11. DETAILED VIBRATION ANALYSIS

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

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

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

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

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

A Detailed Vibration Analysis consists of three parts:

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

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

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

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

11.1 CHARACTERIZING EXISTING VIBRATION CONDITIONS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

11.2 VIBRATION PREDICTION PROCEDURE

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

11.2.1 Overview of Prediction Procedure

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

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

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

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

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

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

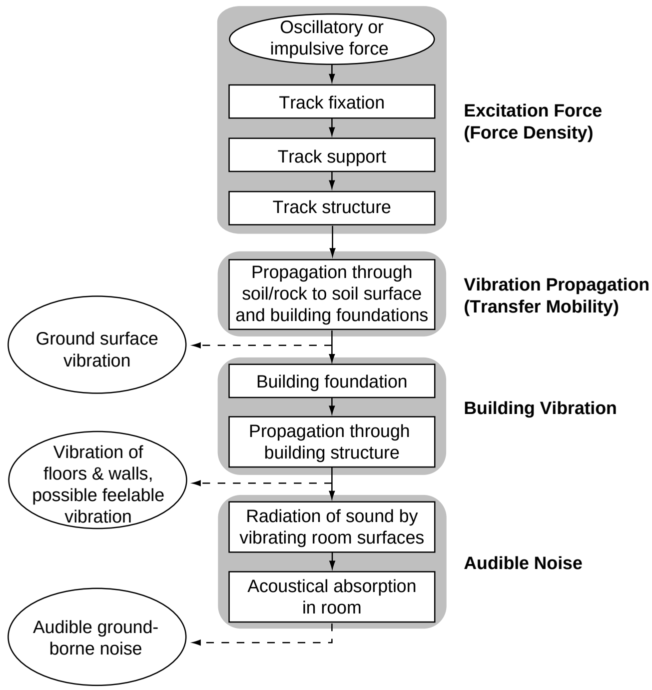

Figure 11-1 Block Diagram of Ground-Borne Vibration and Noise Model

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

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

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

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

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

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

where:

$\mathbf{L_v}$ = rms vibration velocity level in one 1/3 octave band,

$\mathbf{L_A}$ = A-weighted sound level in one 1/3 octave band,

$\mathbf{L_F}$ = force density for a line vibration source such as a train,

$\mathbf{TM_{line}}$ = line source transfer mobility from the tracks to the sensitive site,

$\mathbf{C_{build}}$ = adjustments to account for ground–building foundation interaction and attenuation of vibration amplitudes as vibration propagates through buildings,

$\mathbf{K_{rad}}$ = adjustment to account for conversion from vibration to sound pressure level including accounting for the amount of acoustical absorption inside the room (A value of zero can be used for $\mathbf{K_{rad}}$ for typical residential rooms when the decibel reference value for $\mathbf{L_v}$ is 1 micro in./sec.[(4)]),

$\mathbf{K_{A\text{-}wt}}$ = A-weighting adjustment at the 1/3 octave band center frequency.

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

11.2.2 Major Steps in Detailed Analysis

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

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

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

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

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

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

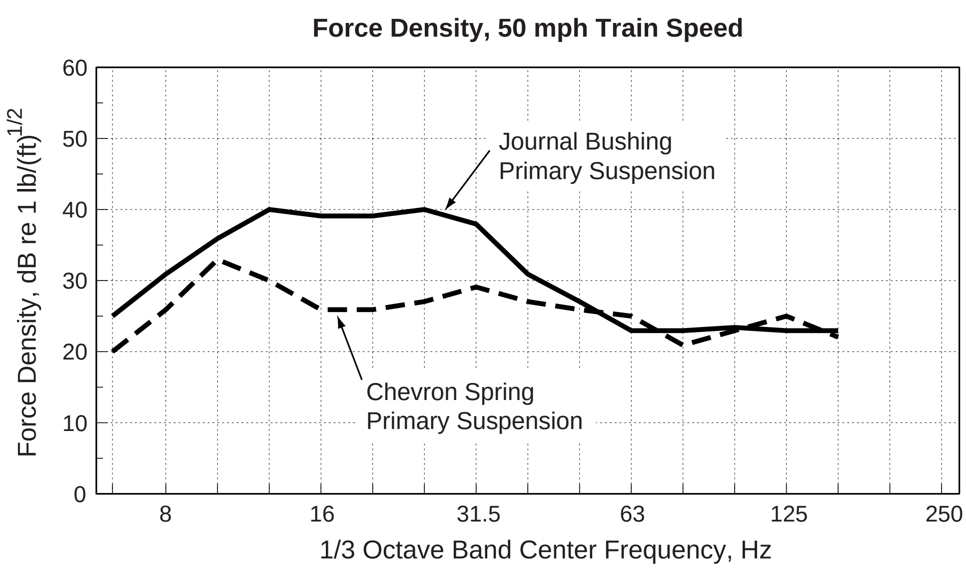

Figure 11-2 Force Densities for Rail Transit Vehicles

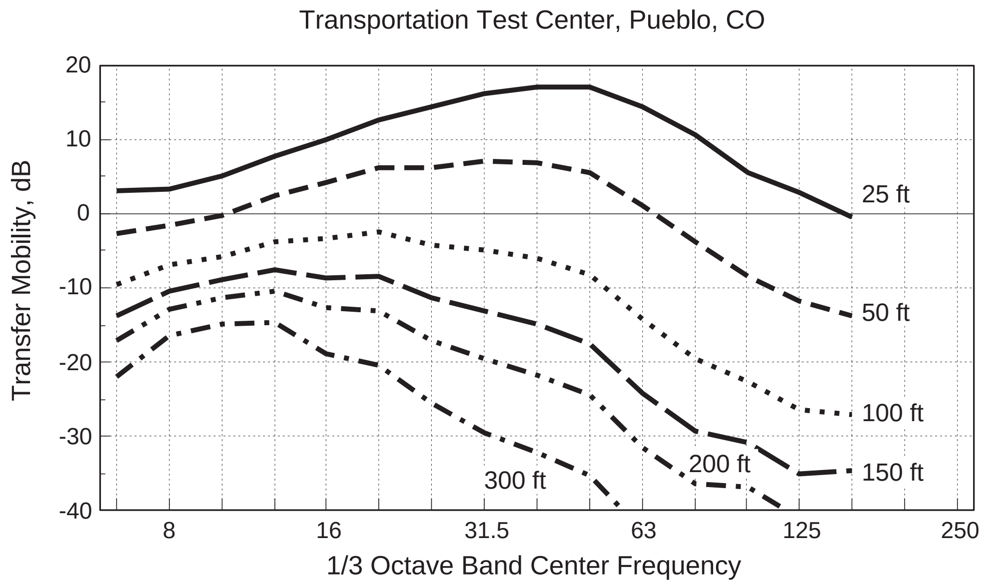

Figure 11-3 Average Point-Source Transfer Mobility

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

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

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

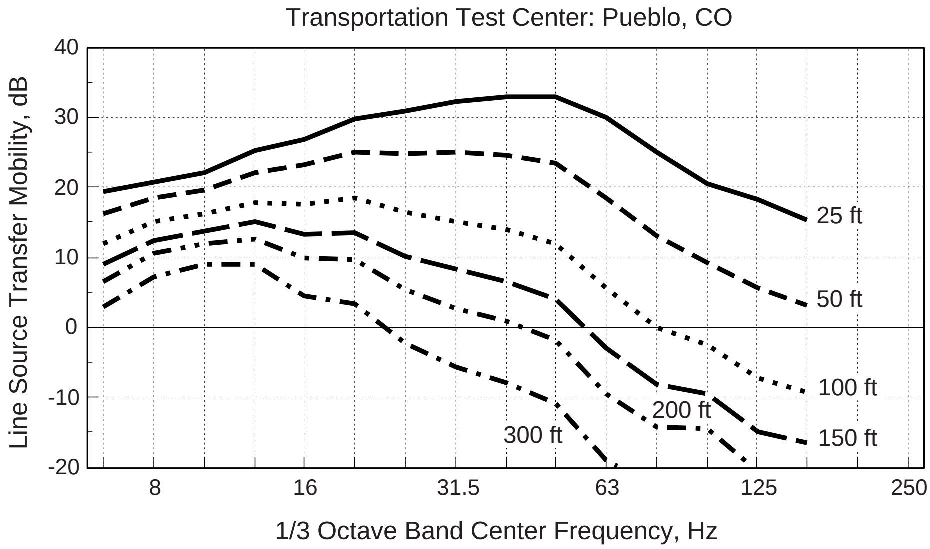

Figure 11-4 Average Line-Source Transfer Mobility

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

1. **Building response or coupling loss.** This represents the change in the incident ground-surface vibration due to the presence of the building foundation. The adjustments in the *Handbook*, which were originally developed by Wilson,(14) are shown in Figure 11-5. Note that the correction is zero when estimating basement floor vibration or vibration of at-grade slabs.

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

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

The projected floor vibration is used to estimate the levels of ground-borne noise. The primary factors affecting noise level are the average vibration level of the room surfaces and the amount of acoustical absorption within the room. As discussed above, the radiation adjustment is zero for typical rooms, which gives:

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

where L_A is the A-weighted sound level in a 1/3 octave band, L_v is the average vibration velocity level, and $K_{A\text{-}wt}$ is the A-weighting adjustment at the center frequency of the 1/3 octave band. The A-weighted levels in the 1/3 third octave bands are then combined to give the overall A-weighted sound level.

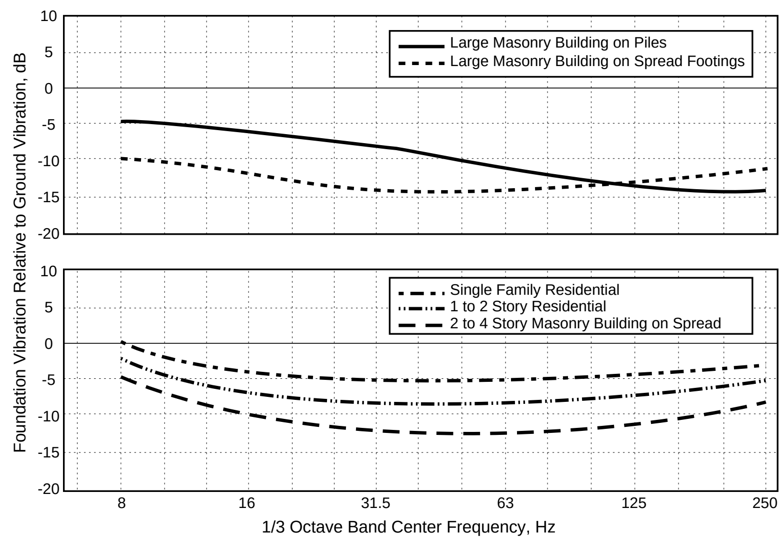

Figure 11-5 Foundation Response for Various Types of Buildings

11.3 MEASURING TRANSFER MOBILITY AND FORCE DENSITY

The test procedure to measure transfer mobility basically consists of dropping a heavy weight on the ground and measuring the force into the ground and the response at several distances from the impact. The goal of the test is to create vibration pulses that travel from the source to the ground surface using the same path that will be taken by the transit system vibration. The transfer mobility expresses the relationship between the input force and the ground-surface vibration.

Figure 11-6 illustrates the field procedure for at-grade and subway testing of transfer mobility. A weight is dropped from a distance of 3 to 4 feet onto a force transducer. The responses of the force and vibration transducers are recorded on a multichannel tape recorder for later analysis in the laboratory. An alternative approach is to set up the analysis equipment in the field and capture the signals directly. This complicates the field testing but eliminates the laboratory analysis of tape recorded data.

When the procedure is applied to subways, the force must be located at the approximate depth of the subway. This is done by drilling a bore hole and locating the force transducer at the bottom of the hole. The tests are usually performed at the same time that the bore holes are drilled. This allows using the soil-sampling equipment on the drill rig for the transfer mobility testing. The force transducer is attached to the bottom of the drill string and lowered to the bottom of the hole. A standard soil sampling hammer, which is usually

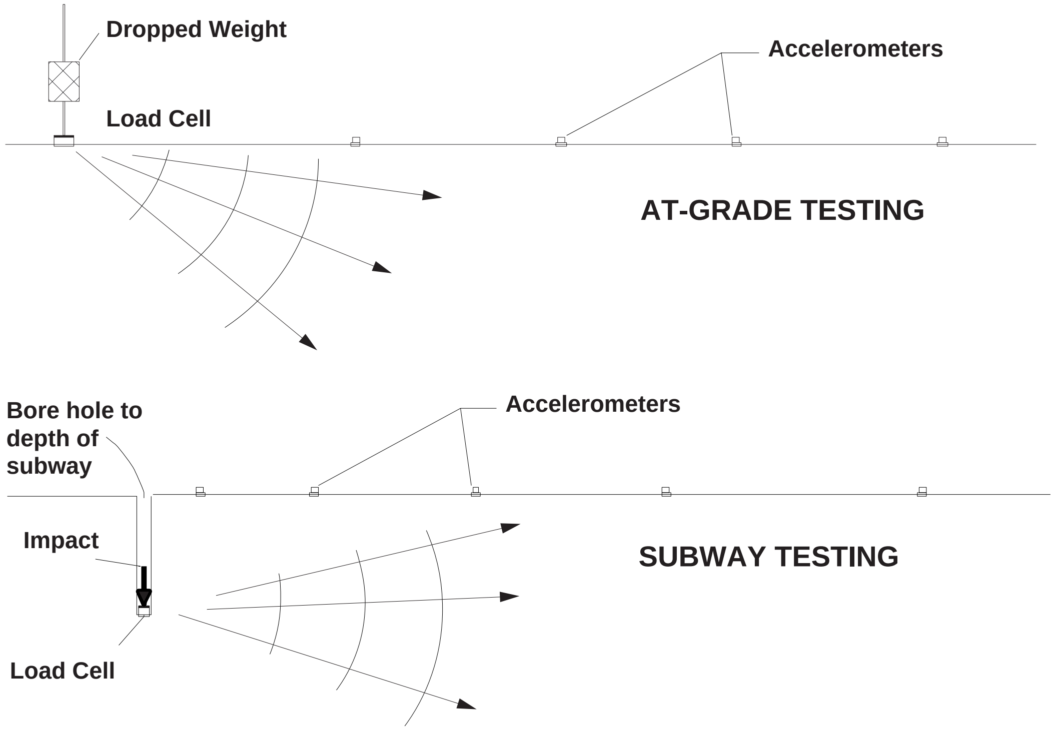

Figure 11-6 Test Configuration for Measuring Transfer Mobility

a 140 lb weight dropped 18 inches on to a collar attached to the drill string, is used to excite the ground. The force transducer must be capable of operating under water if the water table is near the surface or a slurry drilling process is used.

11.3.1 Instrumentation

Performing a transfer mobility test requires specialized equipment. Most of the equipment is readily available from several commercial sources. Commercially available load cells can be used as the force transducer. For borehole testing, the load cells must be hermetically sealed and capable of being used at the bottom of a 30 to 100 foot deep hole partially filled with water. A typical instrumentation array for the field testing and laboratory analysis of transfer mobility is shown in Figure 11-7. The force transducer should be capable of impact loads of 5,000 to 10,000 lb. Either accelerometers or geophones can be used as the vibration transducers. The requirement is that the transducers with the associated amplifiers be capable of accurately measuring levels of 0.0001 in./sec at 40 Hz and have a flat frequency response from 6 Hz to 400 Hz. The tape recorder also must have a flat response over the 6 to 400 Hz frequency range. Adequate low-frequency response usually requires either an instrumentation-quality FM recorder or a digital recorder. The response of most normal direct-record tape recorders is inadequate at frequencies below about 30 Hz.

The narrowband spectrum analyzer is the key element of the laboratory instrumentation. The analyzer must be capable of capturing impulses from at least two channels and calculating the frequency spectrum of the transfer function between the force and vibration channels. All transfer functions should include the average of at least 20 impulses. The averaging of the impulses will provide significant signal enhancement, which is usually required to accurately characterize the transfer function. Signal enhancement is particularly important when the vibration transducer is more than 100 ft from the impact.

The laboratory array in Figure 11-7 shows the spectrum analyzer interfaced with a computer. The computer is usually required to adapt the narrowband transfer function data into a format suitable for evaluation of 1/3 octave band transfer mobility. The raw transfer function data usually include several hundred frequency bands. By transforming a narrowband spectrum into a 1/3 octave band spectrum, each spectrum is reduced to 15 to 20 bands. This step reduces the amount of data that must be evaluated to develop the generalized curves. There are specialized multi-channel spectrum analyzers which have built-in capabilities that are sufficient for this data analysis.

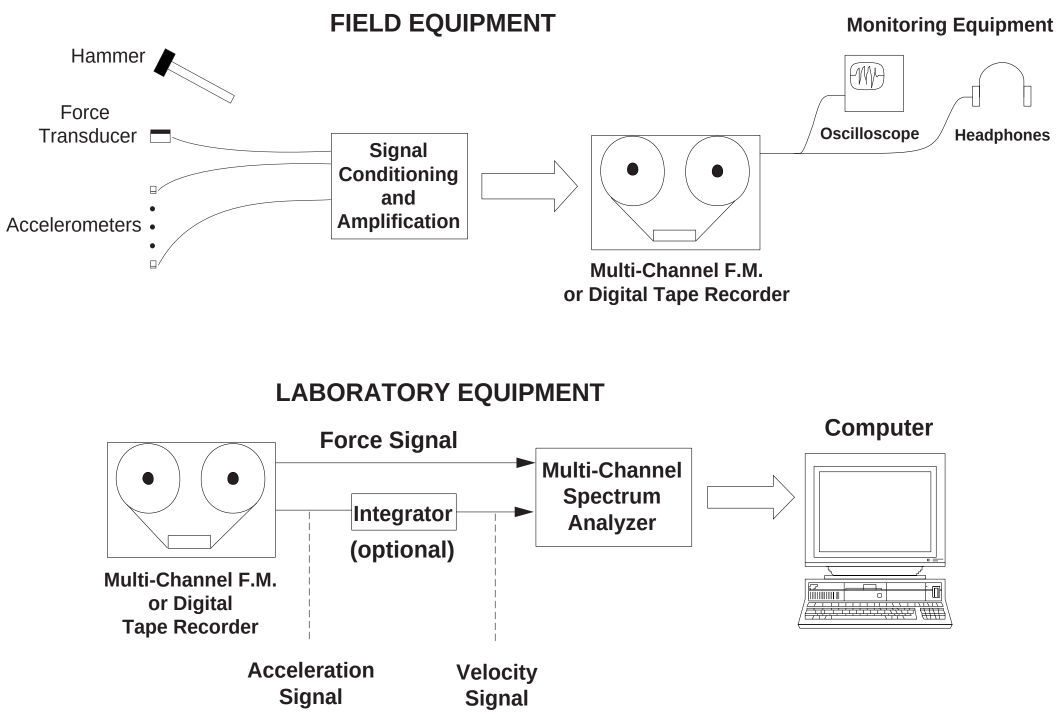

Figure 11-7 Equipment Required for Field Testing and Laboratory Analysis

11.3.2 Analysis of Transfer Mobility Data

Two different approaches have been used to develop estimates of line-source transfer mobility. The first consists of using lines of transducers and the second consists of a line of impact positions. The steps to develop line-source transfer mobility curves from tests using one or more lines of transducers are shown in Figure 11-8. The procedure starts with the narrowband transfer function between source and receiver at each measurement position. There should be a minimum of four distances in any test line. Because of the possibility of local variations in propagation characteristics, if at all possible, two or more lines should be used to characterize a site. A total of 10 to 20 transducer positions are often used to characterize a site. Assuming that the spectrum analyzer calculates 400 line narrowband transfer functions for each position, this means a total of 4,000 to 8,000 numbers for each site.

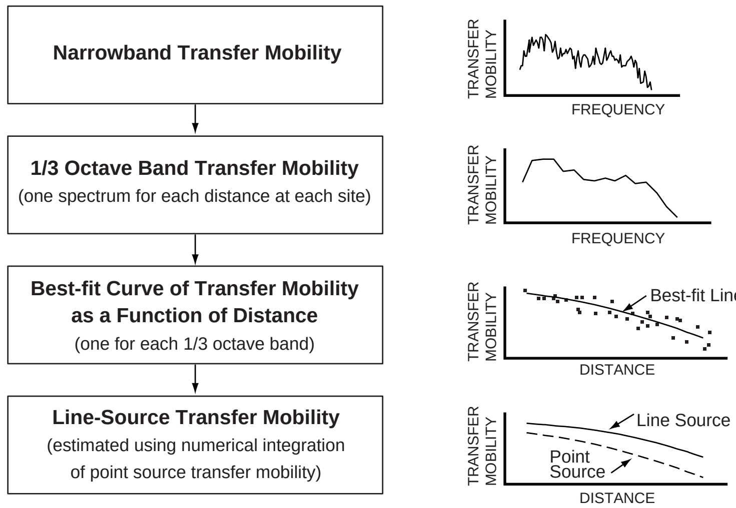

Figure 11-8 Analysis of Transfer Mobility

The first step in the analysis procedure is to calculate the equivalent 1/3 octave band transfer functions. This reduces each spectrum from 400 to 15 numbers. As shown in Figure 11-8, the 1/3 octave band spectrum is much smoother than the narrow-band spectrum. The next step is to calculate a best-fit curve of transfer mobility as a function of distance for each 1/3 octave band. When analyzing a specific site, the best-fit curve will be based on 10 to 20 points. Up to several hundred points could be used to determine average best-fit curves for a number of sites.

The 1/3 octave band best-fit curves can be directly applied to point vibration sources. Buses can usually be considered to be point sources. However, for a line vibration source such as a train, numerical integration must be used to calculate an equivalent line source transfer mobility. The numerical integration procedures are detailed in Reference 4.

The second procedure for estimating line-source transfer mobility, shown schematically in Figure 11-9, is best for detailed assessment of specific vibration paths or specific buildings. The vibration transducers are located at specific points of interest and a line of impacts is used. For example, a 200 foot train might be represented by a line of 21 impact positions along the track centerline at 10 foot intervals. It is possible to sum the point source results using Simpson's rule for numerical integration to directly calculate line-source transfer mobility. This is a considerably more direct approach than is possible with lines of vibration transducers.

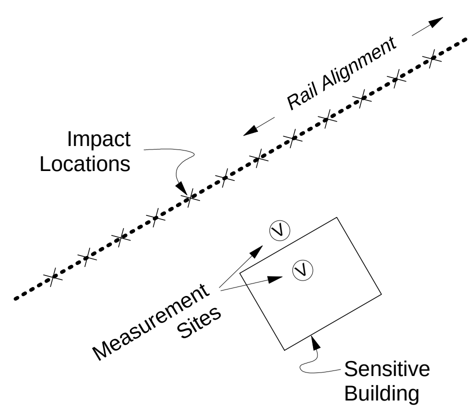

Figure 11-9 Schematic of Transfer Mobility Measurements Using a Line of Impacts

11.3.3 Deriving Force Density

Force Density is not a quantity that can be measured directly, it must be inferred from measurements of transfer mobility and train vibration at the same site. For deriving force density, deriving line-source transfer mobility from a line of impacts gives the best results. The force density for each 1/3 octave band is then simply:

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

where L_F is the force density, L_v is measured train ground-borne vibration and TM_{line} is the line source transfer mobility. The standard approach is to use the average force density from measurements at three or more positions.

11.4 ASSESSMENT OF VIBRATION IMPACT

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

The assessment of vibration impact should proceed according to the following steps:

1. Screen the entire proposed transit alignment to identify areas where there is the potential of impact from ground-borne vibration. The vibration screening method is described in Chapter 9. If no sensitive land uses are within the screening distances, it is not necessary to perform any further assessment of ground-borne vibration.

2. Define the curves of ground-surface vibration level as a function of distance that can be used with the General Assessment. Usually this will mean selecting the appropriate curve from Chapter 10 for the proposed transit mode. For less common transit modes, it may be necessary to make measurements at an existing facility.

3. Use the General Assessment Procedure to estimate vibration levels for specific buildings or groups of buildings. The projected levels are compared with the impact criteria given in Chapter 8 to determine whether vibration impact is likely. The goal of this step is to develop a reasonably accurate catalog of the buildings that will experience ground-borne vibration or noise levels that exceed the criteria. It is generally best to make a conservative assessment of the impact. That is, it is better to include some buildings that may not be impacted than to exclude some buildings that are likely to be impacted. In locations where General Assessment indicates impact, the more refined techniques of Detailed Analysis would be employed.

4. In some cases it will be necessary to perform a vibration survey to characterize existing ambient vibration. As discussed in Section 11.1, although knowledge of the existing ambient vibration is not

generally required to evaluate vibration impact, there are times when a survey of existing conditions is valuable. One common example is when the rail project will be located in an existing rail right-of-way shared by freight trains. Chapter 8 includes some guidelines on how to account for existing vibration that is higher than the impact limit for the project vibration.

5. For the areas where the impact criteria may be exceeded, review potential mitigation measures and assemble a list of feasible approaches to vibration control. To be feasible, the measure, or combination of measures, must be capable of providing a significant reduction of the vibration levels, at least 5 dB, while being reasonable from the standpoint of the added cost. Because vibration control is frequency-dependent, specific recommendations of vibration control measures can be made only after evaluating the frequency characteristics of the vibration.

6. Use the Detailed Vibration Analysis to develop detailed vibration mitigation measures. It is usually necessary to project vibration spectra at buildings which will be affected at levels higher than the impact thresholds. This type of assessment is normally performed as part of the final design rather than during the environmental impact assessment stage. Because a Detailed Analysis is more accurate than a General Assessment, there will be times that the Detailed Analysis will show that the vibration and noise levels will be below the applicable criteria and that mitigation is not required. If the projected levels are still above the limits, the spectra provided by the Detailed Analysis will be needed to evaluate vibration control approaches.

11.5 VIBRATION MITIGATION

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

The discussion in this section focuses on rail systems, the source of most problems with ground-borne vibration. When buses do cause annoying ground-borne vibration, it is usually clear that the source of the problem is roadway roughness or unevenness caused by bumps, pot holes, expansion joints, or driveway transitions. Smoothing the roadway surface will usually solve the problem.

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

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

Maintenance – As discussed above, effective maintenance programs are essential for controlling ground-borne vibration. When the wheel and rail surfaces are allowed to degrade the vibration levels can increase by as much as 20 dB compared to a new or well maintained system. Some maintenance procedures that are particularly effective at avoiding increases in ground-borne vibration are:

- Rail grinding on a regular basis. Rail grinding is particularly important for rail that develops corrugations.
- Wheel truing to re-contour the wheel, provide a smooth running surface and remove wheel flats. The most dramatic vibration reduction results from removing wheel flats. However, significant improvements also can be observed simply from smoothing the running surface.
- Implement vehicle reconditioning programs, particularly when components such as suspension system, brakes, wheels, and slip-slide detectors will be involved.
- Install wheel-flat detector systems to identify vehicles which are most in need of wheel truing.

Planning and Design of Special Trackwork – A large percentage of vibration impact from a new transit facility is often caused by wheel impacts at the special trackwork for turnouts and crossovers. When feasible, the most effective vibration control measure is to relocate the special trackwork to a less vibration-sensitive area. Sometimes this requires adjusting the location by several hundred feet and will not have a significant adverse impact on the operation plan for the system. Careful review of crossover and turnout locations during the preliminary engineering stage is an important step to minimizing potential for vibration impact. Another approach is to use special devices at turnouts and crossovers, special "frogs," that incorporate mechanisms to close the gaps between running rails. Frogs with spring loaded mechanisms and frogs with movable points can significantly reduce vibration levels near crossovers.

Vehicle Specifications – The ideal rail vehicle, with respect to minimizing ground-borne vibration, should have a low unsprung weight, a soft primary suspension, a minimum of metal-to-metal contact between moving parts of the truck, and smooth wheels that are perfectly round. A limit for the vertical resonance frequency of the primary suspension should be included in the specifications for any new vehicle. A vertical resonance frequency of 12 Hz or less is sufficient to control the levels of ground-borne vibration. Some have recommended that transit vehicle specifications require that the vertical resonance frequency be less than 8 Hz.[15]

Special Track Support Systems – When the vibration assessment indicates that vibration levels will be excessive, it is usually the track support system that is changed to reduce the vibration levels. Floating slabs, resiliently supported ties, high resilience fasteners, and ballast mats have all been used in subways to reduce the levels of ground-borne vibration. To be effective, all of these measures must be optimized for the frequency spectrum of the vibration. Most of these relatively standard procedures have been successfully used on several subway projects. Applications on at-grade and elevated track are less common. This is because vibration problems are less common for at-grade and elevated track; cost of the vibration control measures is a higher percentage of the construction costs of at-grade and elevated track; and exposure to the elements can require significant design modifications.

Each of the major vibration control measures for track support is discussed below:

- Resilient Fasteners: Resilient fasteners are used to fasten the rail to concrete track slabs. Standard resilient fasteners are very stiff in the vertical direction, usually in the range of 200,000 lb/in., although they do provide vibration reduction compared to some of the rigid fastening systems used on older systems (e.g., wood half ties embedded in concrete). Special fasteners with vertical stiffness in the range of 30,000 lb/in. will reduce vibration by as much as 5 to 10 dB at frequencies above 30 to 40 Hz.

- Ballast Mats: A ballast mat consists of a rubber or other type of elastomer pad that is placed under the ballast. The mat generally must be placed on a concrete pad to be effective. They will not be as effective if placed directly on the soil or the sub-ballast. Consequently, most ballast mat applications are in subway or elevated structures. Ballast mats can provide 10 to 15 dB attenuation at frequencies above 25 to 30 Hz. Ballast mats are often a good retro-fit measure for existing tie-and-ballast track where there are vibration problems.

- Resiliently Supported Ties: The resiliently supported tie system consists of concrete ties supported by rubber pads. The rails are fastened directly to the concrete ties using standard rail clips. Existing measurement data indicate that resiliently supported ties may be very effective in reducing low-frequency vibration in the 15 to 40 Hz range. This makes them particularly appropriate for transit systems with vibration problems in the 20 to 30 Hz range.

- Floating Slabs: Floating slabs can be very effective at controlling ground-borne vibration and noise. They basically consist of a concrete slab supported on resilient elements, usually rubber or a similar elastomer. A variant that was first used in Toronto and is generally referred to as the double tie system, consists of 5-foot-long slabs with 4 or more rubber pads under each slab. Floating slabs are effective at frequencies greater than their single-degree-of-freedom vertical resonance frequency. The floating slabs used in Washington DC, Atlanta, and Boston were all designed to have a vertical resonance in the 14 to 17 Hz range. A special London Transport floating slab that is under the Barbican Redevelopment uses a very heavy design with a resonance frequency in the 5 to 10 Hz frequency range.[16] The primary disadvantage of floating slabs is that they tend to be the most expensive of the vibration control treatments.

- Other Marginal Treatments: Changing any feature of the track support system can change the levels of ground-borne vibration. Approaches such as using heavier rail, thicker ballast, or heavier ties can be expected to reduce the vibration levels. There also is some indication that vibration levels are lower with wood ties compared to concrete ties. However, there is little confirmation that any of these approaches will make a significant change in the vibration levels. This is unfortunate since modifications to the ballast, rails, or ties are virtually the only options for normal at-grade, tie-and-ballast track without resorting to a different type of track support system or widening the right-of-way to provide a buffer zone.

Building Modifications – In some circumstances, it is practical to modify the impacted building to reduce the vibration levels. Vibration isolation of buildings basically consists of supporting the building foundation on elastomer pads similar to bridge bearing pads. Vibration isolation of buildings is seldom an option for existing buildings; normal applications are possible only for new construction. This approach is particularly important for shared-use facilities such as office space above a transit station or terminal. When vibration-sensitive equipment such as electron microscopes will be affected by transit vibration, specific modifications to the building structure may be the most cost-effective method of controlling the impact. For example, the floor upon which the vibration-sensitive equipment is located could be stiffened and isolated from the remainder of the building to reduce the vibration.

Trenches – Use of trenches to control ground-borne vibration is analogous to controlling airborne noise with sound barriers. Although this approach has not received much attention in the U.S., there are cases where a trench can be a practical method for controlling transit vibration from at-grade track. A rule-of-thumb given by Richert and Hall[(17)] is that if the trench is located close to the source, the trench bottom must be at least 0.6 times the Rayleigh wavelength below the vibration source. For most soils, Rayleigh waves travel at around 600 ft/sec which means that the wavelength at 30 Hz is 20 ft. This means that the trench must be approximately 15 ft deep to be effective at 30 Hz.

A trench can be effective as a vibration barrier if it is either open or solid. The Toronto Transit Commission did a test with a trench filled with styrofoam to keep it open. They reported successful performance over a period of at least one year.[(18)] Solid barriers can be constructed with sheet piling or concrete poured into a trench.

Operational Changes – The most obvious operational change is to reduce the vehicle speed. Reducing the train speed by a factor of two will reduce vibration levels approximately 6 dB. Other operational changes that can be effective in special cases are:

- Use the equipment that generates the lowest vibration levels during the nighttime hours when people are most sensitive to vibration and noise.
- Adjust nighttime schedules to minimize movements in the most sensitive hours.

While there are tangible benefits from speed reductions and limits in operations during the most sensitive time periods, these types of measures may not be practical from the standpoint of service requirements. Furthermore, vibration reduction achieved through operating restrictions requires continuous monitoring and will be negated if vehicle operators do not adhere to established policies.

Buffer Zones – Expanding the rail right-of-way sometimes will be the most economical method of controlling the vibration impact. A similar approach is to negotiate a vibration easement from the affected property owners.

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