

## 7. BASIC GROUND-BORNE VIBRATION CONCEPTS

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

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

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

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

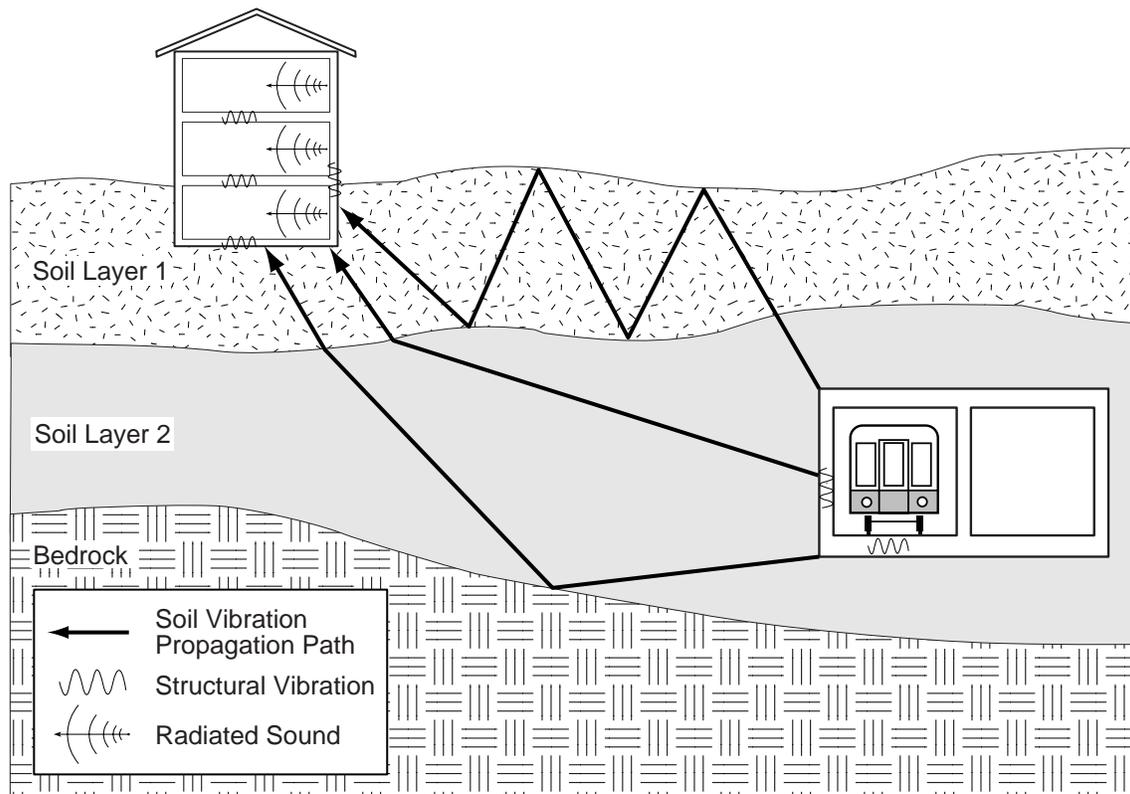


Figure 7-1 Propagation of Ground-Borne Vibration into Buildings

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

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

## 7.1 DESCRIPTORS OF GROUND-BORNE VIBRATION AND NOISE

### 7.1.1 *Vibratory Motion*

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

position. The velocity represents the instantaneous speed of the floor movement and acceleration is the rate of change of the speed.

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

### 7.1.2 Amplitude Descriptors

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

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

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

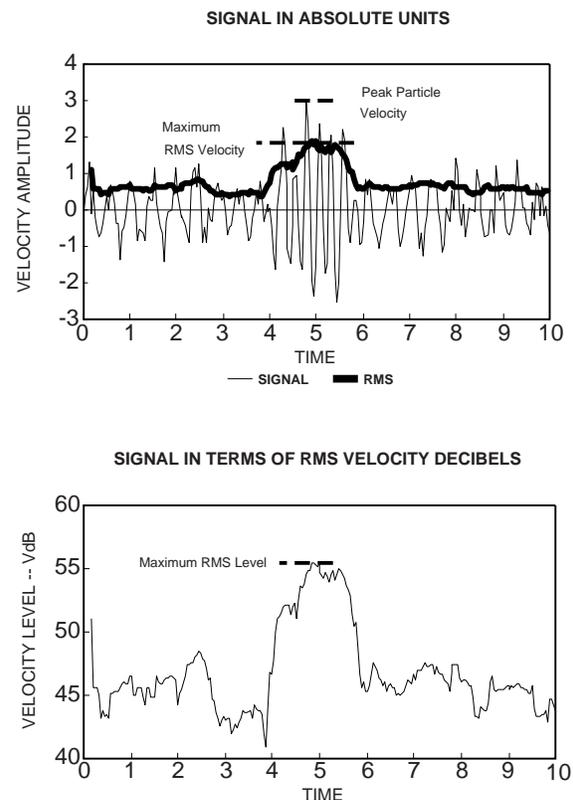


Figure 7-2 Different Methods of Describing a Vibration Signal

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

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

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

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

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

$$VL \approx L_v - 21$$

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

### **7.1.3 Ground-Borne Noise**

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

## **7.2 HUMAN PERCEPTION OF GROUND-BORNE VIBRATION AND NOISE**

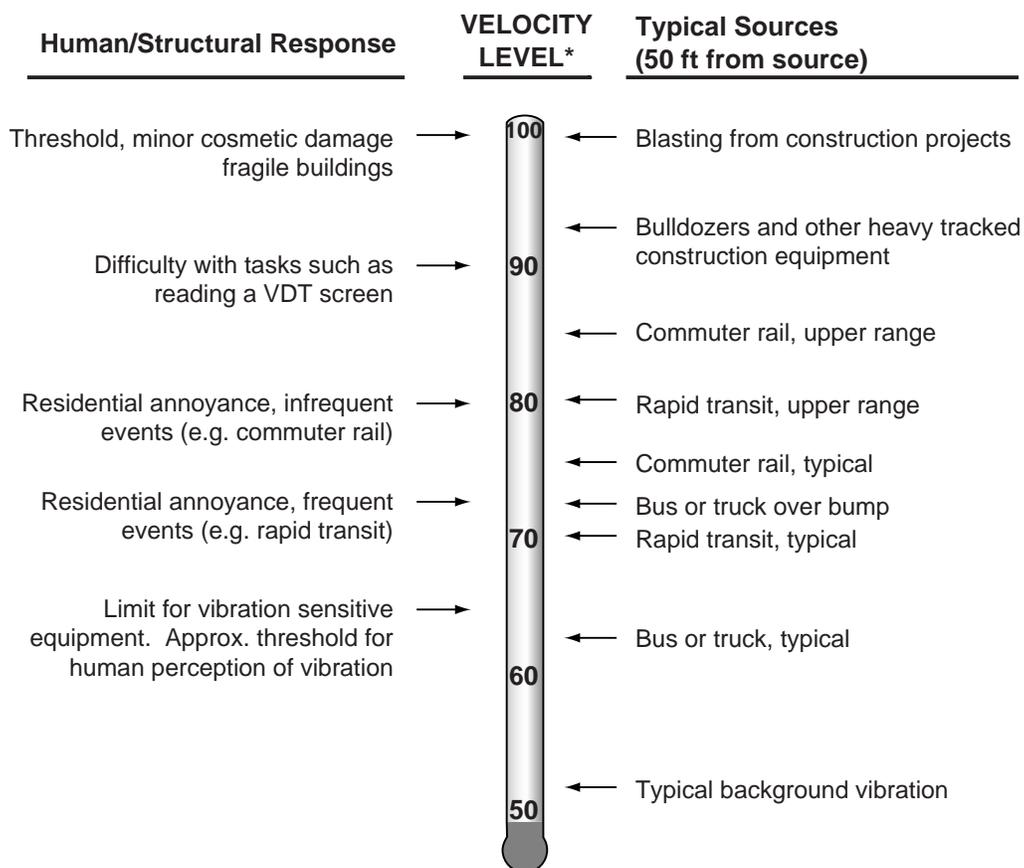
This section gives some general background on human response to different levels of building vibration laying the ground work for the criteria for ground-borne vibration and noise that are presented in Chapter 8.

### **7.2.1 Typical Levels of Ground-Borne Vibration and Noise**

In contrast to airborne noise, ground-borne vibration is not a phenomenon that most people experience every day. The background vibration velocity level in residential areas is usually 50 VdB or lower, well below the

threshold of perception for humans which is around 65 VdB. Most perceptible indoor vibration is caused by sources within buildings such as operation of mechanical equipment, movement of people or slamming of doors. Typical outdoor sources of perceptible ground-borne vibration are construction equipment, steel-wheeled trains, and traffic on rough roads. If the roadway is smooth, the vibration from traffic is rarely perceptible.

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



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

Figure 7-3 Typical Levels of Ground-Borne Vibration

Although the perceptibility threshold is about 65 VdB, human response to vibration is not usually significant unless the vibration exceeds 70 VdB. This is a typical level 50 feet from a rapid transit or light rail system. Buses and trucks rarely create vibration that exceeds 70 VdB unless there are bumps in the road. Because of

the heavy locomotives on diesel commuter rail systems, the vibration levels average about 5 to 10 decibels higher than rail transit vehicles. If there is unusually rough road or track, wheel flats, geologic conditions that promote efficient propagation of vibration, or vehicles with very stiff suspension systems, the vibration levels from any source can be 10 decibels higher than typical. Hence, at 50 feet, the upper range for rapid transit vibration is around 80 VdB and the high range for commuter rail vibration is 85 VdB. If the vibration level in a residence reaches 85 VdB, most people will be strongly annoyed by the vibration.

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

### **7.2.2 Quantifying Human Response to Ground-Borne Vibration and Noise**

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

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

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\*The sound level approximately equals the average vibration velocity level *only* when the velocity level is referenced to 1 micro inch/second. When velocity level is expressed using the international standard of  $1 \times 10^{-8}$  m/sec, the sound level is approximately 8 decibels lower than the average velocity level.

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

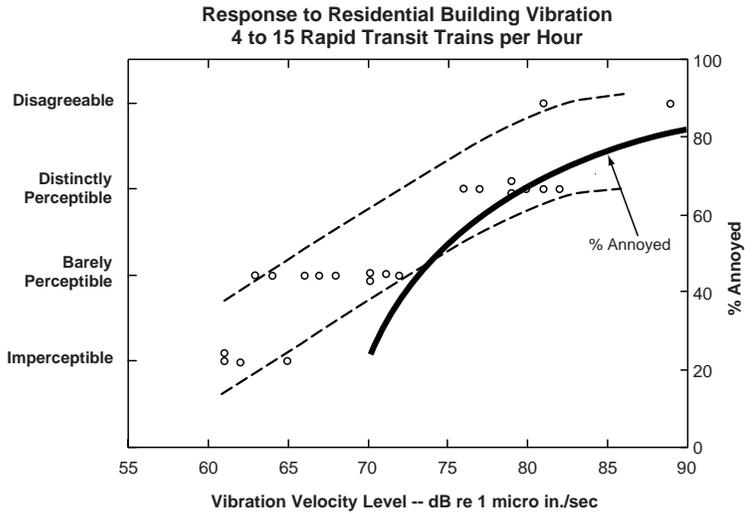


Figure 7-4 Occupant Response to Transit-Induced Residential Vibration

acceptable. That is, the noise caused by vibrating structural components may be very annoying even though the vibration cannot be felt, or the other way around.

Table 7-1 Human Response to Different Levels of Ground-Borne Noise and Vibration			
Vib. Velocity Level	Noise Level		Human Response
	Low Freq <sup>1</sup>	Mid Freq <sup>2</sup>	
65 VdB	25 dBA	40 dBA	Approximate threshold of perception for many humans. Low-frequency sound usually inaudible, mid-frequency sound excessive for quiet sleeping areas.
75 VdB	35 dBA	50 dBA	Approximate dividing line between barely perceptible and distinctly perceptible. Many people find transit vibration at this level unacceptable. Low-frequency noise acceptable for sleeping areas, mid-frequency noise annoying in most quiet occupied areas.
85 VdB	45 dBA	60 dBA	Vibration acceptable only if there are an infrequent number of events per day. Low-frequency noise unacceptable for sleeping areas, mid-frequency noise unacceptable even for infrequent events with institutional land uses such as schools and churches.
Notes:			
1. Approximate noise level when vibration spectrum peak is near 30 Hz.			
2. Approximate noise level when vibration spectrum peak is near 60 Hz.			

### 7.3 GROUND-BORNE VIBRATION FOR DIFFERENT TRANSIT MODES

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

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

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

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

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

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

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

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

## 7.4 FACTORS THAT INFLUENCE GROUND-BORNE VIBRATION AND NOISE

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

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

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

**Geology** – Soil conditions are known to have a strong influence on the levels of ground-borne vibration. Among the most important factors are the stiffness and internal damping of the soil and the depth to

bedrock. Experience with ground-borne vibration is that vibration propagation is more efficient in stiff clay soils, and shallow rock seems to concentrate the vibration energy close to the surface and can result in ground-borne vibration problems at large distances from the track. Factors such as layering of the soil and depth to water table can have significant effects on the propagation of ground-borne vibration.

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

<b>Table 7-2 Factors that Influence Levels of Ground-Borne Vibration and Noise</b>	
<b><i>Factors Related to Vibration Source</i></b>	
<b>Factors</b>	<b>Influence</b>
Vehicle Suspension	If the suspension is stiff in the vertical direction, the effective vibration forces will be higher. On transit cars, only the primary suspension affects the vibration levels, the secondary suspension that supports the car body has no apparent effect.
Wheel Type and Condition	Use of pneumatic tires is one of the best methods of controlling ground-borne vibration. Normal resilient wheels on rail transit systems are usually too stiff to provide significant vibration reduction. Wheel flats and general wheel roughness are the major cause of vibration from steel wheel/steel rail systems.
Track/Roadway Surface	Rough track or rough roads are often the cause of vibration problems. Maintaining a smooth surface will reduce vibration levels.
Track Support System	On rail systems, the track support system is one of the major components in determining the levels of ground-borne vibration. The highest vibration levels are created by track that is rigidly attached to a concrete trackbed (e.g. track on wood half ties embedded in the concrete). The vibration levels are much lower when special vibration control track systems such as resilient fasteners, ballast mats and floating slabs are used.
Speed	As intuitively expected, higher speeds result in higher vibration levels. Doubling speed usually results in vibration levels 4 to 6 decibels higher.
Transit Structure	The general rule-of-thumb is that the heavier the transit structure, the lower the vibration levels. The vibration levels from a lightweight bored tunnel will usually be higher than from a poured concrete box subway.
Depth of Vibration Source	There are significant differences in the vibration characteristics when the source is underground compared to at the ground surface.
<b><i>Factors Related to Vibration Path</i></b>	
<b>Factor</b>	<b>Influence</b>
Soil Type	It is generally expected that vibration levels will be higher in stiff clay type soils than in loose sandy soils.
Rock Layers	Vibration levels often seem to be high near at-grade track when the depth to bedrock is 30 ft or less. Subways founded in rock will result in lower vibration amplitudes close to the subway. Because of efficient propagation, the vibration level does not attenuate as rapidly in rock as it does in soil.
Soil Layering	Soil layering will have a substantial, but unpredictable, effect on the vibration levels since each stratum can have significantly different dynamic characteristics.
Depth to Water Table	The presence of the water table is often expected to have a significant effect on ground-borne vibration, but evidence to date cannot be expressed with a definite relationship.
Frost Depth	There is some indication that vibration propagation is more efficient when the ground is frozen.
<b><i>Factors Related to Vibration Receiver</i></b>	
<b>Factor</b>	<b>Influence</b>
Foundation Type	The general rule-of-thumb is that the heavier the building foundation, the greater the coupling loss as the vibration propagates from the ground into the building.
Building Construction	Since ground-borne vibration and noise are almost always evaluated in terms of indoor receivers, the propagation of the vibration through the building must be considered. Each building has different characteristics relative to structureborne vibration, although the general rule-of-thumb is that the more massive a building is, the lower the levels of ground-borne vibration will be.
Acoustical Absorption	The amount of acoustical absorption in the receiver room affects the levels of ground-borne noise.

## REFERENCES

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