A Prediction Procedure for Rail Transportation Groundborne Noise and Vibration

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A procedure has been developed for predicting groundborne noise and vibration caused by rail transportation systems. The primary focus is the estimation of low-level, low-frequency groundborne noise and vibration between 6.3 and 200 Hz in residential and commercial buildings near at-grade and subway track. Two particular features of the method are the use of impact-testing procedures to characterize vibration propagation in soils and the use of $^1/_3$ octave band force densities to represent specific vehicle and track systems. Directions for future research are discussed, including numerical modeling of subway structures and vibration propagation in soils, truck and track dynamics, and propagation of vibration through buildings.

A prediction procedure for groundborne noise and vibration from rail transportation systems has been developed by Wilson, Ihrig and Associates, Inc. (WIA), funded by the Transportation Systems Center of the U.S. Department of Transportation (DOT/TSC). The work included a literature review of the existing state of the art as of 1980 (1, 2), numerical and theoretical modeling of transit vehicle trucks and subway-soil interaction, and extensive field experimental work. Contributions to the project were made by London Transportation International as subcontractor to WIA in performance of the literature review and initial development of testing procedures (3–5).

The primary focus of the method is estimating low-level groundborne noise and vibration between 6.3 and 200 Hz for a variety of building types, soil conditions, and transit system designs. Resilient direct-fixation (DF) fasteners, floating slab track, resiliently supported ties, continuous welded rail, vehicle suspensions, and other design features of a rail transportation or subway system are considered. A major feature of the method is the use of normalized $^1/_3$ octave band vibration force densities to represent the vibration source characteristics of vehicle and track systems. Predictions may be made for vehicles with different truck suspension systems and different soil conditions. The method hinges on the use of $^1/_3$ octave band line source responses measured by an impact-testing technique and standard transfer function analysis of force and response velocity data. The result is a comprehensive prediction procedure that may be used as a design tool for rail transportation system design.

Although a discussion of a comprehensive prediction procedure is not complete without discussion of suitable criteria, the focus of this paper will be limited to predicting vibration. A complete discussion of criteria for groundborne noise and vibration is presented elsewhere (1).

NATURE OF GROUNDBORNE NOISE AND VIBRATION

Groundborne noise and vibration in buildings consist of low-frequency rumbling noise and perceptible vibration with possibly secondary noise generation, such as rattling windows, picture frames, plates, and so on. Groundborne noise and vibration have caused varying degrees of community reaction at several systems, such as the Toronto Transit Commission (TTC), Washington Metropolitan Area Transit Authority (WMATA), New York City Transit Authority (NYCTA), and the Metropolitan Atlanta Rapid Transit Authority (MARTA) (1, 2). In some isolated cases, litigation over ground vibration impact has delayed construction of new subway sections, with substantial financial impact. In Toronto, groundborne noise has been heard in basements up to several hundred feet from the Yonge Subway Northern Extension (YSNE) tunnel (6). "Perceptible" ground vibration produced by trains on at-grade ballast-and-tie track is more significant than vibration from subway track.

As a result of these experiences, groundborne noise and vibration from rail transit systems and also railroads have become significant factors in designing and locating new subways and at-grade track. For example, as a result of the experience gained with the YSNE tunnel, TTC adopted the policy of providing floating slab track vibration isolation throughout new subway constructions. Floating slabs are a major design feature of the WMATA system in Washington, D.C., the MARTA system in Atlanta, and the Baltimore Region Rapid Transit (BRRT) system. As a result of the high capital cost of providing vibration control provisions at new systems and retrofit of old systems, the need for an accurate and reliable prediction procedure developed.

MAJOR FACTORS

Groundborne noise and vibration are influenced by the following major factors:

- Wheel and rail roughness
- Truck design

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- Subway-soil interaction
- Propagation in soil
- Building foundation response
- Vibration propagation in buildings
- Room acoustics

Wheel and rail roughness is assumed to be the major cause of wheel and rail forces (7). To this might be added inhomogeneities in the material properties of the wheels and rails, imbalance of truck rotating components, and the effect of fastener or cross-tie spacing. Trains running on jointed rail and special trackwork produce vibration levels 5 to 10 dB higher than trains running on continuous welded rail, and rail corrugation will seriously degrade the performance of continuous welded rail in maintaining low levels of vibration (8).

The magnitude of the wheel and rail forces resulting from wheel and rail roughness is strongly controlled by the dynamic characteristics of the truck. One of the single most significant truck design parameters affecting groundborne vibration in the range of 8 to 30 Hz is the primary suspension stiffness and corresponding primary suspension resonance frequency. Tests conducted at the Transportation Test Center in Pueblo, Colorado, reveal that trucks with chevron suspensions exhibiting a primary resonance frequency of 8 Hz produce as much as 15 dB lower ground vibration levels between 16 and 30 Hz than do trucks with elastomer journal bushing suspensions exhibiting a primary resonance frequency in excess of 20 Hz.

Track design has a substantial effect on groundborne noise and vibration. The track support system includes ballast-and-tie track, resilient DF fasteners, or, where substantial vibration isolation is required, floating slab track. Lowering the rail support stiffness usually produces lower levels of vibration at frequencies above, perhaps, 30 Hz. Too high a rail support stiffness may not only give poor isolation, but may contribute to excessive rail corrugation and thus excessive vibration and noise.

Vibration forces transmitted to the ground or subway invert cause vibration to be radiated into the surrounding soil. Interaction between the soil and subway structure influences vibration over a broad frequency range, especially in the case of heavy cut-and-cover subways. For rock tunnels, the effect of the tunnel structure is less significant than it is for soil-founded tunnels. However, below 30 to 60 Hz, vibration from rock tunnels tends to be 10 to 20 dB lower than from soil tunnels because of the high stiffness of the rock relative to that of soil. Vibration from ballast-and-tie at-grade track is higher at low frequencies than vibration from either soil or rock tunnels, especially within 50 ft of the track (1, 2).

Vibration attenuates with increasing distance between source and receiver because of energy spreading and dissipation in the soil. Layering in the soil greatly complicates simple analytical modeling of attenuation with distance. For typical train lengths and source–receiver distances, the train is an incoherent line source, giving a 3-dB spreading loss per doubling of source–receiver distance for shear and compression waves in the ground, and no spreading loss for surface Rayleigh waves. In the case of a shallow soil layer overlying rock, most of the vibration energy may be concentrated in the upper layer, with little or no spreading loss.

In almost all the measurements performed under this project, the observed wave group velocities indicate that the predominant carriers of vibration energy are shear waves or Rayleigh surface waves, or both. Compression waves, though attenuating at a relatively lower rate, are not significant at typical source–receiver distances and at frequencies below about 50 to 100 Hz.

Excess attenuation due to dissipation in saturated or partially saturated layered soils is difficult to model. Most of the data collected in this study suggest that for typical situations attenuation of the level of vibration in decibels is roughly proportional to the logarithm of the source–receiver distance. Although this is inconsistent with usual models of dissipation, similar observations have been made by other researchers (9).

A building foundation's response to incident ground vibration is a complicated function of foundation mass and geometry, soil characteristics, and type and direction of incident vibration. The most practical way to handle the foundation response is by an experimentally or numerically determined "coupling loss," representing the vibration response of the foundation relative to ground surface vibration in the absence of the foundation or structure. Slab-on-grade floors have little or no coupling loss, whereas deep friction pile foundations may exhibit a substantial coupling loss with respect to ground surface vibration. Foundations supported on piers imbedded in stiff soil layers or rock have lower responses than do floating foundations or slab-on-grade floors. On the other hand, direct connections to rock may increase the transmission of high-frequency vibration from rock and mixed-face subways. Massive foundations tend to respond less to incident ground vibration at high frequencies than do foundations with a small ratio of foundation mass to soil-bearing surface area. Amplification of ground vibration due to resonance can occur for heavy foundations with a large ratio of mass to soil-bearing surface areas.

An attenuation of 1 to 3 dB per floor is typical for vibration as it travels to upper floor levels. The attenuation is due to dissipation in the floor and splitting of vibration energy at each floor-wall joint. Data reported by Ishii and Tachibana (10) indicate that near the top of a large building, the floor-to-floor attenuation is less than it is near the ground. Vibration is amplified by resonances of the floors and walls at resonance frequencies.

Vibrating walls, floors, and ceilings radiate noise into rooms, and rooms with a large amount of absorption, provided by carpeting, drapes, and furniture, have lower levels of noise than "live" rooms with very little absorption. At very low frequencies, the relationship between sound pressure level (SPL) and wall vibration velocity is controlled by the bulk air stiffness, size of the room, and leakage (11).

PREDICTION PROCEDURE

Early during the course of the study, a need for normalizing measured ground vibration data and removing the effects of soil characteristics and source–receiver distance became apparent. Vibration data collected in one city were being used for estimating vibration at another city in spite of the fact that different vehicles were being used and different geological

conditions existed. Ground vibration in Toronto along the TTC is entirely different in character from that at BART in San Francisco or at WMATA in Washington, D.C. Accordingly, the prediction method attempts to separate these various factors by using impact-testing procedures for quantifying the vehicle and trackbed vibration forces and the vibration response of the ground. The remaining aspects of the prediction problem—building foundation, structural responses, and noise—have been dealt with in the same way as in previous methods *(1)*. The problem is reduced to estimating ground surface vibration in the absence of buildings. Once ground surface vibration estimates have been obtained, generic curves for coupling losses, floor resonance corrections, and so on, can be applied.

There are four major steps in the prediction procedure:

1. Selection of a trackbed force density,
2. Application of a line source response,
3. Calculation of building response, and
4. Calculation of noise

These steps are described individually in the following sections.

Force Density

The fundamental starting point is the $1/3$ octave trackbed vibration force density, or simply force density. The unit of force density is force divided by the square root of train length,

represented in decibels re 1 $lb/(ft)^{1/2}$. The force density represents an incoherent line source of vibration forces for the transit vehicle and the track support system.

Force densities have been developed from tests with two light rail and two heavy rail vehicles at the Transportation Test Center in Pueblo, Colorado; from tests at BART in a cut-and-cover subway with DF fasteners; and from tests in San Diego and San Francisco with light rail vehicles. More recently, force densities have been developed for the BART and MARTA vehicle on at-grade ballast-and-tie and resilient DF track.

Figure 1 shows the trackbed force density for modern transit trains with elastomer journal bushing and chevron primary suspension systems on ballast-and-tie and subway DF fastener track. These data clearly indicate the advantage of representing individual vehicle types with specific force densities to account for differences of as much as 10 to 15 dB.

Adjustments are added to the trackbed force density if the measured force density does not correspond to the actual design track configuration, strain speed, and so on. Adjustments (not discussed here) are provided for resilient DF fasteners, floating slabs, ballast mats, primary suspension stiffness, and so on.

Line Source Response

The second major element in the prediction procedure is the $1/3$ octave band line source response, which is the ground vibration velocity level at the receiver point relative to the
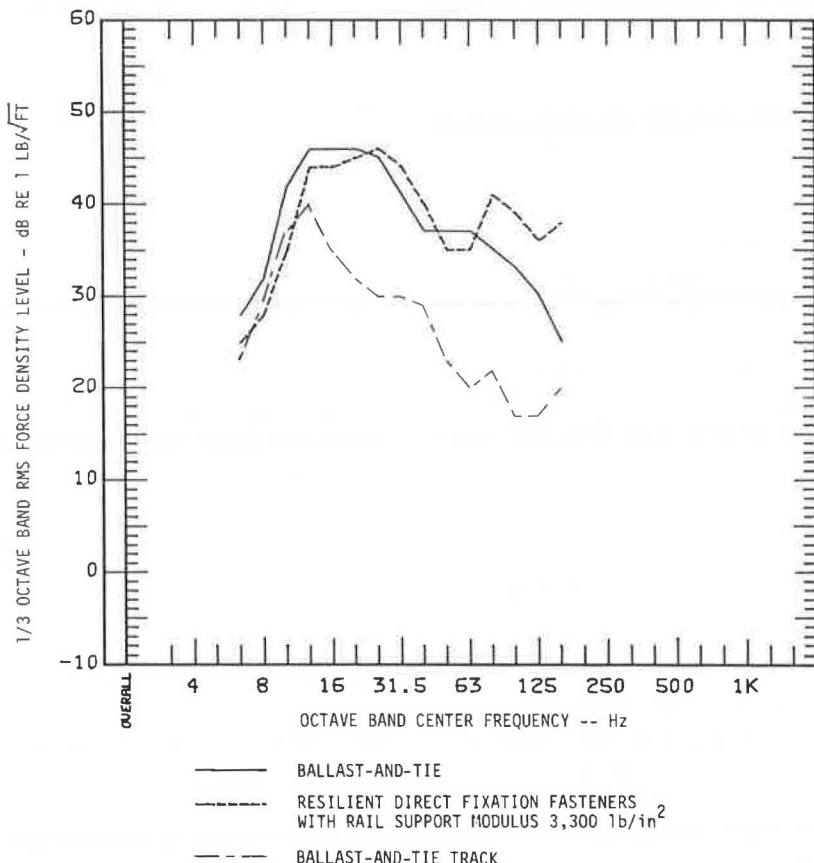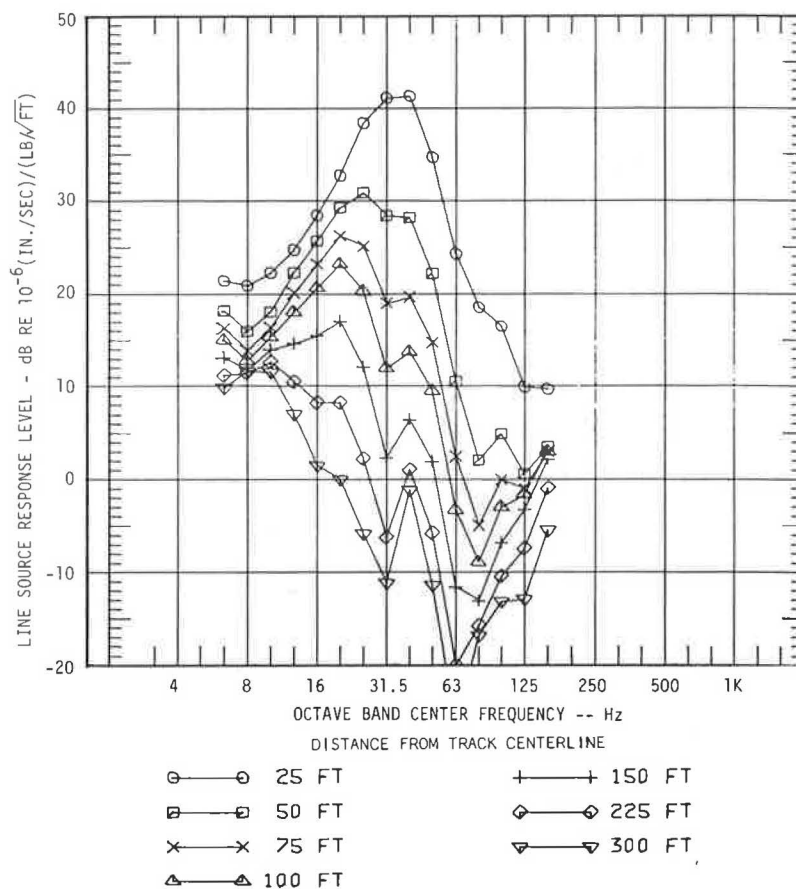

FIGURE 1   Force densities for heavy rail transit vehicles.

FIGURE 2   Line source response for BART Concord line ballast-and-tie track drive for a source length of 400 ft.

vibration force density level in decibels re (1 micro-in./sec)/ [lb/(ft)$^{1/2}$]. One of the significant innovations of the study is the development of a field-testing procedure for determining line source responses by measuring the transfer mobilities from the subway invert to the ground surface, from the bottom of a borehole to the ground surface, or between two points on the ground surface. Numerical regression and integration methods are used to convert the two-point transfer mobilities to the line source response.

Line source responses are used to normalize measured train passby vibration data to obtain the force density estimates introduced earlier. The line source response is thus the key to applying the prediction procedure to transit systems with widely varying train types and soil conditions.

To date, line source responses have been measured at San Francisco's BART and MUNI systems, the MARTA system in Atlanta, the San Diego Trolley, the Guadalupe Corridor light rail system in San Jose, the proposed Los Angeles Southern California Regional Transit District (SCRTD) system, and the Transportation Test Center in Pueblo, Colorado. Recently, line source responses were measured in Carbondale, Illinois, to assess the vibration impact resulting from lowering a railroad about 15 to 20 ft below grade, at the BRRT system in Baltimore to assess vibration impact in the operating theaters of hospitals located near the proposed subway alignment, and along the proposed alignment for the DART system in Dallas.

Figure 2 provides examples of 1/3 octave band line source responses for at-grade track at various source–receiver distances, measured along the BART Concord line with impact-testing procedures. These line source response curves may be contrasted with those in Figure 3 for a BART cut-and-cover double box structure at the Oakland approach to the transbay tube. These two sets of data clearly illustrate a wide disparity between line source responses for at-grade track and subway structures.

Building Vibration Response

The response of buildings to incident groundborne vibration is considered in three parts:

- Foundation coupling loss
- Floor resonance amplification
- Floor-to-floor attenuation

The approach presented in the *Handbook of Urban Rail Noise and Vibration Control* (*12*) has been adopted for estimating building responses. The approach has been used for many transit systems and is based on a variety of groundborne noise and vibration measurements performed over the years, most notably at the Toronto Transit System.
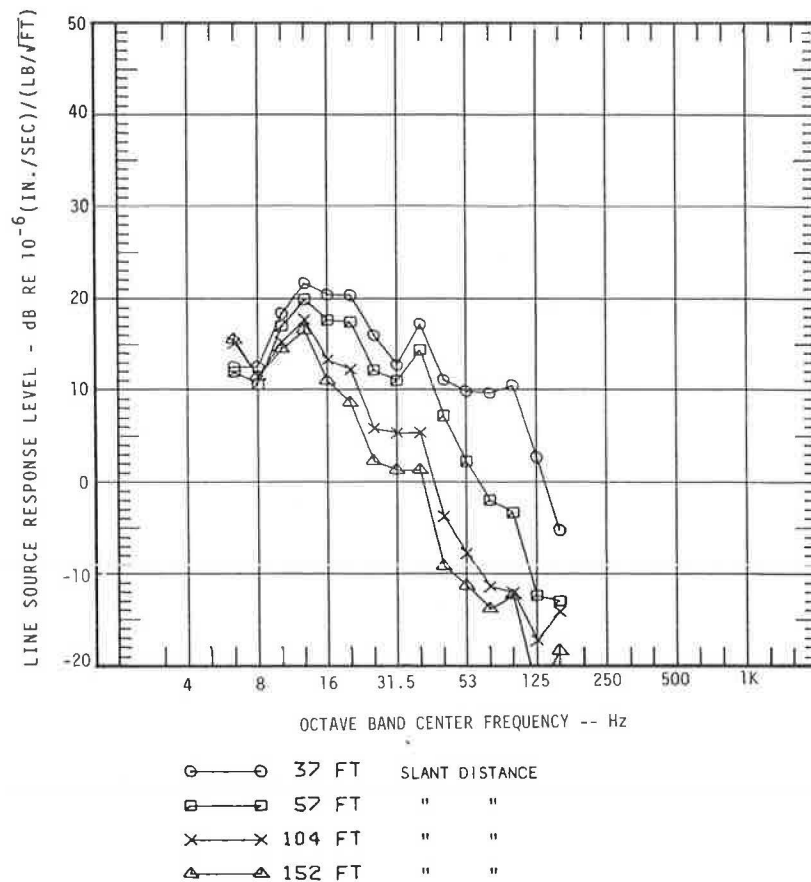
FIGURE 3 BART double box subway line source response for source length of 600 ft (subway depth = 27 ft).

One-third octave band foundation responses are shown in Figure 4. The foundation response is the level of actual foundation vibration relative to the level of incident ground surface vertical vibration that would exist in the absence of the building structure and its foundation. The appropriate response is added to the estimated ground surface vibration levels to estimate building foundation vibration. No correction is applied to the ground surface vibration to estimate basement floor and wall vibration or vibration of slab-on-grade floors.

A range of amplification due to floor resonances is shown in Figure 5. Well below the fundamental floor resonance frequency, little or no amplification may occur, whereas above the resonance frequency a number of vibration modes exist, each mode potentially producing an amplified response. For wood-frame structures, the first bending mode frequency is 8 to 16 Hz, whereas for reinforced-concrete waffle slab floors, the first bending mode frequency may be as high as 20 or 25 Hz. Floor surface areas are generally larger than wall surface areas and thus may have lower bending mode frequencies than do walls.

Noise Generation

The final step in the procedure is the prediction of noise in rooms. Ungar and Bender provide an analysis of the interior room noise due to bending waves in walls, floors, and ceilings *(11)*. For the purposes of this study, the following relation may be used for converting $^1/_3$ octave or $^1/_1$ octave band vibration levels to noise levels.

$$SPL = L_v - 10 \log(a) - 1 \qquad (1)$$

where

SPL = sound pressure level (dB re 20 micropascals),
L_v = vibration velocity level (dB re 1 micro-in./sec), and
a = absorption coefficient.

An alternative approach is to apply the range of observed difference between floor vibration and interior noise (Figure 6) on the basis of measurements in Toronto of simultaneous rail transit groundborne noise and vibration in buildings *(13)*. The theoretical conversion based on the foregoing formula is comparable with the range of observed differences.

Margin of Error

The predicted levels are "best estimates" of the $^1/_3$ octave band levels, and no margin of error is included. For design review and recommendation of noise and vibration control provisions, some safety factor should be applied. At this time, about 5 to 10 dB should be added to the predicted levels to protect the major part of the potential receivers. The method is most accurate in the critical frequency range of about 8 to 30 Hz, where the primary suspension resonance frequencies usually occur and where attenuation in soil is least.
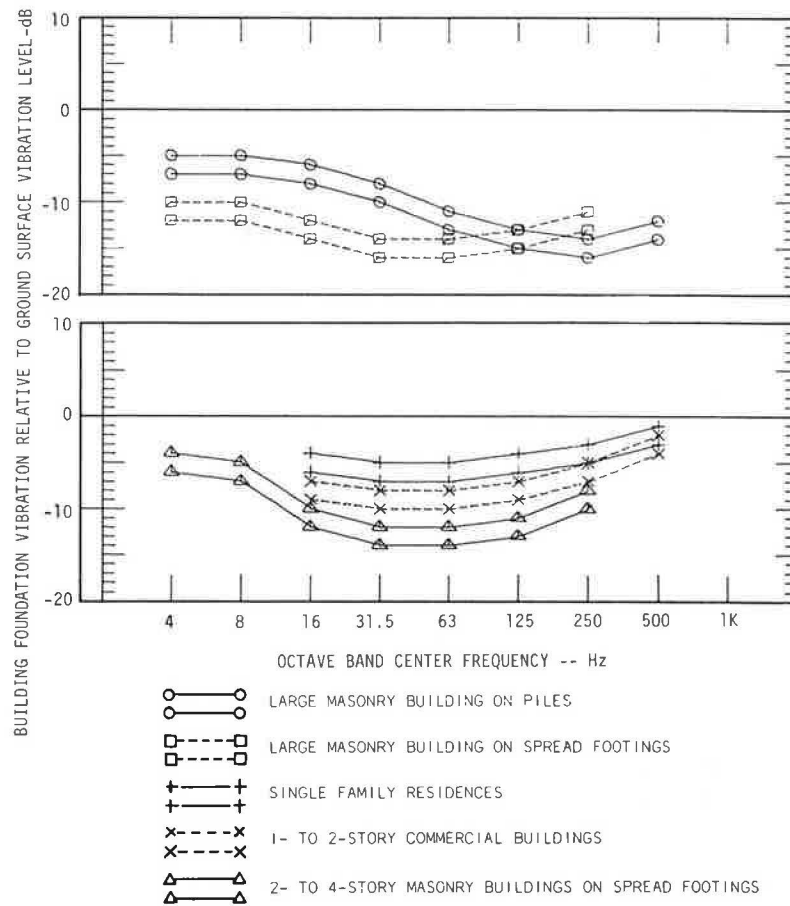
FIGURE 4 Foundation responses for various types of buildings.
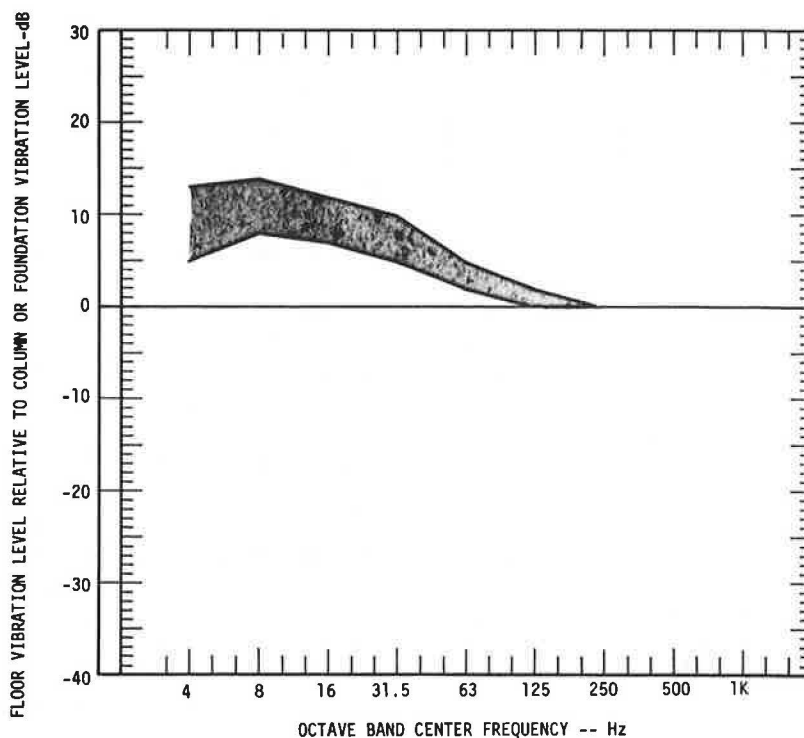
FIGURE 5 Corrections to be added to expected vibration level because of floor vibration amplification.
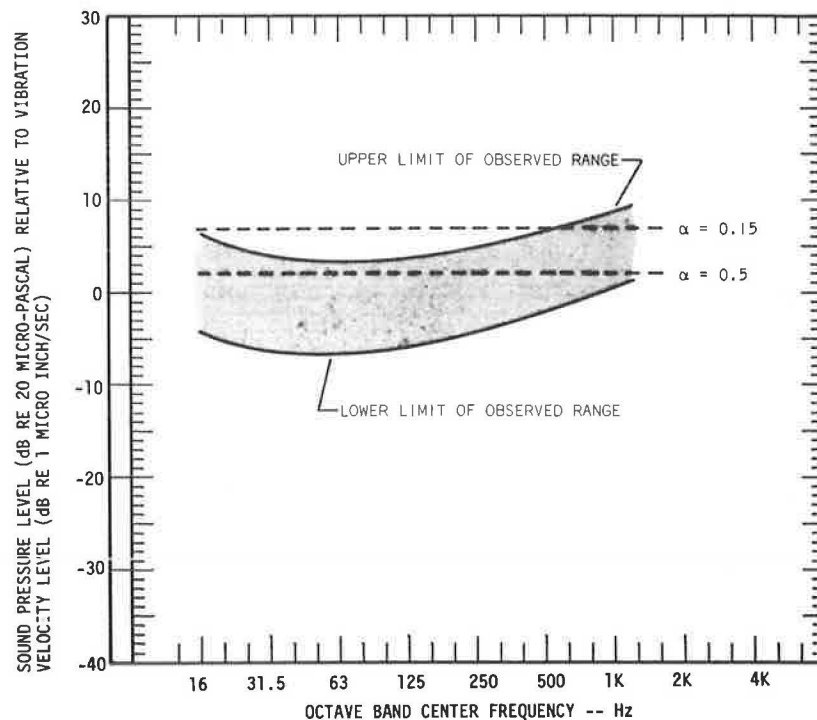
FIGURE 6 Room interior sound pressure level relative to average floor vibration velocity.

LINE SOURCE RESPONSE DETERMINATION

The line source response is a pivotal feature of the groundborne vibration prediction procedure: it provides the connection between the force density and ground vibration at receiver locations and allows normalizing wayside vibration data to remove effects of propagation and attenuation and obtain the trackbed force density, which is the starting point of the prediction procedure. Thus, measurement of the line source response is crucial for supporting the prediction method. By performing field tests, site-specific predictions of ground vibration can be made.

Line source responses can be measured practically. The costs for performing such tests are a small fraction of the capital costs of floating slab vibration isolation provisions, which might be saved if detailed testing indicates that such provisions are unnecessary at even a few locations. The testing procedure is also similar in scope to seismic refraction surveys.

There are five basic steps for measuring the line source response:

1. Measurement of transfer mobilities (Green's functions) between a source and several receiver locations,

2. Conversion of transfer mobility magnitudes to ⅓ octave band frequency responses via energy averaging over each ⅓ octave,

3. Regression analysis of ⅓ octave band transfer mobility levels versus distance,

4. Integration (energy sum) of point source regression curves over train length to obtain line source responses at representative distances from the track centerline, and

5. Regression analysis of line source response levels versus distance.

The transfer mobility is the ratio of the magnitude of a sinusoidal velocity response at a receiver point to the magnitude of a sinusoidal driving force at an input point, expressed as a function of frequency.

Steps 2 through 5 are performed with a computer, without which the procedure would be tedious and easily subject to error. The result of the final step is a polynomial approximation of the line source response level versus distance. The technique also provides a direct measure of the rate of attenuation of vibration with distance.

To measure the transfer mobility, or Green's function, the ground or subway invert is struck with an instrumented hammer and the input force and resulting vibration responses at distances up to 300 ft from the hammer are recorded for laboratory analyses. For predictions along proposed subway alignments, the impact is at the bottom of a borehole drilled to the approximate depth of the proposed subway structure. For at-grade track the impact is delivered at ground surface. Where subways exist and are accessible, impacts at the invert provide a direct measure of the line source response for the structure and soil combination; otherwise a subway-borehole correction must be used to convert borehole test results to line source responses for subways. The line source responses shown in Figures 2 and 3 are the direct result of this measurement procedure.

The underlying assumption for borehole testing is that subway line source responses vary similarly with borehole line source responses as functions of depth, soil stiffness, and dissipation. A correction is applied to the borehole test results to account for soil-structure interaction; this is the subway
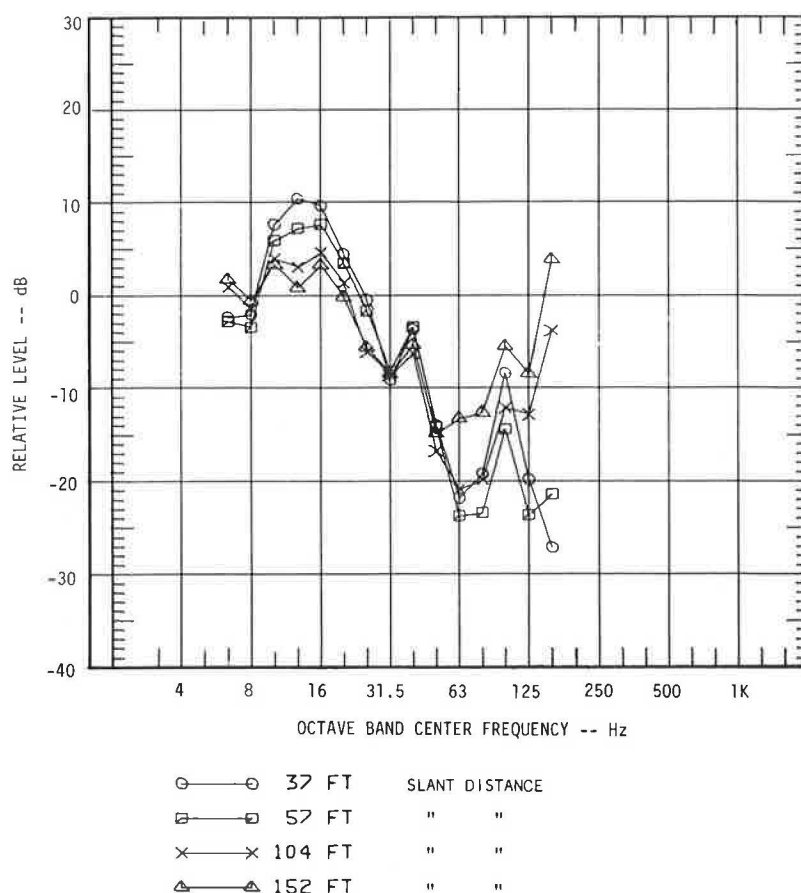
FIGURE 7   Subway relative to borehole line source response for borehole
source depth of 30 ft and source length of 600 ft.

borehole correction. The negative of the subway borehole correction in decibels is the subway structure's coupling loss.

The borehole test procedure includes measuring the transfer mobility from the bottom of the borehole to an array of points on the ground surface. For tests conducted during the project, transfer mobilities were measured at 10-ft increments from ground surface to as much as 60 ft below grade. The analysis of borehole data is the same as that for surface and subway track. Line source responses are developed for each impact depth, and the line source response corresponding to the proposed subway invert depth is used for prediction. The approach is descriptive of the soil's vibration transmission characteristics, providing a direct measure of the effect of subway depth.

Line source responses for boreholes have been measured at BART, MARTA, BRRT, the proposed SCRTD system in Los Angeles, and the DART system in Dallas. The borehole tests for BART and MARTA were conducted adjacent to existing subways for which line source responses were measured directly by striking the subway invert. Subway borehole corrections were then estimated for the BART double box subway by using measured borehole line source responses and direct measurements of the line source response from the subway invert to the ground surface. The results of these measurements are shown in Figure 7. These results cannot be simply extended to other subway structure types and soil conditions, specifically lightweight circular tunnels and very stiff or very soft soils, without allowing for structure size and mass and differing soil conditions.

In coordination with this study and research, a feasibility study was conducted by Structural Software Development, Inc. (SSD) regarding numerical finite-element modeling procedures for use in dynamic analysis of subway structures *(14)*. Numerical calculations were carried out for four model designs by using a plane-strain representation corrected for three-dimensional geometrical effects with the aid of a factor developed from a three-dimensional analytical model of a circular tunnel imbedded in an infinite elastic medium. The four models considered were designed to evaluate effects of grid size, soil layer depth, and soil damping. Numerically computed and measured transfer mobilities for the BART KE Line circular steel tunnel in downtown Oakland, California, are compared in Figure 8. These results are for ground surface response velocities caused by a point force at the outer rail bench.

The data presented in Figure 8 indicate a surprisingly close agreement between measured and calculated levels, except perhaps at 25 Hz and possibly again at about 57 Hz. The basic shape and level of the measured response curve are captured by the numerical result. Even some of the measured dips in the transfer mobility are predicted at about 45 and again at 60 to 70 Hz. The case selected for comparison with the measurement data was Case 2 of the SSD report and was the most representative of actual conditions. The basic conclusion of this feasibility study is that meaningful line source responses can be computed by a suitable extension of the procedures used to produce the results in Figure 8. Future efforts toward numerical
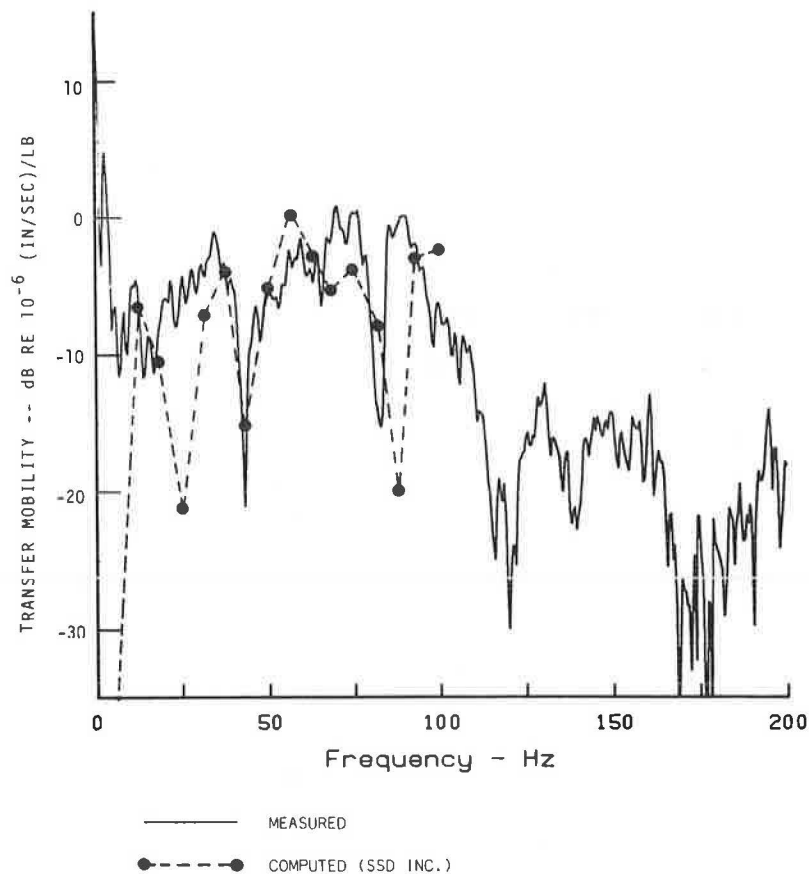
FIGURE 8   Comparison of measured and computed surface transfer mobilities at the BART KE line for impacts at the outer rail bench.

evaluation of subway structure designs with respect to vibration control can only be encouraged.

DIRECTIONS FOR FURTHER RESEARCH

There are several areas that may benefit from additional research and development. These include

- Numerical modeling of subway and soil line source responses and use of borehole test results or soils data, or both as input data;
- Numerical simulation of line source responses for surface and borehole impacts, using soils data as input parameters;
- Modeling and field study of vibration propagation in buildings; and
- Truck and track system dynamics.

Numerical analysis of line source responses will probably be the next phase in advancing the state of the art in predicting groundborne vibration. Numerical modeling software is available that, perhaps with modification, can be used for detailed dynamic modeling of subways as well as general soil-structure interaction, a field that has achieved a relatively high state of development. Recent advances in the boundary element method may further reduce the computer memory normally associated with the finite-element method.

Geophysical research regarding numerical synthesis of seismograms has yielded models of layered media that can be adapted for calculation of line source responses for surface or subsurface sources. Modeling of surface and borehole impact data would aid the theoretical understanding of measured responses and attenuation rates and allow extension of the method to predicting line source responses on the basis of soil properties and layering.

New truck designs have evolved during the course of this study. Many of these incorporate chevron primary suspensions rather than elastomer journal bushing designs. These designs represent a significant advancement for control of groundborne noise and vibration. Computer models were used during the study to model effects of primary suspension stiffness reductions on ground vibration. However, a great deal more may be done. Specific areas that deserve further study include

- Effect of resilient wheels and axle bending stiffness on vibration and
- Interaction of the track with the vehicle truck, including control of rail corrugation.

The view developed during this study and inherent in the concept of the force density is that the vehicle and track are considered together as a system. Interaction between the truck and track support system is of particular interest because it may influence the development of rail corrugations. Control of rail corrugation is as much a vibration (and wayside noise) control problem as it is a maintenance problem.

Finally, miscellaneous factors such as foundation coupling loss and floor resonance amplification deserve additional study.

In a society with ever-increasing technological demands and the need for manufacturing and research facilities with low levels of ambient vibration, the importance of the response of various building floors and foundations to vibration will only increase, regardless of the source of vibration, whether it be vibration produced by trains, truck and automobile traffic, or stationary sources.

ACKNOWLEDGMENT

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