APPENDIX A: FUNDAMENTAL CONCEPTS OF NOISE AND VIBRATION FOR HIGH-SPEED TRAINS

The purpose of this appendix is to provide the reader with some fundamental background information on the concepts of noise and vibration generated from high-speed train systems. This appendix is adapted from Chapter 2 and Chapter 6 of the Federal Railroad Administration (FRA) *High-Speed Ground Transportation Noise and Vibration Impact Assessment* (FRA 2012) manual as it relates to this project. The reader is directed to this reference for further information on the topic.

The discussion here focuses on noise generation, propagation, and mitigation for steel-wheel high-speed train systems. For information on noise and vibration descriptors, noise and vibration impact criteria, and noise and vibration prediction methodology, see Sections 3 and 4 of the main body of this report, respectively.

Basics of Noise for High-Speed Trains

Noise from high-speed train 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" in the United States 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.

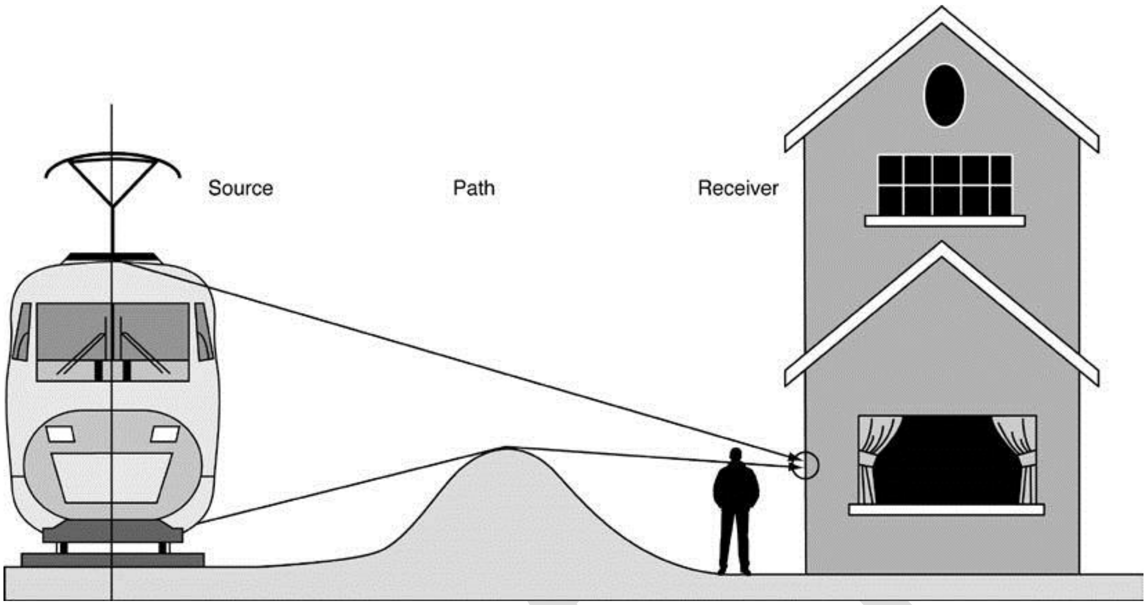
Consequently, this appendix sub-divides these systems into two categories:

- “High-speed,” with a maximum speed of 150 mph.
- “Very high-speed,” with a maximum speed of 250 mph.

Because ancillary sources are not unique to high-speed train systems, noise from electrical substations, maintenance facilities, yards, and stations, are not addressed in this appendix. These noise sources are substantially the same for any type of rail system and do not have characteristics specific to high-speed train systems. The methods described in the corresponding transit noise manual from the Federal Transit Administration are applicable. This section discusses the basic concepts of high-speed ground transportation noise to provide background for the assessment procedures discussed in Section 7. Noise from a ground transportation system is often expressed in terms of a Source-Path-Receiver framework. This framework is sketched on Figure A-1 and is central to all environmental noise studies. Each project **source** generates close-by noise levels, which depend on 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.

This appendix 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 appendix contains an overview of noise **sources**, including a list of major sources specific to high-speed train systems and discussion of noise-generation mechanisms and an overview of noise **paths**, with a discussion of the various attenuating mechanisms in the path between source and receiver.



Source: FRA, 2012

Figure A-1 The Source-Path-Receiver Framework

Sources of High-Speed Train Noise

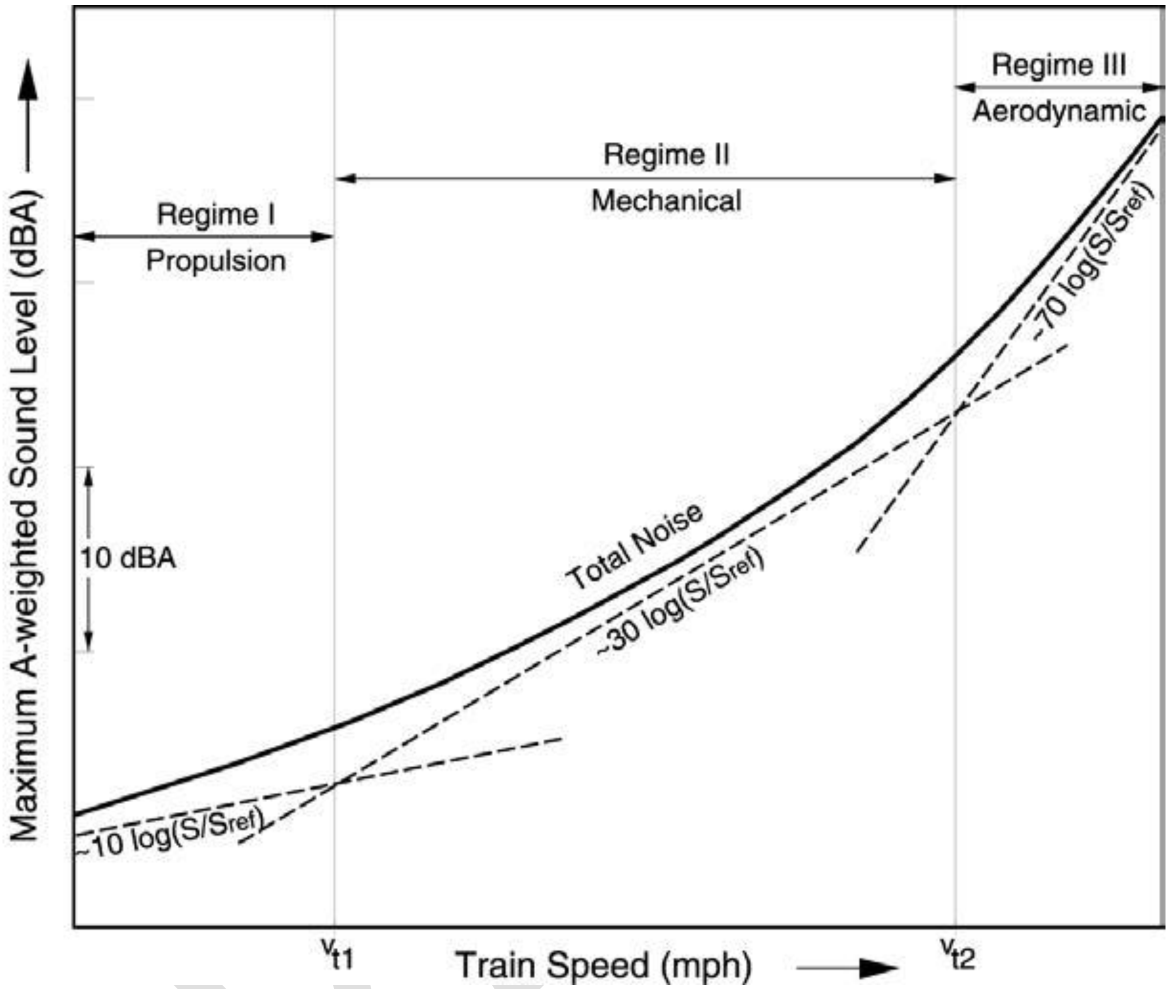
The total wayside noise generated by a high-speed train pass-by consists of several individual noise generating mechanisms, each with its own characteristics of source location, strength, frequency content, directivity, and speed dependence. These noise sources can be generalized into three major regimes:

- Regime I propulsion or machinery noise
- Regime II mechanical noise resulting from wheel/rail interactions and/or guideway vibrations
- 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.

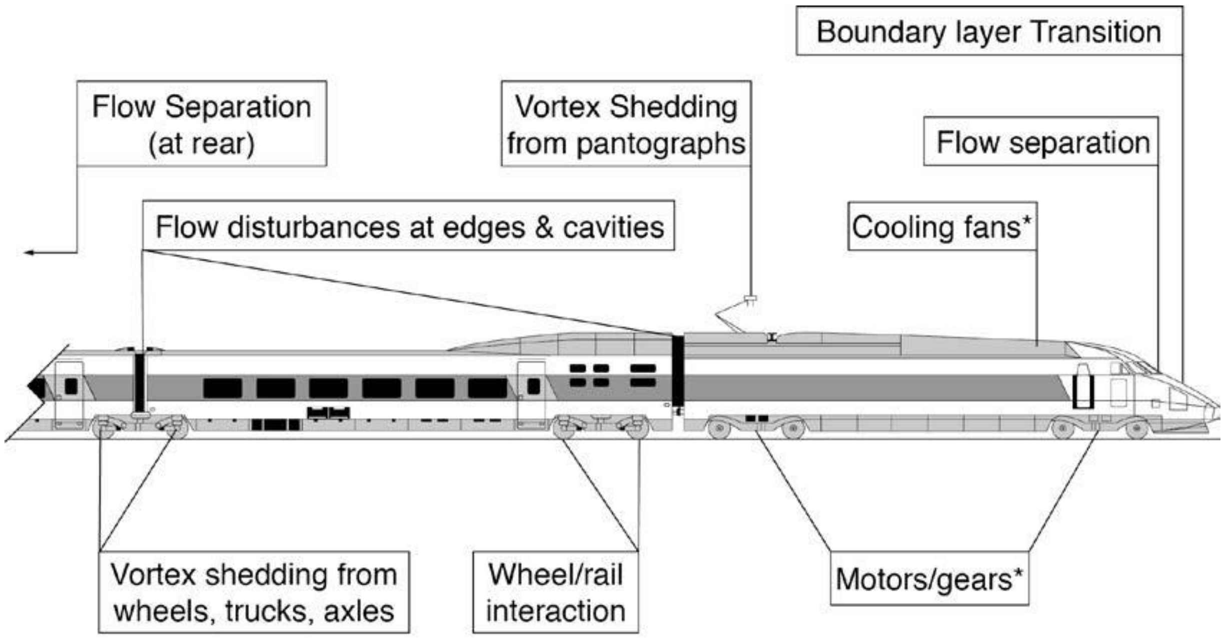
The significance of these different regimes is that, for a given train, there are three distinct speed ranges in which only one sound source dominates the total noise level. The dependence of the A-weighted sound level on vehicle speed (S) for a typical high-speed train is illustrated on Figure A-2. A qualitative indication of the maximum sound level during a pass-by 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, respectively. The speed at which the dominant sound source changes from aerodynamic noise, one to another is called an acoustical transition speed (vt). The transition from propulsion noise to mechanical noise occurs at the lower acoustical transition speed (vt1), and the transition from mechanical to aerodynamic noise occurs at the upper acoustical transition speed (vt2).

The various noise sources for a steel-wheeled high-speed tracked system are illustrated on Figure A-3. These sources differ in where they originate on the train and in what frequency range they dominate.



Source: FRA, 2012

Figure A-2 Generalized Sound Dependence on Speed



Source: FRA, 2012

Figure A-3 Noise Sources on a Steel-Wheeled High-Speed Train System

Regime I: Propulsion Sources

For 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 A-3). 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.

Regime II: Mechanical/Structural Sources

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.

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 steel-wheeled trains, aerodynamic noise is generated from high-velocity airflow over the 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. 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.

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 airborne. 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:

LA = LA(ref) + Cd + Ca + Cg + Cb

where:

LA(ref) = a known A-weighted sound level at some reference distance *ref* from the source

Cd = adjustment factor for attenuation due to divergence

Ca = adjustment factor for excess attenuation due to atmospheric absorption

Cg = adjustment factor for excess attenuation from ground absorption

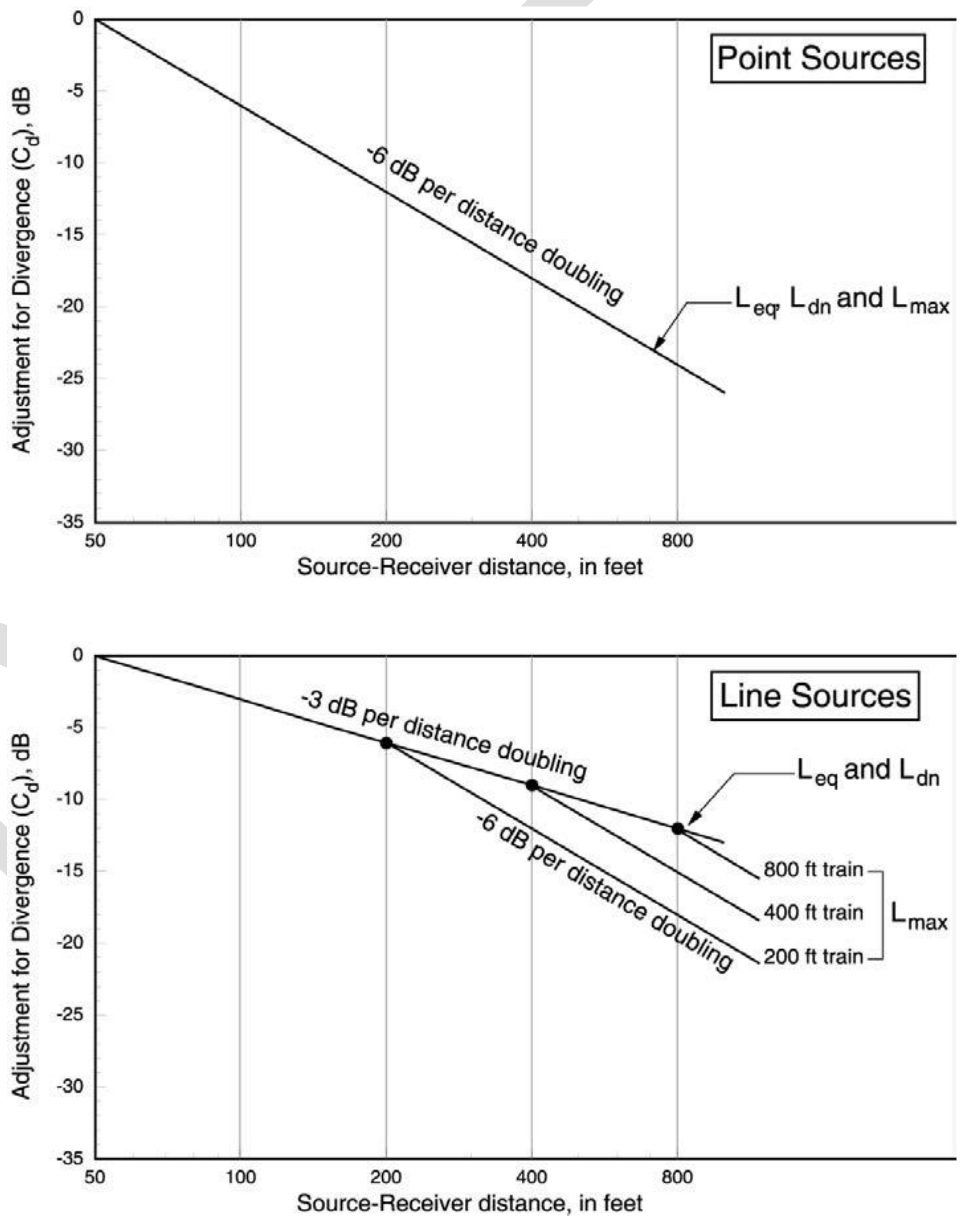
Cb = adjustment factor for excess attenuation due to obstacles such as barriers, berms, and buildings.

In nearly all cases, the adjustment factors are negative numbers due to the nature of the reference conditions. Each of these adjustment factors is discussed below in terms of their mechanisms of sound attenuation. Specific equations for computing noise-level attenuations along source-receiver paths are presented in the FRA guidelines document (FRA 2012). 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 section A2 of this appendix.

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 on Figure A-4. The divergence adjustment factor, *Cd*, 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 A-4, 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 on Figure A-4 are for illustrative purposes only, and the exact equations for these curves given in the FRA Guideline Document are be used for quantitative analyses.

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. A dipole radiation pattern has also been observed in the turbulent boundary layer near the sides of a train. 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.

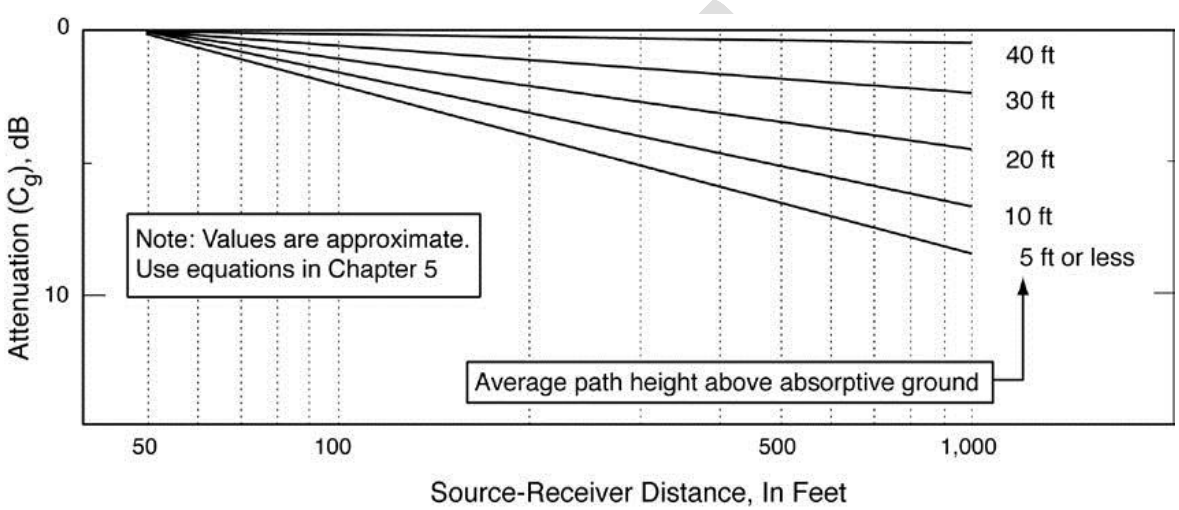


Source: FRA, 2012

Figure A-4 Attenuation Due to Distance

Absorption/Diffusion

In addition to the attenuation from 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 on Figure A-5. In this figure the adjustment factor, *Cg*, 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 on Figure A-5 are presented in Chapter 5 of the FRA Guidelines manual.

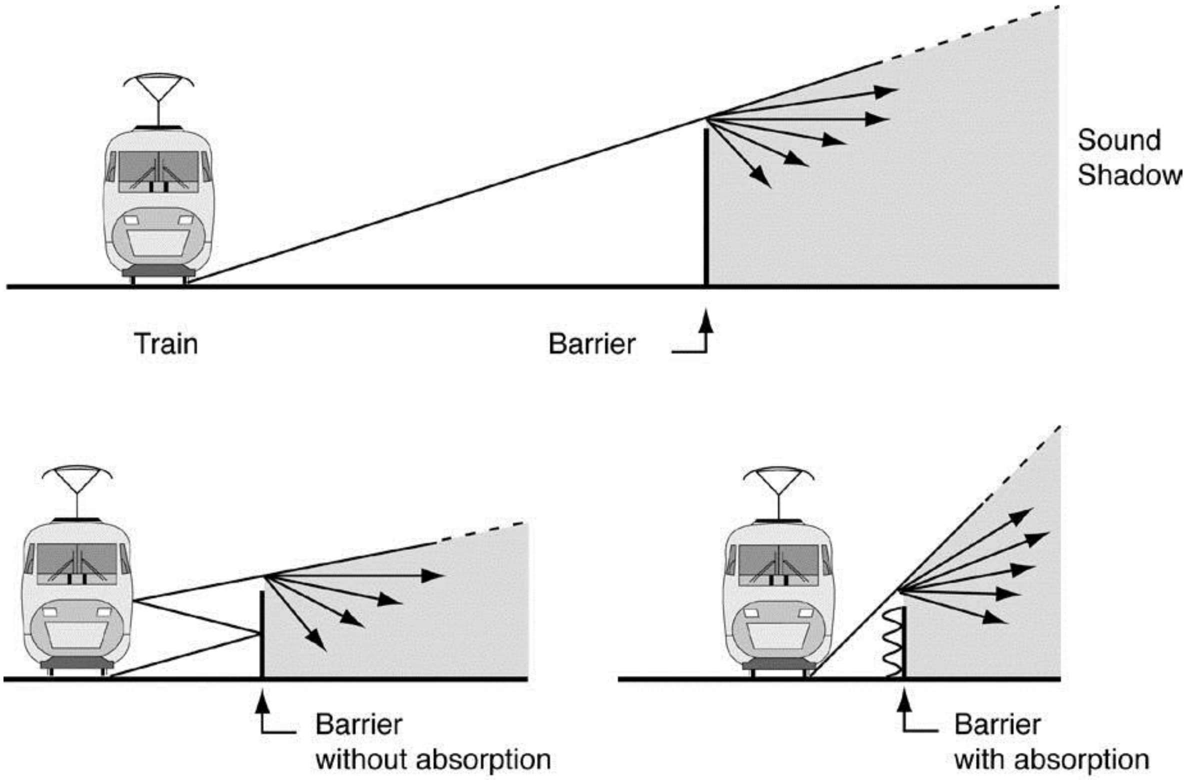


Source: FRA, 2012

Figure A-5 Sound Attenuation Due to Soft Ground

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 on Figure A-6. This diffraction reduces the sound level at the receiver.



Source: FRA, 2012

Figure A-6 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 *Cb* 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 the section on train noise sources, the peak frequencies and source heights of high-speed ground transportation 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, or the use of acoustically absorptive material on the source side of the barrier. These concepts are illustrated on Figure A-6. Acoustical absorption is considered as a mitigation option in detailed noise analysis. Equations for barrier attenuation and equations for other sound-path interruptions are also presented in the Detailed Noise Analysis section of the FRA Guidelines document (FRA 2012).

Basics of Vibration for High-Speed Trains

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 can be 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 section provides a general background on ground-borne vibration and summarizes the available data on ground-borne vibration caused by high-speed trains. The material presented is based largely on empirical data, since ground-borne vibration is a more complex phenomenon than that of airborne noise.

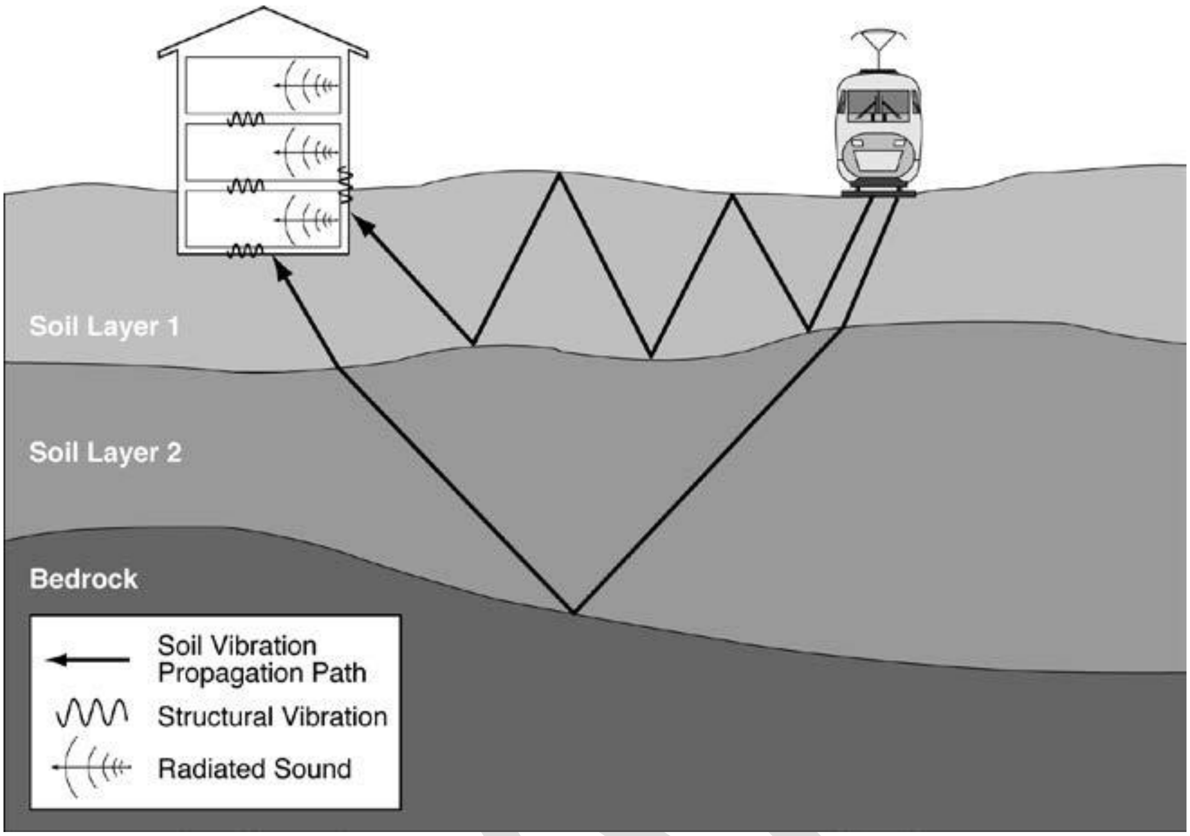
The effects of ground-borne vibration include perceptible movement of the building floors, rattling of windows, shaking of items on shelves or hanging on walls, and rumbling sounds. In extreme cases, such vibration can damage buildings and other structures. Building damage is not a factor for most surface 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 5 to 10 decibels. 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 train system on Figure A-7. 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.

The vibration of the track or guideway 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.



Source: FRA, 2012

Figure A-7 Propagation of Ground-Borne Vibrations Into Buildings

Human Perception of Ground-Borne Vibration and Noise

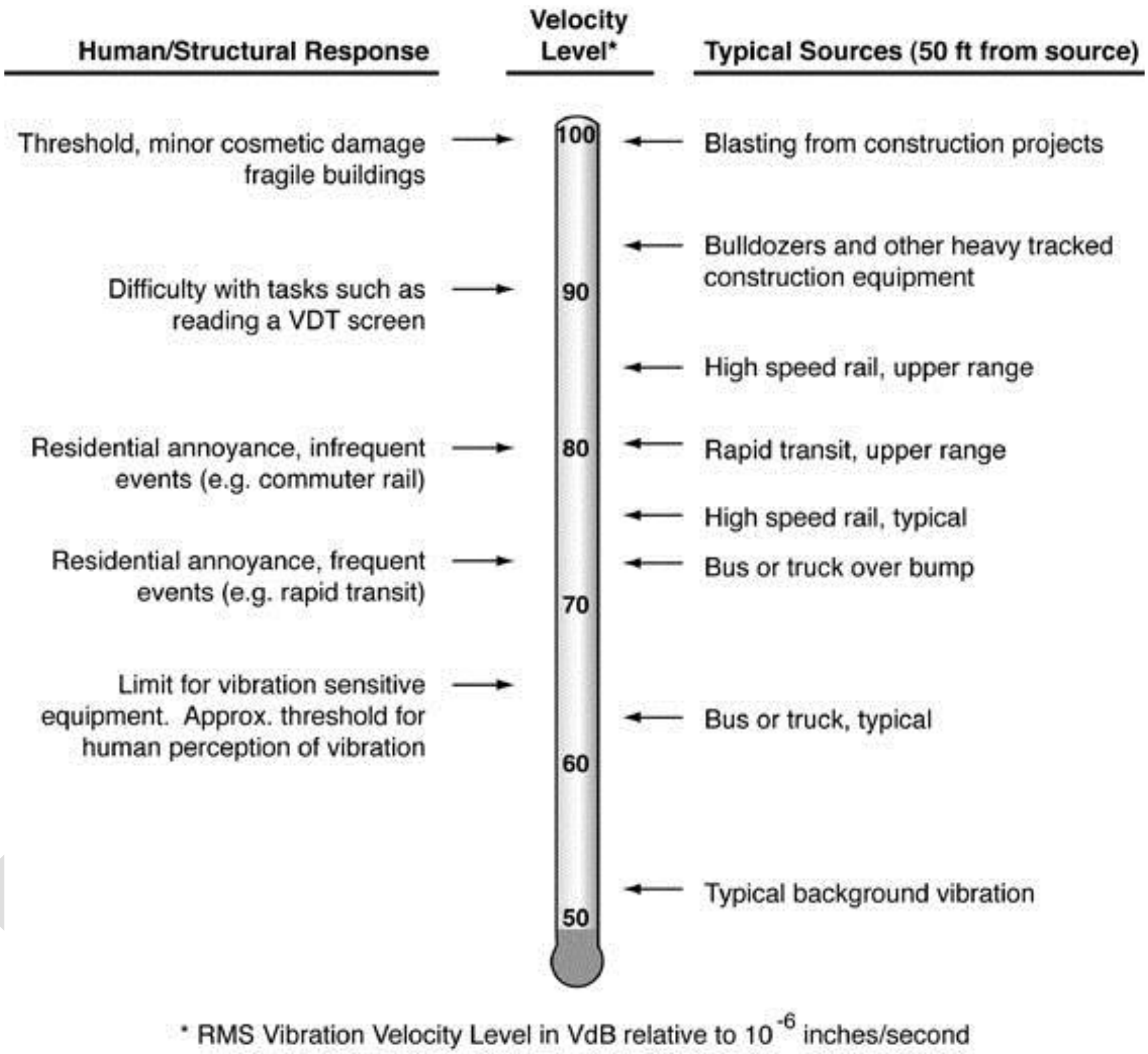
This section gives some general background on human response to different levels of building vibration, thereby establishing the basis for the criteria for ground-borne vibration and noise that are presented in Section 4.2 of this report.

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 RMS vibration velocity level, decibels (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 on Figure A-8. 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 photo 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, he sound pressure level is approximately equal to the average vibration velocity level of the room surfaces. Hence, the A-weighted level of ground-borne noise can be estimated by applying A-weighting to the vibration velocity spectrum. Since the A-weighting at 31.5 Hz is -39.4 dB, if the vibration spectrum peaks at 30 Hz, the A-weighted sound level will be approximately 40 decibels lower than the velocity level. Correspondingly, if the vibration spectrum peaks at 60 Hz, the A-weighted sound level will be about 25 decibels lower than the velocity level.



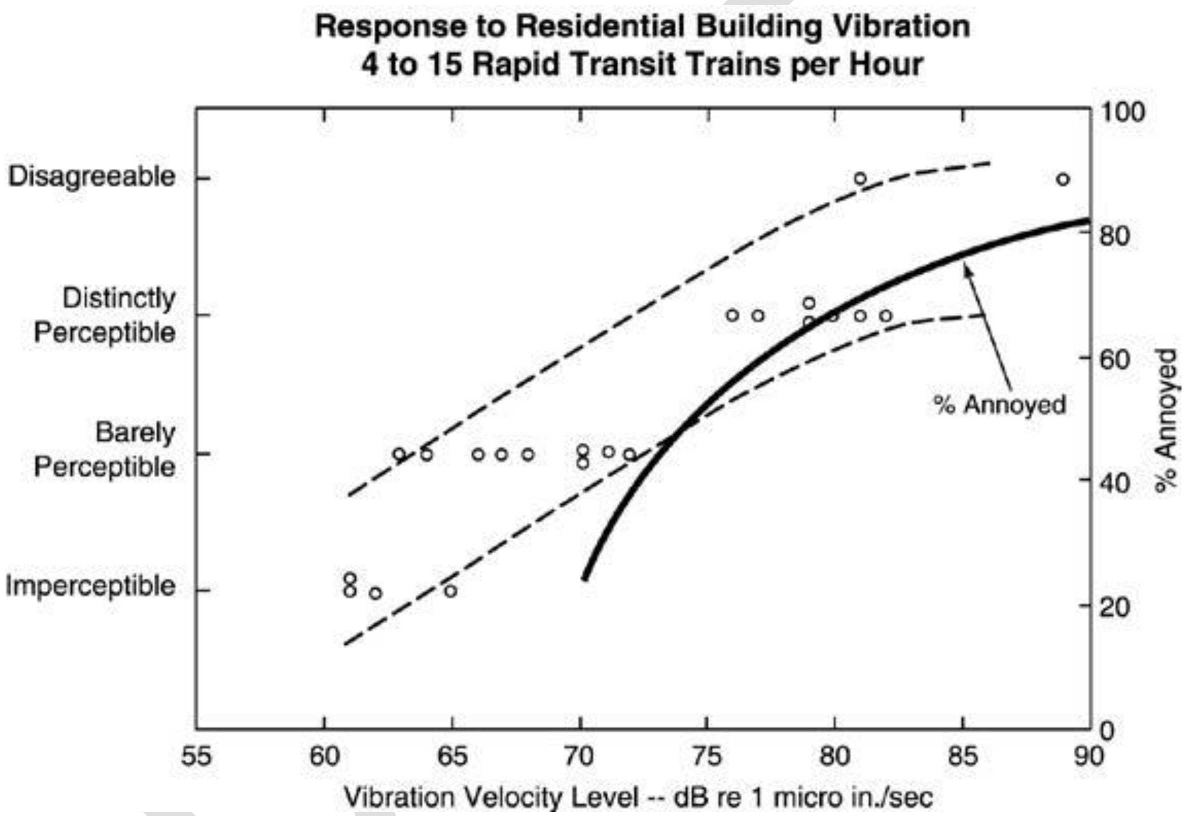
Source: FRA, 2012

Figure A-8 Typical Levels of Ground-Borne Vibration

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.

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 on Figure A-9. 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. 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 shown on Figure A-9 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 are provided by a Japanese study on vibration pollution conducted in 1975. The percent of people annoyed by vibration from high-speed trains in Japan is shown by the "% annoyed" curve on Figure A-9. 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.



Source: FRA, 2012

Figure A-9 Occupant Response to Urban Transit-Induced Residential Vibration

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 reviewed in this section. The physical parameters of the track, and trainsets, geology, and receiving building can 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 train 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 train 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 structures, 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.

Ground-Borne Vibration from High-Speed Trains

Available data on ground-borne vibration from high-speed trains are from measurements of test programs involving the Acela in the United States and the TransRapid TR08 in Germany, and revenue service operations of the X2000 in Sweden, the Pendolino in Italy, and the Trains à Grande Vitesse (TGV) and Eurostar trains in France. Acela and TR08 tests were performed in 2000-2001. The European revenue service data were obtained in May 1995 as part of the data collection task involved in preparing the FRA guidelines (FRA 2012). Vibration measurements were made at two sites in each country, with vibration propagation testing done at one primary site in each country. This measurement program represents one of the first times that the same detailed ground-borne vibration testing procedure 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 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 the Detailed Vibration Assessment section of the

FRA Guidelines document (FRA 2012). 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.
3. Best-fit curves of level vs. distance for each frequency band were obtained using linear regression or other curve-fitting techniques, approximate line-source transfer mobility, and train vibration spectra as a function of distance from the source.

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.

References

Federal Railroad Administration (FRA). 2012. *High Speed Ground Transportation Noise and Vibration Impact Assessment Manual*. May 2012.