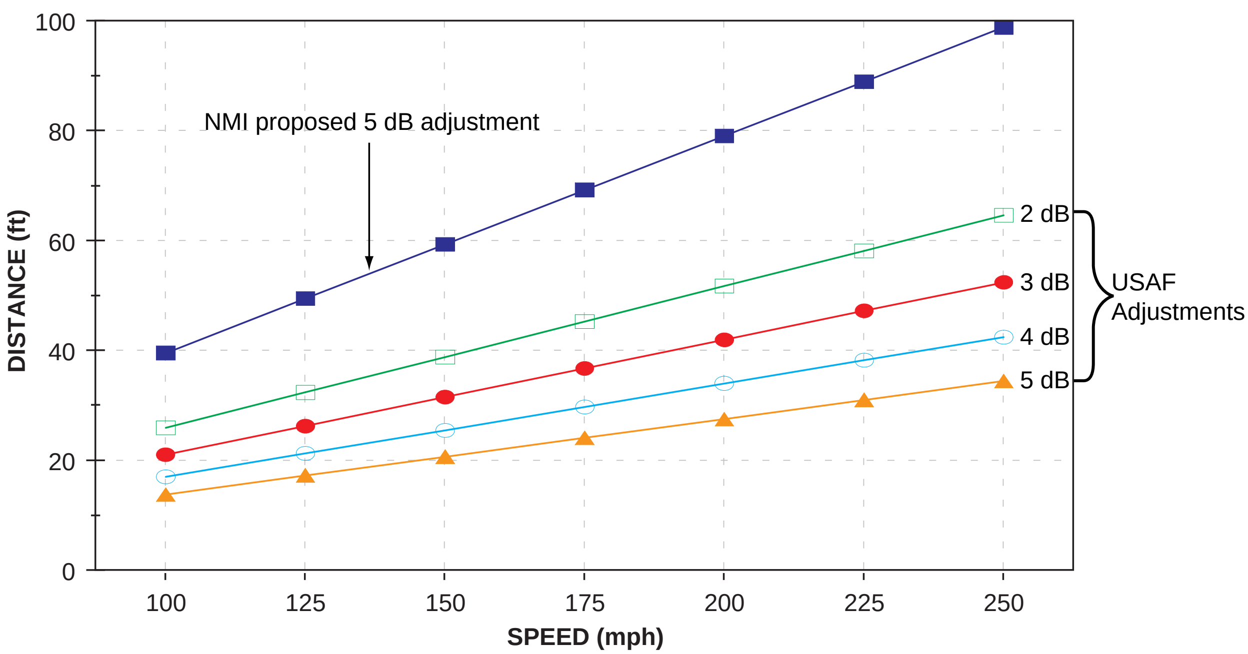

Figure A-7 Zones of Potential Startle Effect

[17] C. E. Hanson, P. Abbot, and I. Dyer. "Noise from High Speed Maglev Systems," US Department of Transportation, Federal Railroad Administration, Report No. DOT/FRA/NMI - 92-18, January 1993.

Applying the same approach, but using the latest revised US Air Force onset rate adjustments starting with 0 dB at 15 dB/sec, results in the relationships shown in Figure A-7. The new Air Force adjustments of 2 dB to 5 dB are plotted along with the original NMI proposed adjustment of 5 dB. The revised adjustments result in the potential for startle to be confined to a much narrower region than was obtained using the NMI method.

The following issues remain unresolved regarding application of the Air Force research to determine the startle effects of high speed rail:

1. What is the effect of scheduled events, such as train passbys, vs. "surprise" events, such as military training flights? Since high-speed trains always will be on the same track and on a schedule, it may be reasonable to expect habituation for long-term residents. Hence, an adjustment to every SEL from passing high-speed trains appears excessive.

2. Sound levels from train passbys are not as high, nor are onset rates as great as they are from low altitude military aircraft. Hence, the startle effect may not be the same.

3. The onset rate adjustments as proposed by the Air Force when applied to high-speed rail systems (Figure A-6) take place in a distance close enough to be affected already by noise. There may be no further reason to add to the impact assessment.

Without better definition of the application of results of noise from aircraft overflights to noise from high-speed rail passbys, it is appropriate to consider startle effects as “additional information” included in the impact assessment, rather than to include a penalty in the calculation of noise exposure itself. What remains to be determined is an onset rate that could be considered significant enough to cause startle on a regular basis. Lacking any other direction from research, the onset rate that would cause a 3 dB adjustment for the Air Force has been adopted for this manual. The resulting distance vs speed relationship is given in Figure 4-2.

A.5 EFFECTS ON LIVESTOCK AND WILDLIFE

A.5.1 Summary

A wide range of studies have been conducted concerning noise effects on animals. For humans, annoyance is considered to be the primary environmental noise effect; thresholds for annoyance in terms of sound exposure have been determined by surveys as described in Section A.3. However, for animals, the effects are not easily determined. Usually the studies require introduction of a specific noise event like an aircraft overflight and a subsequent observation of animal response. Observations of response to noise range from no reaction or mild responses such as slight changes in body position to extreme responses such as panic and attempts to escape. Long-term effects that might change behavior tend to be affected by factors other than short term noise exposure, such as weather, predation, disease and other disturbances to animal populations. Conclusions from research conducted to date provide only preliminary indications of the appropriate descriptor, rough estimates of threshold levels for observed animal disturbance, and habituation characteristics of only a few species. Long-term effects continue to be a matter of speculation. Moreover, most of the noise events used in prior studies are related to aircraft overflights. Consequently, any criteria adopted for effects on animals by high-speed rail noise must be considered interim until further specific research results are known. Following are discussions of descriptors and levels from the literature.[18,19,20,21]

A.5.2 Noise Descriptor

A noise descriptor for noise effects on wildlife has not been universally adopted, but recent research indicates the sound exposure level (SEL) is the most useful predictor of responses. Characteristic of the bulk of research to date has been lack of systematic documentation of the source noise event. Many studies report "sound levels" without specifying the frequency spectrum or duration. A notable exception is a study sponsored by U.S. Air Force that identifies SEL as the best descriptor for response of domestic turkey poults to low-altitude aircraft overflights (ref. 21). Another report questions whether an A-weighted sound level used in the SEL for aircraft overflights is appropriate for animals since their hearing differs from humans (ref. 20). However, since no weighting has been established for representing the hearing characteristics of wild animals, the A-weighted sound level continues to be used.

A.5.3 Thresholds for Disturbance

Most studies have focused on identifying a noise level associated with disturbance effects, even if the type of noise event varied considerably from study to study. In the well-documented study that recommended SEL as the preferred descriptor, a threshold of response for disturbance ("100 percent rate of crowding") of domestic turkeys was identified as SEL = 100 dB (ref. 21). Even if the descriptors are not the same, many studies report levels in the vicinity of 100 dB as associated with an observable effect, as shown in Table A-1. The information in this table is taken from an extensive survey on aircraft noise effects.[22] Until more definitive information on thresholds can be developed, an interim criterion of SEL = 100 dB will be used for disturbance by high-speed rail operations.

[18]K.M. Manci, D.N. Gladwin, R. Villella, and M.G. Cavendish. "Effects of aircraft noise and sonic booms on domestic animals and wildlife: a literature synthesis." U.S. Fish and Wildlife Service National Ecology Research Center, Ft. Collins, CO., Report NERC-88/29, 1988.

[19]P. Dufour, "Effects of Noise on Wildlife and Other Animals: Review of Research Since 1971." US Environmental Protection Agency, Report 550/9-80100, July 1980.

[20]A. M. McKechnie, D.N. Gladwin. "Aircraft Overflight Effects on Wildlife Resources." US National Park Service, NPOA Report No. 93-8, November 1993.

[21]F. Bradley, C. Book, and A.E. Bowles. "Effects of Low-Altitude Aircraft Overflights on Domestic Turkey Poults," Report No. HSD-TR-90-034, US Air Force Systems Command, Noise and Sonic Boom Impact Technology Program, June 1990.

[22]K.M. Manci, D.N. Gladwin, R. Villella, and M.G. Cavendish. "Effects of aircraft noise and sonic booms on domestic animals and wildlife: a literature synthesis." U.S. Fish and Wildlife Service National Ecology Research Center, Ft. Collins, CO., Report NERC-88/29, 1988.

A.5.4 Habituation

There is evidence that some animals demonstrate reduced response to noise after prior exposure, but that a few species never become accustomed to, or **habituate**, to high noise levels. Researchers found that for turkeys, previous exposure to sound levels below the 100 dB threshold was sufficient to eliminate panic responses to higher level sounds (ref. 21). On the other hand, some animals and birds, such as the grizzly bear, Dall sheep, and least tern, have not been observed to habituate (ref. 20). Since habituation is found to be species-dependent, a general criterion cannot be developed at this time.

Table A-1 Summary of Noise Levels Associated with Effects on Animals and Birds (from ref. 20)

Animal Category	Species	Noise Level and Type (if known) Associated with Effect	Effect
Domestic Mammals	Dairy Cow	105 dB	Reduction in milk production
		97 dB	Changes in blood composition
		110 dB, 1 kHz	Changes in blood composition
	Swine	108-120 dB	Hormonal changes
		93 dB	Hormonal changes
		120-135 dB	Increased heart rate
	Sheep	100 dB “white noise”	Increased heart rate, respiration
		90 dB”white noise”	Decreased thyroid activity
		100 dB	Increase in number of lambs per ewe
Wild Mammals	Reindeer	Sonic booms	Startle
	Caribou	Aircraft	Startle, panic running
	Pronghorn antelope	77 dBA, helicopter	Running
Domestic Birds	Chicken	100 dB	Blood composition
		115 dB	Interrupt brooding
Wild Birds	Quail	80 dB	Accelerated hatching
	Canary	95-100 dB	Hearing loss
	Seabirds (general)	Sonic boom	Startle, flush from nest
	Tern	Sonic boom, frequent	Reduced reproduction
	California condor	Blasting, drilling, etc.	Flush from nest; abandon area
	Raptors	Sonic booms	Alarm

APPENDIX B

DETERMINING EXISTING NOISE[1]

This appendix provides additional detail for determining existing noise by: (1) full measurement, (2) computation from partial measurements, and (3) tabular look-up. The words "existing noise" and "ambient noise" are often used interchangeably.

The full set of options for determining existing noise at receivers of interest is as follows:

- OPTION 1: For non-residential land uses, measure a full hour's L_{eq} at the receiver of interest, during a typical hour of use on two non-successive days. The hour chosen should be the one in which maximum project activity will occur. The L_{eq} will be accurately represented.
- The three options for residential land uses are –
    1. OPTION 2: Measure a full day's L_{dn}. The L_{dn} will be accurately represented.
    2. OPTION 3: Measure the hourly L_{eq} for three typical hours: peak traffic, midday and late night. Then compute the L_{dn} from these three hourly L_{eq}'s. The computed L_{dn} will be slightly underestimated.
    3. OPTION 4: Measure the hourly L_{eq} for one hour of the day only, preferably during midday. Then compute the L_{dn} from this hourly L_{eq}. The computed L_{dn} will be moderately underestimated.

[1] This section has been adapted from Federal Transit Administration's noise guidance manual and is included here for completeness.

- OPTION 5: For all land uses, compute either the L_{eq} or the L_{dn} from a measured value at a nearby receiver – one where the ambient noise is dominated by the same noise source. The computed value will be represented with only moderate precision.
- OPTION 6: For all land uses, estimate either the L_{eq} or the L_{dn} from a table of typical values, depending upon distance from major roadways or upon population density. The resulting values will be underestimated significantly.

Option 1: For non-residential land uses, measure the hourly L_{eq} for the hour of interest

Full one-hour measurements are the most precise way to determine existing noise for non-residential receivers of interest. Such full-duration measurements are preferred over all other options. The following procedures apply to full-duration measurements:

- Measure a full hour's L_{eq} at the receiver of interest on at least two non-successive days during a typical hour of use. This would generally be between noon Monday and noon Friday, but weekend days may be appropriate for places of worship. On both days, the measured hour must be the same as that for which project noise is computed: the loudest facility hour that overlaps hours of noise-sensitive activity at the receiver.
- At all sites, locate the measurement microphone as shown in Figure 5-2 (Chapter 5), depending upon the relative orientation of project and ambient sources. A microphone location that is shielded somewhat from the ambient source is preferred. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.
- Undertake all measurements in accordance with good engineering practice (see References 1 and 2 of Chapter 5).

Option 2: For residential land uses, measure the L_{dn} for a full 24 hours

Full 24-hour measurements are the most precise way to determine ambient noise for residential receivers of interest. Such full-duration measurements are preferred over all other options. The following procedures apply to full-duration measurements:

- Measure a full 24-hour's L_{dn} at the receiver of interest, for a single weekday (generally between noon Monday and noon Friday).
- At all sites, locate the measurement microphone as shown in Figure 5-2, depending upon the relative orientation of project and ambient sources. A microphone location that is shielded somewhat from the ambient source is preferred. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.

- Undertake all measurements in accordance with good engineering practice (see References 1 and 2 of Chapter 5).

Option 3: For residential land uses, measure the hourly L_{eq} for three hours and then compute L_{dn}

An alternative way to determine L_{dn}, less precise than its full-duration measurement, is to measure hourly L_{eq}'s for three typical hours of the day and then to compute the L_{dn} from these three hourly L_{eq}'s. The following procedures apply to this partial-duration measurement option for L_{dn}:

- Measure the one-hour L_{eq} during each of the following time periods: once during peak-hour roadway traffic, once midday between the morning and afternoon roadway-traffic peak hours, and once between midnight and 5 am. For locations with no significant traffic patterns, it will be sufficient to measure a morning hour (7 am to 9 am), a midday hour (10 am to 4 pm), and a late night hour (10 pm to 7 am).
- Compute L_{dn} with the following equation:

$$L_{dn} \approx 10 \log \left[(3) \cdot 10^{\frac{L_{eq}(\text{peakhour})-2}{10}} + (12) \cdot 10^{\frac{L_{eq}(\text{midday})-2}{10}} + (9) \cdot 10^{\frac{L_{eq}(\text{latenight})+8}{10}} \right] - 13.8$$

This value of L_{dn} will be slightly underestimated, due to the subtraction of 2 decibels from each of the measured levels before their combination. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn} here, compared to its full-duration measurement.

- At all sites, locate the measurement microphone as shown in Figure 5-2, depending on the relative orientation of project and ambient sources. A microphone location that is shielded somewhat from the ambient source is preferred. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.
- Undertake all measurements in accordance with good engineering practice (see References 1 and 2 of Chapter 5).

Option 4: For residential land uses, measure the hourly L_{eq} for one hour and then compute L_{dn}

The next level down in precision is to determine L_{dn} by measuring the hourly L_{eq} for one hour of the day and then to compute L_{dn} from this hourly L_{eq}. This method is useful when there are many sites in a General Assessment, or when checking whether a particular receiver of interest represents a cluster in a Detailed Analysis. The following procedures apply to this partial-duration measurement option for L_{dn}:

- Measure the one-hour L_{eq} during any hour of the day. The loudest hour during the daytime period is preferable. If this hour is not selected, then other hours may be used with less precision.

- Convert the measured hourly L_{eq} to L_{dn} with the applicable equation:

  For measurements between 7am and 7pm: $L_{dn} \approx L_{eq} - 2$,

  For measurements between 7pm and 10pm: $L_{dn} \approx L_{eq} + 3$, and

  For measurements between 10pm and 7am: $L_{dn} \approx L_{eq} + 8$.

  The resulting value of L_{dn} will be moderately underestimated, due to the use of the adjustment constants in these equations. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn} here, compared to the more precise methods of determining L_{dn}.

- At all sites, locate the measurement microphone as shown in Figure 5-2, depending upon the relative orientation of project and existing sources. A microphone location that is shielded somewhat from the ambient source is preferred. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.

- Undertake all measurements in accordance with good engineering practice (see References 1 and 2 of Chapter 5).

Option 5: For all land uses, compute either L_{eq} or L_{dn} from a nearby measured value

A computation method comparable in precision to Option 4 is to determine the ambient noise, either L_{eq}(h) or L_{dn}, from a *measured* value at a nearby receiver – one where the ambient noise is dominated by the same noise source. This method is used to characterize noise in several neighborhoods by using a single representative receiver. Care must be taken to ensure that the measurement site has a similar noise environment to all areas represented. If measurements made by others are available, and the sites are equivalent, they can be used to reduce the amount of project noise monitoring. The following procedures apply to this computation of ambient noise at the receiver of interest:

- Choose another receiver of interest, called the "comparable receiver," at which:
  - The same source of ambient noise dominates.
  - The ambient $L_{CompRec}$ was **measured** with either OPTION 1 or OPTION 2 above.
  - The ambient measurement at the comparable receiver was made in direct view of the major source of ambient noise, unshielded from it by noise barriers, terrain, rows of buildings, or dense tree zones.
- From a plan or aerial photograph, determine: (1) the distance $D_{CompRec}$ from the comparable receiver to the near edge of the ambient source, and (2) the distance $D_{ThisRec}$ from this receiver of interest to the near edge of the ambient source.
- Also determine N, the number of rows of buildings that intervene between the receiver of interest and the ambient source.

- Compute the ambient noise at this receiver of interest with the applicable equation:

  If roadway sources dominate:

$$L_{ThisRec} \approx L_{CompRec} - 15\log\left(\frac{D_{ThisRec}}{D_{CompRec}}\right) - 3N$$

  If other sources dominate:

$$L_{ThisRec} \approx L_{CompRec} - 25\log\left(\frac{D_{ThisRec}}{D_{CompRec}}\right) - 3N$$

  The resulting value of $L_{ThisRec}$ will be moderately underestimated. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn}, compared to the more precise methods of determining ambient noise levels.

Option 6: For all land uses, estimate either L_{eq}(h) or L_{dn} from a table of typical values

The least precise way to determine the ambient noise is to estimate it from a table. A tabular look-up can be used to establish baseline conditions for a General Noise Assessment if a noise measurement cannot be made. It should not be used for a Detailed Noise Analysis. For this estimate of ambient noise:

- Read the ambient noise estimate from the relevant portion of Table 4-5. These tabulated estimates depend upon distance from major roadways, rail lines or upon population densities. In general, these tabulated values are significant underestimates. As explained previously, underestimates are intended to compensate for the reduced precision of the estimated ambients, compared to the options that incorporate some degree of measurements.

APPENDIX C

CONVERTING BETWEEN L_{max} AND SEL

This appendix provides procedures for:

1) computing L_{max} for a single high-speed train passby using the source reference levels in SEL and methods given in Chapters 4 and 5, and

2) estimating source reference levels in SEL for a General Assessment from either measured or specified values of the single-passby L_{max}.

The first SEL to L_{max} conversion may be useful in determining whether a proposed project or type of equipment will meet the noise limit defined in the project specifications, almost always given in terms of L_{max}. The second procedure, converting from L_{max} to SEL, involves computing reference SELs specific to a certain trainset or project noise specification, which may be different from the generalized levels given in this manual. A General Noise Assessment can then be performed based on measurements, equipment specifications, or project noise limits.

C.1 COMPUTING L_{max} FOR A SINGLE TRAIN PASSBY

The L_{max} conversion procedure from the reference SELs given in Chapter 4 (Initial Noise Evaluation) or Chapter 5 (Detailed Noise Analysis) to a single L_{max} value is summarized as follows:

Step 1. **Select Source Reference SEL(s)**. Classify the project into one of the vehicle categories defined in Table 4-2 or Table 5-2. For General Assessment, the speed regime (I, II or III) also must be selected from Table 4-2, which identifies the single dominant noise source for the given speed and the corresponding reference SEL. For Detailed Analysis, separate subsource SELs are listed in Table 5-2.

Step 2. **Adjust for Project Operating Conditions**. Adjust the reference SEL (General Assessment) or each applicable subsource reference SEL (Detailed Analysis) at 50 feet for operating conditions for the project or for a particular corridor segment, using the methods in Section 4.2.1 or 5.2.2.

Step 3. **Adjust for Propagation with Distance**. Propagate each adjusted SEL out to the specified distance (if other than the reference distance of 50 feet), accounting for attenuation with distance, shielding, and ground effect, if necessary, using the methods in Section 4.2.2 or 5.2.3.

Step 4. **Convert SEL to L_{max}**. Compute L_{max} using the equations in Table C-1. For the Detailed Analysis method, choose the largest of the subsource L_{max} values as the overall L_{max} for the train passby.

Table C-1 Computation of L_{max} for a High-Speed Train Passby using General Assessment or Detailed Analysis Method

Applicable Parameters		SEL–to–L_{max} Equation
General Assessment	**Detailed Analysis**	
Speed Regime I	Propulsion Subsource	
use *len* = **total** length of power units, in feet	use *len* = length of **one** power unit, in feet	$L_{\max} = SEL - 10\log\left(\frac{len}{S}\right) + 10\log(2\alpha) - 3.3$
Speed Regime II	Wheel/Rail or Guideway/Structural Subsource	$L_{\max} = SEL - 10\log\left(\frac{len}{S}\right) + 10\log[2\alpha + \sin(2\alpha)] - 3.3$
use *len* = **total** length of train, in feet	use *len* = length of coaches only, in feet	
Speed Regime III	Aerodynamic Subsources	
use *len* = **total** length of train, in feet	use *len* = subsource length as defined in Table 5-2, in feet	$L_{\max} = SEL - 10\log\left(\frac{len}{S}\right) + 10\log(2\alpha) - 3.3$

Variables are defined as follows:

S = train speed, in mph,

$\alpha = \tan^{-1}\left(\frac{len}{2d}\right)$, in radians,

len = length as defined above, and

d = receiver distance from track centerline, in feet.

C.2 COMPUTING REFERENCE SEL'S FROM L_{MAX} FOR GENERAL ASSESSMENT METHOD

If L_{max} for a specific trainset is available from vehicle noise measurements, manufacturer specifications, or a specific project limit, it is possible to estimate the equivalent reference SELs to use in the General Noise Assessment (Chapter 4) procedure presented in this manual. The Detailed Noise Analysis (Chapter 5) method, however, involves the use of detailed component, or subsource, SELs that cannot be determined accurately from a single passby L_{max} value. Determination of subsource SELs requires more complex measurement techniques, such as a microphone array or controlled single microphone measurements with a low sound barrier to shield wheel/rail noise, in order to isolate certain source components.

If a specific L_{max} value is available for the proposed trainset and Detailed Noise Analysis procedures are to be followed, it is recommended that the subsource SELs provided in Chapter 5 be used to first calculate L_{max} as described in Appendix C (Section C.1). This calculated L_{max} can then be compared with the specified or measured L_{max} and if necessary, one or more of the subsource SELs can be adjusted to account for the discrepancy. This may be an iterative process until the computed L_{max} and the specified L_{max} are the same. This technique should be exercised with caution, however, since judgement and understanding of the subsource mechanisms are required to determine which of the subsource SELs should be adjusted.

The procedure for converting L_{max} to a reference SEL for use in the General Noise Assessment method is summarized as follows:

Step 1. **Identify Vehicle Category**. Classify the project into one of the vehicle type categories listed in Table 4-2.

Step 2. **Identify Major Sound Source and Parameters**. Identify the appropriate speed regime I, II or III from Table 4-2. The speed regime establishes the dominant sound source for the given speed (propulsion, wheel/rail or aerodynamic). For the vehicle category, obtain noise model parameters such as speed coefficient, reference length, and reference speed corresponding to the speed regime from Table 4-2.

Step 3. **Convert L_{max} to SEL**. Compute SEL using the equations in Table C-2. This computation yields the SEL for the operating conditions and distance corresponding to the L_{max} measurement or specification.

Step 4. **Normalize to Reference Conditions**. Adjust the resulting SEL to the reference distance and operating conditions of Table 4-2, using the equation in Table C-2. This adjustment yields a new reference SEL appropriate for comparison with the values listed in Table 4-2.

Table C-2 Computation of SEL for a High-Speed Train Passby from L_{max} for General Assessment

To convert from L_{max} to SEL:

Speed Regime I	$SEL = L_{\max} + 10\log\left(\frac{len}{S}\right) - 10\log(2\alpha) + 3.3$ where *len* = total length of power unit(s), in feet
Speed Regime II	$SEL = L_{\max} + 10\log\left(\frac{len}{S}\right) - 10\log[2\alpha + \sin(2\alpha)] + 3.3$ where *len* = total length of train, in feet
Speed Regime III	$SEL = L_{\max} + 10\log\left(\frac{len}{S}\right) - 10\log(2\alpha) + 3.3$ where *len* = total length of train, in feet

To normalize back to Reference Conditions of Table 4-2:

$$SEL_{ref} = SEL + K\log\left(\frac{S_{ref}}{S}\right) + 10\log\left(\frac{len_{ref}}{len}\right) - 15\log\left(\frac{50}{d}\right)$$

SEL_{ref} = SEL adjusted to reference parameters of Table 4-2 at reference distance,

K = Speed coefficient (from Table 4-2),

S_{ref} = Reference speed, mph (from Table 4-2),

S = Train speed, mph,

len_{ref} = Reference length, feet (from Table 4-2),

d = receiver distance from track centerline, feet, and

$\alpha = \tan^{-1}\left(\frac{len}{2d}\right)$, radians.

APPENDIX D
GLOSSARY OF TERMS

A-weighting – A method used to alter the sensitivity of a sound level meter with respect to frequency so that the instrument is less sensitive at frequencies where the human ear is less sensitive. Also written as dBA.

Aeroacoustic – Acoustical waves generated by pressure fluctuations in moving air.

Ambient – The pre-project background noise or vibration level.

Alignment – The horizontal location of a railroad as described by curved and tangent track.

Auxiliaries – The term applied to a number of separately driven machines, operated by power from the main engine. They include the air compressor, radiator fan, traction motor blower, exciter for the main generator and the boiler blower.

Ballast Mat – A 2- to 3-inch-thick elastomer mat placed under the normal track ballast on top of a rigid slab.

Ballast – Selected material placed on the roadbed for the purpose of holding the track in line and at surface.

Cab – The space in the power unit containing the operating controls and providing shelter and seats for the engine crew.

Catenary – On electric railroads, the term describing the overhead conductor that is contacted by the pantograph or trolley, and its support structure.

Coach – A passenger-carrying rail car, usually with a center aisle and two rows of seats.

Consist – The total number and type of cars and locomotives in a trainset.

Continuous Welded Rail – A number of rails welded together in lengths of 400 feet or longer.

Corrugated Rail – A rough condition on the rail head of alternate ridges and grooves, which develops in service.

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 roadbed.

Crossover – Two turnouts with the track between the frogs arranged to form a continuous passage between two nearby and generally parallel tracks.

Cut – A term used to describe a railbed at a lower level than the surrounding ground.

dB – *see Decibel*

dBA – *see A-weighting*

Decibel – A 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. Also written as dB.

Descriptor – A quantitative metric used to identify a specific measure of sound level.

DNL – *see* L_{dn}

DOT – The Department of Transportation. An agency of the U. S. government having jurisdiction over matters pertaining to all modes of transportation.

Electrification – A term used to describe the installation of overhead wire or third rail power distribution facilities to enable operation of trains hauled by electric locomotives.

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 A-weighted sound energy as the time-varying sound. Also written as L_{eq}.

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.

Flow Separation – Loss of adherence of air to parts of the train's outer surface.

FRA – The Federal Railroad Administration. An agency of the U. S. Department of Transportation with jurisdiction over matters of railroad safety and research.

Frequency – Of a phenomenon that occurs periodically in time, the number of times that the quantity repeats itself in 1 second.

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 gage lines, measured at right angles thereto.

Gage Line – A line 5/8-inch below the top of the center line of head of running rail or corresponding location of tread portion of other track structures along that side which is nearer the center of the tracks.

Gas-Turbine Electric Locomotive – A power unit in which a gas turbine drives electric generators supplying current to electric traction motors on the axles.

Grade Crossing – The point where a rail line and a motor vehicle road intersect.

Guideway – Supporting structure to form a track for rolling- or magnetically-levitated vehicles.

Head-End Power – A system of furnishing electric power for a complete railway train from a single generating plant in the power unit.

Hourly Average Sound Level – The time-averaged A-weighted sound level, over a 1-hour period, usually calculated between integral hours. Also known as L_{1h}.

Idle – The speed at which an engine runs when it is not under load.

Intermodal Car – A rail car designed specifically for handling piggyback trailers or containers, or both.

Intermodal Traffic – Freight moving via at least two different modes of transport, e.g., truck-to-rail.

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_{AE} – Power-averaged value of sound exposure within 10 dB of L_{Amax}, sampled at a time interval of 5/3 second. Used in Japan.

$L_{Aeq,P}$ – Equivalent A-weighted sound-level, energy averaged over the time of passby (train length). Used in Europe.

$L_{Aeq,1h}$ – Sound-pressure level, energy averaged over one hour. See also Hourly Average Sound Level. Used in Europe.

L_{Amax} – Power-averaged "slow" maximum level ($L_{max,s}$) of 20 consecutive train passbys. Used in Japan.

L_{dn} – 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 U.S. for environmental impact assessment. Also written as DNL.

L_{eq} – *see Equivalent Level*

L_{max}(mean) – *see* $L_{Aeq,P}$ (used in Scandinavia)

$L_{p,1h}$ – *see* $L_{Aeq,1h}$

$L_{p,p}$ – *see* $L_{aeq,P}$

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*)

Lead Unit – The first and controlling power unit in a series of locomotives pulling the same train.

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 a electrodynamic system (EDS) wherein a moving vehicle is lifted by magnetic forces induced in the guideway, or a electromagnetic system (EMS) 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. Also written as L_{max}. The standardized time periods are 1 second for $L_{max, slow}$ and 0.125 second for $L_{max, fast}$.

Multiple Unit (MU) – A term referring to the practice of coupling two or more power units or electric 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 – The frequency interval between two sounds whose frequency ratio is 2.

Pantograph – A device for collecting current from an overhead conductor (catenary), consisting of a jointed frame operated by springs or compressed air and having a current collector at the top.

Peak Particle Velocity (PPV) – The peak signal value of an oscillating vibration velocity waveform. Usually expressed in inches/second.

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 to, but insulated from, the track rails, or from a wire suspended above the track. Contact with the wire is made by a pantograph mounted on top of the unit.

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.

Receiver/Receptor – A stationary far-field position at which noise or vibration levels are specified.

Retarder – A braking device, usually power-operated, built into a railway track to reduce the speed of cars by means of brake shoes which, when set in position, press against the sides of the lower portions of the wheels.

Right-of-Way – Lands or rights used or held for railroad operation.

Root Mean Square (RMS) – The average or "mean" level of an oscillating waveform. Obtained by squaring the value of amplitudes at each instant of time. The squared values are then added and averaged over the sample time.

SEL – *see Sound Exposure Level*

Siding – A track auxiliary to the main track for meeting or passing trains.

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. Also written as SEL.

Sound – A physical disturbance in a medium that is capable of being detected by the human ear.

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.

Switch – A track structure used to divert rolling stock from one track to another.

Tangent Track – Track without curvature.

Terminal – An assemblage of facilities provided by a railway at a terminus or at an intermediate point for the handling of passengers or freight and the receiving, classifying, assembling and dispatching of trains.

Top-Ballast – Any material of a superior character spread over a sub-ballast to support the track structure, distribute the load to the sub-ballast, and provide a good initial drainage.

Turbulent Boundary Layer – Fluctuations in the air adjacent to the body of a vehicle moving at high speed.

Track Crossing – A structure, used where one track crosses another at grade, and consisting of four connected frogs.

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 car to drive the axles.

Trainset – A group of coupled cars including at least one power unit.

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.

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 – 10 times the common logarithm of the ratio of the square of the amplitude of the vibration velocity to the square of the amplitude of the reference velocity. Also written as VdB.

Vibration – An oscillation wherein the quantity is a parameter that defines the motion of a mechanical system.

Vortex Shedding – A flow separation (*see definition above*) wherein the air departs periodically in a spinning motion.

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 a curve where the radius of curvature is smaller than allowed by the separation of the axles in a wheel set.

Wye – A triangular arrangement of tracks on which locomotives, cars and trains may be turned.

Yard – A system of tracks within defined limits provided for making up trains, storing cars, and other purposes, over which movements not authorized by time table or by train-order may be made, subject to prescribed signals and rules, or special instructions.