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NOISE AND VIBRATION CHARACTERISTICS OF HIGH SPEED TRANSIT VEHICLES

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HOWARD COUNTY

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TECHNICAL REPORT

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16. Abstract
The rapidly expanding problems of urban transportation have resulted in intensified activity in the development and construction of new fixed route, high speed rapid transit systems and equipment. The community noise and ground vibration caused by such systems and vehicles is a very important factor influencing public acceptance of these systems. Noise and vibration measurements obtained with modern operational and experimental transit vehicles provide a basis for determining the expected wayside or community airborne noise and ground-borne vibration levels for different types of new transit systems. Through the use of modern design concepts and equipment intended to provide reduced noise and vibration, the wayside noise and vibration caused by rapid transit system vehicles can be made acceptable and the operations can be much quieter than traditionally expected despite the general increase in speed of the newer systems which tends to increase noise and vibration. The purpose of this report is to present a review of the available information on wayside noise and vibration generated by rapid transit vehicles, primarily rail transit vehicles, including projection of the expected noise and vibration levels for higher speed vehicles being considered for future applications.

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I. INTRODUCTION

The rapidly expanding problems of urban transportation have intensified activity and development of methods and equipment to improve mobility by using fixed route, high speed rapid transit vehicles. Research and development has been directed at totally new concepts and the improvement of well established techniques in the design of rapid transit systems. At the present time, only those vehicle systems using wheels in contact with the roadway have met the requirement of demonstrated ability to provide successful rapid transit service, however, tracked air cushion vehicles and tube vehicles are receiving considerable attention.

One of the undesirable effects of high speed vehicles, moving either on the surface or in tunnels, is the noise and vibration generated by the vehicles. The noise and vibration are of two principal types; that which is transmitted to the interior of the vehicle, affecting the passengers, and that which is transmitted to the wayside, affecting people in buildings or other locations in the vicinity of the route.

The increasing degree of noise pollution and public awareness of noise in our metropolitan areas indicates the importance of noise and vibration characteristics of rapid transit systems as factors in public acceptance both for the patrons and the wayside residents. Noise and vibration characteristics must, therefore, be considered as important parameters in the design of a rapid transit system.

The purpose of this report is to present a review of the information which is available on the wayside noise and vibration generated by conventional rail vehicles, tracked air cushion vehicles and tube vehicles. Most of the information available relates to conventional rail rapid transit system vehicles such as those typified by the Toronto Transit Commission [TTC] and the Bay Area Rapid Transit District [BARTD]. The noise and vibration data available from these and other test and operational systems provide a basis for estimating the noise and vibration characteristics to be expected from future higher speed vehicles. There is little information available on tracked air cushion vehicles and apparently none on tube vehicles. Also, there is apparently no information available in the open literature on the wayside noise and vibration from the high speed Northeast Corridor trains: the Turbo-Train and the Metro Liner.

The available information for evaluating the noise and vibration from transit vehicles is primarily related to vehicles designed for traveling at speeds of 80 mph or less. The interest now is, of course, in higher speed vehicles including speeds as high as, possibly, 400 to 500 mph. For this reason the data on noise and vibration from transit vehicles has been examined to determine the dependence of the noise and vibration on speed in order to permit prediction of the expected noise level for higher speed vehicles. It has been found, for example, that the increase in noise level and in ground-borne vibration level with increase in speed follow relatively simple laws which permit reasonably accurate extrapolation and prediction of the levels expected from higher operational speeds.

No discussion of the interior noise expected in the vehicles is presented because this is dependent both on the exterior noise levels and on the design of the vehicle body. It is possible to use the exterior noise level information in approximating the increase in sound insulation which is required for the vehicle body in order to maintain the noise in high speed vehicles at the same level as for lower speed vehicles. There are, however, no general estimates of interior noise levels which can be presented because the noise is so dependent on the vehicle body design. Exterior noise is much more readily determined because the sources of noise can be readily defined and the levels are determined by the technology used in the design of the vehicle equipment [except for aerodynamic noise].

"A" weighted sound level in decibels, abbreviated dBA, is used to present data and estimates indicating dependence of the noise on speed and distance. Octave band analyses are presented to indicate approximate spectra or frequency distributions of the noise. For ground-borne vibration both vibration acceleration levels and vibration velocity levels are presented since, in general, the measurements are made in terms of acceleration but the response of people is predominantly determined by velocity levels for the frequency range where ground-borne vibration and noise from transit vehicles is the most significant.

The use of noise levels in dBA permits easy comparison of the expected transit system noise level with other community noises and presents the predicted noise levels in a manner sufficiently accurate to determine the probably subjective community reaction to be expected and certainly gives levels within the accuracy to which wayside passby noise levels and other community noise level measurements can be made.

Similarly, the use of vibration velocity level for the ground vibration level estimates provides a convenient scale for comparisons of the overall vibration level from transit vehicles with ground vibration from other sources. In general, it is found that the vibration levels from transit vehicles are so low that the only effect created is low frequency rumbling noise generated by the vibration. The mechanical motion is of such a level that it is below the threshold of perception for persons seated or standing and, therefore, the vibration is not perceived as a mechanical motion but is rather observed as a rumbling noise; sometimes interpreted by people as a mechanical vibration.

II. AIRBORNE NOISE FROM RAPID TRANSIT VEHICLES

Considering only the wayside effects of rapid transit vehicle operation, for surface operation the primary concern is airborne noise from vehicles. With subsurface operation the primary concern is with regard to ground-borne vibration. In any underground or subway operation the airborne noise from the vehicle affects only the subway and vehicle interior noise. The airborne noise within subways is not transmitted to the wayside unless a building is very close to a subway or shares a common wall with a subway. For most normally encountered underground or subway structure designs the separation between the subway and buildings or other adjacent facilities is sufficient that the only wayside effects are those due to ground-borne vibration.

There are a number of factors which affect the expected wayside noise from surface operations. These include the type of vehicle, the type of propulsion system, the length of trains and the distance from the vehicles to the observation point. For the purposes of this report it will be assumed that the transit vehicles are self-propelled so that each car of a train contributes equally to the noise. In order to determine the expected noise from various types of operations, the wayside noise at a standard distance for individual cars of different design and operational speed are presented. To then account for different train lengths and different observation distances, a general conversion chart is presented which permits deriving the wayside noise level for any length of train at any observation point.

A. Conventional Rail Vehicles

In determining the airborne noise from conventional rail rapid transit vehicles there is a considerable body of information available, particularly from the BARTD Test Track and from the TTC facilities. There are, of course, other modern operational systems which also contribute to the information. See references 1 through 15.

The traditional impression, and the view held by many, is that a rapid transit system using conventional steel wheels and rail must be and can be expected to be noisy. This impression is caused by older elevated and subway transit systems, using old technology, which do create very high and annoying noise levels and which do create a considerable amount of annoying ground vibration. Past experience with the older systems has indicated that they can be noisy and uncomfortable to the passenger and that the wayside noise and vibration can be major intrusions into the neighboring community. With new systems, higher speeds and frequent passage imply the possibility of even more noise and annoyance than with older systems. However, through the use of modern design concepts intended to provide reduced noise and vibration, the community intrusion caused by rail transit systems can be made acceptable and the operation can be much quieter than traditionally expected.

A modern steel wheel and rail system such as the San Francisco Bay Area Rapid Transit District system or the Washington, D. C. Metropolitan Area Transit Authority, Metro system will create considerably less noise and vibration than may be expected and, in fact, the levels will be sufficiently low that the use of such a transportation system presents the potential for reducing overall community noise compared to the use of automobiles and buses for transporting people. A new rail transit system, in direct contrast to an older system, will create no perceptible ground-borne vibration at wayside buildings and the wayside noise levels will be considerably less because of the incorporation of design features which result in reduced noise and vibration.

Sound measurements made at the BARTD Test Track and other facilities have been used to demonstrate the relative contribution of various sources of noise to the overall wayside noise produced by a conventional rail transit vehicle. The main contributors to the wayside noise at current operational speeds are the propulsion system noise and the noise created by interaction between wheels and rails. With proper control placed on the noise radiated by the propulsion system, the wayside noise is then predominantly due to the wheel and rail interaction and is, therefore, dependent on the quality and smoothness of the wheels and rails.

For higher speed vehicles, possibly for speeds exceeding 150 mph, the aerodynamic noise generated by the turbulent boundary layer flow over the vehicle body will add a third noise source which may be significant in terms of wayside noise, depending on the aerodynamic design of the vehicle body.

The auxiliary equipment, such as blowers and compressors, mounted on transit cars does create some wayside noise, however, such noise can be controlled by conventional sound attenuation methods applied to the equipment. Since it is necessary to control the noise from auxiliary equipment to prevent excessive noise in station platform areas, the noise radiated by auxiliary equipment is much lower than the wayside noise caused by the car rolling and by the propulsion system when the vehicle is operating at high speeds. For this reason the noise from auxiliary equipment is significant only at very low speeds.

The design and technology of modern conventional rail transit vehicle systems include many features in the basic design which result in reduced noise and vibration compared to old steel wheel, steel rail systems. Some of these features are included specifically for reducing noise and/or vibration and some are included for other reasons with reduced noise or vibration being an additional side benefit. Standard way structure and vehicle features which are very successful in contributing to improved performance with regard to noise and vibration from transit vehicle operations include:

continuous welded rail,

resilient rail fastenings,

concrete or composite steel-concrete girders for aerial structures,

sound absorption materials in subways and stations,

lightweight trucks with minimized unsprung weight,

resilient chassis mountings,

low noise non-skid braking systems,

resilient wheels,

use of wheel and rail grinders for maintaining the wheels and rails in a smooth condition, and

noise limits in the specifications for the vehicle propulsion systems and auxiliary equipment.

Two of the items listed are extremely important in obtaining the full potential of all the other noise and vibration reduction features which may be included in the design of a system: [1] the maintenance of wheels and rails in good smooth condition and [2] limiting the noise from the vehicle propulsion system and auxiliary equipment through the use of maximum noise limit specifications in the design specification for the vehicle equipment.

Maintenance of the wheels and rails in good smooth condition is essential because the presence of roughnesses on the rail or flats on the wheels can result in noise and vibration level increases in the range of 10 to 15 decibels, a very significant increase which could completely negate all of the potential benefit from other features included in the system design for vibration and noise reduction.

Including noise limit specifications in the design criteria for vehicles is very necessary and significant in achieving low wayside noise levels from transit vehicles because it is possible to have a transit vehicle system with most of the listed features included in the design but still have high or excessive wayside noise due to the fact that the propulsion motors and gear systems can create high sound levels.

Data on the wayside noise for rail transit vehicles have been extensively tabulated and well determined for the speed range from 30 to 80 mph. The noise measurements show good correlation between levels obtained at different facilities and with levels from passenger train cars, see references 1 through 11.

In general, it is found that the wayside noise level for conventional rail transit vehicles with self-ventilated electric propulsion motors is proportional to $30\log_{10}V$ where V is the vehicle speed. In determining the extension of the wayside noise level data to higher speeds, several factors must be taken into account. These factors include the type of propulsion system and the dependence of propulsion system noise on speed and power, the dependence of wheel-rail interaction noise on speed and track condition or design and the contribution of aerodynamic noise to the overall noise, see references 8, 11, 12, 14 and 15.

The noise generated by the self-ventilated propulsion motors used for many conventional transit vehicles is proportional to $50\log_{10}$rpm. Therefore, for a given propulsion system, the wayside noise from the propulsion system increases by a more rapid rate than the vehicle wayside noise with increasing car speed. It has been found that the ground-borne vibration level and hence the wheel and rail vibration level is approximately proportional to $20 \log_{10} V$ and there are some indications that the noise generated by the wheels and rails is proportional to $20 \log_{10} V$, see references 8, 9, and 11. One set of measurements on the wheel and rail noise from freight cars indicates levels proportional to $20 \log_{10} V$ and the vibration level data imply that the wheel-rail noise level should be proportional to $20 \log_{10} V$, see references 10 and 11. The combination of wheel-rail noise proportional to $20 \log_{10} V$ and propulsion system noise proportional to $50 \log_{10} V$ then leads to the conclusion that the $30 \log_{10} V$ proportionality found for wayside noise from transit vehicles in the range from 30 to 80 mph is a fortuitous averaging of the $20 \log_{10} V$ and $50 \log_{10} V$ noise generation characteristics.

In general, the modern rail rapid transit car is designed so that at the maximum speed the propulsion system noise is about equivalent to the wheel and rail system noise. Thus, at the lower speeds the wheel and rail noise predominates and at higher speeds the propulsion system noise would predominate. Since there is a maximum limit on the rpm of electric motors, around 5000 to 6000 rpm for motors of the size used in transit vehicles, it can be concluded that the vehicles designed for higher operational speeds will not use motors operating at higher maximum rpm.

Since the power required to move the vehicles at higher speeds varies according to the third power of the velocity, the increase in horsepower required from the propulsion motors will also vary as the third power of the velocity. In general terms, the noise levels from fans and electric motors is proportional to $10 \log_{10} hp$ for machines operating at about the same rpm. Thus, the noise from the propulsion system at the maximum operational speed should increase according to $30 \log_{10} V$ because the noise from the propulsion motors will increase approximately according to this relationship, if the motors are self-ventilating.

If the transit vehicle propulsion motors are force-ventilated, the noise can be controlled to a greater extent than with the self-ventilated motors and the propulsion system noise could be controlled to be somewhat lower than the wheel and rail interaction noise and, therefore, the wayside noise at all speeds could be determined by the wheel and rail interaction noise. With such an arrangement, the wayside noise level may increase with speed at a rate less than $30 log_{10}V$, perhaps $25 log_{10}V$. This would, of course, require that the wheels and rails be in very smooth condition; a requirement that may also be necessary in order to achieve acceptable ride quality in the high speed vehicles.

Figure 1 indicates the wayside noise levels to be expected from a single conventional rail transit vehicle for operation above the surface at three different design conditions and for speeds up to 220 mph as observed at 50 ft from the track centerline with ballast and tie trackbed at-grade or elevated on earth embankment, with no sound barrier walls or other obstructions between the vehicle and observation point. For operation on aerial structure or on elevated concrete trackbed add 2 to 3 dBA to the levels shown.

Three ranges of noise levels as a function of speed are shown on Figure 1. The upper dotted range shows the noise levels expected for vehicles using electric motor propulsion systems with standard technology with no specific limitations on the noise generated by the propulsion motors and gear systems. The center cross-hatched area shows the expected noise levels as a function of speed for typical rail rapid transit vehicles using self-ventilated electric propulsion motors with the noise limited to the extent that current technology indicates is possible, references 16, 17, and 18. The lower dotted region indicates the noise level which could be expected if the propulsion system electric motors are force-ventilated permitting greater reduction in the propulsion system noise and with improvements in the smoothness of the wheels and rails for higher speed operations.

The noise levels indicated in Figure 1 are based on measured data for operational and test vehicles traveling at speeds up to 70-75 mph with various types of propulsion systems and for various operating conditions. The center range shows the levels which are the most probable for high speed vehicles

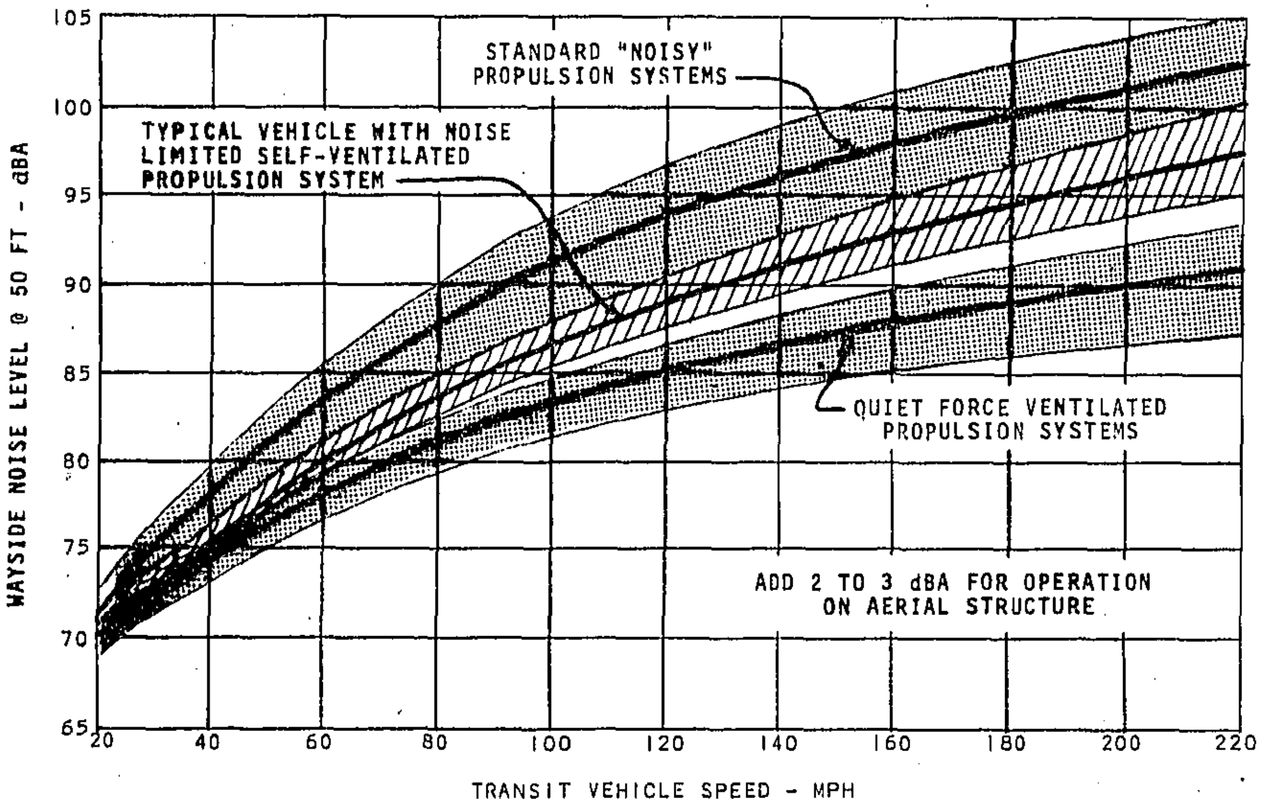


FIGURE 1 WAYSIDE NOISE LEVELS FOR A SINGLE CONVENTIONAL STEEL WHEEL-STEEL RAIL RAPID TRANSIT VEHICLE AT 50 FT HORIZONTAL DISTANCE FROM TRACK CENTER-LINE - BALLAST AND TIE TRACKBED

as indicated by the capabilities of new equipment developed for the BARTD system. The levels at speeds greater than 80 mph were determined by extending the charts for speeds greater than 80 mph using the principles discussed on Pages 7, 8 and 9, and assuming aerodynamic noise does not contribute to the wayside noise.

The ranges shown on Figure 1 for each design condition should be interpreted as a tolerance on the noise levels expected from the vehicles and to account for the differences in noise level which are found with different trackbeds and different facilities of the same design. In general, it is found that the wayside noise is 2 to 3 dBA greater for aerial structure operations compared to operation at-grade or on ballast and ties and differences of 2 to 3 dBA are found between cars of identical design and construction.

It is possible to generalize the noise levels expected from rail vehicles according to the following equations. The expected wayside noise level as observed at 50 ft for a single car passing by can be expressed as given by the following:

[1] Typical vehicle with standard self-ventilating electric motor propulsion system:

$$\text{Noise Level @ 50 ft} = 34\log_{10}V + 24 \text{ dBA}$$

[2] Typical vehicle with quiet gears and self-ventilating motors [noise limited by specifications]:

$$\text{Noise Level @ 50 ft} = 30\log_{10}V + 27 \text{ dBA}$$

[3] Typical vehicle with quiet gears and forced-ventilation motors or exceptionally quiet self-ventilated motors:

$$\text{Noise Level @ 50 ft} = 25\log_{10}V + 33 \text{ dBA}$$

Using these relationships, the charts shown on Figure 1 can be extended to higher speeds although for speeds in the 200 to 300 mph range the tolerance should be increased to ±3 or ±4 dBA and for speeds above 300 mph a range of at least ±5 dBA is probably applicable.

It should be emphasized that Figure 1 and equations [1], [2], and [3] indicate the noise levels that will be achieved when the vehicles are operating at the maximum design speed. When operating at lower than maximum speeds the noise will be less than indicated by the corresponding speed on the chart. For example, a car intended to operate at 140 mph maximum speed would probably make less noise at 80 mph than indicated by the equations or the charts of Figure 1 because the propulsion system noise would be less at 80 mph than for a car which was designed to have a maximum operating speed of 80 mph.

Thus, the equations and the charts on Figure 1 should be interpreted in terms of the expected noise level being that given by equation [2] or the central cross-hatched area at the maximum operating speed and at about half of maximum operating speed the noise will probably be as shown by the lower chart or equation [3] because the noise will be predominantly that from the wheels and rails. At very low speeds, the noise level will approach a minimum determined by the noise from the auxiliary equipment.

It should be further emphasized that the noise levels indicated assume smooth, well maintained wheels and rails and the use of continuous welded rail. If there are rail joints, the wayside noise levels will be 8 to 10 dBA greater than indicated or if there are wheel flats the noise levels will be 8 to 10 dBA greater than indicated. If there is a combination of wheel flats and rail joints, the noise levels can be expected to be 10 to 15 dBA greater than the indicated ranges. In particular, if the wheels and rails are not maintained as smooth continuous surfaces, the noise levels predicted for vehicles using force-ventilated electric propulsion motors could not be achieved and the potential benefit from efforts at quieting the propulsion systems would not be realized.

The frequency distribution of the noise from conventional rail rapid transit vehicles with electric propulsion motors is determined primarily by the noise spectra of the propulsion motors and the spectrum of the wheel and rail noise. Both of these spectra have maximum sound energy in the middle frequency range, i.e., the 500 and 1000 Hz octave bands, and the noise is a fairly broadband random noise typical of machinery noise. With some propulsion systems, there is also significant tonal noise or pure tone componenets in the noise due to cooling fan blade frequencies or gear tooth frequencies, however, the most recent equipment designs indicate that these pure tones can be suppressed or eliminated.

Since the noise spectrum from the electric motors is dependent primarily on the cooling fan noise and the motor rpm, it can be expected that the propulsion system noise spectrum will be essentially the same for higher speed vehicles as it is for present day equipment. For example, the noise spectrum from stationary electric motors is essentially the same over a very wide range of horsepower ratings. Similarly, the noise spectrum of the wheel and rail noise is somewhat dependent on the dynamic characteristics of the wheels and rails and the noise spectrum is not highly dependent on train speed. The amount of sound energy radiated by the wheels and rails varies with train speed because the energy input varies, however, the natural frequencies do not change significantly and, therefore, the spectrum of the noise is not expected to change significantly.

Figure 2 indicates typical octave band spectra obtained at 50 ft from track centerline for speeds of 60 to 75 mph. It can be expected that the noise spectrum for higher speed trains will be very similar. At the highest speeds, of course, there will be some contribution of aerodynamic noise which may significantly change the spectrum shape.

Two typical spectra are shown on Figure 2, one related to vehicles using standard "old" technology propulsion systems which have significant tonal noise in the middle frequencies and one related to vehicles using propulsion systems designed with noise limitations as part of the design criteria and with the pure tone noise components suppressed or eliminated.

On Figure 2 the upper - dashed line - spectrum labeled standard or noisy propulsion system indicates the typical octave band spectrum obtained with transit vehicles having well maintained wheels and rails but with propulsion systems that may have predominant pure tone noise or relatively noisy motors because standard technology was used in the design of the equipment. The lower - solid line - spectrum is typical of that obtained from transit vehicles with propulsion systems that have no predominant pure tone noise and for which the propulsion system noise has been limited by specification and design to minimize noise generation. The upper spectrum

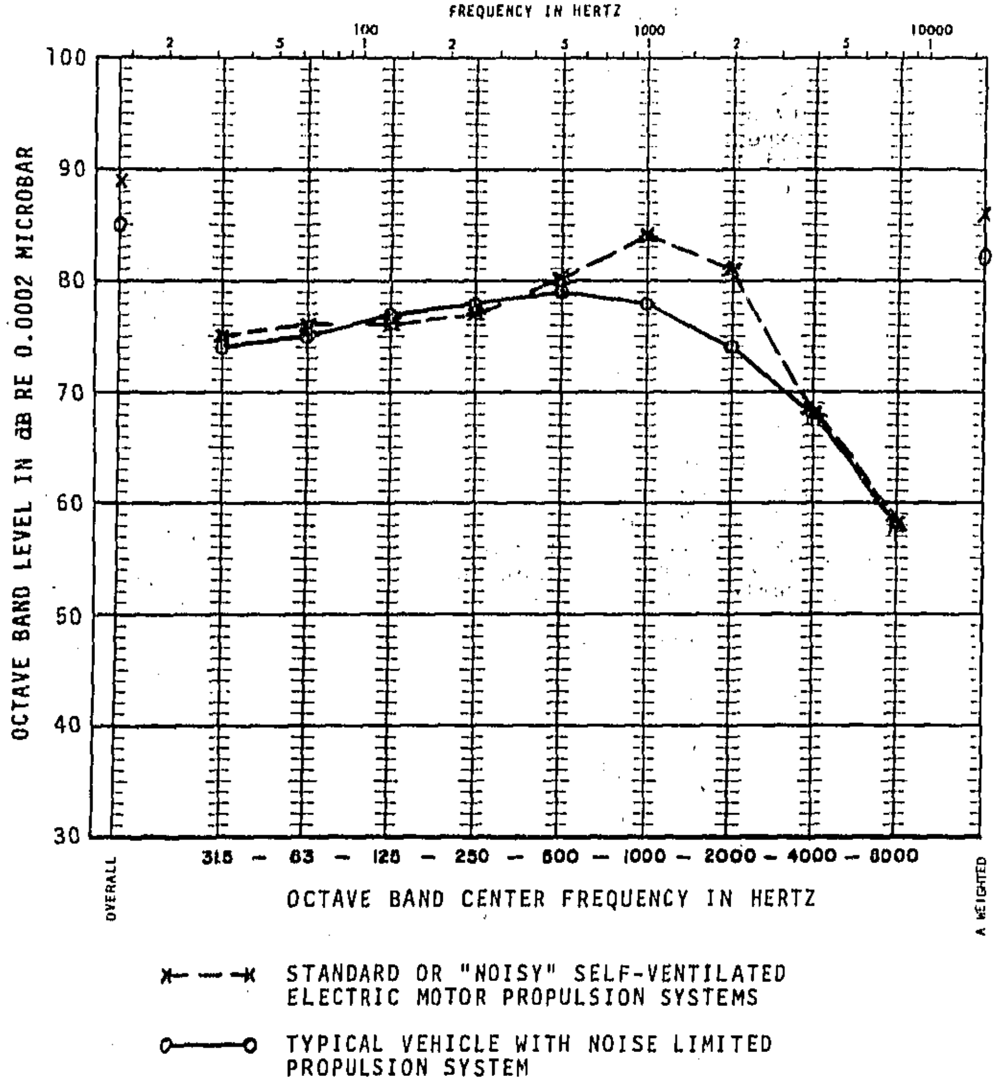


FIGURE 2 TYPICAL WAYSIDE NOISE LEVEL SPECTRA AT 50 FT FROM TRACK CENTER-LINE FOR CONVENTIONAL RAIL TRANSIT VEHICLES. SINGLE CARS AT 60-75 MPH

corresponds with the higher noise level range on Figure 1 and the lower spectrum corresponds with the center and lower noise level ranges of Figure 1.

A reasonable approximation of the octave band analysis of noise from higher speed vehicles can be obtained by using the spectral distributions indicated on Figure 2 and adjusting the levels up or down so that the "A" weighted levels to the right on Figure 2 match with the "A" weighted levels given on Figure 1 for various speeds and conditions of operation.

Frequency analyses of the wayside noise from transit vehicles with propulsion systems other than electric motors have not been included because there is no definitive information on the wayside noise of other types of propulsion systems which might be used for conventional rail rapid transit systems. It can be assumed that diesel engines or gas turbines are probably the only alternates to electric power that are technically and economically feasible. In the event that such combustion engines are used and if adequate noise control measures are used, the wayside noise levels should not be any greater than shown by the center or lower range of Figure 1. With diesel or turbine power plants, the lower frequency octave, i.e., 250 Hz and lower, would probably have somewhat higher levels than shown on Figure 2, however, the increase would not be sufficient to increase the "A" weighted levels if adequate noise control measures were used.

Attempts were made to obtain noise data from the high speed Northeast Corridor trains - the Metro Liner and the Turbo-Train. However, no definite information on noise levels could be found. Apparently, there have been no systematic studies of the wayside noise from these trains or at least there is no record of noise measurements which may have been performed. Wayside noise level data from the Metro Liners and Turbo-Trains would be of considerable value in extending the existing noise level information to the higher speed trains.

It should be noted that the noise level data presented in this section of the report relates primarily to vehicles of 70 to 75 ft lengths with weights in the range of 60,000 to 90,000 lbs and with wheel loadings on the order of 10,000 lbs per wheel. Vehicles with considerably different weight or length and wheel loadings may give significantly different noise levels.

Data from freight and passenger trains do, however, indicate that the wheel and rail noise does not vary greatly with wheel loading, although ground-borne vibration levels do vary considerably with the wheel loading.

Two factors remain to be taken into account in the analysis of wayside noise from surface operated conventional rail vehicles; the contribution of aerodynamic noise to the wayside noise and the variation of noise level with train length and distance of the observation point from the track.

It is not possible to express the variation of noise level with train length and distance from the track by a simple expression, such as the inverse square law for spherical radiation, because the variation in noise is dependent on both the train length and the distance from the track. In reference 1 a relationship and nomograph for deriving the sound radiated by a finite length line source was presented. Using this information, the radiation characteristics for typical rapid transit trains has been derived and is presented in graphical form by Figure 3. The result is similar to an independent derivation given in reference 11.

Figure 3 is a chart which can be applied to the data on Figures 1 and 2 to determine the wayside noise levels for trains of various lengths at various distances to the wayside, assuming relatively flat open terrain. In general, rail transit vehicles are of 70 to 75 ft length so that a 2-car train is about 150 ft long and an 8-car train is about 600 ft long. The chart is arranged to show the amount of noise level which should be added or subtracted from the data on Figure 1 to determine the noise level for any length of train at any observation point. For example, an 8-car [600 ft long] train traveling at 180 mph and observed 200 ft to the wayside would be expected to create a noise level of about 90 ±2 dBA since a single car will create about 94 dBA at 50 ft and the correction for length of train and distance is about -4 dB.

To determine the noise spectrum levels, at any point for any train length and speed, the octave band levels given on Figure 2 should be adjusted first for speed by using Figure 1 and then for train length and observation distance by using Figure 3.

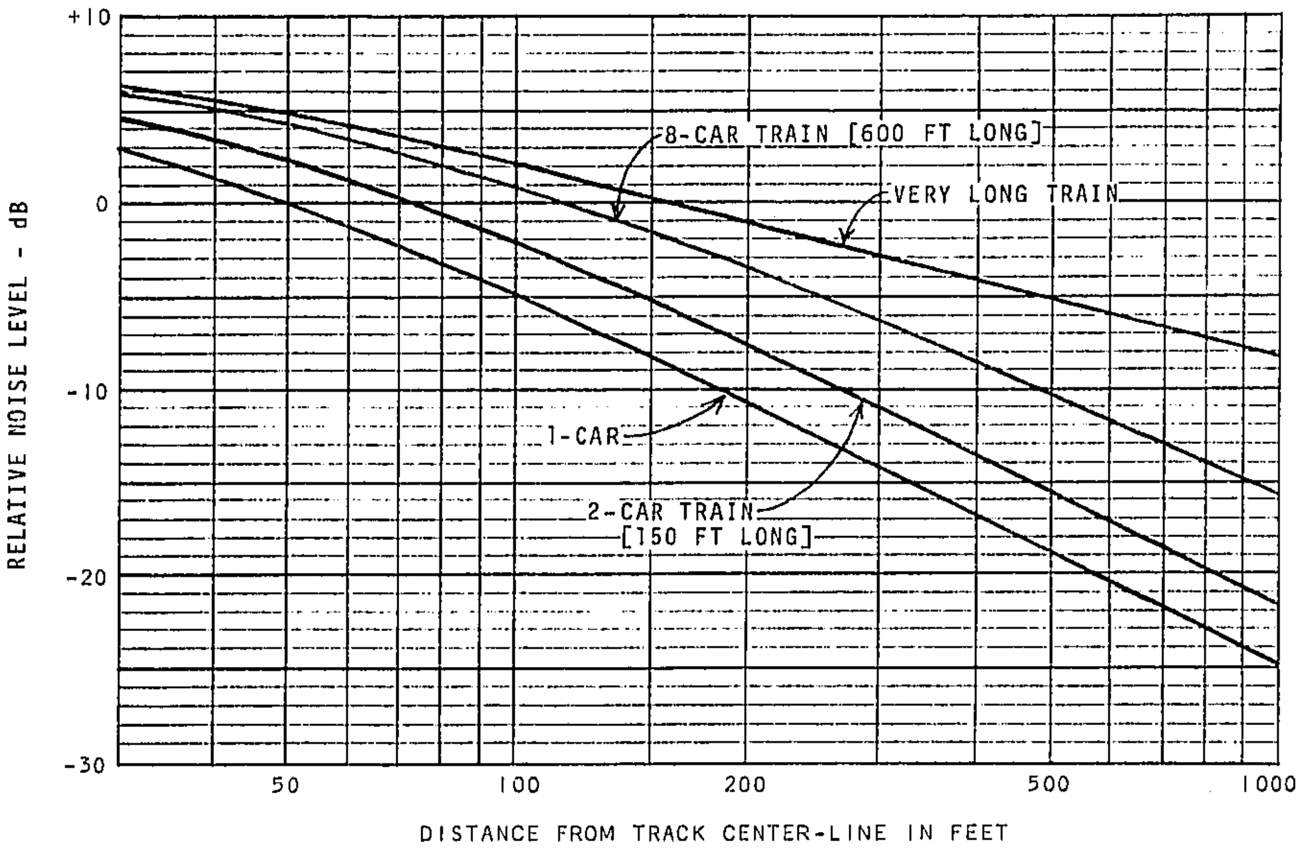


FIGURE 3 CHART SHOWING WAYSIDE NOISE LEVELS FOR TRANSIT TRAINS OF VARIOUS LENGTHS AS A FUNCTION OF WAYSIDE DISTANCE RELATIVE TO A SINGLE CAR AT 50 FT

The contribution of aerodynamic noise to the wayside noise of transit vehicles is difficult and probably impossible to determine at the present state of knowledge because the noise not only depends on the vehicle speed and size but also depends on the thickness of the turbulent boundary layer, see, for example, references 37, 38, and 39. The boundary layer thickness depends greatly on the aerodynamic design of the vehicle and the length of the train so that it is not possible to make any generalized predictions on the sound power generated by the turbulent boundary layer.

The literature on boundary layer noise indicates that the sound power from the turbulent boundary layer and hence the wayside noise due to the turbulent flow does follow a dependence somewhere between V^4 and V^6, with a V^6 dependence being the most likely. This indicates that the aerodynamic noise will be very strongly dependent on the train speed and when it does become significant the noise will increase with speed at a much greater rate than indicated by the charts on Figure 1 or the equations generalizing these charts.

It has been observed that at speeds up to 80 mph the aerodynamic noise is not significant even with square cornered [poor aerodynamic design] vehicles such as the BARTD Laboratory test cars so that it is likely that the aerodynamic noise will not be significant until speeds of 150 to 200 mph are reached. At such speeds, it will be necessary to use aerodynamic design principles in the shaping and other details of the body exterior in order to avoid excessive drag and, therefore, it is likely that the aerodynamic noise generation will be reduced simply because of other design requirements. Nevertheless, aerodynamic noise is a factor which should be considered in the design of high speed transit vehicles.

B. Tracked Air Cushion Vehicles

With tracked air cushion vehicles there are four principle sources of noise; the propulsion system, the air cushion jet, the air cushion compressors and aerodynamic noise.

The contribution of aerodynamic noise to the wayside noise is essentially the same for an air cushion vehicle as for a conventional rail vehicle at similar speeds and the same difficulties arise in attempting to predict the magnitude of the far-field noise level created by the turbulent boundary layer. The air cushion vehicle noises which have been evaluated to some extent in the literature are the air cushion jet, the propulsion system, and compressor noises, see references 40 through 45.

For tracked air cushion vehicles the types of propulsion systems that have been proposed and appear to be practical include jet engines, linear induction motors and the air cushion jet itself using either gas turbines or axial flow compressors for the compressed air. U-shape, inverted T-shape, and box beam guideways or tracks are being considered as practical and feasible, however, the U-shape guideway is receiving the most attention because it presents the possibility for confining at least a portion of the air cushion and compressor noise within the guideway. Two basic types of air cushions have been considered - large area low pressure and small area high pressure cushions - and the most promising is the large area low pressure cushion because it creates lower noise levels.

With any type of propulsion system the minimum wayside noise that can be expected is that created by the air cushions. Estimates presented in the literature indicate that the minimum expected wayside noise at 300 mph is about 90 dBA at 100 ft for an inverted T guideway and high pressure air cushions. To this noise then must be added the expected noise from silenced or unsilenced propulsion systems and air cushion compressors.

Figure 4 presents the range of noise levels indicated by the tracked air cushion research vehicle preliminary design study reports which are available. Most of the noise levels have been calculated assuming a 300 mph vehicle operation on an inverted T guideway with high pressure air cushions. To derive the charts on Figure 4, it has been assumed that the noise levels will be proportional to $30 log_{10} V$. The chart

shows the expected noise levels for tracked air cushion vehicle speeds in the range of 100 to 300 mph. Two basic noise level ranges are shown. The upper range indicates the noise levels expected using unsilenced jet engines or axial flow compressors as the source of power for the air cushion and the propulsive force. The lower range shows the expected wayside noise level with inverted T guideway and silenced jet engines or

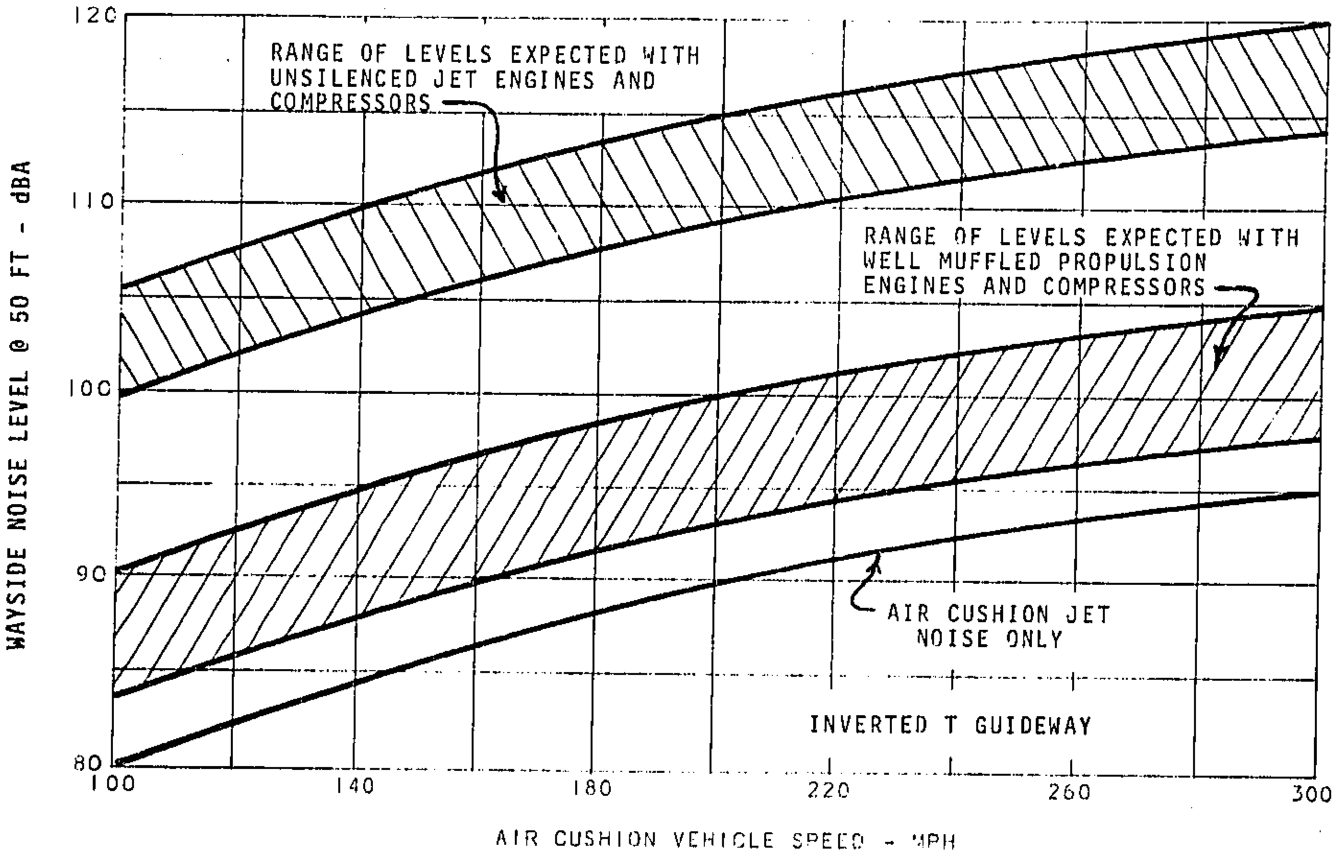


FIGURE 4 WAYSIDE NOISE LEVELS AT 50 FT HORIZONTAL DISTANCE FROM TRACK CENTER-LINE FOR A SINGLE TRACKED AIR CUSHION VEHICLE ON INVERTED T GUIDEWAY AND WITH HIGH PRESSURE AIR CUSHIONS

linear induction motors for propulsion and silenced air compressors for the air cushion air supply. The lower limit of the noise level range indicates the wayside noise level expected from considering only the air cushion exhaust as the noise source, for inverted T guidway and high pressure cushions, see reference 44.

The data on Figure 4 shows the noise levels at a wayside distance of 50 ft for comparison with the wayside noise from conventional rail vehicles shown on Figure 1. The charts indicate that, even with the best silencing which has been predicted or can be expected, the tracked air cushion vehicle on inverted T guideway and with high pressure air cushions creates noise equivalent to or greater than a conventional rail vehicle. The reasons for the high noise level from tracked air cushion vehicles are that they require the use of turbines, axial flow compressors or jet engines and the vehicle must be light in weight so that noise reduction efforts are faced with the same limitations found in attempting to quiet aircraft jet and turbine engines. There are indications, however, that the wayside noise can be reduced to the range of 70-75 dBA at 150 mph with the use of low pressure cushions and a U-shape guideway to confine the air cushion, compressor and propulsion system noise.

It, therefore, appears that from a wayside noise standpoint the only reasonable tracked air cushion vehicle would be one using a linear induction motor for propulsion to minimize the propulsion system noise, using gas turbine or axial flow compressors for the air cushions with attenuators on both the intake of the compressor and in the ducts leading from the compressor to the air cushions, and using low pressure air cushions and a U-shape guideway. Some of the literature on air cushion vehicles indicates designs for muffling the compressor noise between the air cushion and the compressor and the combination of U-shape guideway with low pressure cushions appears feasible.

C. Tube Vehicles

One type of tube vehicle is the gravity vacuum train which consists of a long cylindrical rail vehicle traveling from station to station through a smooth evacuated tube. Propulsion is provided by the pressure differential between the front of the vehicle, which is exposed to the evacuated tube, and the rear of the vehicle, which is exposed to the atmosphere. Shortly after the vehicle leaves the station, a valve closes, sealing the tube behind the train from the station and allowing the air between the valve and the vehicle to expand and continue acceleration of the vehicle.

No definite information was found on the wayside noise to be created by tube vehicles. The main sources of noise for the tube vehicles would be the stationary mounted pumps used to evacuate the tubes and the flow noise created by air flowing into the tube. It should be possible to control the noise from the stationary pumps using conventional sound attenuation procedures so that these would not constitute a significant wayside noise source. The air flowing into the tubes will create noise only at the time when the tube valve is being closed behind the train. This noise would be of the turbulent jet noise type and the only practical means for controlling this noise, at present, since the configuration of the valve and the tunnel opening has not yet been fully designed, is the use of a length of acoustically lined duct between the valve and the station area.

Providing a length of lined tube or duct between the station area and the valve would provide a means for attenuating the noise to prevent high noise levels in the stations or above ground.

Since gravity vacuum and other tube vehicles would be inside a tube, there should be no significant wayside air borne noise. Even if the tube is located on the surface, there is little likelihood of airborne noise, however, in such a case the tube itself would be the noise generator because of vibration induced by the vehicles.

III. GROUND-BORNE VIBRATION FROM RAPID TRANSIT VEHICLES

All types of rapid transit vehicle operations create some degree of ground-borne vibration which transmits to wayside buildings and other facilities. The ground-borne vibration is perceived by observers at wayside locations as either mechanical motion or as a low frequency rumbling noise generated by the mechanical vibration. Vehicle systems using steel wheels and rail create the greatest ground-borne vibration levels, however, the levels are significant only at short distances from either surface or subsurface operations.

Vehicles using pneumatic rubber tires or air cushion suspension systems also create ground-borne vibration, however, the frequencies are lower than for conventional rail vehicles. The present indications are that pneumatic rubber tire vehicles create lower frequencies but similar amplitudes to those from conventional rail and that air cushion supports create lower frequencies and lower amplitudes of ground vibration than for conventional rail vehicles. With improved quality of wheel-rail smoothness and maintenance, these differences may not be significant.

Rapid transit vehicle operation can induce ground vibration by two mechanisms; [1] the airborne noise created by the transit vehicles can cause vibratory motion of the trackbed or subway structure and [2] the rolling wheels or the supporting air cushion can transmit forces to the roadbed which in turn results in vibration of the geologic media adjacent to the track facilities. The result is that this vibratory motion is transmitted through the surrounding geologic media to adjacent buildings and other facilities. As discussed in a later section of this report, Section IV-C, the vibration induced by the airborne noise from surface or subway operations is not significant in terms of wayside ground-borne vibration levels so that only the vibration caused by the vehicle support system or the rolling wheels is significant in determine the wayside vibration levels.

There are many factors which affect the expected ground-borne vibration from surface and subsurface operations of trains. As with airborne noise, these factors include the type of vehicle, the length of the trains and the distance from the observation point to the subway or trackbed. With ground-borne vibration there are also other factors such as the type of geologic media, the type of surface or subway structure, the type of trackbed, the type of rail fastener and the type of transit vehicle wheel which also can affect the vibration levels. The purpose of this section of the report is to present a review of the information available on ground-borne vibration from transit vehicles. The following section of the report, Section IV, discusses the propagation of the ground-borne vibration in various types of geologic media and Section V discusses the effect of the ground-borne vibration on buildings.

A. Conventional Rail Vehicles

There is a considerable quantity of vibration level data available from both the Toronto Transit Commission facilities and the Bay Area Rapid Transit District Test Track. Since the TTC and BARTD equipment represent the latest technology with regard to conventional rail systems, the data from these systems can be used to present estimates of the ground-borne vibration levels to be expected from future systems operating at comparable and higher speeds. There is some limited information available on the vibration characteristics from other operational systems, however, in general, the data from other systems show higher levels due to the use of jointed rail or other design features which cause higher vibration levels than necessary or expected with future systems. See references 1-9, 22, 23, and 24.

Most of the information from the TTC and BARTD measurements is for vibration levels near surface and subway installations where the geologic media supporting the track or subway structure is soil or earth. There is very little information available on the ground-borne vibration levels from rapid transit type vehicles in subways with rock base, however, the data available from earth base structures permits estimates of the ground-borne vibration levels from operations in rock base subways. One project providing measurements of ground vibration levels from rail transit train operations in rock base subways has been completed, reference 25, and the data have been used to confirm and adjust the estimated values and establish the level of ground-borne vibration from operation in rock base subways relative to the levels from operation in earth base subways.

Using comparisons of the mechanical properties of soil and rock, and comparisons of the estimated mechanical impedance of earth and rock base subway structures, it is possible to estimate the expected vibration levels near rock base tunnels. By using the data from the one available set of measurements at the TTC facilities, in areas where the subways are mixed-face configuration with rock base, the estimation procedure for the measured configuration was checked and corrected. With the corrected procedure the expected vibration levels for other configurations have been estimated and are presented herein.

The available ground vibration level information can, therefore, be used to prepare estimates of the vibration and noise levels to be expected from conventional rail transit system operations for surface operations and for earth or rock base tunnels. The accuracy of predicted levels is good because there is considerable background information and the data from the TTC and the BARTD facilities give very similar results.

The measurements indicate that the vibration intensity in the ground adjacent to transit system operations is proportional to the square of the train speed, that is, the vibration level is proportional to $20 \log_{10} V$. The spectrum or frequency distribution of the ground-borne vibration changes very little with car speed, at least for the range of speeds which has been measured, 15 to 70 mph.

The frequency distribution of the ground-borne vibration is not likely to change significantly with higher speed operation because the frequencies of vibration are dependent on natural frequencies in the system, including natural frequencies of the wheels, rails, suspension systems and the characteristic frequencies of the supporting media. At higher speeds there may be some increase in the higher frequency energy content of the vibration due to the more rapid occurrence of impacts between wheels and rails, however, at any distance from the transit facilities, the high frequencies will be greatly attenuated due to the characteristics of earth as a vibration transmission media and, therefore, the spectra will be essentially the same for higher speed vehicles.

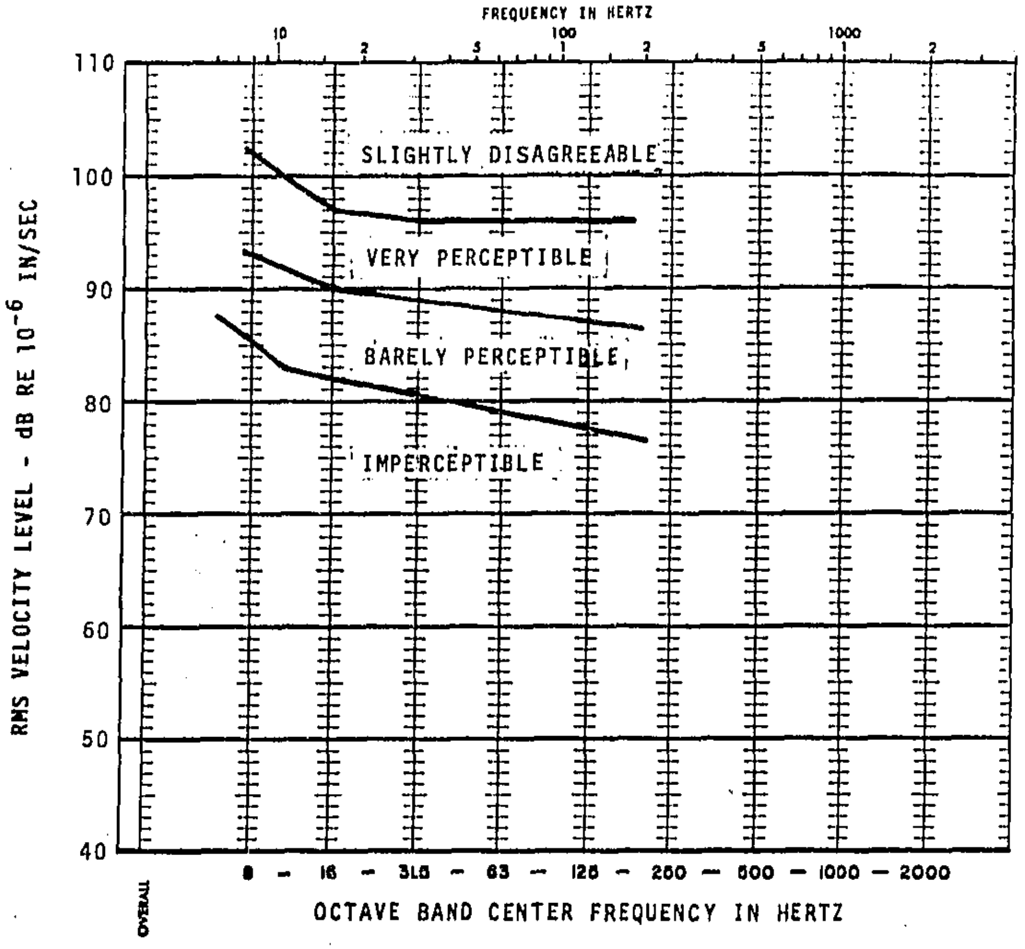
There are two possible ways in which the ground vibration will be perceived by people in wayside buildings or other facilities; [1] as a mechanical motion of the ground or building structure and [2] as airborne noise generated by the mechanical motion. In either case, the perception of the vibration is approximately proportional to the vibration velocity level. Figure 5 indicates the approximate sensitivity to vibration for persons seated or standing. The chart is plotted in terms of rms vibration velocity level and indicates that, for frequencies above about 10 Hz, the sensitivity to small amplitudes of motion is approximately proportional to vibration velocity level, see references 19, 20, and 21.

When noise is generated by large surfaces vibrating at low frequencies, the noise level is approximately proportional to the vibration velocity level of the vibrating surface, therefore, when the vibration is perceived as an induced noise level, the noise is proportional to the vibration velocity and again the level of perception is essentially proportional to the vibration velocity.

Figure 6 indicates the overall ground-borne vibration velocity level expected at 50 ft from surface operations of conventional rail rapid transit vehicles. Figure 7 indicates the overall vibration velocity levels to be expected in the ground at about 25 ft from transit trains operating in earth base subways. The charts on Figures 6 and 7 are shown as overall vibration velocity levels to provide an indication similar to the "A" weighted sound level for airborne noise measurements in order to indicate the relative perception level for different operational speeds and facility configurations.

Figure 8 indicates the typical vibration level spectra to be expected from surface operations of rapid transit vehicles. Figures 9, 10 and 11 indicate the typical frequency distributions and levels of vibration to be expected form subsurface operations for three types of typical subway configurations. The charts indicate the range of vibration levels to be expected and the approximate frequency distribution for earth base subways, rock tunnels and mixed-face configurations where the subway base is located in rock but the building or observation point is located in earth so that the vibration must transmit both through rock and earth.

Figures 10 and 11 indicate the expected vibration levels at 25 ft from a subway structure for a mixed-face configuration and for a subway imbedded completely in rock. The difference



THE CHART INDICATES THE RANGE OF RESPONSE LEVEL FOR SEATED OR STANDING PERSONS SUBJECTED TO VERTICAL MECHANICAL VIBRATION

FIGURE 5 MECHANICAL VIBRATION PERCEPTION LEVELS FOR PEOPLE SEATED OR STANDING

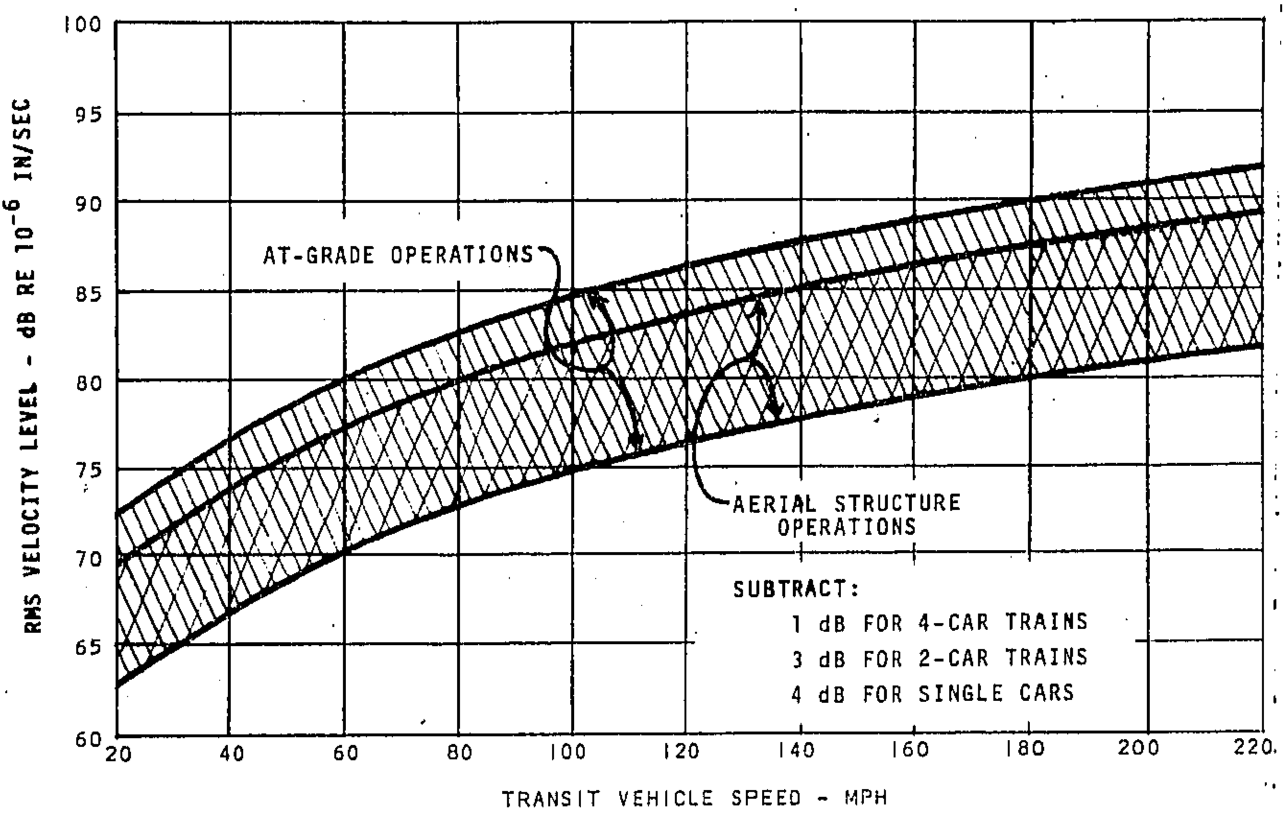


FIGURE 6 OVERALL GROUND-BORNE VIBRATION VELOCITY LEVEL RANGE FOR 8-CAR [600 FT LENGTH] CONVENTIONAL RAIL TRANSIT TRAINS AT 50 FT FROM TRACK CENTER-LINE FOR SURFACE OPERATIONS

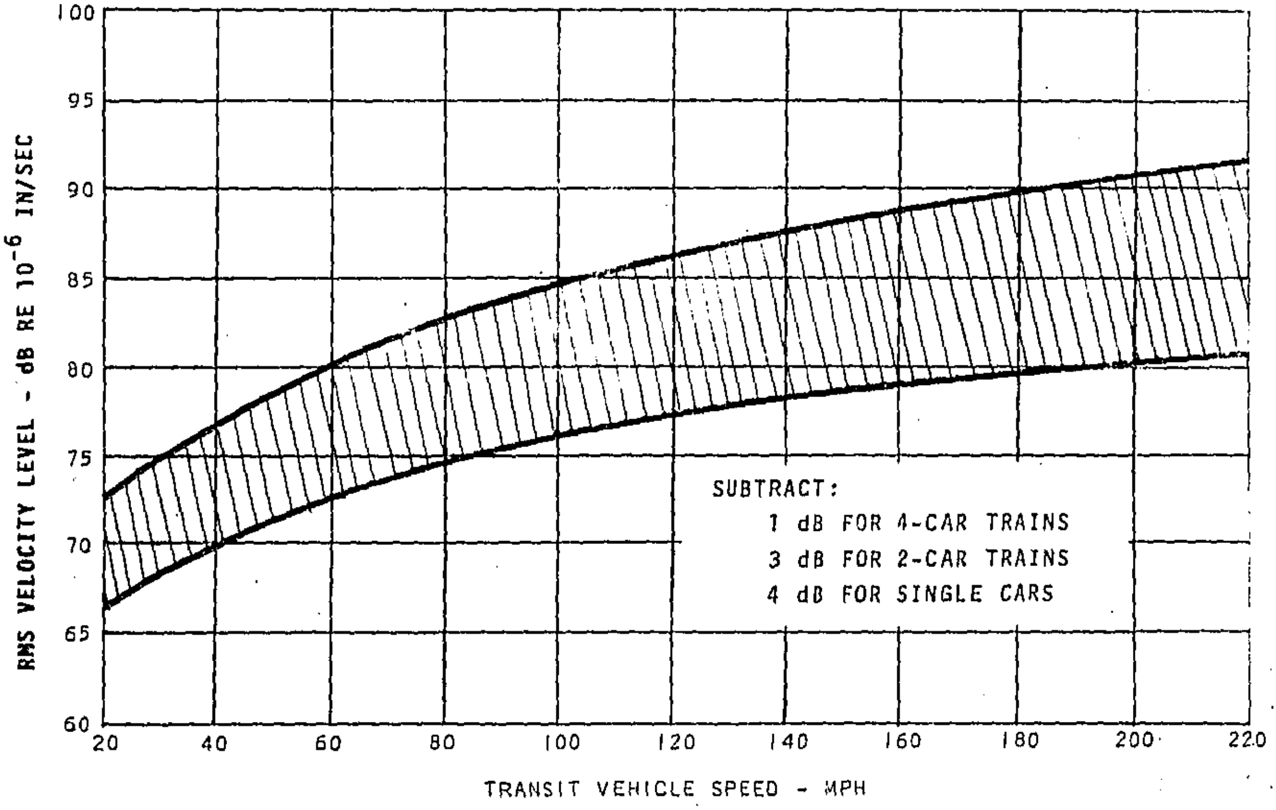


FIGURE 7 OVERALL GROUND-BORNE VIBRATION VELOCITY LEVEL RANGE FOR 8-CAR [600 FT LENGTH] CONVENTIONAL RAIL TRANSIT TRAINS AT 25 FT DISTANCE FROM SUBWAY IN SOIL STRATA

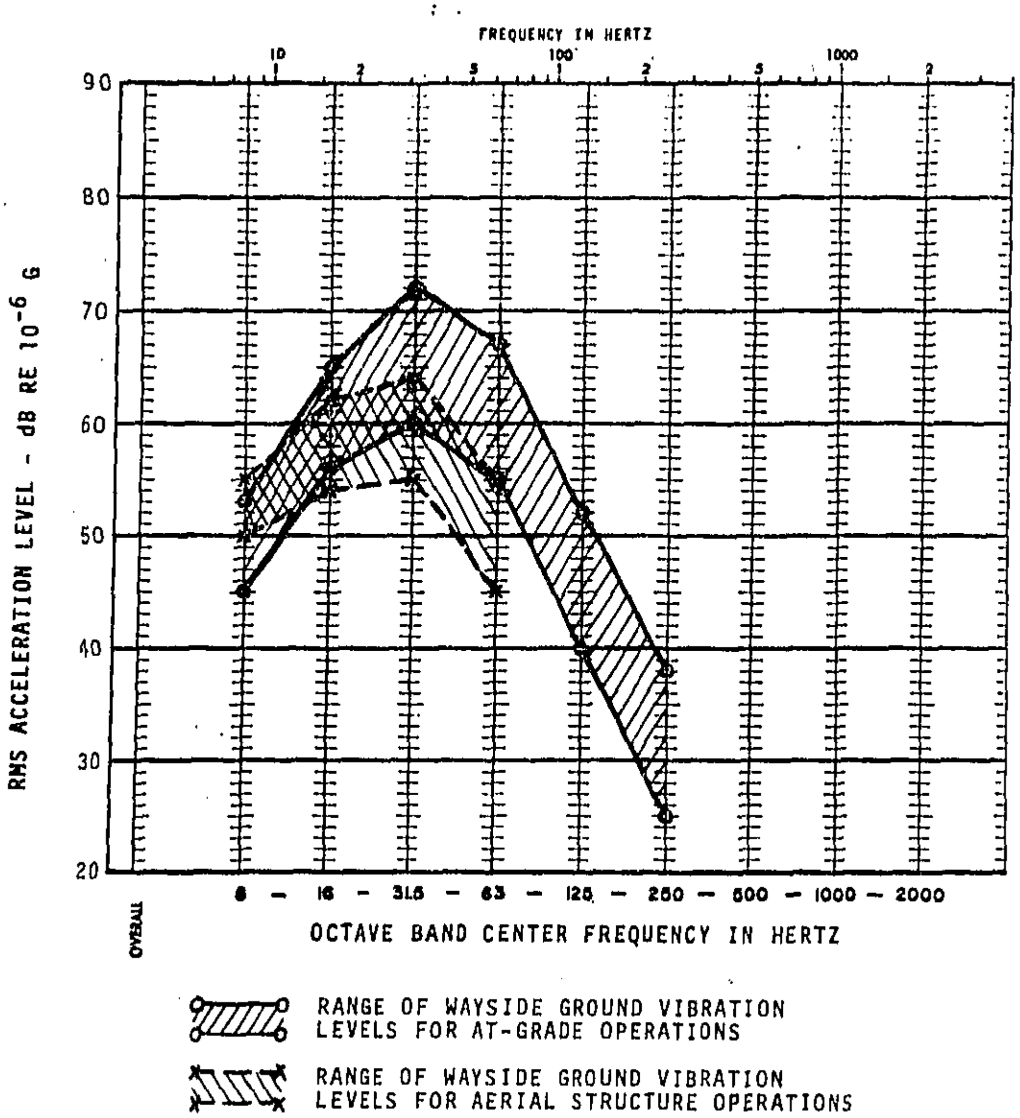


FIGURE 8 TYPICAL RANGE OF GROUND VIBRATION SPECTRA AT 50 FT FROM TRACK CENTER-LINE FOR SURFACE OPERATIONS OF CONVENTIONAL RAIL TRANSIT TRAINS, 8-CAR TRAINS AT 60-70 MPH

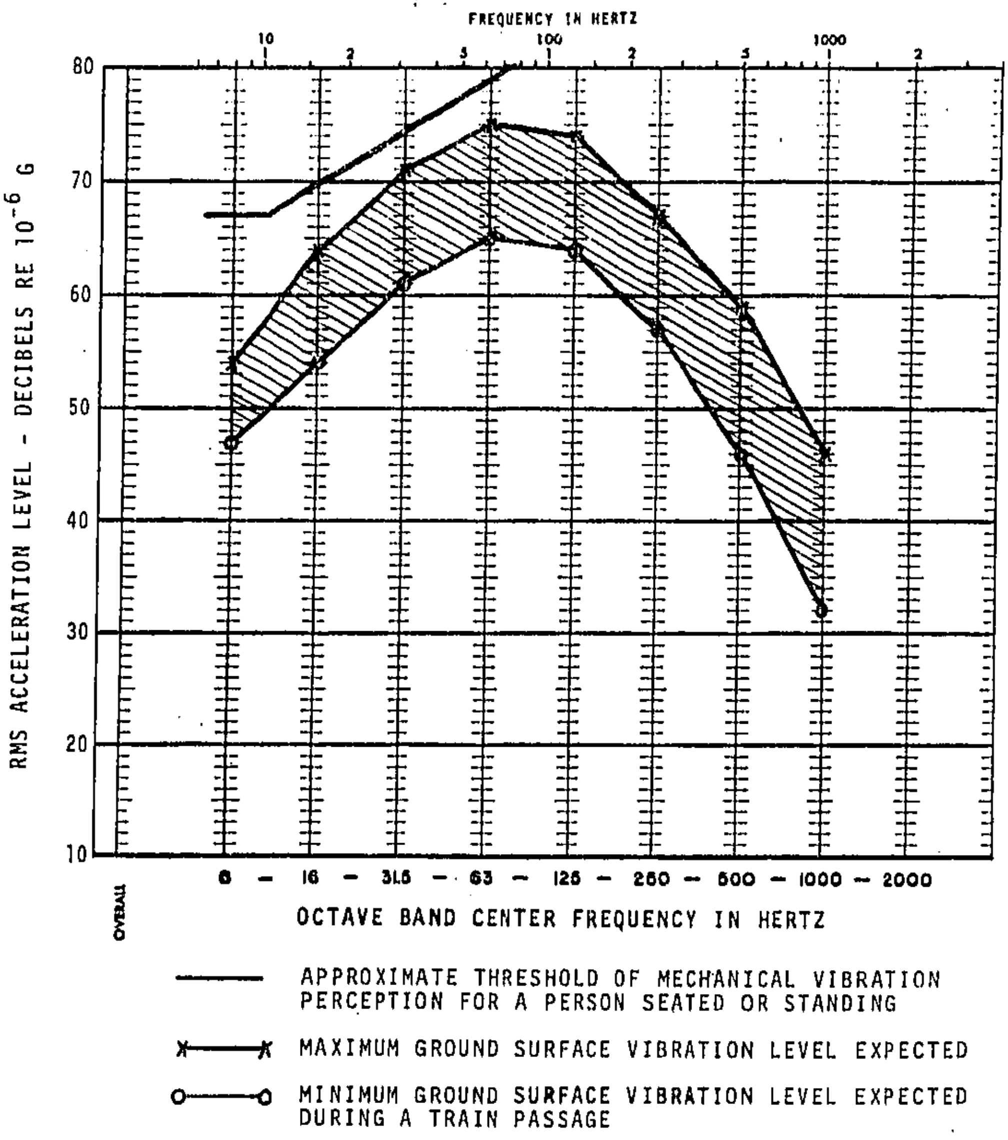


FIGURE 9 EXPECTED RANGE OF VIBRATION ACCELERATION LEVELS FOR A FREE SURFACE AT 25 FT FROM A CONVENTIONAL RAIL SYSTEM SUBWAY IN SOIL STRATA. 8-CAR TRAINS [600 FT LENGTH] AT 75-80 MPH IN A TWO-BOX CONCRETE SUBWAY STRUCTURE

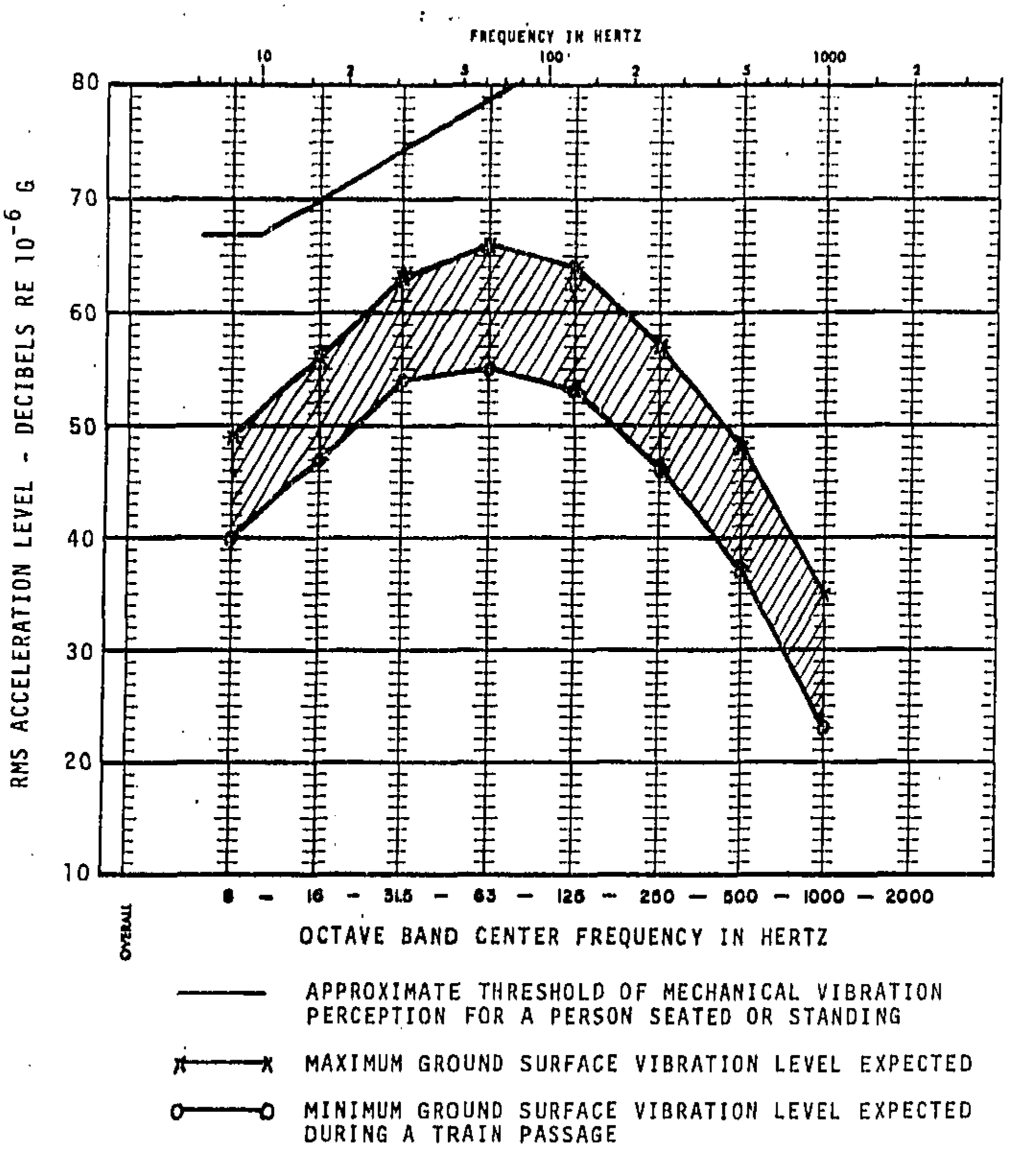


FIGURE 10 EXPECTED RANGE OF VIBRATION ACCELERATION LEVELS AT A FREE SURFACE FOR SOIL STRATA AT 25 FT FROM A CONVENTIONAL RAIL SYSTEM ROCK BASE SUBWAY [MIXED-FACE STRUCTURE]. 8-CAR TRAINS [600 FT LENGTH] AT 75-80 MPH

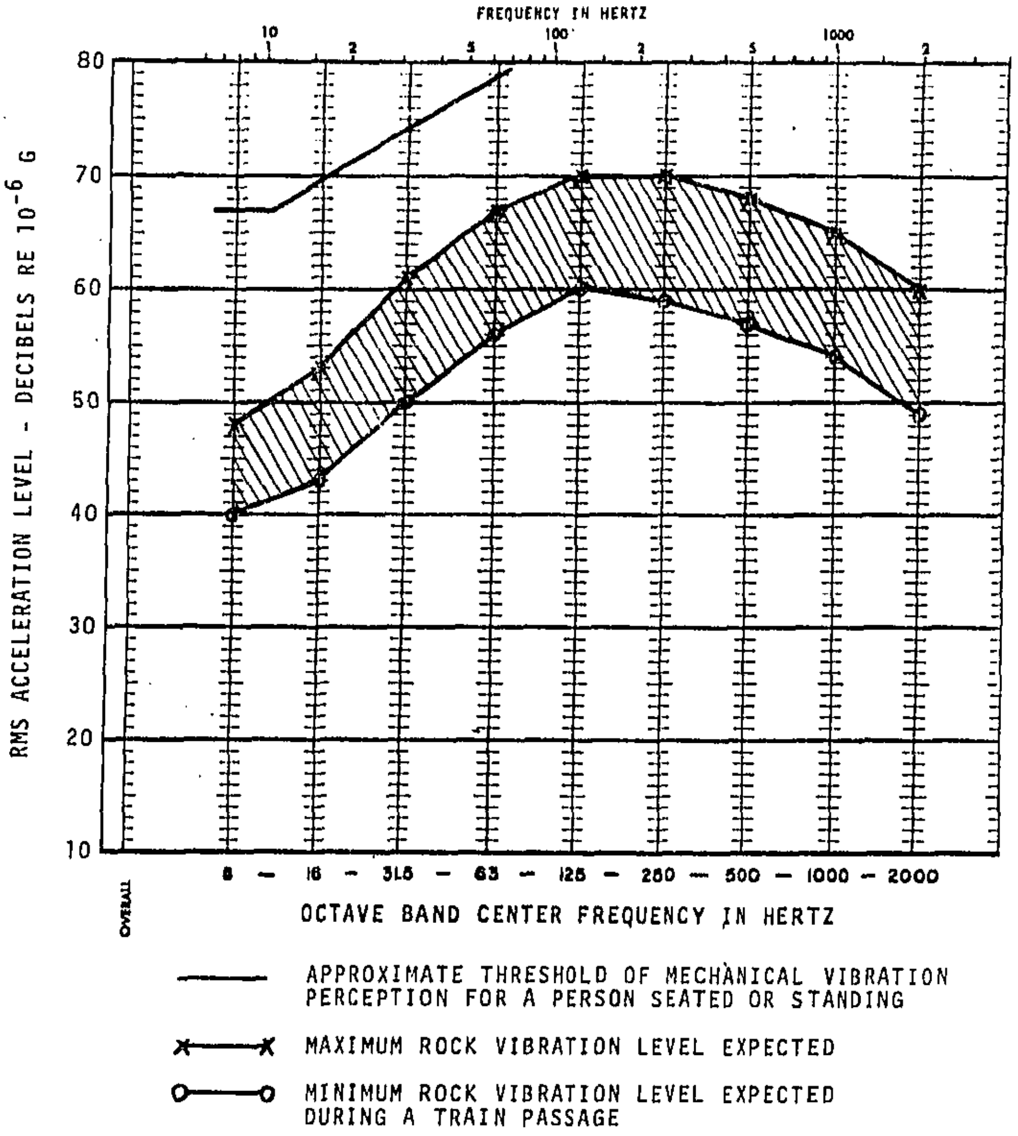


FIGURE 11 EXPECTED RANGE OF VIBRATION ACCELERATION LEVEL IN THE ROCK AT 25 FT FROM A CONVENTIONAL RAIL SYSTEM ROCK TUNNEL. 8-CAR TRAINS [600 FT LENGTH] AT 75-80 MPH

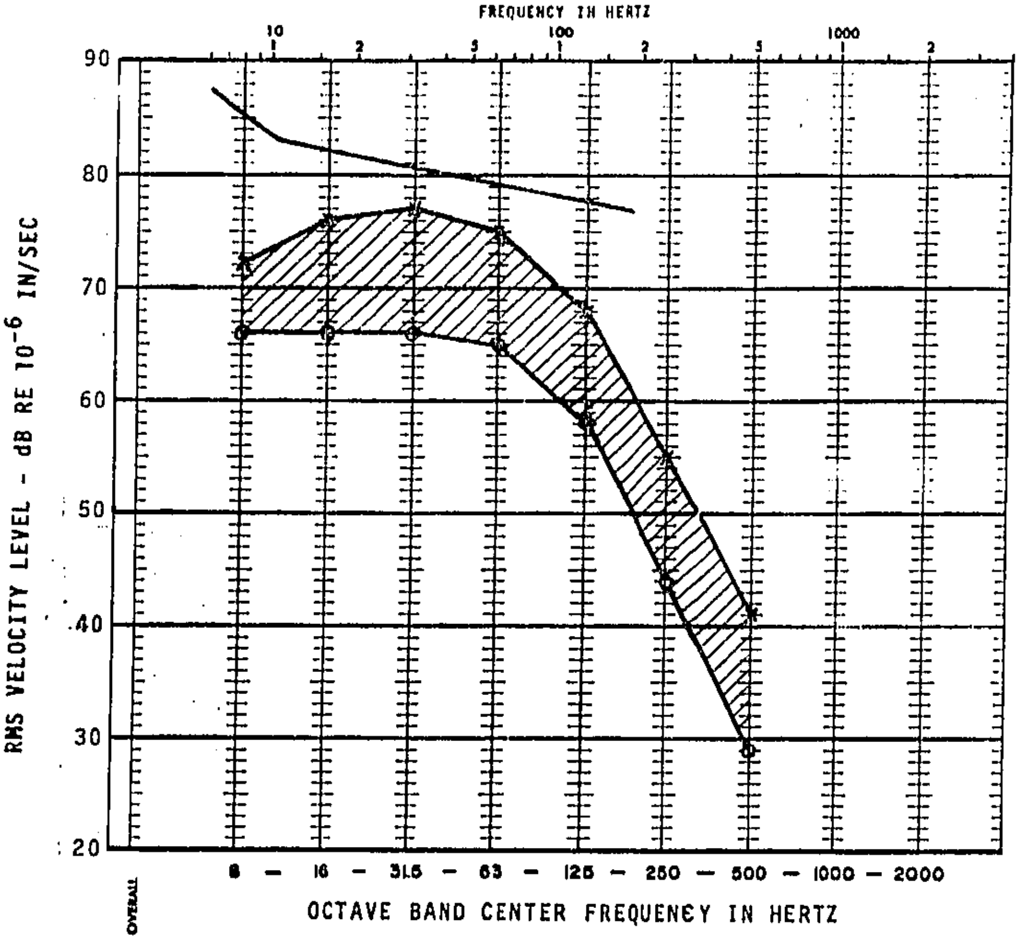
in the shape of the vibration spectrum curves is due to the high frequency attenuation which occurs in earth but which is negligible for vibration transmitted over relatively short distances in rock.

The vibration levels indicated by Figures 6 through 11 are for the free surface of the ground near a transit system way structure, i.e., at the free surface of the ground above a subway or beside a surface installation. In general, it is found that the vibration levels of building structures, especially for heavy masonry buildings, are 10 to 20 decibels less than the free surface vibration levels, whereas the vibration levels of concrete slabs on grade and lightweight building surfaces are similar to the free surface levels.

The octave band frequency distribution charts are shown in terms of vibration acceleration level because most measurements are made and reported in terms of acceleration level. For comparison, Figure 12 shows the spectrum for earth base subways in terms of vibration velocity levels. From Figure 12 it is apparent that the most significant frequency range is the range included in the 16, 31.5, and 63 Hz octaves.

The basis of the subway operation ground-borne vibration level estimates are the results of measurements made at the TTC facilities and the results of measurements made at the Bay Area Rapid Transit District Test Track, which were converted to ground vibration levels next to tunnels, and other data given in the literature [see references 4, 5, 7, 9, 22, 23, 24 and 25]. The vibration levels determined from these completely different sources are consistent and indicate that the ground vibration levels near conventional rail transit system structures can be estimated very closely.

Prediction of the ground-borne vibration levels from rail transit train operations in rock base subways can be accomplished using the vibration levels for operations in earth base subways and applying conversion or correction factors depending on the relative mechanical properties of soil and rock and the subway structures. The most significant factors in determining the ratio of vibration levels at the subway for comparing vibration levels near the subway in rock or in soil are the mechanical or acoustical impedance of soil and rock and the mechanical impedance of the tunnel structures.



—— APPROXIMATE THRESHOLD OF MECHANICAL VIBRATION PERCEPTION FOR A PERSON SEATED OR STANDING

×——× MAXIMUM EXPECTED GROUND SURFACE VIBRATION LEVELS

o——o MINIMUM EXPECTED GROUND SURFACE VIBRATION LEVELS DURING A TRAIN PASSAGE

FIGURE 12 EXPECTED RANGE OF VIBRATION VELOCITY LEVELS AT A FREE SURFACE AT 25 FT FROM A CONVENTIONAL RAIL SYSTEM SUBWAY IN SOIL STRATA. 8-CAR TRAINS [600 FT LENGTH] AT 75-80 MPH IN A TWO-BOX EARTH BASE SUBWAY STRUCTURE

It is reasonable to assume that the forces applied by the rail support pads to the trackbed will be the same in an earth or rock base subway. Since the mechanical impedance is the ratio of force to velocity, the vibration velocity levels and, hence, the acceleration levels of the subway base will be directly proportional to the mechanical impedance at the trackbed. An approximation of the ratio of vibration levels in the earth or rock directly adjacent to subway structures in rock and in earth is given by

$$\frac{a_{RT}}{a_{ET}} = \frac{Z_{st} + Z_s}{Z_{st} + Z_r}$$

where a_{RT} is the vibration in the rock adjacent to a subway structure in rock, a_{ET} is the vibration of the soil adjacent to a subway in soil, Z_{st} is the impedance of the structure, Z_s is the soil impedance and Z_r is the rock impedance.

In determining the mechanical impedance of a system there are two general frequency ranges where the impedance, or at least the ratios of impedances, can be determined from simple, easily determined properties of the system components. In the low frequency region the mechanical impedance is stiffness controlled, that is, the stiffness of the support system is the primary component of the mechanical impedance and the amplitude of vibration is proportional to the stiffness. In the high frequency region the mechanical impedance is mass controlled and the amplitude of vibration is inversely proportional to mass times frequency squared. In the transition area between low and high frequencies the amplitude of vibration is controlled largely by the damping and other coupling factors in the mechanical system.

In the equation given above, at low frequencies, the subway structure impedance, Z_{st}, is small and the ratio of vibration levels is approximately Z_s/Z_r. For soil the acoustic impedance is typically 3,500 to 10,000 lbs secs/cu ft and for rock typical values are 35,000 to 70,000 lbs secs/cu ft. The effect of a rock base should, therefore, reduce the vibration levels by 12 to 20 decibels at low frequencies.

At high frequencies the subway structure impedance, Z_{st}, is large and the vibration levels for a rock or earth supported subway structure are comparable. Since the ratios of low frequency and high frequency vibration levels are considerably different, it is necessary to determine the frequency range where the transition occurs.

In determining the range of frequencies where transition of mechanical impedance from stiffness control to mass control occurs there are two basic sources of information. The literature and information on ground vibration created by blasting in rock and in soil indicates the frequency spectrum shifts upward by a factor of about 3 for rock blasts compared to blasts in soil and the peak acceleration amplitudes remain about the same for equal applied forces. For a typical single or double box subway in soil, the natural frequency of the subway structure on the earth spring is in the range of about 17 to 32 Hz and, therefore, the transition from stiffness control to mass control starts at about 30 Hz for subway structures supported on soil. For a rock base subway the transition, of course, will occur at a much higher frequency, on the order of 125 to 250 Hz. With the information from blasting and the calculated natural frequencies of subway structures, it is possible to construct vibration amplitude ratio curves which bridge the gap or transition section between the low frequency or stiffness controlled region and the high frequency or mass controlled region.

In addition to the comparison of the mechanical impedances and the information on ground vibration from blasting there are several other means available for estimating the probable ratios of amplitudes of vibration next to rock and earth base subways, at least for the low frequency region. The ratio of the coefficients of subgrade reaction for rock and soil indicate a comparison of the support stiffness, see reference 35. The ratio of Young's modulus for rock and soil also indicates a measure of the stiffness of the two support systems. Finally, the radiation impedance or the radiation efficiency for a vibrating cylindrical source in soil and in rock gives an indication of the relative efficiency and relative vibration levels to be expected from a subway structure in soil or rock for long wavelengths [low frequencies]. For each of these ratios the range of properties of soil and rock likely to be encountered indicates that, for the low frequency region, for rock base subways the vibration level will be 10 to 20 dB less than for earth base subways.

The net result of this analysis is that the vibration levels of a rock base subway structure, relative to an earth base structure, should be 10 to 15 dB less for frequencies below about 60 Hz, about 10 dB less for the range from 60 Hz to 250 Hz and 3 to 6 dB less for frequencies above 250 Hz. The measurements at mixed-faced and earth base subways in Toronto confirm this estimate except to indicate less decrease in low frequency range vibration and more decrease in high frequency range vibration.

The net results of the measurements comparing ground-borne vibration levels from earth and rock base subways indicate that the low frequency vibration of the subway and surrounding geologic media is about 8 dB less with rock base. For the mid frequency range the average subway vibration level is 7 to 8 dB less and in the earth above the subway and rock the levels are 10 to 12 dB less. For the high frequency range the subway structure vibration level is about 6 dB less and in the earth above the subway and rock the levels are 10 to 12 dB less. Some of the differences between subway structure and surrounding earth vibration levels are due to wavelength effects at the rock-soil interface. The adjustments to the correction factors, as indicated by the measurements at TTC facilities, have been included in determining the vibration levels given on Figures 10 and 11.

In determining the vibration levels as a function of location in the ground near transit system facilities there are, of course, a number of factors which must be considered because the transmission of vibration through the earth is a more complex phenomonen than airborne sound transmission. It is possible to use the data given in Figures 6 through 12 to evaluate the vibration level at different distances from the transit system facilities and for different operational speeds in a manner similar to that given in Section II for airborne noise from surface operations. The difference is that the attenuation of vibration as it transmits to earth is very frequency dependent and, therefore, the spectrum of the vibration does have a different shape at different distances from tunnels.

In Section IV of the report the transmission of vibration through various types of geologic media is discussed. For the purpose of this section of the report it suffices to indicate that at the 50 ft separation for the surface vibration levels given on Figures 6 and 8 and at the 25 ft separation for subsurface operations given on Figures 9 through 12, the spectrum levels should be shifted up or down according to the overall vibration velocity level charts given on Figure 6 or 7 to estimate the vibration levels as a function of train speed. With the charts given in Section IV of the report, the vibration levels can further be adjusted to account for differences in the separation distance between the transit system facilities and the observation points.

It must be remembered that the estimated vibration levels assume that the track and car wheels will be maintained in good smooth condition. Rail corrugations and wheel flats can result in considerable increase in noise and vibration levels. The TTC has reported a 20 dB decrease in vibration levels by using maintenance procedures eliminating wheel flats and other poor operating conditions of equipment, see reference 8. Measurements of railroad noise and vibration levels indicate increases of 10 to 20 decibels when cars with wheel flats pass by compared to levels with cars having smooth wheels. It is, therefore, apparent that poor maintenance of the wheels and rails could result in vibration levels 10 to 20 dB greater than those indicated in Figures 6 through 12.

B. Tracked Air Cushion Vehicles

For tracked air cushion vehicles the supporting air cushion stiffness will transmit forces to the roadbed which will, in turn, induce ground-borne vibration. The suspension system for a tracked air cushion includes a primary spring which consists of the air cushion between the vehicle and the track, the air cushion structure, and a secondary suspension system between the air cushion structure and the car body. Thus, the suspension system is similar to a conventional rail system with the air cushion assembly analogous to the conventional rail vehicle truck. The forces generated by the suspension system are, therefore, dependent on the natural frequencies of the primary and secondary suspension systems and the amplitudes of motion of the vehicle as it travels on the guideway.

Most of the analyses of tracked air cushion vehicles indicate primary suspension natural frequencies of 5 to 10 Hz and secondary suspension natural frequency of 1 to 5 Hz, see references 42, 43, 44, and 45. These natural frequencies imply that the frequency distribution of ground vibration from tracked air cushion vehicles will be predominantly in the frequency range from 1 to 15 Hz. This is one to two octaves lower than for the conventional rail vehicles and, therefore, is in a range which is much less likely to result in perception of the vibration by people in wayside buildings or other facilities.

Because of the basic requirements of the system, the air cushion vehicles will have gross weights of less than one-half that of similar conventional rail vehicles. In order to have satisfactory ride quality the amplitudes of motion of the vehicle body will necessarily be similar or at least not significantly greater than for a conventional rail vehicle.

Since the stiffnesses of the suspension system must be considerably less than for the conventional rail vehicle in order to obtain the very low natural frequencies for the lighter weight vehicle supporting system, the net forces applied to the supporting structure must be considerably less than for conventional rail. This implies, therefore, that the ground vibration levels will be somewhat or considerably less than for the conventional rail.

With an air cushion vehicle, the forces applied by the suspension system to the supporting track are distributed over a large area because of the nature of the air cushion support. In contrast, the rail vehicle applies large forces in local areas due to impacts between the wheels and rail. The forces applied to the rail are, of course, somewhat distributed by the resilient rail supports, however, the forces applied to the supporting media are more concentrated with the conventional rail than with the air cushion support system. This aspect of the comparison of the two systems also tends to indicate that the vibration levels from the air cushion system should be considerably less than for the conventional rail.

Thus, since the ground-borne vibration frequencies and amplitudes are expected to be lower than for conventional rail rapid transit vehicles, it appears that ground vibration from tracked air cushion vehicles should not create significant wayside intrusion.

C. Tube Vehicles

For tube vehicles the ground vibration would be similar to that expected from conventional rail or air cushion vehicles depending on the type of support used for the vehicles in the tubes. It is possible, of course, to use conventional steel wheel and rail, pneumatic rubber tires or air cushions for the support of a tube vehicle, except for vacuum tube vehicles which require wheels of some type. With steel wheels and rails the vibration levels are expected to be similar to conventional rail vehicles in tunnels. With pneumatic rubber tires, the vibration levels would be expected to be of similar amplitude but approximately one octave lower in frequency than for the conventional rail. With the air cushion support the vibration levels would, as indicated, be lower in frequency and in amplitude than expected from conventional rail vehicles.

IV. NOISE/VIBRATION PROPAGATION IN GEOLOGIC MEDIA

Most of the information available on attenuation of vibration as it transmits through soil or rock is based on the propagation of waves induced by shock excitation such as blasting or earthquakes. There is some data available on the attenuation of transit vehicle induced ground vibration and the combination of this with data available from geophysical studies provides a basis for estimating the propagation characteristics of noise and vibration from transit vehicles in various types of geologic media.

The basic fact which has emerged from studies of ground-borne vibration from transit vehicles is that, for the distances over which transit vehicle vibration levels are significant, there are only two basic types of media which must be considered; soil and rock. For propagation over distances of a few hundred feet the changes in the propagation characteristics of different strata of soil are not significant in terms of deriving the expected vibration levels from a transit train. Similarly, when the vibration is being transmitted through rock, changes in the rock strata do not have a significant effect on the propagation characteristics until the distances involved are very large.

The presence of water in soil does increase the efficiency of energy transfer from a subway to the surrounding soil, and perhaps the efficiency of energy transfer to a building, but it does not significantly effect the propagation of vibration through the soil once the energy has been transmitted to the soil strata.

The amplitudes of vibration from transit vehicles are such that the energy is dissipated in a few tens of feet or at least within a few hundred feet of the source. It is, therefore, only necessary to consider the basic characteristics of soil and the basic characteristics of rock in deriving the propagation characteristics of the vibration from the transit vehicles.

A. Vibration Transmission in Soil

In Section III of this report, vibration levels from conventional rail vehicles as observed at a distance of 25 ft from subways or 50 ft from surface operations are indicated. The vibration levels indicated are for train speeds of 75 to 80 mph and higher levels are to be expected at higher speeds. Also, at lesser distances, the levels will be greater. At larger separation distances, the vibration levels will be less and the spectrum shape changed considerably.

One of the significant factors in terms of vibration level transmitted to the ground by an earth base subway is the presence of water in the earth around the subway. Vibration measurements at the DARTD Test Track showed differences as great as 10 dB in the vibration level when the soil was dry compared with data taken after a heavy rainfall. The study reported in reference 33 indicated an increase of 11 dB in the energy imparted to the ground from blasting in the presence of water when compared to the results from dry earth.

These results on vibration levels with the presence of water in the earth indicate that it can be expected that the vibration levels from the transit system subways could be as much as 10 decibels greater than would be expected from measurements made with dry earth surrounding a subway. The vibration levels for subways in soil, presented on Figures 7, 9, and 12 indicate the expected vibration levels with ground water present. In the absence of water the vibration levels should be near the lower extremes of the ranges shown.

The apparent frequency distribution of the ground-borne vibration from transit trains changes as the distance from the source increases because, in soil, high frequency vibration is attenuated at a more rapid rate than low frequency vibration. This effect is the most significant factor in determining the amplitude and frequency distribution of wayside ground vibration from transit vehicle operations.

In deriving the attenuation of the vibration as it propagates away from a subway structure, two effects must be considered; the reduction in level due to spreading and the reduction in level due to absorption or dissipation in the soil. Attenuation of the vibration waves by dissipation or absorption is the dominant source of attenuation at high frequencies or or at large distances. The attenuation due to spreading is the dominant source of attenuation for low frequencies and short distances. In deriving the absorption two types of waves must be considered; shear and compressive. Shear waves are attenuated more rapidly in a given distance than compressive waves, however, for the purposes of transit train vibration levels the two can be averaged over the relatively short distances involved.

Because of the relatively narrow range of characteristic acoustic impedances for soils, varying from about 3,500 lb secs/cu ft for dry, loose sand to 10,000 lb secs/cu ft for silty clay or soil saturated with water, the attenuation of vibration over relatively short distances is similar for different types of soil strata. The attenuation is at least sufficiently uniform to permit prediction of vibration levels to be expected at wayside distances from rapid transit facilities where the ground-borne vibration is of sufficient level to be significant.

Using values for the soil dissipation which have been determined empirically and listed in the literature, the approximate change in vibration level for transit train operations as a function of distance from a subway structure has been derived. Figure 13 indicates the approximate change in the overall vibration velocity level as a function of distance from a subway structure. This chart was derived considering both the change in spectrum shape and the change in vibration levels at low frequencies as the distance from the source increases.

As a further refinement of the chart on Figure 13, Figure 14 is a chart indicating the approximate change in vibration level as a function of frequency and distance from an earth base subway structure. The chart is plotted in a manner to show the change in vibration levels which should be applied to the spectra on Figures 9, 10, and 12 for locations either closer to or farther from the tunnel structure.

Figure 15 indicates an example of the application of the attenuation factors to vibration levels from a subway. The example shown is the vibration from a 600 ft long train traveling at 70 mph in a concrete box subway in soil. The vibration levels are shown at the subway wall and for distances up to 100 ft.

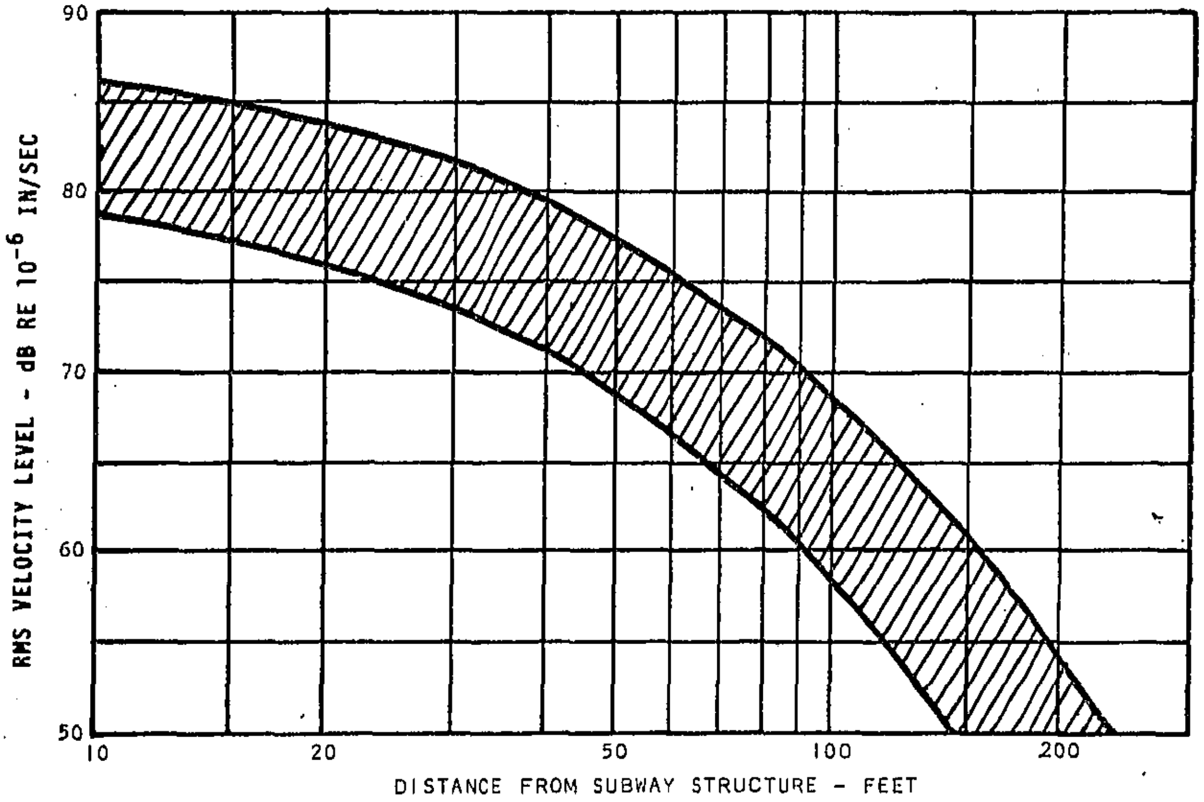


FIGURE 13 RANGE OF EXPECTED OVERALL VIBRATION VELOCITY LEVELS AT THE GROUND SURFACE AS A FUNCTION OF DISTANCE FROM A RAIL TRANSIT SYSTEM EARTH BASE SUBWAY. 8-CAR TRAINS AT 75-80 MPH IN A TWO-BOX CONCRETE SUBWAY STRUCTURE WITH RESILIENT RAIL FASTENERS AND RIGID TRACKBED

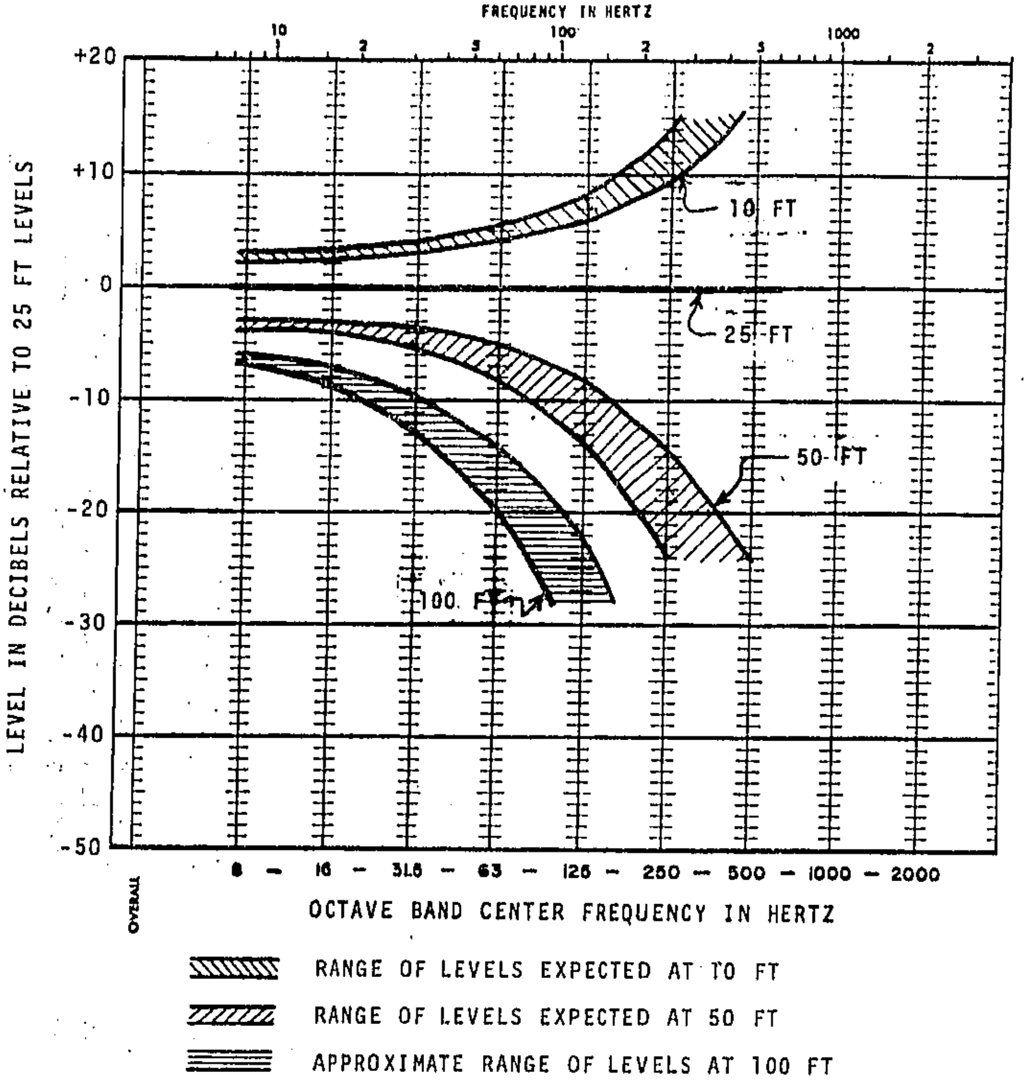


FIGURE 14 GROUND-BORNE VIBRATION LEVELS RELATIVE TO THE LEVELS AT 25 FT FROM A SUBWAY STRUCTURE IN SOIL STRATA. THE CHART INDICATES THE APPROXIMATE ATTENUATION OF VIBRATION BY SOIL AS A FUNCTION OF FREQUENCY AND DISTANCE

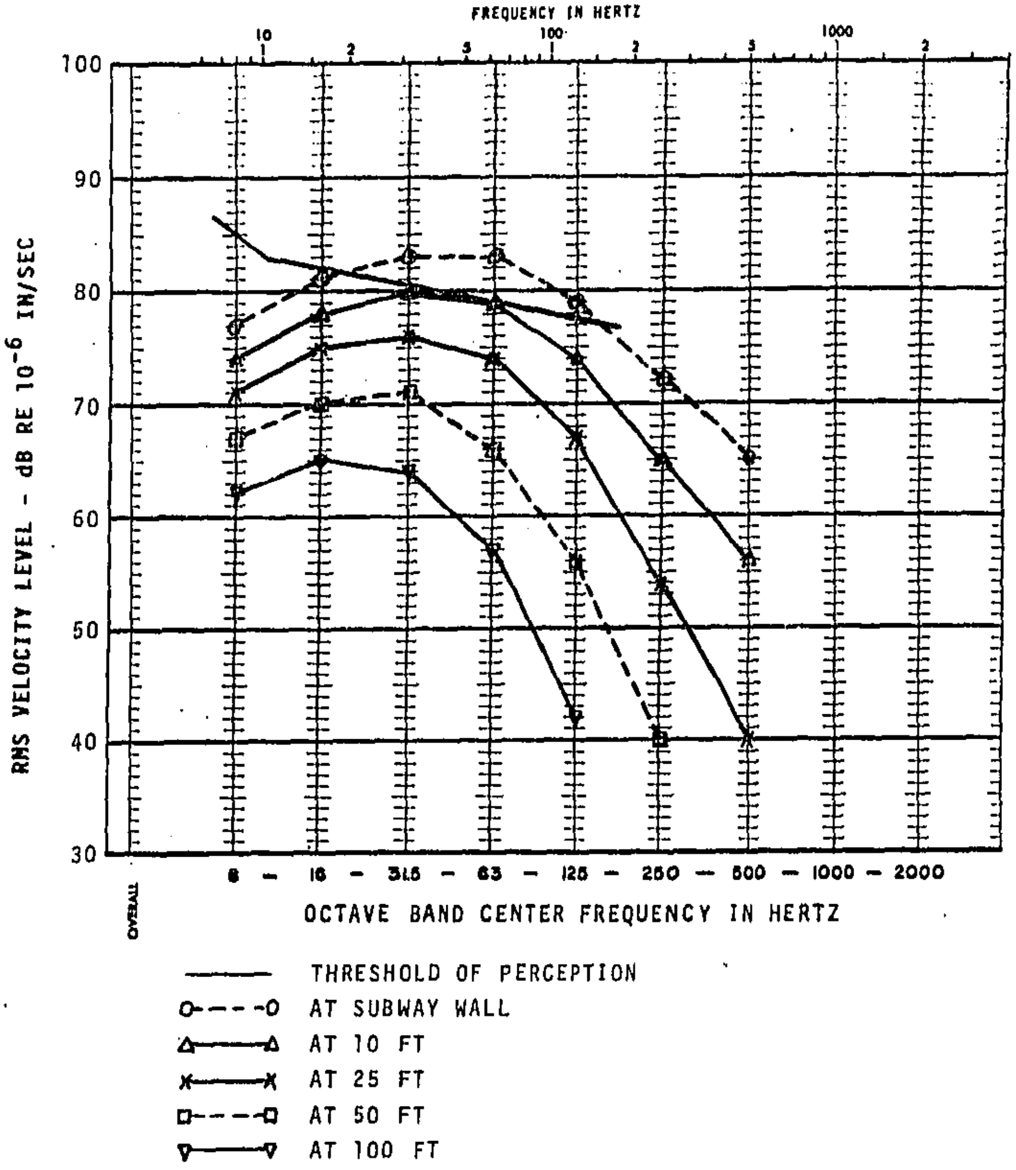


FIGURE 15 MAXIMUM GROUND SURFACE VIBRATION VELOCITY LEVELS EXPECTED AT VARIOUS DISTANCES FROM AN EARTH BASE CONCRETE BOX SUBWAY STRUCTURE. 8-CAR [600 FT LENGTH] TRAINS AT 70 MPH

B. Vibration Transmission in Rock

In rock, the attenuation of vibration levels is predominantly due to the spreading of the vibration energy as it propagates away from the source. There is very little dissipation in rock and the attenuation with distance is essentially independent of frequency. The relative vibration levels can, therefore, be determined from a chart such as Figure 16 which indicates the relative vibration levels as a function of distance from a rock tunnel for the distances at which the vibration from transit vehicles is significant.

Another factor that is very important with mixed-face subways, i.e., for subways in rock with buildings in a soil layer above the rock, is that when vibration transmits across a rock-soil interface there is an impedance mismatch which results in a 5 dB increase in the vibration *amplitude* levels. There is a loss in energy across the interface but when vibration transmits from rock to soil the reflections at the rock face result in increased vibration amplitude level in the soil.

In estimating the vibration levels at surface locations for a tunnel located in rock strata below soil it is necessary to first calculate the vibration levels to be expected at the upper surface of the rock assuming attenuation according to Figure 16 and then to calculate the attenuation through the soil by using Figure 14 to approximate the attenuation as a function of distance through the soil. This type of calculation is more difficult than when the entire intervening media between the source and observing location is either rock or soil because the divergence portion of the soil attenuation is distorted due to diffraction. It is, therefore, not possible to use a simple nomograph to derive the attenuation of the vibration in the soil strata above rock. The rock surface represents a large source of vibration of near plane wave nature and the best result is probably attained by considering only the dissipative portion of the soil attenuation.

C. Northeast Corridor Geology

Charts on the engineering geology of the Northeast Corridor from Washington, D. C. to Boston, Massachusetts indicate that over much of the area the soil components extend to depths as

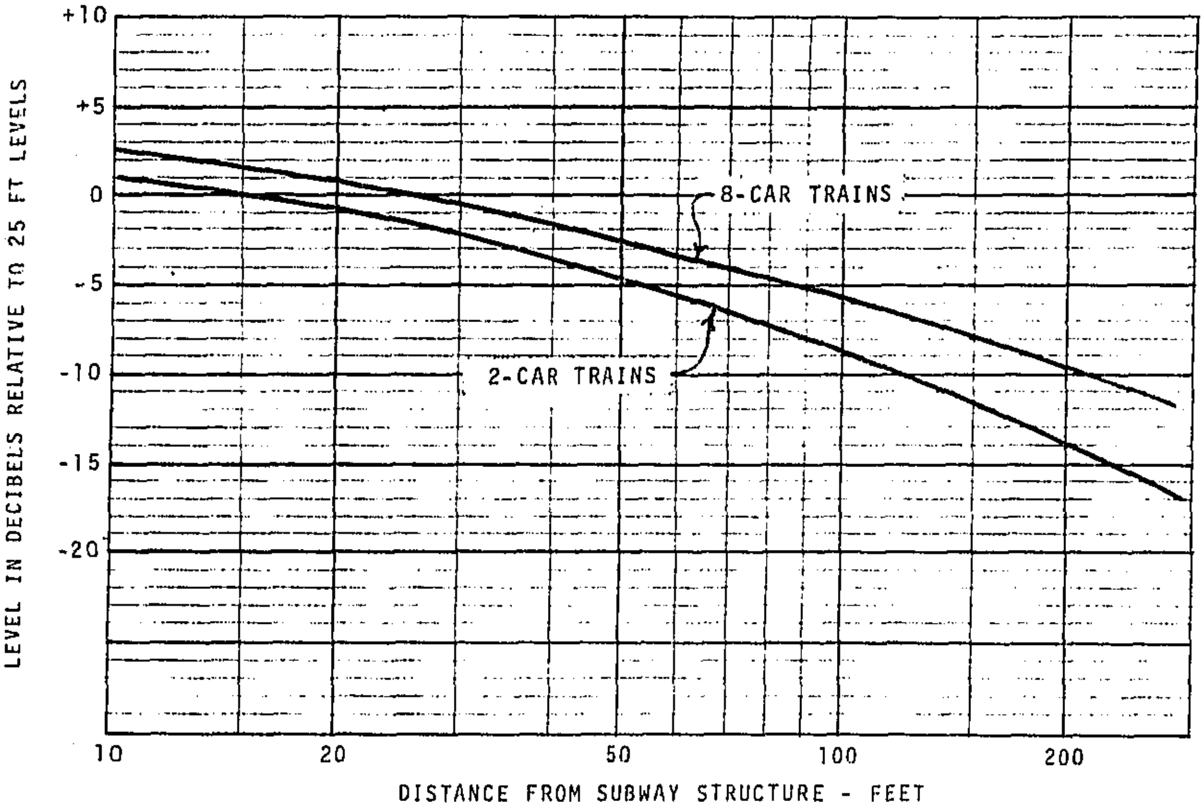


FIGURE 16 VIBRATION LEVELS IN ROCK AS A FUNCTION OF DISTANCE FROM A ROCK TUNNEL. THE ATTENUATION WITH DISTANCE IS NOT FREQUENCY DEPENDENT AND THE LEVELS SHOWN ARE RELATIVE TO 8-CAR TRAIN VIBRATION LEVELS AT 25 FT

much as 1,000 to 2,000 ft. In other areas the bedrock is at or near the surface. It is apparent, therefore, that rapid transit facilities, either on the surface or in subways, in the Northeast Corridor areas will encounter both basic types of base for the track facilities, that is, some will be located in soil and others in rock.

Beginning at Washington, D. C. and extending along the Chesapeake Bay and the Delaware River to Philadelphia the geologic charts indicate that the bedrock is deep and the overlying cover of soil strata is of 500 or more feet depth to the south and east of a line between Washington, D. C. and Philadelphia. The upper layers consist of various types of silt, the middle layers consist of clays, sands and gravels and the lowest levels are primarily sand and clay. North and west of the line approximately between Washington, D. C. and Philadelphia the bedrock extends to the surface so that any subsurface transit facilities would be located in bedrock and surface facilities would have, at best, only a thin layer of soil over the bedrock.

Along the route from Philadelphia to New York, the geology is similar to the section from Washington, D. C. to Philadelphia except that near New York the bedrock is generally more near the surface. To the north and east of New York the geology primarily consists of till overlying bedrock and it can be assumed that any subsurface transit facilities in the area from New Haven to Boston and, perhaps, from New York to New Haven would be in rock.

It appears, therefore, that the generalization that can be made with regard to the Northeast Corridor and vibration from rapid transit vehicles is that in the area from Washington, D. C. to New York the facilities would be located in soil strata and the ground-borne vibration from rapid transit vehicles would not extend to any significant distance along the route wayside. In the area from New York to Boston subsurface rapid transit facilities would probably be located in rock tunnels and while the vibration at the source would be lower in level, the ground-borne vibration would be transmitted to greater distances along the wayside. In either case, the vibration levels from rapid transit vehicles would be of sufficient level to create the possibility of intrusion in wayside buildings or other facilities only when buildings are located closer than about 100 ft to subways in soil and closer than about 200 ft to tunnels located in rock, considering train speeds up to about 150 mph.

It is, of course, possible for the vibration to create intrusion in exceptionally critical buildings at greater distances, for example, concert halls and auditoriums require lower intruding noise levels than typical office buildings or general use buildings. Also, private residences in areas where the outdoor airborne background noise level is very low require lower intruding levels from ground vibration than residential dwellings in areas where the outdoor background noise level is typical of noisier suburban and urban areas.

D. Vibration Induced by Noise in Subways

One of the possible ways in which subsurface operations of transit systems could create ground vibration which would be transmitted to the surrounding geologic media is for airborne noise in subways, which results from the noise created by transit vehicles, to induce vibration of the subway walls. To determine if this mechanism would be a possible source of wayside vibration from a transit system, calculations of the acoustically induced vibration levels have been performed.

The highest level of vibration which could occur due to acoustic excitation of the subway walls would be that due to direct transfer of acoustic energy from the air to the concrete or steel subway liner. The theory for transmission of sound energy from one media to another is well delineated in the acoustical literature and determination of the vibration levels which would result in the subway walls can be determined from application of the relatively simple laws governing transmission between media, see, for example, reference 46.

Figure 17 indicates the typical noise level expected inside a subway for a conventional steel wheel transit train traveling at 70 to 80 mph. The maximum octave band noise levels for the reverberant sound in a subway correspond to about 100 dB sound pressure level. This assumes a reverberant interior in the subway, i.e., no sound absorption on the subway walls. At higher speeds, say in the range of 150 to 200 mph, the octave band levels would be expected to be 10 to 15 dB greater so that the levels might be as great as 110 to 115 dB. The maximum reasonable sound pressure that could be expected,

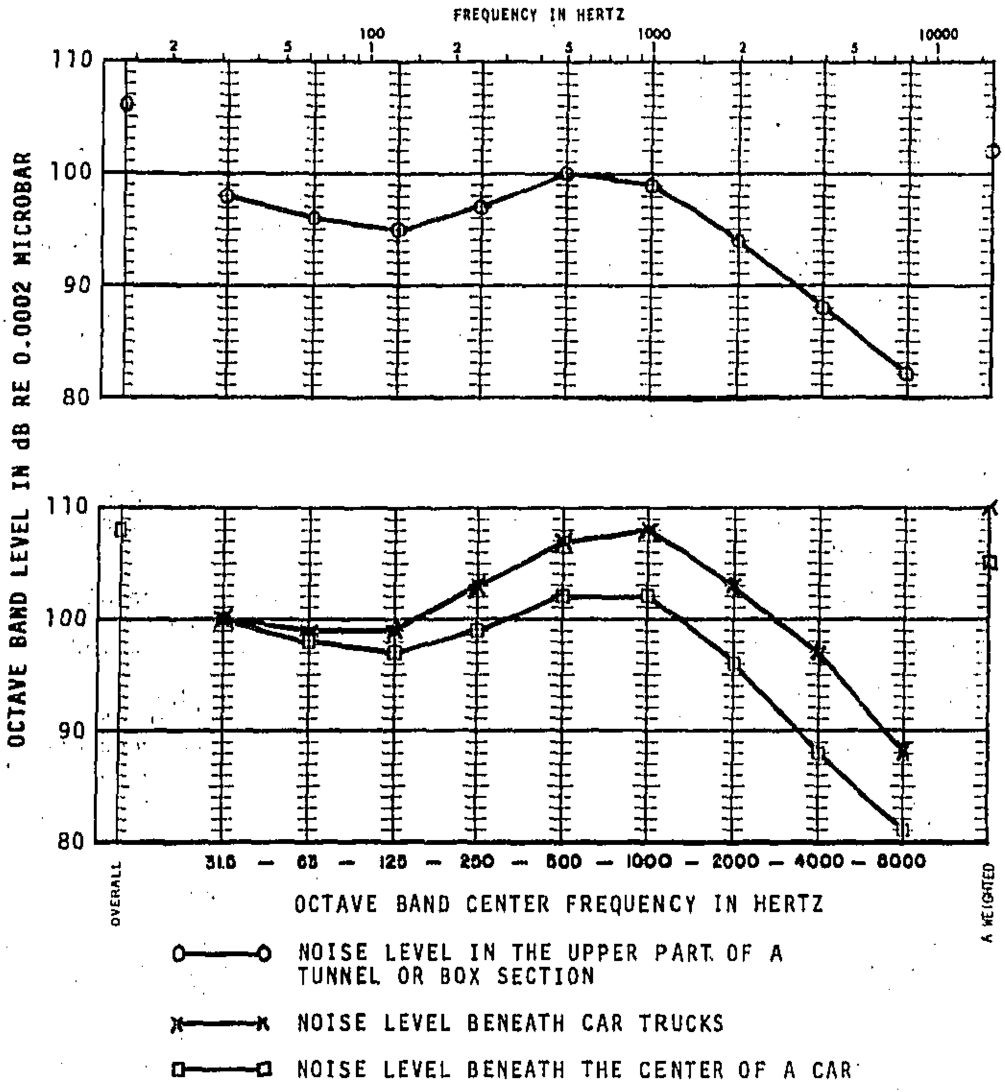


FIGURE 17 TYPICAL NOISE LEVELS INSIDE A SUBWAY FOR A CONVENTIONAL STEEL WHEEL TRANSIT TRAIN TRAVELING AT 70-80 MPH

considering the possibilities for sound insulating the transit vehicle body, is noise in the range of 120 dB octave band Sound Pressure Level.

The characteristic acoustic impedance for air is about 2.6 lb secs/cu ft and for concrete it is 40,000 to 70,000 lb secs/cu ft. Considering transmission of acoustic energy from air to concrete, the power loss at the interface would amount to about 36 dB and the ratio of particle velocity amplitudes would be about 80 dB. Converting the Sound Pressure Level at the subway wall to particle velocity and then to vibration velocity indicates that at 120 dB Sound Pressure Level, the vibration level of the wall would correspond to about 35 to 40 dB re 1 μ-in/sec or at 100 dB octave band Sound Pressure Level, the vibration level would correspond to about 15 to 20 dB re 1 μ-in/sec. These vibration levels are considerably lower than the vibration levels observed at 25 ft to 50 ft from transit system subways in the ground or at adjacent buildings. It is, therefore, apparent that acoustic excitation is not a significant source of ground vibration from transit system operations.

Even considering the subway walls to be thin and converting the Sound Pressure Level in the subway to a vibration level in soil surrounding a subway, the reduction in vibration amplitude due to the impedance mismatch is sufficient to indicate that acoustic excitation is not significant. The typical characteristic acoustic impedance for soil is 3,500 to 10,000 lb secs/cu ft. In typical dry, loose sand it is 3,500 lb secs/cu ft and for typical sand or clay soils with water the impedance is 10,000 lb secs/cu ft. The ratio of these impedances to the characteristic impedance of air is, again, great enough to result in such a large amount of energy loss at the interface that there is no significant vibration level from subway interior noise levels of the maximum value that may be encountered.

From air to soil the power loss is 30 dB at the interface and the particle velocity level decrease in amplitude is 66 dB. In this case, therefore, for 100 dB octave band Sound Pressure Level the maximum expected vibration level would be 30 dB re 1 μ-in/sec velocity and for 120 dB Sound Pressure Level the maximum vibration velocity level of the subway wall would be 50 dB re 1 μ-in/sec. These levels, again, are much lower than the vibration levels observed at some distance from operational subways with comparable sound levels and the conclusion is that the source of the vibration is the mechanical excitation of the subway structure.

E. Noise Generated in Buildings by Geologic Media Borne Vibration

The noise generated in buildings due to ground-borne vibration from transit vehicle operations is essentially proportional to the vibration velocity level. Calculations of noise levels in rooms of buildings where the walls and floors vibrate due to some source of excitation have indicated that there are some general rules which can be applied to derive the Sound Pressure Levels to be expected from a given vibration level.

The sound level in rooms is approximately proportional to the vibration velocity level of the walls and floors and the chart on Figure 18 indicates the approximate relationship between Sound Pressure Level and acceleration or velocity level for the walls and floors of a room. The chart was derived assuming average or typical sound absorption coefficients for the interior surfaces of a room and there is, of course, a range of results to be expected depending on whether the room has typical or unusually large or small amounts of sound absorption present. The range shown on the chart is intended to bridge the range from typical highly reverberant spaces to spaces that are acoustically dead. The chart shows that the sound level is about the same as the vibration velocity level in decibels re 1 μ-in/sec.

The vibration level estimates presented in Section III are the vibration levels expected at the ground surface near buildings or building footings. The degree to which the vibration is transmitted to buildings varies with the type of building, the type of foundation or support provided by the building, and the location within a building at which the vibration is observed. There are, therefore, a number of factors which must be considered in deriving the vibration levels of a building structure from the ground vibration level created by transit system operations. The vibration levels of lightweight buildings or concrete slabs on grade are very comparable or equivalent to the ground surface vibration

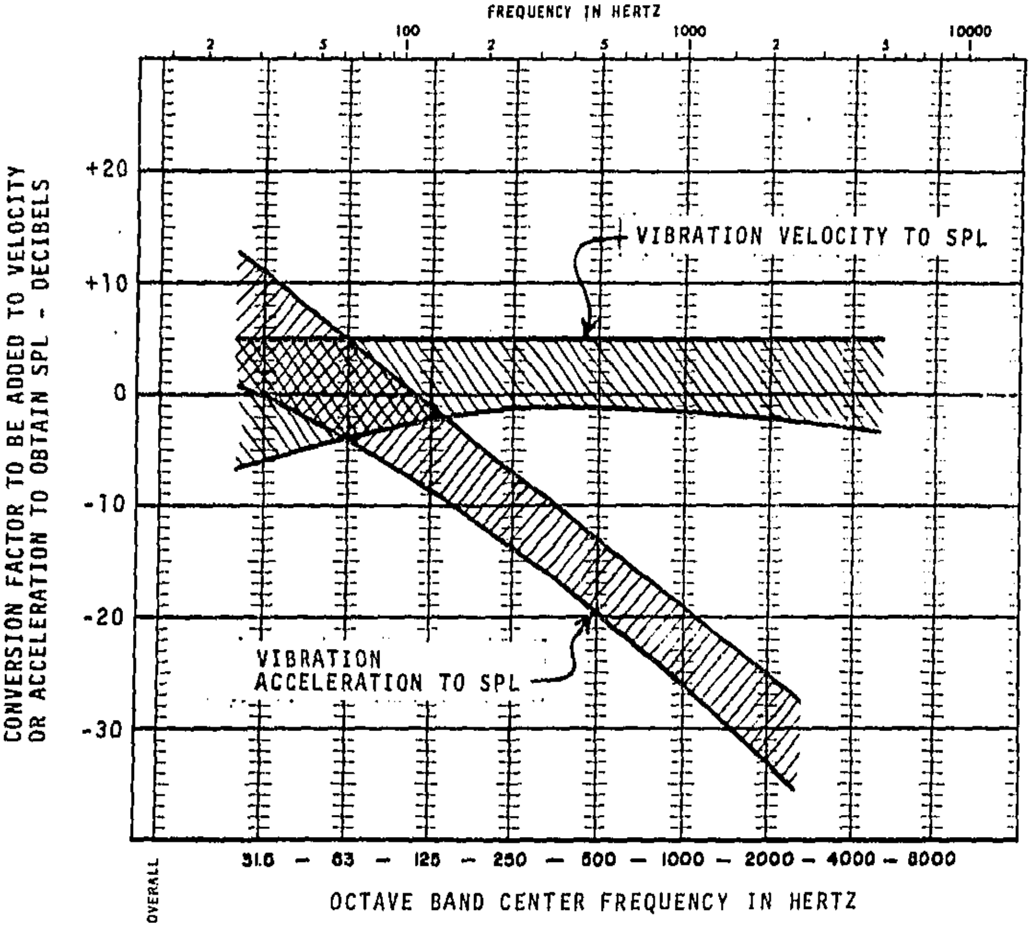


FIGURE 18 CHART FOR DETERMINING THE AIRBORNE NOISE LEVEL INDUCED BY GROUND-BORNE MECHANICAL VIBRATION

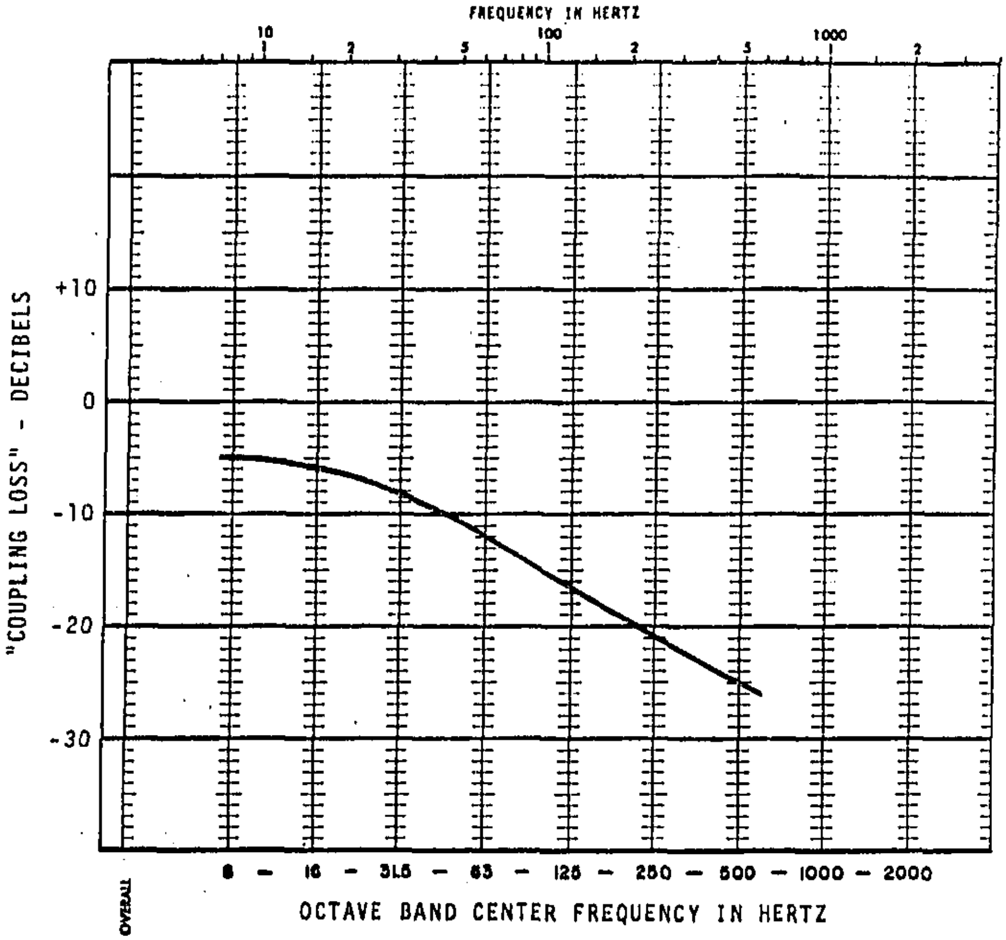
level, however, heavy masonry buildings or buildings on piling have vibration levels somewhat less than the ground-borne vibration level at the surface or in the ground in the areas directly around the building.

For massive reinforced concrete buildings there will be a "coupling loss" in transmitting the vibration from the earth to the building structure. This loss will vary with the type of support and building structure, however, it can be expected to be between 5 and 20 dB. In some types of soil, measurements of vibration transmitted to piling have indicated a coupling loss as great as 10 to 20 dB for buildings supported on piling. Other measurements have indicated differences of 5 to 20 dB between building structure vibration level and adjacent ground surface vibration levels, depending on vibration frequency and building type.

The study reported in reference 32 indicates the degree of "coupling loss" which can be assumed for a heavy masonry building supported on piles. Figure 19 is extracted from the study and indicates the "coupling loss" that can be used to estimate the reduction in vibration levels of such a building relative to the ground vibration level created by trains operating in subways. As a part of the study reported in reference 25, the vibration levels of building structures and the adjacent ground surface were measured as transit trains passed by in subways. Figure 20 indicates the range of "coupling loss" which can be expected for small to large masonry buildings on platform footings.

A further means of reducing vibration transmitted to a building is the use of resilient mounts or pads beneath the building columns. Lead-asbestos pads and rubber pads have been used as resilient mounts for building columns and have resulted in vibration level reductions of 10 to 20 decibels. This, of course, is a factor which can be considered when new buildings are constructed near a transit tunnel site, however, it is probably not possible or practical to add resilient isolation to existing building columns.

In estimating building vibration levels it should be pointed out that slabs on grade can be expected to vibrate at levels 10 to 15 dB greater for the same source of excitation than for heavy masonry buildings with stiff column footings. In a



"COUPLING LOSS" INDICATES THE REDUCTION IN VIBRATION LEVEL AT THE BASE OF BUILDING COLUMNS RELATIVE TO THE GROUND VIBRATION LEVEL. THE LOSS OCCURS BECAUSE THE GROUND VIBRATION IS NOT COMPLETELY TRANSMITTED OR "COUPLED" TO THE PILES, SEE REFERENCE 32

FIGURE 19 APPROXIMATE "COUPLING LOSS" EXPECTED FOR HEAVY MASONRY BUILDINGS SUPPORTED ON PILES

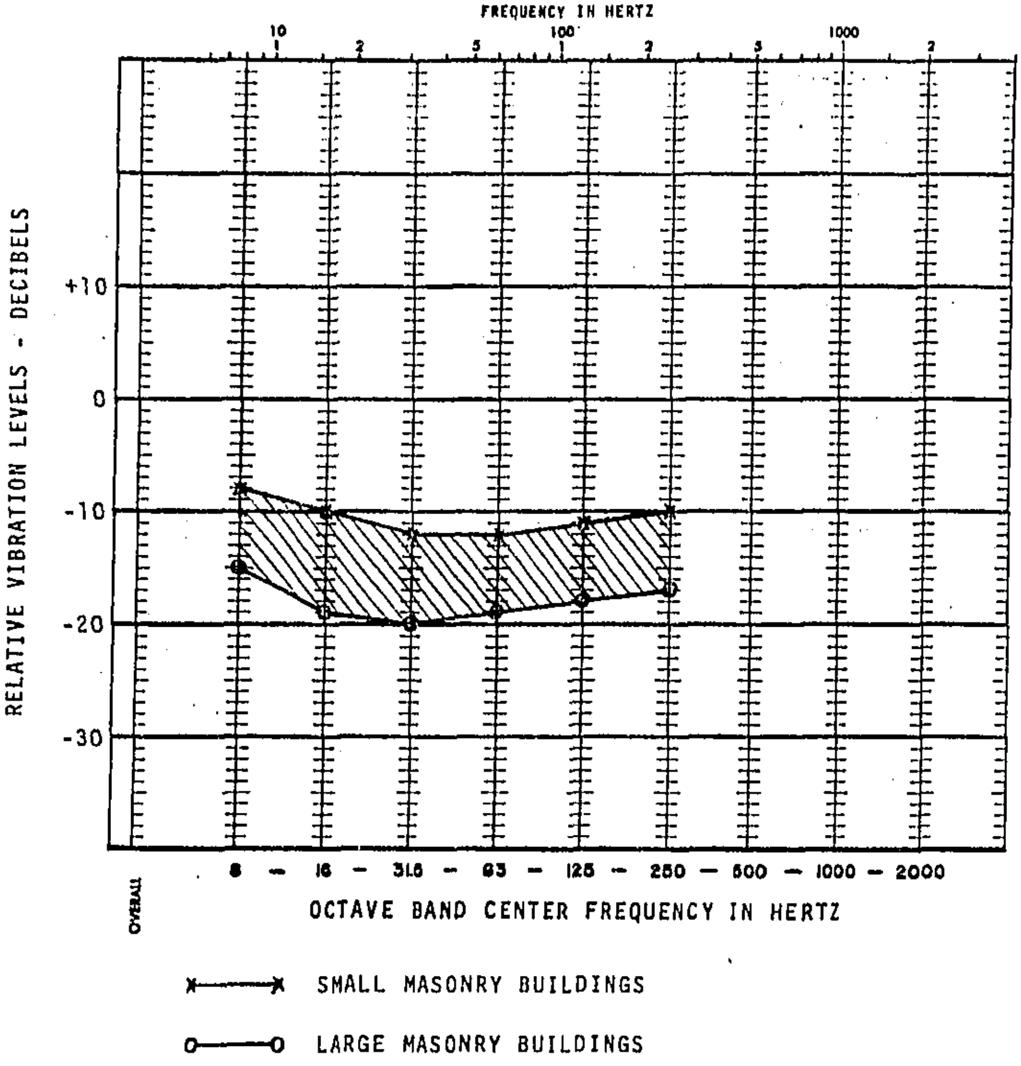


FIGURE 20 VIBRATION LEVELS OF MASONRY BUILDINGS ON PLATFORM FOOTINGS RELATIVE TO THE VIBRATION LEVELS OF THE ADJACENT GROUND SURFACE

building of masonry construction the vibration level generally drops 3 to 4 dB per floor as the vibration is transmitted vertically upward from the building foundation.

Lightweight frame buildings will, in general, show no "coupling loss" and the vibration levels experienced at the foundation will be the same as levels of the surface waves in the ground vibration. There is little or no attenuation of the low frequency vibration as it transmits to the upper floors of lightweight buildings. In fact, in some cases, where resonances are encountered, the level of the vibration can be somewhat amplified in upper floors of lightweight buildings.

Building floor resonances generally are in the range of 10 to 30 Hz. This is the range in which the maximum amplitudes of vibration are expected from the rapid transit trains, therefore, there is the possibility of resonant vibration of floors in some buildings adjacent to the transit train subways. Fortunately, the vibration from the trains is transient in nature and, according to narrow-band frequency analyses of transit car passby vibrations, the frequency of the vibration continually changes during the passage. These two effects will tend to minimize any resonances or sympathetic vibrations of building floors.

For buildings which are located very close or adjacent to a transit subway it is necessary to use a resilient material between the building pile, foundation or structure and the subway structure to prevent direct transmission of subway vibration to the building. Through the use of a resilient material between a building and a subway structure a coupling loss of 10 to 20 dB can be created. For buildings adjacent to the subway structure and where noise and vibration could create an intrusion, it is, therefore, essential to include a resilient material for vibration isolation between the subway and the building structure. In such cases it may also be necessary to consider the use of resilient isolation pads to be placed between the building columns and the footings or support pilings. In the case of buildings which require new underpinnings it may be possible to consider resilient supports to help in reducing the vibration level transmitted from the ground to the building structure.

As an example of the noise levels to be expected in buildings near transit system subways, Figure 21 shows the noise levels expected in a lightweight building located 50 ft from a subway. The levels shown are for a 600 ft long conventional rail train traveling at 100 mph in an earth base concrete subway or tunnel.

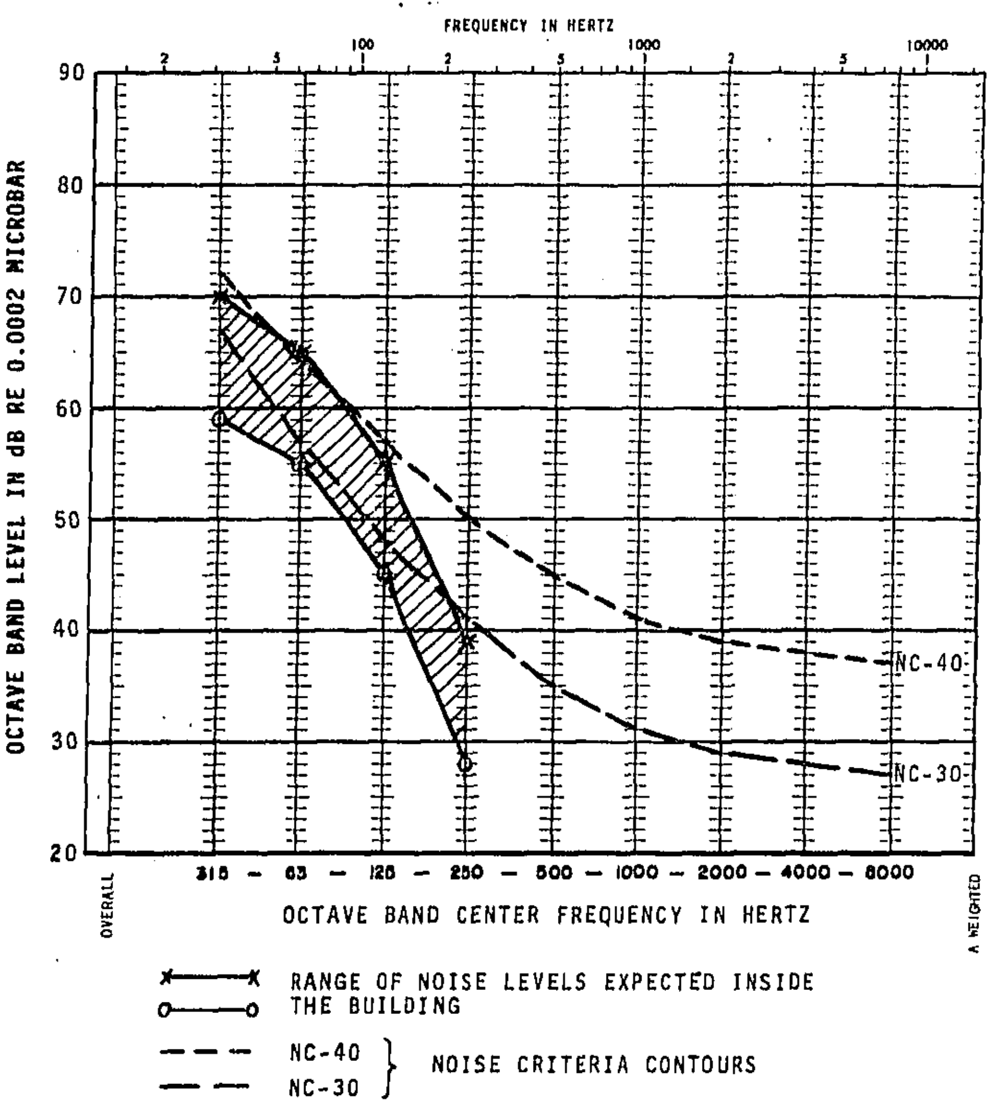


FIGURE 21 RANGE OF NOISE LEVELS TO BE EXPECTED IN A LIGHTWEIGHT BUILDING DUE TO GROUND-BORNE VIBRATION FROM A 600 FT LONG [8-CAR] TRANSIT TRAIN AT 100 MPH IN A CONCRETE SUBWAY [2 BOX STRUCTURE] 50 FT FROM THE BUILDING - SOIL STRATA

V. EFFECT OF NOISE/VIBRATION ON FOUNDATIONS AND STRUCTURES

One of the questions that arises in considering ground vibration from transit vehicles is the effects, if any, of ground-borne vibration from transit vehicle operations on the structural stability of foundations and structures adjacent to the subways. To determine the degree of any effects, the literature on structural vibration and the effects of earthquake tremors has been reviewed. Reference 36 provides an excellent summary of the effects of structural vibration and also presents an extensive bibliography on the subject.

The effects of vibration on building structures begin with the cracking of plaster walls and ceilings at the lower vibration levels and extend to damage to brick-work, masonry or the basic building structure at higher vibration levels.

Complaints are often received attributing cracking and damage to plaster ceilings or walls to some mechanical vibration. When a building owner experiences a minor or severe vibration he tends to believe the vibration is wholly responsible for the formation of cracks seen in the subsequent inspection of the property. Usually these cracks have existed long before the vibration was experienced and had not been noticed. Plaster is a brittle and weak material and the magnitudes of strain produced normally by shrinkage or by expansion and relative movements of the structure are often sufficient to cause cracking.

The U. S. Bureau of Mines developed a considerable amount of valuable information on the damage to plaster ceilings and walls by conducting some experiments in 1940 where a vibrator was used to shake buildings with various combinations of amplitudes and frequencies. In many cases, there was no damage reported when amplitudes as great as 0.3" were involved. For damage to be caused to plaster ceilings by vibration, therefore, the study concluded that amplitudes on the order of 0.1" or accelerations on the order of 1 g appear to be necessary.

Cracking of window glass is generally found to be attributable to internal stressing of the glass inherent in the manufacturing process. The stresses may be increased during installation or settling of a building. Window glass normally withstands very large vibration amplitudes as can be observed from the high amplitudes of vibration created by airborne sound or displacements which can be produced by banging on a window with the fist without causing damage. Amplitudes of the order of hundredths of an inch can be produced without any damage to windows.

In investigating the damage to brick-work it was found that amplitudes of ground vibration necessary to cause cracking of the mortar vary from .008" to 0.6". The conclusion was that there is no risk of cracking of the mortar if the amplitude of ground vibration does not exceed .008".

In a study of cases where severe vibration was experienced at masonry and frame buildings and where some damage did occur, the accelerations were found to be in the range of 0.1 to 0.4 g. In some cases, accelerations of the order of 0.2 g were experienced with no structural damage worse than a few hairline cracks in plaster ceilings and walls.

The work of the U. S. Bureau of Mines and other tests to determine building response, ground vibration and the effects of blasting or mechanical vibrations on buildings have resulted in standards of permissible vibration. For the frequency range from about 3 to 30 Hz, vibration acceleration levels in the range of 70 to 80 dB re 1 micro g are classified as light to medium vibration with no damage occurring for any type of building. Vibration levels from 80 to 90 dB are classified medium to strong vibrations with small or hairline cracks occurring in plaster ceilings and walls. From 90 to 100 dB re 1 micro g the vibration is characterized as strong to heavy vibration with small cracks occurring [light damage]. Levels above 100 dB re 1 micro g are classified heavy vibration with wall damage to destruction expected.

Comparison of these levels with the ground-borne vibration acceleration levels expected from rapid transit vehicles indicates that unless the building is directly attached to a subway structure the vibration levels from the transit vehicle operations are considerably less than that required for any damage to any type of building or to have any effect on the structural stability of buildings. With buildings directly attached to a subway structure, the vibration levels at high operational speeds are in the range which could result in small or hairline cracks in plaster, however, in any new facilities the potential of such results can be eliminated simply by providing for resilient joints between the subway structure and the building structure.

Reference 47 presents a chart indicating suggested upper limits for vibration amplitudes beyond which damage to structures is likely. The vibration amplitudes shown are greater than those indicated in the Bureau of Mines work of reference 36. Figure 22 shows the limits suggested along with the various levels of human response to vibrations as presented in reference 47. For comparison purposes the vibration levels for rail transit system subway structures and the free surface ground-borne vibration levels at 30 ft. from a subway are shown on the same chart. Again, the vibration levels from transit train operations are found to be considerably below the levels which can result in damage to buildings.

The general conclusion that can be drawn is that noise/vibration from high speed transit vehicle operation in subways will not have any detrimental effects on the structural stability of foundations or structures adjacent to the subways.

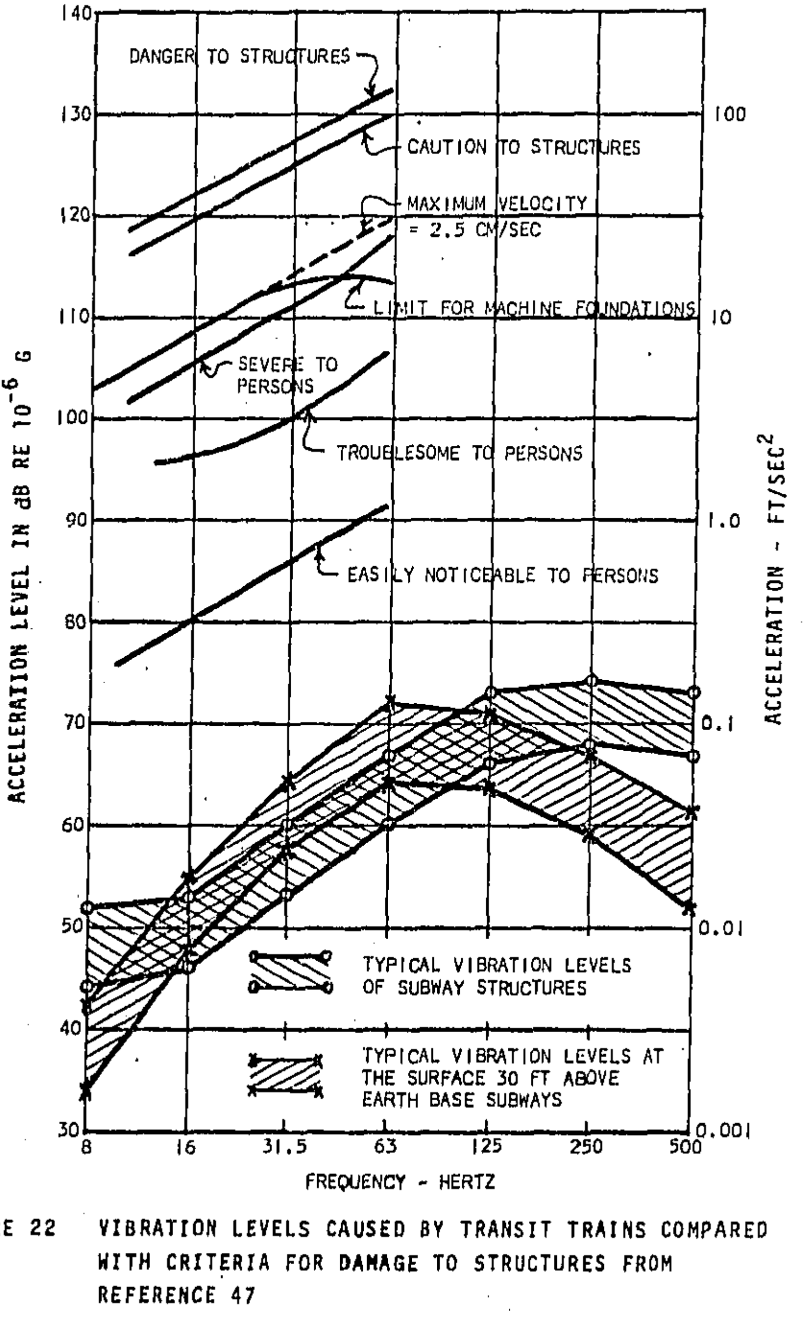


FIGURE 22 VIBRATION LEVELS CAUSED BY TRANSIT TRAINS COMPARED WITH CRITERIA FOR DAMAGE TO STRUCTURES FROM REFERENCE 47

VI. EFFECTS OF SUBWAY DESIGN FEATURES ON NOISE AND VIBRATION

A. Noise and Vibration within a Subway

The primary factors which can affect the noise and vibration within a subway are the use of sound absorption materials on the interior surfaces of the subway and the use of resilient rail fasteners for support of the rails in a conventional rail system.

The use of sound absorbing materials on the interior surfaces of subway walls can result in noise level reductions on the order of 10 to 15 decibels. For example, at the TTC facilities, maximum train noise levels in stations with acoustical tile on the entire ceiling are 10 to 15 dB less than the typical maximum levels for stations with no acoustical treatment. It is also found that in those subways where the tunnel bore is lined with acoustical material the noise level on the interior of the transit car is the same as when the car is traveling in the open on the surface, which implies a considerable reduction in the reverberant noise level within the subway.

The use of resilient rail fasteners for support of the rail in a conventional rail system can result in decreased noise and vibration level in a subway. It is also possible, through the use of exceptionally soft rail fasteners, to have an effective increase in the airborne noise level. With very soft resilient rail fasteners, the wheels and rails are free to vibrate at higher than normal levels creating greater wheel and rail noise. The present indications are that the minimum wheel and rail wayside noise occurs when the resilient support fasteners provide a track support modulus of about 5,000 lbs/in per in of track and that the minimum stiffness which is practical for minimizing vibration levels is obtained at a support modulus of about 3,000 lbs/in per in of track. The difference in the stiffnesses result in an increase of about 3 to 4 dBA in the wayside noise or the noise within a subway when the softer fasteners are used.

With regard to subway structure design features, there are no practical or reasonable procedures for reducing the noise and vibration *within* the subway other than acoustical treatment of the interior surfaces and the use of appropriate resilient rail fasteners for minimizing noise generation.

B. Transmission of Vibration to the Surrounding Geologic Media

In terms of transmission of mechanical vibration from a subway structure there are a number of factors which can have a significant effect on the vibration levels. These include the use of resilient rail fasteners, the type of tunnel liner or subway structure, the mass of the subway structure, the use of resiliently supported or vibration isolated trackbed slabs and the type of geologic media surrounding the subway.

For tunnels in rock the type of tunnel structure has negligible effect on the vibration levels transmitted to the surrounding rock. The only factors which affect the vibration levels are the use of resilient rail fasteners, for conventional rail systems, and the use of vibration isolated roadbed or resiliently supported trackbed slabs within the subway structure.

The actual effectiveness of resilient rail fasteners in reducing vibration levels from conventional rail facilities has not been determined in a systematic manner, that is, there have been no measurements indicating the "insertion loss" provided by the use of resilient rail fasteners. It is, however, known that with systems which use resilient rail fasteners the ground-borne vibration levels are considerably less than with systems not using resilient rail fasteners. Vibration level reductions in the range of 10 to 20 dB have been attributed to the resilient rail fasteners, however, there is no definite confirmation of the order of magnitude of the vibration reduction since, in all cases which have been evaluated, there are other differences besides the use of resilient rail fasteners which prevent direct comparison of results with and without resilient fasteners.

In a rock tunnel it is possible to further reduce ground-borne vibration levels through the use of the resiliently mounted trackbed slabs. Various degrees of isolation can be achieved with resiliently mounted trackbed slabs, references 28, 29, and 31. Configurations extend from simply providing a resilient joint between the edge of the trackbed slab and the subway wall with the slab supported on drainage ballast to the use of a fully floating invert slab supported on rubber or loadbearing fiberglass springs. The vibration level reductions which can be obtained from these facilities are in the range of 5 to 12 dB. Figure 23 presents a chart indicating the vibration level reductions that can be obtained with rock tunnels through the use of vibration isolated invert slabs.

Figure 24 is a schematic diagram of a floating slab trackbed such as those which are to be included in rock or earth base subway structures of the WMATA Metro system at locations where the ground-borne vibration levels may be higher than the desired maximum. The additional vibration reduction which can be obtained by use of floating slabs permits meeting specified maximum noise and vibration criteria in locations where vibration levels are high due to the presence of special trackwork joints or in locations where buildings are very close to the subway structure and are of a critical nature with regard to noise and vibration.

In earth base subways there are a number of factors which affect the vibration levels transmitted to the surrounding area. One of the factors which has been found of significance and has been reported, see reference 8, is that the mass of the subway structure does have an effect on the ground vibration level. For earth base subways of large mass the transmitted vibration levels are lower simply due to the fact that the mechanical impedance of the structure is greater for a more massive subway. The following table indicates the relative vibration levels for several varieties of earth base subway structures.

Earth Base Subway Structures	Relative Ground-Borne Vibration Levels-decibels
Double Box - Concrete	0
Single Box - Concrete	+2
Single Round Tunnel - Concrete	+2
Single Round Tunnel - Cast iron liner	+6
Single Round Tunnel - Steel liner	+8
3-box - Concrete	-2
Massive Station Structure - Concrete	-4

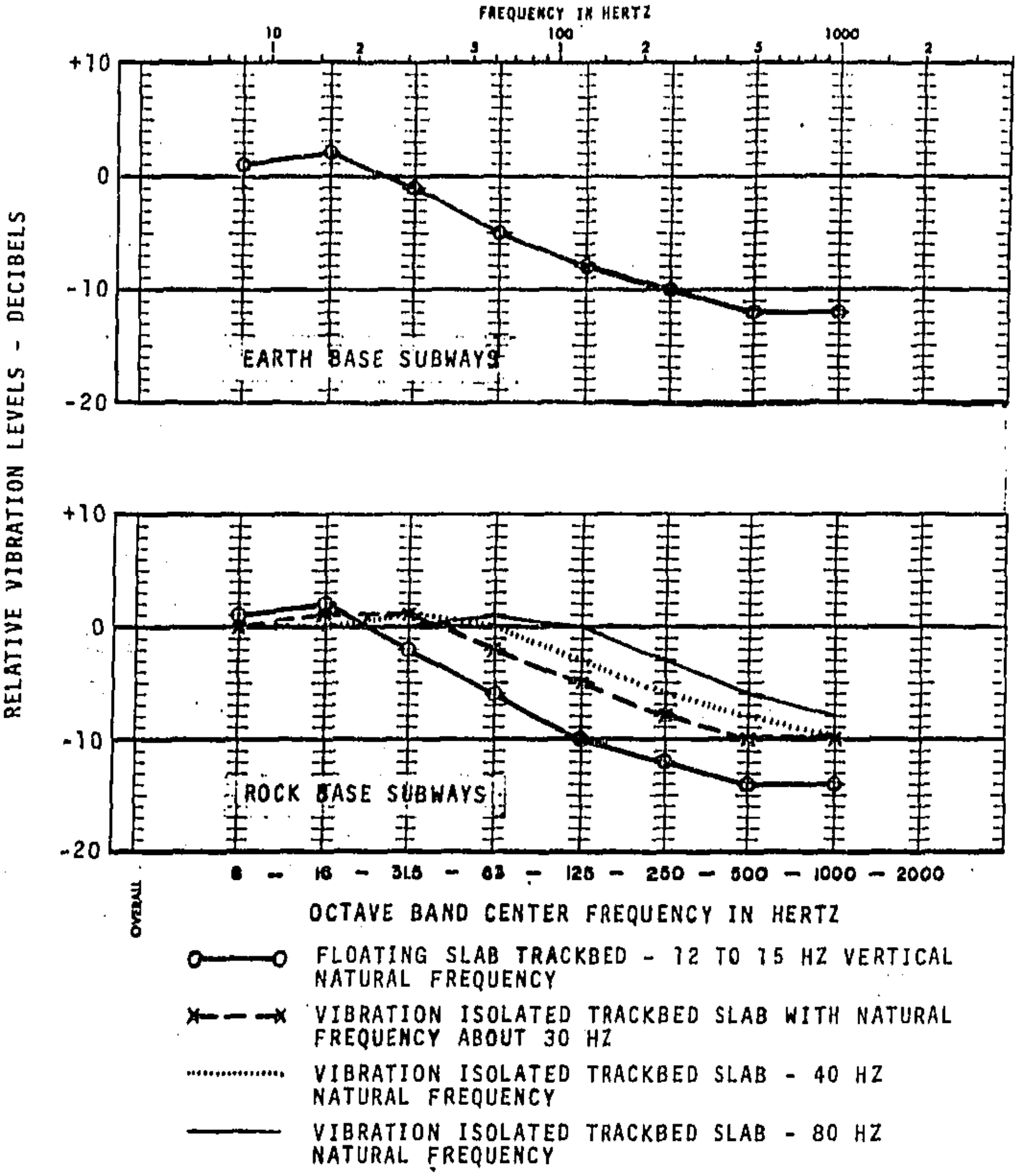


FIGURE 23 CHARTS SHOWING THE EXPECTED VIBRATION LEVEL REDUCTION FOR FLOATING SLAB TRACKBEDS

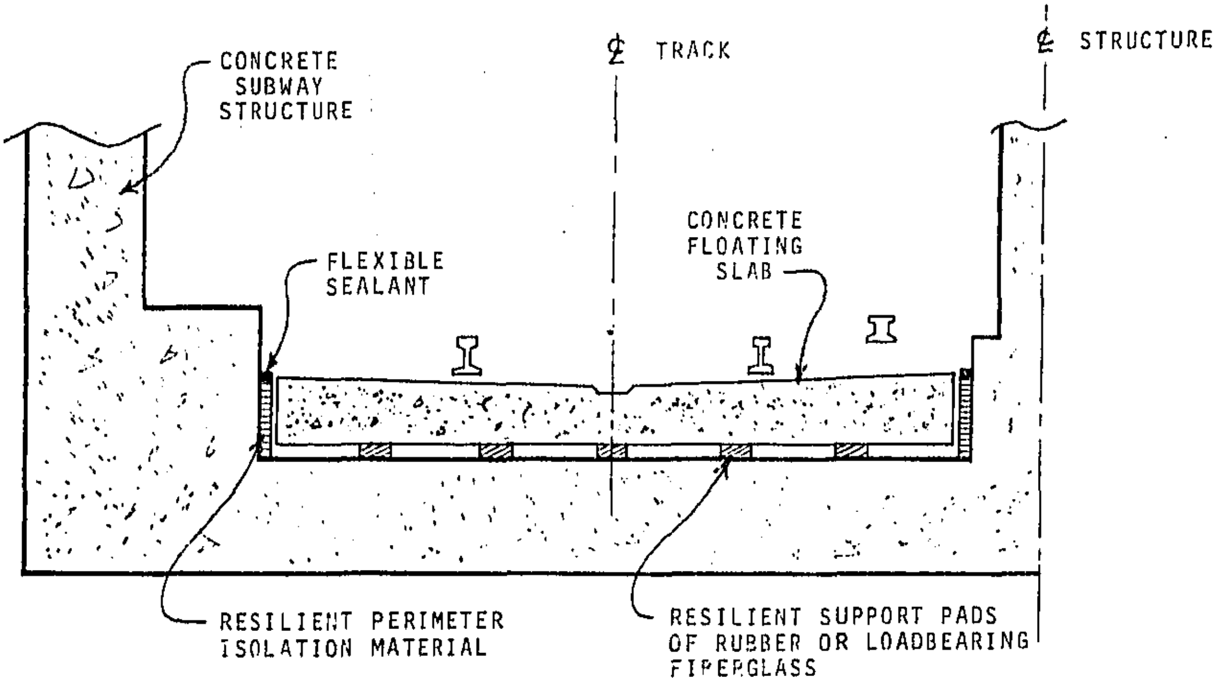


FIGURE 24 SCHEMATIC DIAGRAM OF FLOATING SLAB TRACKBED FOR REDUCTION OF GROUND-BORNE VIBRATION FROM RAIL TRANSIT TRAINS OPERATING IN SUBWAYS

One of the points to note in comparing tunnel structures is that a steel tunnel liner weights about 50 lbs/sq ft, a cast iron tunnel liner weights 75 lbs/sq ft and a concrete tunnel structure weighs about 200 lbs/sq ft. Thus, considering the comparison of the mass of the tunnel structure, the ground vibration levels with steel and cast iron tunnels can be as much as 4 to 6 dB greater than for a concrete tunnel structure. It could also be that resilient rail fasteners will be less effective in a steel or cast iron lined tunnel because the mechanical impedance of the roadbed would be less than for a concrete structure. For best operation the impedance presented at the base of a resilient rail fastener should be large.

In earth base subways the vibration isolated trackbed slab can also be used although it is slightly less effective than in a rock base subway because the mechanical impedance of an earth base subway is somewhat less. Figure 23 shows the expected vibration reduction from the only type of vibration isolated slab which is economically practical in rapid transit system earth base subways. That is, one which is supported on rubber or loadbearing fiberglass pads. It may be possible to obtain greater vibration reductions than shown on Figure 23 through the use of very massive floating slab arrangements in very large subway structures as was done in the Barbican Scheme in London, see reference 29, however, the economics of such a structural arrangement is justified only in the case where the vibration levels are very high such as those encountered with freight trains at the Barbican Scheme site.

Using the relative vibration level figures presented in this section of the report, it is possible to apply the numbers as correction factors to the vibration levels presented in Section III of this report and further refine the vibration level estimates for specific instances. The vibration levels presented in Figures 7 and 9 are for double box concrete subways. Using the relative vibration levels given in the table above for other types of subway structures, the groundborne vibration levels adjacent to the other types of structures can be derived. Also, for either earth or rock base subways the vibration reductions shown in Figure 23 can also be applied to determine the effectiveness of a vibration isolated trackbed for conventional rail vehicles.

By using all of the various correction factors or adjustment factors and the vibration level information given in this report, it is possible to calculate what the vibration level will be at buildings adjacent to transit vehicle subways and, therefore, to estimate the noise level which will exist in the buildings. It is necessary, of course, to make sure that the appropriate vibration levels and correction factors are used depending on whether the subway is supported on earth or rock and whether the vibration transmits through rock or earth, or both, to the building adjacent to the subway structure. The levels must also be adjusted to account for other factors discussed in Section IV-E, i.e., factors associated with the buildings and other items not directly related to the transit system facility design.

VII. EFFECTIVENESS OF NOISE AND VIBRATION ABATEMENT TECHNIQUES

A. Wheel Damping

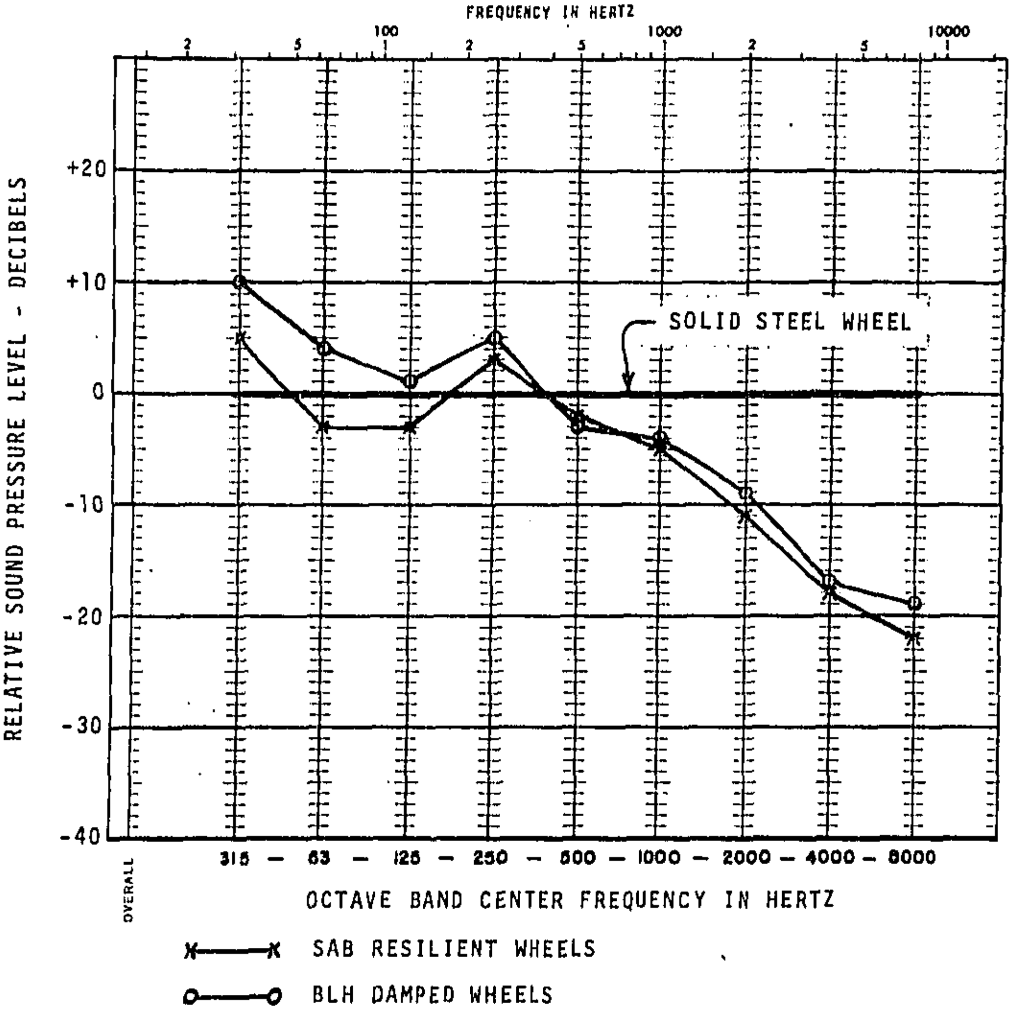
The primary effectiveness of wheel damping is in the reduction of wheel squeal on turns. Figure 25 is a chart indicating typical noise level reductions obtained from wheel damping in short radius turns. In general, it is found that for tangent track the noise reduction due to wheel damping is on the order of 1 to 2 dBA and is, therefore, not significant.

There is one possible benefit through the use of highly resilient wheels which has not yet been thoroughly investigated. At the BARTD Test Track it was found that SAB resilient wheels did reduce ground-borne vibration levels, in the 16, 31.5 and 63 Hz octaves, by about 10 decibels. The test also, however, indicated an increase in the ground-borne vibration and wayside noise levels in the 125 and 250 Hz octaves. The chart on Figure 26 indicates the reduction in ground-borne vibration levels with vehicles using the SAB resilient wheels compared to vehicles using solid steel wheels. The vibration data was obtained at a facility using resilient rail fasteners so that the data represents the results of using both resilient rail fasteners and resilient wheels compared to the use of resilient rail fasteners and solid steel wheels.

The reduction of low frequency ground-borne vibration levels with the use of highly resilient wheels has subsequently been confirmed during tests comparing the performance of PCC streetcar wheels with the performance of less resilient wheels.

B. Absorption Materials in Subways

As mentioned in Section VI, the main effect of absorption materials applied to the interior surfaces of subway structures is to reduce the level of airborne noise within a subway structure. The noise reduction that can be obtained amounts to 10 to 15 dB, which is very effective with regard to airborne noise but there is no beneficial effect with regard to subway structure or ground vibration.



SEE REFERENCE 2 FOR WHEEL DESIGN DETAILS

FIGURE 25 CHART INDICATING THE REDUCTION IN WHEEL SQUEAL NOISE WHICH CAN BE OBTAINED BY USING DAMPED OR RESILIENT WHEELS. THE DATA WAS OBTAINED AT 30 FT TO THE WAYSIDE AT A 500 FT RADIUS CURVE

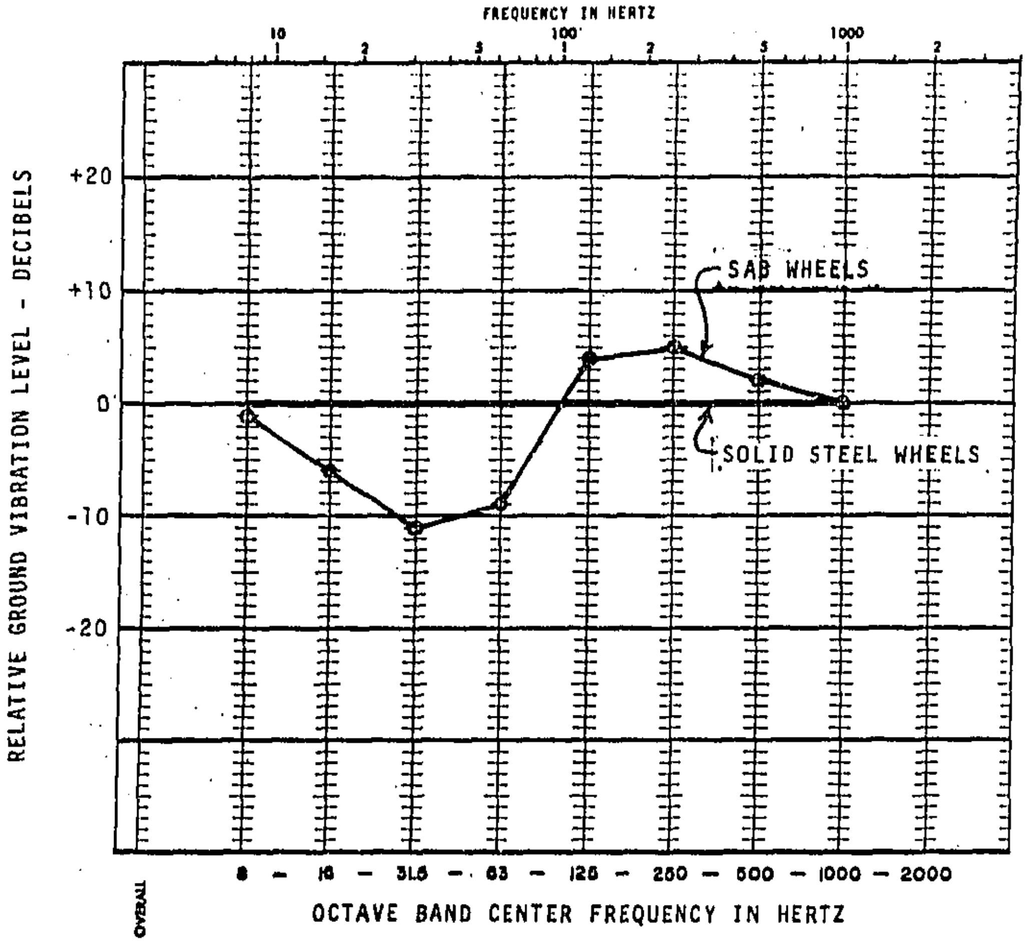


FIGURE 26 GROUND-BORNE VIBRATION LEVELS WITH SAB HIGH RESILIENCE WHEELS COMPARED WITH SOLID STEEL WHEELS. BARTD LABORATORY CARS AT 60 MPH ON TANGENT TRACK

C. Vehicle Structure Insulation

The sound insulation of vehicle structures can, of course, be used to limit the noise level in the passenger spaces. Measurements of the sound insulation of present day vehicles indicate that the noise reduction provided by vehicle bodies is on the order of 25 to 30 dBA; inside noise level relative to outside noise level. Aircraft structures provide sound insulation of considerably greater magnitudes, however, the ease with which passengers can enter and leave the vehicles is considerably less than for rapid transit vehicles. It is possible that through refinements of door opening and body panel designs that improved sound insulation can be obtained. The present indications are, however, that sound insulation on the order of 30 to 35 dB Sound Transmission Class represents a practical achievement for transit vehicle bodies.

D. Limiting the Distance Between Subways and Adjacent Structures

The most obvious and most effective means for limiting the noise and vibration level exposure at wayside buildings and other facilities is to limit the distance between subways and adjacent structures. The expected vibration levels from conventional rail vehicles, which are the type that will cause the greatest ground vibration levels, indicate that at distances of 100 ft or more for earth base subways that the vibration levels should not be excessive except in the most critical of situations. With rock base subways, the vibration levels at wayside buildings are somewhat more difficult to define because the vibration can travel at greater distances through rock and the buildings may be located in soil above the rock or may be located on pilings which extend to the rock base. In some instances it may be found that buildings at 200 ft from a rock base subway will have excessive vibration levels and in other instances buildings within less than 100 ft of a subway in rock may experience no perceptible vibration or noise.

It is possible to state general rules on the minimum separation which should be used in locating subways near buildings, however, the general rules should be derived for each individual situation. For example, it has been possible to derive some general guidance criteria for use in the design of the Washington, D. C. Metro System. It was also found possible to derive some general guidelines for location of the subways in the Los Angeles Rapid Transit System. Deriving general rules for location of structures along the Northeast Corridor would require review of the different characteristic areas of the Corridor to determine the appropriate limiting distance between transit facilities and adjacent buildings. The main point is that it is possible to prevent intrusion at adjacent buildings due to ground-borne vibration by using separation distances that are relatively small compared to the separation distances required for other types of transportation systems.

E. Subway/Roadway Designs

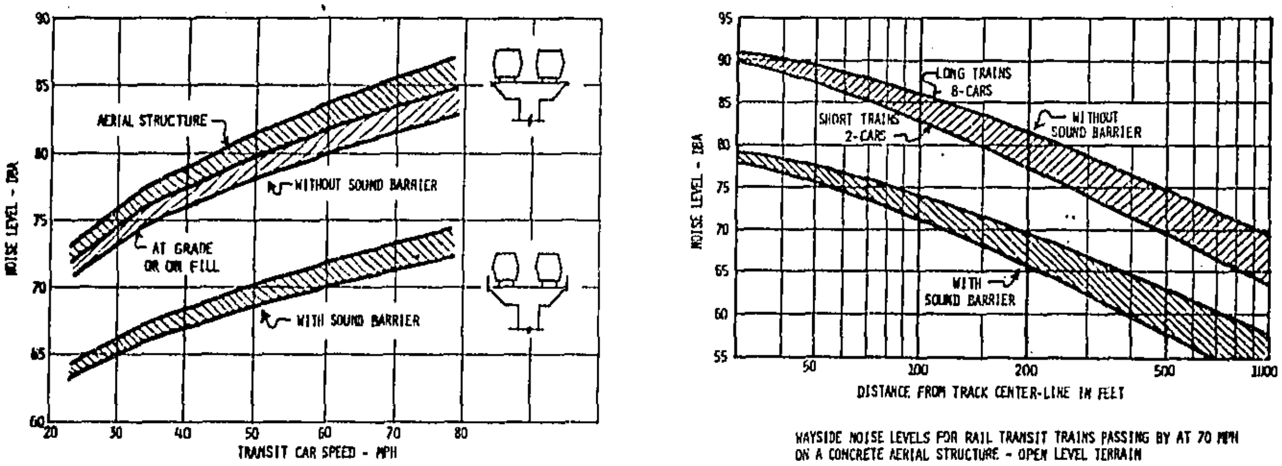
In determining the effect of various subway/roadway designs on noise and vibration the main factors which are of significance have been discussed in other sections of this report. These factors include, for earth base subways, the mass of the subway structure, the use of resilient rail fasteners, the use of floating trackbed slabs and the location of the subway relative to adjacent buildings. For rock base subways the significant factors include the use of resilient rail fasteners, vibration isolated trackbed slabs and location of subways relative to the nearby buildings.

In areas where subsurface transit facilities are to be located in soil the minimum vibration levels will be obtained with conventional rail systems by using massive concrete subway structures with resilient rail fasteners and with vibration isolated trackbed slabs. In locations where transit system subway structures will be in close proximity to the buildings, as in central districts of large metropolitan areas, the subway structures should be equipped with resiliently supported trackbed slabs and there should be resilient materials placed between the subway structures and the buildings when the two structures would otherwise be in direct contact. Vibration reductions on the order of 10 to 20 dB can be achieved by including these design features in the subway design.

For surface operations of rapid transit vehicles there are a number of design features which can be included in the system design to minimize or reduce wayside noise levels. These include the use of sound barrier walls and the use of cut sections with embankments or retaining walls on each side of the track route to shadow the sound transmitted to the wayside and thereby reduce the wayside noise levels.

The most effective single addition to a transit system roadway for reducing the wayside noise from aerial structures and from grade level tracks is a sound barrier wall. A sound barrier wall consists of a simple 1.5 to 2.0 lbs/sq ft weight wall of 3 to 4 ft height along each side of the track with minimum separation from the vehicles. Such a wall can result in 12 to 14 dBA reduction of the wayside noise level. Figures 27, 28, and 29 are reproductions of figures from a previous report, reference 14, and are included to show the effectiveness of the use of sound barrier walls and depressed roadway sections in reducing wayside noise levels.

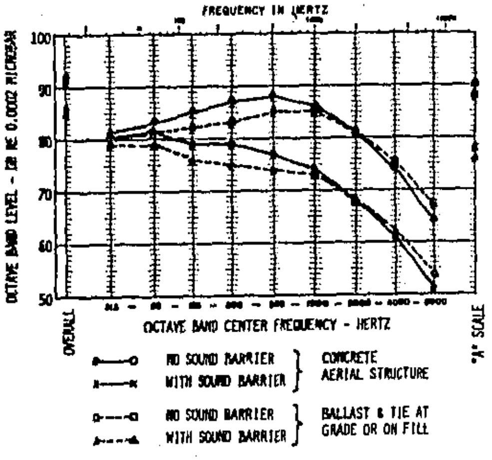
The reduction of wayside noise levels which can be obtained by using a sound barrier wall, and shown on Figures 27, 28 and 29, are based on measurements made at the BARTD Test Track with experimental sound barrier walls. Measurements were made at 5 ft and 30 ft above grade along a section of 30 ft height aerial structure, with transit cars traveling both on the track next to the barrier wall and on the far track, to determine the effectiveness of a sound barrier wall in reducing wayside noise for various operating conditions and at various wayside locations. The charts shown on Figures 27 and 28 are based on the experimental data. Using the data obtained with the experimental sound barrier walls as a base, calculations were made to determine the wayside noise level contours for aerial structures which are given on Figure 29. Using information on wayside noise level reductions with depressed freeways, further calculations were made to determine the expected wayside noise level contours for transit trains in cut sections as shown on Figure 29.



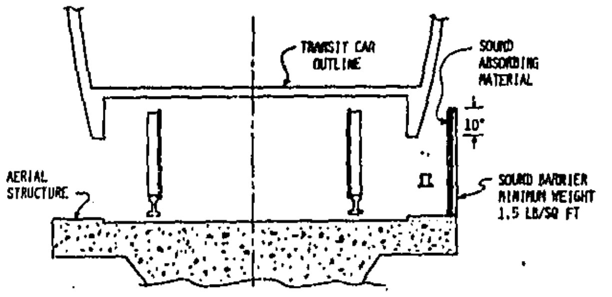
WAYSIDE NOISE LEVELS FOR A SINGLE STEEL WHEEL RAPID TRANSIT CAR AT 50 FT HORIZONTAL DISTANCE FROM TRACK CENTER-LINE

WAYSIDE NOISE LEVELS FOR RAIL TRANSIT TRAINS PASSING BY AT 70 MPH ON A CONCRETE AERIAL STRUCTURE - OPEN LEVEL TERRAIN

FIGURE 27 CHARTS INDICATING THE EFFECTIVENESS OF SOUND BARRIER WALLS IN REDUCING WAYSIDE AIRBORNE NOISE FROM CONVENTIONAL RAIL TRANSIT VEHICLES

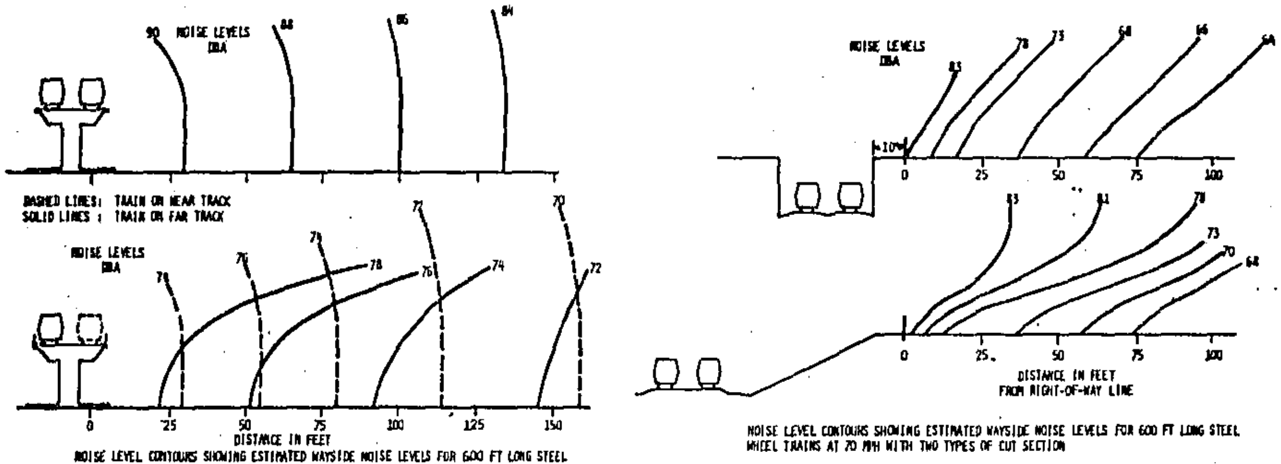


PREDICTED TYPICAL WAYSIDE NOISE LEVEL SPECTRA AT 50 FT FROM TRACK CENTERLINE WITH A 600 FT LONG (8-CAR) STEEL WHEEL TRAIN PASSING BY AT 70 MPH



SCHEMATIC REPRESENTATION OF A SOUND BARRIER WALL FOR WAYSIDE NOISE REDUCTION WITH TRANSIT TRAINS OPERATING ON A TYPICAL CONCRETE AERIAL STRUCTURE

FIGURE 28 CHART SHOWING THE EFFECT OF A SOUND BARRIER WALL ON THE WAYSIDE NOISE SPECTRUM AND A DRAWING SHOWING THE SCHEMATIC CONFIGURATION OF A SOUND BARRIER WALL FOR A CONVENTIONAL RAIL SYSTEM



NOISE LEVEL CONTOURS SHOWING ESTIMATED WAYSIDE NOISE LEVELS FOR 600 FT LONG STEEL WHEEL TRAINS PASSING BY AT 70 MPH WITH & WITHOUT SOUND BARRIER WALLS

NOISE LEVEL CONTOURS SHOWING ESTIMATED WAYSIDE NOISE LEVELS FOR 600 FT LONG STEEL WHEEL TRAINS AT 70 MPH WITH TWO TYPES OF CUT SECTION

FIGURE 29 NOISE LEVEL CONTOUR DRAWINGS SHOWING THE EFFECTIVENESS OF SOUND BARRIER WALLS AND CUT SECTIONS IN REDUCING WAYSIDE NOISE LEVELS

VIII. AREAS WHERE RESEARCH IS NEEDED

There are a number of gaps in the general knowledge of noise and vibration from high speed rapid transit vehicles. It is, therefore, appropriate to outline those areas in which some benefit could be obtained from further research.

The noise and vibration characteristics of resilient rail fasteners for conventional rail systems is one of the areas in which there is a need for further research to determine the effectiveness of rail fasteners and the appropriate design parameters for the stiffness. To date, no systematic measurements have been made of the "insertion loss" created by resilient direct fixation rail fasteners, that is, the amount of vibration reduction obtained by using resilient rail fasteners, with no changes in other conditions, has not been documented.

Some very valuable information on the appropriate design parameters for resilient rail fasteners could be obtained from a systematic study of the wayside vibration levels and noise levels with controlled experiments where only the stiffness of the rail fastener support pad is varied. In all other projects where similar measurements were made, there were a number of other variables also present which obscured the effects of rail fastener stiffness on the overall results.

Another area which appears promising for reduction of airborne noise and for ground-borne vibration level reduction with subway facilities is the use of highly resilient wheels such as the SAB and PCC type wheel. A systematic investigation of the wayside noise and ground vibration levels with resilient wheels of varying stiffness would also lead to development of appropriate design parameters for minimizing wayside noise and ground vibrations.

In extending the operation of rapid transit vehicles, particularly rail vehicles, to higher speeds it will be necessary to have smoother track or roadways in order to attain ride quality which is comparable to present day ride qualities and which is within a tolerable range for passengers on the vehicles. This requirement for smoother track and roadway will result in reduced levels of the vibratory forces applied to the roadbed and thereby will probably result in reduced vibration levels compared to estimates made with present day track and roadways.

The effectiveness of smoother roadway and track in reducing noise and vibration levels should be evaluated in order to determine the degree of benefit which can be obtained, in terms of noise and vibration reduction, from the efforts required to create the desired ride quality. To date, there have been no studies correlating the noise and vibration levels with ride quality obtained from a given quality of track or roadway. A systematic study attempting to identify wayside noise and vibration levels with ride quality obtained could be appropriate in determining the specifications for track and roadway quality for the higher speed vehicles.

There is a considerable amount of data available on the wayside noise from conventional steel wheels and rails, however, a program intended to determine the characteristics of noise generated by wheels and rails without the presence of noise from propulsion systems, aerodynamic noise or other interferring noises would be of particular value. This is perhaps related to a study of the effects of smoother roadway on wheel and rail noise, however, it could be arranged as a separate study project intended simply to determine the parameters which are significant in the generation of wheel and rail noise and to determine the basic characteristics of wheel and rail noise.

There have apparently been no systematic studies on the effects of truck unsprung weight on wayside noise and ground vibration levels. Useful and probably valuable design parameter information could be obtained from a study designed to determine the effects, on airborne noise and ground vibration, of truck weight, sprung to unsprung weight ratios, and the use of primary suspension springs to minimize unsprung weight. Such a study should include the use of resilient wheels to determine the interaction effects or the relationship of truck design parameters to resilient wheel stiffness.

The use of vibration isolated trackbed slabs for conventional rail transit systems, and perhaps for pneumatic rubber tire transit systems, presents the possibility for reduction in wayside ground vibration level which is as dramatic as the reduction in wayside airborne noise levels that can be achieved with the use of a sound barrier wall. The Washington, D. C. Metro System is pioneering the use of resiliently mounted or vibration isolated trackbed slab in the United States, however, there is no operational experience with the type of design being used for the Metro tunnels. In other locations, notably the Barbican Scheme in London, vibration isolated or "floating" slab trackbeds have been used and have given considerable wayside ground vibration level reduction. In some cases, no significant vibration reduction was achieved, probably due to excessively high resonant frequency of the slab support system.

A study of the effects of varying the various design parameters of vibration isolated concrete slabs when used as floating trackbed slabs would be of considerable benefit in determining the optimum design for subway structures where vibration must be minimized. Some of the variables which should be reviewed include the ratio of the mass of the floating slab to the mass of the vehicles, the ratio of the mass of the floating slab to the mass of the subway structure, the resonant frequency of the slab and its support system, the length of floating slabs and the length of segments of the floating slabs. A program intended to provide information on the relative effects and the optimum mass and stiffness ratios for floating slabs would, of course, lead to optimizing the vibration reduction and the cost of construction of floating slabs in subways.

While there is considerable information on the effectiveness of sound barrier walls for wayside noise reduction, there has been no systematic study showing the effectiveness or the requirement for sound absorption materials on the barrier walls and the relative effectiveness of different heights of barrier walls at different distances from the transit vehicles. It would, therefore, be appropriate to perform a study intended to determine the appropriate design parameters for sound barrier walls. From such a study it would be possible to relate the sound reduction achieved to the cost of the sound reduction facility and to determine the most efficient sound barrier wall design. The effect of car side skirts or combinations of car side skirts and sound barrier walls should be included in such a study.

The aerodynamic noise from high speed transit vehicles apparently cannot be predicted with the information that is now available. A project intended to determine, on a theoretical and experimental basis, the far field noise radiated by the turbulent boundary layer flow around a high speed transit vehicle is, therefore, needed. If nothing else, such a project would determine the speed range at which aerodynamic noise becomes significant in the wayside noise from transit vehicles and thereby would determine the practical limits on noise control which can be applied to the noise from propulsion systems and wheel and rail interaction, rubber tire noise generation or air cushion jet noise. Without knowledge of the far field aerodynamic noise levels, it is not possible to determine at what point further reduction of the noise from the propulsion systems and rolling contact systems becomes impractical or unnecessary.

With regard to the noise and vibration from the higher speed vehicles, there have apparently been no studies intended to evaluate the *wayside* noise and vibration from the high speed Northeast Corridor trains. Information to assist in extending the existing data and to provide some confirmation or adjustment factors for the high speed noise and vibration levels presented in this report could be obtained from a series of measurements at the Turbo-Train and Metro Liner facilities. Measurements from the operations of these trains would, in particular, provide information on wayside noise with other types of propulsion systems and with different vehicle weights to add to the data obtained from standard electric motor powered transit vehicles. A study program for evaluating the wayside noise levels and wayside ground-borne vibration levels from the Metro Liner and the Turbo-Train is, therefore, recommended.

Similarly, data on the noise and vibration from the operations of the Tokaido Line high speed trains in Japan would be of considerable value in determining the accuracy of predicted levels for higher speed trains and extending the knowledge to higher speeds. The appropriate sound and vibration measurements may have already been performed and reported, however, it was not possible to determine if this information is available. An appropriate project for future study would be to determine of measurements have been made at the Tokaido Line facilities and, if so, the data should be documented and disseminated. If the measurements have not been made, it would be appropriate to complete a project to determine the noise and vibration levels from these trains.

The suggested subjects for further research are summarized in the following list:

[1] Determination of optimum stiffness for resilient rail fasteners for minimizing wayside noise and ground-borne vibration.

[2] Determination of the optimum design characteristics for resilient wheels in the reduction of wayside noise and ground-borne vibration.

[3] Determination of the effects of smoother roadway, required for satisfactory ride quality at higher speeds, on the noise and vibration generated by wheel and rail interaction.

[4] Study of the characteristics of airborne noise generated by conventional steel wheel and rail interaction.

[5] Study the effects of truck design on wayside noise and ground-borne vibration including the effects of resilient wheels on truck characteristics.

[6] Study of the design parameters for floating trackbed slabs to determine the optimum mass ratios and spring stiffnesses or resonant frequencies.

[7] Determination of the optimum design parameters and effectiveness of sound absorption materials for sound barrier walls and car side skirts.

[8] Determination of the aerodynamic noise generated by transit vehicles traveling at high speeds.

[9] Measurements of wayside noise and vibration from existing operational high speed vehicle systems.

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