RAIL TRACKED TRAFFIC NOISE

Steven L. Wolfe
Wilson, Ihrig & Associates, Inc.
5776 Broadway
Oakland, California 94618
USA

INTRODUCTION

With the increase in population in and around metropolitan cities, the need for efficient transportation systems is ever present. Rail based transportation systems have been embraced by more and more cities. Although the USA and Canada had, at one time, extensive rail "trolley" systems and interurban systems every where, most of these systems were abandoned by the 1940's with the advent of improved roads and automobile expressways. Fortunately, there were some cities which retained these systems as was done throughout most of Europe.

Today existing lines are being extended, while new rail systems are proposed for most metropolitan cities due to congestion, air pollution, the high cost of gasoline, etc. For classification purposes, rail systems for passenger transport fall into three basic categories:

1. Conventional and high speed railways in urban areas, generally operating on existing railroad rights-of-way.
2. "Heavy" rail transit in high density cities.
3. "Light" rail transit in medium to high density cities and metropolitan areas.

Another category which encompasses all three of the previously mentioned categories include railway yards and transit stations which may generate an entirely different set of environmental problems than the operation of trains along the tracks.

With respect to noise and vibration generation there are at least three ways that noise and vibration problems can occur: 1) Introducing a new line into a community or neighborhood 2) the neighborhood expands adjacent to existing facilities, and 3) changes in operations on existing facilities. Since these conditions can create significant impact on people living or working near the transit facilities, a number of environmental standards, recommendations and assessment procedures have been developed to minimize this impact and assiist in the development of feasible mitigation measures.

The character of noise from trains operating at-grade or on aerial structure is different than the character of noise which arises from trains operating underground in subway. The noise from trains operating at-grade or on aerial structure is airborne and can be perceived by individuals outside of a building or inside of a building at an attenuated level after the noise has passed through the windows, door or walls of the building. The noise from trains operating in subway is groundborne and can be perceived only when an individual is inside a building near the subway. Outdoors groundborne noise is inaudible. A train operating in subway creates vibration at the wheel/rail interface which is transmitted to the subway structure, to the ground and then through the ground to a building structure where it is then radiated in the form of a low-frequency noise which can be heard and sometimes felt as mechanical vibration only inside buildings near the subway. Trains operating on aerial structure will produce vibration levels in the ground which are generally low enough in level that they will not be felt by occupants of adjacent buildings, while the vibration levels produced by trains operating in subway or at-grade can in some situations be high enough in level that they can be felt by occupants of nearby buildings or affect very vibration sensitive laboratory-type equipment. As for the groundborne noise, vibration from train operations can only cause impact to people or special equipment inside buildings.

This presentation focuses on particular situacions encountered in North America, including particular noise and vibration problems of a number of operating systems with examples of mitigation. The focus includes airborne noise, groundborne noise and groundborne vibration.

STANDARDS AND REGULATIONS

Before discussing some particular situations with respect to the generation and control of noise and vibration, a discussion of the standards and regulations which are used is in order. As proviously indicated, there are at least three ways that noise and vibration problems can effect a community: 1) a new rail transit line is constructed in the neighborhood, 2) the neighborhood expands adjacent to existing facilities, and 3) there are operational changes at existing facilities. There are different standards which can apply to each of these situations. However, the standards and criteris for each of these situations can be divided into two basic types: those that are based on an absolute limit and those that are based on a relative limit. The absolute limit is generally based on L_{max} or on some upper limit of L_{eq} or L_{dn}. Relative limits are almost always based on an increase in hourly L_{eq} or in L_{dn}. The use of appropiate absolute standards has been shown to be very successful over the years, while relative standards can be less successful if not applied appropriately.

In the United States, some of the standards and regulations have resulted from the implementation of the National Environmental Policy Act (NEPA) which established a national charter for the protection of the environment. Although the Act produced a general document which applies to many areas other than noise, it sets the framework for what various agencies must do in order to achieve the goals of the Act. The appropriate federal agency is the Department of Transportation. Other standards and regulations have resulted from requirements at the state and local (city) level. Standards of rail transit noise have also been formulated by an industry group, the American Public Transit Association (formerly the Institute for Rapid Transit).

The main goals of noise and vibration criteria and standards as they apply to rail traffic noise and vibration are to 1) minimize adverse impact of system operations on the community by controlling the transmission of noise and vibration to adjacent properties, and 2) provide noise and vibration control consistent with economic constraints and appropriate technology.

Some of the standards which are based on absolute limits include those of the American Public Transit Association (APTA), the Railroad Noise Emission Compliance Regulations of the U.S. Federal Railroad Administration, the Canadian Proposed Policy on the Environmental Protection of New Development Adjoining Railways, and the State of California's Sound Transmission Control Standards (Title 24). Standards which are based onrelative limits (at least for noise) include those contained in the U.S. Department of Transportations, Urban Mass Transportation Administration (UMTA) publication, "Guidelines for Preparing Environmental Assessments" and UMTA's draft publication, "Guidance Manual for Transit Noise and Vibration Impact Assessment".

APTA Guidelines

A set of criteria based on the allowable single event maximum noise level (L_{max}) are contained in Section 2-7-.6 of the American Public Transit Association publication, "Guidelines for Design of Rapid Transit Facilities". These criteria are designed to be applicable to new transit lines (heavy or light) being built in a community with a passby frequency typical of most systems.

The typical existing ambient or background noise and vibration livels vary signigicantly from one thpe of community to the next. Therefore, it is necessary to make a judgement as the nature of the community where the transit system is to be located before determinig the appropriate criterion for permissible noise or vibration levels from the transit system in that community.

Table 1 indicates the five generalized categories of waysides areas into which the community along transit corridors can be categorized for the purpose of assigning appropriate noise and vibration criteria. The table indicates the description of the areas and the normal expected range of ambient noise levels. These categories and noise levels are based in part, on the information developed from several studies of rail transit corridor environments along with the data presented in the 1974 U.S. Environmental Protection Agency (EPA) document, "Information on Levels of Environmental Noise Requisite to Proptect Public Health and Welfare with an Adequate Margin of Safety", usually referred to as the "Levels Document" and ogher field data obtained in many community areas in the U.S.A. and Canada.

TABLE 1
GENERAL CATEGORIES OF COMMUNITIES ALONG RAIL SYSTEM CORRIDORS

Area Category	Area Description	Typical Ambient Noise Level-dBA (Average or L_{50}*)	Typical Day/Night Exposure Levels-L_{dn}
I	Low Density urban residential open space park, suburban residential or quiet recreation area. No nearby highways or boulevards.	40-50 - day 35-45 - night	Below 55
II	Average urban residential, quiet apartments and hotels, open space, suburban residential, or occupied outdoor areas near busy streets.	45-55 - day 40-509 - night	50-60
III	High Density urban residential, average semi-residential commercial areas, urban parks, museum, and non-commercial public building areas.	50-60 - day 45-55 - night	55-65
IV	Commercial areas with office buildings, retail stores, etc., primarily daytime occupancy. Central Business Districts.	60-70	Over 60
V	Industrial areas or Freeway and Highway Corridors.	Over 60	Over 65

* L_{50} is the long-term statistical median noise level.

The categories defined in Table 1 are used in defining appropriate desing guidelines. Tables 2 and 3 present the desing guidelines for airborne noise in transit corridor communities. The APTA Guidelines also contain guidelines for groundborne noise. Groundborne noise criteria with some minor changes based on experience since 1979, are presented in

TABLE 2
*APTA CRITERIA FOR MAXIMUM AIRBORNE NOISE FROM TRAIN OPERATIONS **

		Maximum Passby Noise Level		
	Community Area Commercial Categoty	Single Family Dwellings	Multi-Family Dwellings	Buildings
I	Low Density Residential	70 dBA	75 dBA	80 dBA
II	Average Residential	75	75	80
III	High Density Residential	75	80	85
IV	Commercial	80	80	85
V	Industrial/Highway	80	85	85

* These criteria are generally applicable at the nearside of the nearest dwelling or occupied building under consideration or at 50 ft from the track centerline, whichever is closer.

TABLE 3
*APTA CRITERIA FOR MACIMUM AIRBORNE NOISE FROM TRAIN OPERATIONS NEAR SPECIFIC TYPES OF BUILDINGS **

Building or Occupancy Type	Maximum Passby Noise Level
Amphitheaters	65 dBA
"Quiet" Outdoor Recreation Areas	70 dBA
Concert Hall, Radio and TV Studios	70 dBA
Churches, Theaters, Schools, Hospitals, Museums, Libraries	75 dBA

* These criteria are generally applicable at the nearside dwelling or occupied building under consideration or at 50 ft from the track centerline, whichever is closer.

Table 4. The guidelines for groundborne noise are applicable inside buildings adjacent to the underground or subway portions of the rail transit alignment. In addition to the groundborne noise and vibration generated by transit trains operating in subway and the airborne noise generated by transit trains operating at-grade or on aerial structure, there is the airborne noise associated with ancillary facilities such as fan and vent shafts, traction power sub-stations, emergency power generation equipment and chiller plants.

TABLE 4

APTA CRITERIA FOR MAXIMUM GROUNDBORNE NOISE FROM TRAIN OPERATIONS

A. Residences and Buildings with Sleeping Areas

Community Area Category		Maximum Passby Groundborne Noise Level (dBA) Single Family Dwellings	Multi-Family Dwellings	Hotel/ Motel Buildings
I	Low Density Residential	30	35	40
II	Average Residential	35	40	45
III	High Density Residential	35	40	45
IV	Commercial	40	45	45
V	Industrial/Highway	40	45	50

B. Special Function Buildings

Type of Building or Room	Maximum Groundborne Passby Noise Level (dBA)
Concert Halls and TV Studios	25
Auditoriums and Music Rooms	30
Churches and Theaters	30-35
Hospital Sleeping Rooms	35-40
Courtrooms	35
Schools and Libraries	35-40
University Buildings	35-40
Offices	35-45
Commercial Buildings	45-55

APTA criteria for these facilities and operations are summarized in Table 5. As with other aspects of the design criteria, the appropriate noise level criterion depends on the actual land use of an area as well as the ambient noise in the area. The acceptable levels of noise from transient and continuous operations or activities are different. This is because transient noises are acceptable at higher levels than continuous noises. For example, the transient noise level limits apply to the train passby noise transmitted from vent shaft openings while the continuous noise level limits apply to the fan noise from fan shaft openings.

TABLA 5
*APTA CRITERIA FOR NOISE FROM TRANSIT SYSTEM ANCILLARY FACILITIES **

Community Area Category		Maximum Noise Level (dBA) Transiet	Maximum Noise Level (dBA) Continuous **
I	Low Density Residential	50	40
II	Average Residential	55	45
III	High Density Residential	60	50
IV	Commercial	65	55
V	Industrial/Highway	75	65

* These criteria are generally aplicable at the nearside of the nearest dwelling or occupied building under consideration or at 50 ft from the shaft outlet or other ancillary facility.

** For transformer noise or other sources with tonal components, these levels should be 5 dBA less.

Table 6 presents the appropriate criteria for the maximum groundborne vibration for various types of residential buildings in terms of vibration velocity level (re: 1.0 micro in/sec). These criteria would be 8 dB greater if referenced to 10^{-8} m/s. The criteria apply to the vertical vibration of floor surfaces within the buildings. As with the noise criteria, there are some types of buildings for which design criteria for groundborne vibration should be applied, regardless of community area category. These criteria ave been developed by Wilson, Ihrig & Associated, Inc. and adopted by many transit agencies to prevent excessive feelable vibration, since the APTA Guidelines do not includes criteria for groundborne vibration.

Groundborne vibration which complies with these design criteria will not be imperceptible in all cases; however, the level will be sufficiently low so that no significant intrusion or annoyance should occur. In most cases, there will be vibration from street traffic, other occupants of a building, or other sources, which will create intrusion that is equivalent or greater in level than vibration from the transit train passbys.

TABLA 6

*CRITERIA FOR MACIMUM GROUNBORNE VIBRATION FROM TRAIN OPERATIONS **

A. Residneces and Buildings with Sleeping Areas

Community Area Category		Maximum Single Event Groundborne Vibration Velocity Level (dB re 10^{-6} in/sec)		
		Single Family Dwellings	Multi-Family Dwellings	Hotel/ Motel Buildings
I	Low Density Residential	70	70	70
II	Average Residential	70	70	75
III	High Density Residential	70	75	75
IV	Commercial	70	75	75
V	Industrial/Highway	75	75	75

B. Special Function Buildings

Type or Building or Room	Maximum Single Event Vibration Velocity Level (dB re 10^{-6} in/sec)
Concert Halls and TV Studios	65
Auditoriums and Music Rooms	70
Churches and Theaters	70
Hospital Sleeping Rooms	75
Courtrooms	75
Schools and Libraries	75
University Buildings	75-80
Offices	75-80
Commercial & Industrial Buildings	75-85
Vibration Sensitive Industrial or Research Laboratory	60-70

* Criteria apply to the vertical vibration of the ground surface or of floor surfaces within the buildings.

Railroad Noise Emission Compliance Regulations of the FRA

The U.S. Department of Transportation thorough the Federal Railroad Administration enforces a set of standards developed by the U.S. Environmental Protection Agency in 1976. The provisions of these standards apply to the sound emitted by moving rail cars and locomotives, active retarders (at yards), switcher locomotives, car coupling operations (at yards), and load cell test stands operated by a common carrier. Common carrier generally refers to a freight railroad in the U.S. These standards do not apply to transit systems or warning devices operated for public safety. Table 7 presents a summary of the noise standards. Most of the standards are in terms of L_{max}, however, there are a few standards based on L_{90}, and two regarding yard operations which are based on $L_{adj\ ave\ max}$, a metric which has an adjustment based on the number of certain events shich occur in a certain time period. More discussion is focused on this metric later in this presentation. Generally these standards allow for the emission of relatively high levels of noise, however, their development is designed to limit the noise from defective equipment as well as some of the noisiest.

TABLE 7

SUMMARY OF RAILROAD NOISE EMISSION COMPLIANCE REGULATIONS

Noise Source	Noise Standard A-weighted Sound Level In dB	Noise Measure[1]	Measurement Location
All locomotives manufactured on or before December 31, 1979			
Stationary, Idle throttle setting	73	L_{max} (slow)	30m (100 ft)
Stationary, All other throttle settings	93	L_{max} (slow)	30m (100 ft)
Moving	96	L_{max} (fast)	30m (100 ft)
All locomotives manufactured after December 31, 1979			
Stationary, Idle throttle setting	70	L_{max} (slow)	30m (100 ft)
Stationaty, All other throttle settings	87	L_{max} (slow)	30m (100 ft)
Moving	90	L_{max} (fast)	30m (100 ft)
Additional Requirements for Seitcher Locomotives Manufactured on or Before December 31, 1979 Operating in Yards Where Stationary Switcher and other Locomotive Noise Exceeds the Receiving Property Limit of			
	65	L_{90} (fast)[2]	Receiving Property
Stationary, Idle throttle setting	70	L_{max} (slow)	30m (100 ft)
Stationary, All other throttle settings	87	L_{max} (slow)	30m (100 ft)
Moving	90	L_{max} (fast)	30m (100 ft)

TABLE 7 (continued)

Noise Source	Noise Standard A-weighted Sound Level In dB	Noise Measure[1]	Measurement Location
Rail Cars			
Moving at speeds of 45 mph or less	88	L_{max} (fast)	30m (100 ft)
Moving at speeds greater than 45 mph	93	L_{max} (fast)	30m (100 ft)
Other Yard Equipment and Facilities			
Retarders	83	$L_{adj\ ave\ max}$ (fast)	Receiving Property
Car Coupling Operations	92	$La_{dj\ ave\ max}$ (fast)	Receiving Property
Locomotive Load Cell Test Stands, Where the Noise from Locomotive Load Cell Operations Exceeds the Receiving Property Limits of			
	65	L_{90} (fast)	Receiving Property
Primary Standard	78	L_{max} (slow)	30m (100 ft)
Secondary Standard ir 30m measurement not feasible	65	L_{90} (fast)	Receiving Property

[1] L_{max} = Maximum sound level
L_{90} = statistical sound level exceeded 90% of the time
$L_{adj\ ave\ max}$ = Adjusted average maximum sound level
[2] L_{90} must be validated by determinig that L10-L99 is less than or equal to 4 dB (A).

Canadian Proposed Policy on the Environmental Protection of New Development Adjoinig Railways

This detailed policy was originally proposed in 1983 for use in the Province of Ontario as it applied to new residential development proposed to be built adjacent to railway rights-of-way. although never officially adopted by the Province it has been used extensively for new residential developments with considerable success and has recently been expanded to include the entire spectrum of land uses adjacent to railways. These standards are not applicable to heavy or light rail transit, but rather to the freight and passenger railways of Canada. The standards are comprehensive and set noise standards with respect to L_{eq}, vibration standards with respect to ISO 2631, and safety standards with respect to set-back lines. The policy specifies appropriate measurement procedures and minimum acceptable mitigation measures intended to limit Lmax at residential buildings. Since the standards are so comprehensive, they are not presented here. In general, the noise standard for residential sleeping quarters is an L_{eq} or 35 dBA, for living rooms is an L_{eq} of 40 dBA and for outdoor recreation areas is an L_{eq} of 55 dBA, evaluated eigher for the daytime period (0700 to 2300) or the nighttime period (0700 to 2300). Groundborne vibration mitigation is required for dwellings within 75m of the tracks or where neasured levels exceed the residential building standard for vertical vibration in ISO 2631.

State of California Sound Transmission Control Standards (Title 24)

These standards, in effect only in the State of California, establish minimum noise insulation performance standards to protect persons in new hotels, motels, apartment houses, and dwellings ogher than detached single-family dwellings from the effects of excessive noise. This applies to new construction of a particular set of dwellings and is designed to limit interior noise from all exterior sources to an annual community noise equivalent level (CNEL) or L_{dn} of 45 dB in any habitable room. For new construction adjacent to all railroad rights-of-way, the standards apply, except where daytime operations (0700 to 2200) do not exceed four per day. This standard has generally been successful except near railway lines which may have a significant number of operations per 24 hour period, with several operations during the night.

UMTA Relative Criteria

Presently the Urban Mass Transportation Agency (UMTA) of the U.S. Department of Transportation has not officially adopted any specific noise and vibration guidelines or criteria for rail transportation systems. UMTA has, however, issued a draft version of their "Guidance Manual for Transit Noise and Vibration Impact Assessment" which does contain detailed noise impact criteria based on the relative increase in L_{eq} for the noisiest hour or relative increase in L_{dn}. Prior to issuance of the draft "Guidance Manual", UMTA had issued some general guidelines for evaluating the significance of noise impacts contained in "guidelines for Preparing Environmental Assessments", UMTA C5620.1. These guidelines indicate that noise impacts are generally not significant (1) if no noise sensitive sites are located in the project area, and (2) if increases in the equivalent noise levels (L_{eq}) with implementation of the project are expected to be ≤3 dBA at noise sensitive locations and the proposed project would not result in violations of noise ordinances or standards. Noise impacts are possibly significant if increases in equivalent noise levels (L_{eq}) with implementation of the project are expected to be no greater than 5 dBA.

Determination of significance must consider existing noise levels and the presence of noise-sensitive sites. Noise impacts are generally significant if the proposed project would cause (1) noise standards or ordinance sto be exceeded, (2) an increase in the equivalent noise level (L_{eq}) of 6-10 dBA in built areas, and (3) an increase in the equivalent noise level (L_{eq}) of 10 dBA or more.

This relative criteria requires careful characterization of the existing environment in order to accurately apply the guidelines. It also effectively allows each successive project (if based on the same guidelines) to significantly raise the noise level in a community. The draft "Guidance Manual" attempts to alleviate this problem by assigning maximum limits of L_{eq} or L_{dn}. This document also indicates that any transit project (rail, bus, etc.) should only be evaluated with respect to Leq or Ldn without regard to L_{max}. The reasoning behind this choice of metric is so that the potential impact of various modes of transit can be compared. Unfortunately, unless the maximum limits of L_{eq} or L_{dn} are set low enough, neglecting the Lmax of rail transportation is likely to cause erroneous impact assessment, since there have been several railroad noise studies which show community response correlates better with L_{max}, or Lmax with a duration correction, than with L_{eq}.

The draft "Guidance Manual" also discusses vibration impact criteria. For both groundborne noise and vibration criteria, the maximum passby level has been used, much as the APTA Guidelines. So in this area, at least, an absolute standard is used. These criteria have only three land use categories and an arbitraty assignment of "frequent events" as more than 70 vibration events per day and "infrequent events" as less than 70 vibration events per day.

Although it is not unreasonable for a "Guidance Manual" to be issued, this document will be used by many who do not have experience in acoustics, since it will be the officially approved mehod for impact assessment because most new transit systems rely on some percentage of federal fundig in order to undertake new projects. Unfortunately, if the proposed procedures and standards are incorrect, because they have not been thoroughly tested in the field, then it is likely that the impact determinations may also be incorrect resulting in greater community annoyance than anticipated. Fortunately this document was subject to peer review, and some revisions are likely before the final document is released.

PRACTICAL EXPERIENCES

Perhaps the best way to determine the effectiveness of the criteria and standards as well as the effectiveness of the mitigation to achieve those standards is by examination of particular situations. The examples chosen are representative of various rail systems including conventional railways, "heavy" rail transit and "light" rail transit.

Conventional Railways

The term "conventional railways" refers to those that move freight and passengers between cities and also between major cities and suburban areas. In the U.S. and Canada most of these trains are powered by diesel electric locomotives rather than purely electric locomotives. The diesel electric locomotive generally produces higher noise levels with a different character than electric locomotives, and this in itself can be a problem with community acceptance of railroad noise.

Example #1- New Development by Existing Right-of-Way

The first example involves a new development in the State of California with single-family and multi-family dwelling within 110 ft (33m) of the railway tracks. The developer had two noise sudies done prior to approval of the project by the city. The mitigation proposed by the second consultant was adopted and assurances made that all applicable standards would be achieved. Unfortunately, a number of the residents, primarily those in the single-family dwellings complained about the noise from the railroad passbys of which there are 8 to 10 per day with at least half of these during the night.

The development was approved with the assurance that the interior CNEL would not exceed 45 dB as required by the State of California Sound Transmission Control Standards (Title 24). The noise level guidelines of the City stipulated that the development could proceed if the exterior L_{dn} or CNEL was 60 dB or less. There was no Lmax limit set or discussed by either of the two consultants. There is, of course, the L_{max} standard of the Federal Railroad Administration, which is really designed to eliminate operation of defective quipment and limit noise levels for extreme situations. Achieving the standards of the FRA is the railroad's responsibility, while achievement of the long-term noise exposure standards is the responsibility of the developer.

The developer built an 8 ft high wooden sound barrier wall between the dwellings and the railroad right-of-way as recommended by the second consultant. This consultant indicated that the wall would easily achieve a minimum of 10 dB reduction of the railroad passby noise. Unfortunately, the wall was built virtually equidistant from the railroad tracks and the single-family dwelling. Near fhe multi-family dwellings, the wall is within 15 ft of the buildings. Although providing some benefit for the ground floor, no benefit is provided to the second floor. In order to assess the situation, long term and short term measurements were made both inside and outside selected dwellings. The long term measurements were made over a 48-hour period to ensure that the measurements were characteristic with typical railroad operations. Results inside the front bedroom of a single-family dwelling which faces the tracks indicated an L_{dn} of 36 dB for one 24-hour period and 38 dB for the other. Long term measurements made immediately outside this same house indicated an Ldn of 62 dB for one 24-hour period and 63 dB for the other. Short term measurements during train passbys indicated that inside the bedroom, L_{max} for the locomotives was typically in the range of 48 to 53 dBA, while that for the cars was 47 to 48 dBA. During the nigt,the typical noise level in this same bedroom without any trains passing by was 20 dBA or less.

These measurements indicate general compatibility of the existing noise levels with applicable adopted guidelines and standards. Unfortunately, the adopted guidelines and standards do not adequately address this situation, with approximately 8 to 10 high noise levels events per day. Although the use of L_{dn} provides for a 10 dB penalty durint the nighttime sleeping hours, this penalty still does not adequately account for the intrusion from high level sounds which occur periodically during the night.

The typical railroad train passby increases the noise level by as much as 30 dB. Clearly, the effect of these few high noise level events is evident in the sleep disturbance of the residents. Although adopted guidelines and standards are achieved, the community complaints regarding the noise from the railroad train passbys indicate that these standards are not adequate in this situation.

Example #2- Operational Changes on Existing Right-of-Way

The second example involves a chenge in operations on an existing commuter line, specifically a change in the type of operating equipment. This commuter line has operations on a double track line without private right-of-way (i.e. not fenced) between the cities of San Francisco and San Jose in California. This service had been operated for many years by a private operator with a diesel-electric locomotive always leading the passenger cars. Due to financial loses by the private operator, the operation was taken over by the State of California (Caltrain). In order to attract new riders, the State ordered new equipment with the capability for push-pull operations. With push-pull operations, the locomotive is always positioned at one end of the train, but the train has controls at both ends, so that the train can be operated without repositioning or turning the locomotive.

The new locomotives for the Caltrain operations were essentially the same as those used by Amtrak, with the same type of warning horn. The cab control car at the other end of the train also has this type of horn. The horns on these trains are vey important as warning devices since the line is not fenced and there are a number of grade-crossings.

Once the new equipment began operations, community complaints were forthcoming due to the "excessive" noise from the train horns. Many people claimed that the nornos on the new trains were much louder than before. A group called HALT (Homeowners Aganist Loud Trains) was formed to attempt to reduce the sound of the horns or eliminate thir use altogether. An extensive investigation of the problem was undertaken. It was determined that the horns on the new Caltrain equipment were different than those previously used. Each locomotive air horn is made up of a number (usually 2 to 5) of separate horns or bells, commonly referred to as chimes. The old locomotives had three-chime horns, with two chimes in the forward direction and one chime in the reverse direction. The Caltrain horns are five-chime horns, with all chimes in the forward direction. The pitch of each chime is determined by the length and chape of the bell. For this reason it is possible to have horns which look similar to have a very different sound quality. The frequencies of the horn chimes for the 3 chime horns are 277.2 Hz and 440 Hz for the two forward chimes and 323.5 Hz for the reverse chime. The horn chime frequencies for the 5 chime horns are 311 Hz, 370 Hz, 415 Hz, 494 Hz and 622 Hz.

Measurement of the sound levels from the new and old hons was undertaken at both wayside locations with the trains moving at speed and at a distance of 100 ft from the front of a stationary locomotive or cab control car. The stationary measurements were taken in accordance with the Federal Railroad Administration Railroad Locomotive Safety Standards. These Standards specify the minimum sound level, although there is no maximum. The FRA Standards require that the sound level of the horn must be at least 96 dBA at 100 ft when measured 4 ft above the ground at centerline of the track.

No significant difference in the measured sound level was found. The stationary measurements at 100 ft indicated a range of 108 to 113 dBA for 5 chime horns and a range of 107 to 112 dBA for 3 chime horns. Emasurements at 100 ft from track centerlie with the trains moving indicated a range of 91 to 101 dBA for 5 chime horns and 96 to 106 dBA for 3 chime horns.

In determining both an appropriate soun level and sound quality of a warning device, there are a number of factors which must be considered. The basic purpose of a train horn is to provide warning to pedestrians, motorists, and others on the right-of-way that a train is approaching. In order to be effective, the horn must have a sufficient sound level to penetrate the consciousness of an individual who may be involved with another task with sufficient time for that individual to avoid a potencial collision. In addition, the sound quality must be distinctive to prevent it from blendig into the background noise, or for someone to mistake the horn sound as something other than from a train.

One of the primary considerations in specifying the five-chime horn for the Caltrain equipment was fue to the nature of the new push-pull equipment. With an entire train operating in the "reverse" direction, it is especially important to warn people that what appears to be the rear of the train is actually the front. Utilizing a horn which has a different character than that previously used, but whch is still emmediately identifiable with the railroad has the advantage of alerting the public to the new type of service. Althousgh the waiside community may claim that it is well aware of this new service, there are many who may be infrequent visitors to the area and may be totally unaware that anything but conventional trains operate on the line.

Since it was determined that the actual sound levels were no greater than before, no changes were made which would reduce the sound levels, particularly since none of the wayside cities were silling to accept the responsibility for any accidents which might be attributable to reducing the sound level of the horns. It has now been over 5 years since the new equipment was introduced and there are now few if any complaints from the wayside community. It appears that with the passage of time, the wayside community has accepted the new character of the train horns.

Example #3- Noise from Railroad Yards

Although not a problem for most communities, there are approximately 100 large railroad classification yards throughout the USA and Canada. Ablut half of these are located in areas with populations exceeding 100,000. As previously indicated, the U.D. Railroad Noise Emission Standards which apply to yards are enforced by the Federal Railroad Administration. These Standards took effect on January 15, 1984. Some of the noise problems from these yards have existed for years, and only after implementation of these standards has there been any effective reduction of wayside noise levels. Other noise problems have resulted because new residential developments have been built adjacent to these facilities.

Although the Railroad Noise Emission Standards apply to active retarders, they do not apply to one of the major noise sources in many yards, cars being pulled through inert retarders. Although there are many noise generators eithin a yard, the squeal noise emitted from retarders has elicited many complaints from wayside communities and yard personnel.

Most major rail classification yards in the U.S. and Canada are "hump" yards; that is, they have a hump which is elevated above the rest of the yard which is used to sort the various cars into trains bound for particular destinations. The hump of the yard operates on a gravity basis. No locomotives are used to impart speed to the cars; rather, gravity is used to accelerate the cars from the crest of the hump to the appropriate classification track. The cars are uncoupled at the crest of the hump and then roll freely down the incline until slowed by means of the master and group (sometimes called secondary) retarders. Once in the proper classification track, the car is kept from rolling out the end of the track by a slight opposite incline, as well as an inert retarder. The retardation pressures of the master and group retarders and the disposition of the classification track switches are controlled by various operators in towers where they can view the cars coming down the incline, or in the case of more modern yards, are controlled by a computer which acts upon destination data and the weight and speed data entered from weighing rails and speed sensors.

The noise which is created by the clasping of the wheels of the car by the retarder is a high frequency squeal or screech sound which is typically in the frequency range of 2000 Hz to 4000 Hz and lasts for a period of approximately one to five seconds. This squeal is created by the stick-slip mechanism between the retarder's brake shoe or beam and the wheel. This stick-slip action produces forced vibrations of the system and is related to the natural frequencies of the wheel/brake beam system.

Without going into detail as to the procedure for determining the adjusted average maximum soun level at the receiving property for checking compliance with the FRA Standards, suffice it to say that high noise levels are acceptable, as long as they are infrequent. The more frequent the retarder squeals, the lower the average sound levels must be in order to meet the standards. The nature of the formula for adjusted average maximum sound level gives a strong bias towards any high readings and frequent occurrences, such as would be most objectionable to people. Since the 1960's, a number of studies have been performed to determine effective ways of reducing this squeal noise from retarsers. Unfortunately, most reduction meghods have been either unsuccessful or have been unsatisfactory from an operational standpoint. A factor which contributes to the difficulty in developing an effective noise control scenario is the fact that the noise generating factors are quite variable. At some yards neither the duration of the squeal nor the level of the squeal show strong correlation with the car weight or speed. The generation of squeal is more or less a random occurrence, correlating at least to some degree with the condition of the sides of the car wheels.

Potencial noise control methods fall into two general categories. The noise can be controlled or reduced at the source, or the path between the noise and the receiver can be blocked or attenuated. For controlling the noise at the source, potential solutions include lubricating the car wheels an/or brake rails of the retarder, the use of a softer or alternative material for the brake shoes, or the use of a non-clasp type retarder. The path between the noise source and receiver can be blocked using sound barriers near the retarders or receivers.

Generally, noise control methods must be designed specifically for the particular yard. For some yards softer or ductile iron shoes have not reduced the retarder squeal, while at other yards, clearance problems may preclude the use of sound barriers. Lubrication of the car wheels and/or brake shoes has generally been shoen to be impractical since this significantly reduces the adhesion or retardation of the cars, which is contraty to the objective of the retarder.

At one yard, the nearest homes are approximately 400 to 600 ft from four active retardes. The adjusted average macimum noise level was as high as 94 dBA, with Lmax in the range of 71 dBA to 102 dBA and as many as 124 squeal sounds in an hour. Installation of ductile iron shoes on one of the four retarders indicated a reduction in the number of cars that squealed and a reduction in the maximum noise level. The ductile iron shoes reduced the number of loaded car "squealers" from 91% to 46% ñof all loaded cars, and reduced the number of unloaded car "squealers" from 29% to 15% of all unloaded cars. In addition, analysis of the noise levels produced by the same percentage of cars passing through the retarder with the ductile iron shoes indicates that when squeal occurs. the noise level on average is reduced by approximately 10 dBA. At this yard, the use of the ductile iron shoes appears to be effective at reducing wayside noise levels, a situation which has not been found at some other yards. Unfortunately these shoes are approximately 60% more expensive and wear at a rate approximately three times faster than the standard shoes. This year the ductile iron shoes are being applied to all four active retarders although sound barriers are being investigated, and may be a viable alternative if clarance problems can be solved.

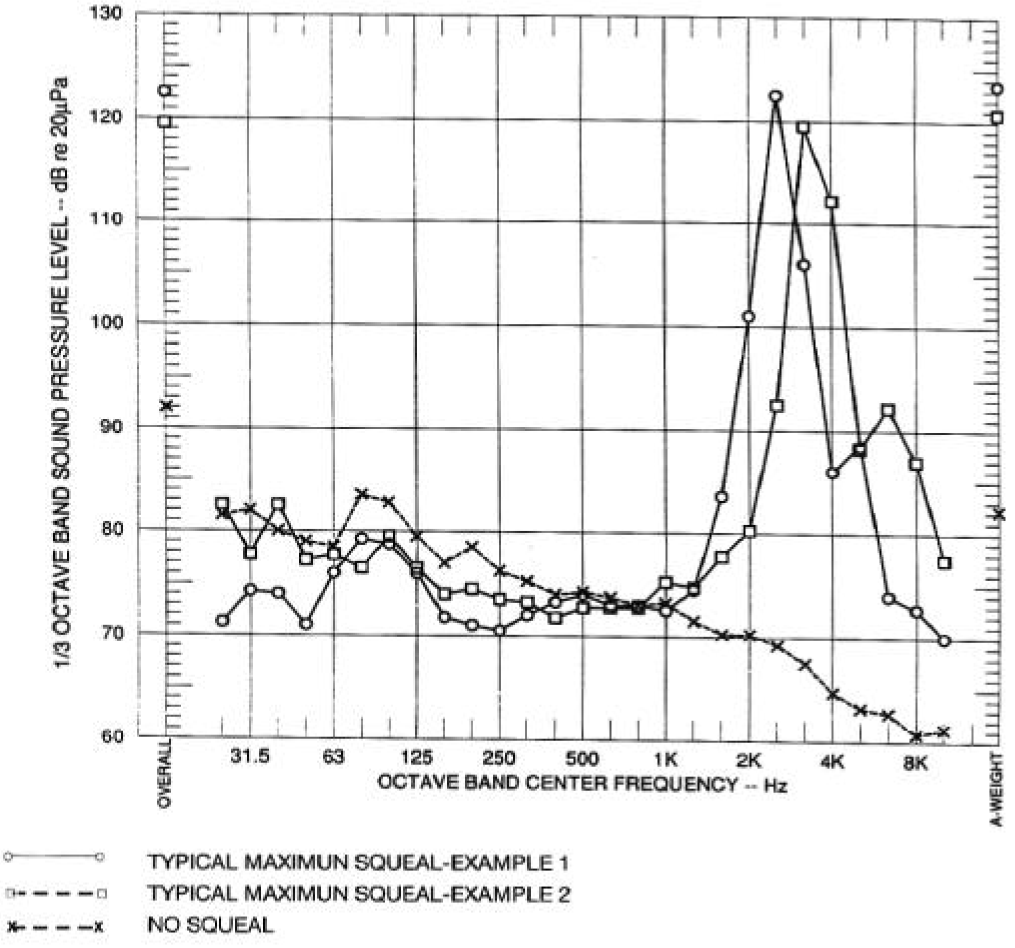

Figure 1 Noise levels at approximately 10 ft from track centerline as freight cars are pulled through inert retarder

At another yard, noise level complaints from yard personnel and a new residential development prompted the installation of a sound barrier wall adjacent to one of the active retarders and the replacement of the inert retarders with anon-clasp type retarder. Although not in violation of the FRA Standardas, since inert retarders are not covered, the installation of sthe non-clasp type retarder has significantly reduced the noise level in the yard (by as much as 30 dBA) and in the adjacent community by eliminating the squeal entirely.

For the noise produced from inert retarders, individual cars humped into a track do not present a problem. Significant noise levels (squeal) are only produced when a cut of cars is pulled out of a classification track through a closed retarder. Squeal arises as each car is pulled through the retarder affecting not only the wayside community, but also the carmen and switchmen which must be in the yard or ride the train out through the retarder. An inert retarder is generally just two rails which are spring loaded in such a way that they apply pressure to both the inner flange and out edge of the wheels.

An obvious control technique is to use a releasing retarder when a train pulls out of a classification track. A releasing inert retarder is commonly referred to as a power operated skate retarder. In newer yards, these have been installed. However, to install power operated skate retarders in an existing yard is an extremely expensive undertaking. In adition, there have been problems in yards when the power operated skate retarders for one reason or another do not open.

A non-clasp type retarder that has been available since the 1970's, is the hydraulic or "oil pressure" type retarder or resistor made by the Dowty Corporation and commonly referred to as a Dowty Retarder. Although it has been installed at a limited number of installations in the United State since tha late 1970's, it has only recently been considered as the ideal method for reducing the noise from the standard non-operable inert retarder.

The Dowty Retarder is a relatively simple mechanical device which is attached to the inside of the rails and with proper engineering can take the place of a standard inert retarder at a reasonable costo. The principal of operation is best desceibed by the manufacturer:

> Each retarder consists of two basic components, a cast pot which is bolted to the inside of the rail and capsule which is housed in the pot. The capsule consists of a sliding cylinder made from high tensile steel with a hardened mushroom shaped head, into aehich fits a piston assembly containing a relief valve and speed valve. Capsules are charged with oil and nitrogen under pressure.
>
> The retarders are bolted to the rails at pre-determined intervals. As a car mover along the rails, the flange of each wheel contacts the mushroom shaped head of the capsule and depresses it into the pot.
>
> Each retarder capsule is adjusted during manufacture to a control speed setting varying between 0 and 16.4 ft/sec.
>
> With the car traveling below the control speed the capsule closes without absorbing any appreciable energy.
>
> With the car traveling above the control speed, energy is dissipated hadraulically within the capsule.
>
> With the car traveling above the control speed energy is dissipated hadraulically within the capsule. The amount of energy extracted from the car is dependent on the car velocity.

The return stroke is dampened and is achieved by the expansion of the compressed nitrogen in the cylinder.

The units are distributed along the track with a density proportional to maximum axlw weight, control speed, minimum rollability and the track gradient.

For replacement of existing clasp-type inert retarders, the central spring is removed and the "zero-set" unit will extract energy from every wheel regardless of speed.

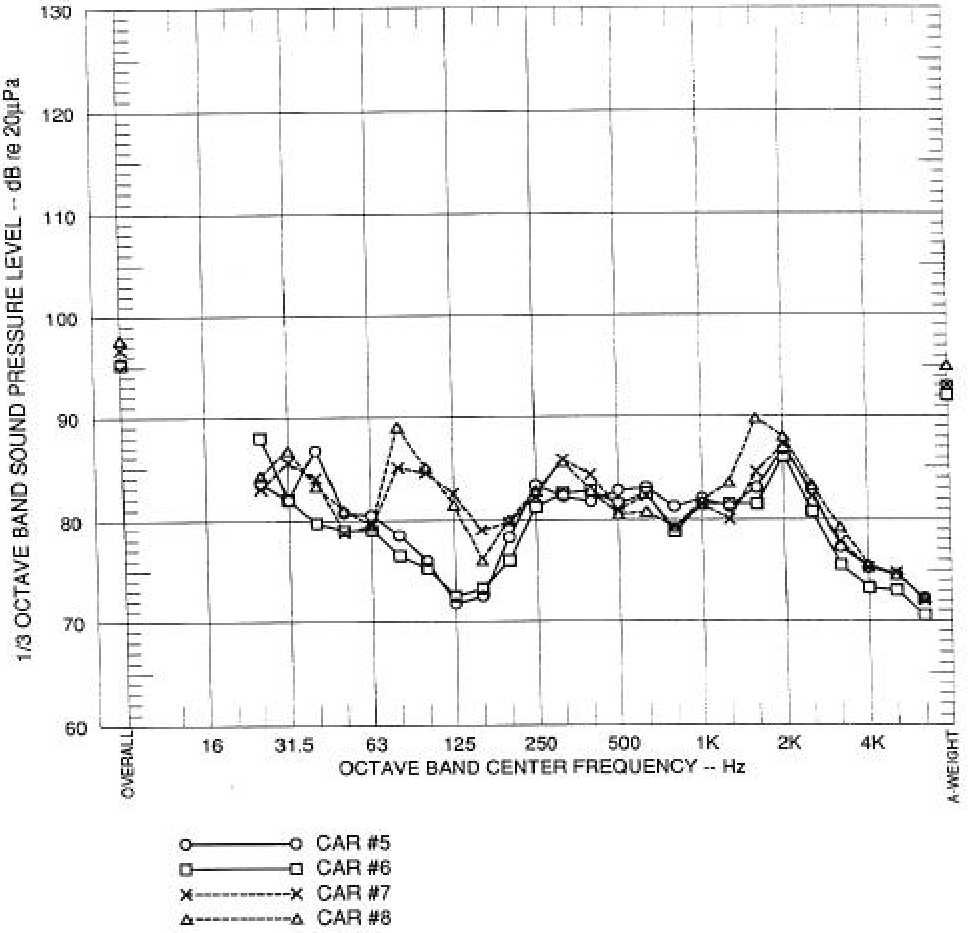

Figure 2 Noise levels at approximately 10 ft from track centerline as freight cars are pulled through dowty arrestor zonw

Figure 1 shows 1/3 octave band spectra of the noise in the vicinity (10 ft from track centerline) of an inert retarder as cars are pulled out. Figure 2 shows 1/3 octave band spectra of the noise from a group of Dowtys for the same conditions. Due to the non-clasp characteristics of the Dowty, there is no squeal. Comparison of Figures 1 and 2 shows the dramatic noise reduction achieved with the use of the Dowty Retarders.

Heavy Rail Transit

The term "heavy rail transit" generally refers to urban rail passenger transportation systems that have an exclusive right-of-way, are electrically powered, and have relatively frequent stops or stations. Rather than focus on particular practical experience at several different heavy rail transit systems, the discussion here is with respecto to the Metropolitan Atlanta Rapid Transit Authority (MARTA) System which operates in Atlanta, Georgia. Initial system operations commenced in the late 1970's, and extensions to the initial system are still under construction. The system currently has 32 miles of line in operation, with 29 stations. Twelve miles of line and 5 stations are currently under construction, with another 16 miles and 11 stations in planning stage.

The basis for the noise and vibration mitigation measures used at the MARTA system is the APTA Guidelines with the addition of criteria which apply to groundborne vibration. These criteria are presented in Tables 1 through 6. Although the expected noise and vibration levels from the operation of the transit trains were based on operations at other systems and theoretical considerations, extensive noise and vibration measurements have been made since operations started to update the noise and vibration data base for future design, to assess the effectiveness of the mitigation measures, and to ensure that the criteria have been achieved.

Presented are data for airborne noise from aerial and at-grade operations, and groundborne vibration from at-grade and subway operations. The effectiveness of the mitigation measures which have been used at the MARTA system is also presented.

Airborne Noise From Aerial Structure Operations

Some of the first airborne noise measurements of train passbys on aerial strcuture were made in 1979 at the damped and undamped aerial structure along the East Line. Although these measurements were made primarily to evaluate the effects of damping treatment added to the composite steel/concrete structure, an evaluation of the effectiveness of the sound barrier walls installed on the north side of the structure was also made at that time. Table 8 presents the measured data along with predicted levels.

TABLE 8

WAYSIDE NOISE LEVELS AT 25 FT FROM TRACK CENTERLINE FOR TWO-CAR MARTA PASSBYS ON AERIAL STRUCTURE ADJACENT TO DEKALB AVENUE

	No soun Barrier Wall		With Sound Barrier Wall	
Speed	Measured (dBA)	Predicted (dBA)	Measured (dBA)	Predicted (dBA)
30 mph	79-82	79-81	71-72	70-72
45 mph	83-85	84-86	75-76	74-76
60 mph	87-90	87-89	78-79	77-79

An extensive set of noise measurements was made in 1984 in an area adjacent to the aerial structure. These measurements were made to determine if criterion compliance was achieved by MARTA train passbys since complaints of excessive noise were received by MARTA via a neighborhood association. Table 9 is a summary of the noise data obtained at that time. Although the table appears to be misleading in the fact that the residences near sound barrier wall locations are further from alignment than those sithout the barrier wall, this is simply a consequence of the measurement program to obtain measurements at locations where complaints were received. However, the table clearly indicates that the measured noise levels do not exceed the appropriate wayside passby noise criterion of 75 dBA and that these noise levels compare favorably with the predicted levels.

TABLE 9
WAYSIDE NOISE LEVELS AT AVRIOUS DISTANCES FOR MARTA REVENUE TRAIN PASSBYS AT 40 TO 60 MPH ON AERIAL STRUCTURE-NORTH LINE

Distance from Near Track Centerline (ft)	Measured * (dBA)	Predicted (dBA)
No sound Barrier Wall		
250 **	74	73-75
280	73	73-75
290	73	72-74
300	72	72-74
With Sound Barrier Wall		
310	66	62-64
250	65	61-63
500	60	58-60

* Average of three to eleven passbys
** Partial Barrier

Airborne Noise From At-Grade Operations

Table 10 presents measured and predicted wayside passby noise levels for a variety of conditions. In adittion to standard at-grade ballast-and-tie measurements, data are also presented for measurements made near a crossover, near two sections of resiliently supported track and at the West Trinity Place Underpass. Although the West Trinity Place Underpass is not at-grade, it is a ballasted deck bridge and has noise characteristics which are characteristic of at-grade operations rather than aerial structure operations with resilient direct fixation fasteners.

TABLE 10

WAYSIDE NOISE LEVELS FOR MARTA REVENUE TRAINS (FOUR TO SIX CARS) OPERATING AT-GRADE AT 45 TO 50 MPH

Condition	Distance From Near Track Centerline (ft)	Measured (dBA)	Predicted (dBA)
No Sound Barrier Wall			
East Line, Station 198 Nelms Avenue	125	76	76-78
East Line, Station 207+50 Connecticut Avenue	100	76	77-79
East Line Crossover, Station 205	300	75	75-77
North Line, Station 336	45-50	78 * 73-75 ***	81-83 **
Northeast Line, Station 556+50	300	66 * 61-63 ***	69-71 **
East Line, West Trinity Place Underpass (ballasted deck bridge)	50	77 * 73-75 ***	81-83 **
	100	73 * 69-71 ***	77-79 **
With Sound Barrier Wall			
Northeast Line, Section N710 STEDEF Track	50	73	74-76
South Line, U-wall Section S610 NUCOR Track	50	73	74-76

* Some shielding (see text)
** Without effects of shielding
*** With full shielding (sound barrier wall)

The first three entries on Table 10 are from measurements made in 1979 when a re-evaluation was made of the need for sound barrier walls at specified locations along the East and West Lines. Most of the sound barrier wall recommendations were originally made in the mid-1970's in order to comply with the Design Criteria. The measurements made after commencement of revenue service generally indicated that some complaints regarding wayside were warranted and confirmed the need for sound barrier walls at the specified locations. Unfortunately, few before and after measurements were made to determine the noise reduction due to the implementation of the sound barrier walls. One measurement was made before and after installation of a sound barrier wall at the back building line of 1761 New York Avenue. Before the sound barrier was installed, a two-car train on the near track passing by at 63mph produced 78 dBA. After the wall was installed, this level was reduced by 8 to 12 dBA and was then acceptable to the residents of 1761 New York Avenue.

The partially shielded measurements presented on Table 10 show that the partial shielding reduces the noise to an intermediate level somewhere between that predicted with a sound barrier wall and without a sound barrier wall. The measurement along the North Line at Station 336 is of far track trains which have some shielding due to the third rail coverboard and car body since the measurement position was elevated with respect to the alignment. The measurement location along the Northeast Line at Station 556+50 was depressed with respect to the alignment with some shielding due to a railroad alignment between tha MARTA alignment and the measurement location. The passby noise from trains traversing the West Trinity Place Underpas is partially shielded due to the through girder which forms part of the bridge structure.

Both of the measurement locations with sound barrier wall have resiliently supported ties with a concrete slab track. The expected noise levels for this type of trackbed is similar to that of aerial structure with concrete trackbed rather than ballast-and-tie, and thus, the expected noise levels are somewhat greater than for other at-grade locations. The sound barrier wall along Section N710 is very high and the measured noise level of 73 dBA at a height of 5 ft above the ground is expected, although the predicted level shown on Table 10 is the noise level expected for a relatively low wall, approximately 3.5 to 4 ft above top-of-rail. The high sound barrier wall here is warranted due to the nearby two-story apartment building.

Along Section S610, the alignment consists of a U-wall section, with significant shielding equivalent to a sound barrier wall of height greater than 3.5 to 4 ft. Thus, the measured average noise level of 73 dBA is not unexpected, although the predicted level shown on Table 10 is marginally greater since this prediction assumes a 3.5 to 4 ft high wall.

Groundborne Vibration From At-Grade Operations

Significant groundborne vibration from MARTA train operations at-grade was not initially expected. This was due primarily to previous experience with at-grade operations at other new systems such as BART in the San Francisco Bay Area and WMATA in Washington, D.C. However, the relatively stiff trucks of the "old" MARTA vehicles combined with the characteristics of the soil in much of the Atlanta area led to some significant levels of groundborne vibration experienced at wayside locations along both the East and West Lines. Based on the wayside groundborne vibration measured in 1980 and 1981, the indication is that there could be significant groundborne vibration impact for residential buildings within 150 ft of the alignment.

Unlike airborne noise, groundborne vibration propagation is very dependent on the characteristics of the soil between the alignment and the building structure, and the characteristics of the building structure itself. For this reason, the analysis of groundborne vibration propagation must be analyzed on a spectral basis for each individual situation. The factors influencing groundborne vibration generation, propagation and perception could encompass an entire presentation, and are thus not further detailed here.

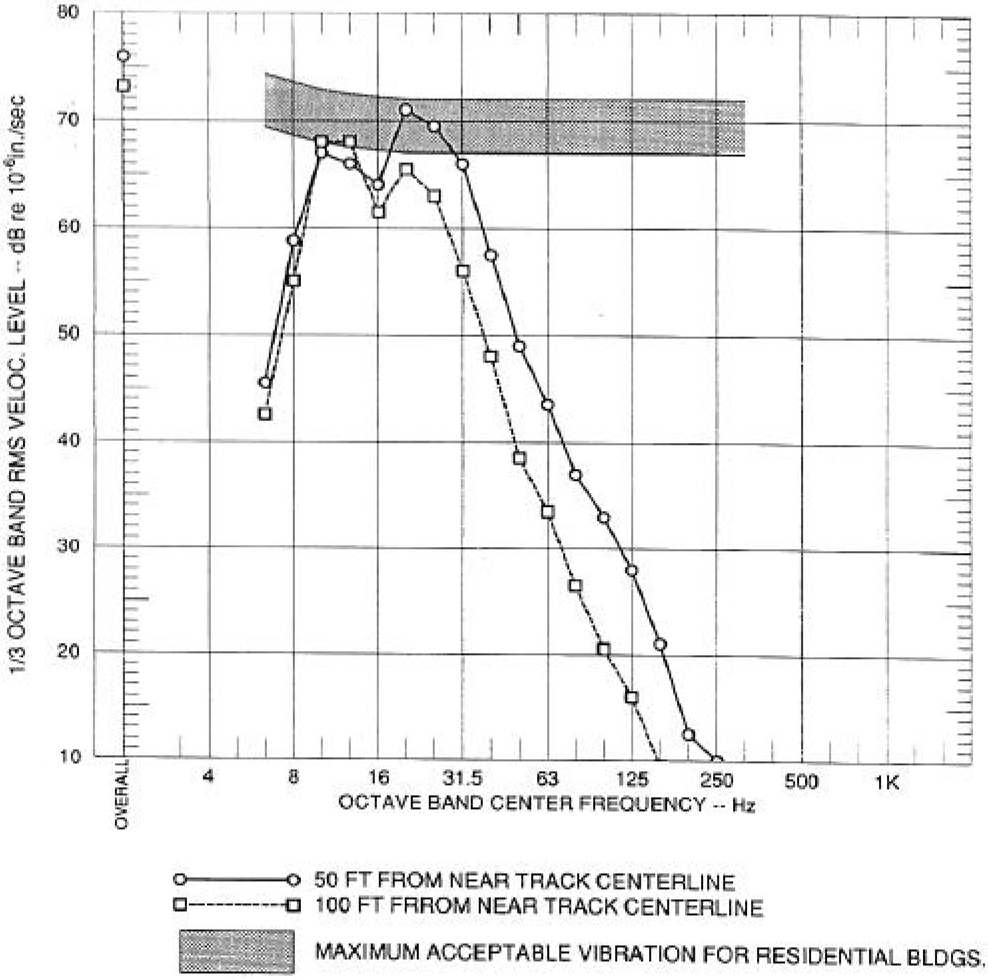

Figure 3 Average of ground vibration levels measured at marta in 1980 & 1981

Figure 3 presents groundborne vibration due to MARTA train passbys measured in 1980 and 1981 at locations on the West Line at the end of Sharon Street, on the West Line at the end of Howard Street, and on the East Line in the Swanton Hill area. These data are ground surface measurements and thus do not indicate the building coupling loss or fllor amplification possible in residential buildings. Generally, the net effect is an increase in vibration inside the structure of 5 to 10 dB. Figure 3 also indicates the rante of maximum acceptable groundborne vibration from transit trains as perceived in residential building. Factoring in the potential vibration amplification in the structure, the potential for vibration problems is clearly seen.

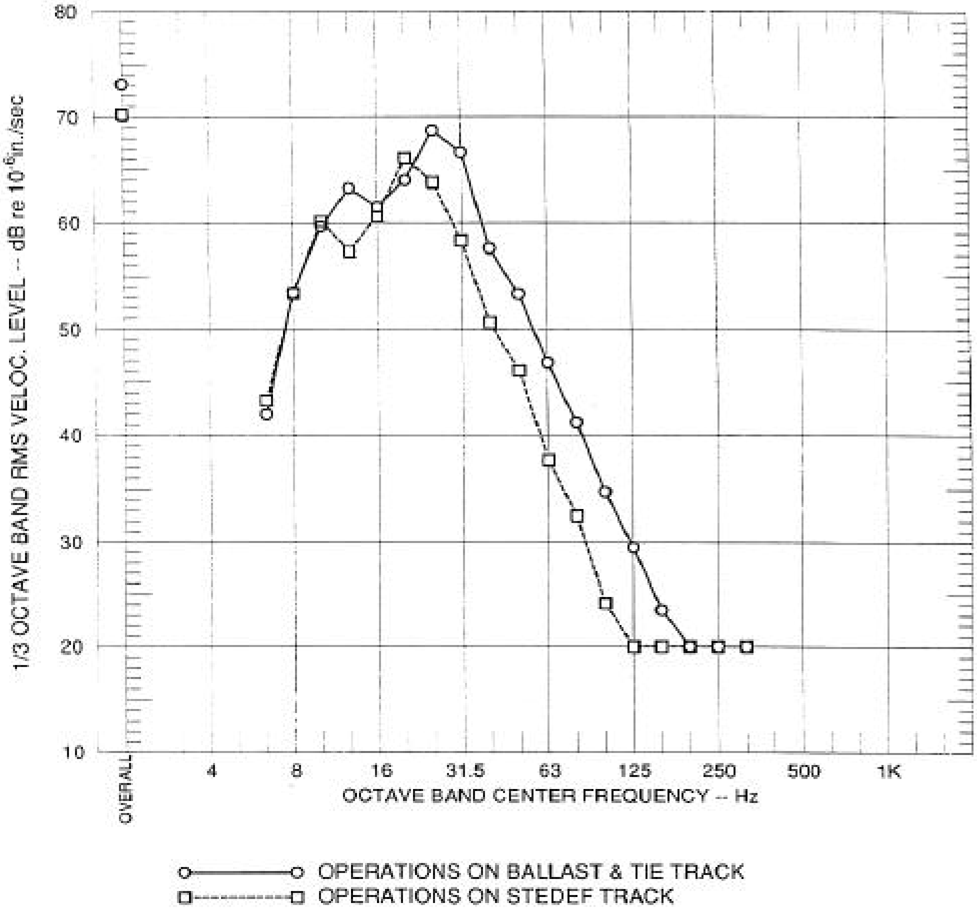

Figure 4 Ground vibration levels @ 50 ft from nl track centerline 4 car trains - "old" cars

After an extensive study of potential mitigation measures to reduce the groundborne vibration from at-grade operations, resiliently supported ties (sleepers) in rubber boots on a concrete trackbed (STEDEF resiliently supported sleepers) were considered most suitable, particularly sonce resiliently supported ties in a section of MARTA subway had already indicated a reduction of groundborne vibration. In 1986, measurements adjacent to the STEDEF installation were made to assess the reduction of groundborne vibration due to trains operating on STEDEF track when compared with trains operating on standard ballast-and-tie track. An important corollary of that analysis was an assessment of the groundborne vibration effects of the reduction in the primary suspension vertical stiffness of the trucks for the "new" vehicles being delivered to MARTA at that time.

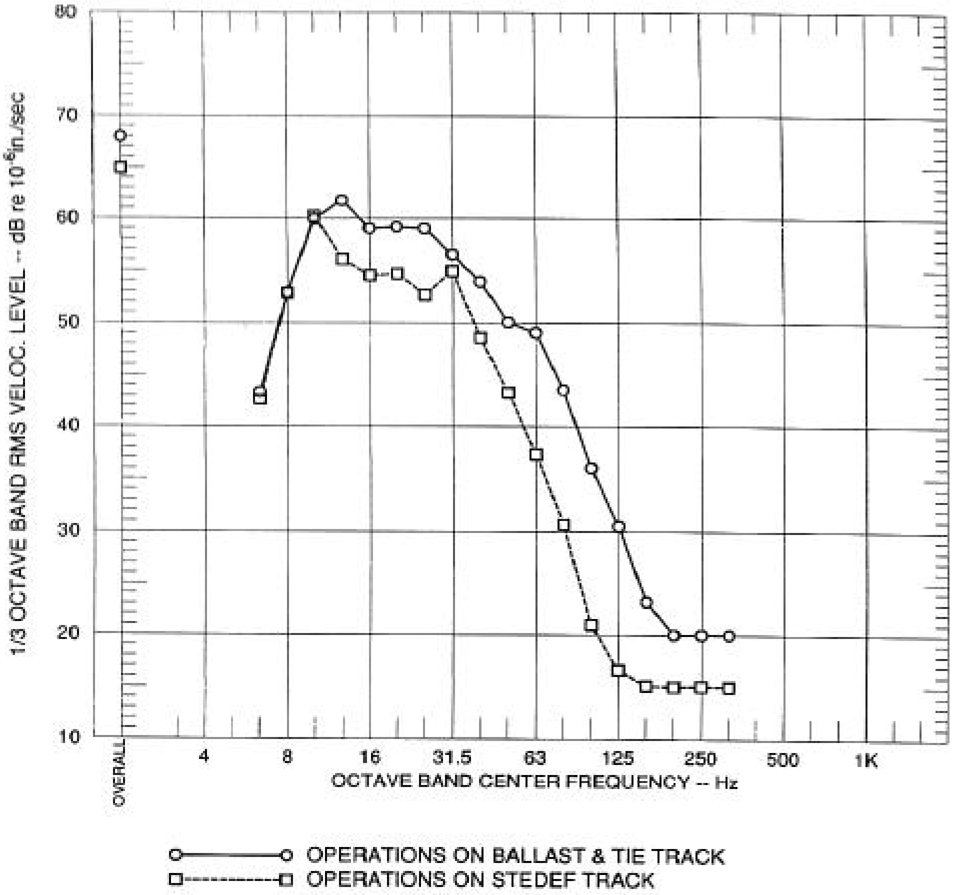

Figure 5 Ground vibration levels @ 50 ft from nl track centerline 4 car trains - "new" cars

Figure 4 presents ground vibration levels at 50 ft for four-car trains of "old" cars operating on STEDEF and standard ballast-and-tie track. Figure 5 presents ground vibration levels at 50 ft for four-car trains of "new" carts operating on STEDEF and standard ballast-and-tie track. Figure 6 presents both the results of measurements as well as the predicted reduction of groundborne vibration with the STEDEF track relative to ballast-and-tie track. figure 7 shows the measured and predicted redution of the groundborne vibration with the new low resonance truck. Figures 6 and 7 clearly show that the STEDEF track and the low resonance trucks are both beneficial at reducing groundborne vibration at locations near the MARTA right-of-way. The reduction in groundborne vibration with the new cars is significant enough that if the entire fleet of MARTA vehicles had low resonance trucks, then the length of the resiliently supported track could be reduced or eliminated at some locations.

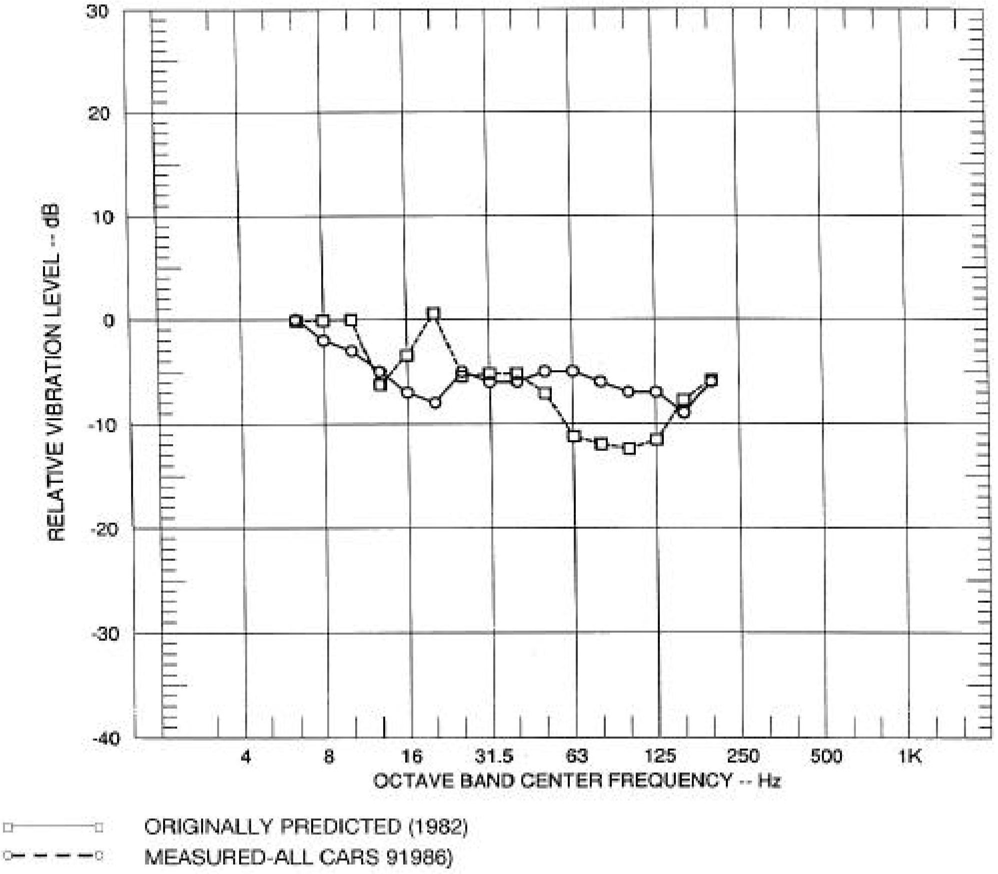

Figure 6 Ground vibration levels with stedef track relative to ballast & tie track (at-grade)

Groundborne Vibration and Noise From Subway Operations

Where the MARTA subway structure is within close proximitily to certain types of buildings, significant levels of groundborne noise were expected prior to system operations. Experience at other systems had indicated that for certain situations, reduction of the groundborne noise would be necessary, primarily at relatively small structures with noise and vibration sensitive users that are located closer than 50 to 100 ft from the subway structure. A suitable mitigation measure that had been used with considerable success at ogher systems was the floating slab trackbed, and this was recommended for use at the MARTA System during the initial designs of the 1970's. A typical discontinuous floating slab trackbed is shown in Figure 8. Where an intermediate level of mitigation was needed, resiliently supported ties (STEDEF) were recommended.

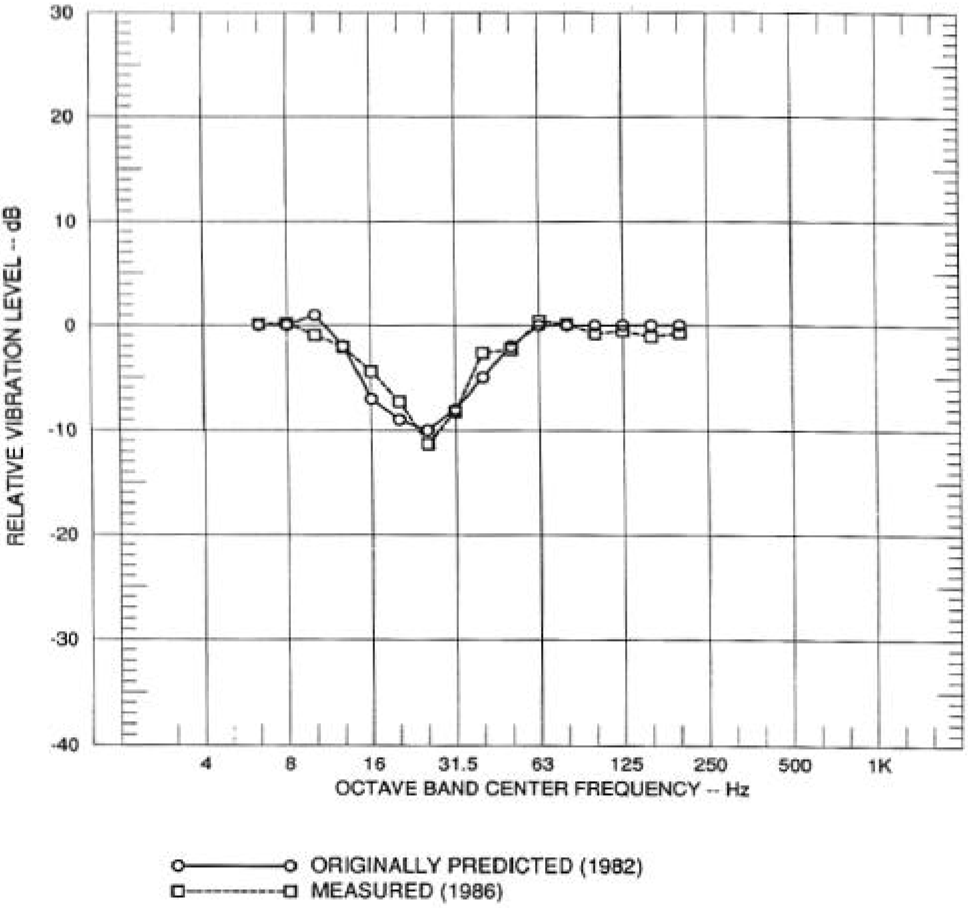

Figure 7 Ground vibration levels with new low resonance trucks (12 hz) relative to old trucks

After MARTA train operations commenced, it was determined that feelable groundborne vibration, in addition to groundborne noise was a potential problem at certain wayside locations. The reason for this was previously discussed in the section on groundborne vibration from at-grade operations. The control of groundborne vibration was addressed with the establishment of criteria for groundborne vibration. Thus, for extensions of the MARTA system which include subway, predictions of both groundborne vibration and groundborne noise are generally made and compared with appropriate criterion to determine the need for mitigation.

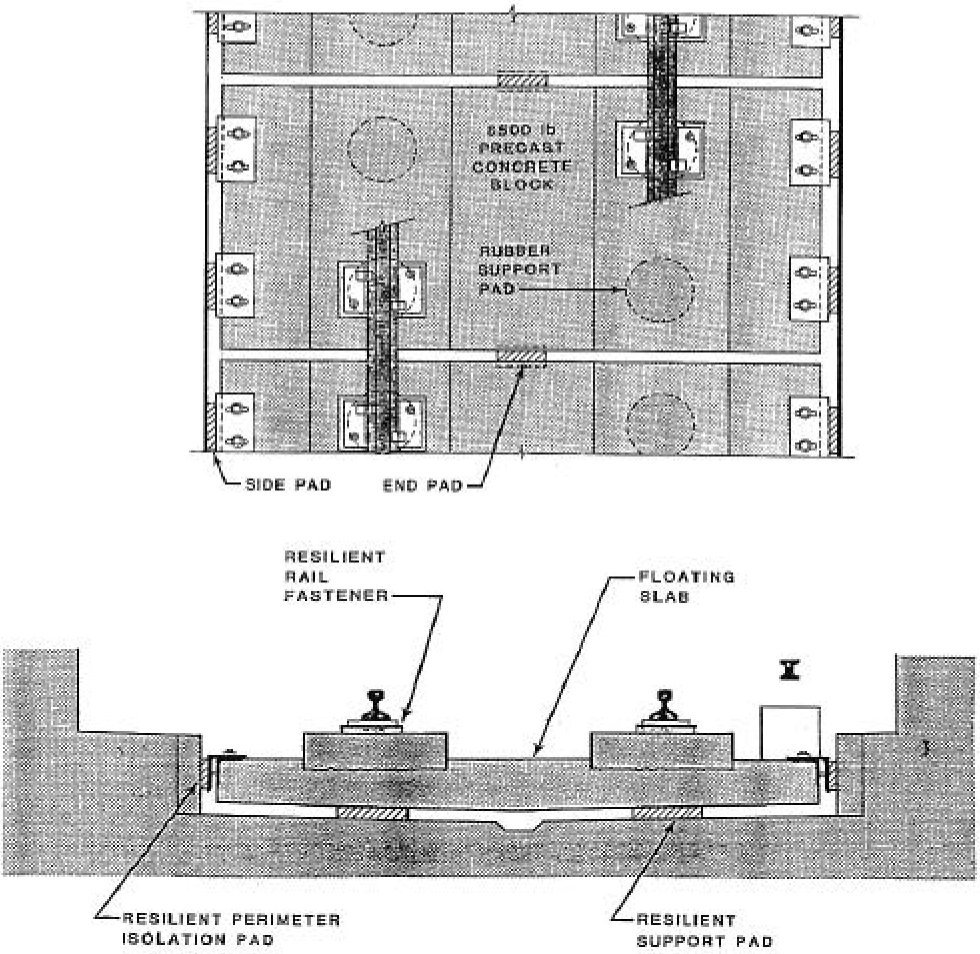

FIGURE 8 GENERAL CONFIGURATION OF DISCONTINUOUS FLOATING SLAB TRACK SUPPORT INSTALLED AT THE ATLANTA (MARTA) RAPID TRANSIT SYSTEM

Figure 8 General configuration of discontinuous floating slab track support installed at the atlanta (marta) rapid transit system

Evaluation of the effectiveness of the floating slab trackbed and resiliently supported ties at reducing groundborne noise and vibration were made at MARTA in 1980. Rather than determine the noise and vibration reduction afforded inside any specific building, the evaluation focused on the vibration of the subway structure and ground surface directly over the subway and within 25 ft of the near track centerline. The evaluation was done in this manner to minimize the effects of building response and site-specific soil characteristics. Minimiznig these effects is necessary unless tests can be performed in the same building structure with a change of the track fixation in the subway structure. Even a test of this nature would not eliminate the effects of building response and site-specific soil characteristics. Even in performing tests on the subway structure and in very close proximity to the subway structure, the effects of the local soil characteristics cannot be completely eliminated.

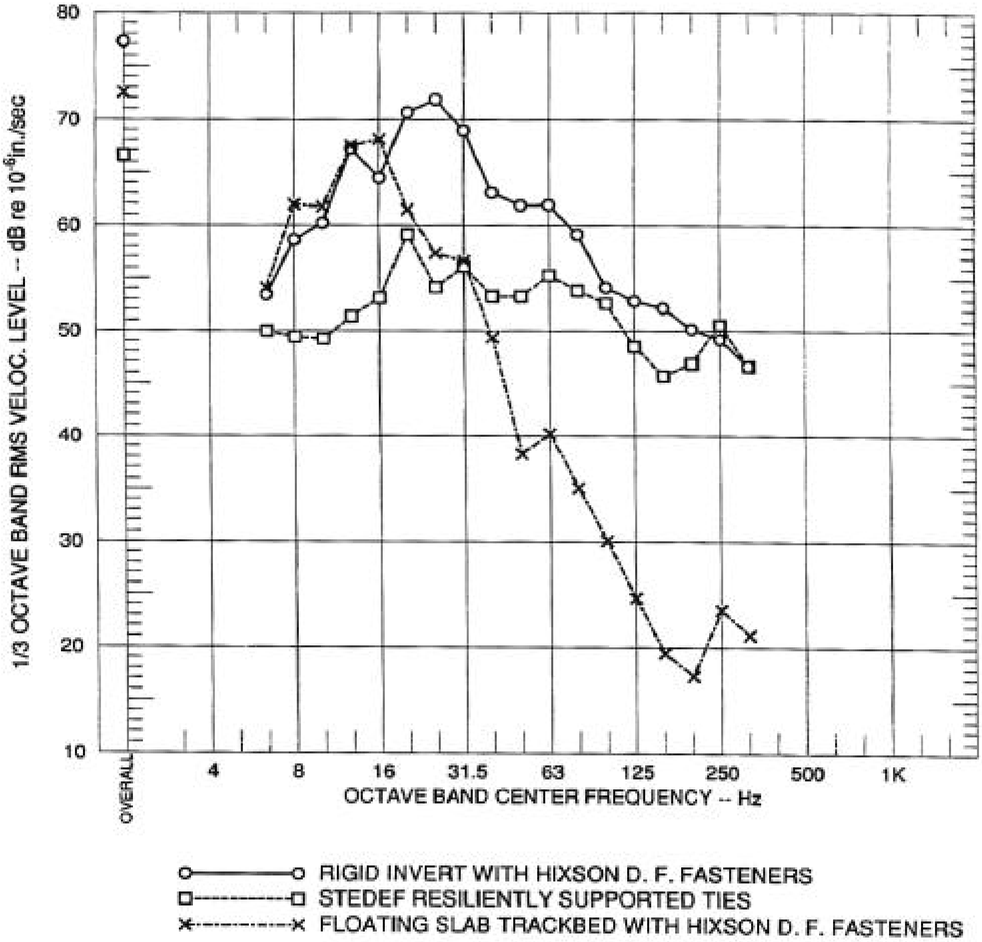

Figure 9 subway structure vibration levels for revenue trains of "old" cars operating at 45 to 50 mph - average of side and center bench vertical vibration

Since these tests were performed in 1980, the trains consisted only of "old" cars with the relatively stiff primary suspension. As previously discussed, these cars tend to produce higher vibration levels in the low frequency range (16 to 30 Hz) than for the new transit cars having a lower stiffness of primary suspension for the trucks. Thus, it is reasonable to conclude that as measured for at-grade operations, the operation of "new" cars in subway will produce lower levels of groundborne vibration in the low frequency range, as shown on Figure 7.

Figure 9 shows the subway structure vibration levels for rigid invert, STEDEF resiliently supported ties and floating slab trackbed. Figure 10 shows ground surface vibration levels for the same three types of track support. Figures 11 and 12 show the vibration reduction relative to rigid invert. Figures 13 and 14 show the average measured vibration reduction relative to rigid invert with the originally predicted reduction expected prior to these measurements.

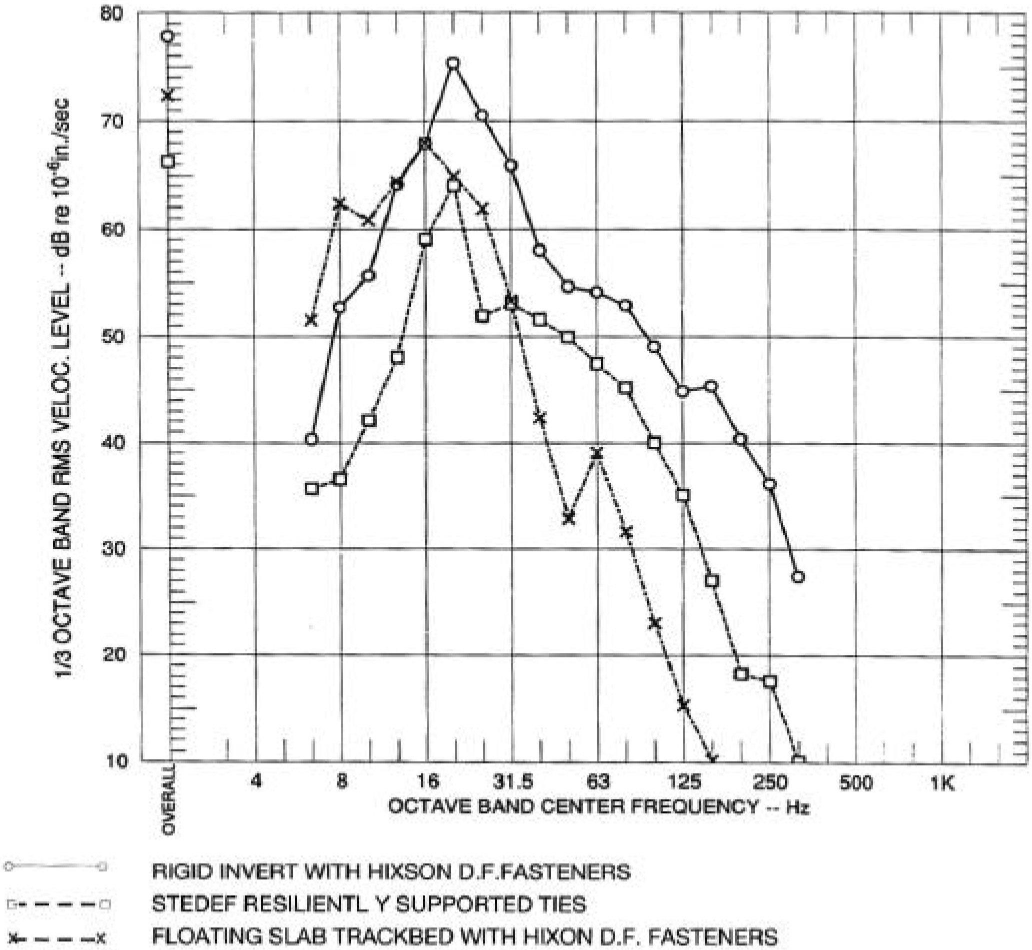

Figure 10 Ground surface vertical vibration levels above the subway for revenue trains of "old" cars operating at 45 to 50 mph - average of two measurement positions

The overall results indicate that the relative improvement in vibration levels produced by MARTA transit trains traveling on the STEDEF resiliently-supported tie system compared to rigid invert is about 10 dB in the frequency range of 8 to 40 Hz and about 5 dB for the range from 40 to 125 Hz. This result is similar to the expected performance except that it extends to lower frequencies than previously observed. This lower frequency effectiveness at MARTA may be due to the vehicle truck and soil characteristics. The results for the floating slab trackbed for frquencies of 20 Hz and above are similar to those obtained at ogher transit facilities and amount to a reduction of 20 to 30 dB for the audible frequency range, which translates into a significant reduction of groundborne noise inside nearby wayside buildings.

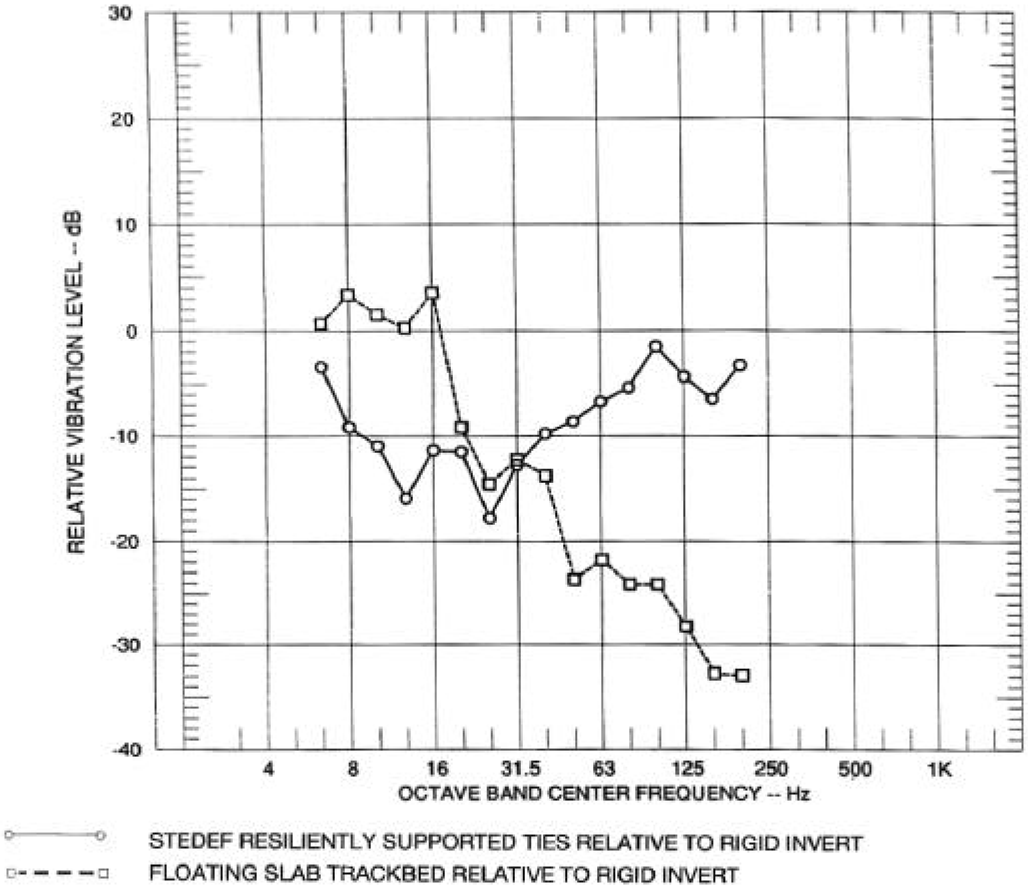

Figure 11 Relative vibration levels in the subway for revenue trains of "old" cars operating on various track support systems

For frequencies below 20 Hz, the results with floating slab are also similar to those measured at other systems, if apparent differences in soil and vehicle characteristics are considered. Despite the effective reduction of transit train generated groundborne noise and vibration with the use of either resiliently supported ties or a floating slab trackbed, if relatively small buildings strctures containing residential or other noise and vibration-sensitive uses are located within 25 ft of the subway structure, then these mitigation measures may nor provide sufficient vibration reduction to achieve criteria compliance and preclude complaints. However, for noise and vibration sensitive structures located between 25 and 150 ft from the subway structure, these mitigation measures are very effective at reducing the groundborne noise and vibration from MARTA train operations.

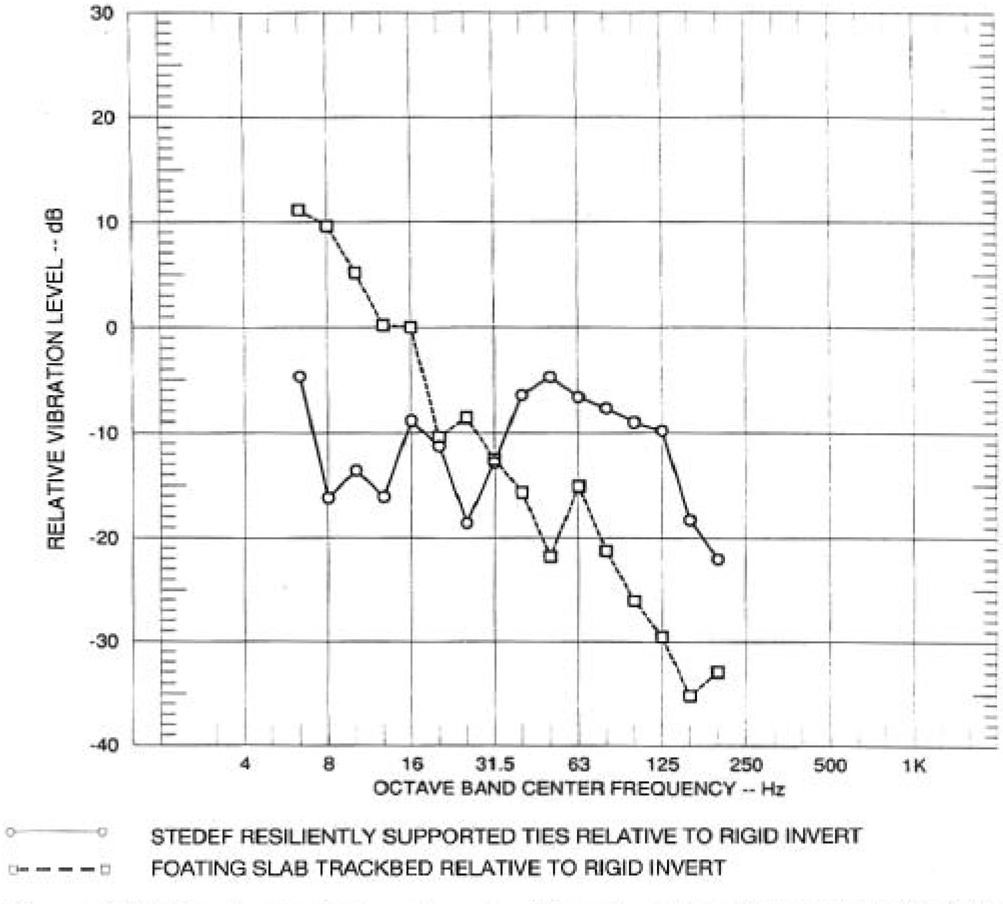

Figure 12 Relative vibration levels on the ground above the subway for revenue trains of "old" cars operating on various track support systems

Light Rail Transit

The term "light rail transit" generally refers to urban and suburban rail passenger transportation systems that do not have a completely exclusive right-of-way, that may have tracks in streets, are electrically powered, generally have relatively short trains, and relatively frequent stops or stations. This discussion focuses on just one potential problem at one system, the San Francisco Municipal Railway or MUNI. Currently the system includes light rail, clable cars, trolley bus and diesel bus operations.

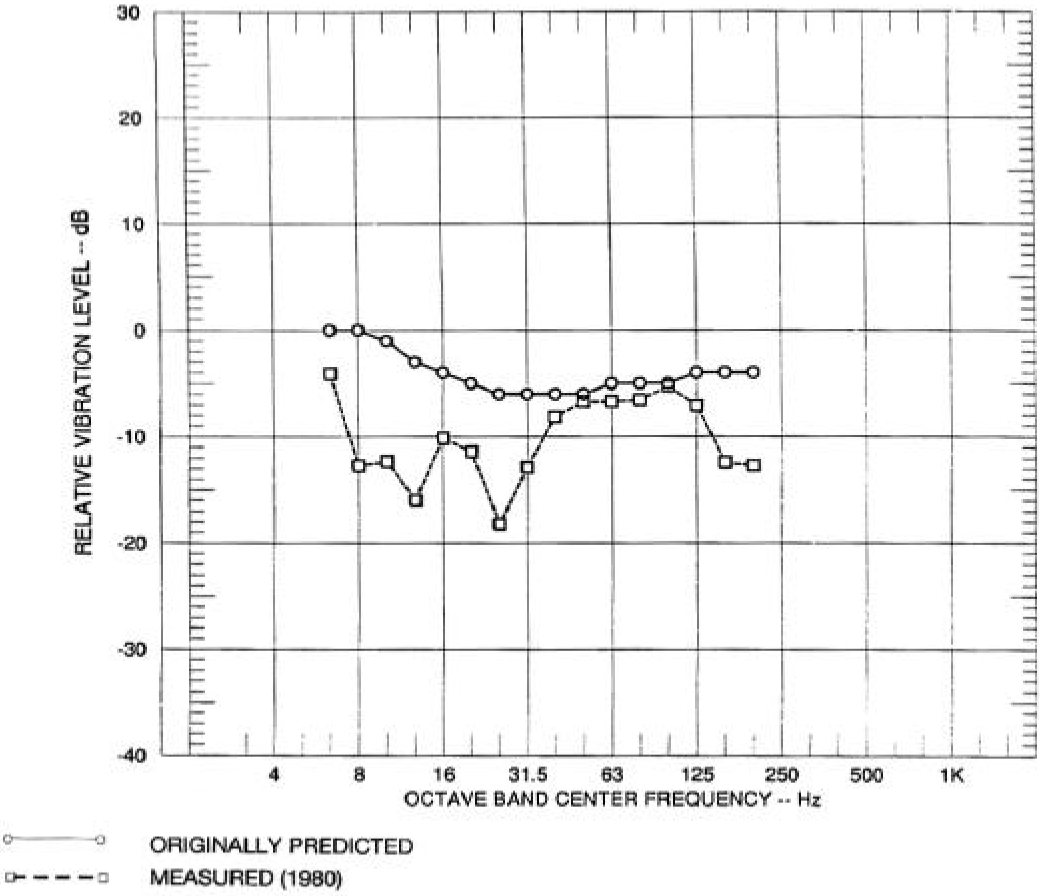

Figure 13 Relative vibration levels for subway operations with stedef resiliently supported ties relative to rigid invert

Streetcar or ligt rail operations have continued on Market Street since the turn of the century. In the late 1970's, the surface operations on Market Street were moved underground with the construction of BART (the heavy rail system serving the San Francisco Bay Area). The surface tracks were never removed, and for a number of years during the summer months, historical trolleys were operated on these tracks. Due to favorable public response, it was decided to rebuild the tracks on Market Street and run streetcars at the surface all year long. Rather than use the newer light rail vehicles that are used in the subway under Market Street, it was decided to use the older PCC (Presidential Conference Commission) type streetcars, a design developed in the 1930's.

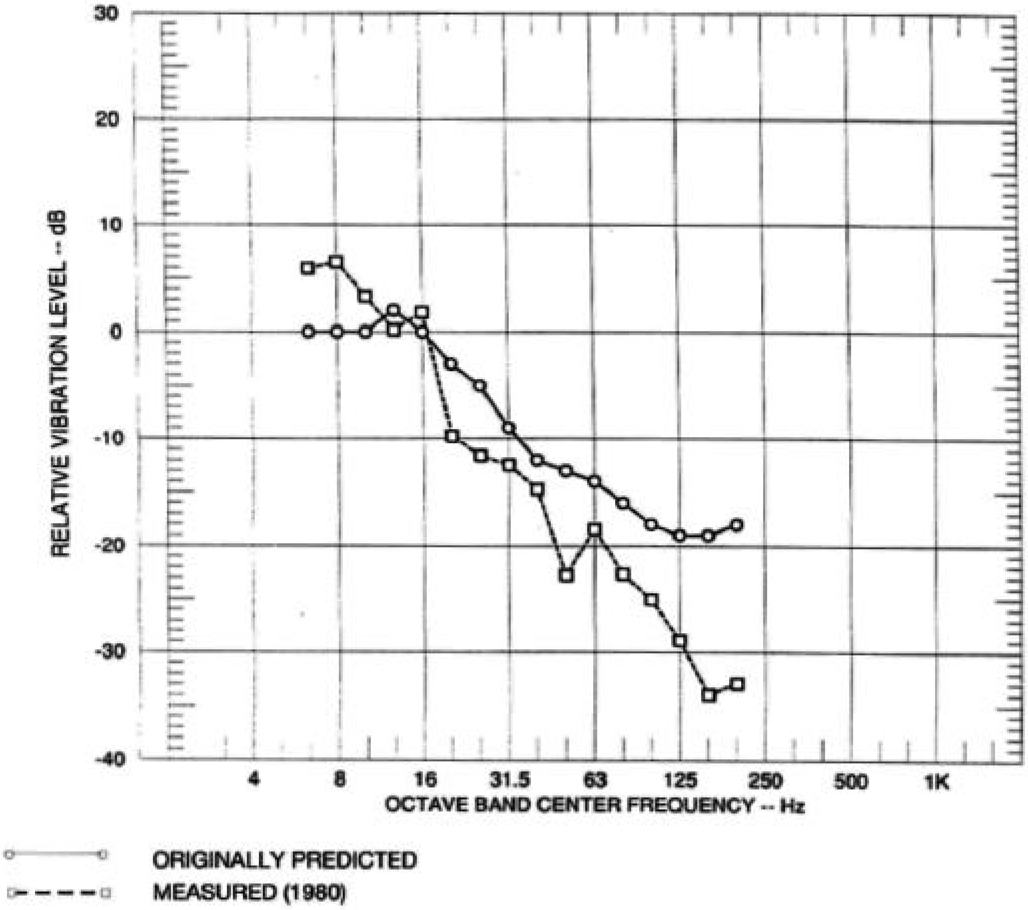

Figure 14 Relative vibration levels for subway operations with floating slab trackbed relative to rigid invert

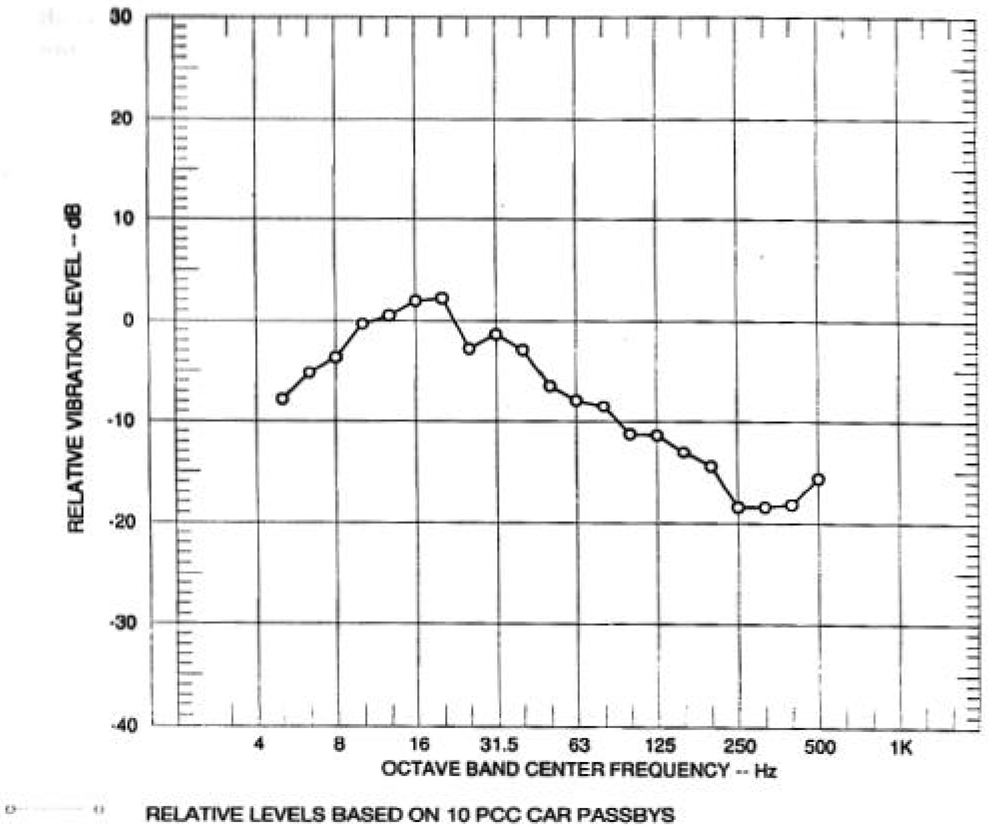

Figure 15 Vibration levels for pcc streetcars operating on embedded track on ballast mat relative to standard embedded track - market st. west of 5th st.

As part of the resumption of surface operations on Market Street, tracks would be necessary on one block of Noe Street between Market and 17th Streets where there had never been any previous operations. It was determined that a study should be made of the potential vibration impacts on the multi-family residences due to PCC car operations on Noe Street where the new track would be as close as 25 ft from track centerline. Previous experience indicated that the groundborne vibration from the operation of the PCC cars could cause a significant number of complaints particularly when running close to residential buildings.

Studies completed in 1988 indicated that for the extension of the MUNI J-Line, the use of a ballast mat under the track for vibration reduction would be quite efective for

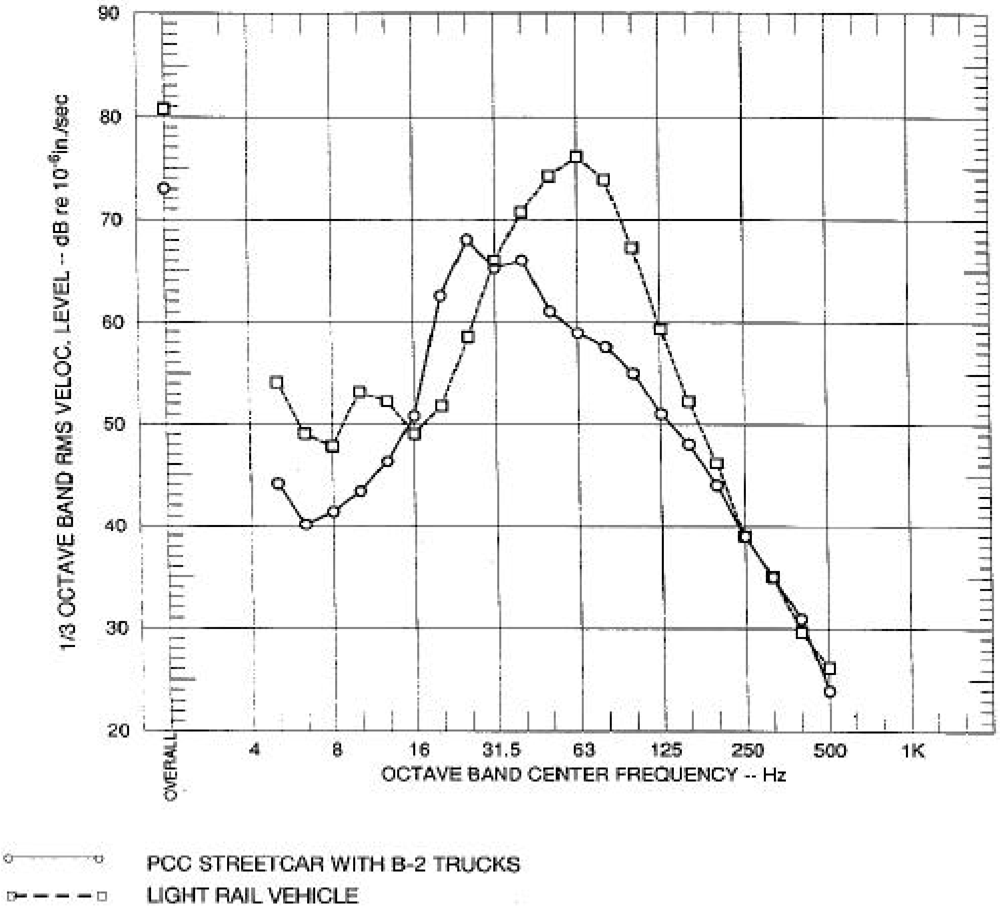

Figure 16 Average levels of groundborne vibration from pcc car & lrv operating at apx. 25 mph on embedded track 25 ft from track centerline

operations of the ligt rail vehicles. Although it was naturally assumed that the ballast mat under the tracks on Noe Street would also prove beneficial, it was decided to perform a series of tests which would indicate if this was true.

In addition to the ballast mat sections installed on the J-Line Extension, there were some short sections installed where the track had already been rebuilt on Markes Street. No revenue operations had commenced on these sections of track, however, the ballast mat section on Market Street west of 5th Street could be tested with PCC cars only. Light rail vehicles could not be tested here because of the configuration of the overhead power wires. Figure 15 shows the insertion loss or vibration reduction for the ballast mat based on these PCC car operations. The indication is that the ballast mat installation is effective

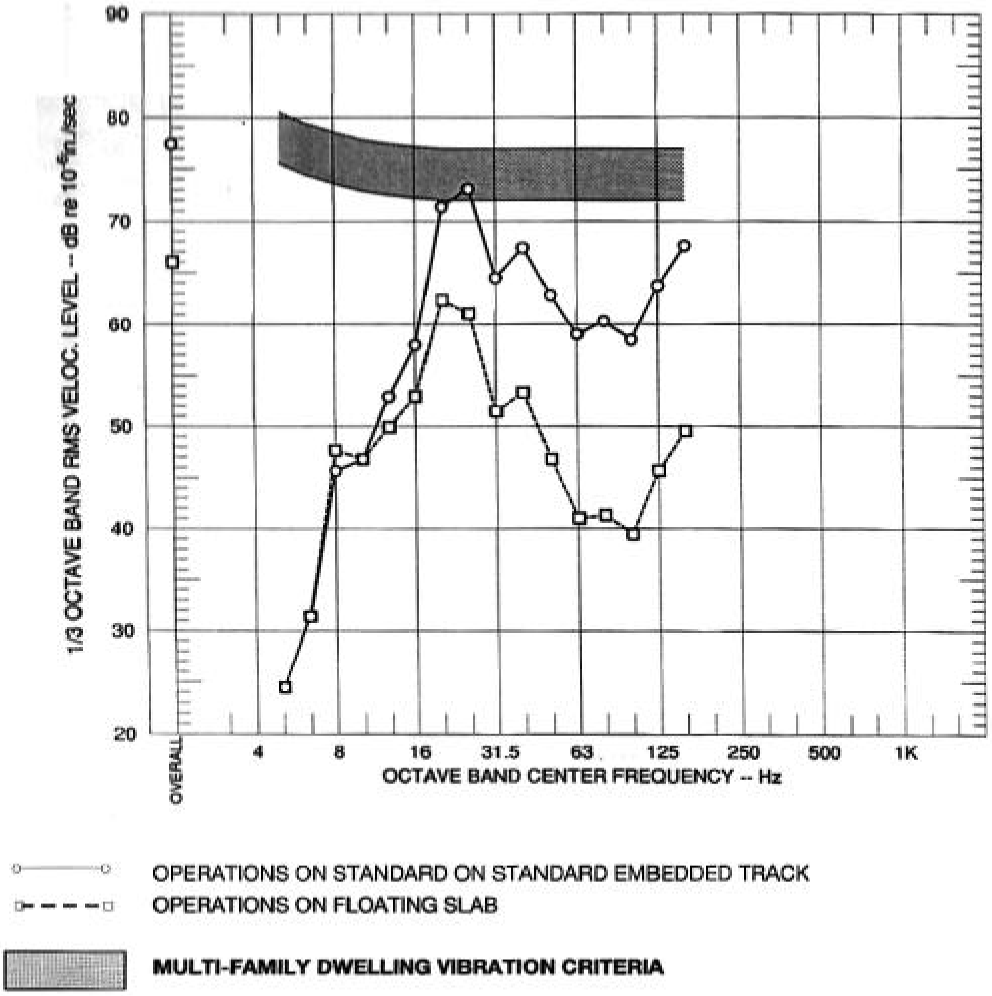

Figure 17 Estimated ground fllor vibration inside nearest residences on noe st. for pcc streetcars operating at 25 mph

above 40 Hz. The reduction below 10 Hz was influenced by background vibration and is not considered significant. Tests of ballast mat performance at other systems has shoen somewhat better performance between 20 Hz and 40 Hz, and the lack of more significant reduction around 30 Hz may be due to construction problems at the edge of the ballast box which retains the ballast mast near the street surface.

A second test location without ballast mat was used in order to obtain a comparison of the vibration characteristics of the PCC streetcars and the light rail vehicles. Figure 16 shows the vibration velocity spectra for the PCC streetcar with Clark B-2 trucks and simplified super-resilient wheels (the type that will be used on future Market Street operations) and the light rail vehicle with Acoustaflex or Bochum type resilient wheels for operations at 25 mph and at a measurement distance of 25 ft. The indication is that the light rail vehicles produce higher levels of groundborne vibration for similar operating conditions than do the PCC streetcars, with the predominant frequency of vibration in the 63 Hz one-third octave band. The predominant frequency of vibration of the PCC streetcars is generally in the 20 or 25 Hz one-third octave band. Based on these data, the ballast mat will provide a significant reduction of groundborne vibration for light rail vehicle operations, but only marginal reduction of groundborne vibration for PCC streetcars with B-2 trucks.

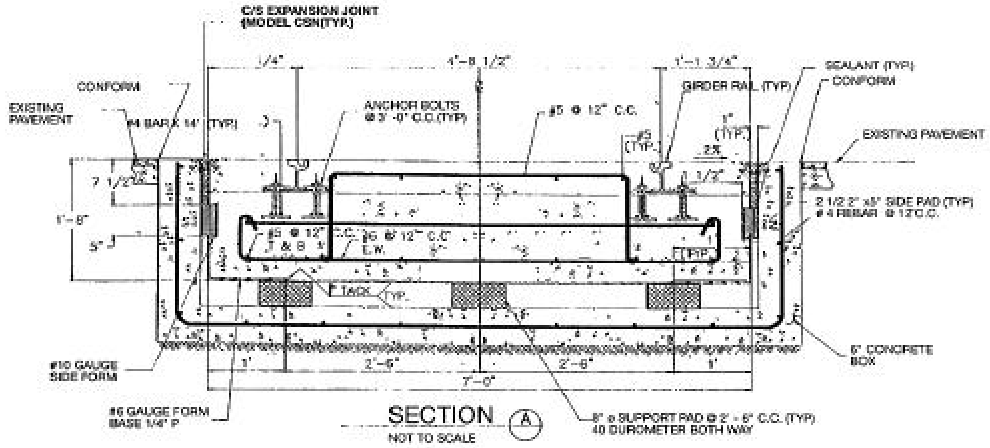

Figure 18 Preliminay configuration of floating slab trackbed for street installation on noe street in san francisco

Estimates of the expected maximum 1/3 octave band vibration velocity levels have been made for the first fllor locations in the nearest buildings on Noe Street. The procedures used to estimate the future groundborne vibration in these ewellings are described in a paper by Nelson, et al (1987) and is not delailed here. Figure 17 presents the maximum levels expected in the nearest buildings with PCC streetcar operations at 25 mph. Maximum levels of acceptable vibration are also plotted. The cross-hatched area applies to multi-family dwellings and represents the single-number design criterion of 75 dB as presented in Table 6 on a spectral basis.

Although a severe problem is not anticipated, these estimated levels will generally be feelable and in order to achieve compliance with the criterion, it was decided that vibration mitigation would be appropriate. The only possible method that would reduce the low frequency groundborne vibration from the operation of the PCC streetcars is with the use of a floating slab trackbed adopted for street installation. The maximum levels of groundborne vibration with operations on the floating slab trackbed are also shown on

Figure 17. The proposed basic configuration is shown in Figure 18. The slabs will be cast in place, are 40 ft long and have a design natural frequency of less than 10 Hz. The support pads will be 40 durometer natural rubber pads of 8 in diameter with 4 in thickness, mounted 3 across every 2.5 ft on centers. The desing details are being finalized, with full revenue operations anticipated by the beginning of 1993.

SUMMARY

Rail based transportation systems do produce noise and vibration that can cause annoyance or problems in the community without application of appropriate mitigation. Standards and regulations have been developed to control the levels of noise and vibration so that the nearby community will find the rail tracked traffic noise and vibration acceptable. As shown by the examples of practical experience, careful application of the standards and regulations will generally indicate if mitigation measures are necessary to achieve community acceptance. However, there are still some situations where inappropriate or inadequate regulations or mitigation measures have been applied which have not alleviated community annoyance.

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