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16. Abstract

As systems manager for the Urban Mass Transportation Administration's Rail Supporting Technology Program, the Transportation Systems Center has undertaken research in rail transit noise abatement. As part of this effort, this report contains the results of a critical review of current technology for the prediction and control of urban rail transit noise and vibration, with primary emphasis on the parameters affecting propagation paths. Specifically included are tools for the prediction of wayside noise and vibration adjacent to both at-grade and elevated transit track, groundborne noise propagation from subway tunnels, and noise in cars and in stations. In addition, several noise and vibration control techniques are evaluated including resilient rail fasteners, floating slabs, noise barriers, elevated structure enclosures, structural damping, and acoustical treatment of stations and tunnels. Specific recommendations are made for areas requiring further research and development. Two of these areas, elevated structure noise and groundborne vibration from tunnels, have been selected for continued investigation under this contract.

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PREFACE

This report has been prepared by Cambridge Collaborative, Inc. (CC), under Contract DOT-TSC-643 as part of the Urban Rail Supporting Technology Program managed by the Transportation Systems Center, Cambridge, Massachusetts, under the sponsorship of the Rail Programs Branch, Urban Mass Transportation Administration, Washington, D.C.

In preparing this report the authors have received extensive assistance from other members of the Cambridge Collaborative staff and from the staff of Parsons, Brinckerhoff, Quade and Douglas, Inc., who have served as subcontractors. Professor Stephen H. Crandall from the Massachusetts Institute of Technology and Professor Manfred Heckl from the Technical University at Berlin have contributed to the report by providing information on the propagation of ground vibration away from subway tunnels and on noise in stations. Finally, the technical monitor of the contract, Dr. Leonard Kurzweil, has provided a great deal of worthwhile information that has been included in the report.

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1. INTRODUCTION

1.1 Objective

The noise and vibration generated by rail transit vehicles are the result primarily of wheel/rail interactions. The fluctuating forces generated at the wheel/rail interface result in vibrations of the wheel and the rail. These vibrations, in turn, result in radiated noise and transmission of vibration into the roadbed and adjacent structures as shown in Fig. 1.1. Secondary noise radiation resulting from the vibration of elevated structures often exceeds the primary radiation from the wheels and rails.

Several techniques have appeared over the years for the prediction and control of radiated noise and transmitted vibration from rail vehicles and track structures. The objective of this report is to provide a critical review of these techniques. Emphasis of the review is on the effect of guideway design on noise and vibration. A review of the mechanisms of noise generation at the wheel/rail interface is the topic of another contract study [1].*

In recent years a number of advanced technology transportation systems that do not use steel wheel on steel rail guideways have been proposed and developed. These systems exhibit their own unique noise and vibration characteristics which will not be discussed in this report.

1.2 Background

As systems manager for the U. S. Urban Mass

*References are given at the end of the report.

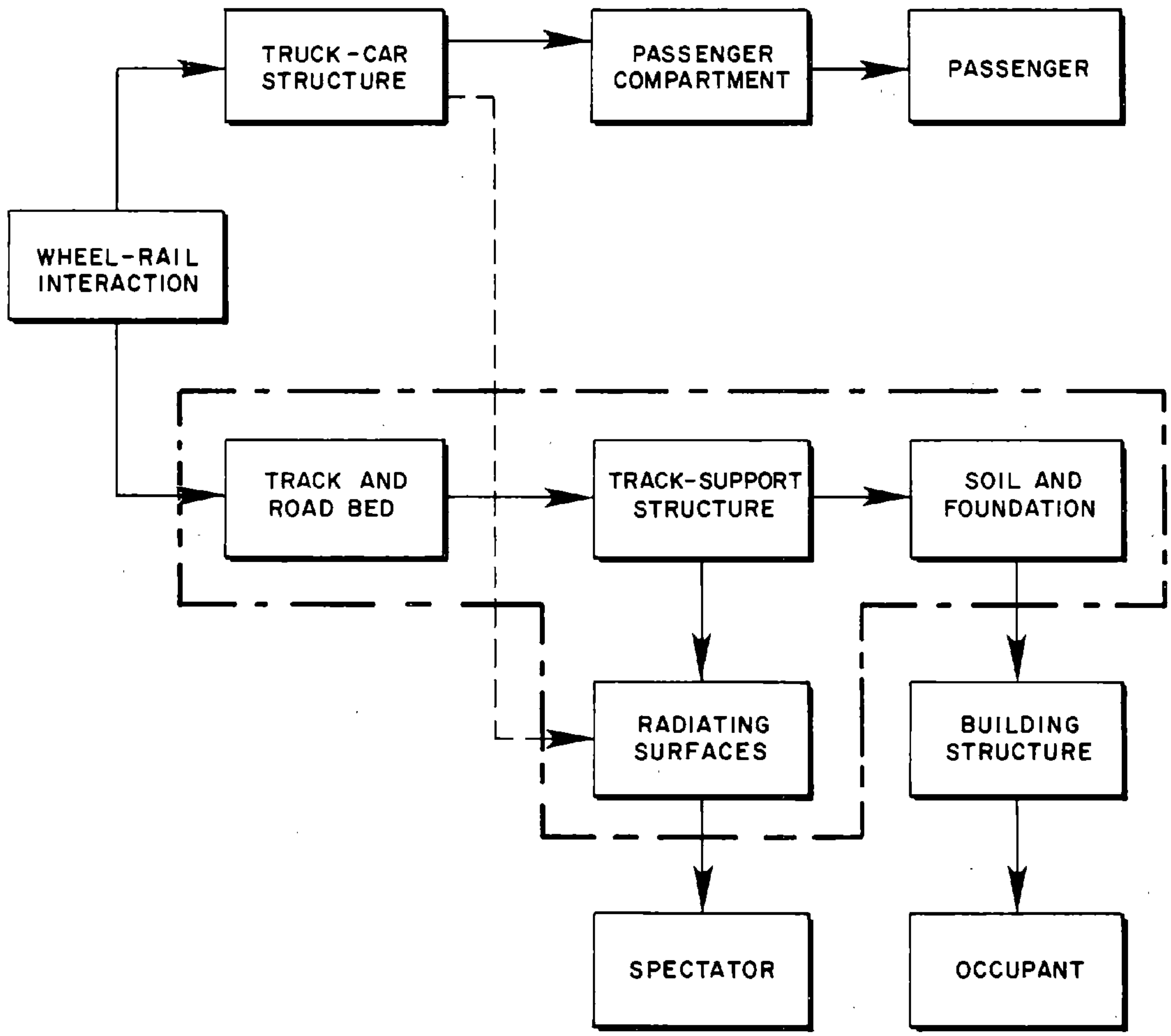


FIG. 1.1 SOURCE, PATHS, AND RECEIVERS OF RAIL TRANSIT NOISE AND VIBRATION

Transportation Administration (UMTA) Rail Systems Supporting Technology Program, Transportation Systems Center (TSC) is conducting research, development and demonstration efforts directed towards the introduction of improved technology in urban rail systems applications. As part of this program, TSC is conducting analytical and experimental studies directed towards noise and vibration reduction in urban rail systems.

The UMTA Rail Noise Abatement effort will bring together and improve existing and new elements into a unified technology consisting of: design criteria for establishing goals, noise control theory, design methods, test procedures, and appropriate documentation. The program has been organized into four concurrent and interrelated parts which will be closely coordinated with each other by TSC. They are:

1. Assessment of Urban Rail Noise and Vibration Climates and Abatement Options;
2. Test and Evaluation of State-of-the-Art Urban Rail Noise Control Techniques;
3. Wheel/Rail Noise and Vibration Control Technology
4. Track and Elevated Structures Noise and Vibration Control Technology.

The contract under which this report was prepared deals with Part 4 of the overall program. This Interim Report deals only with the assessment of existing technology. The development of new technology will be the concern of continued effort and will be documented in a final report in July 1974.

1.3 Organization

The conventional approach to solving noise and vibration problems is to consider separately the source, the transmission path, and the receiver. The receiver, for the problem under discussion in most of this report, is the community; secondary emphasis is given to the rider in the car and the patrons at stations. Noise from rail vehicle operations propagates into the community and into people's homes where it may interfere with activities or simply be annoying. Vibration from rail vehicle operations also propagates into the community and into people's homes. Vibration levels in the community are usually well below levels that would cause structural damage. However, people may feel the vibration or more likely hear its effects - window rattling or a low frequency rumble - and be annoyed. The criteria for evaluation of noise and vibration levels in the community and a general approach to noise control are reviewed in Chapter 2 of this report.

The dominant source of both noise and vibration is the wheel/rail interaction. However, the transmission paths for these two quantities are almost entirely different - the path for noise being predominantly air-borne while the path for vibration is predominantly structure-borne. Because of the difference that exists between propagation paths, community noise (Chapter 3) and community vibration (Chapter 4) are treated separately in this report.

Chapters 5 and 6 of the report deal with the somewhat different problems of noise in transit cars and in stations. In these cases, the receiver is a passenger or employee of the transit system - either in the car or on the station platform.

Over the past years many techniques have appeared for the reduction of wayside noise and vibration. These techniques usually have inter-related effects. For example, use of floating slab track in tunnels has the effect of reducing the ground vibration transmitted away from the tunnel. But at the same time use of this type of track can lead to higher noise levels in the tunnel.

Chapters 3 through 6 briefly describe the noise and vibration control techniques that are appropriate to the problem being discussed. In Chapter 7, the overall aspects of each method of control are discussed. The specific methods include use of:

1. resilient rail fasteners
2. ballast
3. resiliently mounted (floating) trackbed slabs
4. noise barriers
5. elevated structure enclosures
6. structural damping
7. acoustical treatment of stations and tunnels
8. trenches.

The last Chapter of the report, Chapter 8, summarizes results and identifies a variety of topics requiring further work.

2. GENERAL APPROACH

Within the present state-of-the-art there are no standardized design practices for the control of rail transit noise and vibration. The most commonly used approach has been one of trial and error. Promising techniques are implemented on a test section of track and the noise and vibration levels at the test section are compared with levels near conventionally designed track.

Unfortunately, the state-of-the-art has not advanced to the point where the trial and error approach can be dropped. However, since a number of noise and vibration control techniques have already been evaluated on test tracks, we can formulate an approach that has a high probability of success in coping with most noise and vibration problems.

In general terms, five basic steps are involved in a general approach, as shown in Fig. 2.1. Each of these steps will be discussed in future sections of this Chapter. First, however, we will give a general idea of how each step fits together to form a cohesive approach.

The first step is to measure or estimate the noise and vibration levels to determine whether or not a problem exists. This step is more easily accomplished for existing rail lines, since the levels can be measured. For new rail lines the anticipated noise and vibration levels must be calculated using the procedures discussed in this report or by using measurements from other sections of similarly constructed track with similarly designed vehicles. The calculation procedures, which are discussed in Chapters 3, 4, 5 and 6 are not precise. They lead to a range within which the levels for operation on the new

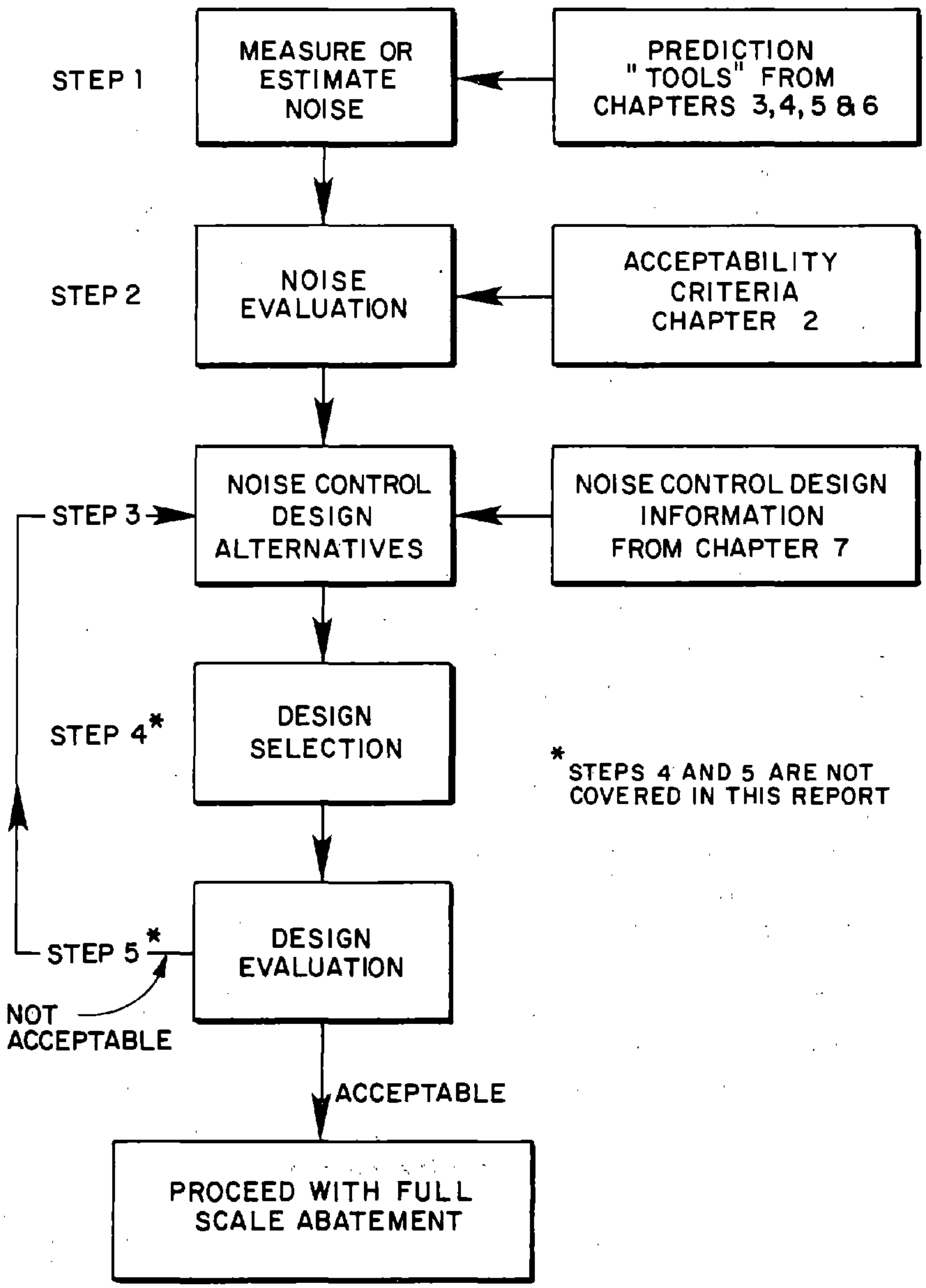


FIG. 2.1 GENERAL APPROACH TO NOISE AND VIBRATION CONTROL FOR RAIL SYSTEMS

rail line are expected to fall.

The second step of the general approach is to evaluate the noise and vibration levels by comparing them with criteria for acceptability. Again, this step is more easily accomplished for existing rail lines, since a history of complaints or acceptance exists. Numerical criteria for acceptability are not precise unless a particular legal code or regulation (standard) is involved. Thus, some uncertainty is almost always involved in the evaluation of noise and vibration levels.

In rare cases, the entire range of anticipated levels will be clearly acceptable. Then, a noise or vibration problem can be assumed not to exist. In the more usual case, some uncertainty exists. If the entire range of levels is clearly unacceptable, a noise or vibration problem will occur. However, the amount of noise or vibration control required will not be exactly defined. Techniques can be designed to bring the entire range of levels within clearly acceptable limits. However, costs to implement these techniques might be prohibitive, in which case a compromise solution must be sought.

The procedure to follow in arriving at the best solution is in two parts. First, noise and vibration control techniques are found that can be expected to reduce the levels by varying amounts. This is Step 3 of the general approach. Next, a tradeoff study is carried out to allow selection of the best technique. This is Step 4.

Finally, because of uncertainties in the initial predictions and in the expected performance of the noise and vibration control procedures, an evaluation should be carried out on a test track. This evaluation is Step 5. An added advantage in carrying out a test track evaluation is that contractors can become familiar with the required construction methods.

2.1 Determination of Noise and Vibration Levels

Noise and vibration levels in a community near a rail line are due both to operation of the rail vehicles and to other community noise and vibration sources. Levels due to rail vehicle operations are significant only when the vehicles are passing by the observer. The rest of the time other sources are dominant.

A complete specification of rail vehicle noise or vibration requires: (a) the expected number of operations, (b) the maximum level during each operation, and (c) the time history and duration of the levels for each operation.

Information as to number of operations is well known and detailed predictions are made in the planning stage for every new line.

Methods for calculating the maximum levels for a single train pass-by are given in Chapters 3 and 4.

The time history of the levels at a given distance from the track is most strongly dependent on the train length and speed. However, the directional characteristics of the radiated noise and the effects of the propagation path are also important. A detailed calculation of the time history can be made using mathematical models; see Appendix A. However, in view of the limited accuracy with which peak levels can be predicted, the detailed calculation is not needed. As an approximation the integrated noise or vibration exposure during a train pass-by can be calculated by assuming the duration of the maximum level is equal to the time in which the train passes.

The determination of noise levels in stations and in rail vehicles requires consideration of many different sources. However, in this report we consider in detail only the wheel/rail noise.

2.2. Criteria for Acceptability

A large number of criteria have been developed over the years for the purpose of judging the acceptability of noise and vibration. The criteria have focused on two topics - first, the technical objective of coming up with a single number rating that would allow relative comparison of the annoyance of different noises; and, second, psychological data allowing an absolute scale for annoyance so that community reaction to noise could be predicted.

From the beginning it was clear that the attitudes of the people in the community toward the noise maker had a large effect on their reaction. For example, in airport noise studies the following factors were found to be most important in influencing psychological acceptance or hostility toward the noise: [2]

1. Feelings about the necessity or preventability of the noise,
2. Feelings of the importance of the noise source and the value of its primary function,

3. The extent to which there are other things disliked in the residential environment,

4. Belief in the effect of noise on general health.

In a second example, over 300 people living near or within sight of a major highway were interviewed to determine their attitudes and reactions to the highway [3]. Factors such as odor, noise, vibration, lights, appearance, convenience to work, convenience to recreation, convenience to shopping, ease of driving, and necessity for the number of cars were considered and ranked according to convenience, attractiveness, intrusion and necessity. Using an individual's reaction to all of the above factors allowed successful prediction of his reaction to the noise in 64% of the cases. When pictures were used in addition to questionnaires to described the situation, prediction accuracy increased to 82%. When only the factor of noise level was used, the prediction accuracy fell to below 50%.

The importance of the attitude of people toward the noise maker and toward noise and the neighborhood in general has been confirmed for train noise in a recent French study [4]. Based on the results of a social survey the study concluded that people with an unfavorable attitude toward trains, noise and their neighborhood will be annoyed by noise levels that are judged to be acceptable by people with a more favorable attitude.

As a general rule the attitude of people in the community leads to a ± 5 dB correction factor to be applied to the community noise levels in rating the annoyance. The effective level of the noise can be reduced approximately 5 dB when attitudes are favorable and must be increased 5 dB when attitudes are unfavorable. However, caution must be used in applying these correction factors since attitudes do change.

scales for the measurement of noise*

Historically there have been some 60 various scales developed to relate the physical aspects of sound on a single number basis to human perception and reaction. Two such scales are most often used to represent the noise emission from transportation vehicles. The A-weighted sound level, dB(A), is widely used for surface transportation and occasionally for aircraft. A-weighted sound level is also used in the description of ambient community noise, the control of industrial noise, and the measurement of noise characteristics of appliances, etc. The A-weighted scale will be discussed in more detail below. The second commonly used scale is the Effective Perceived Noise Level, EPNL. This scale is used by the Department of Transportation in the regulation of noise emission from aircraft. This scale is not used for rail vehicle noise.

Noise in buildings is often rated by Noise Criteria, NC, curves or Speech Interference Levels, SIL. These criteria are also sometimes used to rate noise inside of transportation vehicles. The Noise Criteria scale, Speech Interference Levels, and other related scales will also be discussed below.

A-weighted sound level

Sound can be described in terms of the sound

*Much of this section is taken from ref. [5].

pressure levels in various bands of frequency encompassing the entire audible range. The overall level, C-scale on a Sound Level Meter, weighs all frequencies within the audible range, 20 to 20,000 Hz, equally. The auditory system does not respond equally to all frequencies. Hearing tests show that low frequencies cannot be heard as readily as some of the higher frequencies. For example, in the absence of any noise background, a sound with frequency components in the range around 50 Hz must have a sound pressure level of 40 dB in order to be audible, while a sound composed of frequencies near 2000 Hz requires a level of only 0 dB* to be audible.

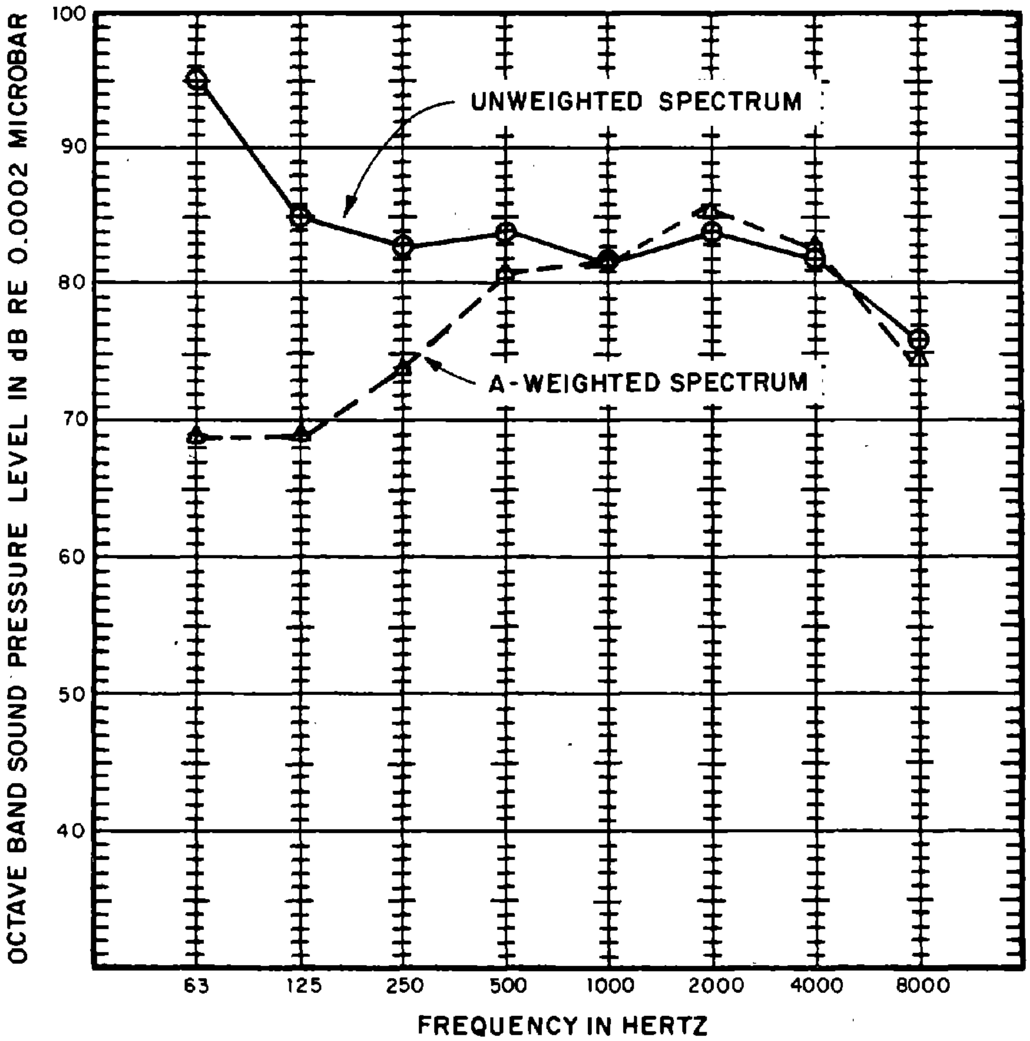
Since the auditory system is less sensitive to low frequency components, a band of noise with frequencies near 63 Hz will not be as loud as noise with the same pressure level at higher frequencies. The A-weighting scale first adjusts the sound according to the general loudness sensitivity in each frequency band and sums up the contributions from all bands to give a single reading in dB(A). Fig. 2.2 shows the weighting factors and illustrates their use.

2.2.1 General Application Noise Criteria

Studies of the effectiveness of different noise ratings show, on the average, that the A-weighting sound level correlates as well with subjective response as any other measure [6].

Recent trends show increased use of A-weighted levels as the basis for criteria on both community noise and noise in buildings and houses.

*Noise levels in dB are defined as 20 $\text{Log}_{10}(p^2/p_{ref}^2)$ where p is the rms pressure in dynes/cm^2 and p_{ref} is the reference pressure of 0.0002 dynes/cm^2 (20 μN/m^2).



FREQUENCY	31	63	125	250	500	1000	2000	4000	8000 Hz
A-WEIGHTING FACTOR	-39.4	-26.2	-16.1	-8.6	-3.2	0	1.2	1.0	- 1.1 dB

FIG. 2.2 A- WEIGHTING FACTORS WITH EXAMPLE

Noise Criteria curves

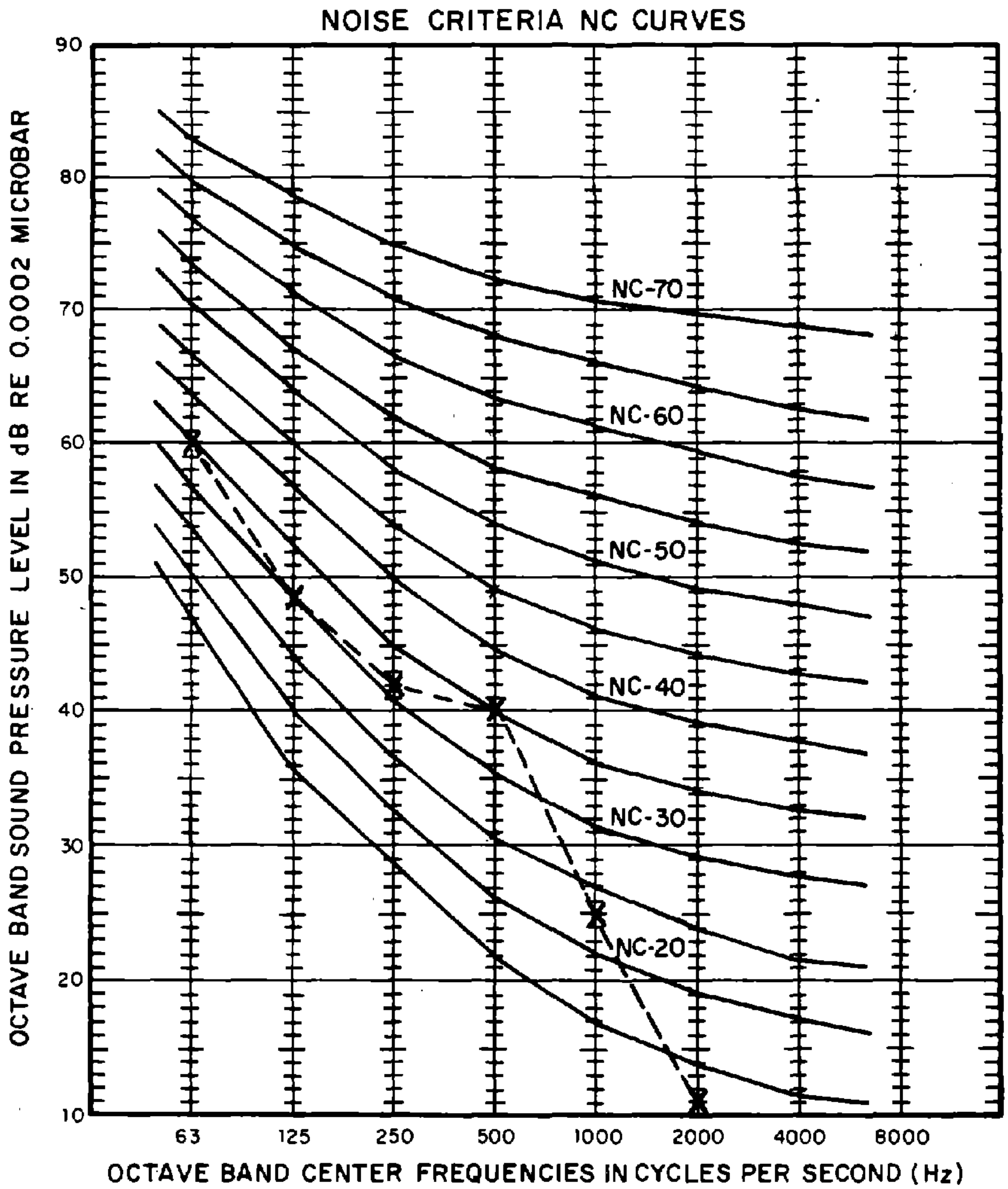
Noise Criteria curves are often used to rate noise inside of buildings and transportation vehicles. The Noise Criteria (NC) curves are shown in Fig. 2.3. To use these curves the sound pressure levels in each octave band of frequencies are plotted on Fog. 2.3. The NC rating corresponds to the lowest curve for which the sound pressure levels in each octave band exceed the levels of the noise. For example, we plot in Fig. 2.3 a typical octave band spectrum for noise in a basement near a subway line. The A-weighted level of this noise is 40 dB(A) while the NC rating is 35.

The NC curves have been criticized recently by some users, since a noise spectrum with octave band levels equal to those of a particular NC curve does not sound pleasant but has both a "rumbly" and a "hissy" character. This criticism has lead to the introduction of Preferred Noise Criteria (PNC) curves [7]. These newer PNC curves have not as yet achieved general acceptance.

speech interference levels

The Speech Interference Level of a noise relates the extent to which the noise interferes with speech communication. Two definitions have been used: one related to octave-band filter sets with the "old" cutoff frequencies, the other with a new band center frequencies.

The SIL (old) is the arithmetic average of the sound-pressure levels in the three octave bands: 600 to 1200 Hz; 1200 to 2400 Hz; and 2400 to 4800 Hz.



X---X NOISE LEVELS IN BASEMENT
A-WEIGHTED LEVEL 40
NC RATING 35

FIG. 2.3 NC RATING OF NOISE IN BASEMENT NEAR SUBWAY

The PSIL (new) is the arithmetic average of the sound-pressure levels in the three octave bands with the preferred, geometric-mean, center frequencies at 500, 1000 and 2000 Hz.

Table 2.1 shows the maximum PSIL values for which reliable speech communication is barely possible between persons at the distances and noise efforts shown. The interference levels are for average male voices (reduce the levels 5 dB for female voices) with speaker and listener facing each other.

Speech Interference Levels are strongly correlated with A-weighted levels for a wide range of different noise spectrum shapes. For rail noise in the community, in the car, or in the station the Speech Interference Levels equal the A-weighted sound levels within approximately ± 3 dB.

noise exposure

During the course of a day, the sound levels to which a community is exposed vary quite widely. A noisy vehicle is heard for a period of time and then is gone. If one were to describe the noise level in the community as the maximum level received during this period of time, an inadequate descriptor of what was happening would result. A listing of the number of times a certain level of noise was reached would help expand upon the picture and if a count of noise events at a variety of levels were made, this would give an even better descriptor of the noise environment or noise exposure of that particular site. However, such a lengthy listing of levels and numbers of noise events would present such a mass of numbers as to be incomprehensible to the layman and too cumbersome for the acoustician. Thus, a

Speech interference levels (PSIL) of steady continuous noises in decibels at which reliable speech communication is barely possible* between persons at the distances and voice efforts shown. The interference levels are for average male voices (reduce the levels 5 dB for female voices) with speaker and listener facing each other, using unexpected word material. It is assumed that there are no nearby reflecting surfaces that aid the speech sounds.

Distance between talker and listener ft(m)	PSIL, dB† Talker's voice effort: Normal	Raised	Very Loud	Shouting
0.5 (0.15)	74	80	86	92
1.0 (0.30)	68	74	80	86
2.0 (0.60)	62	68	74	80
4.0 (1.20)	56	62	68	74
6.0 (1.80)	52	58	64	70
12.0 (3.70)	46	52	58	64

*Corresponding to an articulation index of about 0.40.

†SIL (calculated from old octave bands) ≈ PSIL -3 dB.

TABLE 2.1 RELATIONS AMONG PSIL, VOICE EFFORT AND BACKGROUND NOISE [7] single number descriptor has been sought which includes important factors of noise exposure, such as the number of noise events of given noise levels occurring during given periods of the day and the noise level extent between identifiable noise events.

Many varied single number noise exposure scales have been developed. The simplest of these is the Average Sound Level, L_{eq}, defined as the level of a continuous sound that would have the same cumulative energy as the fluctuating community noise levels during a given time interval. The time interval should always be specified.

Other related noise exposure scales are:

1. The Day-Night Average Sound Level, L_{dn}, which is the Average Sound Level over a 24 hour period with night time levels (2200 to 0700hrs) increased 10 dB(A);
2. The Hourly Noise Level, L_h, which is the Average Sound Level over a period of one hour; and
3. The Community Noise Equivalent Level, CNEL, which is the Average Sound Level over a 24 hour period with levels existing between 1900 and 2200 hours increased 5 dB(A) and levels existing between 2200 and 0700 hours increased by 10 dB(A).

Statistical measures are slightly more complicated than Average Sound Levels or Community Noise Equivalent Levels, but serve well in evaluating noise from highways where a number of sources contribute to the noise at a given time. The most commonly used statistical measures are L_{10}, L_{50}, and L_{90}. These are the levels exceeded 10%, 50% and 90% of the time. Cumulative distributions are also used as statistical measures. For time varying sound levels, the distribution is usually described by a table or graph showing the percentages of a given test sample or time period during which the varying sound level equals or exceeds stated levels.

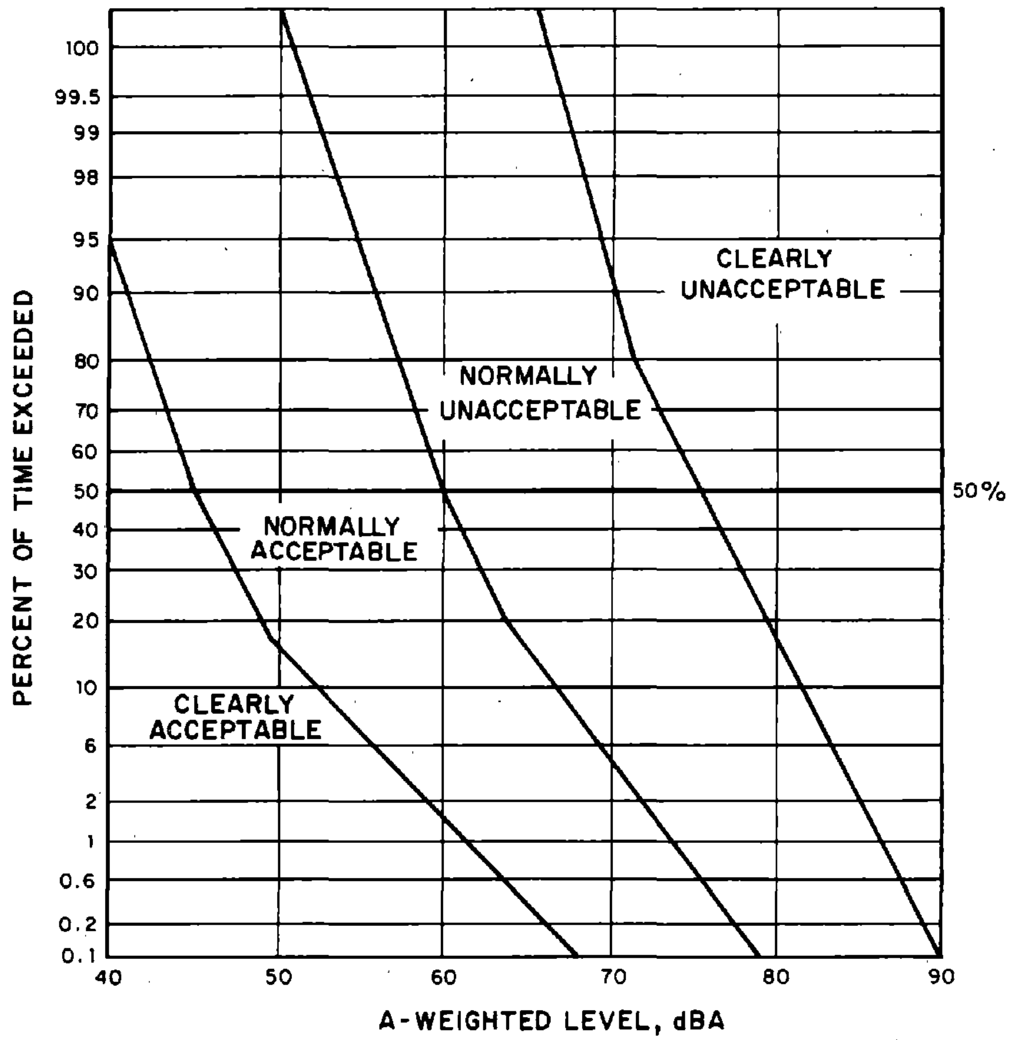
Noise near airports is rated in terms of Noise Exposure Forecasts (NEF) or other similar measures. These rating scales are similar to the Community Noise Equivalent Levels except that only noise from aircraft operations are considered and night operations are weighted somewhat differently.

A model that can be used to calculate the noise exposure due to rail noise is presented in Appendix A.

exposure criteria

There are a number of criteria that have been proposed for judging the acceptability of noise. It is not our purpose in this report to review these criteria nor to select the most useful. However, as an example, we show in Fig. 2.4 guideline criteria recently adopted by the U.S. Department of Housing and Urban Development for non-aircraft noise measured outdoors in residential areas [8]. These criteria are based on a cumulative distribution of sound levels. Therefore, in applying the criteria one must first calculate or measure the time-history of the A-weighted community noise level over a representative period of time. From this time history it is possible to construct a plot of the percent of time during which a particular level is exceeded versus level. The constructed plot represents a cumulative distribution that can be compared with the criteria in Fig. 2.4.

Rail noise exhibits itself in the community as a number of discrete events. In typical situations the fre-



NOTE: THIS CRITERIA IS PRESENTED AS AN EXAMPLE AND IS NOT BEING PROPOSED AS A SPECIFIC RECOMMENDATION FOR RAIL TRANSIT NOISE

FIG 2.4 GUIDELINE CRITERIA RECENTLY ADOPTED BY HUD [8] quency of train passage is low enough that rail noise exceeds the general background noise in the community only a small percentage of the time. We see from Fig. 2.4 that a noise level of 73 dB(A) is acceptable if the noise exists less than 1% of the time, whereas if the noise exists 99% of the time, its level must be below 53 dB(A) to be acceptable -- a 20 dB difference.

Criteria for noise in buildings have been developed and are summarized in Table 2.2 [9]. These criteria are not specifically intended for use in evaluating rail noise. We have included them in this report in order to give the reader an overview of the commonly used noise criteria.

<u>regulations</u>

Many urban and suburban communities are enacting noise regulations. These take various forms. However, as a rule they specify the maximum allowable noise levels in dB(A) at a fixed distance from the source. A summary of state and city regulations can be found in reference [10].

2.2.2 Rail Noise Criteria

As an example of the application of noise criteria we present the design goals for the new Washington Metropolitan Area Transit System in Table 2.3 [11]. These goals are commensurate with the noise criteria recently proposed by the Institute for Rapid Transit (IRT) Technical and Operative Committee [12] with one exception: the IRT criteria for noise in buildings are in terms of A-weighted noise levels rather than NC levels. The difference between the two criteria are small.

An example of criteria for noise in stations and in transit cars is shown in Table 2.4, which has been taken from the proposed IRT criteria [12].

Type of Space	NC Units
Broadcast studios	15-20
Concert halls	15-20
Legitimate theaters (500 seats, no amplification)	20-25
Music rooms	25
School rooms (no amplification)	25
Television studios	25
Apartments and hotels	25-30
Assembly halls (amplification)	25-35
Homes (sleeping areas)	25-35
Motion-picture theaters	30
Hospitals	30
Churches (no amplification)	25
Courtrooms (no amplification)	25
Libraries	30
Restaurants	30
Coliseums for sports only (amplification)	50

TABLE 2.2 EXAMPLE OF NOISE CRITERIA FOR ROOMS [9]

Criteria for Maximum Levels of Rumbling Noise Which Can Occur in Residential Buildings Near Tunnels as Transit Trains Pass By

Type of Building or Space	Type of Residential or Community Area	Acceptable Noise Level	IRT Criteria [12]
Sleeping Rooms in Private Residences	1	NC-20 to 25	25 to 30 dB(A)
	2	NC-20 to 25	30 to 35
Apartments (in Residential Units)	1	NC-25 to 30	30 to 35
	2	NC-30 to 35	35 to 40
	3	NC-35 to 40	40 to 45
Hotels (in Residential Units)	2	NC-30to 35	40 to 45
	3	NC-35 to 40	40 to 45

1. Quiet residential areas where the exterior background noise may be 35 to 40 dB(A) at night.
2. Average urban or suburban residential areas with background noise level of 40 to 45 dB(A) at night.
3. Noisy residential or background semi-residential commercial areas with background noise level of 45 to 55 dB(A) at night.

TABLE 2.3 NOISE CRITERIA USED FOR DESIGN OF THE WMATA SYSTEM [11]

Criteria for Maximum Levels for the Rumbling Noise Which Can Occur in Occupied Spaces of Buildings Near Tunnels as Transit Trains Pass By

Type of Building or Space	Recommended Maximum Noise Level	IRT Criteria
Auditoriums and Concert Halls	NC-20	25-30 dB(A)
Churches and Theaters	NC-25	30-35
Music Rooms and TV Studios	NC-25	30-35
Hospital Sleeping Rooms	NC-30	35-40
Courtrooms	NC-30	35-40
Schools	NC-30	35-40
University of Buildings	NC-30 to 35	35-40
Offices	NC-30 to 35	40-45
Commercial Buildings	NC-40 to 45	45-50

TABLE 2.3 NOISE CRITERIA USED FOR DESIGN OF THE WMATA SYSTEM (CONTINUED)

Ambient Noise Levels at Night in General
Community Categories Along Metro Corridors

Area Category	Area Descriptions	Typical Measured Ambient Noise Levels at Night
I	Quiet urban, residential, open space park, suburban residential or recreational area. No nearby highways or boulevards.	35-40 dB(A)
II	Average urban residential, quiet apartments and hotels, open space, suburban residential, or occupied outdoor area near busy streets.	40-45 dB(A)
III	Busy urban residential, average semi-residential/ commercial areas	45-55 dB(A)
IV	Commercial areas with office buildings, retail stores, etc. with daytime occupancy only. Open space, parks and suburban areas near highways or speed boulevards with distant residential buildings.	Over 55 dB(A)
V	Industrial or Freeway and Highway Corridors with either residential or commercial areas adjacent.	Over 60 dB(A)

TABLE 2.3 NOISE CRITERIA USED FOR DESIGN OF THE WMATA SYSTEM
(CONTINUED)

Criteria for the Maximum Pass-By Noise
Above Ground Metro Train Operations

Community Area Category		Maximum Single Events Pass-By Noise Level Criterion
I	Quiet Residential	70 dB(A)
II	Average Urban Residential	75 dB(A)
III	Semi-Residential/Commercial	80 dB(A)
IV	Commercial	85 dB(A)
V	Industrial and Highway Corridor	85-90 dB(A)

These criteria are to be applied at a point about 50 ft from the track centerlines. In some cases, particularly in residential areas, where buildings or occupied areas are farther from the transit line, the criteria may be referenced to the building or area being considered. The criteria are used with caution in areas where the transit line is adjacent to schools, radio and TV studios, theaters, amphitheaters, churches and auditoriums. Maximum noise levels at such locations should not exceed 70 to 75 dB(A) outside the building regardless of the type area in which it has been categorized.

TABLE 2.3 NOISE CRITERIA USED FOR DESIGN OF THE WMATA SYSTEM (CONTINUED)

Item	Criteria
TRANSIT VEHICLES, NOISE AND VIBRATIONS	
Vehicle Int. Noise Levels (Empty Car)	
In open (ties and ballast) at maximum speed	68 dB(A)
In open (concrete trackbed) at maximum speed	72 dB(A)
In tunnels at maximum speed	78 dB(A)
All auxiliaries operating, car stationary	65 dB(A)
One auxiliary system operating, car stationary	60 dB(A)
Door operation	65 dB(A)
Vehicle Exterior Noise Levels (50 ft from T & B track)	
Car stationary, auxiliaries operating	60 dB(A)
Two-car train at 80 mph	86 dB(A)
Two-car train at 60 mph	82 dB(A)
Vehicle Equipment Noise Levels (15 ft from car)	
Propulsion system at equivalent to 80 mph	90 dB(A)
Propulsion system at equivalent to 60 mph	84 dB(A)
Car stationary, auxiliaries operating	65 dB(A)
Decrease in criteria for presence of pure tones	3 dB(A)

TABLE 2.4 SUMMARY OF TRANSIT NOISE AND VIBRATION CRITERIA PROPOSED BY IRT [12]

Item	Criteria
<u>Vibration Levels</u>	
Measurements taken on car interior surfaces unless noted. Displacements measured peak-to-peak. Velocity and acceleration are:	
Maximum amplitude	0.10 in.
Maximum acceleration, up to 10 Hz	0.01 g
Maximum velocity, 10 Hz and over	0.03 in/sec
Maximum amplitude on detached traction motors	0.0005 in.
<u>NOISE IN UNDERGROUND STATIONS</u>	
Platform level, trains entering and leaving	80 dB(A)
Platform level, trains passing through	85 dB(A)
Platform level, trains stationary	67 dB(A)
Maximum train room reverberation time	1.6 to 2 sec.
Platform level, only station ventilation system operating	55 dB(A)
In station attendants' booth	45 dB(A)
<u>NOISE IN ABOVE-GROUND STATIONS</u>	
Platform level, trains entering and leaving	70-75 dB(A)
<u>NOISE IN SUBWAY TUNNELS</u>	
Min. design reduction in reverberant noise levels with acoustic treatment	10 dB(A)

TABLE 2.4 SUMMARY OF TRANSIT NOISE AND VIBRATION CRITERIA PROPOSED BY IRT (CONTINUED)

2.3 Noise Control Design

The remaining Chapters of this report are oriented toward the effective design of noise and vibration control treatments. In Chapter 3 through 6, we discuss noise and vibration problems for different types of track. In Chapter 3, noise from track on the surface is discussed. The Chapter is divided into three subheadings dealing with track-at-grade, on embankments and in cuttings, and on elevated structures. In Chapter 4, vibration from track on the surface and in tunnels is discussed. In Chapter 5, the problem of noise in cars is discussed. And in Chpater 6, the problem of noise in stations is discussed. In each of these Chapters, the noise and vibration control techniques that are effective for the particular situation in question are mentioned. Then in Chapter 7, we discuss each of the control techniques separately.

2.4 Selection of Design

The process of selecting a specific noise or vibration control technique is a trade-off between cost and effectiveness. Because of the uncertainty in predicting noise and vibration levels there is always some latitude for decision.

The first step toward reaching a decision is to establish the performance versus cost for each appropriate control technique. This is done by selecting a range of performance, say 7.5 to 12.5 dB reduction, and then coming up with a minimum cost design. The step is repeated for a number of different performance ranges and for each control technique until a series of curves can be drawn as shown in Fig. 2.5. Given this information, a selection can be made taking into account other political, social and economic factors of importance.

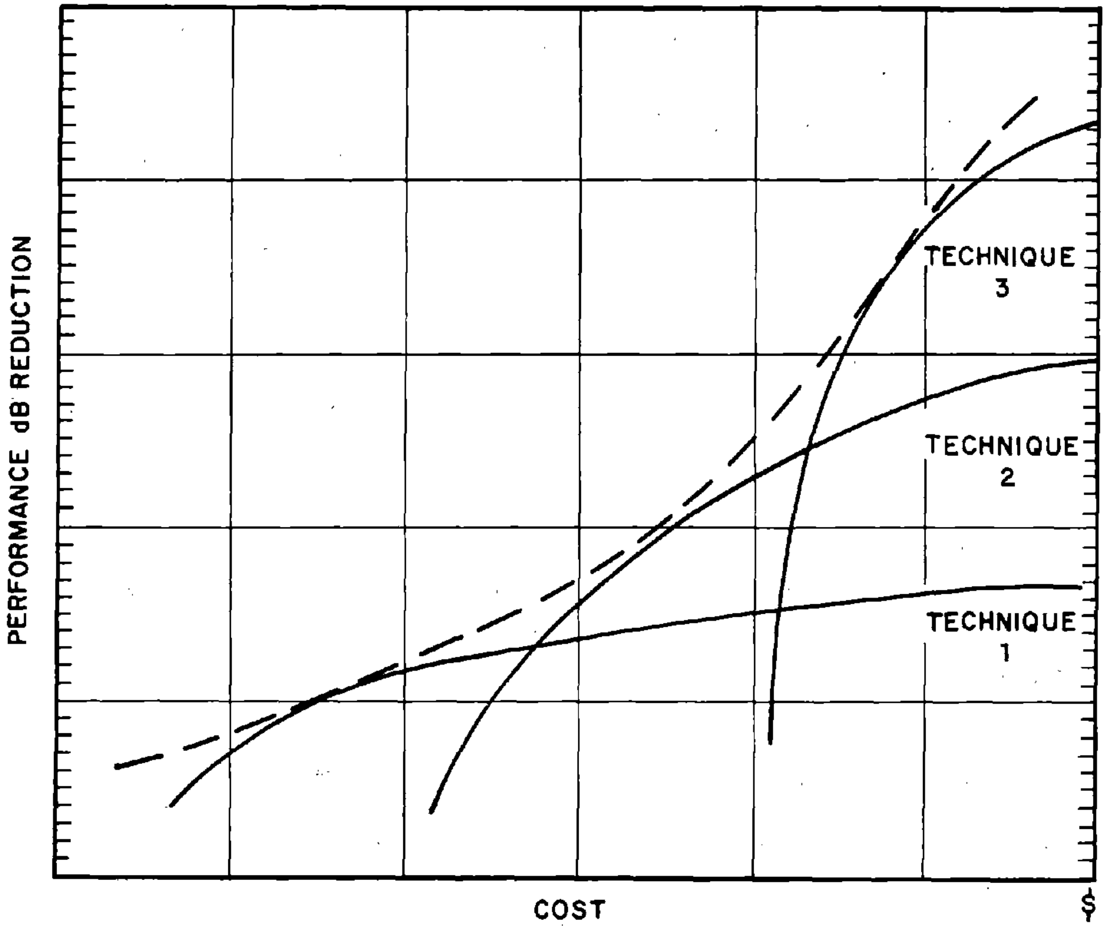


FIG. 2.5 HYPOTHETICAL COST PERFORMANCE CURVES

Detailed engineering designs and cost estimates for the noise control techniques discussed in this report are not given. However, each of the techniques proposed has been tried in actual practice on a rail line and been shown to be practically feasible in at least one case. Many of the techniques are quite innovative, in which case the existing cases of practical application are very limited. The importance of careful design and cost evaluation in putting these techniques into practice cannot be over-emphasized.

2.5 Evaluation

An evaluation of the selected noise or vibration control technique is required to eliminate uncertainties in the expected levels. In some cases it is possible to take measurements on existing rail lines in which the noise control technique has been used. When this is not possible the technique should be applied to one track on a dual track section of the existing line or on a new test section. Then, comparisons can be made of the performance of the new design relative to that of the conventional design.

3. COMMUNITY NOISE

The wayside noise produced by passing trains is a problem of major concern in urban and suburban rail systems particularly when the track is located near residential dwellings or quiet parkland. In order to apply the general procedures discussed in Chapter 2, the designer of a new rail line must first predict the level of noise to be expected in the community. Then, if the predicted levels are too high, one must plan effective methods of noise control.

When noise problems arise from existing rail lines the designer can measure the offending community noise levels. However, in order to reduce the rail vehicle noise one must be able to identify the dominant noise sources and paths and to devise effective noise control procedures.

3.1 Prediction Procedure

The problem of predicting community noise must be divided into two steps: first, a determination of the amount of noise generated by the trains; and, second, a determination of the effects of the propagation path on the noise levels.

The wayside noise generated by passing trains depends in part on the type of track and the supporting substructure. The mechanisms of noise generation for trains on surface tracks and track on earth embankments exhibit certain characteristics while those for trains on elevated structures exhibit others. The noise generation mechanisms for trains on underground track exhibit still a third set of characteristics. However, community noise due to underground track is only a problem in rare cases where ventilation shaft outlets are located very close to noise sensitive areas. In such a case noise control is accomplished by treating the shafts with sound absorbing material. Further discussion of noise from trains on underground track is contained in Chapter 4 where ground vibration and the resulting rumble in buildings is presented.

Noise propagation characteristics also depend on the type of track. The propagation of noise away from at-grade track exhibits a different characteristic than propagation of noise away from elevated track or track in a cutting.

In line with the above discussion, the general problem of predicting community noise from rail vehicle operations will be divided into three parts: prediction of community noise from (1) surface track, Section 3.2; (2) track on embankments or in cuttings, Section 3.3; and (3) track on elevated structures, Section 3.4.

3.2 Surface Track

3.2.1 Roadbed Construction

Much of the track in urban and suburban rail systems is laid at ground level using conventional tie and ballast construction. Typically, wooden ties are laid in a bed of crushed rock ballast on an earth subgrade. The rails are usually fastened to wooden ties with spikes in the U.S., while in Europe a variety of different rail fasteners are used.

In some cases concrete ties are being used instead of wood. The decision to use concrete ties is usually based on an estimated lower life-cycle cost.

Tie and ballast construction offers the advantages of being relatively inexpensive and of allowing the track subgrade to be easily leveled after ground settling. Rather frequent maintenance is required. However, the maintenance procedures have been semi-automated so that maintenance is not necessarily a problem for transit systems that can afford the required equipment.

Tie and ballast track is currently being used in Japan and France on lines with train speeds of 200 km/hr (125 mph). However, for higher speeds it is generally believed that a slab trackbed with direct rail fastening must be used to maintain ride dynamics and proper track geometry.

3.2.2 Noise Generation

It is observed that the noise generated by a train on at-grade tie and ballast track is below that generated by trains on elevated structures or on non-ballasted track beds [13]. For this reason it is common to use tie and ballast track to form a baseline condition.

noise prediction procedure

At present, analytical techniques for predicting the amount of noise generated by a train traveling over a specified track do not exist. Therefore, noise measurements from existing rail systems must be used to form empirical prediction procedures. Since the propagation path can have a major effect on the noise levels, the data on which a prediction procedure is based must be carefully selected. Measurements taken at large distances from the track cannot be used because of the unknown effect of the intervening terrain on the noise levels. Also, measurements taken very close to the train cannot be used because levels there are indicative of the noise generated by individual noise sources and not the noise generated by the entire train.

To form a basis for comparing the noise generated by different passing trains, it is necessary that data used for the comparison be taken under standardized conditions. Measurements in the U.S. are most often taken at a distance of 50 ft (15 meters) from the center of the track and 4 ft (1.2 meters) above ground over a smooth flat terrain. At this measurement point the maximum noise levels during a train passage are not greatly affected by the terrain or atmospheric effects. Also at this distance the maximum noise levels are not affected by train length for trains with two or more cars (see Fig. 3.2. on page 40.)

In Europe measurements of train noise are commonly taken at a distance of 25 meters (82 ft) from the center of the track and 3.5 meters (11.5 ft) above the height of the rail. Measurements at 7.5 meters (25 ft) and at 15 meters (50 ft) are occasionally reported for urban situations in which measurements at 25 meters (82 ft) over open terrain are not possible.

Measurements of noise from intercity trains are often taken at 25 meters (82 ft), 50 meters (163 ft) and 100 meters (325 ft). At the greater distances the measured levels are somewhat affected by the ground cover, particularly in the low frequency range 200 to 400 Hz [14]. The ground effect is more pronounced for measurement points close to the ground. For example, the A-weighted noise levels measured 25 meters (82 ft) from the track at a height of 1.2 meters (4 ft) are approximately 1 dB(A) below levels measured at 3.5 meters (11.5 ft) [15]. For measurement distances 50 ft (15 meters) or less from the track, the ground effect has only a small effect on the A-weighted noise levels.

When possible, new measurements should be taken in accordance with recommended standards [16]. These standards typically call for measurements to be taken 7.5 meters (25 ft) from the track and 1.2 to 1.5 meters (4 to 5 ft) above rail height or at a distance of 25 meters (82 ft) from the track and 3.5 meters (11.5 ft) above the rail height.

Any distance within the range 7.5 meters (25 ft) to 25 meters (82 ft) can be used for the purpose of identifying the amount of noise generated by passing rail vehicles. Measured levels at one distance within this range can be used to infer levels at another distance with good accuracy using Fig. 3.2. As a general rule, the following conversion can be used:

TO CONVERT LEVELS AT		TO LEVELS AT		ADD
distance	height above rail height	distance	height above rail height	
7.5 m	1.2 → 1.5 m	50 ft	4 → 5 ft	- 4 dB(A)
15.0 m	1.2 → 1.5 m	50 ft	4 → 5 ft	0 dB(A)
25.0 m	1.2 → 1.5 m	50 ft	4 → 5 ft	1-2*dB(A)
25.0 m	3.5 m	50 ft	4 → 5 ft	3 dB(A)

*depending on the ground cover

a general prediction of wayside noise

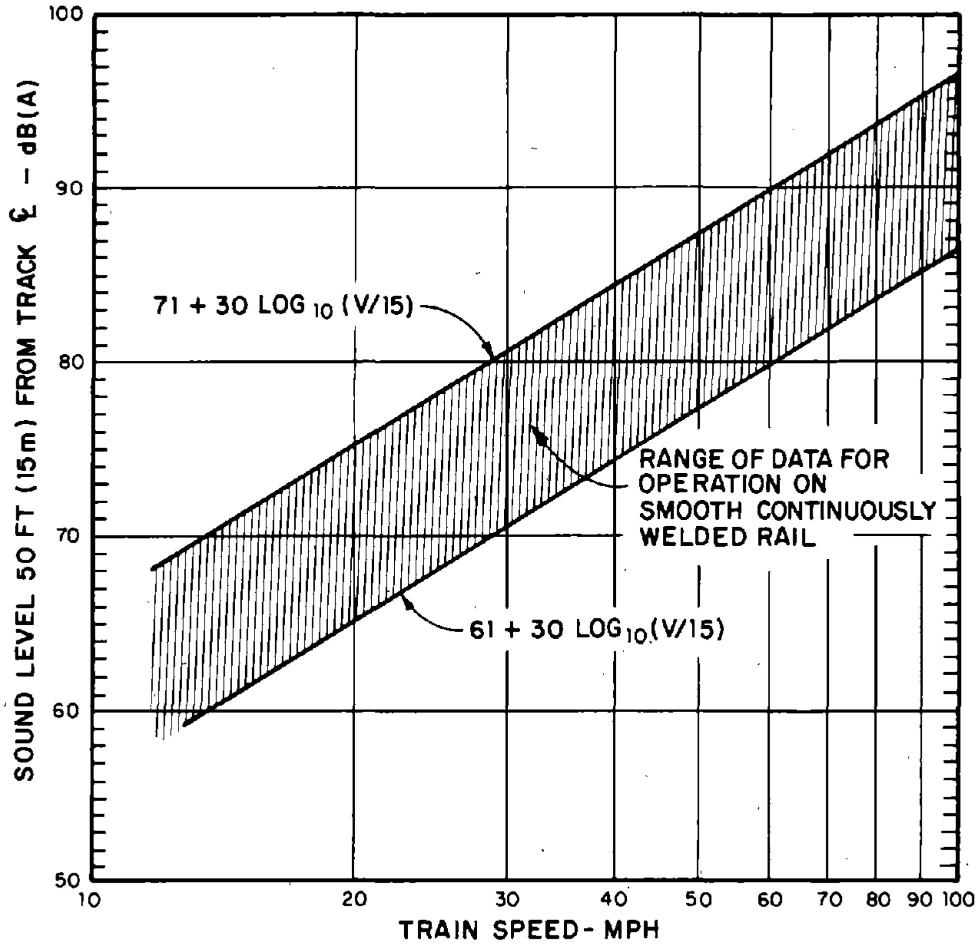
A generalized prediction of the noise levels to be expected 50 ft (15 meters) from the track centerline and 4 to 5 ft (1.2 to 1.5 meters) above the rail height is shown in Fig. 3.1. This prediction is based on measured data from rail systems in the U.S., Europe and Japan. Detailed support for the prediction procedure is given in Appendix B.

Within the 10 dB(A) band shown in Fig. 3.1 lie data for many different vehicle designs. Vehicles generating noise levels which lie toward the lower limit of the band have some type of noise and vibration control treatment applied to them.

noise characteristics

The noise generated by trains on surface track can be described by general terms used for all types of track. For operation on straight tangent track the noise is composed of: (1) impact noise due to rail joints or wheel flats and (2) roar due predominantly to wheel/rail roughness, but in some cases also to propulsion motor noise.

On curved track the noise can increase markedly due to wheel squeal, a high frequency tone, and curve howling, a low frequency tone. The occurrence of these noises can increase the wayside noise levels by up to 15 dB(A) [17].



CORRECTION FACTORS *	ADD
JOINTED RAIL	8 to 10 dBA
WHEEL FLATS	8 to 10 dBA
NEW OR ROUGH RAILS	3 to 6 dBA
ROUGH WHEELS	3 to 6 dBA
CORRUGATIONS	UP to 15 dBA

* ADD ONLY ONE CORRECTION FACTOR — THE LARGEST APPLICABLE

FIG. 3.1 WAYSIDE NOISE FOR AT-GRADE OPERATIONS ON TIE & BALLAST TRACK

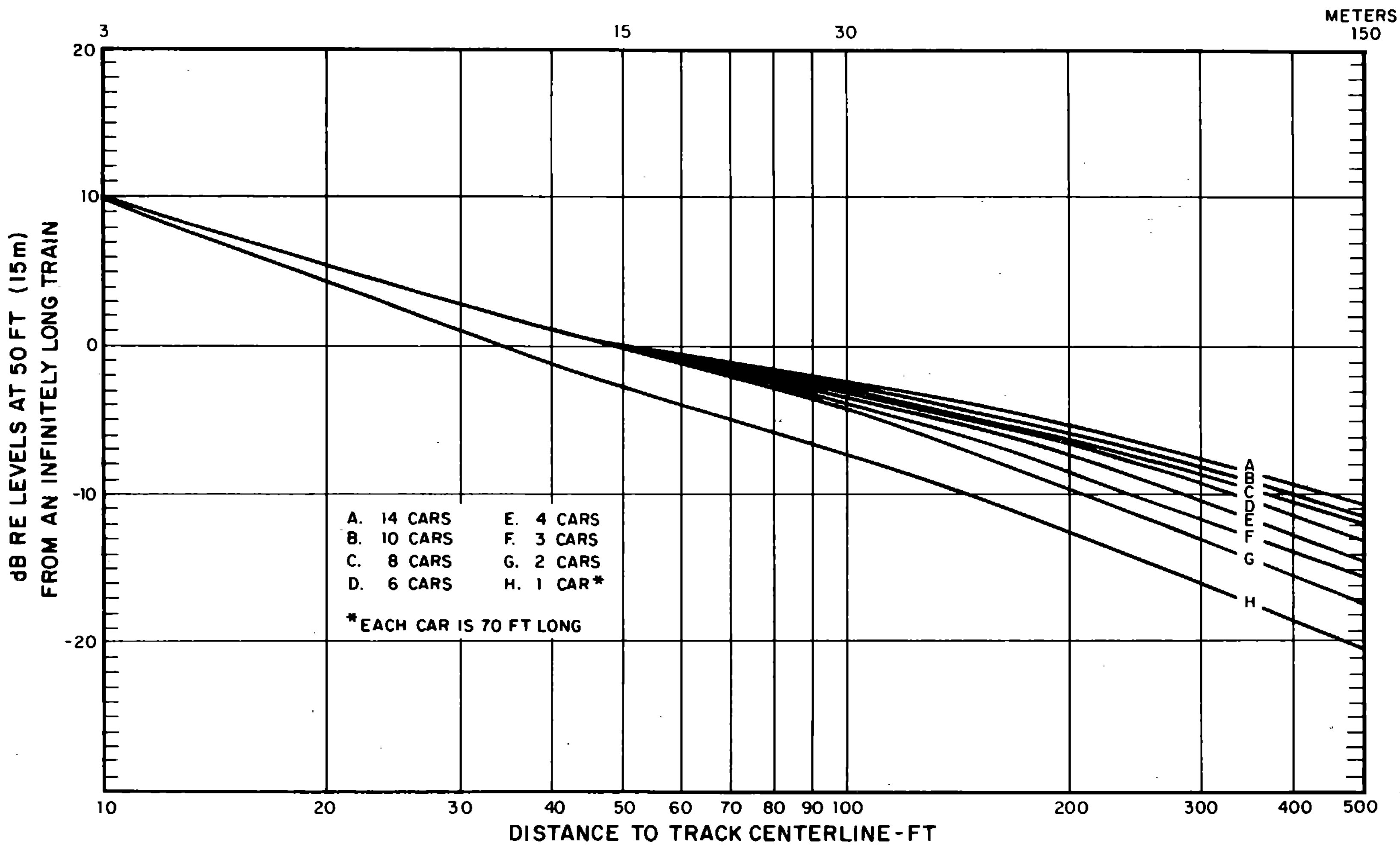


FIG. 3.2 DECREASE IN SOUND LEVEL WITH DISTANCE FROM THE TRACK

Wheel squeal and curve howling result from a complex wheel/rail interaction. The only effective means of noise control is to eliminate the mechanism in those cases where it occurs. Techniques that have been tried include use of damped or resilient wheels and rail lubrication systems. Further discussion is contained in Reference [1]. As a general rule, wheel squeal and curve howling are not problems on surface track since the radii of curvature for the track are normally quite large. In tight curves, however, these noise mechanisms will be important.

effect of design for tie and ballast track

The amount of noise generated by a passing train on tie and ballast track depends both on the design of the cars and of the track. However, the major design parameters for a tie and ballast track -- such as axle loading, ballast bed depth, tie spacing, and rail weight -- do not have a large effect on the noise generation [18]. The major parameter affecting noise is the condition of the rails and wheels. Vibration due to wheel/rail roughness is transmitted to the rails and ties and to the wheels and trucks of the car, which provide noise radiating surfaces. By a similar mechanism, vibration due to impacts at rail gaps and due to wheel flats produces impact noise.

The use of resilient rail fasteners is also believed to have some effect on the noise due to wheel/rail interaction. However, the effect is small. See Section 7.1 on the use of rail fasteners for noise and vibration control.

rail and tie radiation

The relative contributions of rail and tie radiation and wheel and track radiation are not known. However, in Appendix C we present data and calculation to show that rail and tie radiation is of secondary importance in determining the total noise radiation from currently operating trains. This conclusion is supported by reported cases in which the rail vibration has been reduced by application of a damping material but the total noise radiation has not changed [47].

As a general conclusion, we can state that the rail and ties are secondary noise sources for most vehicles. Documented evidence of a case in which rail vibration is a significant noise source has not been found. However, for those cases in which a large amount of noise and vibration control has been used in the wheel, truck and car design it may be possible for the rails and ties to become the dominant noise sources.

propulsion system noise

For most rail systems, the noise due to the wheel/rail interaction is dominant. However, noise from the propulsion system may also be important in some cases.

The problem of determining the relative role of wheel/rail noise and propulsion noise in an operating system has not been fully solved. A commonly used procedure is to measure the wayside noise with the car jacked up and the wheels spinning [19]. The measured noise is taken to be equal to the propulsion noise during vehicle operation. A second measurement is taken on the same section of track with the vehicle passing by. This measurement is taken to be equal to the sum of propulsion noise and wheel/rail interaction noise.

The procedure of measuring the noise with the car jacked up and the wheels spinning does not take into account the effect of propulsion system load on noise generation. Therefore, additional tests should be carried out on the same section of track with the car at steady speed, at maximum acceleration, and coasting. For the same vehicle, the wheel/rail noise is predominantly dependent on vehicle speed. Thus, any changes in noise for these three tests will be the result of changes in propulsion noise under various loads. If no change in noise level is found, it can be concluded that either (1) the propulsion noise does not contribute significantly to the total wayside noise or (2) that the propulsion system noise does not depend on load, in which case the measurement with the car jacked up can be taken to be a valid indication of propulsion noise.

Many general comments can be made regarding the role of propulsion noise. Comparison of data for many different vehicles and transit systems indicates that the noise with the cars jacked up and wheels spinning is below that with the car under power passing by. Thus, it is generally concluded that the wheel/rail interaction is the dominant noise source [19, 20, 21]. This conclusion has been supported by data taken for cases in which it has been possible to clearly identify the propulsion and the wheel/rail noise. For example, measurements for a case in which only one truck on each car was powered show that the noise near the trucks is the same for both the powered and unpowered units [22].

Although the wheel/rail interaction is believed to be the dominant source of noise for current vehicles, propulsion noise will become increasingly important as the wheel/rail noise is reduced. For example, if the wayside propulsion noise for a particular vehicle is 4 dB(A) below the wheel/rail noise, then a 10 dB(A) reduction in wheel/rail noise will bring about only a 4.5 dB(A) reduction in total wayside noise and the propulsion system will become the dominant source.

To insure that the propulsion system continues to be a secondary source of wayside noise, it is important to set noise specifications for new cars. The Chicago Transit Authority (CTA) new car specifications call for a level of 80 dB(A) at 50 ft with the car jacked up and the wheels spinning at a speed corresponding to 60 mph [23]. The specification also calls for a level of 82 dB(A) at 50 ft for the car passing by at 50 mph. A monetary credit is given in the bid price for each dB below 82 and a penalty for each dB above this level. This specification is realistic and within the state-of-the-art as shown by data presented in Appendix and summarized in Figure 3.1 on page 39.

effect of wheel and rail condition and train speed

The quietest operation is achieved on tie and ballast track in which the rails and wheels are smooth and the rails continuously welded. For these track conditions the vehicle speed is the most important variable in determining the amount of noise generated.

For a given train, the noise levels increase with vehicle speed. Based on reported data the increase in noise level for each doubling of train speed is between 6 and 10 dB(A), the exact value depending on the specific rail system being studied. Most systems exhibit a 9 dB(A) per speed doubling. This velocity dependence, which is equivalent to a 30 Log_{10} V dependence, also has some theoretical support [1].

The noise prediction procedure in Fig. 3.1 shows that the noise increases 10 dB(A) per doubling of train speed. We believe this to be near the proper speed dependence for most cases. Data from those cases in which a different speed dependence has been reported fall within the 10 dB(A) range of levels shown in Fig. 3.1 for all speeds.

The overall noise level (no frequency weighting or C scale on a sound level meter) shows a different dependence on vehicle speed. Generally, a 6 dB increase occurs for each doubling of speed.

Rail or wheel roughness increases the wayside noise levels by 3 to 6 dB(A). A quantitative relationship between roughness and noise has not been validated. However, it should be noted that new rails and wheels are rough and result in noise levels that are approximately 5 dB(A) higher than levels resulting from operation with wheels and rails that have been ground smooth.

Rail wear often takes the form of corrugations. These are small periodic irregularities of the rail surface which lead to howling tones that are up to 15 dB(A) above the baseline noise level for operation on smooth rail [17].

Rail joints or wheel flats lead to impact noise which increases the maximum noise levels during a train passage by 8 to 10 dB(A) above levels for operation on smooth continuously welded rail [24, 25].

The effects of rail and wheel condition listed above are not additive. For example, it has been observed that jointed rail leads to the same increase in noise level for both cars without wheel flats and those with flats [26]. The accepted procedure in applying the corrections is to add only one correction factor -- the largest one applicable to the particular situation. This procedure is based on empirical observations and not on theoretical considerations.

concrete slab track

For tie and ballast track it can be assumed that the track design has very little effect on generated noise. However, when a concrete slab track is used instead of a tie and ballast design the noise levels increase 2 to 4 dB(A) [27]. It has also been observed that noise levels in and under the car increase when it passes from a ballasted section of track to a nonballasted slab track. These increases are believed to be due to the replacement of ballast, which absorbs sound, with concrete which is highly reflective.

It is also possible that the higher noise levels on concrete slab track are due to secondary radiation of sound from the slab. In such a case, the trackbed design would have some effect on the radiated noise. At present, the studies of at-grade slab track are not sufficiently detailed as to allow a complete understanding of the noise radiation mechanisms.

3.2.3 Noise Propagation

Once the amount of noise generated by the train has been predicted, it is necessary for the rail system designer to predict the effect of the propagation path on the noise levels. It is useful in making this prediction to use simple analytical models for the noise source. One model, that has been supported by comparisons with data is a line of dipole sources with one source located at each truck location. As discussed in Appendix A this model can be used to predict both the time history of the noise level as the train passes by and the variation of the maximum noise level as the distance from the train to the receiving point increases.

As discussed earlier, the noise levels measured at 50 ft (15 meters) are indicative of the noise generated by the train. The levels at this distance do not change appreciably as the number of cars changes. However, at greater distances from the train the noise levels will depend directly on the length and the number of cars in the train. A graph showing the decrease in noise level with distance over flat ground for trains of different lengths is shown in Fig. 3.2. Curves in this graph are based on calculations using the dipole source model. Field data taken at measurement point heights greater than 10 ft (3 meters) support the information given in this figure for distances up to 750 ft (230 meters) [28]. At greater distances the field data lay below the predictions due primarily to atmospheric effects and the effects of the ground cover.

When the measurement point is at head height, the measured noise levels for distances greater than 50 ft (15 meters) are observed to be 2 to 4 dB(A) below the levels predicted using Figures 3.1 and 3.2.

This observed decrease in level is due to the "ground effect", a complex interaction of the sound waves coming directly from the source along a line-of-sight path with the sound waves coming from the source along a path that reflects off the ground. At distances less than 750 ft, the ground effect is small and leads to the 2 to 4 dB(A) reduction in level noted above. At larger distances the ground effect can be large and can lead to significant reductions in noise level. As a general rule, the magnitude of the ground effect increases with distance between the source and receiver. Therefore, we expect a 1 dB(A) reduction in level due to ground effect for distances less than 50 ft, a 2 dB(A) reduction for distances in the range 50 to 250 ft, a 3 dB(A) reduction for the range 250 to 500 ft, and a 4 dB(A) reduction for distances between 500 and 750 ft. These values should be subtracted from levels shown in Fig. 3.2 to account for propagation over flat ground.

<u>effect of terrain</u>

The effect of a hill between the source and the receiver is to provide a natural noise barrier. Noise levels can be reduced by terrain by as much as 25 dB(A), but reductions of 5 to 10 dB(A) are more commonly observed. The effect of a valley or gully between the source and receiver is slight. The effect of propagation through rows of densely packed houses or buildings is to reduce the levels given in Fig. 3.2 by up to 20 dB(A).

The above discussion is intended to provide an estimate of terrain effects. More detailed information is to be found in Section 7.4 which deals with the attenuation by barriers and in Section 3.2 which deals with noise when a track is located in a cut or on an embankment.

urban areas

The prediction of propagation effects in an urban situation is complex because of the many buildings that offer large reflecting surfaces for the sound waves. Noise levels in front of large buildings will be 3 to 6 dB(A) higher than in open space because of reflections and possible reverberation of the sound between buildings [29]. Levels behind large buildings will be 10 to 20 dB(A) lower than in open space because of the shielding effect of the buildings [30].

3.2.4 Noise Control

Noise control for surface track involves a number of steps. First, the rails should be continuously welded when possible and wheel flats should be eliminated to reduce impact noise. For those cases in which the rail cannot be welded because of the signaling system or other factors, careful consideration should be given to the design of rail joints that reduce the impact as the wheel crosses the joint [31].

The elimination of rail corrugations is equally important. Rails should be reground whenever corrugations appear.

The next step of a noise control program is to grind the rails and wheels to a smooth finish. After this step the noise level from the trains should fall within the bounds of Fig. 3.1.

car modifications

Further reductions in wayside noise can be gained by incorporating noise control features into the cars.

Resilient materials and vibration damping materials should be used to prevent vibration transmission from the wheel/ rail interface up into the trucks. Damped or resilient wheels may provide some noise reduction. However, in practice the damping treatments are not as effective in reducing the roar or impact noise as they are in reducing the high pitch wheel squeal. Further work on this matter is needed.

Pneumatic car suspension is also believed to provide some noise control compared to other types of suspension [32]. Similarly, car skirts which extend down over the trucks and wheels have been found to provide some wayside noise reduction, 2 or 3 dB(A) [33].

Noise control applied to the car is limited in the extent to which it can reduce the total noise generated. Reductions of the noise level to more than a few dB(A) below the lower limit shown in Fig. 3.1 will probably require some means of reducing rail vibration and noise radiation. See, for example, predictions of rail radiation in Appendix B.

noise barriers

As a final measure, noise barriers can be used to reduce the wayside noise 5 to 15 dB(A) below the lower limit shown in Fig. 3.1. A detailed discussion of the use of barriers is presented in Section 7.4.

ineffective techniques

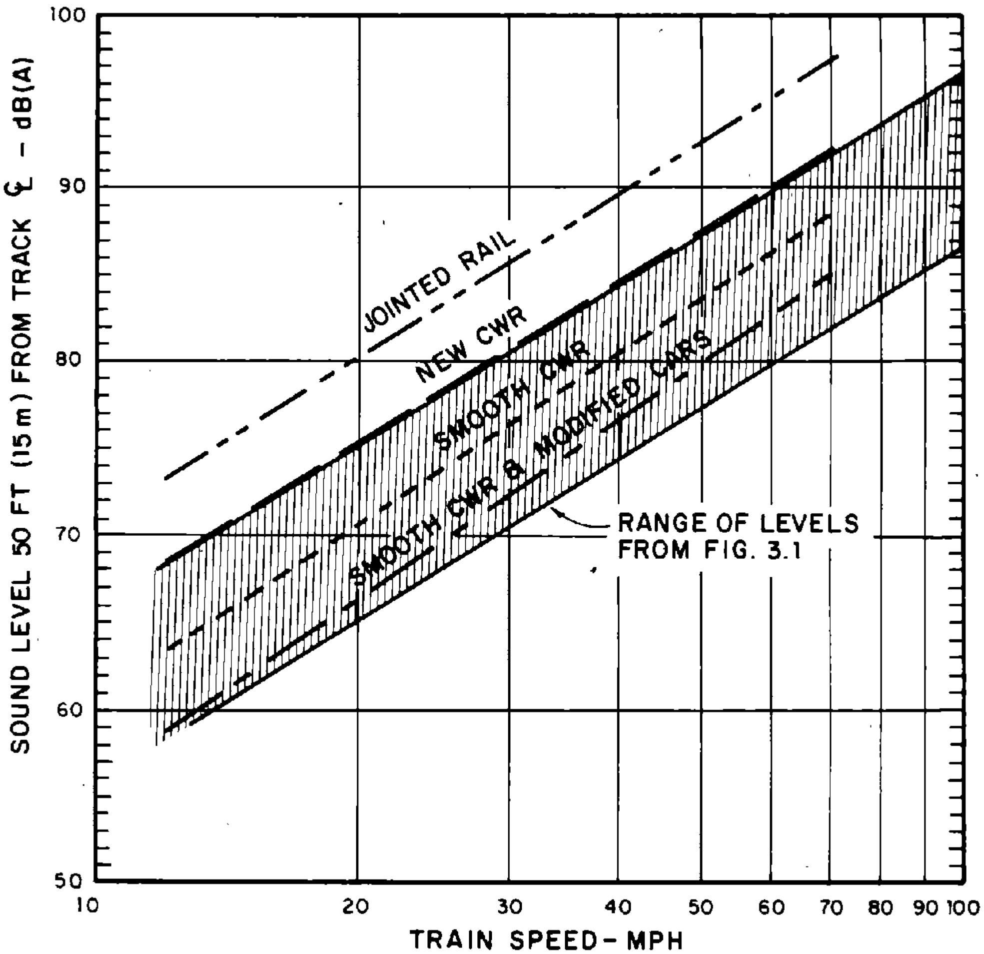
It is worthwhile to mention also some noise control measures that are not particularly effective. Resilient rail fasteners have very little effect, if any, on wayside noise. Use of concrete ties is believed by some to result in lower noise, but only by 2 dB(A) [34]. And, finally, a reduction in axle load has only a slight effect on noise.

<u>example of noise control</u>

As an example of the noise control procedure for at-grade tie and ballast track we present data taken for the Chicago Transit Authority [35]. The data, shown in Fig. 3.3, indicate measured noise levels vs. vehicle speed for four different conditions: operation on jointed rail; operation on continuously welded new rough rails; operation on continuously welded smooth ground rail; and operation on smooth continuously welded rail with cars modified to obtain more noise control.

On joined rail, the measured levels are 5 dB(A) above the upper limit of the generalized prediction shown in Fig. 3.1. Replacement of the joined rail with new continuously welded rail gave a 5 dB(A) reduction in noise level so that the measured levels lie close to the upper bound of the generalized prediction. The new rail, which can be considered to be rough, was then ground smooth. The resulting reduction in noise level was an additional 3 dB(A) so that the measured noise levels for this condition lie within the two bounds. The condition of operation on smooth continuously welded rail is the baseline condition on which the bounds for the generalized noise prediction procedure are based. For the fourth condition, the cars were modified by replacing the rubber journal sleeves with sleeves that were 30 times softer. The noise levels dropped an additional 4 dB(A) so that the measured levels are near the lower bound of the prediction.

Based on our study of noise levels from at-grade tie and ballast track, we conclude that the standard CTA cars (series 2000 Pullman cars with LFM trucks for the



CONDITIONS

OPERATION AT GRADE ON TIE & BALLAST TRACK

—-·-·— JOINTED RAIL

— — NEW CONTINUOUSLY WELDED RAIL (CWR)

- - - - - SMOOTH CWR

—·— SMOOTH CWR, MODIFIED CARS

DATA FROM REF. 35

FIG. 3.3 EXAMPLE OF MEASURED WAYSIDE NOISE USING CHICAGO TRANSIT AUTHORITY DATA measurement being discussed) are representative of the typical state-of-the-art car with regard to wayside noise generation. The modified cars do not represent an advancement in the state-of-the-art. However, they are among the quietest in the world with regard to wayside noise generation.

Further reduction of noise levels for the modified CTA cars could be achieved by use of noise barriers, which would provide an additional 5 to 15 dB(A) reduction. An advancement of the state-of-the-art in car and track design might also provide further noise reduction.

3.3 Embankments and Cuttings

The community noise from rail vehicles on an embankment or in a cutting is significantly affected by the geometry of the propagation path. A reduction in noise level occurs at points where the direct line-of-sight path for sound propagation is blocked by the terrain as shown in Fig. 3.4.

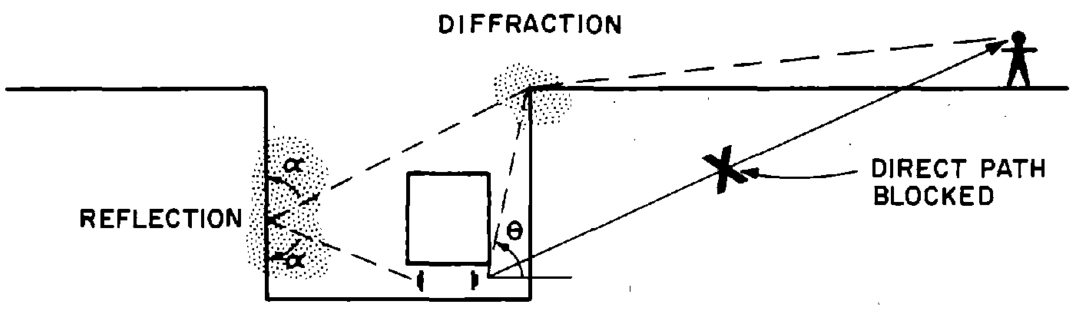
noise generation

Although the community noise level is affected by the geometry of the propagation path, the amount of noise generated by the rail vehicles is not changed. Our approach, therefore, is to use the prediction procedure developed in Section 3.2 for at-grade track with a correction to be applied to account for the effect of embankment or cutting geometry.

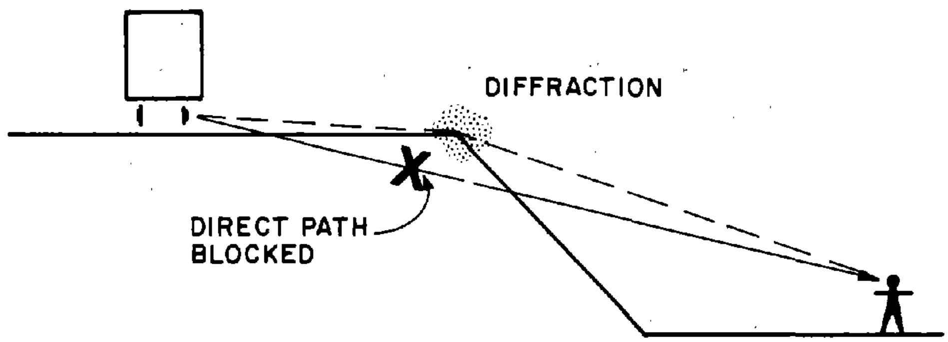
embankments

When a train passes through a community on an embankment, the wayside noise level at rail height is approximately equal to the level observed for the same train passing by at the same speed on track at grade. Small differences in the levels observed for these two cases occur at distances greater than approximately 50 ft (15 meters) due to the differences in ground effect, see Section 3.2.

For measurement points near the ground and close to the track, the wayside noise levels are reduced due to the shielding effect of the embankment. This shielding effect is more pronounced for trains on the far track when the embankment carries more than one track.



TRACK IN CUTTING



TRACK ON EMBANKMENT

FIG. 3.4 EXAMPLES SHOWING THE ELIMINATION OF THE DIRECT LINE OF SIGHT TRANSMISSION PATH

Measurements taken by the Japanese National Railway (JNR) indicate that the noise levels 1.2 meters (4 ft) above the ground near an embankment increase as the distance from the track increases, reach a maximum level at approximately 25 meters (82 ft), and then decrease with further increases in distance [22]. The exact distance at which the noise levels reach their maximum value depends on the height of the embankment.

noise prediction

The effect of embankment geometry can be predicted using design charts that have gained acceptance for use in highway noise calculations. The use of these charts is valid since the source characteristics of a line of automobiles on a highway are similar to those of a train. For both sources, the A-weighted noise spectrum is similar, the source height is approximately the same, and the length of the source is sufficiently long that it can be treated as a line source.

The highway design charts are shown in Fig. 3.5. The procedure for their use is to calculate needed geometrical parameters in feet and to use Fig. 3.5 to determine an adjustment in dB. This adjustment is applied to the community noise levels calculated using Figs. 3.1 and 3.2 for at-grade operation.

example

As an example, we consider a 4-car train passing at 40 mph over smooth welded rail on a 30 ft high embankment. The geometry is shown in Fig. 3.6.

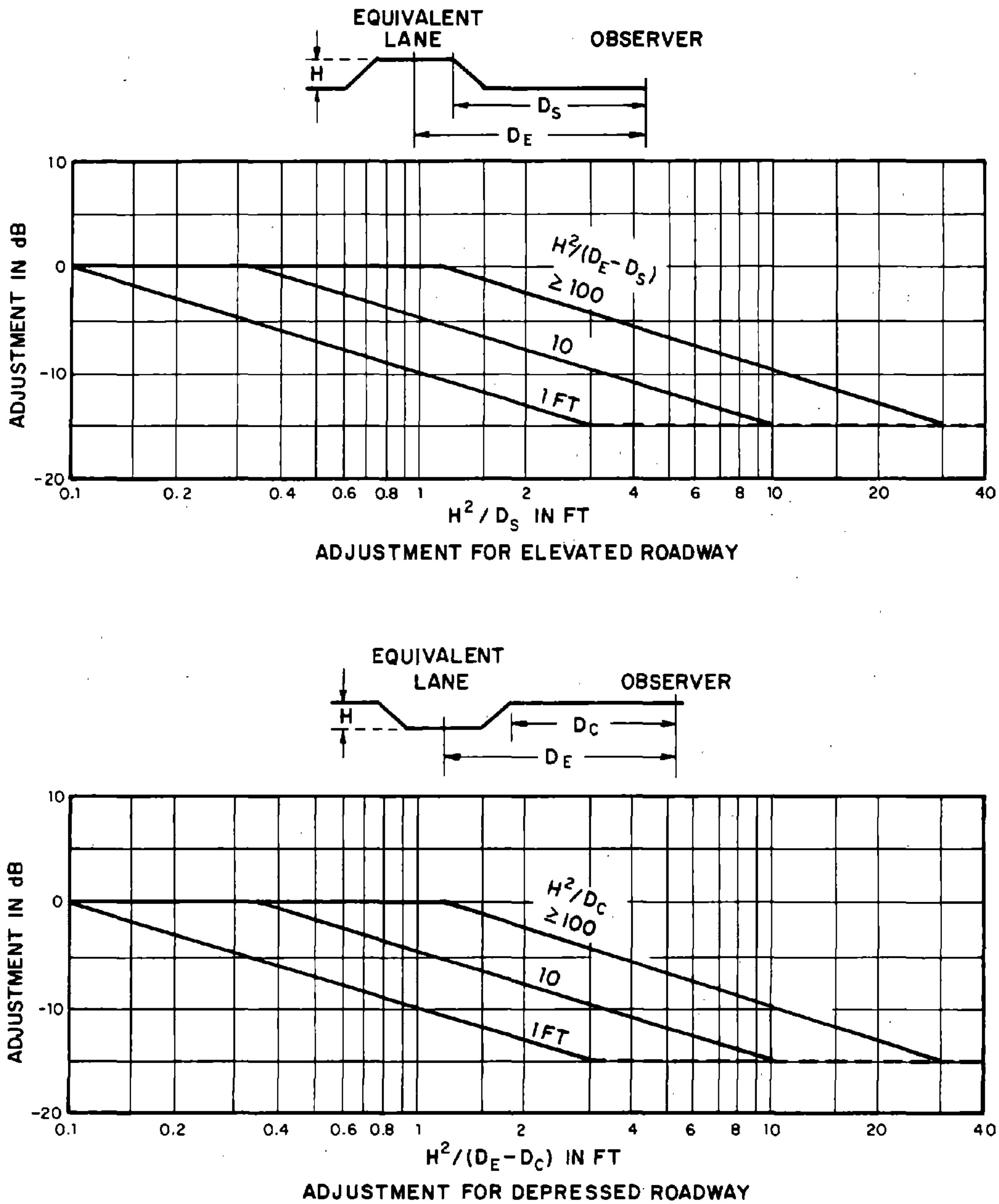


FIG 3.5 DESIGN CHARTS FOR PREDICTING NOISE FROM ELEVATED AND DEPRESSED HIGHWAY [FROM REF. 36]

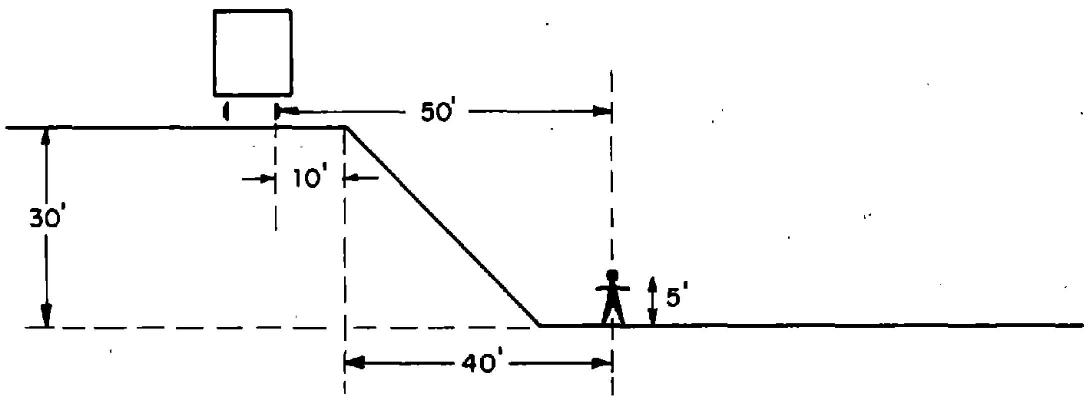


FIG. 3.6 DIMENSIONS FOR EMBANKMENT EXAMPLE

For this case, the parameters are

$$\frac{H^2}{D_S} = \frac{(30 - 5)^2}{40} = 15.6$$

$$\frac{H^2}{D_E - D_S} = \frac{(30 - 5)^2}{(50 - 40)} = 62.5$$

From the design chart the dB adjustment is approximately minus 12 dB. From Figs. 3.1 and 3.2 we calculate the noise level at 50 ft for a 4-car train at-grade to be between 75 and 85 dB(A). Applying the adjustment of minus 12 dB we expect the noise levels due to train operation on the embankment to be between 63 and 73 dB(A). Variations within this range will depend on many unspecified factors -- the most significant of which is car design.

cuttings

Community noise levels are also reduced due to shielding effects when a train passes through a cut. In this case, the reduction in level is smallest near the track and increases with increasing distance.

The direct line-of-sight transmission path is blocked for all observer points except those near the edge of the cut or in buildings high above ground level. Thus, in most cases sound waves reach the observer either by diffraction over the edge of the cut, by reflection off the banks or walls of the cutting, or by a combination of these two processes as shown in Fig. 3.4 on page 55.

When the sides of the cutting are inclined, the sound waves tend to be reflected up in the air and reflected sound does not enter into a calculation of noise level near the ground. However, when the sides of the cutting are vertical, the dominant transmission path is typically one involving reflections.

noise prediction

To predict the community noise near a cutting, each path of sound transmission must be considered separately. The first prediction is for the sound transmitted directly from the source location near the wheel/rail interface to the edge of the cutting and by diffraction to the observer. For this prediction two correction factors must be applied to the levels predicted for at-grade operation using Figs. 3.1 and 3.2. The first correction factor is due to the directivity of the source. Measurements indicate that rail vehicle noise is directive with levels measured at an angle of 30° from horizontal being approximately equal to levels at rail height, 0°, while levels at 60° are 3 to 4 dB(A) lower and levels directly above the car, at 90°, are 6 to 9 dB(A) lower [37]. A directivity pattern based on these measurements is shown in Fig. 3.7.

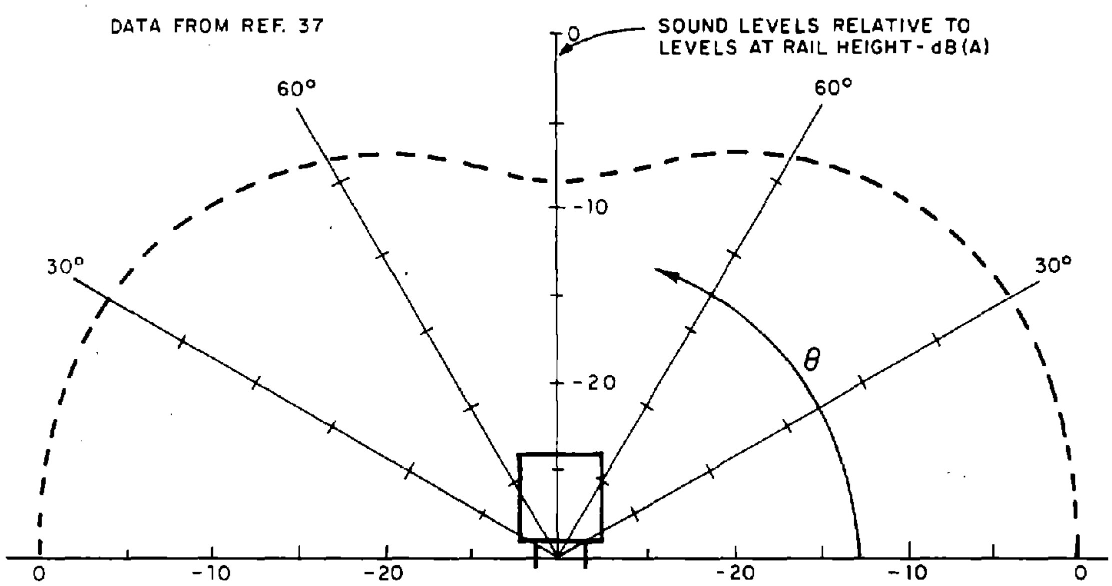


FIG. 3.7 DIRECTIVITY OF WAYSIDE NOISE FROM TRAINS ON TIE AND BALLAST TRACK

To calculate the first correction factor we compute the angle between horizontal and a line from the top of the rail on the near side of the car to the edge of the cutting. Using this angle in Fig. 3.7 we obtain the first correction factor. To calculate the second factor for the direct-diffracted path we use the highway design charts shown in Fig. 3.5. The procedure for their use is to calculate needed parameters and to use Fig. 3.5 to determine the second correction factor.

A second prediction is now made for the sound transmitted by a path involving reflections. Acoustical image sources are formed by constructing each transmission path with the constraint that the angle of incidence be equal to the angle of reflection. An illustration of image formation and the prediction procedure are shown in Fig. 3.8.

3.4 Elevated Structures

When a rail vehicle passes through a community on an elevated structure the wayside noise levels can increase as much as 20 dB(A) above levels for the same vehicle on at-grade track. This large increase in level is due to radiation from the structure, henceforth termed elevated structure noise.

In a few cases, such as travel on heavy stone or concrete viaducts with high side walls, the wayside noise decreases. The decrease occurs because of the shielding effect of the side walls on noise coming directly from the vehicle. The shielding effect can be sufficiently large as to make radiation from the structure the dominant source of noise.

A precise prediction of the noise radiated by an elevated structure is not within the state-of-the-art. However, a general understanding of the problem has been achieved and enough information exists to make basic design decisions. This information is contained in Section 3.4.1.

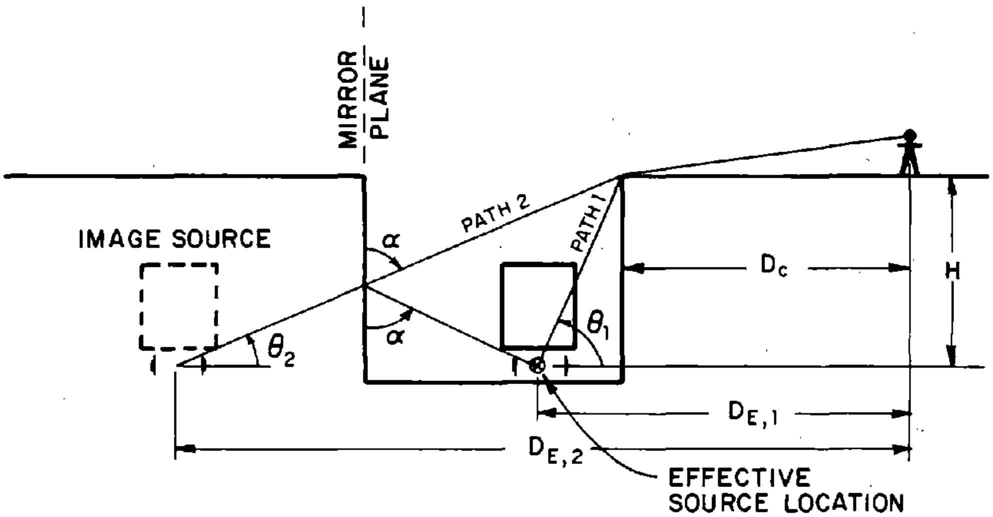


FIG. 3.8 AN EXAMPLE OF IMAGE FORMATION

CALCULATION PROCEDURE

FOR PATH (1) CALCULATE:

a) Level at distance $D_{E,1}$ from Figs. 3.1 and 3.2; $L_{AG,1}$

b) Directivity correction from Fig. 3.7 for angle θ_1; $L_{D,1}$

c) Cutting correction from Fig. 3.5 for distances

H, $D_{E,1}$, and D_C; $L_{C,1}$

d) Level from Path (1); $L_1 = L_{AG,1} + L_{D,1} + L_{C,1}$

FOR PATH (2) CALCULATE:

a) Level at distance $D_{E,2}$ from Figs. 3.1 and 3.2; $L_{AG,2}$

b) Directivity correction from Fig. 3.7 for angle θ_2; $L_{D,2}$

c) Cutting correction from Fig. 3.5 for distances

H, $D_{E,2}$, and D_C; $L_{C,2}$

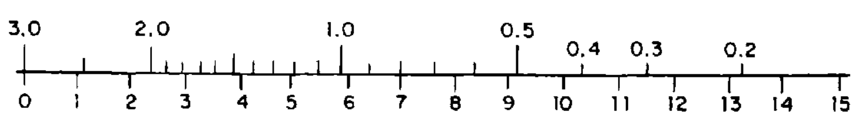
d) Level from Path (2); $L_2 = L_{AG,2} + L_{D,2} + L_{C,2}$

TOTAL LEVEL AT OBSERVER DUE TO BOTH PATHS IS L_T

$$L_T = 10 \ \mathrm{LOG}_{10} \ [10^{L_1/10} + 10^{L_2/10}]$$

ADD TO HIGHEST LEVEL

LEVEL ADDITION NOMOGRAPH



DIFFERENCE BETWEEN LEVELS

Further insight into elevated structure noise can be gained from simple analytical studies [38]. Ideas from these studies support the general concepts in Section 3.4.1 but at this time do not result in predictions of radiated noise. The goal of our future work is to extend these ideas to the point where accurate predictions and precise design guidelines can be formulated.

Methods of elevated structure noise control are discussed in Section 3.4.3.

3.4.1 Noise Prediction

A recent study has been conducted by the ORE on radiation from a number of railroad bridges [39]. In this study, measurements were taken of wayside noise due to the passage of a single locomotive on the bridge and on at-grade tie and ballast track. Although the vehicles used in the ORE study are not truly representative of urban mass transit vehicles, the measured increases in noise level for different types of bridge construction agree with more limited data from Chicago Transit Authority (CTA) and Bay Area Rapid Transit (BART) [40,41].

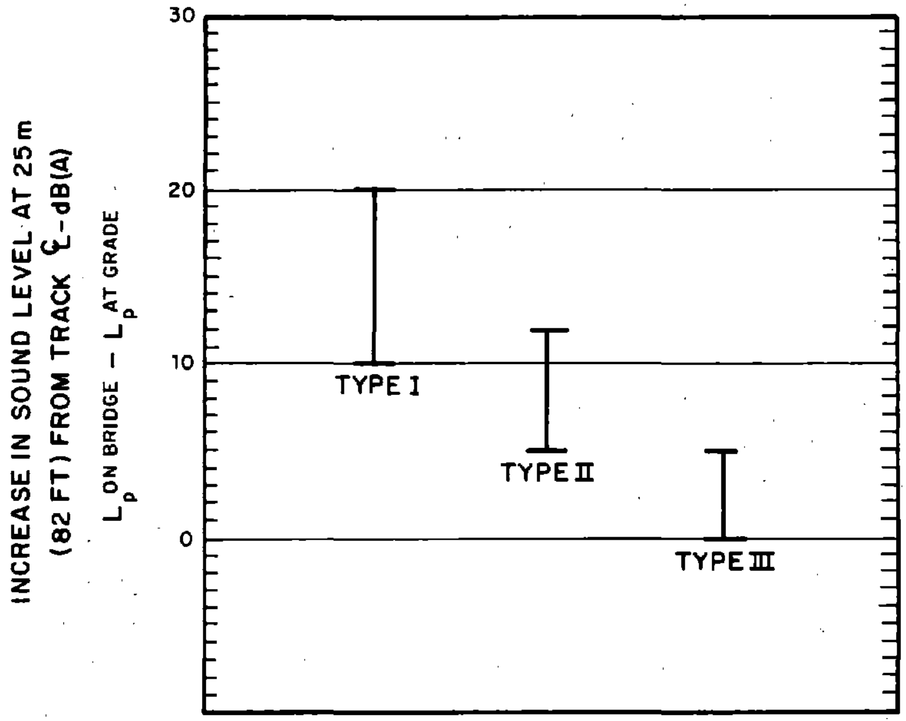
The following general conclusions appear to have universal validity. Steel plate bridges with direct rail fastening and no applied damping treatment produce noise levels at a distance of 50 ft from the track that are 10 to 20 dB(A) above levels for operation on at-grade tie and ballast track. Sidewalls on the bridge produce no shielding effect and actually increase wayside noise levels by increasing the radiating area of the bridge.

Steel girder or lattice type bridges with direct rail support or with ties directly supported produce noise levels that are 5 to 12 dB(A) above levels for at-grade tie and ballast track. Finally, steel plate bridges with tie and ballast rail connection and concrete bridges or viaducts with either direct or tie and ballast rail connection produce levels 0 to 5 dB(A) higher. A summary of these results is shown in Fig. 3.9.

Other data supporting the validity of the results shown in Fig. 3.9 have been found. Noise levels 50 ft from the Chicago open and closed-web steel girder structures with directly supported ties are reported to be 10 dB(A) above levels for at-grade tie and ballast track [41]. BART data for operation on concrete structures with direct rail fastening are 2 or 3 dB(A) above levels for at-grade tie and ballast track [40]. JNR reports levels for an open steel girder bridge with ties directly connected that are 10 dB(A) above levels for operation on at-grade tie and ballast track [42].

The elevated structure noise is caused by vibrations transmitted from the rail to the structure. Therefore, the amount of noise generated by the structure is dependent on rail and wheel condition. We expect the effect of rail joints and roughness to be approximately the same for structure-borne noise as for wheel/rail noise during at-grade operation. Similarly, we expect the dependence of structure noise on vehicle speed to be the same as for noise at-grade. Using these results we predict the wayside noise at 50 ft (15 meters) from the track by first predicting the noise level for at-grade operation using Fig. 3.1 and then increasing the levels according to Fig. 3.9.

A prediction obtained using the above procedure does not take into account the shielding effect that can



TYPE I: ALL STEEL BRIDGE, PLATE CONSTRUCT, DIRECT RAIL FASTENING, WITH OR WITHOUT SIDE WALLS

TYPE II: a) ALL STEEL BRIDGE, OPEN GIRDER CONSTRUCTION, DIRECT RAIL FASTENING OR RAIL FASTENED TO DIRECTLY - SUPPORTED TIES
b) STEEL/CONCRETE COMPOSITE STRUCTURES [SEE NOTE]

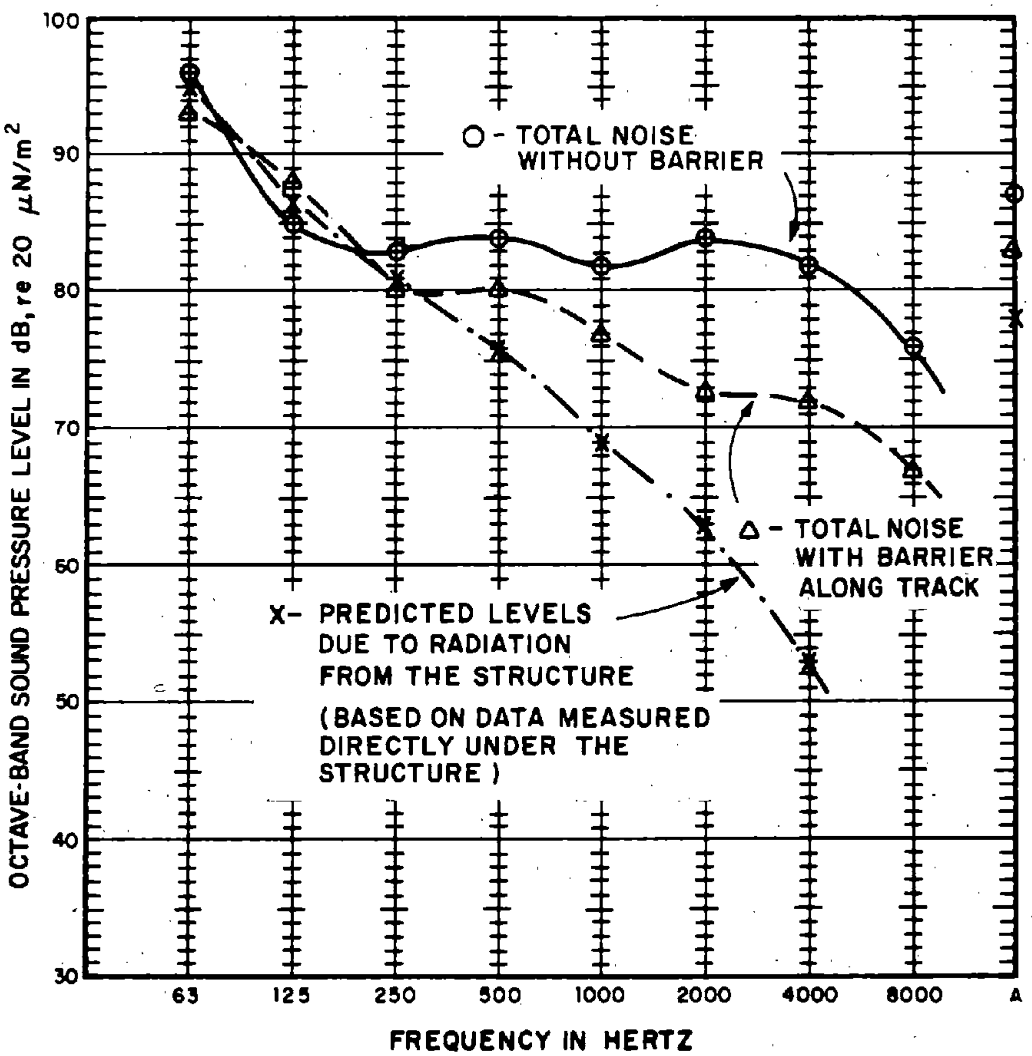
TYPE III a) TYPE I WITH BALLASTED TRACK
b) ALL CONCRETE

AUTHORS' NOTE: COMPOSITE STEEL STRUCTURES WITH CONCRETE SLAB ROADBEDS WERE NOT INCLUDED IN THE TESTS. WE BELIEVE THE NOISE INCREASE FOR THESE STRUCTURES TO BE IN THE RANGE 3 to 7 dB (A)

REF. 39

FIG. 3.9 INCREASED NOISE DUE TO ELEVATED STRUCTURE RADIATION occur on concrete structures. To do this we must divide the calculations into two parts: first, a calculation of elevated structure noise, and second, a calculation of the effect of the shielding on noise from the wheels and rails. To calculate the structure noise we use data measured under the structure where shielding of noise from the wheels and rails is most pronounced. A rough estimate of the contribution of structure noise to the total wayside noise is obtained by correcting the levels measured under the structure for distance using a 3 dB per distance doubling law. For example, JNR reports measurements of noise levels at a point 5 meters (16 ft) under a concrete viaduct and at a distance of 25 meters (82 ft) to the side [43]. We take the measurements under the viaduct to be indicative of the elevated structure radiation. The increase in distance from 5 meters to 25 meters corresponds to 2.25 distance doublings so that the level of elevated structure noise 25 meters (82 ft) to the side of the track is estimated to be 7 dB below levels measured under the structure. Figure 3.10 shows frequency spectra for the estimated elevated structure noise and total noise measured at a distance of 25 meters (82 ft) from the track. These spectra show that the overall wayside noise level (no frequency weighting) can be attributed to the low frequency noise radiated by the structure. However, since the A-weighting network de-emphasizes the low frequencies, the structure noise does not contribute appreciably to the total A-weighted wayside noise levels.

Further measurements were taken by JNR to determine the effectiveness of noise barriers in reducing noise from trains on the concrete viaducts [43]. Their data, see Fig. 3.10, indicate that the wayside noise level at 25 meters (82 ft) is reduced to a level that is 2 or 3 dB(A)



MEASUREMENTS OF TOTAL NOISE
TAKEN 25 m (82 FT) FROM THE TRACK
CENTERLINE, 1.3 m (4 FT) OFF GROUND

TRAIN SPEED – 200 km/h (125 mph)

DATA FROM REF 43

FIG. 3.10 WAYSIDE NOISE LEVELS COMPARED WITH PREDICTED LEVELS DUE TO RADIATION FROM A CONCRETE ELEVATED STRUCTURE above the estimated elevated structure noise. Thus, a significant improvement in barrier performance would not result in any appreciable drop in A-weighted wayside noise level, although levels in the high frequency range above 500 Hz would decrease.

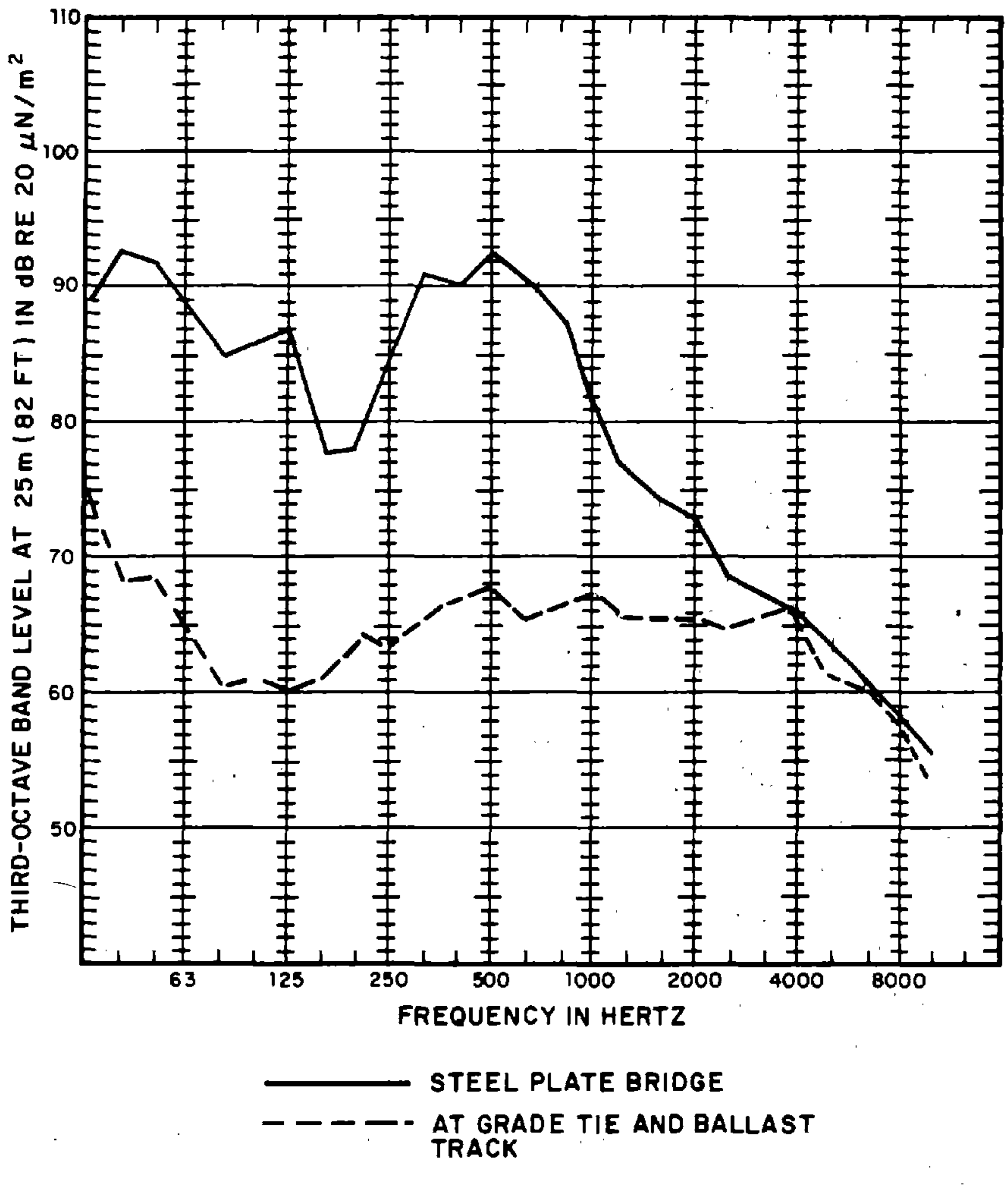
design guidelines

Largely as a result of the ORE study, many rail systems in Europe no longer build steel bridges with direct rail fastening. Additional support for this conclusion comes from recent studies in which unsuccessful attempts were made to reduce the noise from this type of structure by using soft resilient rail fasteners.[44]

Sufficient data to evaluate the noise produced by steel/concrete composite bridges have not been found. However, data taken with shaker excitation of a steel span with a concrete deck indicate the noise levels to be no greater than for an all concrete span [45]. In this same series of tests, a damping treatment was applied to the steel plate. This treatment reduced the noise levels during shaker excitation 5 to 7 dB(A).

3.4.2 Analytical Formulation

When a train passes over a bridge or on an elevated structure, the vibrations generated at the wheel/rail interface couple into the structure. A comparison of the wayside noise spectrum 25 meters (82 ft) from a steel plate bridge with the spectrum 25 meters (82 ft) from at-grade tie and ballast track is shown in Fig. 3.11.



REF. 39

FIG. 3.11 WAYSIDE NOISE SPECTRA FOR OPERATION ON STEEL PLATE BRIDGE AND ON AT GRADE TRACK

The vibratory power transmitted from the rail to the bridge can be expressed in terms of the rail vibration as [46]

$$W_{in} = \frac{R_b}{1 + \frac{\omega^2 |z_b|^2}{K^2}} \quad V_r^2 \tag{3.1}$$

where P_{in} is the power transmitted per unit length, R_b is the resistive component of the bridge impedance, ω is the radian frequency, $|z_b|^2$ is the magnitude squared of the bridge impedance, K is the spring constant per unit rail length for the rail fasteners, and V_r^2 is the mean square velocity of rail vibration.

The vibration of the bridge is related to the vibratory power input, W_{in}, the bridge damping, η, and the mass per unit length of the bridge, m_ℓ, by Eq. 3.2

$$V_b^2 = \frac{W_{in}}{\omega \eta m_\ell} \tag{3.2}$$

where V_b^2 is the mean square velocity of the bridge vibration. Finally, we can express the acoustic power radiated per unit length of the bridge, W_{rad}, as

$$W_{rad} = \rho_o \, c_o \, A_b \, \sigma_b \, V_b^2 \tag{3.3}$$

where $\rho_o \, c_o$ is the acoustic impedance and A_b is the bridge surface area per unit length, and σ_b is the radiation efficiency of the bridge.

All of the parameters required to evaluate Eqs. 3.1 through 3.3 may not be known for typical bridge constructions. However, we can use these equations to gain some physical insight into the problem.

The surface area plays a direct role in determining the amount of noise radiation through Eq. 3.3. Thus, we would anticipate the observed result that steel plate bridges generate more noise than girder bridges which have much less surface area. From Eq. 3.2 we see that heavy bridges or bridges with high damping have lower vibration levels for a given amount of power input from the rail. The lower vibration levels lead to lower radiated noise levels, see Eq. 3.3. This trend is supported by the fact that concrete bridges and steel bridges with ballast, which are much heavier and have more damping than steel bridges without ballast, generate less noise. Finally, we observe that at low frequencies the input power from the rail does not depend on the rail fastener stiffness, while at high frequencies the power input per unit rail vibration falls off rapidly with increasing frequency. This observation is supported by data which show the bridge noise radiation to be predominantly a low frequency rumble.

3.4.3 Noise Control

The noise from elevated structures is due to transmission of vibration from the rail. Therefore, techniques which control rail vibration also control elevated structure noise. The effective techniques are to eliminate rail joints and maintain wheel and rail surfaces as smooth as possible. The reductions in structure noise are expected to be comparable to those observed for at-grade noise as given in Fig. 3.1.

Rail damping treatments are of questionable value. In general, damping treatments are most effective in reducing the resonant vibration of structures. The vibration of continuous rails is both resonant and nonresonant, however, so that damping treatments may not be very effective [47].

Another effective means of noise control is to use heavy concrete structures for bridges and viaducts. The noise from these structures is typically below the level of noise from the wheels, rails and other parts of the car. Therefore, noise barriers can be effectively used to reduce the total wayside noise to levels below those shown in Fig. 3.1.

When steel bridges are used, some type of noise control will be needed. Considerations of weight and clearance under the bridge make direct rail fastening attractive. However, with such construction, an increase in noise level is bound to occur.

A number of techniques have been proposed for the control of noise from steel bridges. In Europe, a system of direct rail fastening on a steel plate bridge was replaced with tie and ballast track. The noise levels 25 meters (82 ft) from the bridge were reduced 13 dB(A) to a level only 5 dB(A) above levels for operation on at-grade track. However, the weight of the bridge was increased from 1.9 to 4.9 metric tons/meter (2 to 5 tons/yard). In spite of this the German railway uses ballast on all new steel bridges and is adding ballast to old bridges that can withstand the additional weight.

In other tests the direct rail fastening was maintained but the steel plate was covered with a 6.2 cm

(2.44 in) thick layer of sand [48]. The noise level under the bridge was reduced 6 dB(A) while the bridge weight increased from 1.9 to 2.4 metric tons/meter (2 to 2.5 tons/yard). The sand was not viewed as a suitable treatment because of maintenance problems and was removed after the tests. Then, a 0.6 cm (0.24 in) layer of mineral coal emulsion with quartz sand (similar to asphalt) was placed on the bridge. This layer gave approximately 5 dB(A) of noise reduction under the bridge and was much lighter.

The effectiveness of resilient rail fasteners depends on the type of structure. Efforts by the ORE to reduce noise from a steel plate bridge by using various fasteners were not successful [49]. However, it is reported that use of resilient fasteners in Rotterdam on elevated concrete structures was effective in reducing wayside noise [50]. Referring back to Eq. 3.1 and the discussion there we expect that the impedance of the steel bridge is less than that of the fastener, K/ω, so that input vibratory power does not depend on fastener stiffness.

Stockholm has had some success in reducing noise from a steel viaduct by placing 8 mm (0.315 in) thick ribbed rubber pads between the ties and the structure. A 5 dB(A) noise reduction is reported [51].

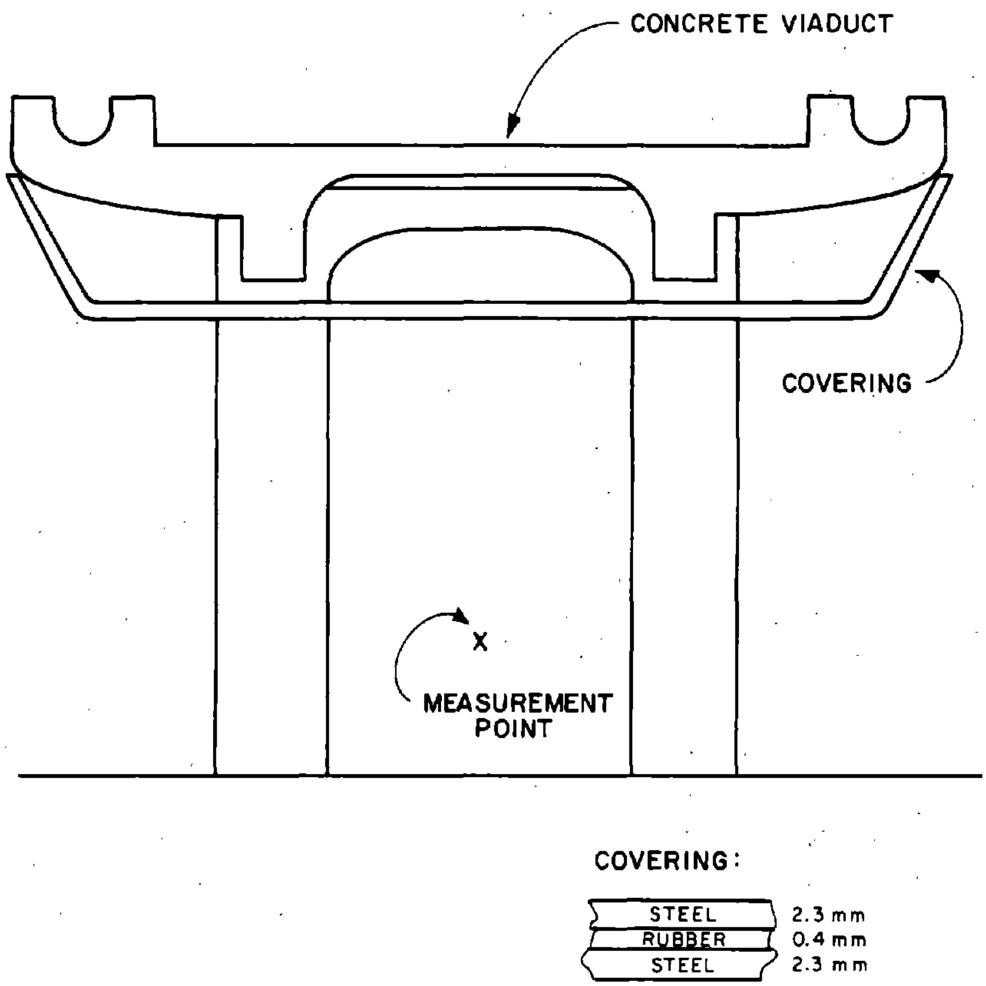
The Japanese National Railway has used many effective means of structure noise control [52]. Their measurements confirm the result that replacing direct rail fastening with tie and ballast track on a steel plate bridge gives a large reduction in wayside noise -- 13 dB(A) at 25 meters (82 ft).

JNR has also placed a 3 cm (1.18 in) rubber mat under the ballast on a concrete viaduct and reduced noise levels under the viaduct by 7 to 8 dB(A). A similar reduction in noise under a concrete viaduct with direct rail fastening was obtained by enclosing the underside of the structure with sheet metal as shown in Fig. 3.12. The sheet metal was a laminate with 2.3 mm (0.09 in) steel sheets bonded together with a .4 mm (0.016 in) of rubber damping material, so that the damping was high. No mention was made in the report as to whether or not sound absorbing material was placed in the cavity formed by the sheet metal enclosure and the structure. However, good noise control practice would incorporate such a treatment. We recommend using spray-on materials discussed in Section 7 to achieve an average absorption coefficient of at least 0.5 over the frequency range 250 to 2500 Hz. It is also important that the sheet metal damping be maintained.

JNR has also used enclosures on steel plate and steel girder bridges. Results are shown in Fig. 3.13. The enclosures resulted in a 10 to 12 dB(A) reduction in the noise levels under the bridge.

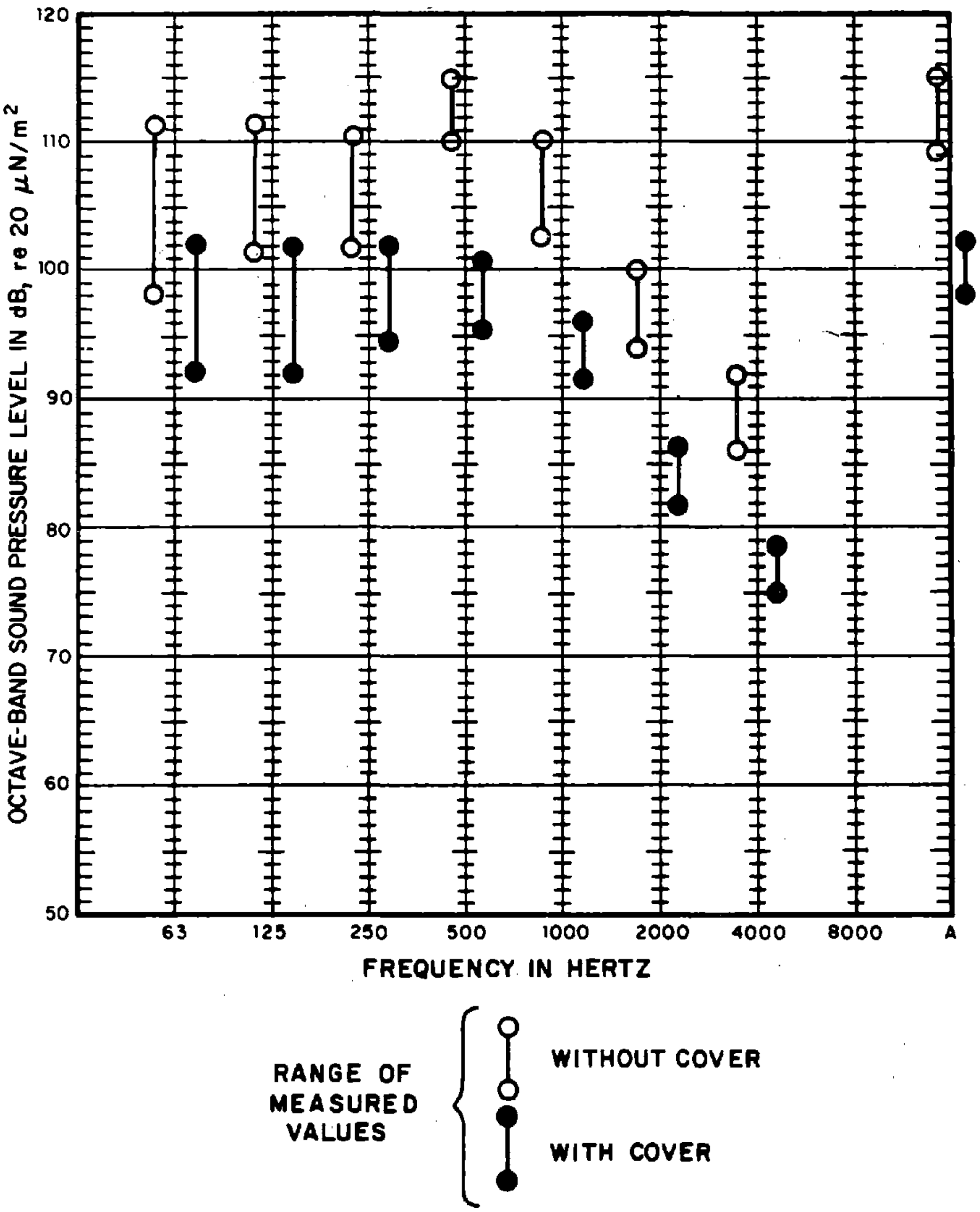
Damping treatments are also effective means of noise control. Tests by JNR show that a 20 mm (0.78 in) treatment applied to a 9 mm (0.35 in) web plate of a stringer reduces levels of vibration by ∿10 dB.

In other tests for the BART system, a 3/8 in (0.95 cm) to 5/8 in (1.59 cm) treatment was applied to the 5/8 in (1.59 cm) steel plate of a steel structure with a concrete deck. Noise levels under a test span were reduced 9 dB(A)[64].



REF. 43

FIG. 3.12 JNR VIADUCT WITH NOISE REDUCING COVER



REF. 43

FIG. 3.13 NOISE MEASURED UNDER A STEEL GIRDER BRIDGE WITH NOISE REDUCING COVER

4. COMMUNITY VIBRATION

In urban areas the track for mass transit systems must necessarily be located near buildings because of restrictions on the amount of space available. With buildings in close proximity to the track, community vibration generated by passing rail vehicles becomes as important as community noise. Indeed, for underground track, problems due to vibration are of primary concern.

4.1 Effects of Vibration

High vibration levels are a cause of complaints in many communities near surface track or subway tunnels. In severe cases, the vibration levels in buildings near the track are high enough to cause rattling of windows and dishes. In many other cases, a low rumbling noise can be easily detected by occupants of buildings and judged to be annoying.

High vibration levels in buildings can sometimes actually be felt by people. However, in the usual case the people do not feel the vibration, but are aware of it because they hear the rumbling noise. Fig. 4.1 compares a commonly accepted threshold for feeling vibration [53] with the threshold for hearing rumbling noise that results from the vibration of the walls and floors. This second curve was constructed from the relationship between vibration and noise (see Section 4.4.4) and the threshold for hearing the noise in a room with a low background noise having a spectrum following an NC-20 curve [54]. In this figure, the region of frequencies below 10 Hz has been left blank. Indications are that people are very sensitive to vibrations at these low frequencies and, therefore, feel the vibration rather than hear the resulting noise [55]. However, the velocity induced in a building by a passing transit vehicle

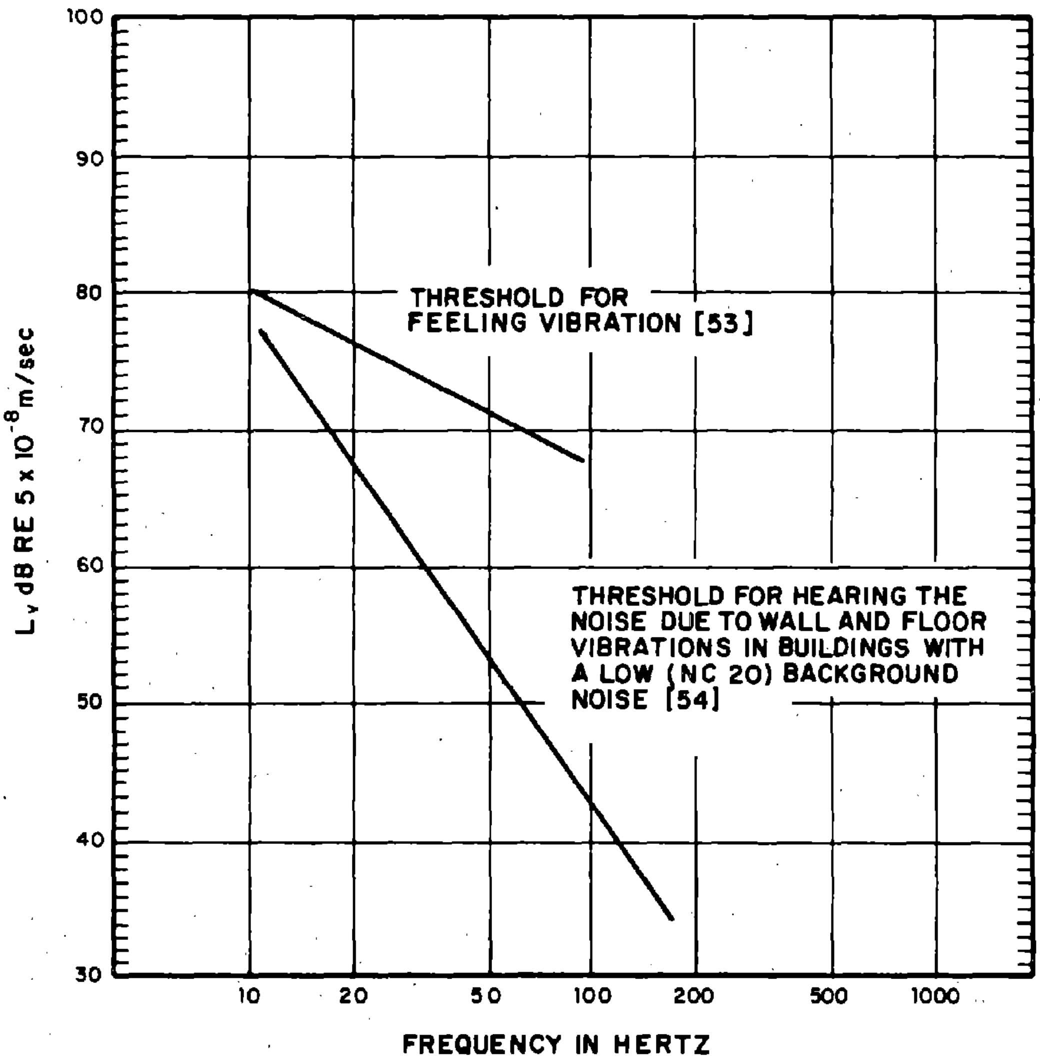


FIG. 4.1 THRESHOLDS OF PERCEPTION
FOR VIBRATION AND THE RESULTING NOISE IN BUILDINGS

has its maximum value at frequencies near 30 Hz so that the rumbling noise is heard at levels well below those at which the vibration can be felt.

Criteria for judging the annoyance of low frequency noise and vibration are more difficult to formulate. Criteria developed for noise and vibration acceptability in transportation vehicles are not valid for buildings since people expect some vibration and noise in a vehicle. It is generally accepted that people in buildings are annoyed when they feel the vibration or when dishes and other small items are caused to rattle [56]. However, it should be noted that the noise level associated with feelable vibration is very high. Using the NC rating described in Chapter 2, we find the rating of noise due to feelable vibration to be NC = 50. Noise with this rating is unacceptable for almost all activities other than manufacturing and busy commercial business (see Table 2.2 on page 23).

4.2 Prediction Procedure

The ground vibration due to operation of mass transit vehicles is the direct result of vibrations generated at the wheel/rail interface. Ground vibration also results from excitation of the ground or tunnel walls by airborne noise. For surface operation, this mechanism is dominant at large distances from the track since the vibration transmitted through the ground attenuates more rapidly with distance than the airborne noise. However, the levels of vibration at these large distances are so small that the mechanism of ground excitation by airborne noise can be ignored. Excitation of tunnel walls by noise can also be ignored inspite of the high noise levels that exist in a tunnel.

The low frequency rumbling noise in buildings near subways is the result of vibration transmitted through the ground to the building walls. A second transmission path exists for operations at-grade and on elevated structures. Following this path, the airborne noise excites the walls of the buildings and causes them to vibrate and radiate noise inside the building. The relative effectiveness with which the airborne noise and the ground vibration induce vibration in the building walls is not known at present. However, the large attenuation with distance of the ground vibration makes the ground-borne vibration path less important as the distance from the track increases.

Analytical means to predict the ground vibration level near rail lines do not exist. Therefore, we must approach the problem empirically as was done for wayside noise in Section 3. However, even the empirical approach is fraught with difficulties because the methods of data collection and presentation vary from author to author. In many cases, measurements of ground vibration are taken with the transducer on top of a metal or concrete rod which has been pounded into the ground. In other cases, measurements are taken on foundation piles before the construction of a building. In still other cases, measurements are taken on the walls and floors of buildings exposed to the ground vibration. And, finally, measurements are taken on the walls or floors of subway tunnels. The state-of-the-art is such that it is difficult to make meaningful comparisons between data taken by two different methods at different sites. For this reason, we are limited in the accuracy and confidence with which we can predict vibration levels for a given situation. What we can do, however, is give a general idea of the vibration levels to be expected and show examples of the change in vibration level due to changes in various design parameters.

The approach in the following sections is to divide the discussion into three parts: vibration from surface track, vibration from underground track and sound in buildings resulting from wall and floor vibration.

4.3 Surface Track

When the track is on the surface, either at ground level or on an elevated structure, vibration generated at the rail/wheel interface travels through the trackbed and is carried along the ground predominantly in the form of surface waves. (A more detailed discussion of propagation through soil is presented in Appendix D).

To predict the ground vibration level we proceed as was done in Section 3.2 in predicting wayside noise to identify first the amount of vibration generated by the rail vehicles. Then, we take into account the effect of the propagation path. And, finally, we predict the response of buildings to the ground vibration.

vibration generation

The ground vibration levels due to a passing train decrease rapidly with distance from the track due to attenuation in the ground. The attenuation is strongly frequency dependent so that the frequency spectrum of the vibration changes with distance from the track. Also, the amount of attenuation changes with the type of ground being higher for clay than for sand, silt, or gravel and being very low for rock.

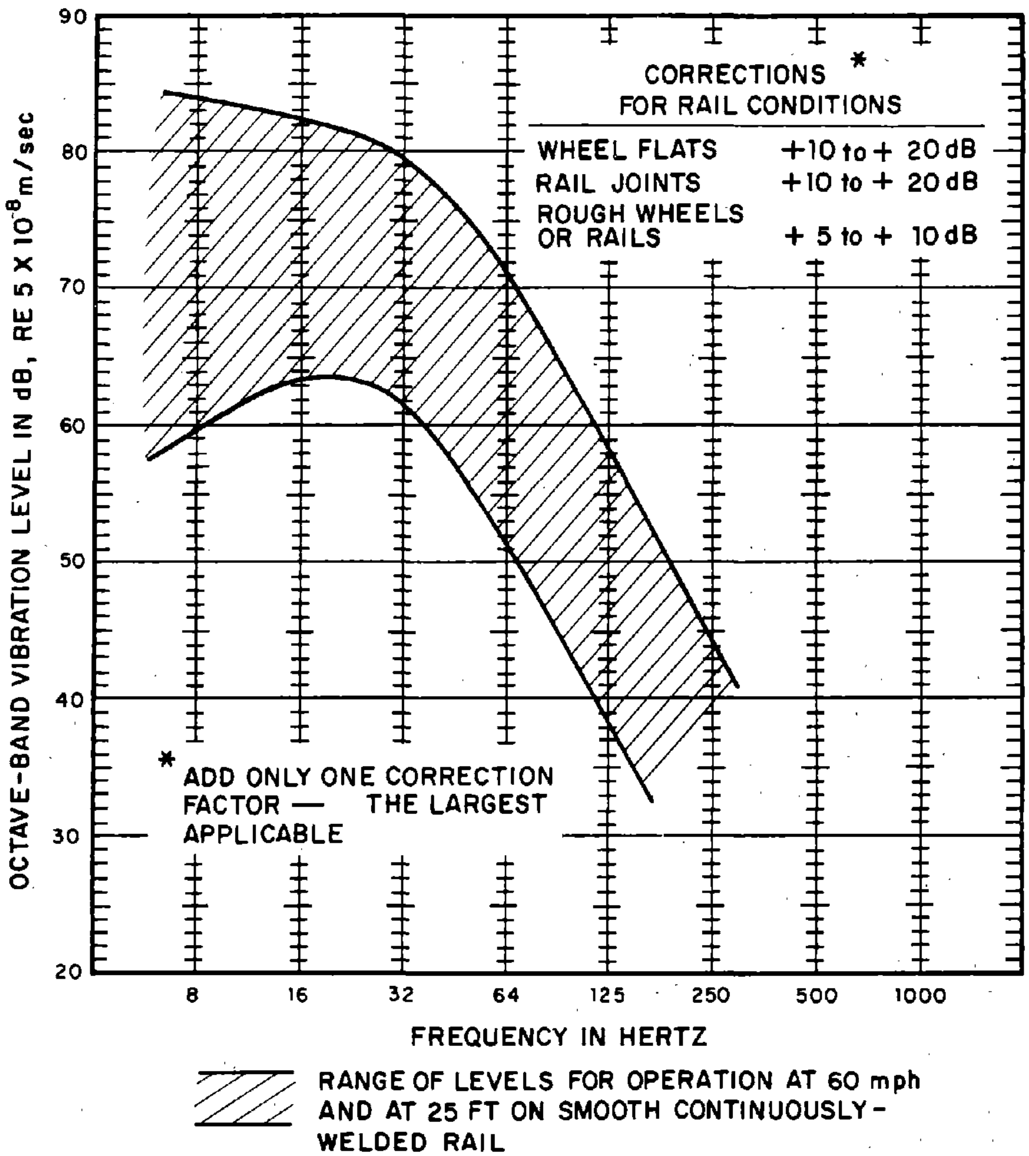
The effect of ground attenuation is smallest near the track. Therefore, to identify the amount of vibration generated by the train and to eliminate as much as possible the effects of ground attenuation, we will use data measured 25 ft (7.5 meters) from the track centerline. The primary motivation for specifying this distance comes from the fact that it is the smallest distance at which a significant amount of data has been taken. We also will use octave band frequency spectra of the ground vibration at 25 ft (7.5 meters) so that the frequency dependent attenuation effects can be accounted for in predicting the ground vibration at other distances from the track.

The range of ground vibration levels to be expected 25 ft (7.5 meters) from at-grade tie and ballast track is shown in Fig.4.2. Data used to establish this range are presented in Appendix E. The variation in octave band vibration levels is 20 dB or more in each frequency band. This large variation is due in part to differences in track and vehicle design. However, it is also due to differences in soil characteristics. Measurements taken by the German National Railway at 8 measuring points, 20 meters apart and 15 meters (50 ft) from the track show variations in octave band levels of 10 to 15 dB for identical measurement conditions [57]. Therefore, in predicting the ground vibration levels, we must be prepared for large variations in level. To be conservative one would assume the worst case and use levels corresponding to the upper limit in Fig. 4.2.

effects of design parameters

The levels shown in Fig. 4.2 are for operation of mass transit vehicles at 60 mph on continuously welded rail without corrugations.

The effect of decreased vehicle speed is to reduce the ground vibration levels. The dependence is generally agreed to be 6 dB per doubling of speed [58,59].



ADD 20 $\log_{10} \frac{V}{60}$ FOR OTHER TRAIN SPEEDS

60 mph = 100 km/h
25 ft = 7.5 m

FIG 4.2 GROUND VIBRATION LEVELS
25 FT FROM AT GRADE TIE & BALLAST TRACK

Thus, for operation at 40 mph the range of levels shown in Fig. 4.2 should be lowered 4 dB.

The effect of train length on the vibration levels at 25 ft (7.5 meters) is expected to be small. Modeling the train as a collection of point sources located at each track we would expect train length to have no effect on ground vibration levels at distances closer than 50 ft (15 meters) from the track. However, based on data from the Toronto and BART systems, Wilson concludes that ground vibration levels increase with train length [60]. Levels for 8-car trains are 1 dB greater than for 4-car trains and 3 dB greater than for 2-car trains. We do not have sufficient data to verify or disprove this dependence. Fortunately, the effect is small compared to the large variations in level shown in Fig. 4.2. It is at least approximately correct to assume that train length has no effect on the levels at 25 ft (7.5 meters).

Wheel and rail condition is known to have a large effect on ground vibration levels. Elimination of wheel flats and wheel and rail roughness has been reported to give as much as 20 dB reduction in vibration level. Therefore, since levels in Fig. 4.2 are for operation on smooth continuously welded rail, we expect as much as 20 dB more vibration due to poor wheel or rail condition. Rail joints are expected to have approximately the same effect as wheel flats. However, as in the case of noise generation, the effects are not additive. We expect the range of vibration levels for cases with either wheel flats or track joints or both to be 10 to 20 dB above levels shown in Fig. 4.2. In this case, rail and wheel roughness would have no effect. On continuously welded rail without wheel flats, we expect the range of levels for rough wheels or rails (or both) to be 5 to 10 dB above levels shown in Fig. 4.2.

Damped or resilient wheels are reported to have a beneficial effect on ground vibration levels. Measurements on the BART test track show resilient wheels to generate 5 to 10 dB less ground vibration than steel wheels in the frequency range 16 to 63 Hz, which is the most important range for ground vibration [61]. The resilient wheels produced 5 dB more vibration than the steel wheel at 250 Hz. However, because of the large attenuation of ground vibration that occurs, an increase in vibration level at this frequency is not a problem except perhaps for increased noise.

Ground vibration levels due to heavy locomotives are approximately 10 dB above the range of levels shown in Fig. 4.2 [62]. This increase is due in part to the increase in axle load and in part to the different suspension systems.

The effect of other design parameters such as tie spacing, rail weight and vehicle suspension on vibration from at-grade track has not been established. However, we expect the effects of track design on tunnel wall vibration to be the same for ground vibration. Therefore, the reader should also refer to Section 4.4.2.

propagation along the ground surface

A complete review of the state-of-the-art in predicting the effects of propagation on ground vibration levels is presented in Appendix E. Here we present only the results of this review.

Fig. 4.3 shows correction factors that are to be applied to predicted levels at 25 ft (7.5 meters) to account for the effects of propagation on ground vibration levels at

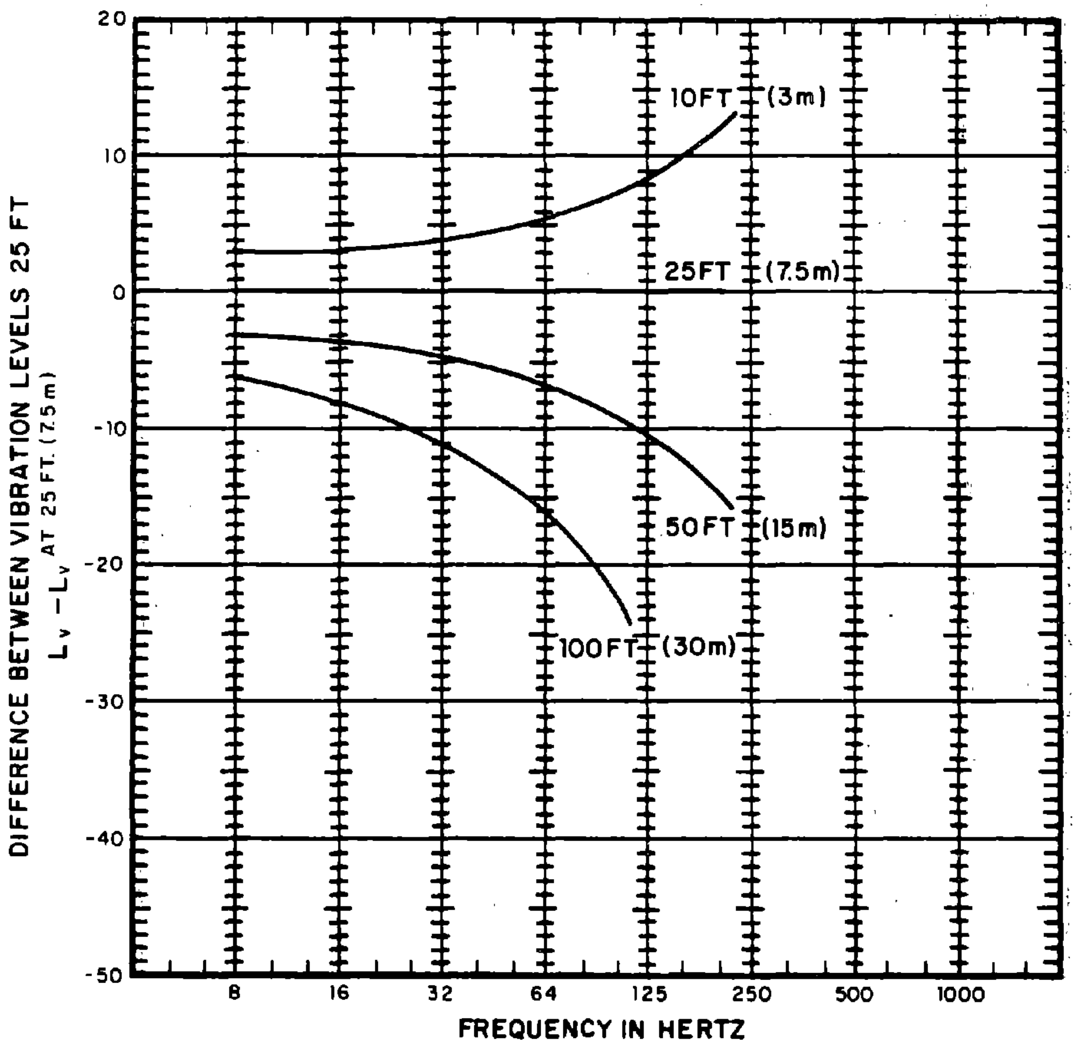


FIG. 4.3 EFFECTS OF PROPAGATION ON VIBRATION LEVELS AT THE SURFACE OF THE GROUND [63]

other distances. This figure is based on Fig. 14 from Reference [63] by Wilson. We have not shown the range of values for each distance as proposed by Wilson, since the data that we have reviewed exhibits deviations that are much greater than Wilson's proposed range. From the data we have reviewed, the correction factors may be in error for particular freqeuncy bands and particular measurement locations as much as 15 dB. However, the errors incurred are smaller at low frequencies and at distances close to the track. For the important frequency bands centered on 31.5 and 63 Hz the correction factors shown in Fig. 4.3 will be within ± 5 dB of observed values.

elevated structures

Very little data exists on the ground vibration due to train passage on elevated structures. Data taken near the BART test track show ground vibration levels near concrete elevated structures to be comparable to levels near tie and ballast track [64]. In the frequency range below 32 Hz, ground vibration levels near these two types of track are approximately equal. At 32 Hz the levels near the elevated structure are 5 dB lower. And at 63 Hz the levels near the elevated structure are 10 dB lower.

4.4 Underground Track

Ground vibration and the induced vibration of buildings near subway tunnels is of great concern. Because of this concern considerable time and effort have gone into the development of techniques to reduce the ground vibration. Large amounts of money have been spent to incorporate these vibration control techniques into the design of recent transit systems.

The vibration levels induced by a subway train are below levels expected to cause structural damage. In addition, the rumbling noise due to building vibration from subways is heard at vibration levels well below the threshold for feeling the vibration. Therefore, our objective in this section is to predict noise levels in buildings and to learn how to reduce these levels.

The approach in this section is to proceed in steps. First, we predict the level of vibration expected at the subway tunnel wall and floor. Next we predict the decrease in level from the tunnel wall to the building wall. Finally, we predict the resulting noise in the building. However, as a general rule we cite the result of a study by Lang [65]. Based on a large number of measurements in Europe for a wide range of vehicle speeds, tunnel and building constructions and trackbed designs, the A-weighted sound levels in cellar rooms between 1 to 20 meters (3 to 65 ft) from a subway wall is found to lay within ± 10 dB of the level given by

$$L_p = 59 - 20\log R \quad dB(A) \qquad (4-1)$$

where R is the distance in meters from the tunnel wall to the building wall. From the predictions that follow, it can be concluded that this simple prediction is valid. Systems with poor wheel or rail condition and direct rail fastening to the tunnel floor produce levels near the upper limit of Lang's prediction while systems with good wheel and rail condition and a tie and ballast trackbed or a soft direct rail fastening produce levels near the lower limit.

As we will show in future sections, the spectrum of noise is such that the A-weighted noise level given by Eq. 4-1 is approximately equal to the NC rating. Therefore, we can use Eq. 4-1 to obtain a prediction of either the A-weighted noise level or the NC rating.

4.4.1 Roadbed Construction

Subway track is laid either with the rail fastened directly to the tunnel floor or with ballast and tie. In some systems the rail fastening is accomplished by wood ties which are supported on the tunnel floor. In other cases rail fasteners are used.

Cost is a major factor for using direct rail fastening rather than tie and ballast construction. The ballast bed requires greater tunnel size and consequently greater tunnel depth in a cut and cover tunnel. Both factors increase cost. Tie and ballast track also requires greater maintenance.

The major advantage of ballasted track is lost in a tunnel since the ballast is not supported on the earth but on the tunnel floor where settling is not a problem.

Cost differences between direct rail fastening and ballasted track are significant but not so great that ballasted track is never used. Many older systems, such as in Boston, use ballasted track in subways. Also, some recently constructed rail systems in Europe use tie and ballast track in tunnels. One of the reason for their decision is the good performance of ballast in reducing the level of vibration transmitted to nearby buildings.

In general the vibration levels produced by trains on ballasted track are less than levels produced on track with direct rail fastening. This is not an ironclad rule, however, since direct rail fasteners exist that perform better than ballasted track in reducing ground vibration.

4.4.2 Tunnel Vibration

The path of vibration transmission for underground track is from the rail through the rail fasteners or ballast to the tunnel floor and walls and from the tunnel floor and walls and to the ground. Measurements of tunnel wall vibration have been taken for a great variety of track conditions and designs. Therefore, as the basis for an empirical prediction procedure we use the vibration level at the tunnel wall as an indication of the amount of vibration generated by a passing train. The coupling of the tunnel vibration to the ground and the propagation to buildings will be discussed in Section 4.4.3.

The range of tunnel wall vibration levels expected for operation at 40 mph (65 km/h) on continuously welded rail in two section concrete box tunnels is shown in Fig. 4.4. Substantiating data are given in Appendix F. The range of levels shown is for systems with many different fastener types or with ballast. In general the levels toward the lower limit of the range are for systems with ballast or soft rail fasteners. Levels near the upper limit are for systems with hard rail fasteners or ties directly supported on the tunnel floor.

earth and rock-based tunnels

Data used to support the range of levels shown in Fig. 4.4 are for earth supported subway tunnels 5 to 25 ft (1.5 to 7.5 meters) below the surface. We have not obtained data for rock based tunnels. However, based on data

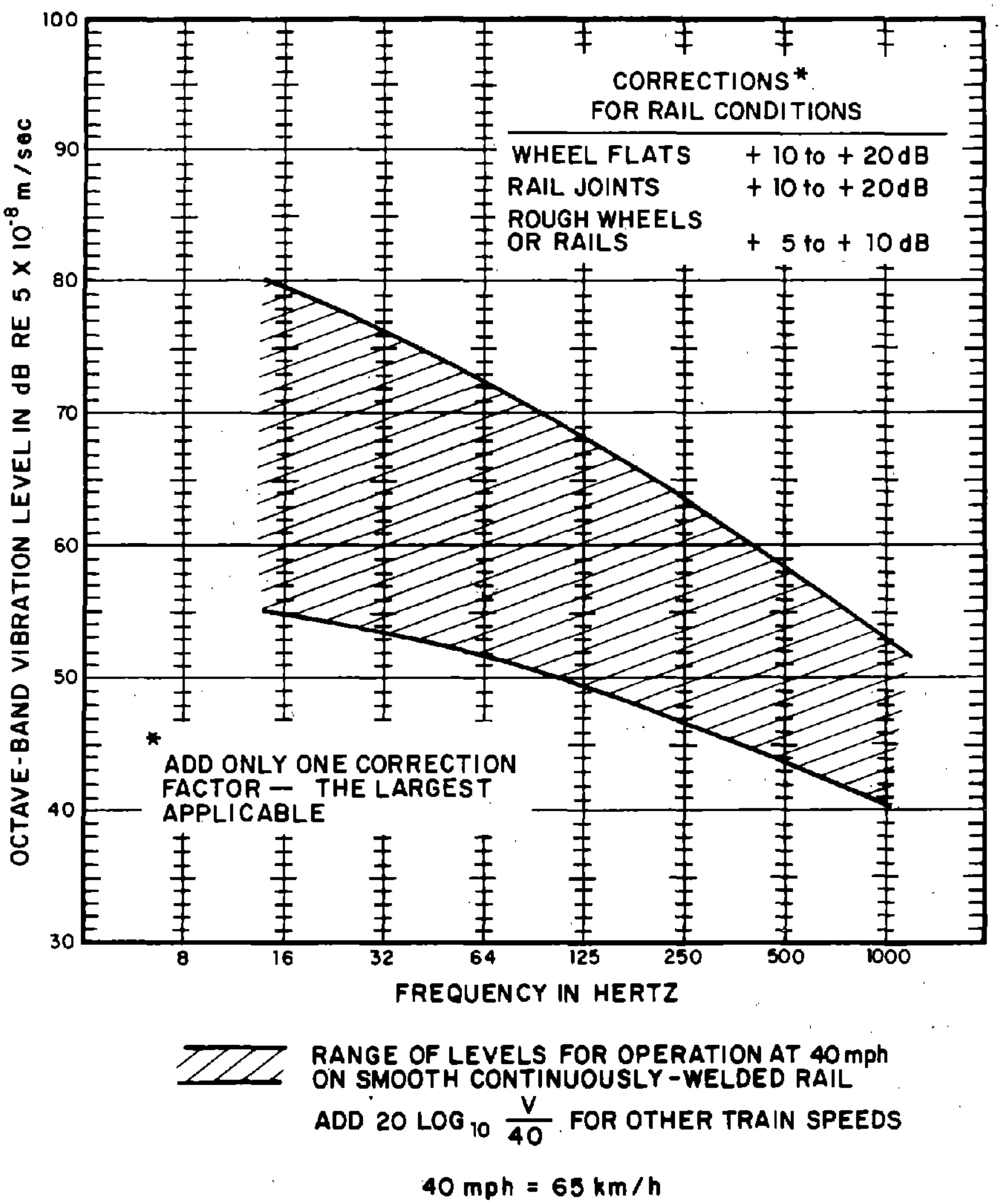


FIG. 4.4 RANGE OF TUNNEL WALL VIBRATION LEVELS

from Toronto, Wilson states that low frequency (below 60 Hz) vibration levels of the rock based tunnel wall are 3 dB lower, mid-frequency (60 to 250 Hz) levels are 7 to 8 dB lower, and high-frequency (above 250 Hz) levels are 10 to 12 dB less [66].

effect of track and tunnel design

The range of levels for tunnel wall vibration is quite large due to variations in the many different parameters of importance. Within the state-of-the-art, however, we cannot reduce the range of values by correlation of the levels with parameter values. But by using data from tests in which only one variable was changed we can infer the dependence of the tunnel wall vibration levels on a number of different parameters.

train speed

As for the case of ground vibration due to train passage on surface track, it is generally agreed that the tunnel wall vibration levels increase 6 dB per doubling of speed, a $20 \, Log_{10} \, V$ dependence, where V is the train speed.

rail and wheel condition

Vibration levels in Fig. 4.4 are for operation on smooth rails and wheels without rail joints or wheel flats. Measurements in Toronto indicate a 10 to 20 dB increase in vibration levels for passage of a train with poor wheel condition [67]. We expect rail joints or wheel flats to increase vibration levels 10 to 20 dB. Wheel or rail roughness will increase levels 5 to 10 dB on jointless rail without wheel flats. On jointed track or when wheel flats occur roughness will not increase levels significantly, unless large corrugations in the rail occur.

axle load

Measurements of tunnel wall vibration with a car empty, 6 tons per axle, and with the same car fully loaded, 12.5 tons per axle, show a 2 to 4 dB increase in vibration level at all frequencies for the higher axle load [68]. These measurements were also made at different speeds and on different track design with the same result.

vehicle suspension

The range of suspension system types used in mass transit vehicles is sufficiently narrow that measurements for different vehicle suspensions show no difference in tunnel wall vibration [69].

resilient wheels

Resilient wheels which are used to reduce wheel squeal also affect the ground vibration. Measurements on the BART test track show that resilient wheels produce up to 10 dB lower ground vibration levels below 100 Hz and 4 or 5 dB higher levels in the 100 to 300 Hz range than the solid steel wheels [61].

rail fastener stiffness

Use of soft rail fasteners has been shown to reduce the level of vibration transmitted to the ground. When the rail is fastened directly to the tunnel floor, fastener stiffness above 20,000 lbs/in per inch of rail (1.33×10^8

Newtons/meter per meter of rail) has no effect on the tunnel wall vibration level since the fastener stiffness is typically on the order of or greater than the tunnel floor stiffness [70]. Below 20,000 lbs/in^2 (1.33 x 10^8 N/m^2) the vibration levels are proportional to 20 Log K, where K is the stiffness. This dependence was originally based on analytical work [71] but has recently been supported by data from NYCTA [72].

From the point of view of vibration the fastener stiffness should be as low as possible. However, it is believed that requirements to maintain ride quality and safety limit the stiffness to be above 3000 lb/in^2 (2×10^7 N/m^2) [73].

Further information on the use of rail fasteners to control vibration is given in Chapter 7.

ballast bed thickness

For tie and ballast track in tunnels, the thickness of the ballast bed in the range 12 to 26 inches (30.5 to 66 cm) under the ties has been found to have no effect on tunnel wall vibration [74].

tunnel wall thickness

The thickness of the tunnel wall is governed by the static loads on the tunnel and, therefore, depends on the depth of the tunnel. For the same track and vehicle conditions thicker tunnel walls vibrate less. Measurements in concrete box tunnels show a 10 to 12 dB decrease in vibration level when the tunnel wall thickness increases from 18 to 28 in (45.7 to 71 cm) [75].

Wilson gives correction factors to be used in predicting ground vibration levels near tunnels [66]. The same factors should be applicable to tunnel wall vibration. From these factors the cast iron liner in a tube tunnel weighing 75 lbs/sq. ft. (366 kg/sq. meter) is expected to have vibration levels 4 dB higher than a concrete liner with a weight of 200 lbs/sq. ft. (997 kg/sq. m.) while a steel liner weighing 50 lbs/sq ft (244 kg/sq.m.) is expected to have levels 6 dB higher. We have little data on which to judge the validity of these correction factors. However, data cited in ref. [75] show that the thickness of the tunnel wall has a much greater effect than indicated by Wilson.

4.4.3 Propagation

Vibration is transmitted away from the tunnel wall in the form of compressional and shear waves in the soil. During propagation the high frequency vibration is attenuated more rapidly than the low frequency vibration. Therefore, the spectrum of the vibration changes with distance. (Compare Figs. 4.2 and 4.4).

Within the state-of-the-art two prediction techniques have been proposed [76,77]. These techniques are reviewed in Appendix D and are compared with a number of measurements. The result of the comparison is that Wilson's prediction of the decrease in ground vibration at the surface with increasing distance [76] can also be used to predict the decrease in vibration level from the tunnel wall to the wall of a building various distances away.

Predicted values for the difference between tunnel wall vibration level and cellar wall vibration level as a function of frequency for different distances between the tunnel and the cellar walls are shown in Fig. 4.5. These values agree within ± 5 dB of most measured values. However, in some cases the measured values show much greater attenuation.

The attenuation of vibration in rock is small and due only to the geometric spreading of the vibration [77]. For distances between 15 and 100 ft (4.5 and 30 meters) away the tunnel can be modeled as a line source so that the vibration levels will decrease 3 dB per doubling of distance. Little decrease in level occurs for distances less than 15 ft (4.5 meters) away from the tunnel in rock.

4.4.4 Induced Noise in Buildings

The low frequency vibration of building walls and floors due to passing subway trains is heard in the buildings as a low rumble. As shown in Appendix E the sound pressure level in the buildings in dB(A) is approximately equal to the velocity vibration level of the walls in dB referenced to 5×10^{-8} m/s. More complex techniques have been proposed but do not appear to be as accurate.

4.4.5 Vibration Control

Effective vibration control requires (1) maintenance of smooth wheel and rail surfaces (2) use of soft resilient rail fasteners with a stiffness near 3000 lbs/in per inch (13,350 Newtons/meter per meter) of rail. Using these two procedures the tunnel wall vibration level should be near the lower limit of levels shown in Fig. 4.3. Further vibration control can be obtained by a number of different procedures. The most effective is to use a resiliently supported track

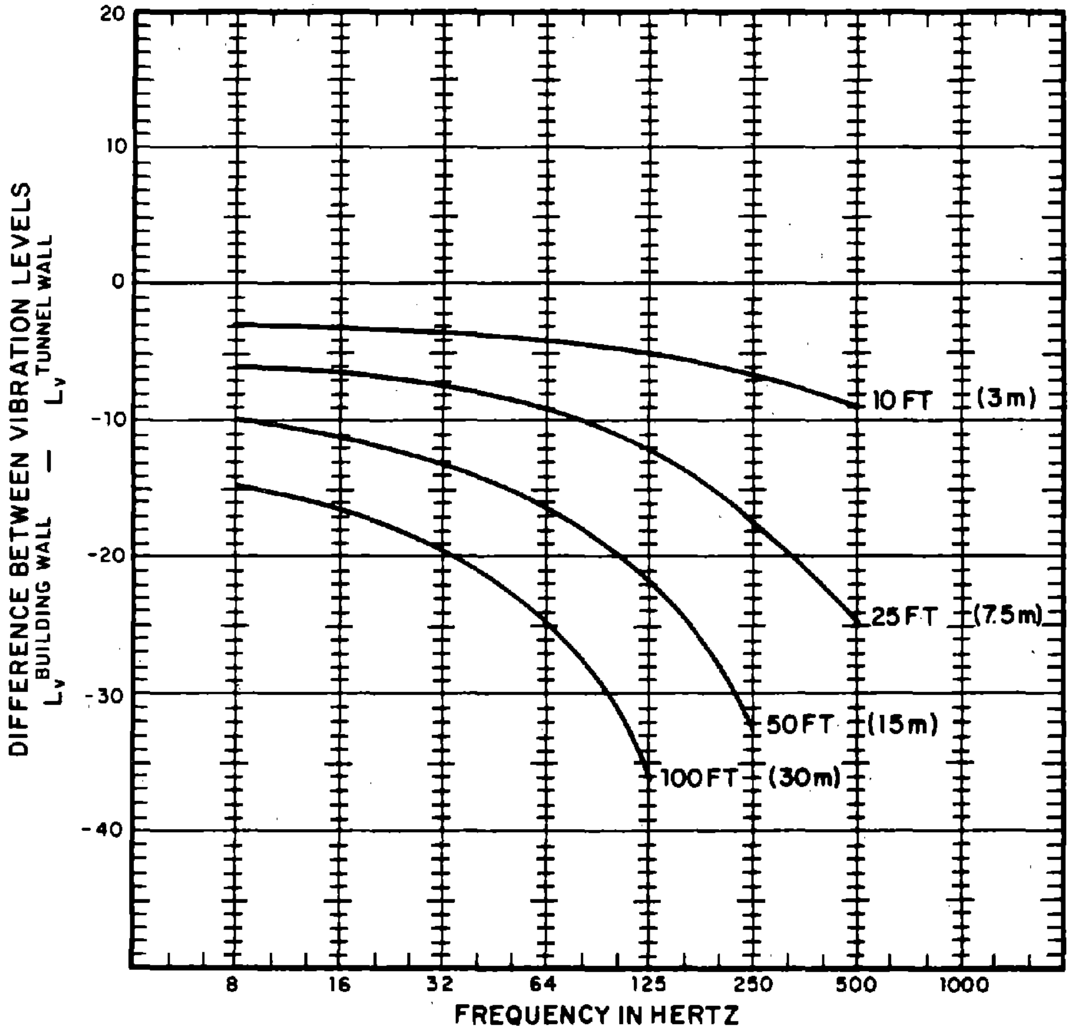


FIG. 4.5 BUILDING WALL VIBRATION RELATIVE TO TUNNEL WALL VIBRATION [63]

slab. With this treatment vibration levels can be reduced 10 to 15 dB below the lower limit of levels shown in Fig. 4.3. Further discussion on the use of floating slabs is given in Section 7.3.

Other noise control treatments that have proven successful in some applications include (1) placing a rubber mat under the ballast bed, $\sim$ 10 dB reduction [78]; (2) placing ribbed rubber pads between the tie and the tunnel floor [79]; and (3) placing ribbed rubber pads between the tie and the rail pad [80]. These techniques are effectively the same as reducing the rail fastener stiffness.

Use of a cork or other soft layer between the tunnel and a rock base has been proposed and may be effective, but appears to be impractical.

Finally, use of pads under the foundation piles of buildings and between the ground and the building walls will also be effective if the pads are softer that the effective stiffness of the building.

Trenches are probably not effective in controlling vibration from subways since they cannot be deep enough.

5. NOISE IN THE CAR

The passengers of rail vehicles are exposed to noise from many sources. However, as in the case of wayside noise, the most significant source is the wheel/rail interaction. Following one path, vibration is transmitted up through the suspension system to interior surfaces of the car which radiate noise. Following a second airborne path, noise radiated from wheels and other vibrating surfaces is transmitted into the car through open windows, leaks in door seals, or through the induced vibration of windows and car body surfaces.

The most important path by which noise is transmitted into a car is largely determined by car design. However, for cars designed within the current state-of-the-art, the second airborne path of transmission is most important. This conclusion is based on the observation that in-car noise increases when a car enters a tunnel. If the rail condition and track design are the same, there is no reason to expect the noise due to vibration transmission through the suspension to increase. On the other hand, noise levels outside the car increase markedly.

Track design can influence the in-car noise to the extent that it influences noise outside the car. For example, in-car noise on concrete slab track is higher than on ballasted track because the noise levels under the car are higher.

5.1 In-Car Noise Criteria

The primary criteria for noise in transit cars is based on speech interference. The noise level should be low enough that a passenger can talk to a neighboring passenger, but not so low that he feels a loss of speech privacy. For example, noise in the car with a Speech Interference Level (PSIL) of 62 dB allows conversation between male speakers 2 ft (0.6m) apart with normal voice effort, see Table 2.1 on page 7. If the in-car noise were reduced 6 dB so PSIL = 56 dB, then conversation could be overheard by someone 4 ft (1.2 m) away.

The recently proposed IRT criteria states that "for ease of communication and passenger comfort, the sound level (in the car) should not exceed 68 dB(A)" [12]. The frequency spectrum of noise in a typical well-designed car on smooth continuously welded rail is shown in Fig. 5.1. For these spectra the A-weighted noise levels are 5 dB above the Speech Interference Level. Therefore, the IRT criteria implies that PSIL should not exceed 63 dB. This is consistent with goals set out in the above discussion. Efforts to reduce in-car noise below the IRT criteria would result in some loss in speech privacy and, therefore, would be undesirable.

New cars with air conditioning, properly sealed doors and double glazed windows tend to meet or come close to meeting the IRT criteria for surface operation at maximum speed on tie and ballast track with smooth continuously welded rail [81]. However, for operation in a tunnel or on rough or jointed rail, the criteria levels are greatly exceeded.

5.2 Noise in Tunnels

As a car enters a tunnel, reflections from the tunnel wall cause the noise level outside the car to increase.

The increase in exterior noise level causes the in-car noise level to increase a similar amount, typically 5 to 10 dB(A). Octave band noise levels for a newly designed car in the open and in a tunnel without noise control are shown in Fig. 5.1 [82]. Very similar increases in octave band noise levels have been observed for New York City IRT line cars [83]. However, noise levels are approximately 15 dB(A) higher than levels shown in Fig. 5 1 for both operation in the open and in a tunnel. The large difference in levels is due to different car designs and different wheel and rail conditions.

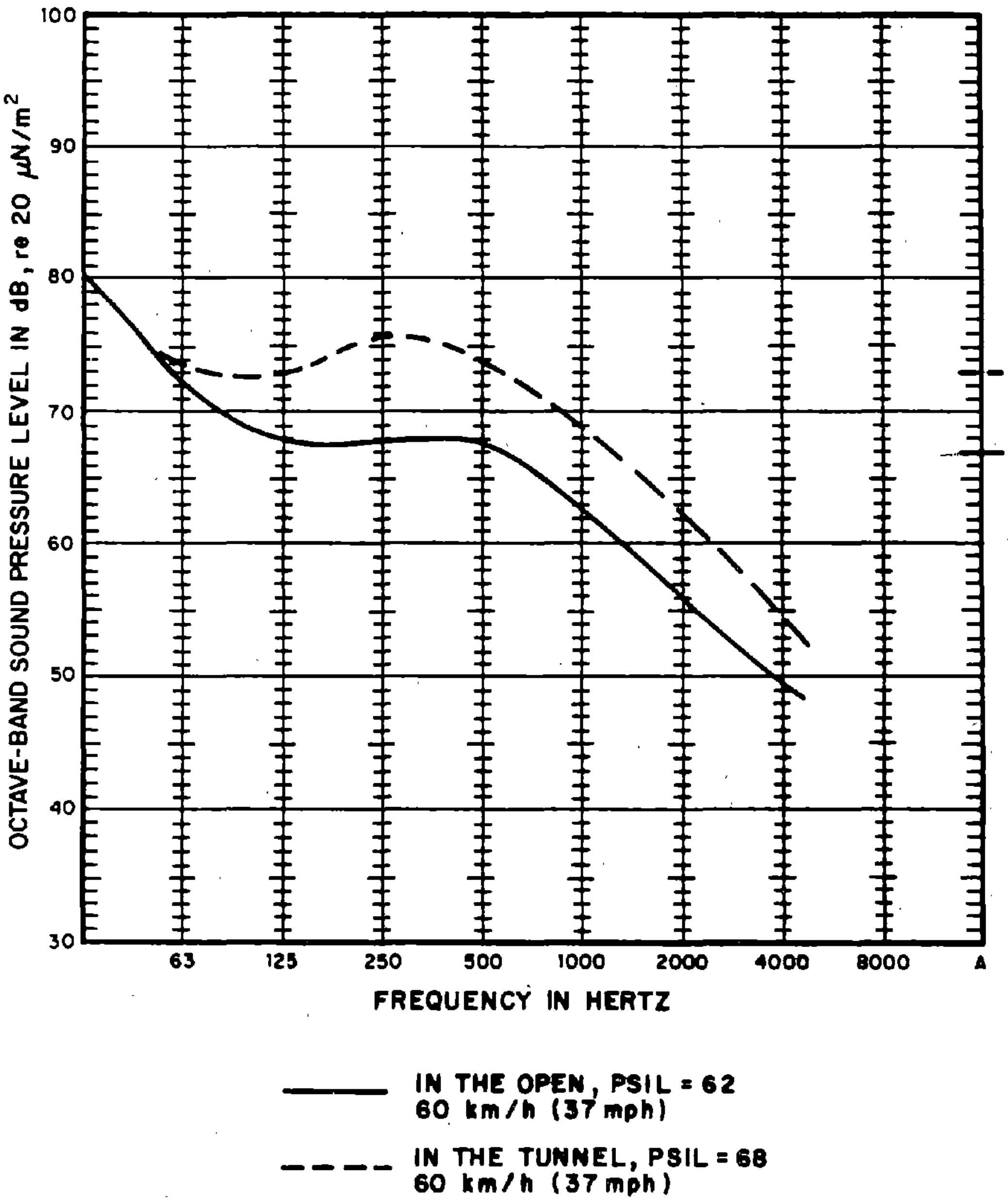
5.3 Effect of Track Design

wheel and rail condition

Poor wheel and rail condition cause the in-car noise to increase. Data taken in New York show that in-car noise levels were reduced 10 dB(A) by maintaining smooth wheel surfaces through periodic grinding procedures [84]. It can be presumed that rail joints also cause an increase in noise levels in the car. We surmise that the general correction factors used in Chapter 3 to account for wheel and rail condition are also valid, at least approximately, for in-car noise.

slab track

When a vehicle passes from a section of ballasted track in the open to a section of concrete slab track without ballast, the noise levels under the car increase 4 to 5 dB(A) [85]. A slightly smaller increase is noted in the in-car noise levels, 3 dB(A). The increase in noise level is due to the elimination of the ballast which prevents the reverberant build-up of noise under the car because of its



REF. 82

FIG. 5.1 NOISE IN A NEW CAR ON TIE AND BALLAST TRACK sound absorbing properties.

The difference between in-car noise levels for ballasted and slab track in a tunnel can be even larger. If the tunnel has no other absorbing surfaces, then removing the ballast will cause the reverberant levels in the tunnel to increase greatly, up to 10 dB(A). Tests were conducted in Paris with a 6 to 8 cm. (2.4 to 3.2 in.) layer of ballast on a concrete trackbed. The resulting in-car noise levels were the same as levels observed on conventional tie/ballast track.

floating slab track

When a train passes from a ballasted trackbed to a floating slab trackbed, the noise levels in the car increase approximately 10 dB(A) [86]. The increase is due in part to the loss of the absorption provided by the ballast. It is also due to the noise radiated by the slab. For further discussion of floating slabs, see Section 7.3.

rail fastener stiffness

In Paris, measurements of in-car noise were taken under similar conditions over ballasted and ballastless track with different rail fasteners [87]. The in-car noise was higher on ballastless track in all cases. Increases of 4 to 11 dB(A) were noted depending on the fastener used. There was no correlation between fastener stiffness and in-car noise levels. Although the softest fastener gave the smallest increase in noise, the next softest fastener resulted in the highest in-car noise level.

track with noise barriers

Noise barriers are sometimes installed along the track to reduce wayside noise levels. The barrier can cause in-car noise to increase by reflecting the wheel/rail noise back onto the sides of the car. The problem is solved by making the surface of the barrier absorbing so no reflection occurs.

5.4 Noise Control

An obvious method of noise control is to improve the car design. For further discussion, see reference 81. A second method is to use improved track design. When slab track is used, the absorptive properties of the ballast can be replaced by the absorptive materials placed on the slab or under the car. In tunnels the walls can be covered with absorbing material to reduce both the in-car noise and the noise in the tunnel. Further discussion of absorptive treatments is given in Section 7.7.

6. NOISE IN STATIONS

The patron of a mass transit system can be exposed to intense levels of noise while he is waiting on the station platform. A time history of the A-weighted noise levels in the station of a typical transit system is shown in Fig. 6.1 [84]. The maximum noise occurs when the train enters and leaves the station. Although brake screech is evident, the most important noise source appears to be the wheel/rail noise in the case shown. In other cases, the screech is more intense and can be dominant.

Since a major part of the station noise is due to wheel/rail noise, much of the preceeding work in this report is applicable. The effects of track design on wayside noise will be much the same as for station noise. However, the propagation path for noise in the station is different. Noise levels shown in Fig. 6.1 are for a station and tunnel with slab track and no absorbing materials. Ballasted track will reduce noise levels in the station due to the absorbing characteristics of the ballast. The treatment of station walls and ceiling with absorbing material also reduces noise levels.

6.1 Effect of Ballast

Fig. 6.2 shows station noise levels measured under similar conditions for trains on ballasted and non-ballasted track [88]. In both cases, the noise was measured in the center of the station platform and no sound absorbing materials other than the ballast were present. The data shows that the ballast reduces peak noise levels approximately 10 dB(A).

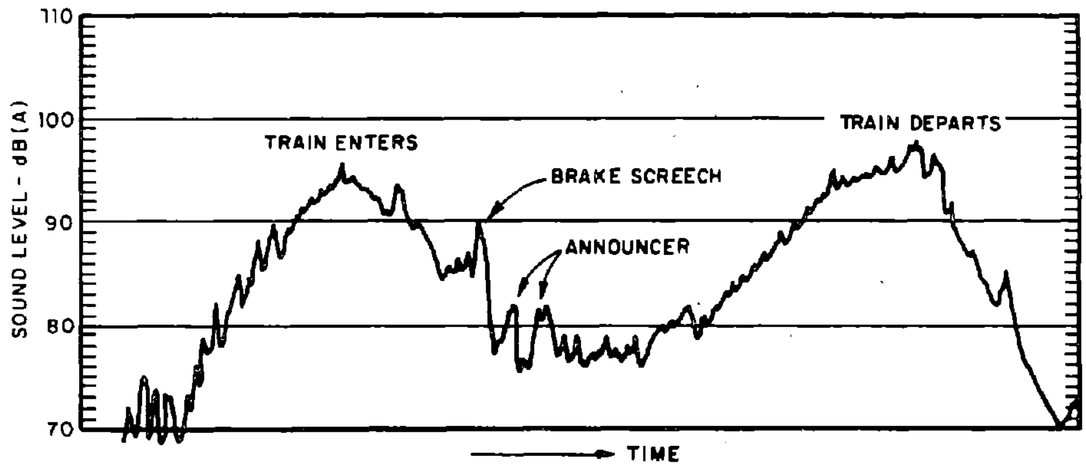
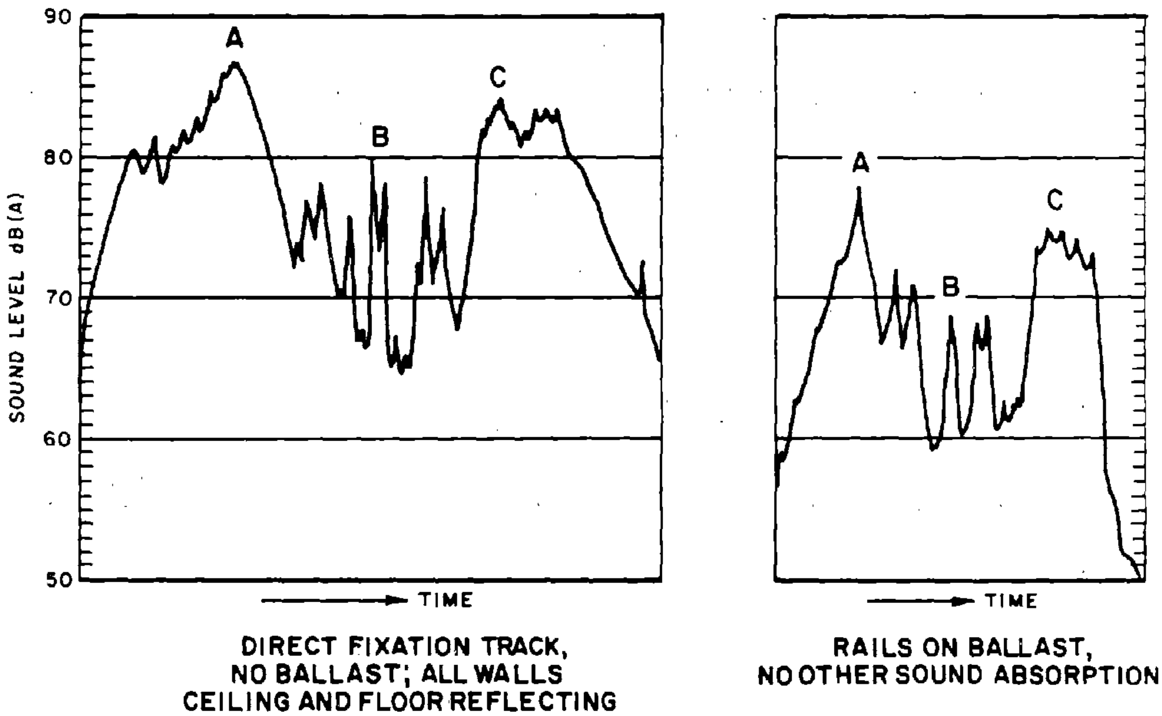


FIG. 6.1 TIME HISTORY OF NOISE IN A STATION



A TRAIN SLOWING

B PUBLIC ADDRESS SYSTEM

C TRAIN STARTS

REF. 88

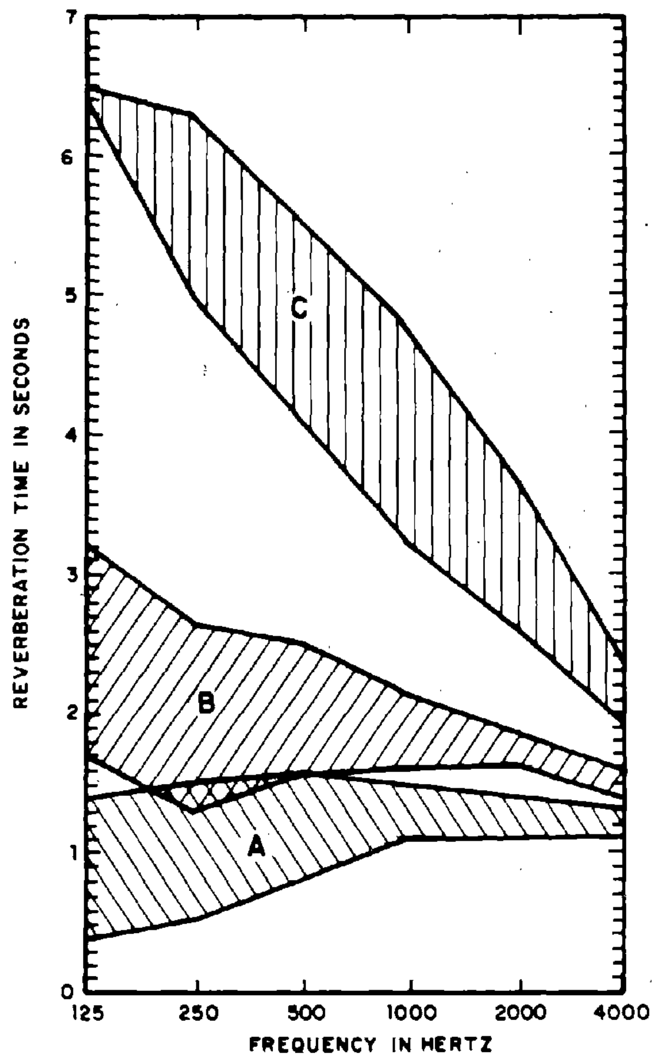
FIG. 6.2 TIME HISTORY OF STATION NOISE— BALLASTED AND NON-BALLASTED TRACK

Because of its sound absorption, ballast also affects the time history of the noise before the train enters the station and after it leaves. Without ballast in the tunnel the sound level was observed to drop 0.75 dB(A) per second after the train had left the tunnel. With ballasted track the level was observed to drop 1.5 dB(A) per second [88]. The increased rate at which the sound level decreases is due to the absorption of the noise in the tunnel.

Finally, ballast shortens the reverberation time of the station. Data are shown in Fig. 6.3. The generally accepted criteria for reverberation time is that it be in the range 1.5 to 2 seconds for the octave bands centered at 500, 1000 and 2000 Hz [12]. A station with sound absorbing walls or ceiling meets this criteria. A station with only ballast for sound absorption comes close to meeting the criteria.

6.2 Noise Control

The greatest reduction in station noise is obtained from sound absorption near the source. This result follows from the fact that the passengers on the station platform are in the direct field of the source. The use of ballasted track is one way to locate sound absorbing materials near the soruce. If ballast is not used, absorbing materials should be placed near the source as indicated in Fig. 6.4. Further discussion on such materials is in Section 7.7.



A. WITH SOUND ABSORBING WALLS OR CEILING (WITH OR WITHOUT BALLAST)

B. BALLAST, WALLS AND CEILING REFLECTING

C. NO BALLAST, ALL REFLECTING

FIG. 6.3 REVERBERATION TIME IN STATIONS

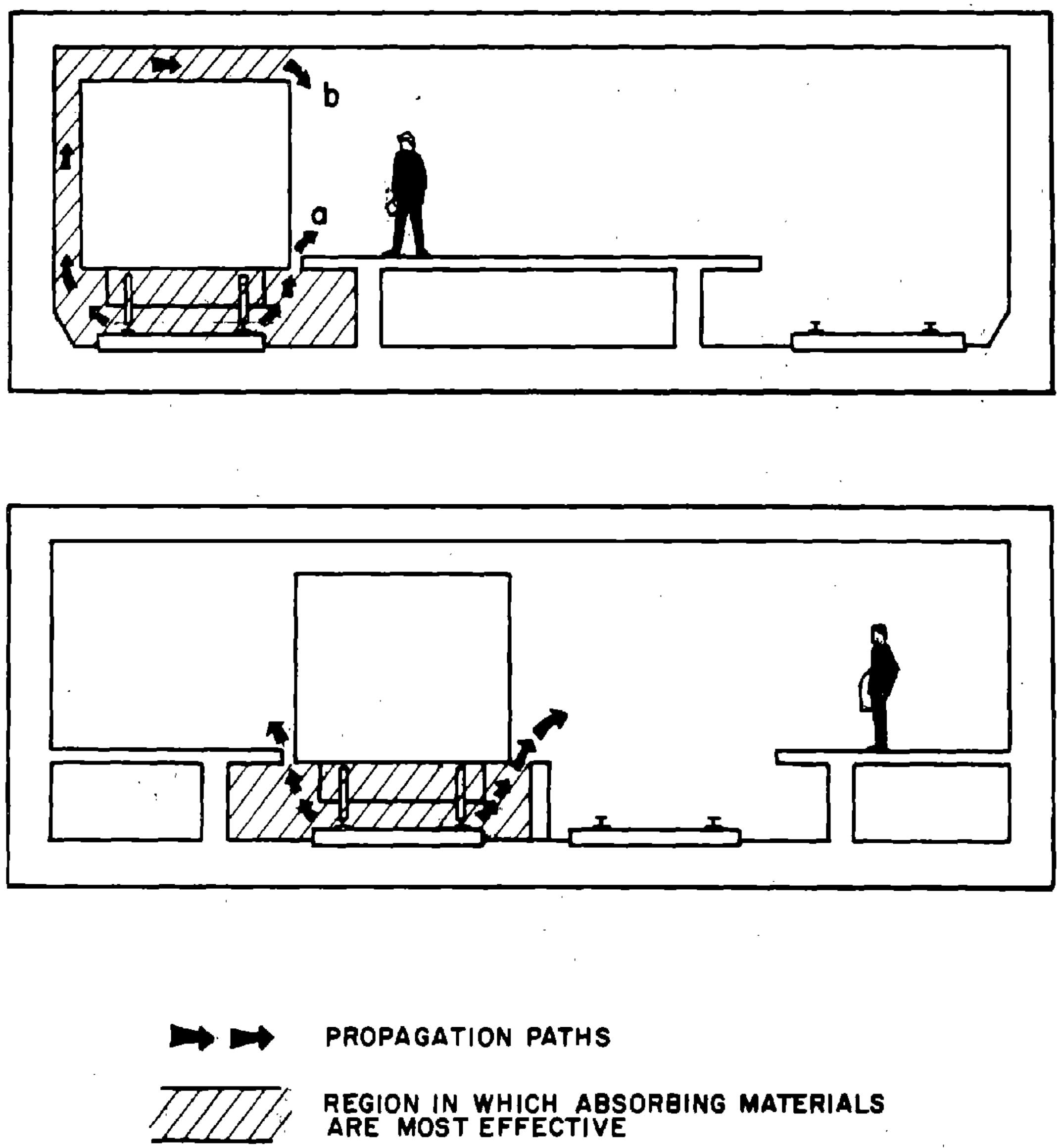


FIG. 6.4 LOCATION OF SOUND ABSORBING MATERIALS IN STATIONS

7. NOISE AND VIBRATION CONTROL TECHNIQUES

In this chapter, we review each of the techniques that has been mentioned in earlier chapters. The possible applications of the technique, design guides and important limitations are discussed. However, costs of the various techniques will not be included in the discussion.

7.1 Resilient Rail Fasteners

The primary purpose of the rail fastener is to maintain track alignment under the large vertical and transverse loads during a train passage. When it is resilient, the rail fastener softens the impact loads and thereby extends the life of the rails and ties or concrete roadbed.

A secondary purpose of resilient rail fasteners can be to reduce the vibration transmitted from the wheel/rail interface to the trackbed. To do this effectively, the fastener should be as soft as possible. Wilson indicates a value of 3000 lbs/in per inch (2×10^7 N/m^2) of rail for the minimum practical value for fastener stiffness [73]. Softer fasteners would further reduce the transmitted vibration. However, they might also bring about track alighment and stability problems.

Rail fastener stiffness has a major effect on the vibration transmitted to the roadbed. Soft resilient fasteners are an effective means for controlling the vibration transmitted to tunnel walls and to the ground. Data taken on tunnel wall vibration suggest that soft resilient fasteners result in up to 20 dB less vibration than nonresilient fasteners without ballast. Conventional tie and ballast track results in wall vibration levels that are approximately 5 dB higher than levels for track with the rails directly supported on the tunnel floor with soft rail fasteners.

Soft resilient rail fasteners can also be effective in reducing noise from elevated structures. However, field studies suggest that in the worst case of steel plate or girder bridges, the rail fasteners cannot be made soft enough to be effective due to track alignment and stability considerations [49].

Rail fastener stiffness has counteracting effects on the noise from passing trains. Soft fasteners allow the rail vibration and noise radiation to increase but reduce somewhat the vibration transmitted to the wheels and trucks. Wilson suggests an optimum value for fastener stiffness of 5000 lbs/in^2 (3.31×10^7 N/m^2) of rail with regard to reducing noise radiation and a 3 to 4 dBA increase in noise for a stiffness of 3000 lbs/in^2 (2×10^7 N/m^2) [89].

The theoretical formulation presented in the following paragraphs does not support this conclusion, however. Therefore, until further studies are completed we cannot confidently predict the effect of rail fastener stiffness on wayside noise.

theoretical formulation

A theoretical study of the use of rail fasteners in reducing vibration has been carried out by Bender [71]. In this study a rough wheel is assumed to roll over a rough rail with contact maintained between the wheel and the rail so that the wheel and rail must move relative to one another.

The extent of the relative motion is governed by the wheel and rail roughness.

The results of the study are in terms of the driving point impedances of the wheel and the rail. The point impedance of the rail, z_r, gives the response amplitude and phase at the driving point relative to the excitation force amplitude and phase. For example, if the rail is excited by a vertical downward force, f(t) where

$$f(t) = F\ e^{i\omega t}; \qquad (7\text{-}1)$$

$i = \sqrt{-1}$, F is a complex amplitude with a real and imaginary part, ω is radian frequency, and t is time, the rail velocity at the driving point, v(t), is given by

$$V(t) = V\ e^{i\omega t}; \qquad (7\text{-}2)$$

where

$$V = \frac{F}{z_r} \quad . \qquad (7\text{-}3)$$

The rail impedance is, in general, a complex number with a real and imaginary part. A similar formulation can be made for the wheel impedance, z_w. Then, following Bender's approach we compare the vibration transmitted to the track-bed for two different fasteners by comparing the root mean square forces, f_{rms}, transmitted through the fastener to the roadbed. The result is:

$$\frac{f^{(2)}_{rms}}{f^{(1)}_{rms}} = \frac{K^{(2)}}{K^{(1)}} \quad \frac{1 + z_r^{(1)}/z_w}{1 + z_r^{(2)}/z_w} \qquad (7\text{-}4)$$

where (1) signifies results for a fastener with stiffness $K^{(1)}$, (2) signifies results for stiffnes $K^{(2)}$, z_r is the rail impedance, z_w is the wheel impedance. Both rail and wheel impedances are frequency dependent.

Continuously welded rail can be modeled as a beam on an elastic foundation to calculate the rail impedance. The calculation gives

$$z_r = \frac{2EI}{\omega} (1 + i)\, K_p^3 \text{ for } \omega > \omega_r, \tag{7-5}$$

and

$$z_r = \frac{2\sqrt{2}\, EI}{\omega}\, i\, K_p^3 \text{ for } \omega < \omega_r, \tag{7-6}$$

where

$$\omega_r^2 = \frac{K}{\rho_\ell} \tag{7-7}$$

and

$$K_p^4 = \frac{K}{EI} \left| \frac{\omega^2}{\omega_r^2} - 1 \right|, \tag{7-8}$$

$||$ signifies "the absolute value of", EI is the bending stiffness of the rail, ρ_ℓ is the mass per unit length of the rail, and K is the fastener spring constant per unit length of the rail.

In the frequency range between 20 Hz and the first resonance frequency of the wheel ($\sim$ 350 to 400 Hz) the wheel impedance is simply

$$z_w = i \omega M_w \tag{7-9}$$

where M_w is the mass of the wheel. A plot of the magnitude of the rail and wheel impedances for typical parameter values is shown in Fig. 7.1. Two frequency ranges can be identified.

At low frequencies, the rail impedance is greater than the wheel impedance. From Eq. 7-4 we find the root mean force to be proportional to

$$f_{rms} \propto K^{1/4} \qquad \text{low frequencies} \tag{7-10}$$

so that the vibration levels of the tunnel wall in this low frequency range are expected to increase with 5 $\log_{10}$ K. As shown in Fig. 7.1, the frequencies at which this result is expected are in the range 20 to 30 Hz for a soft fastener and 1000 lb (453 Kg) wheel mass.

At high frequencies the wheel impedance is greater than the rail impedance so that Eq. 7-4 gives

$$f_{rms} \propto K \qquad \text{high frequencies} \tag{7-11}$$

and the vibration levels of the tunnel wall are proportional to 20 $\log_{10}$K. The general validity of this result has been supported by field studies in New York [72].

The above result is limited to frequencies below approximately 350 to 400 Hz. Therefore, it is not applicable to A-weighted noise levels which are dominated by the higher frequencies. However, the general approach is still applicable. In particular, Eq. 7-5 for the rail

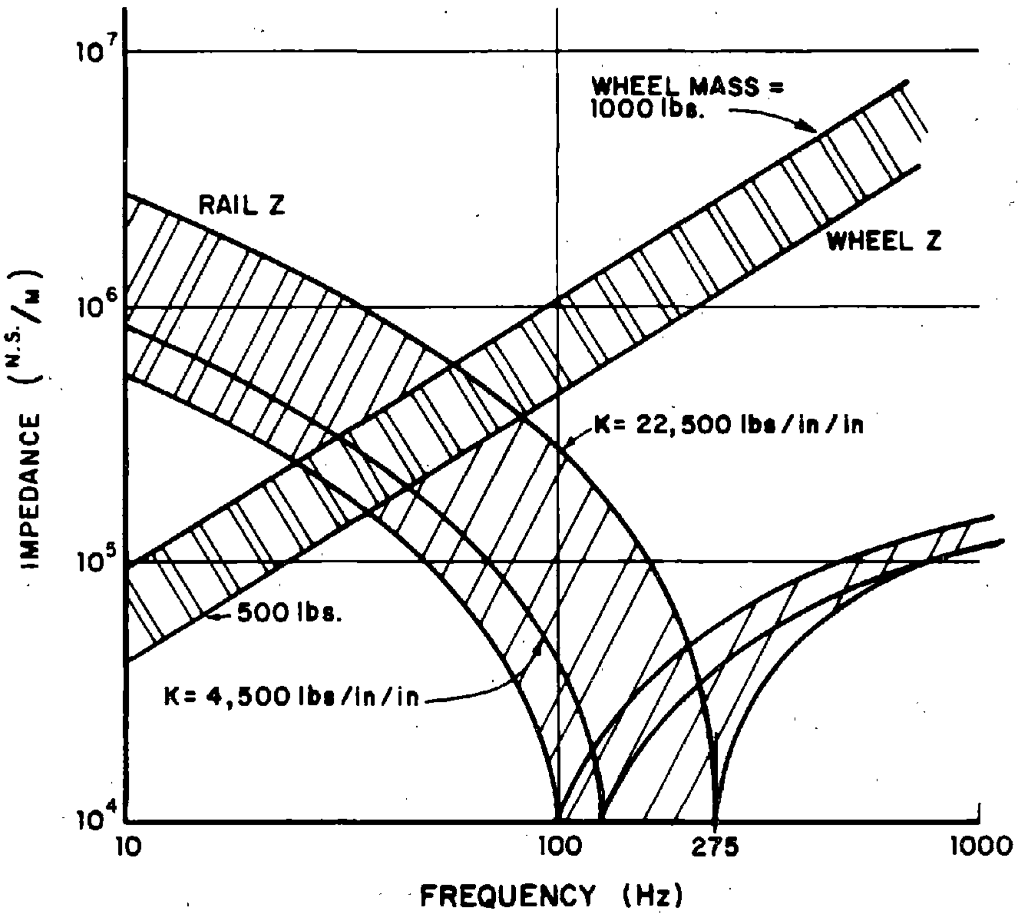


FIG. 7.1 CALCULATED WHEEL AND RAIL IMPEDANCES FOR TYPICAL POINT FORCE EXCITATION [53]

impedance is valid over a wide range of frequencies. This equation shows that the rail impedance does not depend on fastener stiffness for frequencies above a frequency ω_r, where

$$\omega_r^2 = \frac{K}{\rho_\ell} \tag{7-12}$$

For a soft fastener with a stiffness of 3000 lbs/in/in and typical rail with weight 100 lbs per yard, this frequency is approximately 100 Hz. Above this frequency, the fastener stiffness has no effect on the rail impedance and therefore should not affect the level of vibration at the wheel/rail interface. For even a very stiff fastener, 30,000 lbs/in/in, the stiffness should not affect the vibration above 300 Hz.

The theoretical model presented above leads to the conclusion that the rail fastener stiffness does not affect high frequency vibration levels and, therefore, should not affect the A-weighted noise levels. On the other hand, Wilson [89] has concluded that A-weighted noise levels do increase somewhat for soft fasteners. He bases this conclusion on his practical experience and data that he has obtained. We are unable to resolve this difference at present.

practical application

Most resilient rail fasteners are designed using a rubber, neoprene, or cork pad between two steel plates. A typical design is shown in Fig. 7.2. The resilience of these fasteners is controlled by the spring constant of the pad, which in turn depends on the elastic properties of the material, the shape of the pad, the static load, and frequency. Calculation of the pad stiffness for a given design may be difficult since the fastener load depends on its stiffness and at the same time the fastener stiffness can depend on its load.

Typical load deflection curves for a number of rail fasteners are shown in Fig. 7.3. These curves show a pronounced nonlinearity for some designs while others are linear.

An additional factor that must be taken into account is the frequency dependence of the fastener stiffness. French data show values for dynamic stiffness that are from 1.5 to 2.5 times higher than values for static stiffness depending on fastener design [87].

The complex dependence of pad stiffness on design parameters make both static and dynamic tests of a proposed rail fastener necessary. Static tests should be run to determine load deflection curves and the static stiffness under the design load. Dynamic tests should be run to determine the increase in stiffness with frequency and also the fastener damping. One such test involves mounting a known mass on the rail fastener, exciting the mass with a pure tone force, and varying the frequency until a peak in response of the mass is found. The dynamic stiffness at that frequency is given by

$$K = M\,4\pi^2\,f^2 \tag{7-13}$$

where M is the mass, K is the dynamic spring constant and f is frequency. The dynamic stiffness at different frequencies can be found by varying the mass.

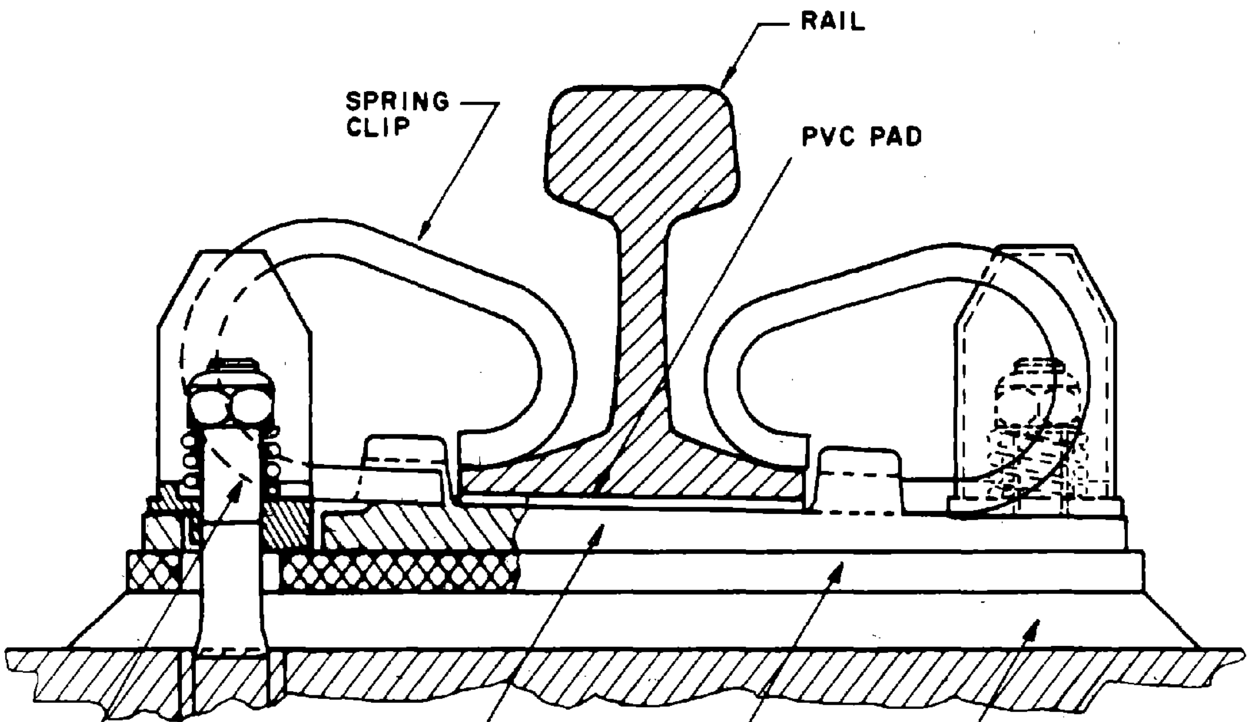


FIG. 7.2 TYPICAL RESILIENT FASTENER DESIGN

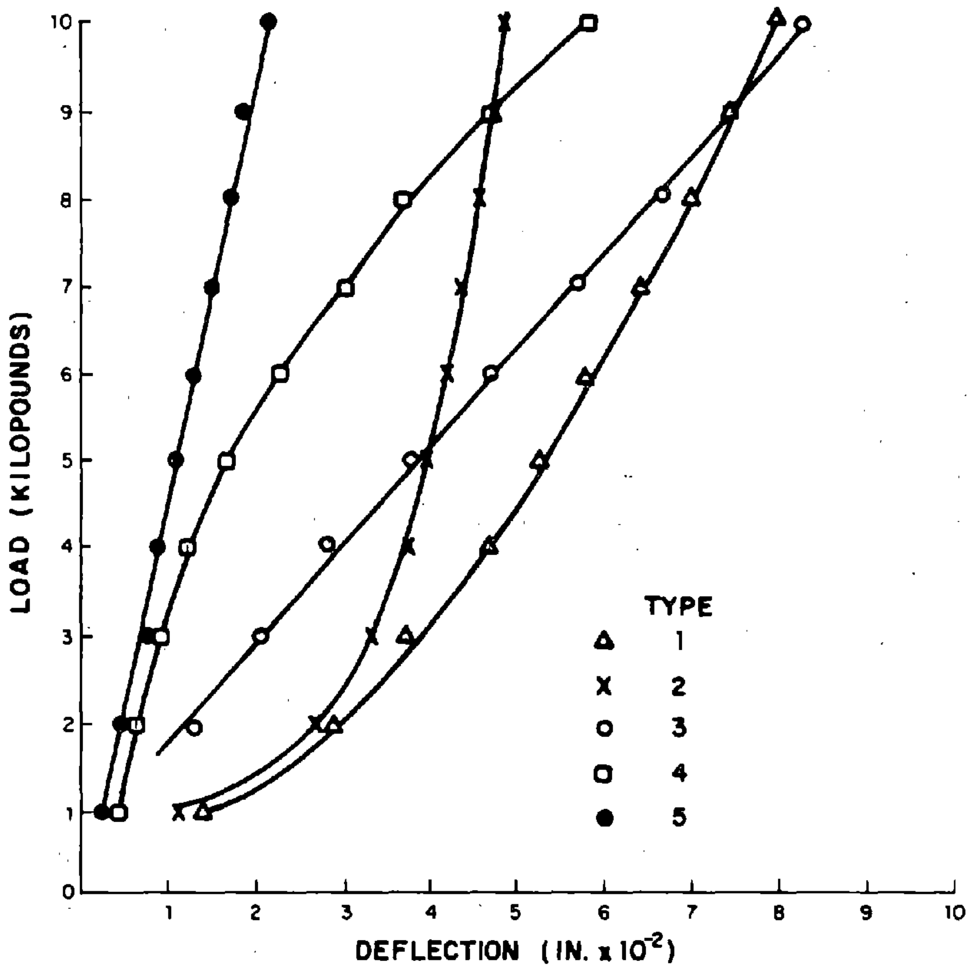


FIG. 7.3 LOAD DEFLECTION CURVES FOR TYPICAL RAIL FASTENERS [53]

The damping is found by varying the frequency to find the frequencies above and below the resonance frequency at which the response is 3 dB below its peak level. The damping loss factor, η [90], is given by

$$\eta = \frac{\Delta f}{f} \qquad (7\text{-}14)$$

where Δf is the difference between frequencies at which the response is 3 dB below its maximum level.

Determination of the dynamic stiffness under various static loads at a constant frequency is difficult. A valid approximate technique is to assume that the percentage increase in dynamic stiffness over static stiffness is valid for all loads.

A number of rail fastener designs are being marketed. However, one should not hesitate to consider with new designs. These may be better suited to a particular purpose and cost less. An example of a "do-it-yourself" design is in reference [72].

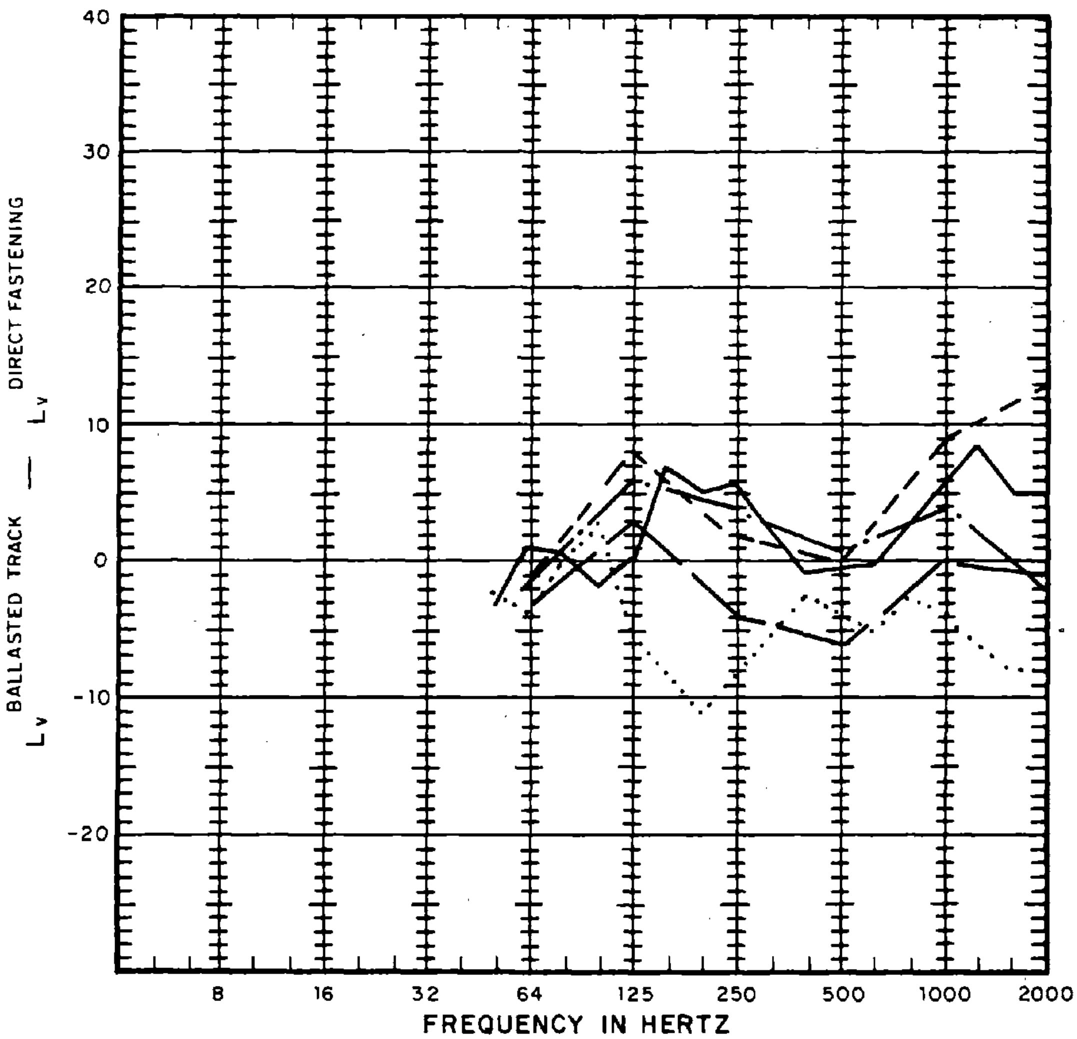
field data

Numerous measurements of tunnel wall vibration for different rail fastener designs exist. We cannot compare these measurements directly because of differences in tunnel wall thickness, vehicle speed, rail roughness and other design parameters. Therefore, we limit our presentation to field studies in which measurements for tie and ballast track were also taken. As discussed in Chapter 4, the ballast bed thickness has no large effect on vibration levels within the range 12 to 26 inches (0.30 to 0.65 meters) of ballast under the rail. Thus, the measurements for tie and ballast track can be used as a basis for comparison. Figure 7.4 shows tunnel wall vibration levels in different frequency bands for a number of different fasteners. Also listed in this Figure are reported data on static fastener stiffness. In the case of the French data, both static and dynamic stiffnesses were found for each fastener and are given in the fastener stiffness were estimated.

We have not shown data for Toronto type fasteners which have a stiffness near 4000 lbs/in^2 (2.67×10^7 N/m^2) for 24 in. (61 cm) fastener spacing. One of the fasteners for which data is given in Fig. 7.4 is very similar to the Toronto fastener and has a stiffness of 3790 lbs/in^2. Therefore, we assume the performance of the two fasteners would be comparable.

Based on the data in Fig. 7.4, the most effective fastener is the RS-STEDEF design. This fastener is also somewhat different from the Toronto type fastener in that resilient pads are placed both between the rail and the tie and between the tie and the tunnel floor. However, the pad between the rail and the tie is very stiff. We surmise that the STEDEF fastener gives the best performance because it is the softest fastener tested.

It is interesting to note that of the three direct rail fasteners tested by the French [87], the STEDEF fastener results in the lowest noise levels in the tunnel. At first glance this result contradicts Wilson's suggestion that soft rail fasteners increase the wayside noise. However, there is no contradiction, since the STEDEF design increases the effective impedance of the rail over a broad range of frequencies by maintaining a very stiff connection between the rails and ties. Further investigation of this type of fastener is called for.



STIFFNESS (LB/IN/IN)

	DYNAMIC	STATIC	FASTENER
———— (solid)		~ 3,500	CLOUTH
— — — (dashed)	4,000	2,900	STEDEF
········· (dotted)		~15,000	BK
—·— (dash-dot)		3,800	RATP
— — (long dash)	20,000	8,500	SNCF

[REF. 87, 123]

FIG. 7.4 TUNNEL WALL VIBRATION LEVELS FOR DIFFERENT RAIL FASTENERS COMPARED WITH LEVELS FOR TIE AND BALLAST TRACK

7.2 Ballast

Ballast is normally not thought of as a noise and vibration control material. However, it possesses many properties that serve to reduce noise and vibration levels.

general uses

When used on elevated steel structures, ballast reduces the structural vibration and radiated noise levels by (1) greatly increasing the weight of the structure without increasing its stiffness*, (2) increasing the damping (conversion of vibratory energy to heat), and (3) providing a resilient layer between the rails and the elevated structure.

When used in tunnels, ballast reduces tunnel wall vibration and tunnel noise. The mechanisms by which wall vibration is reduced are the same as above, although their relative importance is no doubt changed. Tunnel noise is reduced because the ballast provides an acoustically absorbing surface under the car.

When used on surface track, ballast reduces noise levels under the car by providing an absorbing surface. The effect on wayside noise is small. However, in-car noise levels may be noticeably changed.

The effect of ballast in reducing ground vibration levels near surface track has not been established.

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*This effect is certainly not an advantage to the structural designer who must cope with the problem of supporting the weight.

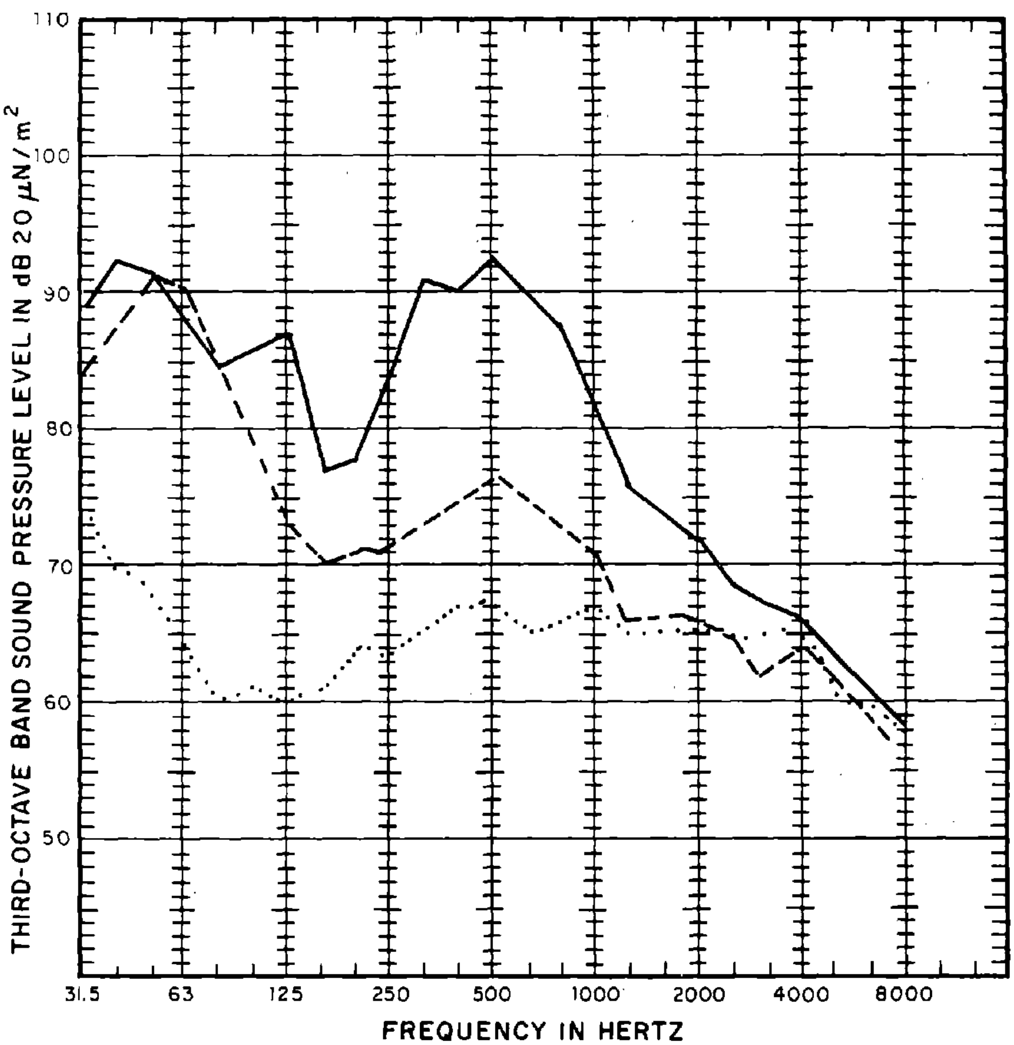
elevated structure noise reduction

Use of ballasted track has been shown to be an effective means of noise control for steel plate and girder bridges. The only other means of noise control on these types of structures that have proven effective are use of bridge enclosures, described in Section 7.5, and structural damping, described in Section 7.6.

Data showing the effects of ballast on wayside noise near a steel plate bridge are shown in Fig. 7.5 [92]. In the initial configuration the rails were directly fastened to the bridge plating with resilient rail fasteners. The resiliencewas provided by a 5/8 in (1.6 cm) thick rubber pad. The rail fastener stiffness is not given, but we estimate it to be in the range 4000 to 5000 lbs/in per inch of track. The wayside noise level for the initial configuration was 95 dB(A) at a distance of 25 ft (7.5 meters) from the track, while the level for the same vehicle at the same speed on at-grade tie and ballast was measured to be 76 dB(A).

Track on the bridge was then relaid using wooden ties on a 24 cm (9.5 inch) ballast bed. The wayside noise was reduced to 82 dB(A). However, the weight of the bridge was increased from 1.9 metric tons per meter* to 4.9 t/m. As shown in Fig. 7.5, the ballast is very effective in reducing the noise at frequencies which are most important to the A-weighted levels. The low frequency noise is not significantly affected. Therefore, although the noise levels for the ballasted bridge will be less annoying, the rumbling noise from the bridge will continue to be very noticeable. The overall level (no frequency weighting

*A metric ton per meter is approximately equal to one ton per yard.



OVERALL dB(c)	dB (A)		
101	95	————	DIRECT RAIL FASTENING WITH RESILIENT FASTENERS ON BRIDGE
96	82	— — —	BALLASTED TRACK ON BRIDGE
81	76	…………	AT GRADE TRACK

OPERATION OF LOCOMOTIVE ON CONTINUOUSLY WELDED RAIL AT 80 km/h (50 mph)

FIG. 7.5 WAYSIDE NOISE NEAR A STEEL PLATE BRIDGE [39] on C-scale on a sound level meter) for operation on the bridge with ballasted track is still 15 dB above levels on at-grade track.

Vibration measurements taken before and after the re-laying of the track on ballast show that the rail vibration decreases slightly, 1 to 4 dB, with the use of ballast and that the steel plate and steel girder vibration levels decrease approximately 10 dB, with the largest decreases occurring at high frequencies. As would be expected, the decrease in vibration velocity level is similar to the decrease in wayside noise except at high frequencies above 2000 Hz where the decrease in vibration level is much greater. The noise radiation from the elevated structure probably does not significantly contribute to the wayside noise at these high frequencies.

<u>tunnel wall vibration reduction</u>

When used to support the track in a tunnel, the ballast provides effective control of the tunnel wall vibration levels. Data presented earlier in Fig. 7.4 show the tunnel wall vibration for a number of direct rail fasteners without ballast compared to the vibration with tie and ballast track. By and large the ballasted track performance is comparable to that of the better direct rail fasteners. However, because ballasted track requires larger tunnels, it should not necessarily be selected over one of the better direct rail fastening systems.

Measurements of tunnel wall vibration with ballasted track show that the ballast bed depth has no effect on vibration, at least in the range of 12 to 26 in (30 to 66 cm) deep.

It should be mentioned that in some cases the ties are only partially supported by the ballast with the remaining support from concrete inverts on the tunnel floor. Tunnel wall vibrations for this type of track will be higher than for conventional tie and ballast track.

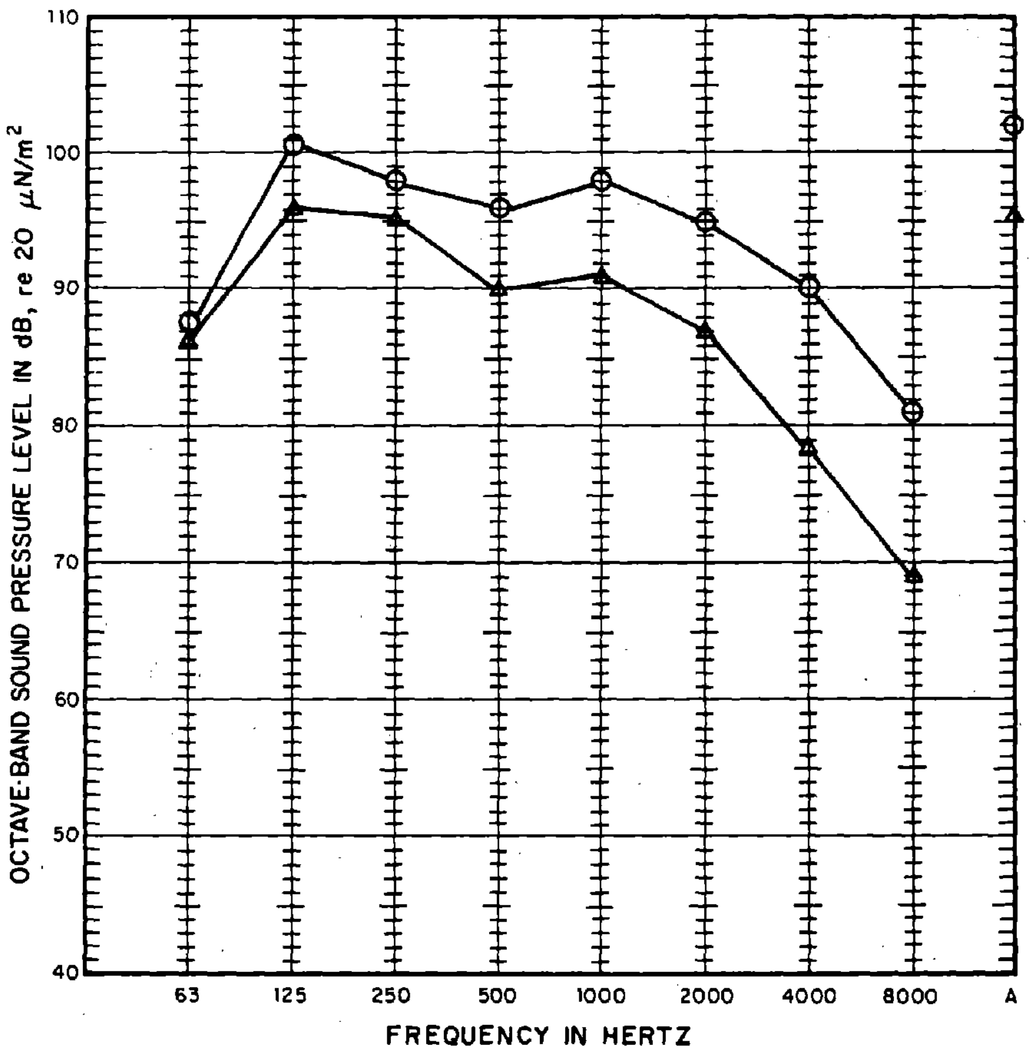
tunnel noise reduction

When a subway train passes from a ballasted track section to a section with direct rail fastening, there is an increase in noise. This increase is due to the loss of acoustic absorption provided by the ballast. Data in Fig. 7-6 show tunnel noise levels with and without ballast [87]. In both cases the rails were mounted to the tunnel floor by the STEDEF fastening system. The ballast was incorporated into the design for the sole purpose of reducing tunnel and in-car noise.

The absorptive properties of ballast depend on the interstices between the rock being open. When dirt and oil contaminate the ballast, its absorptive properties are reduced. For this reason, it may be more economical to use other special purpose absorptive treatments in the tunnel that will not be adversely affected by the environment.

7.3. Resiliently Mounted (Floating) Trackbed Slabs

Resiliently mounted trackbed slabs have been used in a number of cases to reduce the level of vibration transmitted to the tunnel wall and to adjacent buildings. The reduction in level, relative to levels achieved using soft resilient rail fasteners mounted directly on the tunnel floor is in the range 10 to 20 dB for a well-designed slab.



DIRECT RAIL FASTENING ON CONCRETE INVERT

Δ WITH 6 to 8 cm (2.4 to 3.1 in.) THICK BALLAST COVERING

O WITHOUT BALLAST

TRAIN AT 80 km/h (50 mph)

REF. 87

FIG. 7.6 NOISE IN TUNNELS WITH AND WITHOUT BALLAST

The resonant frequency of the slab on its elastic mounts and the damping appear to be the most important design parameters. Good performance requires a low resonant frequency and high damping. In practical applications, resonance frequencies are in the range 5 to 20 Hz. Values for damping are not commonly given.

theory

A very simple theory is used as the basis for floating slab design [93]. In this theory, the propagation of vibration down the track is ignored and the slab is modeled as a simple mass -- spring system, Fig. 7.7. For this simple model the ratio of the mean square force on the foundation to the mean square force on the mass is given by

$$\frac{F^2_{foundation}}{F^2_{mass}} = \frac{1}{[1 - (\frac{\omega}{\omega_0})^2]^2 + \eta^2} \qquad (7\text{-}15)$$

where $F_{foundation}$ is the rms force on the foundation, F_{mass} is the rms force on the mass, ω is radian frequency, η is the damping loss factor, and ω_o is the resonant frequency of the mass on the spring.

Eq. 7-15 predicts that the floating slab has no effect on the forces transmitted to the tunnel floor below the resonant frequency and therefore, should not affect the tunnel wall vibration or the vibration transmitted to the ground. This prediction is supported by tests conducted in an evaluation of the floating slab to be used on the new WMATA system [94]. Results are shown in Fig. 7.8.

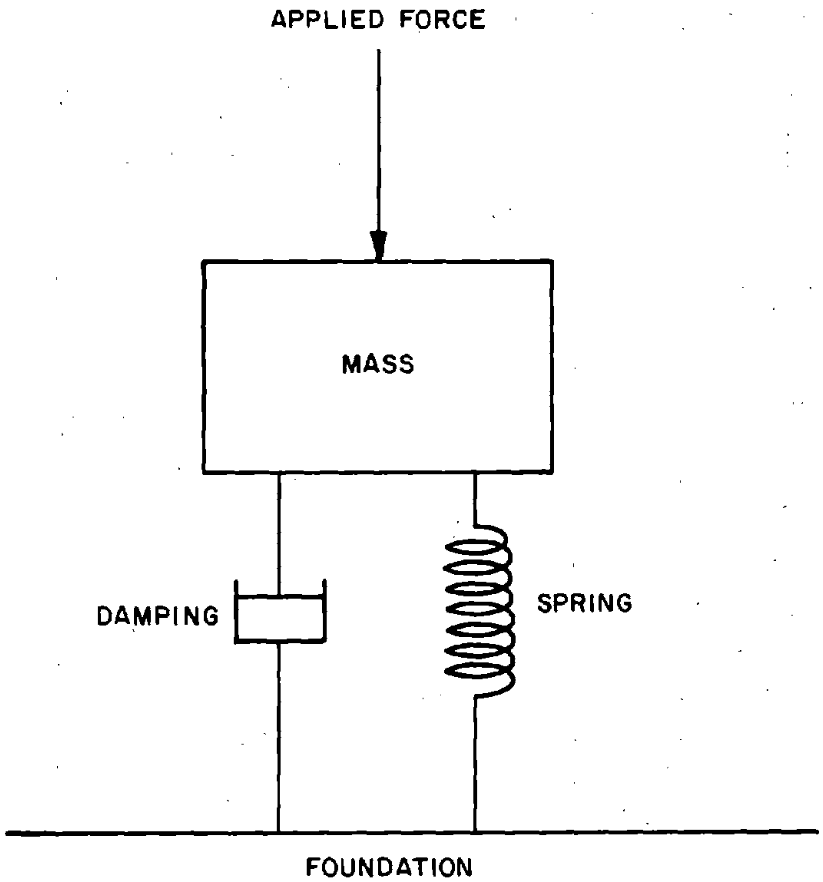
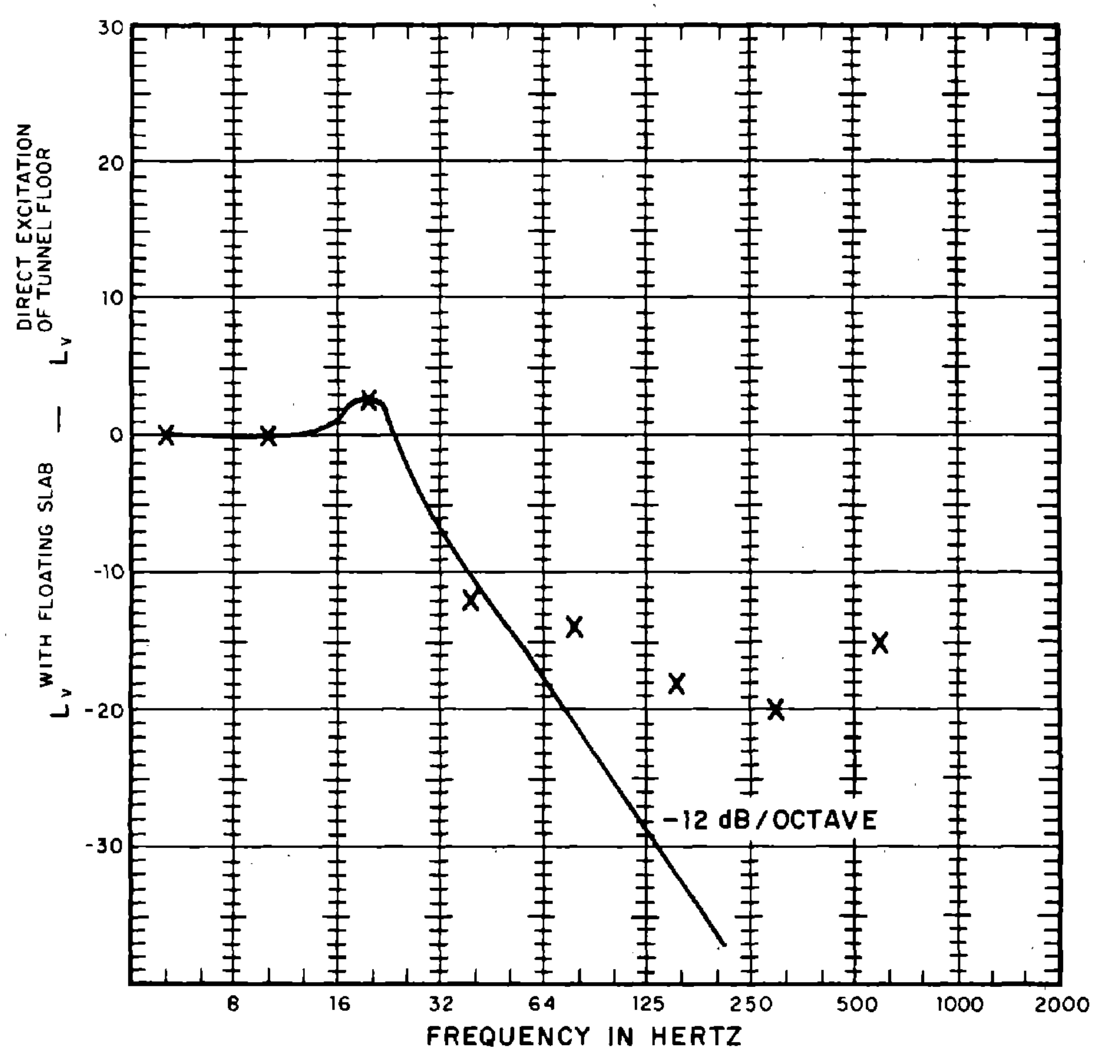


FIG 7.7 SIMPLE MODEL FOR FLOATING SLAB PERFORMANCE



X DIFFERENCE BETWEEN VIBRATION LEVELS OF THE INVERT FOR 1) DIRECT EXCITATION OF THE TUNNEL FLOOR WITH NO SLAB AND 2) EXCITATION OF THE FLOATING SLAB

—— SIMPLE THEORETICAL PREDICTION

FIG. 7.8 WMATA FLOATING SLAB TEST DATA [94]

At the resonant frequency the forces on the foundation are greater than those on the mass when the damping loss factor is less than one. Again, the prediction is supported by the WMATA data, which shows an increase in tunnel vibration and ground vibration at the resonant frequency.

Above the resonant frequency the force on the foundation should decrease with increasing frequency at a rate of 12 dB per octave. The WMATA data support the prediction only for one octave above the resonant frequency. At higher frequencies the vibration levels decrease more slowly than is predicted by the simple theory.

The deviations between data and prediction are due to two effects:

(1) the occurrence of wave propagation effects and resonant vibrations in the slab, and
(2) non-springlike behavior of the slab mounts at high frequencies.

A more precise analytical study of floating slabs was carried out by Bender to predict the noise radiated by the slab [95]. Bender's study is therefore concerned with the high frequency vibration of the slab and does not result in design criteria based on reducing ground vibrations

In conclusion, the existing theoretical analyses do not accurately predict floating slab performance.

field data

A number of urban rail systems in Europe have installed floating slab trackbeds, [96,97]. Measurements of tunnel wall vibration have been taken for many of these installations. However, the data cannot be compared directly because of differences in tunnel design, vehicle condition, etc. As a basis of comparison we use the difference between the tunnel wall vibration levels in the same section of tunnel with conventional tie and ballast on one track and with floating slab on the other track. Following this procedure, we compare data for the three different designs shown in Fig. 7.9. The data comparison is shown in Fig. 7.10 along with data for the "best" (least vibration) direct rail fastener.

The data show that floating slabs can provide a significant reduction in tunnel vibration -- a reduction that cannot be achieved using the best rail fasteners.

An interesting experiment was carried out on the Cologne floating slab [97]. The design of this slab is such that it can be lowered to the point where it rests directly on the tunnel floor. Relative tunnel wall vibration levels for the slab resting on the floor and for the slab floating are shown in Fig. 7.11. In the frequency range 25 to 40 Hz the vibration levels with the slab floating are below those with the slab on the tunnel floor. This is also the case at frequencies above 200 Hz. However, in the important frequency range from 40 to 200 Hz the vibration levels with the slab floating are not significantly different from levels when the slab is resting on the tunnel floor. A possible explanation for this is that the impedance of the tunnel floor is less than

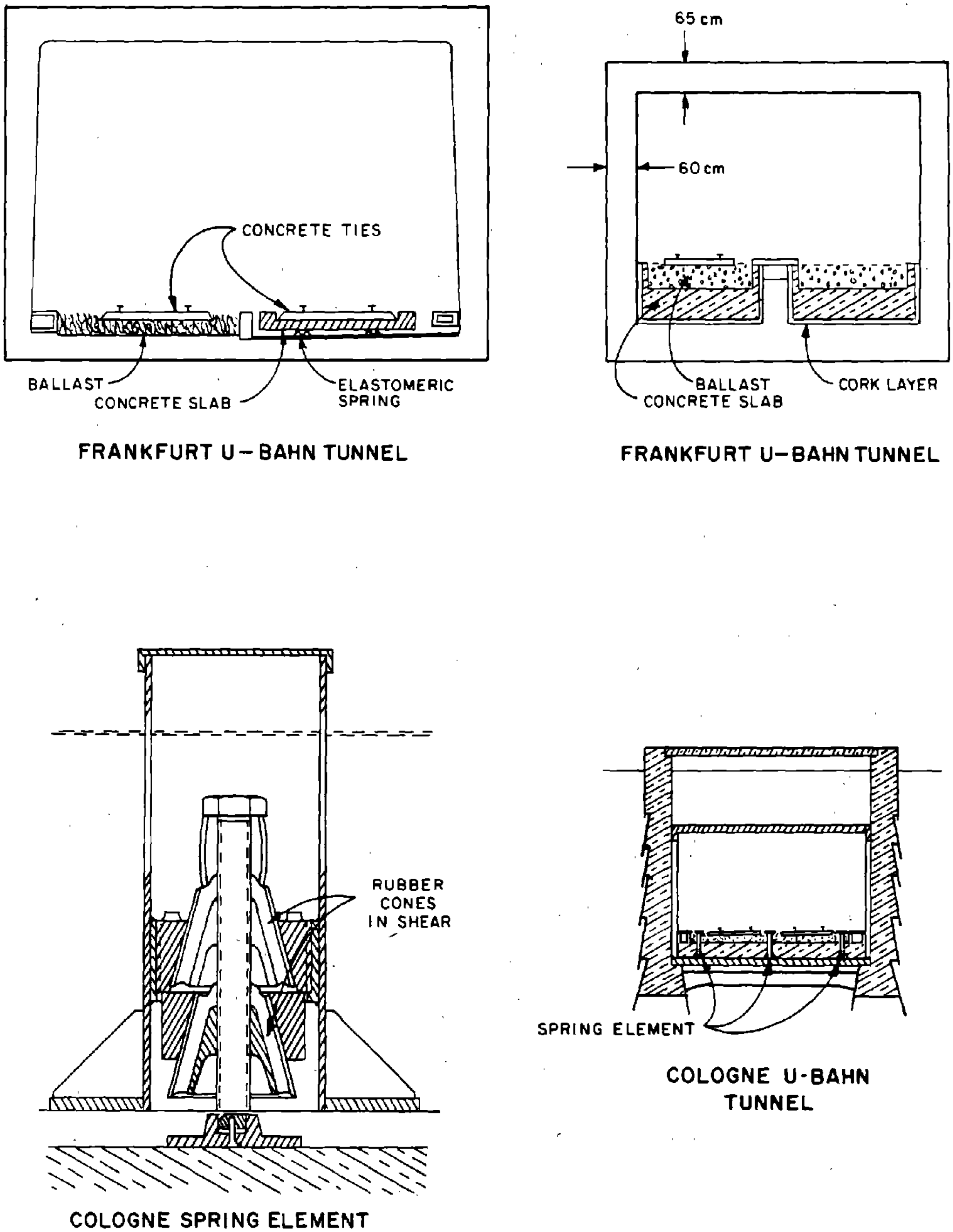


FIG. 7.9 TYPICAL FLOATING SLAB DESIGNS USED IN GERMANY [75]

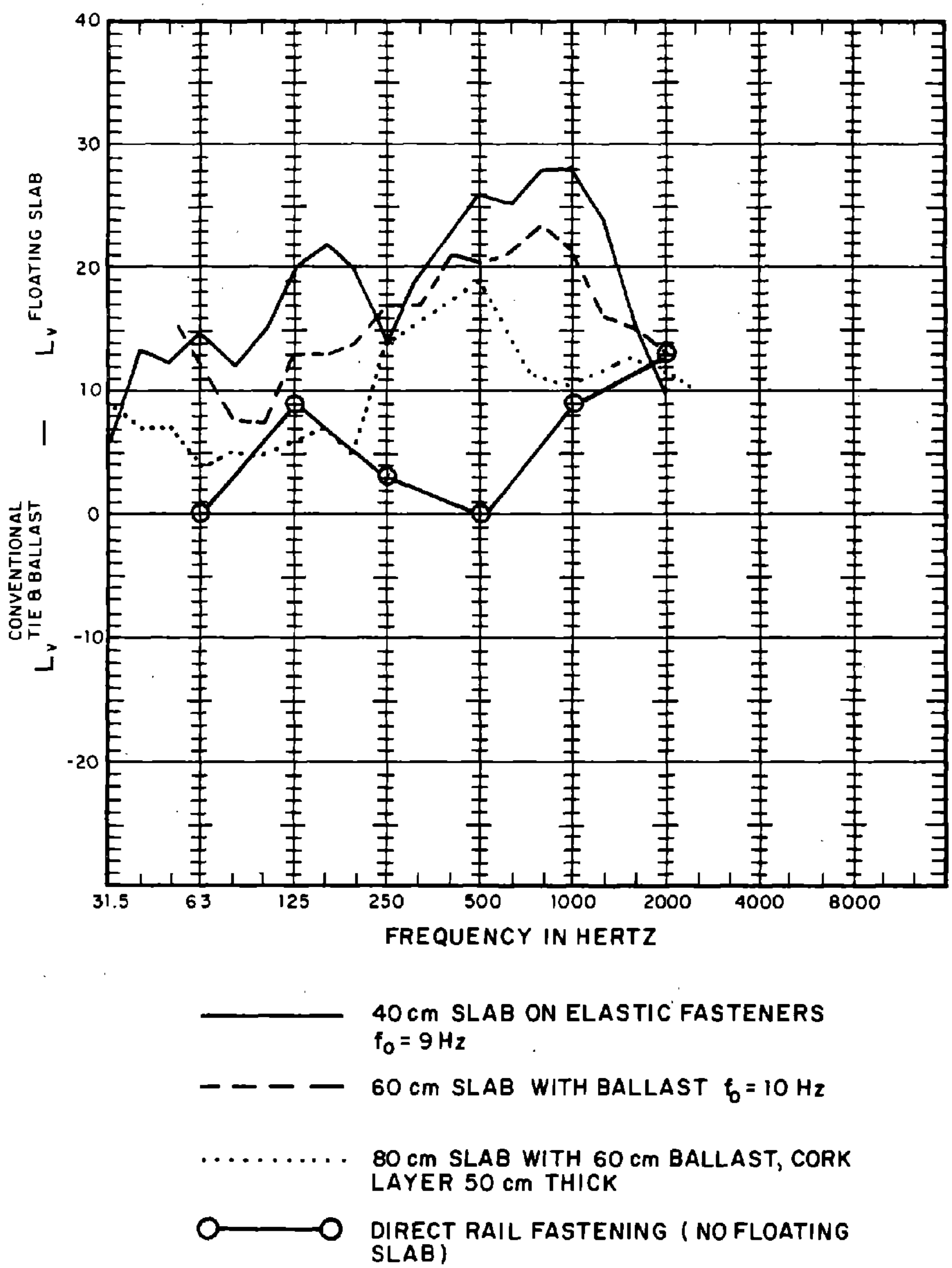


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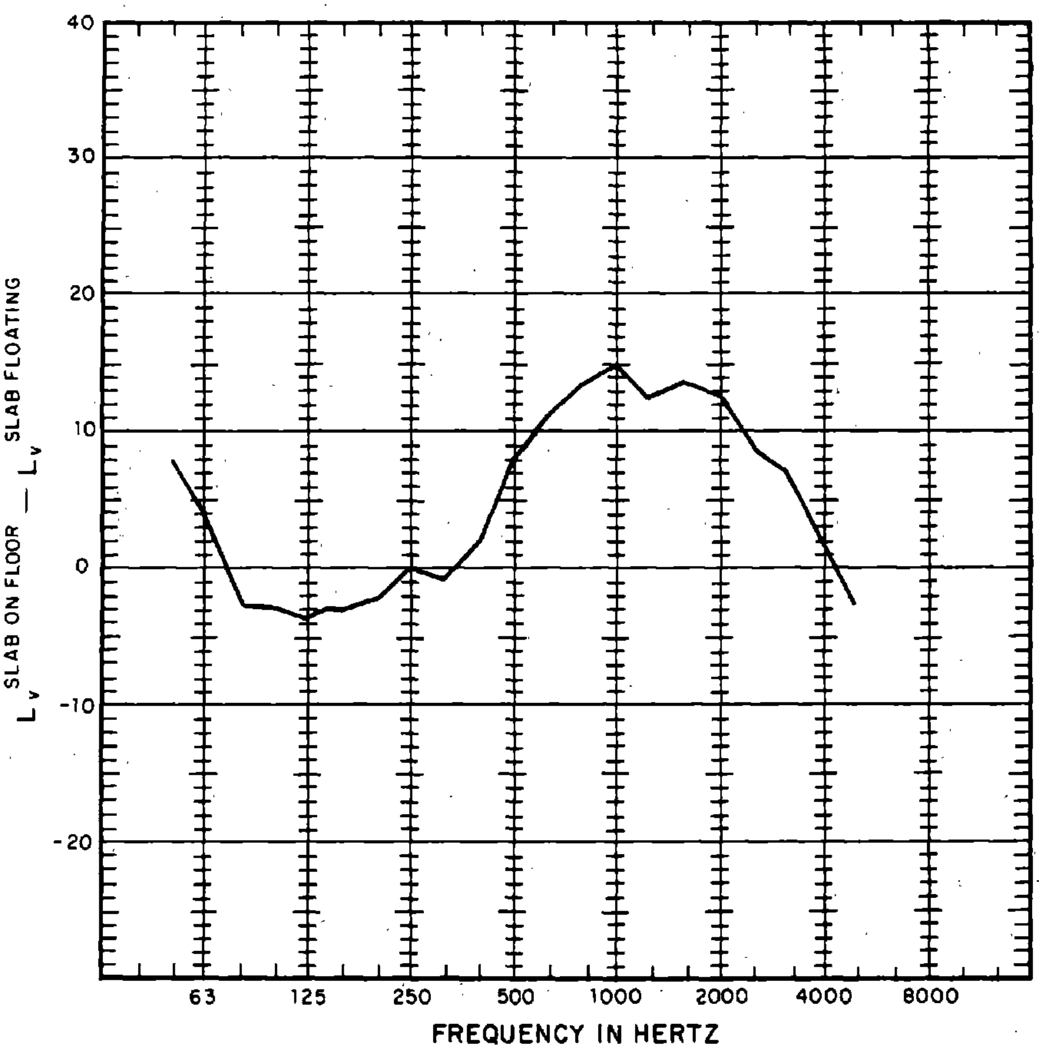
FIG. 7.10 TUNNEL WALL VIBRATION LEVELS FOR TRACK ON FLOATING SLABS COMPARED WITH LEVELS FOR CONVENTIONAL TIE AND BALLAST TRACK



DATA FOR 60 cm CONCRETE SLAB WITH TIE AND BALLAST TRACK IN COLOGNE U-BAHN

REF. 75

FIG. 7.11 DIFFERENCE BETWEEN TUNNEL WALL VIBRATION LEVELS FOR FLOATING AND NON FLOATING SLABS that of the slab mounts below 200 Hz. In such a case the stiffness of the mounts is not important. The reduction in tunnel wall vibration is due only to the added mass.

Not all floating slabs have proven successful. Measurements in the Victoria Park Station of the Toronto subway show that the vibration levels of the floated slab increase to such an extent that the transmission of vibration from the floating slab is the same as from the nonfloating slab [98]. The observed ineffectiveness is believed to be due to a lack of damping. Therefore, damping should be included either in the slab or in the mounts to prevent a build-up of vibration in the slab.

disadvantages

The major disadvantage of the floating slab is its cost and the requirement for a larger tunnel. However, a second disadvantage is the possible increase in tunnel noise. Fortunately, this increase in noise can be minimized by using an absorptive treatment on the slab on the tunnel walls.

7.4. Noise Barriers

Barriers have been used in the U.S., Europe and Japan to reduce wayside noise from rail vehicle operations. In the U.S. barriers have been used on the BART system.

Wayside noise measurements near a test section of the BART track with a 4 ft (1.2m) high barrier 8 inches (20 cm) from the side of the car show the barrier to be quite effective in reducing the noise. A 10 to 12 dB(A) reduction in noise levels at 50 ft (15m) is observed [99]. The performance obtained for the final installation was only 5 dB(A) because a 4 in (10 cm) gap was left between the bottom of the barrier and the roadbed, which in this case is a concrete elevated structure [100].

In Europe the ORE has carried out a detailed study of barrier performance on at-grade track [101]. Most measurements were taken near existing natural barriers so that an exact comparison of wayside noise levels with and without the barrier is impossible. However, comparison of levels measured on different section of track with and without barriers indicates that the barriers studied give reductions in wayside noise level at 25 m (82 ft) in the range 10 to 20 dB(A).

The most detailed study of barriers was done in Japan by the Japanese National Railroad [102]. They have used barriers extensively on elevated sections of their high speed rail line and have obtained reductions in wayside noise levels at 25m (82 ft) of up to 15 dB(A).

theory

Many analytical and experimental studies of the effects of barriers on noise levels have been carried out. Because of the potential value of barriers in reducing community noise from transportation vehicles on fixed right-of-ways, further studies are underway and many more are being planned.

At present, the state-of-the-art prediction procedure is to use design charts based on a number of scale model experiments carried out by Maekawa* [103]. These charts are presented in Fig. 7.12.

Use of the Maekawa design charts requires that the noise source be small compared to the distance from the source ot the top edge of the barrier and that its exact location be known. These conditions are not met when the barrier is placed close to the train. If we assume the effective source location to be at the center of a wheel on the barrier side of the train, we find the calculated values of noise reduction to be higher than observed in field studies. However, if we locate the effective source at axle height over the center line of the track reasonable agreement between prediction and field data is achieved.

For specific applications, the Maekawa design charts can be simplified. If we assume that the distance from the receiver to the barrier is large compared to the distance from the source to the barrier and that the receiver is at the same height as the source, then the parameter δ in Fig. 7.12 is given by

$$\delta = A - x \qquad (7\text{-}16)$$

where x is the distance from the source to the barrier. If we further assume that the parameter N in Fig. 7-12 is greater than .3, the Insertion Loss** (IL) of the barrier is given approximately by

$$IL = 10 \text{ Log } N + 13 \text{ dB} \qquad (7\text{-}17)$$

*Maekawa's work is preceded by many other useful studies that have led to very similar results.

**Insertion Loss is defined as the difference between noise levels before and after the barrier is installed.

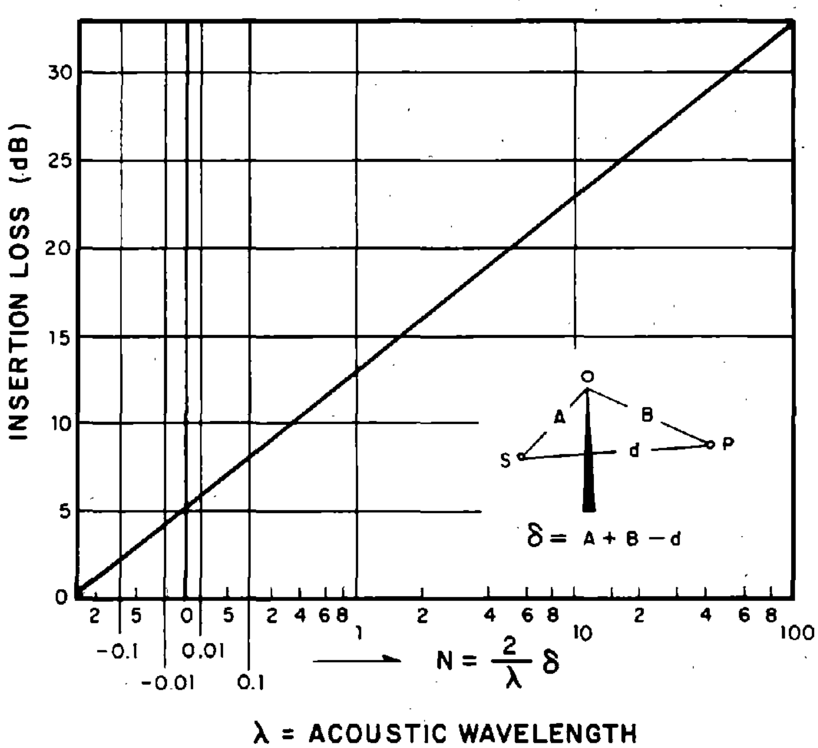


FIG. 7.12 MAEKAWA DESIGN CHART
FOR SOUND ATTENUATION BY BARRIERS [103]

Finally, if we assume a typical spectrum for rail vehicle wayside noise, the A-weighted noise reduction by a barrier can be expressed as a function of only the height of the top edge of the barrier above the source and the distance from the source to the barrier. Results are shown in Fig. 7.13. Figure 7.14 shows the Insertion Loss as a function of frequency for barriers giving 10 and 15 dB(A) reduction in wayside noise levels. Note that at higher frequencies the IL increases 3 dB per octave.

The predicted noise reductions in Fig. 7.13 are for barriers that are acoustically absorbing on the inside face (toward the train) and have a Sound Transmission Loss greater than the anticipated Insertion Loss. Barriers that are not absorbing allow sound waves to reflect off the barrier onto the side of the coach and out into the community. Non-absorbing barriers are expected to be 3 to 5 dB(A) less effective than absorbing barriers.

Overall accuracy of the Maekawa design charts is approximately ±3 dB(A). As shown in the next Section, however, the Insertion Loss predicted using these charts tends to be higher than observed values in some field studies.

<u>field data</u>

To support the general validity of the design chart in Fig. 7.13 we compare the predictions with available data.

Barriers used on elevated sections of the BART test track are 2 ft (61 cm) above axle height and 6 ft (1.83 in) from the track centerline. Predicted and measured Insertion Loss are shown in Fig. 7.15 [102].

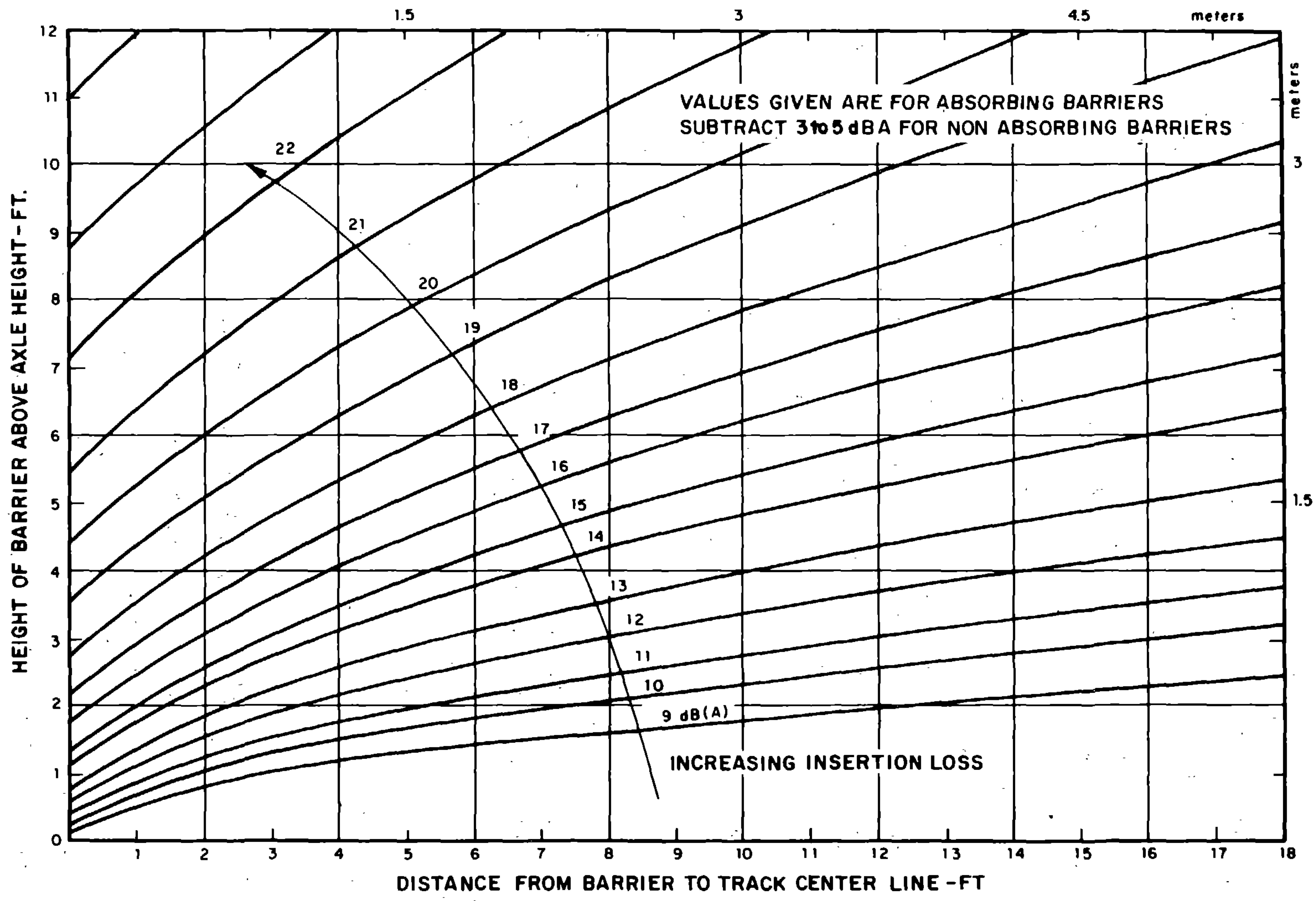


FIG. 7.13 BARRIER DESIGN CHART

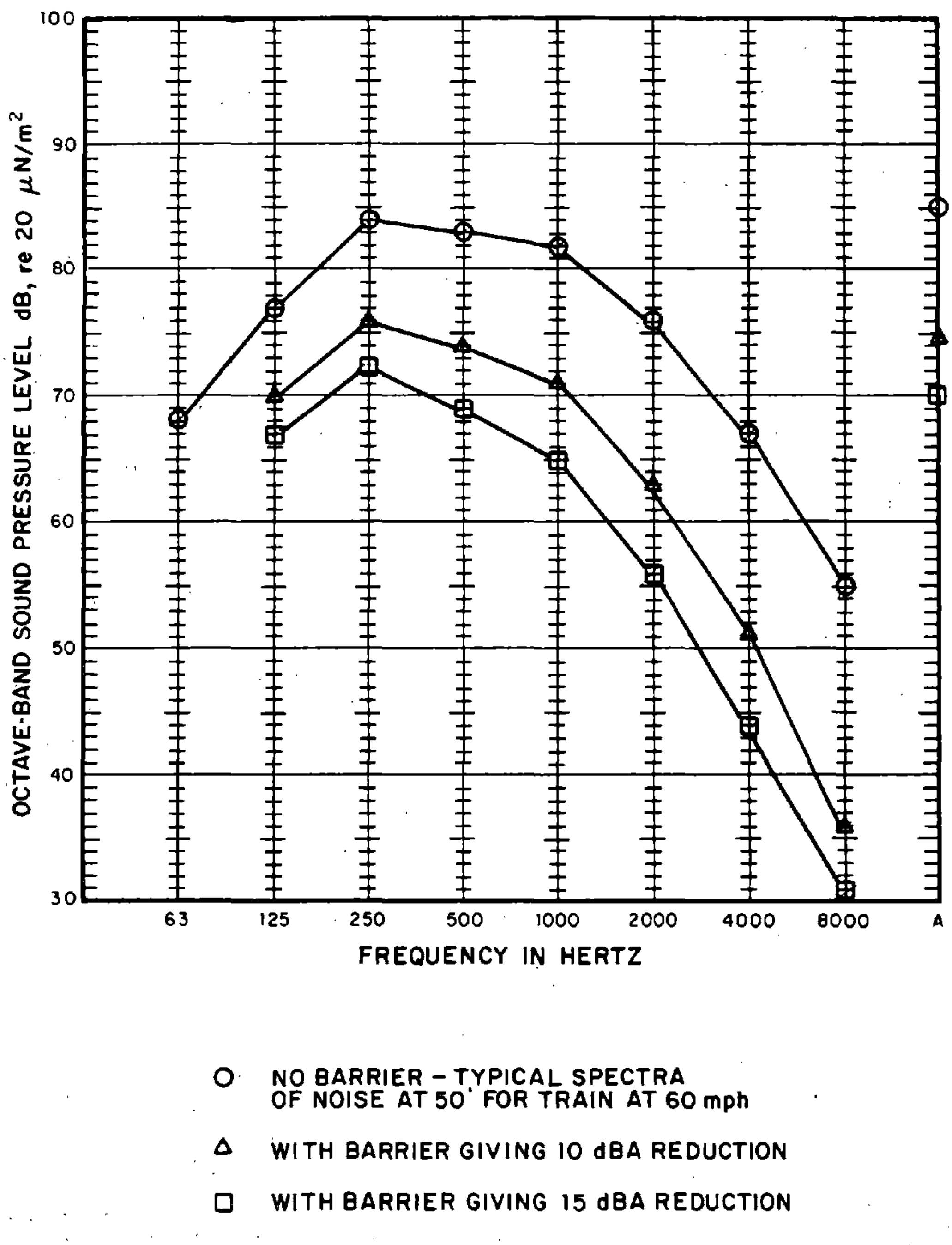


FIG. 7.14 CALCULATED NOISE SPECTRA FOR TWO DIFFERENT BARRIERS

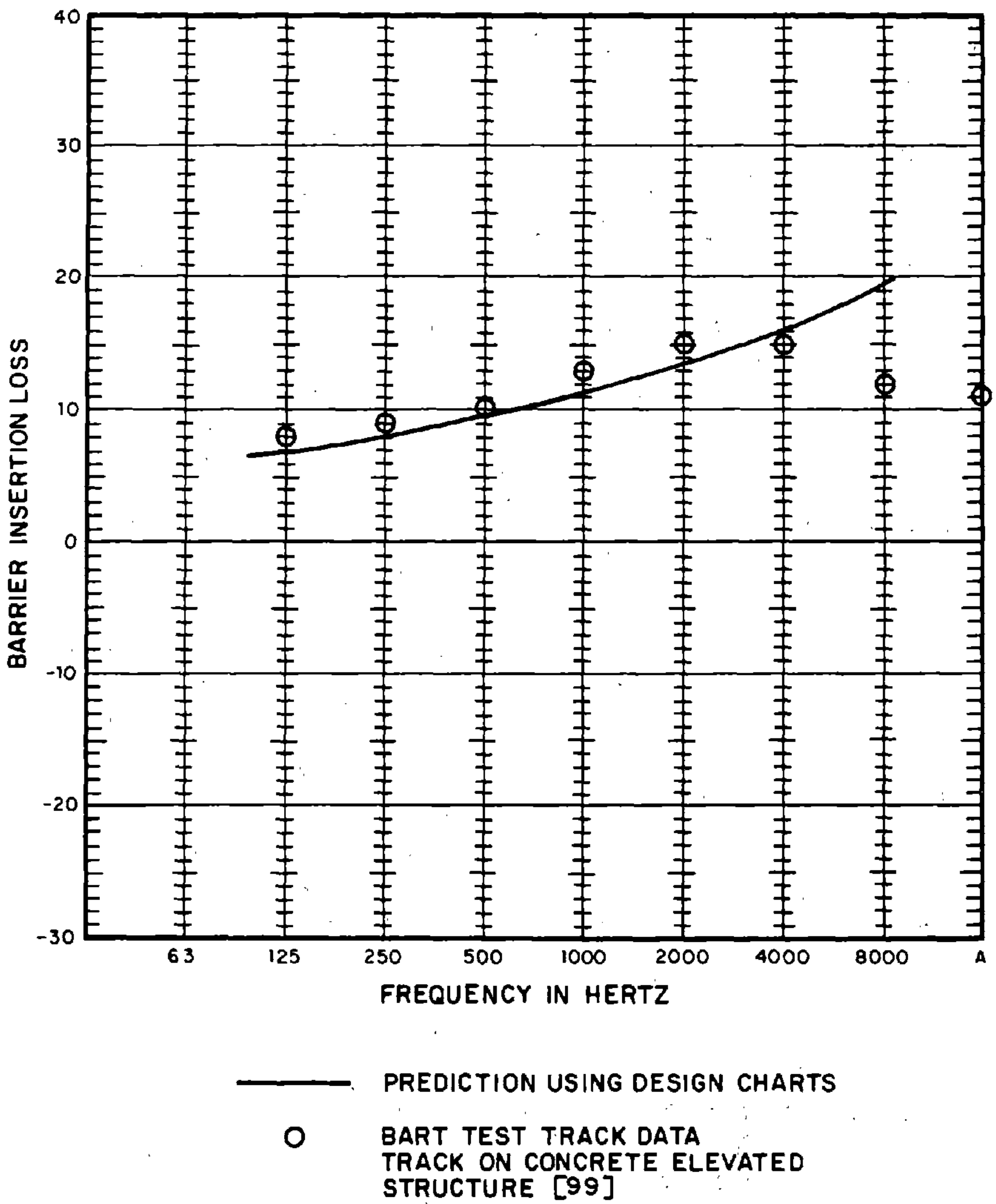


FIG. 7.15 COMPARISON OF PREDICTION WITH FIELD DATA FROM BART TEST TRACK

Barriers of different heights and at different distances from the track centerline were evaluated by JNR on their high speed rail line [102]. A comparison of data with prediction is shown in Fig. 7.16. In this case the Insertion Loss measured in the field are consistently below predicted values. Many possible explanations can be made for the difference. Most probably the radiation from the concrete viaduct limits the maximum Insertion Loss that can be achieved to the range 10 to 15 dB(A). Also, it is not clear from the presented data whether the barriers are absorbing or not.

practical application

The practical application of barriers is more difficult in northern cities where snow removal is required. As shown for the BART application, a gap between the bottom of the barrier and the supporting structure would facilitate snow removal but, as shown in the BART, applications would also greatly reduce the performance of the barrier. Further work is needed to solve this problem.

Consideration must also be given to the problem of making the barrier surface absorbing. Many commercially available materials will be severely affected by weathering. Unfortunately, if absorption is not used the barriers will reflect the sound back onto the coach and increase in-car noise. The reflected sound will also reflect a second time off the coach and into the community.

7.5. Elevated Structure Enclosures

Noise radiation from elevated structures can be an important source of wayside noise for some constructions, as discussed in Section 3.4. This noise source will become

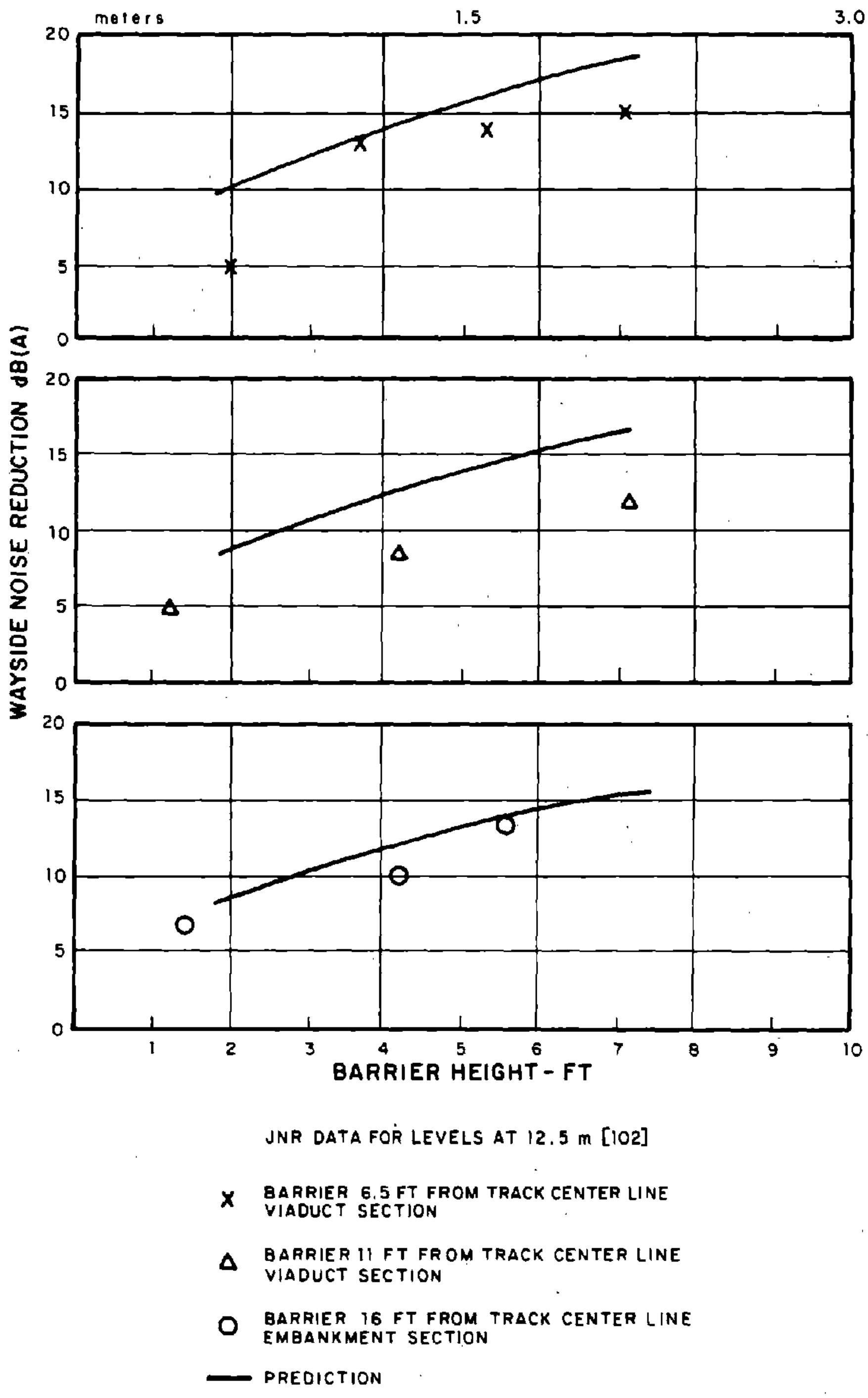


FIG 7.16 COMPARISON OF PREDICTION WITH FIELD DATA FOR JNR MEASUREMENTS OF BARRIER PERFORMANCE

increasingly more important as the radiation from the car wheels and trucks is reduced through noise control measures. Tests carried out by the Japanese National Railway (JNR) show that a light-weight structure with enclosures on the sides and underside of the elevated structure can significantly reduce the wayside noise levels [43].

In this Section, we discuss the rationale of enclosure design for elevated structures as well as present guidelines for their use.

design objectives

The primary objectives in the design of enclosures are to contain radiation from the original structure and to contain radiation from the wheels and trucks in open girder type structures. In addition, non-acoustical benefits can be achieved, since an enclosure can improve the appearance of the original structure, and can trap falling dirt and oil.

advantages and disadvantages

Enclosures when used with barriers can give large wayside noise reductions with little weight increase. In addition, they can be added to existing structures without interfering with normal operation.

The primary disadvantage of enclosures is that they may not be cost-effective, since special materials and careful construction are needed.

analysis

Figure 7.17 is a conceptual illustration of an elevated structure enclosure. The direct line-of-sight

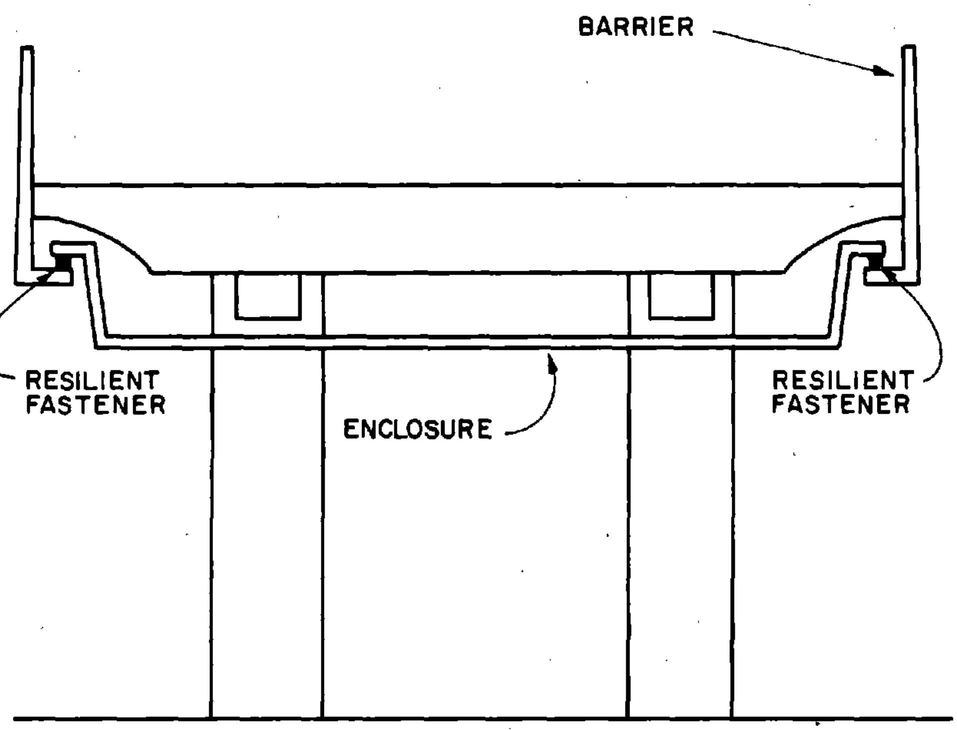


FIG. 7.17 ILLUSTRATION OF AN ELEVATED STRUCTURE ENCLOSURE

transmission path between the structure and a wayside observer is now blocked. Acoustical energy can reach the observer only by diffraction over the barrier or by radiation from the vibrating surfaces of the enclosure. Techniques for predicting the noise transmitted by means of diffraction over the barrier are briefly discussed in Section 7.4.

The acoustic radiation from the enclosure can be divided into two components:

(1) Transmission of acoustic energy radiating directly from the original structure through the enclosure;

(2) Transmission of vibration from the original structure to the enclosure and subsequent noise radiation.

Acoustic radiation due to component (1) is controlled by using an enclosure that has a high Sound Transmission Loss [104] together with a sound absorbing treatment inside the enclosure that prevents a reverberant build-up of acoustic energy in the enclosure. Acoustic radiation due to component (2) is controlled by using a damping treatment on the panels of the enclosure, by connecting the enclosure to the elevated structure at points where the vibration levels are low, and by using resilient fasteners to connect the enclosure to the structure.

Limitations of Performance

The practical limitations of the enclosure performance are primarily acoustic leakage through holes, radiation from columns of the elevated structure, degradation of absorption ability of absorbing materials due to dirt, limitations or fastener design properties and cost.

Leakage can be the single most important factor which limits enclosure performance. If openings in the enclosure total 10% of its surface area the Insertion Loss can be no more than approximately 10 dB(A).

field data

The JNR has carried out field tests with enclosures on both steel girder structures and concrete viaducts. Detailed information has not been obtained. However, results for the reduction in noise level under an enclosed steel girder structure are given in Fig. 3.13 on page 76.

7.6 Structural Damping

Damping is an effective means of noise and vibration control in many applications. When used on a built-up steel structure, a damping treatment can reduce vibration and noise levels by 10 to 15 dB(A). The reduction in levels that can be achieved on concrete structures is less, since the inherent damping of concrete is greater than that of steel. Typically, the damping loss factor of built-up steel structures is in the range 3×10^{-3} to 10^{-2} while that of concrete is in the range 1 to 5×10^{-2} [91].

By application of commercially available damping treatments, it is possible to bring the damping of steel structures up to a value equal to or greater than that of concrete structures.

As a general rule, damping treatments are more effective at higher frequencies and, therefore, can be expected to have their greatest effect in reducing A-weighted noise levels radiated by elevated steel structures. Use of a damping treatment also improves the performance of floating slabs in reducing the transmission of vibration from the wheel/rail interface to the tunnel wall and to buildings nearby. However, since the frequencies of major interest are low, the treatment will not be as effective in this application as it is in reducing elevated structure noise.

analysis

Analytical techniques for predicting the noise radiated by an elevated structure have not been completely developed. Therefore, we cannot analytically predict the effect of increased damping on the noise radiation. Certain general conclusions can be reached, however.

The vibratory response of any generalized structure can be represented by the response of its modes of vibration. The response in any given band of frequencies will consist of the sum of the responses of modes whose resonance frequencies lie within the band-resonant response --plus the responses of modes whose resonance frequencies lie either above or below the frequency limits of the band--nonresonant or forced response. Damping has its greatest effect on the resonant response; and within the limits of damping loss factors that can be reasonably achieved in practice, has little effect on the nonresonant response. Therefore, damping will be effective in reducing the radiated noise only if the noise is predominantly due to the resonant response. In other cases, an increase in the damping will have no effect on noise radiation.

Although an exact calculation has not been carried out, we surmise that the radiation from elevated steel structures is due to vibration of resonant modes of the structure. Therefore, the noise can be reduced by increasing the damping. However, the radiation by non-resonant modes will limit the amount of noise reduction that can be achieved. Based on our experience, we expect the limiting amount of noise reduction to be in the range of 10 to 15 dB(A).

Nonresonant vibration plays a more important role in concrete and steel/concrete composite structures, since the damping of the untreated structure is higher than for a steel structure. We expect the limiting noise reduction that can be achieved by increasing damping to be in the range 5 to 10 dB(A).

practical application

The practical application of damping requires a detailed evaluation of its temperature characteristics, bonding requirements and aging. Damping materials have properties that are very temperature dependent [105]. In general the stiffness increases with decreasing temperature and increasing frequency of excitation. The damping exhibits a peak such that materials are sometimes designed to be used within a specified narrow limit of temperatures. To provide good performance, the material must be well bonded to the surface which is to be damped. This can be a practical problem. Finally, damping materials tend to lose their effectiveness with age.

design charts

Many design charts have been developed to assist in the design and selection of a damping treatment [91,106]. We present in Fig. 7.18 the most useful of these charts. This chart can be used to predict the damping of plate structures with single layer treatments. Design charts for multilayered treatments also exist [91]. These treatments can give good performance, but may cost more.

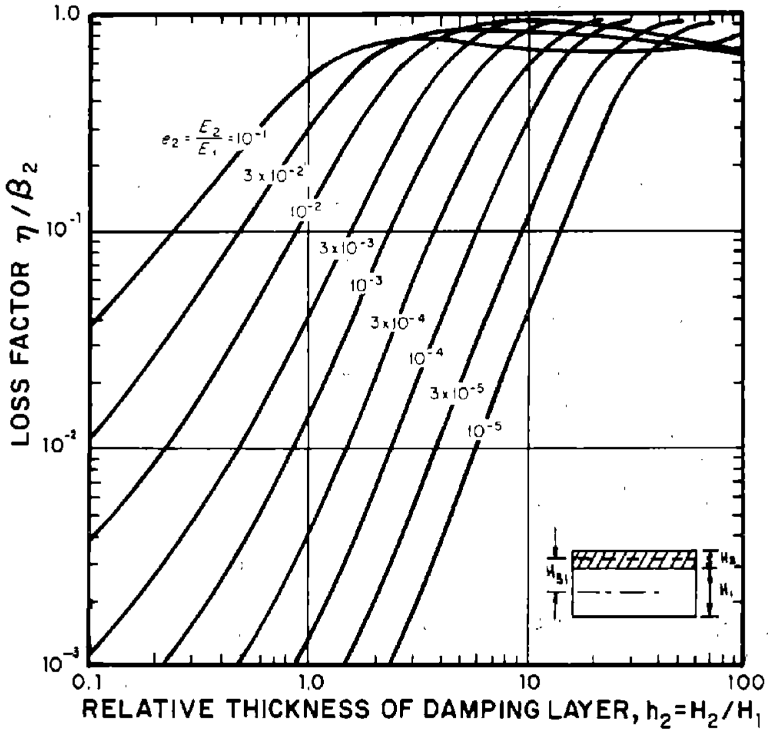
example

JNR has applied a damping treatment to a steel girder bridge [52]. Very little information is given about application. Its effect, however, is shown from data in Fig. 7.19.

7.7 Acoustical Treatment of Tunnels and Stations

Acoustical treatments are used in tunnels and stations to provide sound absorption. A large number of treatments are available and offer different advantages. Spray-on treatments are most useful in tunnels because both material and application costs are low (approximately $1.25/sq ft applied). When used in stations, however, these treatments may discolor and be difficult to clean.

In present applications a 1/2 in to 1 in (1.27 to 2.54 cm) thick treatment is applied to the tunnel walls from the floor of the tunnel to approximately window height. The absorption coefficient of such a spray-on treatment ranges from 0.3 at 250 Hz to 0.9 at 2000 Hz. Thicker treatments are needed to provide more absorption at low frequencies.



η COMPOSITE LOSS FACTOR

β_2 LOSS FACTOR OF APPLIED TREATMENT

E_1 YOUNG'S MODULUS OF STRUCTURAL MATERIAL

E_2 YOUNG'S MODULUS OF DAMPING MATERIAL

FIG. 7.18 SINGLE LAYER
DAMPING TREATMENT DESIGN CHART [91]

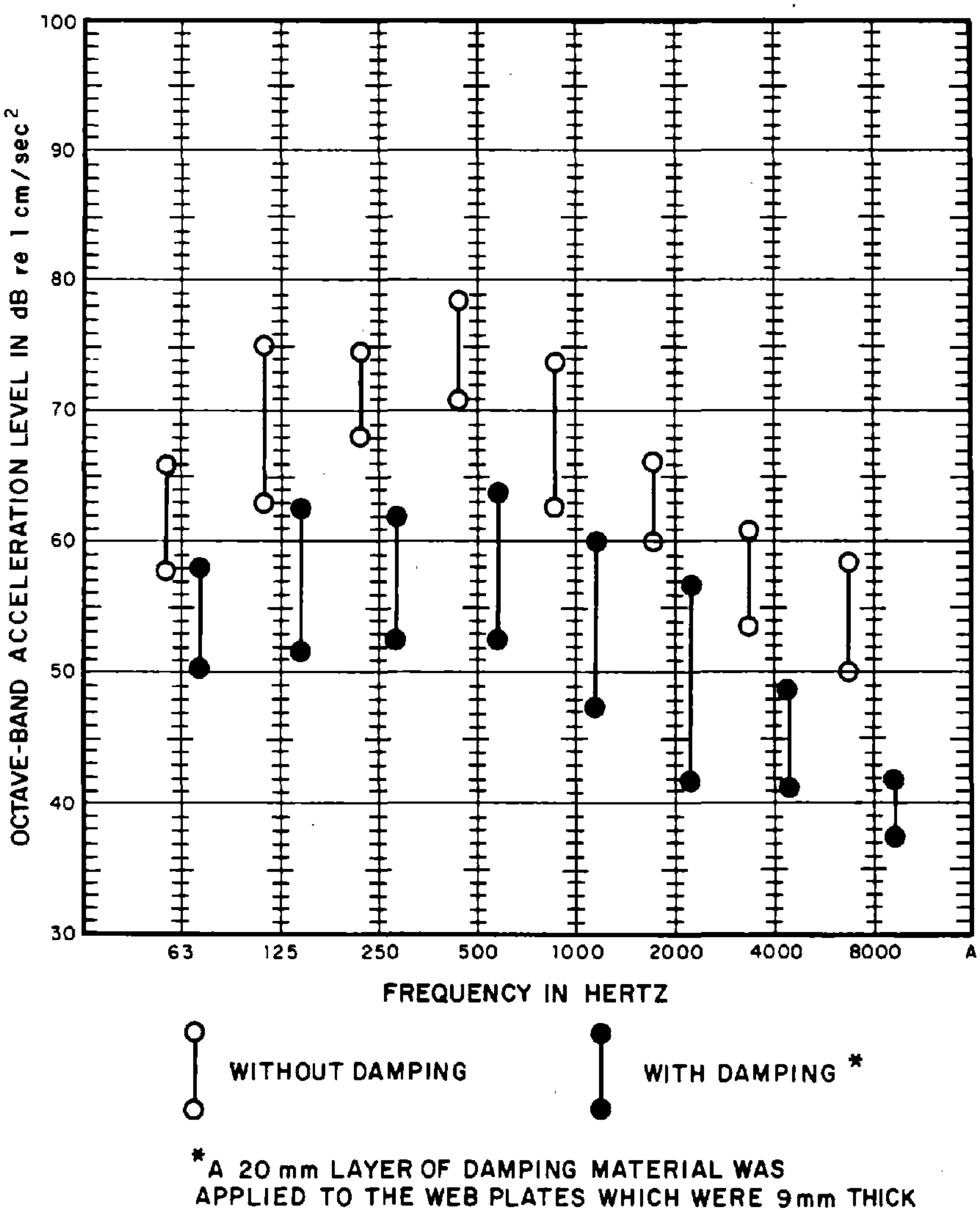


FIG. 7.19 EFFECT OF DAMPING FOR A STEEL PLATE BRIDGE [52]

criteria for selection

In selecting among materials that are acoustically effective, many other questions need to be asked:

- Does it meet fire, health and safety codes?
- Will the material have to be applied around, or can it be applied over, existing tunnel equipment?
- Can tunnel fittings be fastened over it?
- Can it be easily washed to restore acoustic effectiveness without damage?
- If a wet application, does a minimum drying rate have to be exceeded in order for it to meet specifications?
- Can the material be readily patched or replaced?
- Will it require special surface preparation and coating for a bond?
- If a spray, how is the material checked for desired thickness and acoustical specification?
- How much will it cost to apply a given amount of absorption.

7.8 Trenches

The intended purpose of trenches is to act like barriers in reducing ground vibrations. Soil vibrations are sufficiently different from airborne noise that the noise barrier design charts cannot be used. However, the same type of behavior occurs. A trench or sheet piling reduces the vibration levels by preventing vibration transmission. Trenches, as long as they do not fill up with water, prevent transmission across the trench so that the vibration waves can only travel under or around the trench. A "shadow zone" is formed in which vibration amplitudes are due only to diffracted waves. Based on an experimental study by Woods [107] in order to be effective the trench must extend at least 0.6 wavelengths below the source of vibrations and must be long enough that the angle formed between lines from the receiver to the ends of the trench is at least 90°. For sources on the surface, the wavelength should be that of shear or Rayleigh waves. Validity of the criteria for underground sources is open to questions.

The Rayleigh wavelength depends on frequency and the type of soil. Wavespeeds in various soils are in the range 500 to 100 ft/sec. Typically, the wavespeed decreases with increasing water content [77]. Wavespeeds in rock are approximately 10 times higher. Using these typical values the wavelength in soil for a frequency of 31.5 Hz is in the range 15 to 30 ft. It follows from the criteria above that a trench must extend 9 to 18 ft below the level of the source to be effective. In rock, the trench would have to be 90 to 180 ft deep! The expected attenuation of vibration levels behind the trench is 12 dB or more when the criteria on depth and length is met. Sheet pile barriers are less effective since they do not completely eliminate transmission through the barrier. On the other hand, they are much more easily installed and maintained.

practical application

Trenches and sheet piling have been used in many cases in an attempt to reduce ground vibration near foundations holding large reciprocating engines or drop presses [107]. The ratio of failures to successes is quite large, however, so that a practical application of trenches should be approached with caution.

8. SUMMARY AND CONCLUSIONS

8.1 Assessment of the State-of-the-Art

It has long been known that the wheel/rail interaction is a primary source of noise and vibration. Because of this awareness, much effort has gone into the design of techniques to control the noise and vibration associated with this mechanism.

The important role of wheel and rail roughness, rail joints and wheel flats in determining noise and vibration levels has been clearly identified. Although a quantitative relationship between roughness and noise or roughness and vibration has not been determined at this time, it is known that the noise and vibration levels can be controlled by eliminating wheel flats and rail joints and by maintaining smooth wheel and rail surfaces. A summary of the effect of wheel and rail condition is given below. The noted increases in level are relative to smooth wheels running on smooth continuously welded rail.

CONDITION	INCREASE IN LEVEL*
Jointed rail	8 to 10 dB
Wheel Flats	8 to 10
Rough Rail	3 to 6
Rough Wheels	3 to 6
Corrugations	up to 15

These increases apply to both noise and vibration and to all track configurations including at grade, elevated, and underground track.

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*The increases are not additive so that only the largest applicable increase in level should be used.

__wayside noise__

Measurements of wayside noise from vehicles on at-grade smooth continuously welded rail show a 30 Log_{10} V dependence on train speed, V. However, for operation at a given speed the measured noise levels show approximately a 10 dB range of levels. We believe that this 10 dB variation in level is due to differences in track design. A procedure for calculating the wayside noise level is established in this report. The procedure is to determine the noise level at 50 ft using Fig. 3.1; apply correction factors to account for distance, Fig. 3.2; ground terrain, Fig. 3.5; and elevated structure radiation, Fig. 3.9.

It is known through field measurements that noise barriers can be used to reduce wayside noise levels up to 15 dB(A). An empirical design chart is given in Fig. 7.13.

Measurements of elevated structure noise show an increase in wayside noise over at-grade operation of up to 20 dB(A). An analytical prediction of the increase for a specific design is not within the state-of-the-art. However, from the data we can obtain simple correlations between the increase in noise level and the type of structure. The correlation is shown in Fig. 3.9. Steel structures with direct rail fastening give significant increases in noise. Structures with ballasted track and concrete or steel/concrete structures, which are much heavier, produce only a small increase in noise.

Three methods of noise control have proven successful in reducing noise from elevated structures. Noise from steel plate bridges with direct rail fastening has been reduced by relaying the track on ballast. Noise from both concrete and steel structures has been reduced by enclosing the sides and bottom with a damped sheet metal enclosure.

Either method provides 10 to 20 dB(A) of noise reduction. Use of damping treatments will also be effective in reducing noise from elevated structures.

Efforts to reduce the noise from steel bridges by use of resilient rail fasteners have been unsuccessful, although in concept the approach seems promising.

Barriers have been used to reduce the noise from trains on elevated concrete structures. The noise reduction that was achieved is limited by the radiation from the structure.

vibration

Ground vibration and the vibration of buildings near subways can only be predicted empirically within a broad range of values. For operation on surface track, the prediction procedure is to use Fig. 4.2 to establish the range of ground vibration levels at a distance of 25 ft (7.5m) from the track. Then, Fig. 4.3 is used to predict the levels at other distances. Based on the limited data available we surmise that the ground vibration levels for operation on elevated structures is also within the range shown in Fig. 4.2. For operation in tunnels the prediction procedure is to use Fig. 4.4 to predict the range of tunnel wall vibration levels. Then, Fig. 4.5 is used to predict the vibration levels of nearby building walls. Finally, the rumbling noise levels are predicted by assuming that $L_p = L_v$ where L_p is the sound pressure level and L_v is the building wall vibration level, re 5×10^{-8} m/s calculated by the above procedure for each octave band of frequency. A shorter and equally accurate approach to predict the A-weighted noise level in building cellars is to use Eq. (4-1) on page 88.

Methods for controlling the vibration produced by passing rail vehicles are known. Resilient rail fasteners are quite effective. Both theory and field data indicate that the vibration levels above approximately 50 Hz are proportional to 20 $\log_{10}$ K, where K is the fastener stiffness per unit length of rail. The softest fastener that can be used because of constraints on track alignment and stability has a stiffness of 3000 lbs/in per inch of rail. Since softer fastener would allow further reductions in vibration levels, these constraints should be looked into more carefully.

The replacement of fasteners that rigidly connect the rail to the tunnel floor with soft resilient fasteners should provide up to 20 dB reduction in vibration level, depending on the impedance of the tunnel floor. Results are shown in Fig. 7.16.

Floating concrete slab tracks give a further reduction in vibration level. A variety of designs using both direct rail fastening and ballasted track have been constructed. These designs are 5 to 15 dB more effective in reducing vibration than the softest rail fastener mounted directly on the tunnel floor.

A detailed analysis of floating slab performance is possible. However, only the simplest aspects of this analysis have been taken into account in past slab designs. Based on a simple single degree of freedom analysis, the resonance frequency of existing slabs has been made as low as practically possible within constraints of track stability. Damping has been incorporated into the designs to limit the slab response at this resonant frequency and to damp bending waves in the slab, and slab supports have been selected which give the desired stiffness under design loads and have a ratio of dynamic to static stiffness near unity.

Floating slabs can increase the noise level in the tunnel. However, it has been found that tunnel noise can be successfully controlled by use of absorptive materials on the tunnel walls and floor.

in-car noise

The dominant path by which noise is transmitted into the car is airborne. Therefore, in-car noise levels are typically 5 to 10 dB(A) higher for operation in tunnels than for operation in the open. Car design plays a major role in determining in-car noise levels. However, the increased noise levels for operation in a tunnel can be controlled by covering the trackbed and the tunnel walls with the absorbing material. Ballast has been used for this purpose on the trackbed.

station noise

Wheel/rail noise and brake screech are the dominant sources of station noise. The screech can be controlled by improved braking systems. The wheel/rail noise can be controlled by techniques sued to control wayside noise. Both types of noise can be reduced by using absorbing materials in reducing station noise is greatest when the materials are near the wheel/rail interface. Ballast has been effectively used on the trackbed as an absorbing material.

other considerations

The wheels and suspension of a rail vehicle clearly must have an effect on noise and vibration. However, within the range of designs used for urban mass transit vehicles, the effect is not large and has not been precisely determined. Resilient wheels have shown some effect in reducing the low frequency vibration of concrete elevated structures on the BART Test Track. Although resilient and damped wheels are effective in reducing wheel squeal, they have had no significant effect on noise for operation on straight track.

The use of resilient pads under building foundations has been proposed and implemented in a number of cases. However, conclusive proof that these pads effectively reduce the transmission of vibration has not been found.

The use of resilient layers between subway walls and the earth has also been proposed. Again, there is no proof that the technique works.

Finally, the use of trenches to reduce the transmission of ground vibration has been proposed. However, the successful application of this technique has not been accomplished and appears to be impractical for the dominant wave lengths contained in groundborne vibration.

8.2 Recommendations for Future Research

From the discussion in the previous section, it is clear that noise and vibration control techniques exist that could be used to solve many problems. However, these techniques are not necessarily the most effective techniques nor are they necessarily the least expensive. Further studies are required to find more cost/effective noise and vibration control techniques.

State-of-the-art predictions of noise and vibration are not very precise. This lack of precision makes it difficult to plan a new line and to identify locations where noise and vibration control will be needed. Again, further studies are needed.

A number of topics on which we believe further study is needed are discussed below:

(1) Noise from operations of vehicles on elevated steel structures is a problem in many urban areas. Effective means of control must be found. Re-laying the track on ballast is an effective means of noise control but not always possible because of the large increase in weight. Use of damping treatments and enclosures should be thoroughly investigated. Finally, the question of whether or not resilient rail fasteners can reduce noise from steel structures should be answered.

(2) More precise techniques for predicting the noise in buildings near subway tunnels are needed. Measurements of the static and dynamic stiffness of existing rail fasteners should be taken so that tunnel wall vibration data can be correlated with fastener stiffness. Methods to predict the impedance of tunnel floors should be developed so that wall vibration can be related to tunnel design. The coupling between the tunnel wall and the ground and the building walls must

be determined. Measurements of vibration propagation effects in the ground must be correlated with ground properties, and finally, techniques to predict the transmission of vibration through the buildings and the resulting noise must be identified.

(3) Resilient rail fasteners are known to provide a reduction in tunnel wall vibration. At present the minimum fastener stiffness is set by track alignment and stability conditions. These conditions should be carefully looked into so that softer fasteners can be used if at all possible.

(4) Studies should be carried out to determine the cause of the difference between measured barrier noise reduction and predicted values. Scale model studies combined with field studies would be useful.

(5) Standardized techniques to measure ground vibration should be developed so that measurements can be compared.

(6) The major radiating surfaces contributing to wayside noise on at-grade track should be identified for typical vehicles. The relative role of noise radiation from the wheels, trucks, rails, etc. should be determined.

(7) Many successful noise and vibration control techniques have been identified. It is very important that studies into the practical application and cost/effective use of these techniques be continued.

8.3 Conclusions

Within the state-of-the art wayside noise from surface operations of rail vehicles can be reduced to below 80 dB(A) at 50 ft (15m) for train speeds of below 60 mph (100 Km/h). The conditions that must be met are:

(1) control of propulsion noise to below 80 dB(A) at 50 ft.
(2) use of continuous welded rail
(3) elimination of wheel flats
(4) maintenance of smooth wheels and rails by periodic grinding
(5) barriers <u>may</u> be necessary in some cases*
(6) use of concrete or concrete/steel elevated structures, or steel structures with ballasted track
(7) enclosures <u>may</u> be necessary for the sides and bottoms of elevated structures.

Vibration levels near subway tunnels can be reduced 30 to 50 dB below levels experienced for track with jointed rail rigidly connected to the tunnel floor. Elimination of rail joints (on wheel flats) gives approximately 10 dB of reduction. Use of soft rail fasteners, 3000 lbs/in^2 of rail, gives an additional 20 dB reduction, and use of floating slab tracks gives a further 10 to 20 dB reduction.

In-car noise can be reduced to 68 dB(A) on surface track but not in tunnels unless absorptive treatments are used in the tunnel.

Station noise is not as great a problem when ballasted track is used. Absorptive treatments must be placed close to the source to provide effective control.

---

*If barriers are used, propulsion noise can be 90 dB(A) at 50 ft when measured without a barrier present.

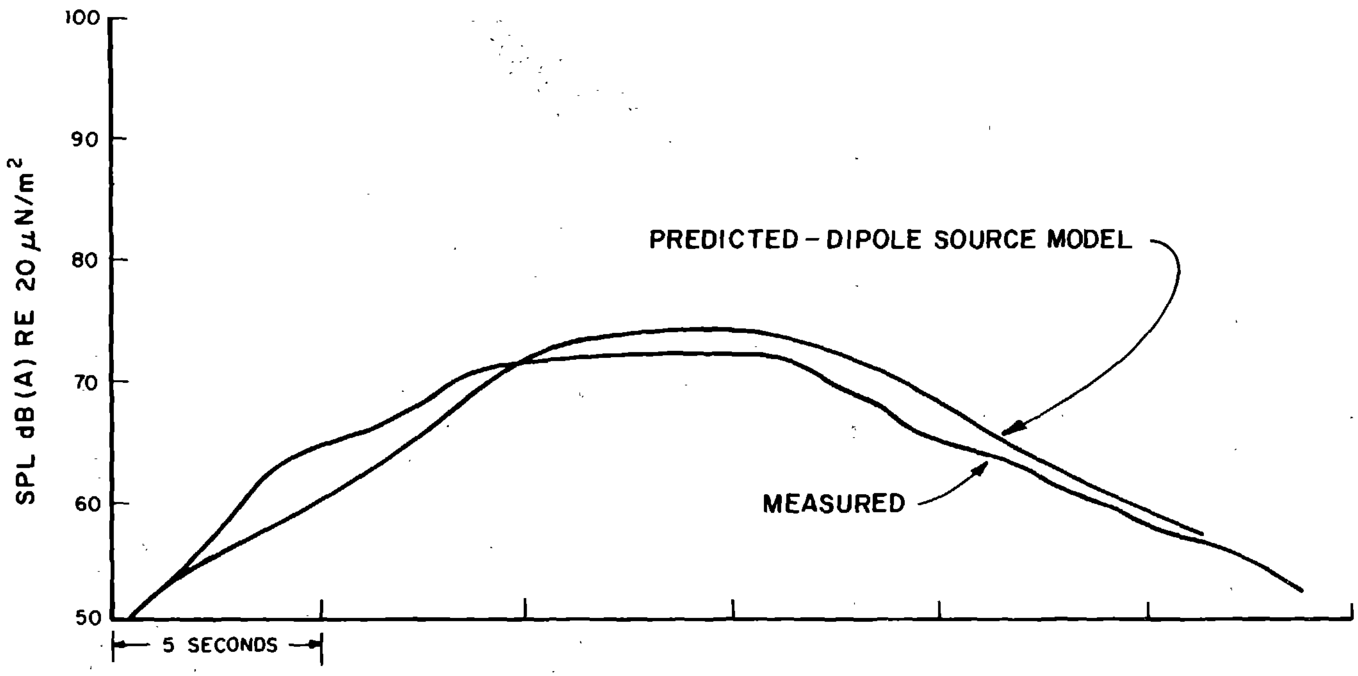
APPENDIX A   A MODEL FOR PREDICTING WAYSIDE NOISE

Three studies have been made to determine simple models that can be used to predict noise levels [22, 28, 108]. Each study concluded that the proper model was a line of dipole noise sources with one source at each truck location. The direction of highest radiation was at right angles to the track in a plane parallel to the ground.

In ref. [108], Peters studies the problems of predicting the noise as the train approaches, passes by and leaves. Data he obtained show that the noise levels when the train is approaching are below those predicted by a line of omni-directional sources. As shown in Figure A-1, a line of dipole sources gives an accurate prediction.

In ref. [22], the problem of predicting the wayside noise levels near the train is considered. At these measurement locations the noise levels fluctuate, being highest when a pair of wheels on a truck go by. The difference between the highest and lowest levels increases as the measurement location comes nearer to the train. However, in all cases, the difference is greater than that predicted by a line of omni-directional sources. As shown in Fig. A-2, the dipole model achieves good agreement with measured data.

In ref. [108], the problem of the fall off of noise level with increasing distance is considered. Typical results are shown in Fig. A-3. The theoretical predictions are for a line of dipole sources. Again, reasonable agreement is achieved.



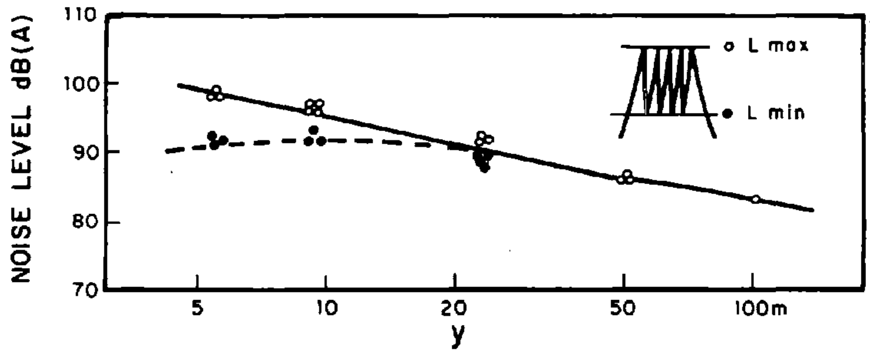
TRAIN SPEED ; 144 Km/h

OBSERVER TO TRACK DISTANCE ; 200 m

TOTAL TRAIN LENGTH ; 287 m

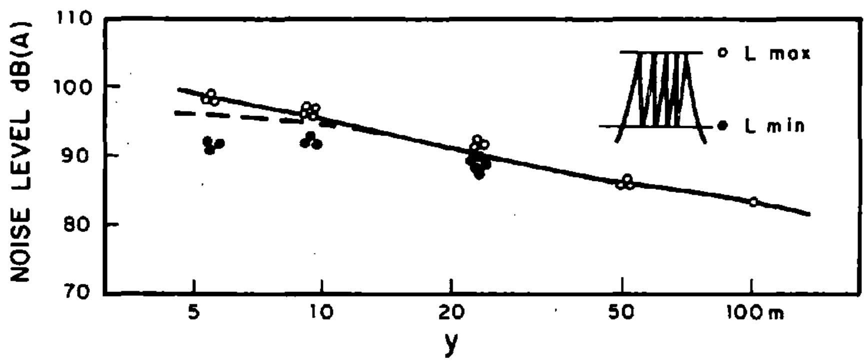
REF. 108

FIG. A-1 COMPARISON OF MEASURED AND PREDICTED SOUND PRESSURE LEVELS DURING PASSAGE OF A TRAIN



MEASURED

CALCULATED (AS DIPOLE SOURCE MODEL)



MEASURED

CALCULATED (AS POINT SOURCE MODEL)

12 CAR (300 m)
LINED TO BE 90 dB (A) AT y = 25 m

REF. 22

FIG. A-2 FLUCTUATION OF LEVELS NEAR THE TRAIN

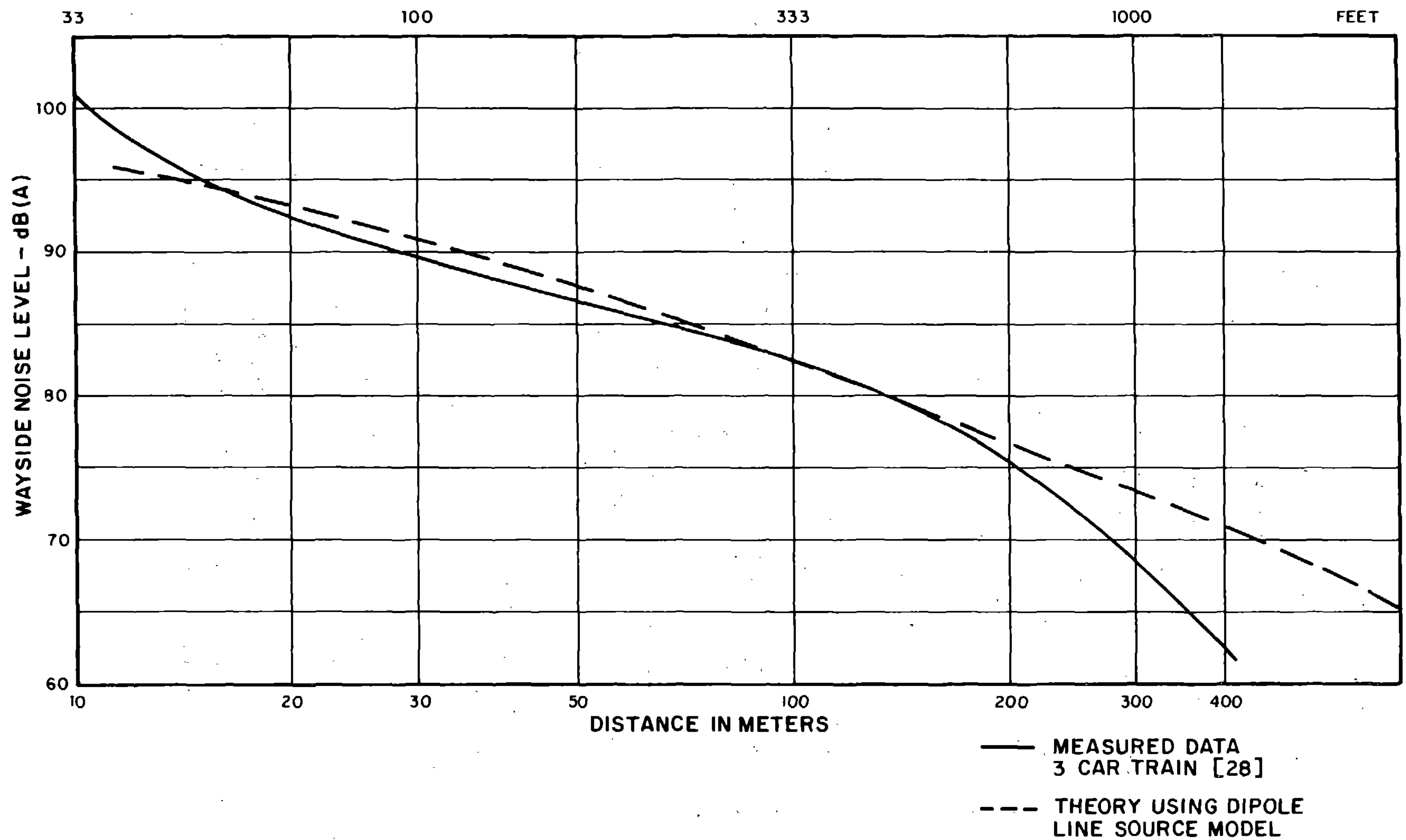


FIG. A-3 WAYSIDE NOISE LEVEL VERSUS DISTANCE

APPENDIX B WAYSIDE NOISE

To establish an empirical prediction technique for wayside noise from operations on at-grade tie and ballast track we have assembled reported data from a number of different rail systems. The data selected for presentation is for operation on continuously welded rail. In most cases the rail and wheel roughness were not specified. Thus, some data applies to rough rails and wheels.

The selected data are for noise levels either 50 ft (15 meters) or 25 meters (82 ft) from the track center-line. Distance has been removed as a variable by extrapolating levels at 25 meters to a distance of 15 meters. Only data measured over flat ground with no nearby reflecting objects are used.

Data presentations are made in Figs. B-1 through B-5 for three types of rail vehicles -- subway type cars, suburban type trains, and intercity passenger trains. In each figure we also present a 10 dB(A) range of levels from Fig. 3.1 that represents a reasonable inclusion of all data. This range of levels is the basis of our proposed empirical prediction technique, see Section 3.2.

Figure B-1 shows noise levels reported by Wilson for the Chicago Transit System [35]. The data show the importance of rail joints, wheel flats, and roughness on wayside noise. The data also indicate that levels can be reduced by modifications to the vehicle -- in this case use of soft journal sleeves.

Figure B-2 shows data for subway type cars on at-grade track. Data for the German U-Bahn [18] and the BART test track [40] are within the range of the empirical prediction. Data for the Boston red line show levels approximately 5 dB higher [109]. The increase in noise level may be due to rail or wheel roughness or wheel flats.

Figure B-3 shows data reported by Bender and Heckl [110]. The test conditions are not accurately described and this may account for the large variation between the Berlin and Hamburg systems.

Figure B-4 shows data for suburban type trains [18 , 28]. These trains have larger cars and higher axle loadings than the subway type cars. The low levels for the German S-Bahn are attributed to use of wheel skirts and pneumatic suspension [18].

Finally, in Fig. B-5 we present data for passenger trains. The high speed trains show noise levels below the empirical prediction. No explanation for this result has been found.

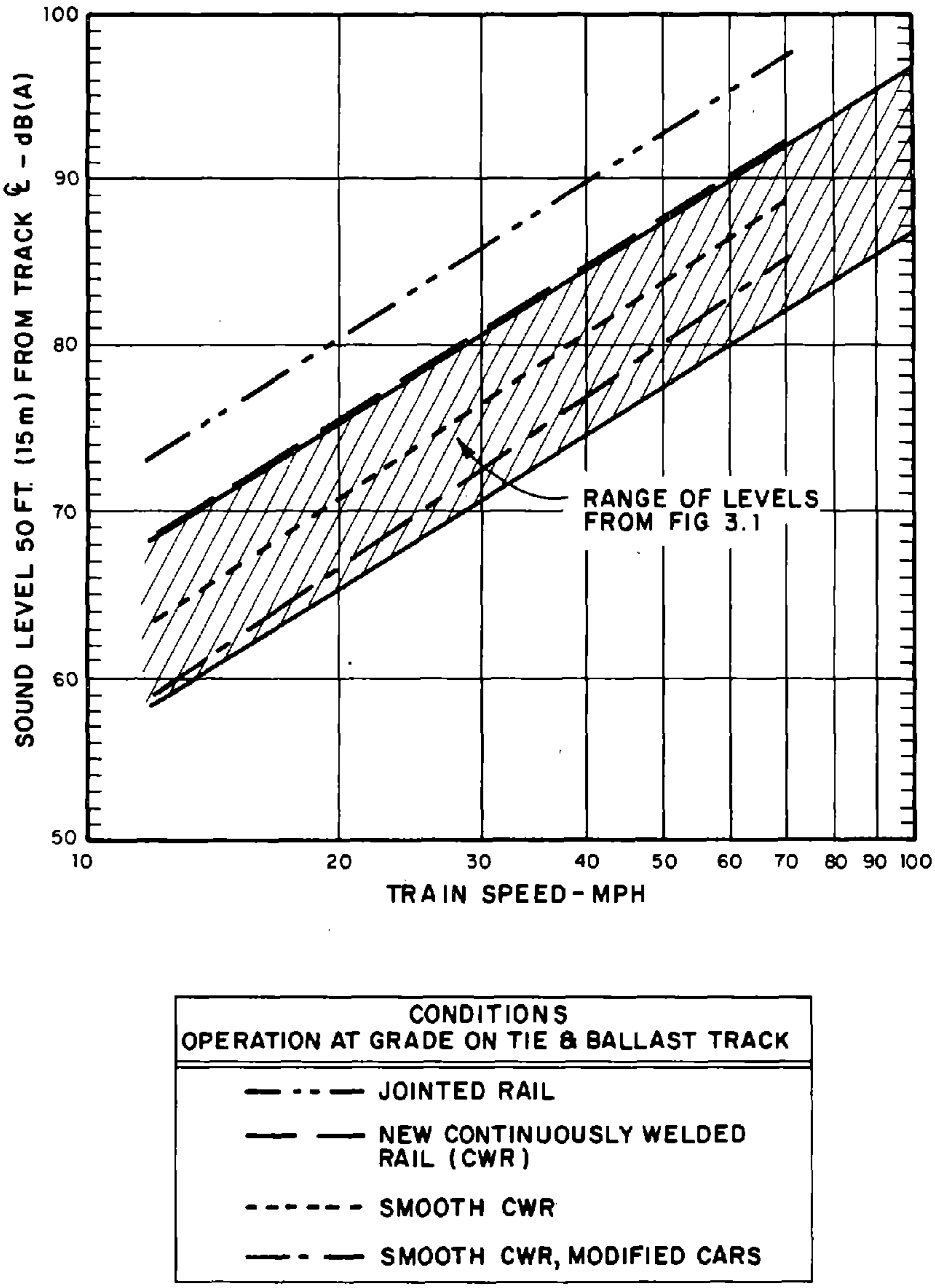


FIG. B-1 FIELD DATA FOR WAYSIDE NOISE LEVELS
- CHICAGO -

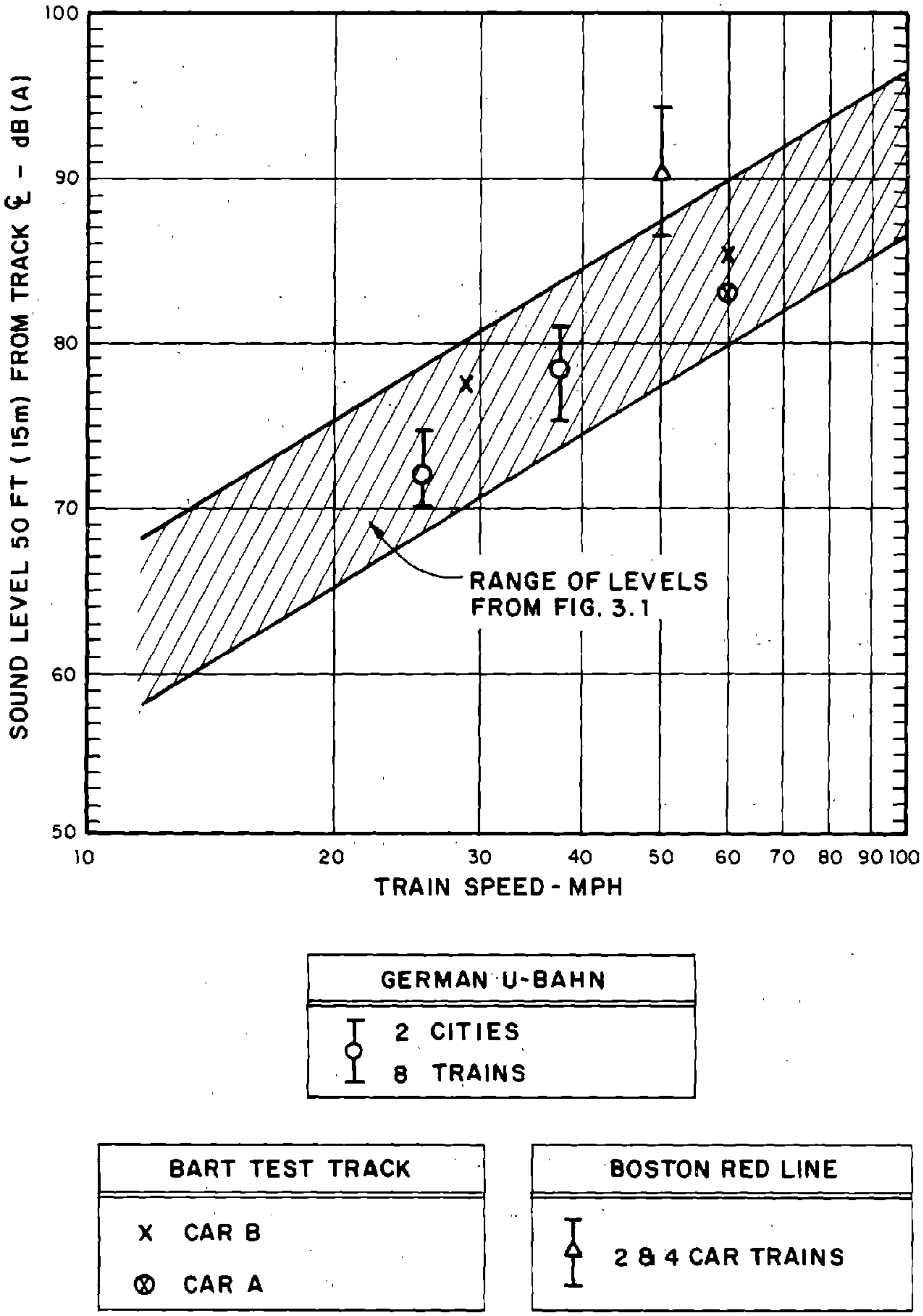
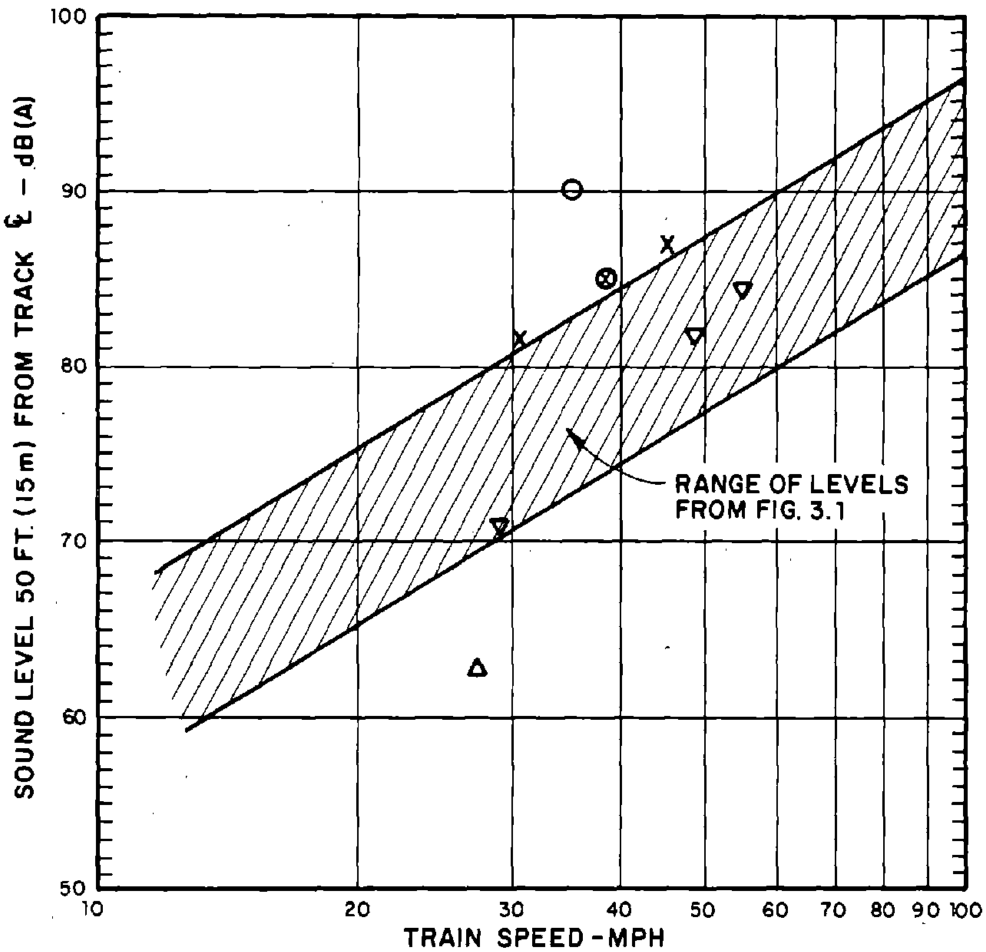


FIG. B-2 FIELD DATA FOR WAYSIDE NOISE LEVELS
— URBAN TRANSIT VEHICLES —



LONDON	STOCKHOLM
▽ DATA BY BENDER & HECKL	X DATA BY BERGLUND ⊗ DATA BY BENDER & HECKL

BERLIN	HAMBURG
△ DATA BY BENDER & HECKL	O DATA BY BENDER & HECKL

FIG. B-3 FIELD DATA FOR WAYSIDE NOISE LEVELS
– FROM REF. 110 –

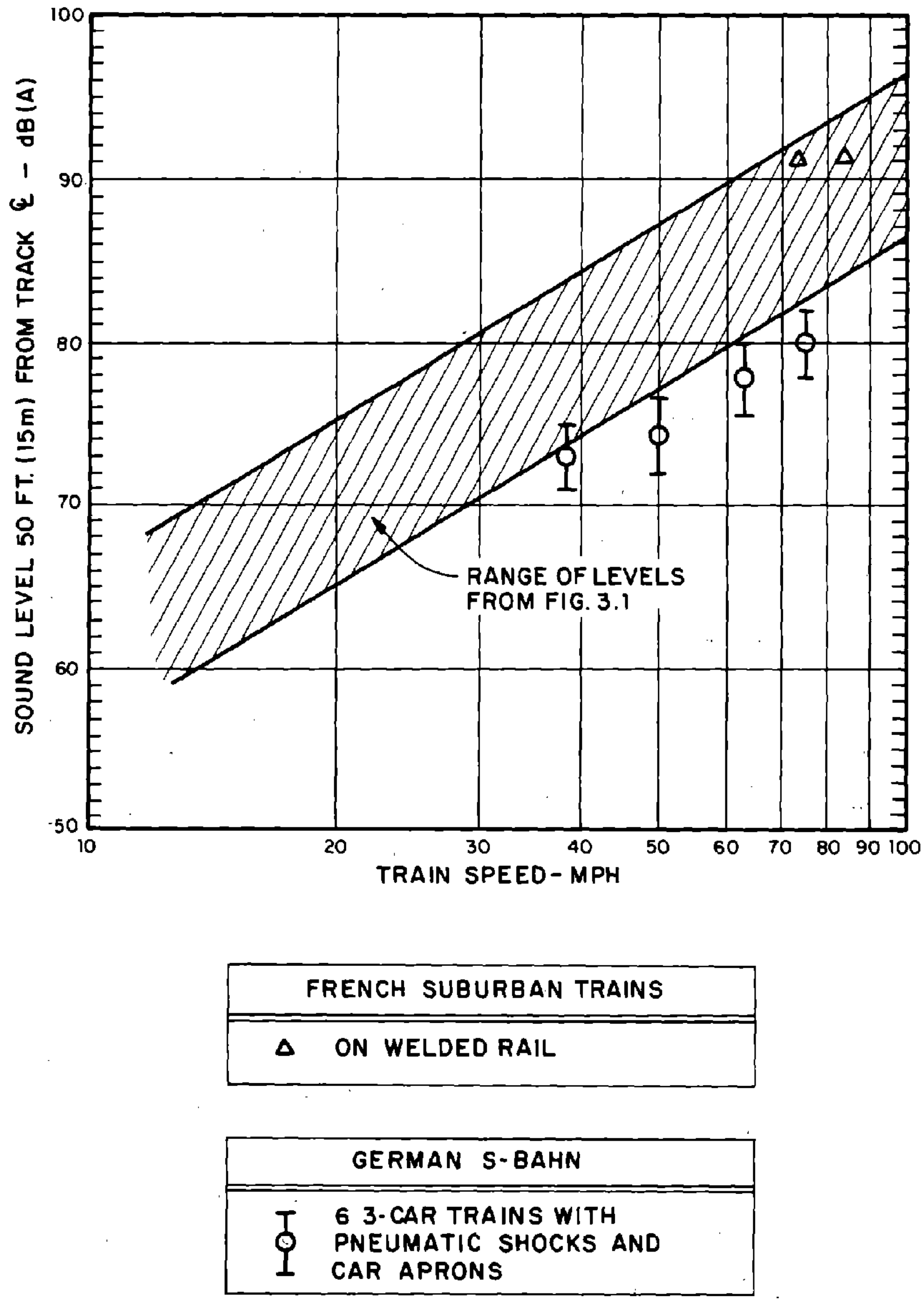


FIG. B-4 FIELD DATA FOR WAYSIDE NOISE LEVELS
– SUBURBAN TRAINS –

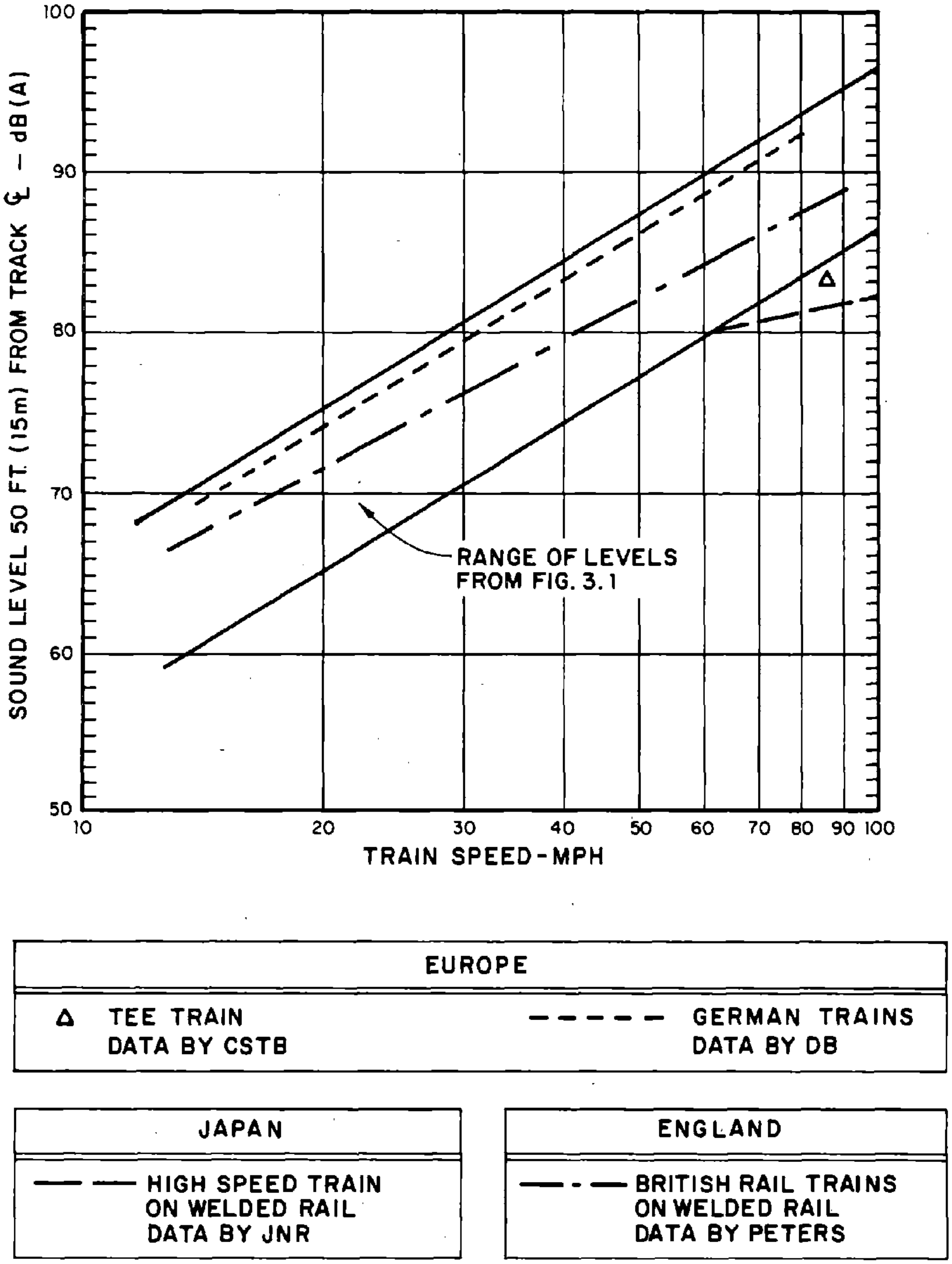


FIG. B-5 FIELD DATA FOR WAYSIDE NOISE LEVELS
— INTERCITY TRAINS —

APPENDIX C METHODS FOR PREDICTION OF NOISE FROM RAILS AND TIES

C.1 Rail Radiation

The acoustic power radiated by the rail, W_R can be given by

$$W_R = \rho_o c_o A_R \sigma_R \langle v_R^2 \rangle , \qquad (C-1)$$

where $\rho_o c_o$ is the acoustic impedance (42 in cgs units), A_R is the effective radiating area, σ_R is the radiation efficiency, and $\langle v_R^2 \rangle$ is the mean square rail velocity. The area A_R is the product of the rail perimeter and an effective length of rail. The effective radiating length, L, has not been studied extensively up to this time. However, data of track vibration during a passby indicates that the regions of large vibration levels are fairly well localized near the trucks. From the data, an effective radiating length of 5 meters (16.4 ft) per truck is calculated.

The radiation efficiency, σ_R, is given by Remington and Bender [111] with theory and experiment. Using definitions of rail perimeter, P, as given by Remington and Bender (for vertical vibration P = head width + foot width; for horizontal vibration P = height) one finds P = 6 in. (15.2 cm) in both cases. For the purpose of these calculations the experimental (rather than theoretical) values of σ_R should be used. When the effects of two rails and two trucks are included, the sound pressure level, L_p^R, at a distance of 50 ft (15 m) from the car due to rail radiation becomes

$$L_p^R = L_a^R + 10 \text{ Log } \sigma_R - 20 \log f + 123, \text{ dB re } 20\ \mu N/m^2$$

$$@\ 50 \text{ ft} \tag{C-2}$$

where L_a^R is the peak acceleration level of the rail in dB re 1 g.

C.2 Tie Radiation

A tie can be likened to a baffled rectangular piston of dimensions a x b (a = 6 in, b = 6 ft). The spectral force required to induce a uniform velocity $U(\omega)$ in such a piston is given by

$$F(\omega) = \rho_o c_o U(\omega)\ ab \left[\frac{a^2\theta(ka) - b^2\theta(kb) - ia^2\chi(ka) + ib^2\chi(kb)}{a^2 - b^2}\right] \tag{C-3}$$

where θ and χ are tabulated functions [112].

The radiated power is given by

$$W_T = \frac{1}{2} \text{ Re } [F\ U^*] \tag{C-4}$$

Since $\frac{U^2}{2} = \langle U^2 \rangle$, we find the radiated power and the radiation efficiency given by

$$W_T = \langle U^2 \rangle\ \rho_o c_o\ ab\ \frac{[a^2\theta(ka) - b^2\theta(kb)]}{a^2 b^2}, \tag{C-5}$$

and

$$\sigma_T = \frac{[a^2\theta(ka) - b^2\theta(kb)]}{a^2 - b^2} \tag{C-6}$$

But since $b >> a$ and $\theta(kb) \geq \theta(ka)$ we can approximate σ_T as

$$\sigma_T \approx \theta(kb) \qquad (C-7)$$

or using asymptotic expression for $\theta(kb)$

$$\sigma_T \approx \frac{1}{1 + \frac{16}{(kb)^2}} \qquad (C-8)$$

If we assume that 20 ties under each truck are excited at any time, then the sound pressure level at 50 ft (15m) is related to the tie acceleration by the following relationship (assuming hemispherical spreading)

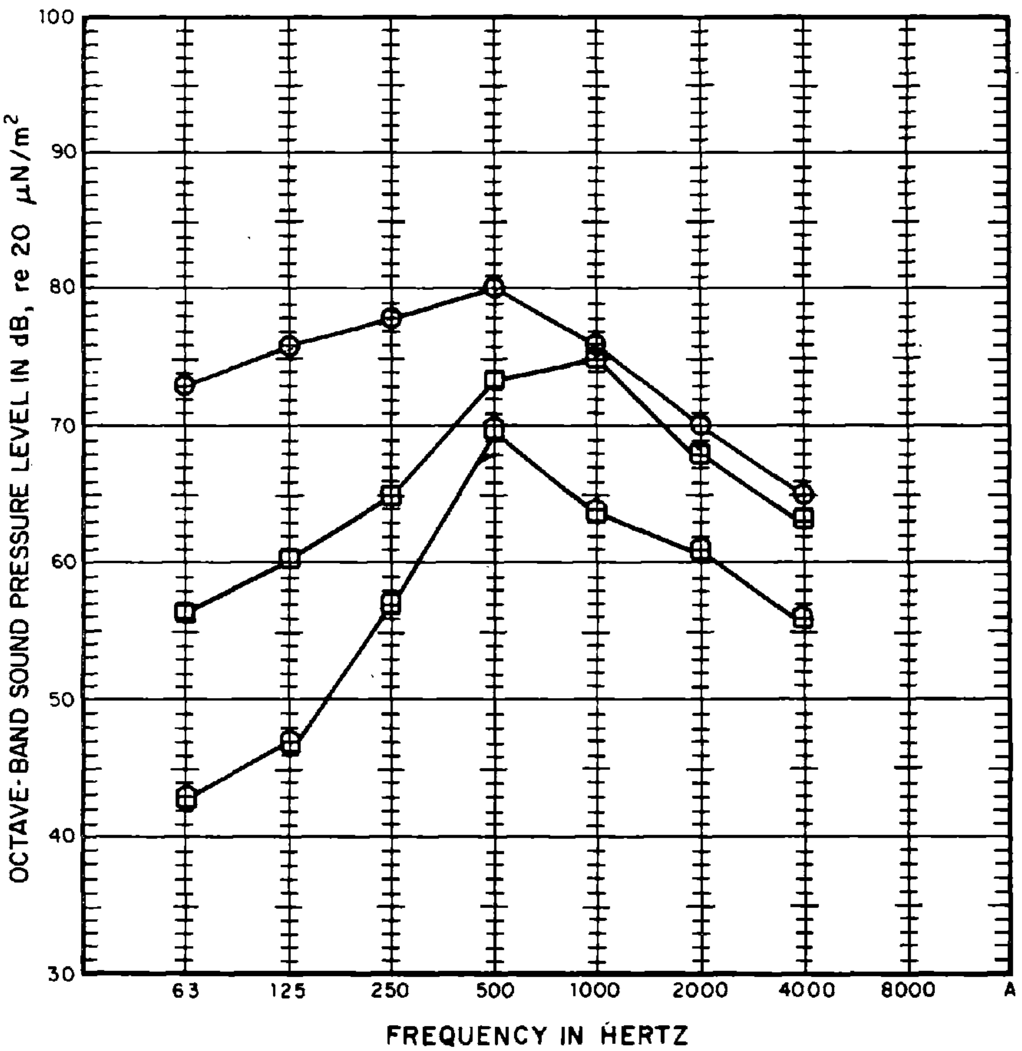
$$L_p^T = L_a^T + 10 \text{ Log } \sigma_T - 20 \text{ Log } f + 129 \qquad (C-9)$$

where L_a^T is the peak tie acceleration.

C.3 Examples of Rail and Tie Radiation

The data that can be rigorously analyzed in this manner is limited since very few rail transportation noise studies have reported simultaneous rail and tie vibration and wayside noise. However, data on BART test car A2 was recorded in a way appropriate for this analysis [113].

The results of these calculations are shown in Fig. C-1, where the measured wayside noise is plotted along with predicted rail and tie radiation.



BART TEST CAR A2

O MEASURED WAYSIDE NOISE LEVEL AT 50 FT (15m)

□ PREDICTED LEVEL FROM RAIL VIBRATION

O PREDICTED LEVEL FROM TIE VIBRATION

FIG. C-1 PREDICTED NOISE LEVELS DUE TO RAIL RADIATION COMPARED WITH MEASURED WAYSIDE NOISE [147]

Figures C-2 and C-3 also show wayside noise levels and predicted rail radiation for the S-Bahn, based on data reported by Stüber and Hauck for track in ballast bed [114].

From these Figures, it can be inferred that rail radiation is not the dominant source of acoustic radiation. At frequencies above 500 Hz the computed acoustic rail noise is from 1 to 6 dB below the overall noise level, while tie radiation is more than 9 dB below the overall noise level.

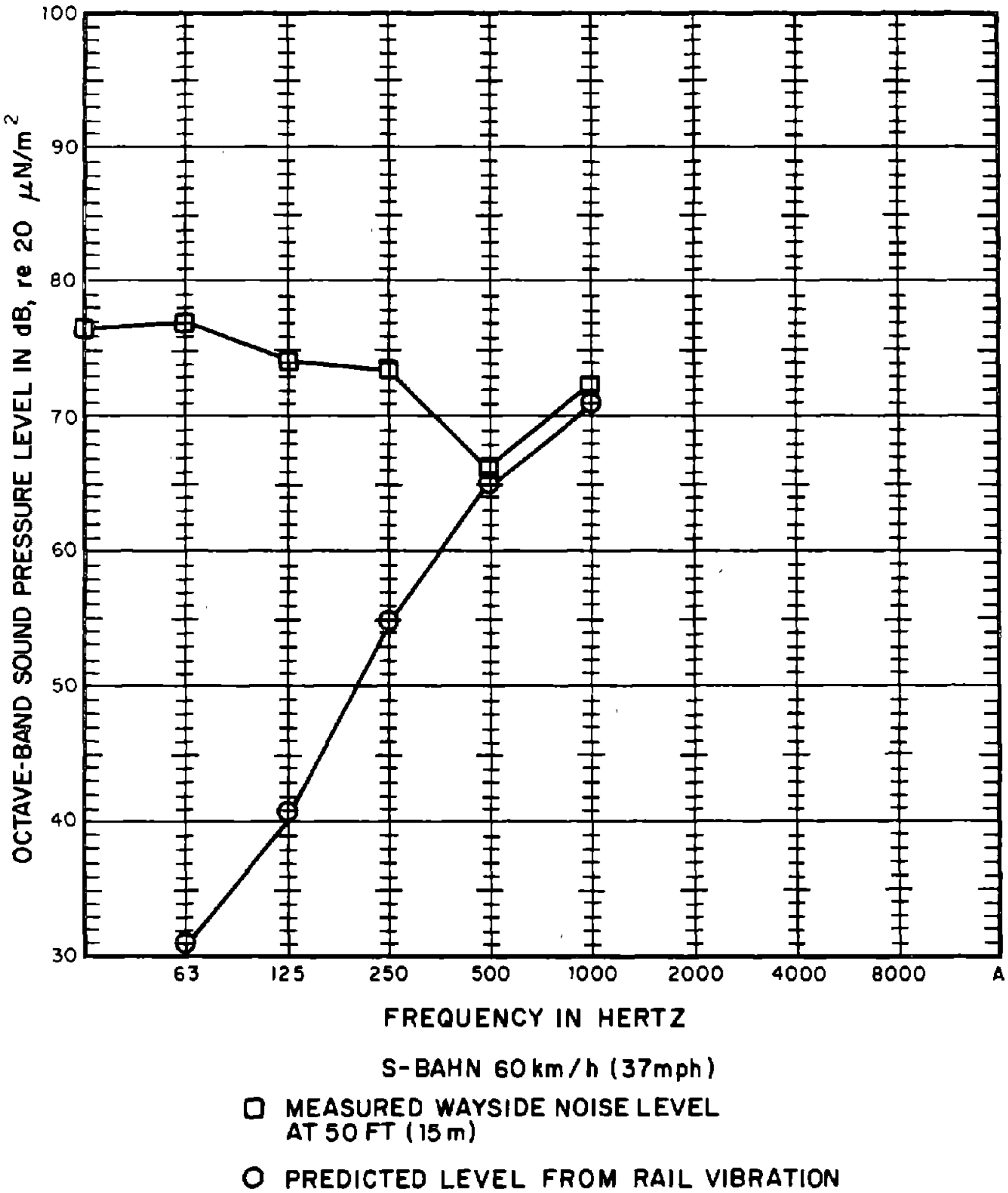


FIG. C-2 PREDICTED NOISE LEVELS DUE TO RAIL RADIATION COMPARED WITH MEASURED WAYSIDE NOISE

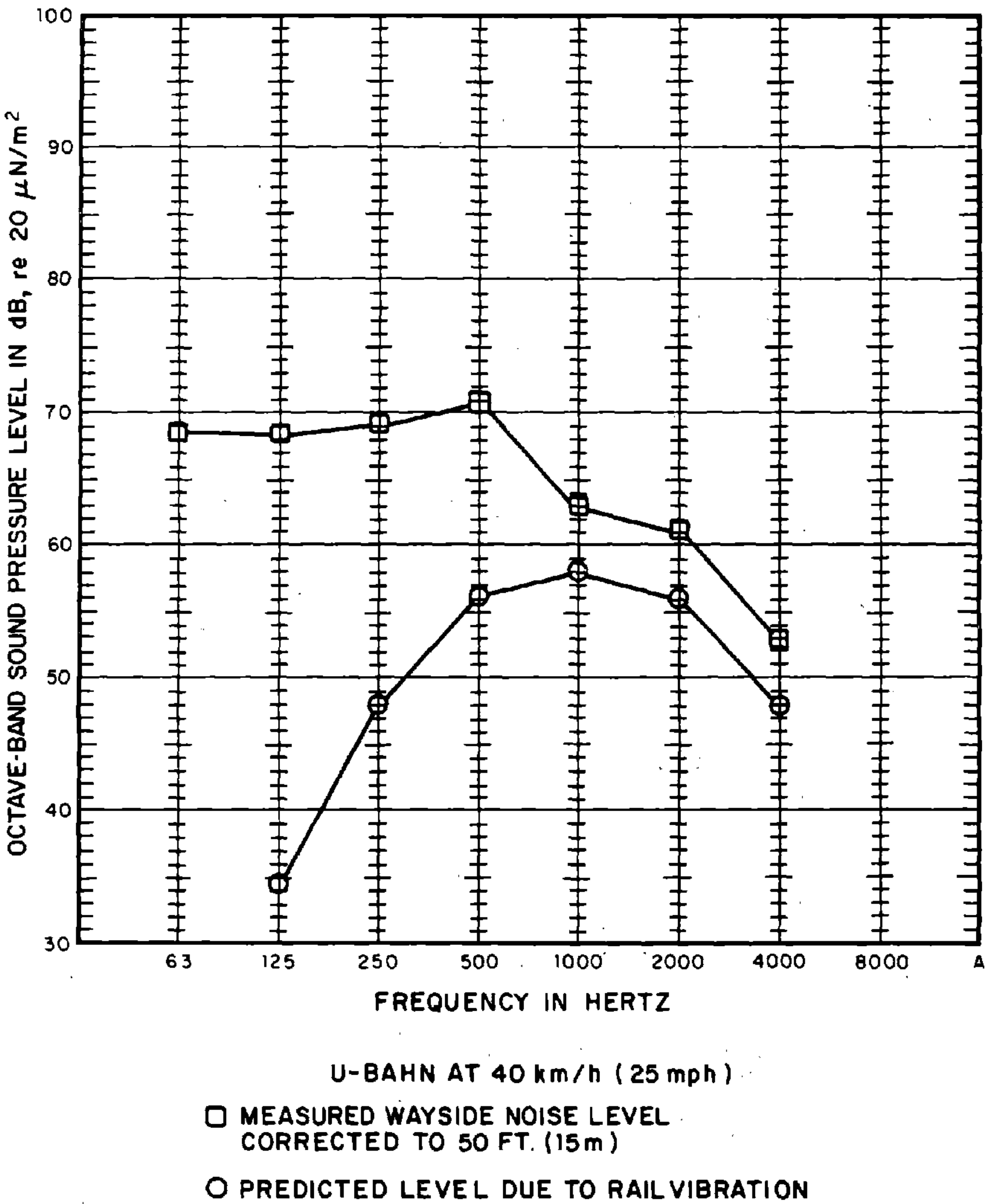


FIG. C-3 PREDICTED NOISE LEVELS DUE TO RAIL RADIATION COMPARED WITH MEASURED WAYSIDE NOISE [150]

APPENDIX D PROPAGATION OF NOISE AND VIBRATION THROUGH SOIL

The propagation of dynamic distrubances in the earth has long been of interest in seismology for earthquake analysis and for petroleum exploration. Generally, the propagation in these cases is over relatively long distances and far field analyses are used [115]. There has also been a strong interest in the local dynamic behavior of the earth as a foundation for vibrating machinery [116]. Here the driving point characteristics of the soil have been of major interest.

Recently, in connection with noise generated by trains and subways, there has been an upsurge of interest in the propagation of dynamic disturbances over relatively short distances through the soil. The distances involved generally range from a few feet to a few hundred feet. The constitutive behavior of the earth near the surface can vary widely. It may be nearly homogeneous rock, or sand, or clay or gravel, or a heterogeneous mixture with a varying water content. Most analytical models used to predict the dynamic behavior of soil employ one or more layers of ideal homogeneous isotropic linearly-elastic or viscoelastic material. Wave propagation in such systems is complicated by the presence of three different types of waves: dilatational or P-waves, shear or S-waves, and surface or interface waves such as Rayleigh waves, Love waves or Stoneley waves. At present only very simple models have been used to interpret and predict the propagation of vibration from subway tunnel walls to nearby basement rooms. It is sometimes assumed that the dilatational waves alone are responsible for the energy transfer. In the case of railway excitation at-grade or of excitation through the columns of elevated rapid transit tracks it is probable that the major share of energy propagated away through the earth is in the form of surface waves; e.g., Rayleigh waves.

The discussion which follows is divided into two parts. The first part deals with propagation in the interior of the soil when surface waves are not present. The second part deals with propagation near the surface where surface waves play a major role. In both parts the nature of current estimation procedures are discussed and compared with measurements where possible. A technique for making future measurements of soil vibration is recommended.

propagation within the interior of a soil medium

Although soil usually deforms nonlinearly under the large static loads applied by structural foundations, for the small disturbance levels involved in soil vibrations due to transit vehicles it is generally adequate to model the soil as a linear viscoelastic medium. For an ideally accurate model of a particular soil location it would generally be necessary to employ a non-isotropic viscoelastic medium whose dynamic parameters varied with position, temperature, frequency, moisture and previous strain history. Such an ideal model is far beyond the realm of practical attainment in the present state of the art. At the present time, the model universally proposed is a single homogeneous isotropic medium or a (small) number of layers of such media. A homogeneous isotropic viscoelastic medium is characterized by the following dynamic properties. The mass density ρ, the complex shear modulus $G(1 + i\eta_s)$ for strains with a time factor $e^{i\omega t}$, where G is the elastic shear modulus and η_s is the shear loss factor, and the complex dilatational modulus $D(1 + i\eta_d)$ D is the elastic dilatational modulus and η_d is the dilatational loss factor. The elastic parameters G and D can be expressed in terms of the Lamé parameters λ and μ as follows

$$D = \lambda + 2\mu \qquad G = \mu \tag{D-1}$$

or in terms of the tension modulus E and Poisson's ratio ν as follows

$$D = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \qquad G = \frac{E}{2(1+\nu)} \tag{D-2}$$

For certain soils [117] the loss factors η_s and η_d appear to be equal to one another. In such cases the viscoelastic Poisson's ratio remains real and there are only four independent dynamic parameters instead of five.

In a plane dilatational wave propagating in the x-direction through a homogeneous isotropic viscoelastic medium all stresses and strains fluctuate in proportion to [117]

$$\mathrm{Re}\,\{e^{-\alpha_d x}\, e^{i\omega(t - \frac{x}{c_d})}\} \tag{D-3}$$

where α_d is the dilatational attenuation factor and c_d is the dilatational wave velocity. These quantities are given by

$$\alpha_d = \beta_d \frac{\omega}{2c_d} \qquad c_d = \psi_d\sqrt{\frac{D}{\rho}} \tag{D-4}$$

where β_d and ψ_d depend on the loss factor η_d as follows

$$\beta_d^2 = 4\,\frac{\sqrt{1+\eta_d^2}-1}{\sqrt{1+\eta_d^2}+1} \qquad \psi_d^2 = \frac{2\,(1+\eta_d^2)}{\sqrt{1+\eta_d^2}+1} \qquad \text{(D-5)}$$

For light damping these can be approximated by

$$\beta_d = \eta_d \qquad \psi_d = 1 \qquad \text{(D-6)}$$

The error involved in Eq. D-6 is about 2% when $\eta_d = 0.25$ and about 9% when $\eta_d = 0.5$.

Corresponding results apply to a plane <u>shear</u> wave. It is only necessary to substitute the subscript s in place of the subscript d in Eqs. D-3, D-5 and D-6 and to take in place of Eq. D-4.

$$\alpha_s = \beta_s \frac{\omega}{2c_s} \qquad c_s = \psi_s \frac{G}{\rho} \qquad \text{(D-7)}$$

The dynamic properties of the soil in a given location should ideally be measured by dynamic tests in situ [119]. In general such properties depend on frequency, temperature, moisture content and on the previous strain history of the soil. The large strains involved in removing a sample for test in the laboratory can cause large shifts in the dynamic parameters [117,118].

In the measurements of underground railway and transit noise propagation that have been reported so far, there has been no attempt made to measure any of the dynamic properties of the soil at the site. For purpose of estimation it is usual to assume nominal values from tables [116,119] of values that have been assembled from various sources.

<u>propagation of vibration from a subway wall surface to a nearby cellar wall or floor</u>

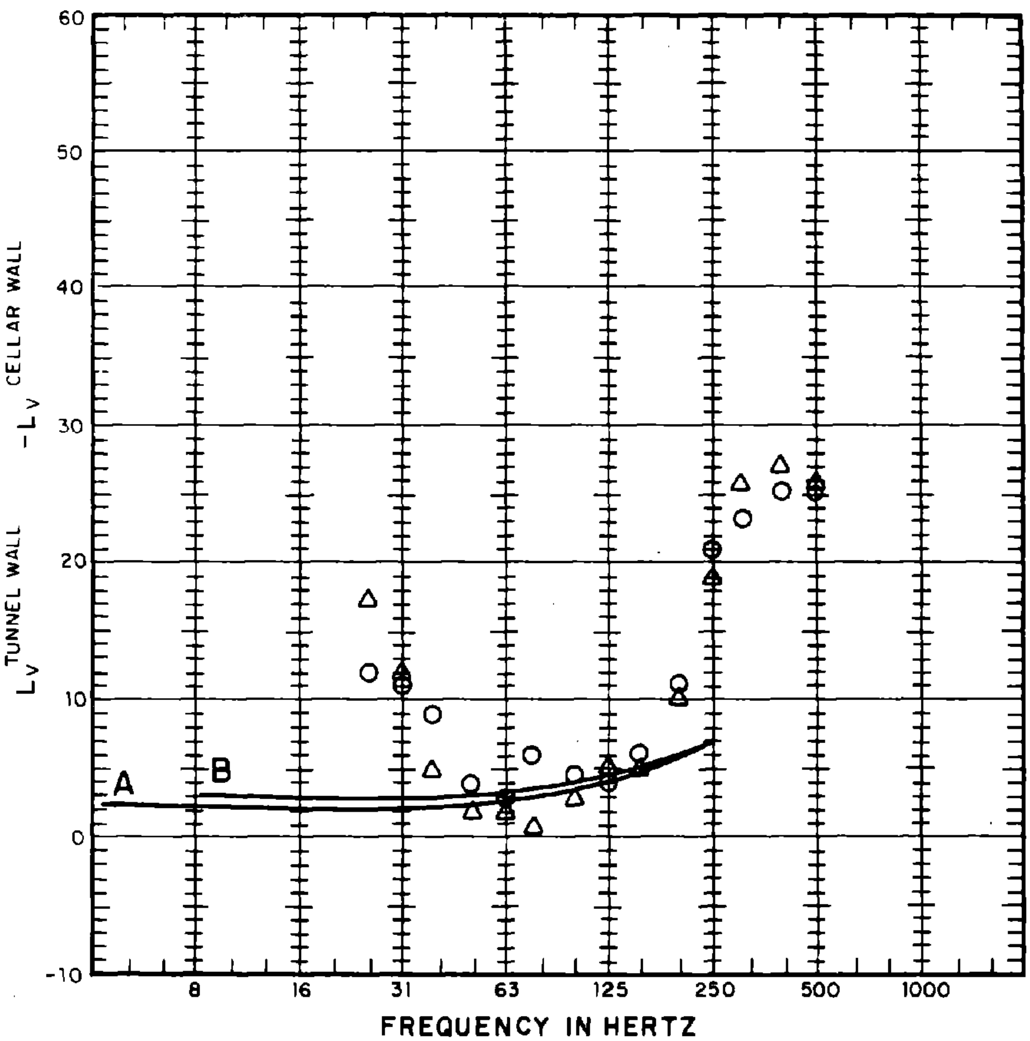
There have been a number of measurements made of the vibration levels of the walls and ceilings of subway structures and of the vibration of the walls or floors of adjacent cellars. A realistic analytical model of this phenomenon appears to be beyond our present capabilities. In principal it should be possible to go from a space-time description of the subway wall motion to a complete description of the vibration field in the soil and to the response of the nearby cellar structure. Unfortunately, the problem of coupling between a subterranean structure and a surrounding visco-elastic medium is much more difficult than the corresponding problem of coupling between a vibrating structure and a surrounding acoustic medium. In both cases there is a non-radiating near field and a radiated far field with an associated directivity pattern. In the acoustic field these have only a single dilatational component while in the viscoelastic field these have both dilatational and shear components. When the subterranean structure is close to the surface the radiated field also includes Rayleigh waves. In addition, the data presently consists of band-averaged levels of motion at either a single point on the structure, or a small number of separate points with no cross-correlation information.

A reasonably complete model of the transmission of vibration through the soil from a subway structure to a nearby cellar thus appears to be unattainable. As a consequence, grossly oversimplified models have been employed

[119,120,121] to predict subway induced noise and vibration. Generally, the vibration level measured at a single point on the tunnel wall is assumed to define an omni-directional field, any near field or free surface wave interaction is neglected, the far field is taken to be either a simple dilatational wave [119] or an assumed combination of dilatational and shear waves [120,121] which attenuate 3 dB per distance doubling due to cylindrical spreading and 8.68 α dB per meter due to dissipation (here the attenuation factor α is either α_d for simple dilatational waves [119] or an effective attenuation depending on both α_d and α_s when both dilatational and shear waves are present [120,121]). Finally it is assumed that the cellar structure does not interfere with the radiating far field. The predicted value of cellar wall motion is simply assumed to be the same as that of the soil in the far field at the same distance from the source.

To illustrate the predictive powers of these simplified models, measurements from six different subway systems are compared with predictions according to References [119] and [121] in Figures D-1 through D-6. In each case the differences between the vibration level on the subway wall and the level on cellar wall or floor, in decibels, is plotted against frequency.

The two models differ in the assumed value of soil loss factor and in the assumed value of effective source diameter. As can be seen in the figures, the two models predict essentially the same attenuation for short distances (less than 10 ft. or 3 meters) and increasingly diverge for larger distances, until at 56 ft (17 meters) there is 3 to 10 dB difference in the frequency range from 8 to 250 Hz.



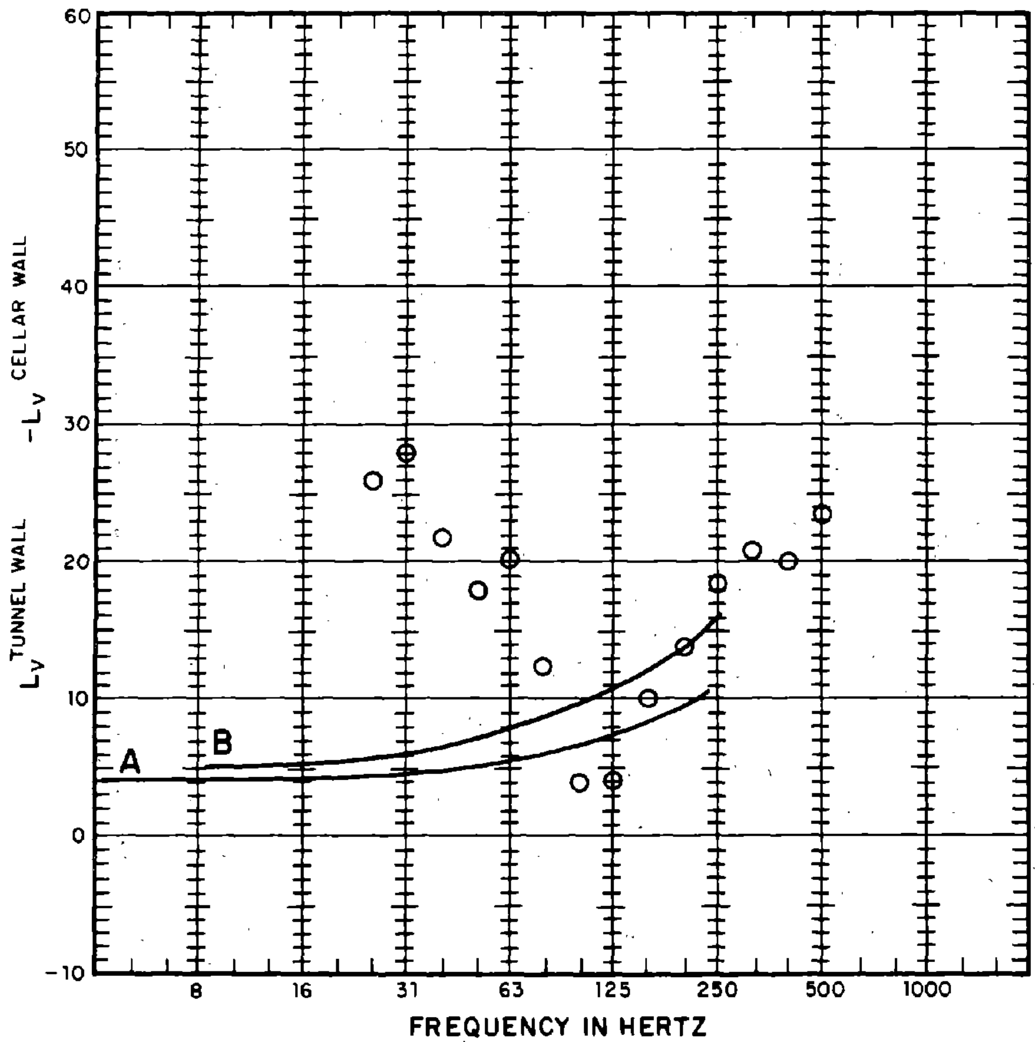
A - PREDICTION FROM REF. [119]

B - PREDICTION FROM REF. [121]

Δ - MEASUREMENT, MUNICH U-BAHN, RUBBER-CORK COVERING ON TIES, UNDER TRACK REF. [122]

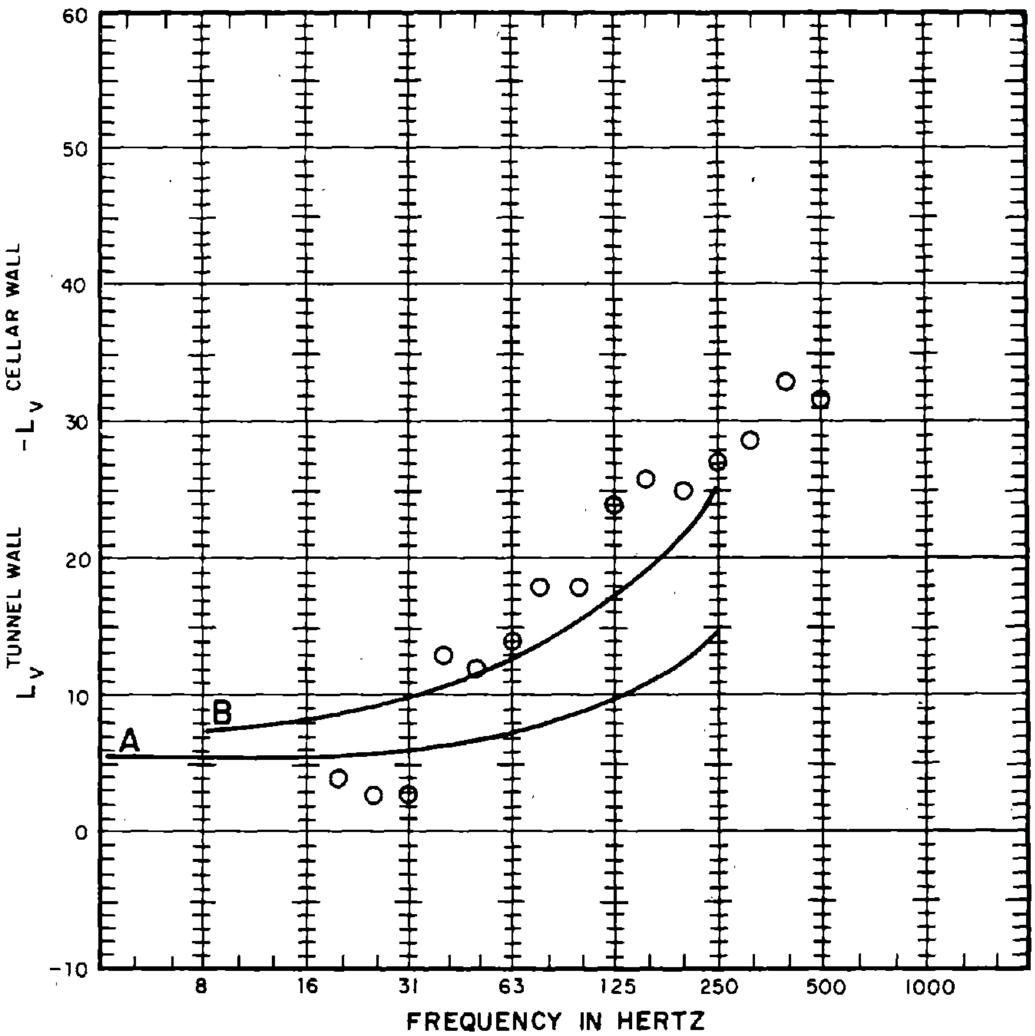
O - MEASUREMENT, MUNICH U-BAHN, POPLAR WOOD TIES REF. [122]

FIG. D-1 DIFFERENCE BETWEEN ONE-THIRD OCTAVE BAND TUNNEL WALL VIBRATION LEVELS AND THE VIBRATION LEVELS OF A CELLAR WALL 10 FT (3.05 METERS) AWAY



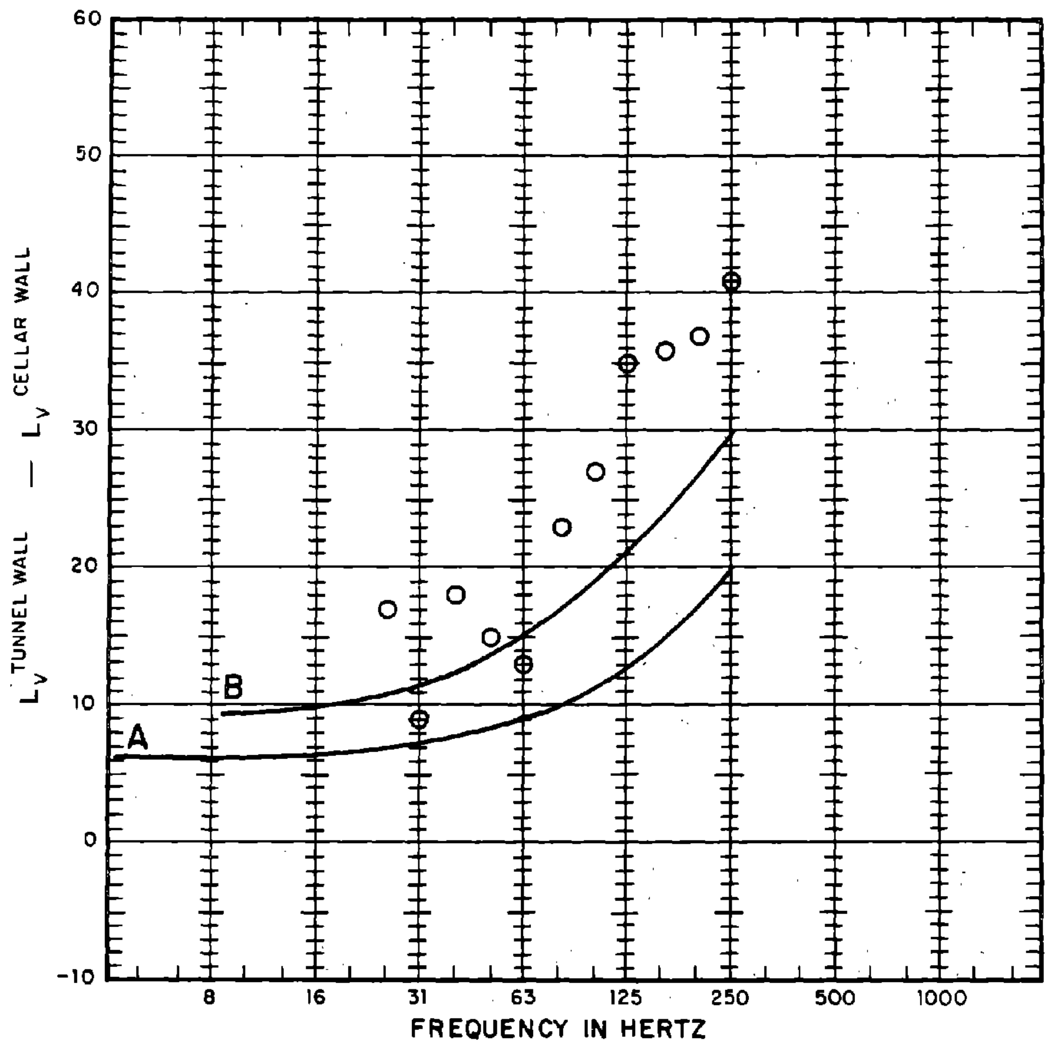
A - PREDICTION FROM REF. [119]
B - PREDICTION FROM REF. [121]
O - MEASUREMENT, TORONTO SUBWAY [123]

FIG. D-2 DIFFERENCE BETWEEN ONE-THIRD OCTAVE BAND TUNNEL WALL VIBRATION LEVELS AND THE VIBRATION LEVELS OF A CELLAR WALL 20 FT (6.1 METERS) AWAY



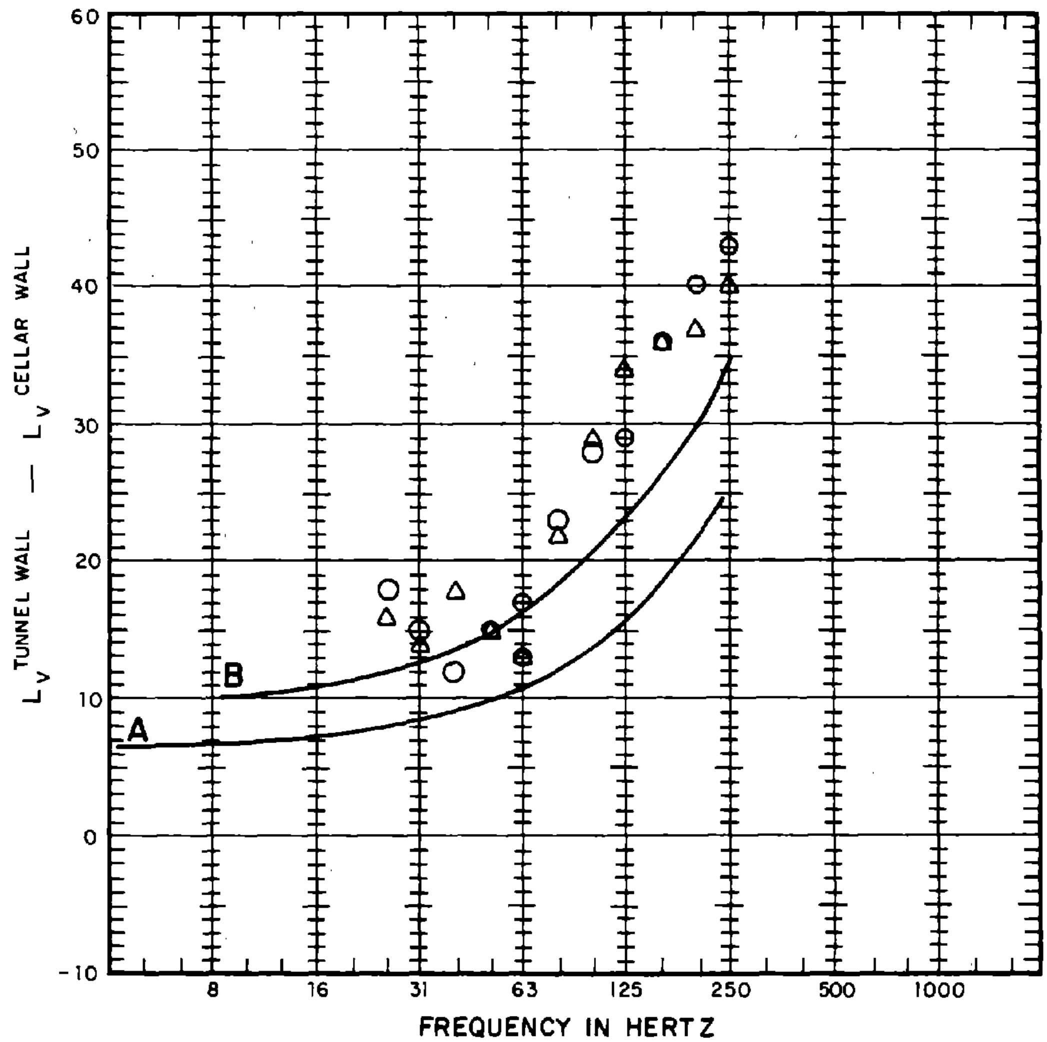
A - PREDICTION FROM REF. [119]
B - PREDICTION FROM REF. [121]
O - MEASUREMENT, MUNICH S-BAHN [124]

FIG. D-3 DIFFERENCE BETWEEN ONE-THIRD OCTAVE BAND TUNNEL WALL VIBRATION LEVELS AND THE VIBRATION LEVELS OF A CELLAR WALL 33 FT (10.1 METERS) AWAY



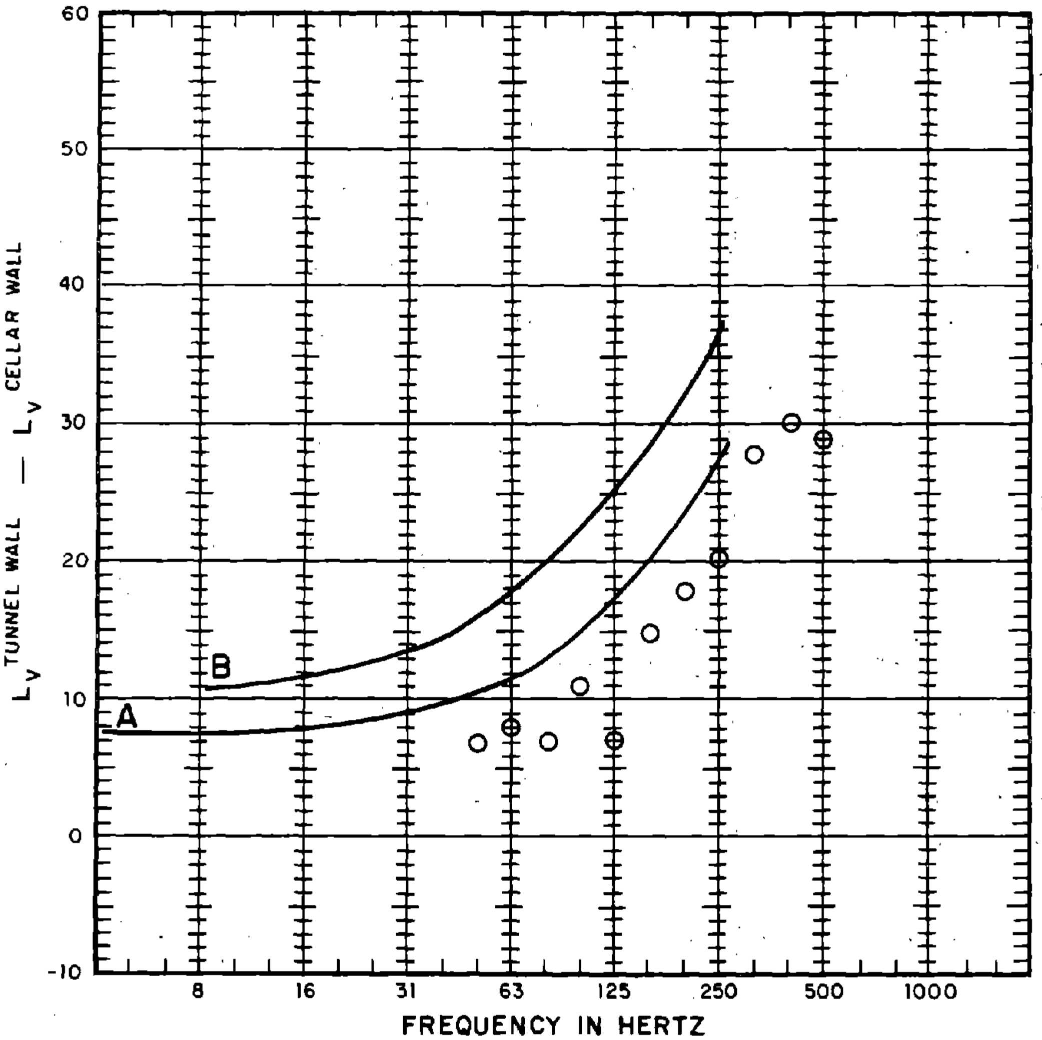
A - PREDICTION FROM REF. [119]
B - PREDICTION FROM REF. [121]
O - MEASUREMENT, MUNICH U-BAHN [124]

FIG. D-4 DIFFERENCE BETWEEN ONE-THIRD OCTAVE BAND TUNNEL WALL VIBRATION LEVELS AND THE VIBRATION LEVELS OF A CELLAR WALL 43 FT (13.2 METERS) AWAY



A - PREDICTION FROM REF. [119]
B - PREDICTION FROM REF. [121]
Δ - MEASUREMENT, HAMBURG U-BAHN, BALLASTED STRUCTURE [122]
O - MEASUREMENT, HAMBURG U-BAHN CLOUTH STRUCTURE [122]

FIG. D-5 DIFFERENCE BETWEEN ONE-THIRD OCTAVE BAND TUNNEL WALL VIBRATION LEVELS AND THE VIBRATION LEVELS OF A CELLAR WALL 49 FT (15 METERS) AWAY



A - PREDICTION FROM REF. [119]
B - PREDICTION FROM REF. [121]
O - MEASUREMENT, NURNBERGER U-BAHN [125]

FIG. D-6 DIFFERENCE BETWEEN ONE-THIRD OCTAVE BAND TUNNEL WALL VIBRATION LEVELS AND THE VIBRATION LEVELS OF A CELLAR WALL 56 FT (17 METERS) AWAY

There is some correlation between the measurements and the predictions, but not much. In general, the scatter of the data points is greater than the discrepancy between the two simplified predictions. The greatest single discrepancy between measurement and prediction is 23 dB. In retrospect, the poor prediction in Fig. D-6 for the Nurnberger measurement can be partially explained by the shallow location of the subway and the surmise that considerable energy must have been propagated by surface waves which don't have any spreading loss from a line source.

The data points shown in Fig. D-2 were obtained by using the high wall measurements in the Woodbine to Main tunnel for input and the cellar floor measurements in Mr. Austin's cellar [123] for output. The relative position of the subway and cellar as given in [120] is sketched in Fig. D-7. The distance between the measurement points as shown in Fig. D-7 is approximately 20 ft (6 meters).

propagation by surface waves along the ground

When the source of vibration is a transit vehicle in a deep tunnel the noise and vibration is propagated to neighboring structures by dilatational and shear waves as discussed above. In the cases of tracks at grade and of elevated guideways the vibrations of transit vehicles transmitted to the ground will excite significant surface waves in addition to dilatational and shear waves. Here the predominant traction of vibratory energy transmitted to neighboring structures can be due to surface wave propagation.

In a homogeneous viscoelastic half space there is only one type of surface wave: the Rayleigh wave. This is a nondispersive wave with a propagation velocity c_R somewhat

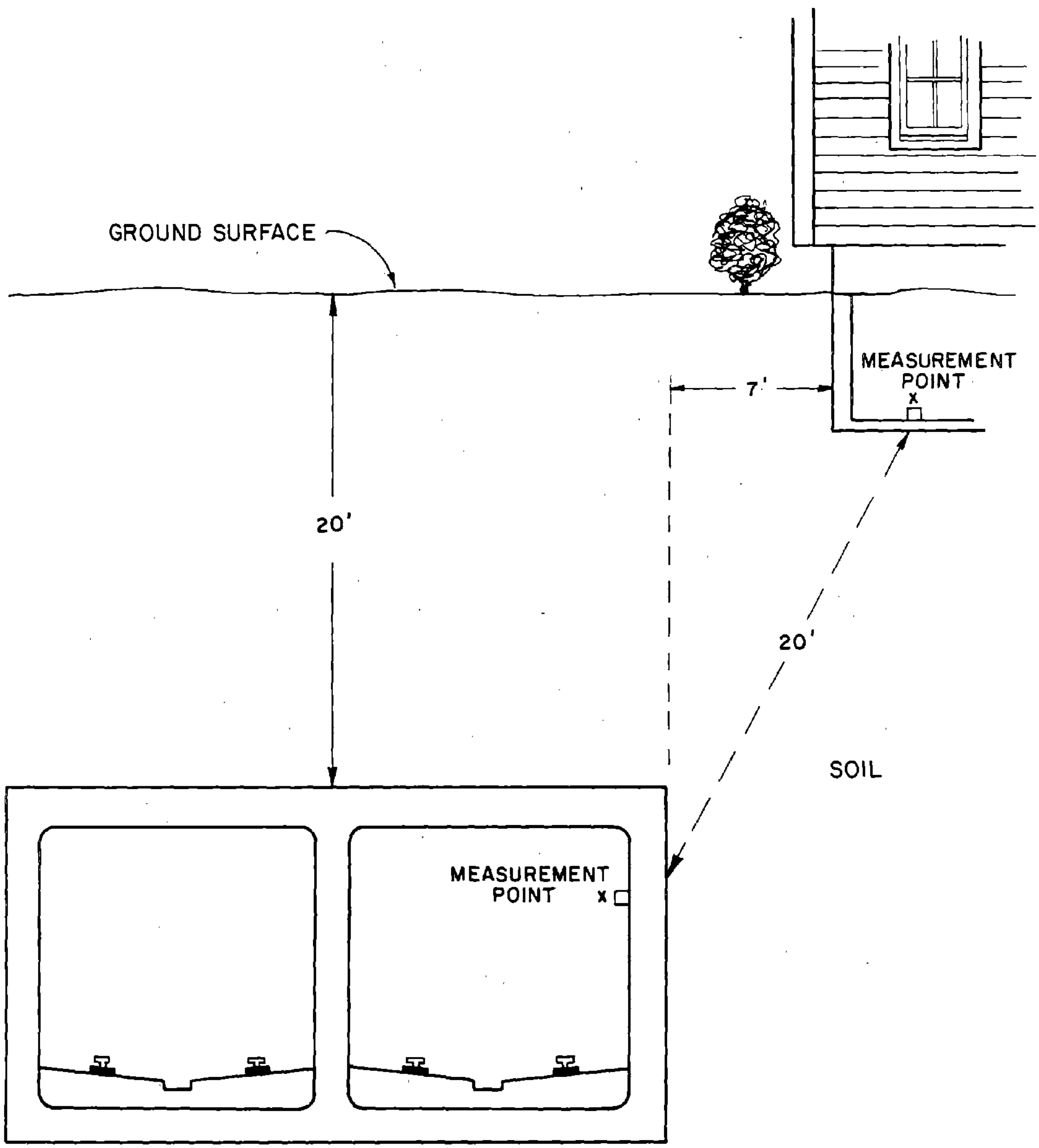


FIG D-7 SIMPLIFIED SCHEMATIC OF SUBWAY-CELLAR CONFIGURATION AT HOME OF L. AUSTIN, TORONTO smaller than the shear wave velocity c_S (in a lossless medium c_R/c_S ranges between 0.8741 and 0.9554 as Poisson's ratio changes from 0 to 0.5 [126]). The particle motion in a plane Rayleigh wave consists of elliptic orbits in a vertical plane parallel to the direction of propagation. The size and orientation of the orbits vary with depth below the surface. At the surface the orbit is retrograde and the vertical axis of the ellipse is about twice as long as the horizontal axis. In the first half wavelength below the surface the vertical axis changes very little (first increasing and then decreasing) while the horizontal axis decreases to zero and then grows again to nearly half its original magnitude. The sense of the orbit changes from retrograde to direct at the level (about 1/6 to 1/4 of a wavelength) where the horizontal motion vanishes. At depths below 1/2 of a wavelength the size of the orbit decays substantially exponentially with depth with little change in the aspect ratio. At a depth of one wavelength the level of the orbital motion is about 10 dB down from that of the surface. For greater depths the attenuation rate is greater than 16 dB per wavelength (the specific value depends on Poisson's ratio ν and the dissipation: for no dissipation the attenuation per wavelength ranges from 16.1 dB for $\nu = 0.5$ to 26.5 dB for $\nu = 0$).

The behavior of Rayleigh waves just cited follow from the theory. Unsuccessful attempts to verify this behavior by measurements in soil are reported by Barkan [116]. It is possible that this reflects the difficulty of making dynamic measurements in soil rather than a failure of the theory.

A considerable amount of theoretical information is known about the dynamics of a homogeneous isotropic elastic halfspace. Starting with Lamb [127] the nature of the far field has been carefully studied [115]. Miller and Pursey [128] calculated that when the half space is excited by a steadily oscillating circular disk the energy propagated away in the far field is portioned as follows, when $\nu = 0.25$:

surface wave (Rayleigh)	67%
body waves	
shear wave	26%
dilatational wave	7%

The body waves are subject to a 6 dB per doubling of distance attenuation due to spreading in the interior, while the Rayleigh wave on the surface is subject to only 3 dB per doubling of distance attenuation. At large distances from the source the total surface motion can be decomposed into a (large) Rayleigh wave component and (small) shear and dilatational wave components. These latter two surface components decay at the rate of 12 dB per doubling of distance.

The local dynamic response of a half-space due to excitation by an oscillating disk has been widely studied. Starting from the initial formulation by Reissner [128] the solution of the problem has been gradually improved by numerous authors, until now reasonably complete, accurate results are available [130,131] for the driving point impedance of an elastic half space when driven by a rigid circular disk in vertical, horizontal, rocking or twisting motion. For example, under vertical excitation the half space reacts like a highly damped spring for low frequencies. The damping is due to the radiation of energy away on the surface (by Rayleigh waves) and into the interior (by shear and dilatational waves) At higher frequencies the half space reacts like a highly damped mass. The crossover from springlike to masslike behavior occurs when wavelength of the surface waves generated is about the same length as the diameter of the disk. These results for an elastic half space can be extended to a viscoelastic medium by a simple approximation due to Bycroft [131] and Kurzweil [132].

These impedance results can be used to predict the dynamic response of foundations and structures by application of Thevenin's theorem [132] provided the dynamic soil properties are known. They can also be used in reverse to infer the dynamic soil characteristics[132,133] from measurements of a disk response.

The combination of a simple rigid massive disk placed on a visco-elastic half space behaves very much like a damped oscillator with six degrees of freedom. When the soil is lightly loaded (small mass with large diameter) the combination is heavily damped. When the soil is heavily loaded (large mass with small diameter) the combination is lightly damped and has strong resonances. For disks of appreciable thickness the coupled rocking and horizontal modes have lower natural frequencies than the vertical mode while the torsional mode has a higher natural frequency than the vertical mode.

Recently, computer studies have been made [134-137] of the vibratory response of a disk on an elastic half space excited by the motion of a second disk some distance away on the half space. This is a very important problem whose complete solution will provide a useful tool for estimating vibration propagated by surface waves. The solutions so far obtained are limited to particular parameter choices and to the case where the transmitting and receiving disks are identical. The center-to-center distance between disks is usually 5 disk diameters, although some calculations for the case of 15 disk-diameter spacing have been made.

When the transmitting disk is excited in the vertical direction at various frequencies the receiving disk responds well when the excitation coincides with the vertical resonant frequency or a coupled horizontal and rocking resonant frequency, of the receiving disk. It is possible for the vertical motion at the edge of the receiver disk during a rocking resonance to be greater than the receiver vertical motion during the vertical resonance even though the transmitter motion has the same amplitude at both frequencies.

A simple acoustical explanation can be given for the propagation phenomena involved in the two-disk problem. Figure D-8 shows a transmitter disk of mass m_1 being excited by a harmonic force. The driving point response amplitude A_1C_1 can be obtained from a simple calculation involving the impedance of the mass and the driving point impedance of half space. Also from the far field solution [142] the amplitude of the diverging Rayleigh wave can be determined. At large distances the free surface motion is essentially just the Rayleigh wave component. This amplitude is indicated by A_2B_2 in Fig. D-8. The amplitude of the Rayleigh wave component when extrapolated back to the edge of the transmitter disk (taking into account the circular spreading and dissipation) is A_1B_1.

If the receiver disk with mass m_2 were absent the vertical surface amplitude at that location would be A_2B_2. For simplicity, only the vertical response is considered here. The actual amplitude A_2C_2 when the disk is present can

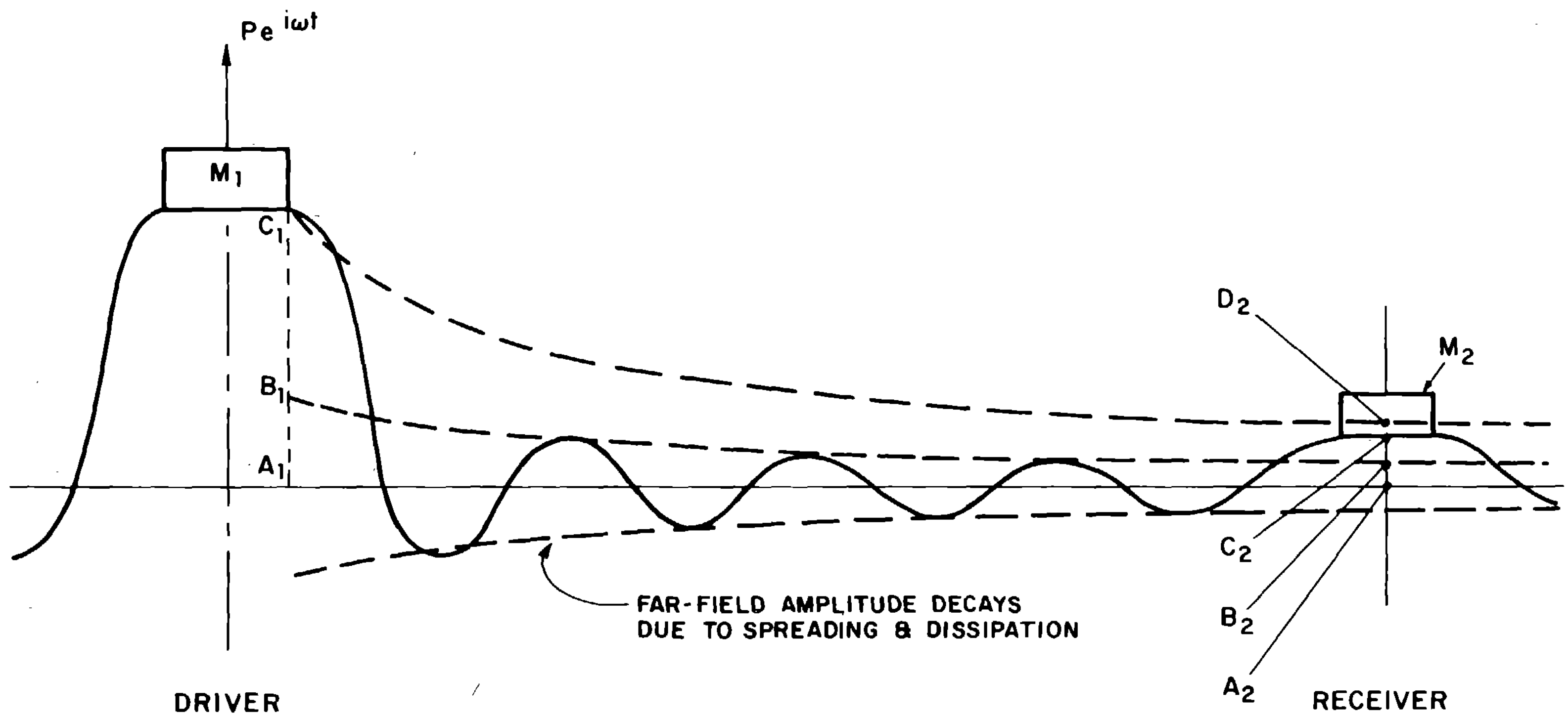


FIG. D.8 ILLUSTRATION OF GROUND-BORNE VIBRATION TRANSMISSION be estimated from a simple application of Thevenin's theorem, using the driving point impedance and the free motion of the half space to drive the impedance of the mass m_2. Strictly speaking, this acoustic approximation is incomplete because it neglects the effects back at the transmitter due to the interaction force introduced between the receiver and the half space. Nevertheless, the quantitative results obtained in this way agreed with the more exact computer solution to within 10% for the case where the center-to-center spacing between disks was 5 diameters and the half space was an elastic medium with $\nu = 0$. For this case, the various amplitude ratios in Fig. D-8, expressed in decibels, are:

$$20 \log \frac{A_1C_1}{A_1B_1} = 10.3 \text{ dB},$$ ratio of driving point vibration amplitude to Rayleigh wave component amplitude

$$20 \log \frac{A_1B_1}{A_2B_2} = 10.0 \text{ dB},$$ attenuation due to spreading

$$20 \log \frac{A_2C_2}{A_2B_2} = 5.3 \text{ dB},$$ response magnification factor.

An alternative interpretation of this kind of result has been given by Blazier [139]. The actual amplitudes of the transmitter and receiver are A_1C_1 and A_2C_2 respectively. If the attenuation due to spreading and dissipation were applied to the entire input amplitude, the curve C_1D_2 would be obtained. The ratio between the fictitious amplitude A_2D_2 and the actual amplitude A_2C_2 is said to define a coupling loss factor or, expressed in decibels, a coupling loss attenuation. For the particular case just cited the coupling loss attenuation is

$$20 \log \frac{A_2 D_2}{A_2 C_2} = 5.2 \text{ dB}$$

Some measurements of coupling loss for an array of piles are reported in [139].

<u>attenuation of surface waves</u>

Surface waves attenuate with distance due to spreading and to dissipation. Using the far-field of a Rayleigh wave as a model one would expect a spreading loss of 3 dB per doubling of distance when the source can be taken as a point source and no spreading loss at all when the source appears like an infinitely long line source. The dissipation loss would have the form

$$\text{dB per wavelength} = 27.3\ \eta_R \qquad \text{(D-8)}$$

where η_R is the Rayleigh wave loss factor. If η_R is independent of frequency, the attenuation due to dissipation in a fixed distance should be inversely proportional to wavelength; i.e., directly proportional to frequency.

A limited number of measurements of surface vibration measurements due to railway and transit trains have been reported. The results do not fall into any simple pattern. One contributing factor is the lack of a standardized procedure for making ground vibrations.

On the basis of a survey of measurements made on the Toronto Transit Commission facility and the Bay Area Rapid Transit Commission Test Track, reference [140] proposed that ground vibration attenuation should be estimated on the basis

0.2 dB/ft (0.66 dB/m) with a scatter band of ± 5 dB.

On the basis of a similar survey of measurements on German S-Bahns reference [140] states that the attenuation for distances up to 49 ft (15 meters) of the track is of the order of 0.3 dB/ft (1.0 dB/m) with greater attenuation occuring at higher frequencies. On the other hand, with respect to long-haul trains, measurements at distances of 24.6 ft., 49.2 ft. and 98.4 ft. (7.5m, 15m and 30m) from the track were reported in the same reference [144] that appeared to show a 6 dB attenuation with doubling of distance independently of frequency.

A similar result was reported in [141] based on measurements at 17 ft. (5.2m) and at 48 ft. (14.7m). The average difference in octave-band vibration level at these two distances (for different types and speeds of trains and different specific pick-up locations) was approximately

$$20 \log \frac{48}{17} = 9 \text{ dB}$$

independent of frequency.

From a study of measurements made on piles 10.5 to 15.7 ft. (4-6m) long driven into the ground within 44.5 ft. (13.5 m) of the Nürnberger U-Bahn, Heckl [142,125] has suggested that attenuation of ground vibrations can be approximately described by the following "rules". For frequencies between 8 and 125 Hz the attenuation is at the rate of 4 dB per doubling of distance, while the frequencies between 250 and 1000 Hz the attenuation is at the rate of 10 dB per doubling of distance.

While not strictly the same kind of phenomenon, it is of interest to note that, overall sound levels dB(A) in cellar rooms near subways appear to decrease by 6 dB per doubling of distance from the subway tunnel wall. This was pointed out by Lang [147] who showed that a number of European measurements (for a wide range of trains, speeds, tunnel constructions, etc.) of sound levels in cellar rooms between 3.3 to 56 ft (1-20m) from a subway tunnel wall lay within ± 10 dB of the level given by

$$dB(A) = 59 - 20 \log \frac{R}{R_0} \qquad (D\text{-}9)$$

where R is the distance between the tunnel wall and the cellar wall in meters and R_o is one meter.

A measurement of ground vibrations out to 400 ft (122 m) in the neighborhood of a highway overpass has been recently reported [148]. One-third octave band levels exceeded 10% of the time at distances of 1.5, 100, 200 and 400 ft (0.46, 30.5, 61 and 122m) were measured and shown to be roughly correlated (scatter of individual measurements up to 15 dB) by an attenuation law of the form (8); i.e., no geometric spreading and a frequency-distance dependent dissipation law represented by a constant loss η_R. No measurements of the soil's dynamic characteristics were made. If it were estimated that the Rayleigh wave velocity was 450 ft/sec (137m/s) then the value of η_R which best fits their data is $\eta_R = 0.035$.

<u>use of trenches as barriers to surface waves</u>

Several unsuccessful attempts to use trenches and sheet-pile barriers to isolate transmitters of undesirable surface waves are reported in [116]. A thorough experimental investigation of surface wave barriers was made by Woods [145]. He showed that under certain circumstances, trenches could be effective in introducing 12 dB or more attenuation.

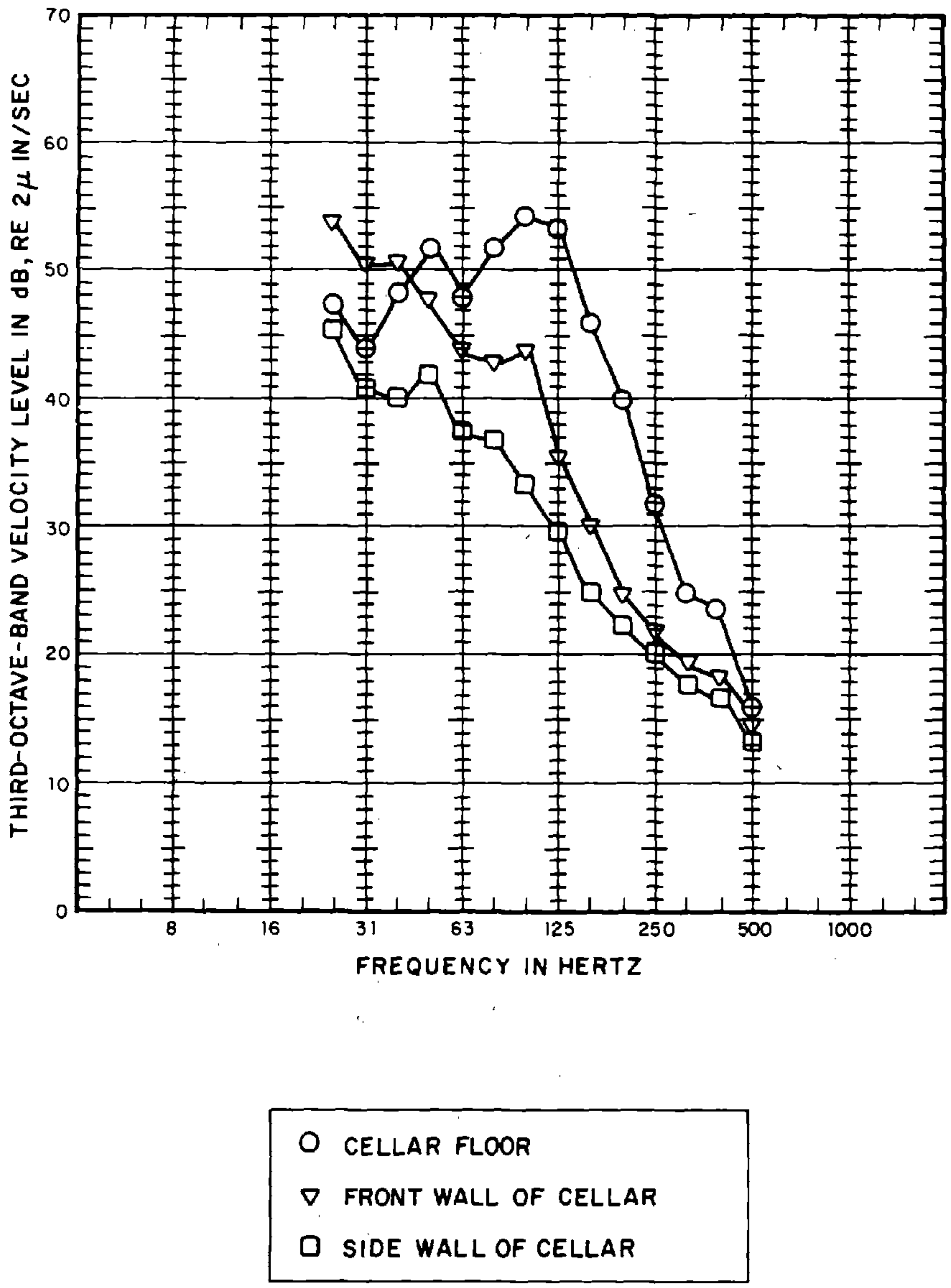
The principle requirements are that the trench depth be greater than 0.6 wavelengths and that the trench be sufficiently long that buffer zones subtending additional 45° sectors from the source are included at each end. Trench width, if greater than 1/8 of a wavelength, had little effect. Sheet pile barriers were not as effective as trenches.

sound levels in cellars due to subway noise propagated through the soil

The difficulty of accounting for the interaction between a vibrating structure and the soil in which it is imbedded has been alluded to above. In this section it is pointed out that the simpler problem of estimating the effect of the interaction between a vibrating structure and an enclosed acoustic volume is itself a difficult task.

In [123] measurements of the vibration levels at a point on the floor, at a point on the front wall (facing the subway tunnel) and a point on an end wall are reported for the cellar room indicated in Fig. D-7. These measurements, expressed as third-octave velocity levels in dB re 2×10^{-6} inches per second (5×10^{-8} m/s) are shown in Fig. D-9. Note that in general the floor levels are highest and the end-wall levels are lowest.

The reference velocity 2×10^{-6} in/sec (5×10^{-8} m/s) is the rms particle velocity in a plane acoustic wave in air at room temperature when the rms pressure difference in the wave is the standard reference pressure, 0.0002 microbars, for sound levels. If a large rigid plane area oscillates with a normal rms velocity whose level is n dB re 2×10^{-6} in/sec then, as pointed out



[REF. 122]

FIG. D-9 VIBRATION LEVELS OF CELLAR FLOOR AND WALLS by Cremer and Heckl [146], a plane acoustical wave will be generated in the adjacent air and the sound level of that wave will be n dB re 20 μN/m^2.

In [120] a procedure is given for estimating the sound pressure level in a room from measurements of wall vibration. The procedure is based on an assumption that many acoustic modes are excited and that the radiation efficiency of each vibrating surface is unity. When all walls, floor and ceiling are vibrating equally, the sound pressure level is estimated as

$$L_p = L_v + 6 - 10 \log \bar{\alpha} \qquad \text{(D-10)}$$

where L_v is the vibration velocity level and $\bar{\alpha}$ is the average absorption coefficient for the room. For the cellar room sketched in Fig. D-7, it is assumed in [120] that $\bar{\alpha}$ = 0.15 and that because the cellar floor vibration is so much greater than that of the walls, the vibration level inserted in (10) is that of the floor alone and in addition 5 dB are subtracted from (10) to account for the reduced effective area of radiation. The resulting prediction is shown as curve A in Fig. D-10.

In [119] an alternative procedure for making the same estimation is described. The starting point for the method is the static pressure response in a room due to the displacement of one wall in a low frequency bending mode. The basic static relation is then corrected for dynamic effects due to the presence of resonant acoustic modes. The result is a table for coverting vibration velocity level L_v on one wall, or floor, to sound pressure level L_p in the room.

Frequency, Hz	31.5	63	125	250	500
$L_p - L_v$, dB	-7	-5	-4	-10	-24

The resulting prediction of L_p when applied to the cellar room sketched in Fig. D-7, using the floor vibration level as L_v, is shown as curve B in Fig. D-10.

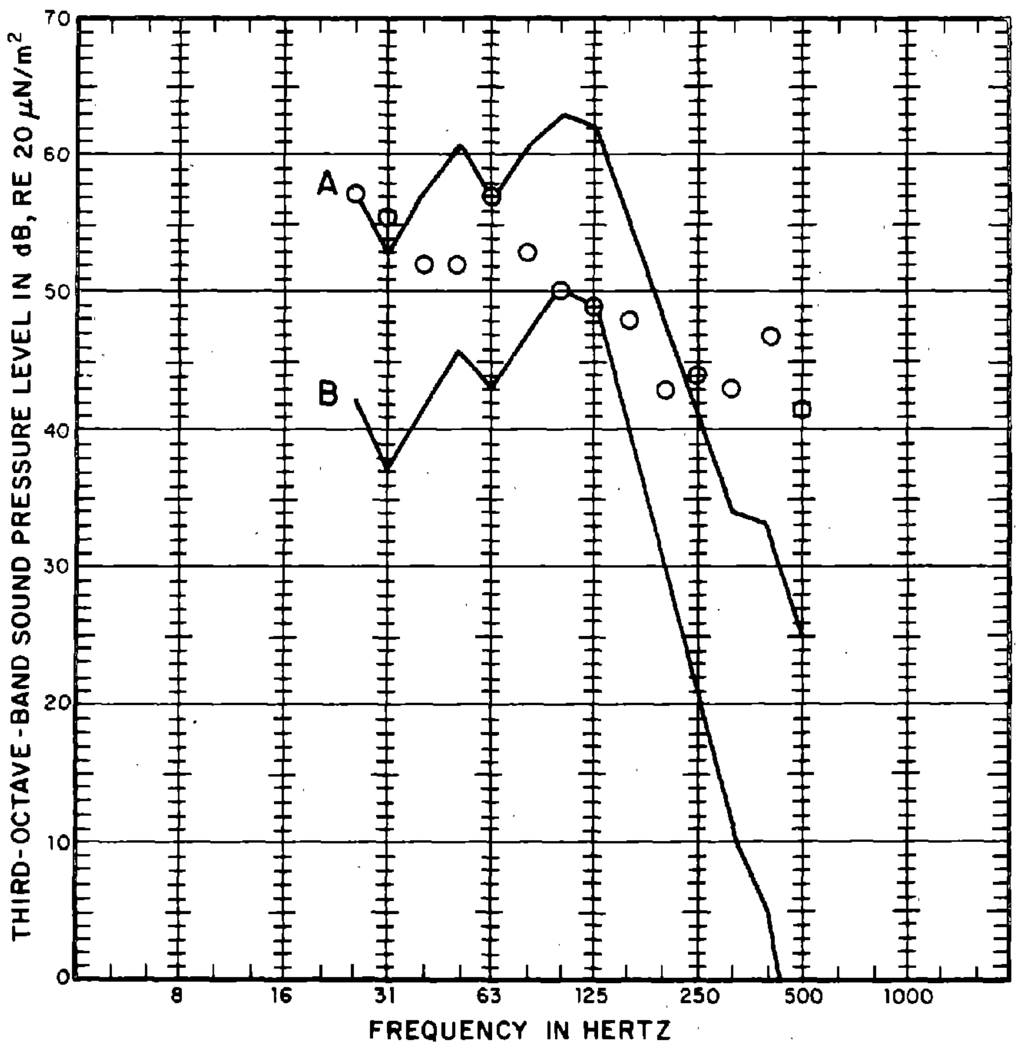
Actual measurements of sound pressure level are also indicated on Fig. D-10 by circled points. Note that there is 12 or more dB difference between the two predictions.

As an alternative to these prediction methods, it is possible to make the simpler assumption that the sound pressure level in the room is simply the same as the largest vibration velocity level measured on any surface of the room. The prediction according to this assumption is shown as curve A in Fig. D-11. This prediction falls about midway between the two predictions in Fig. D-10 and certainly correlates the data at least as well as either of the other two.

Fig. D-11 also shows the A-weighted noise levels measured in a cellar and compares this level with a prediction from Eq. D-9. The agreement between measurement and prediction for this case is quite good and adds support for the use of this simple prediction technique.

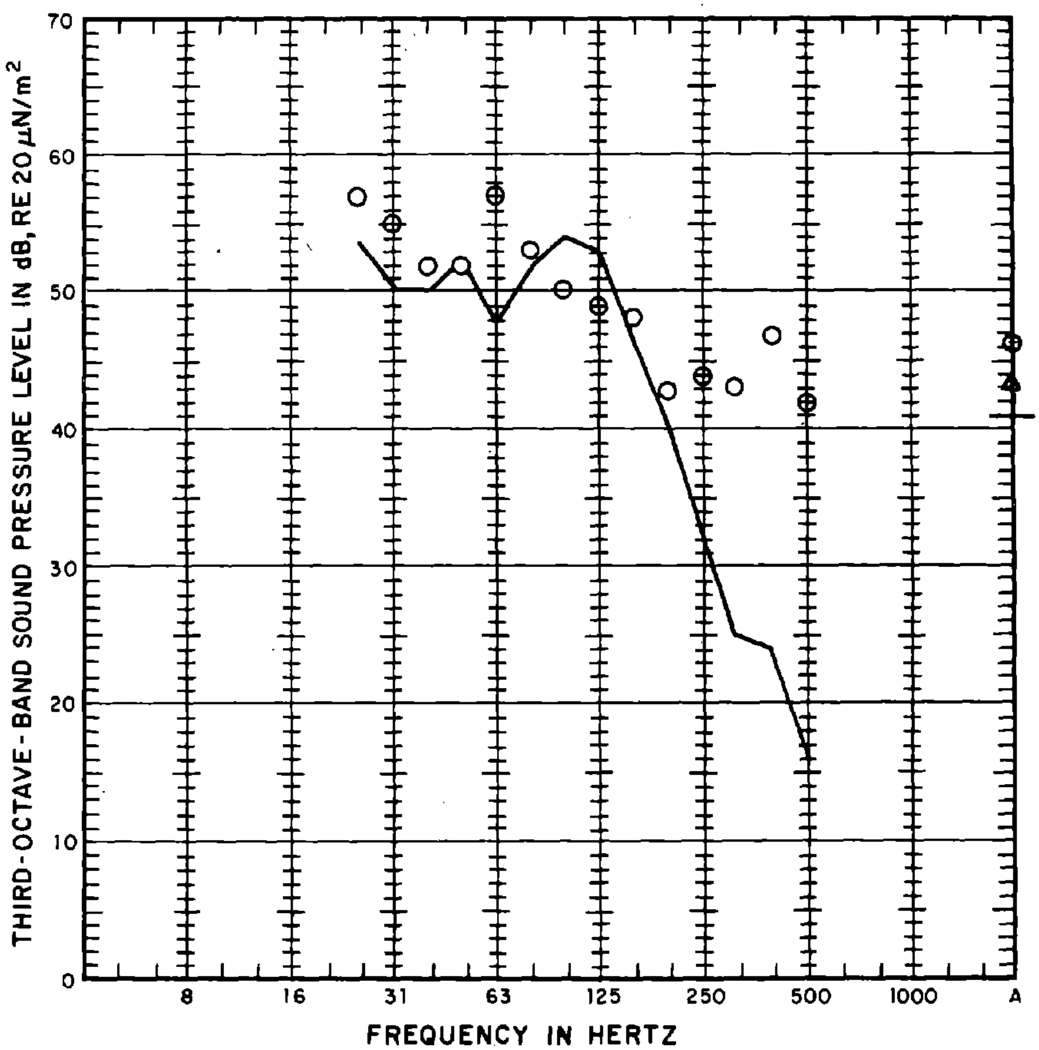
measurement of soil vibration

One of the difficulties with assessing soil vibration measurements is that as yet there is no universally accepted method of making such measurements. Very often a peg or stake of arbitrary length is driven into the ground and an accelerometer is attached so as to read vertical or horizontal response (or the greater of the two). As yet, there is no theoretical or experimental information with respect to the relationship between the vibratory motion



A - PREDICTION ACCORDING TO REF. [120]
B - PREDICTION ACCORDING TO REF. [119]
O - MEASURED LEVELS REF. [123]

FIG. D-10 COMPARISON OF PREDICTED ONE-THIRD OCTAVE SOUND PRESSURE LEVELS IN A CELLAR WITH MEASURED LEVELS



— - PREDICTION ON BASIS $L_p = L_v$

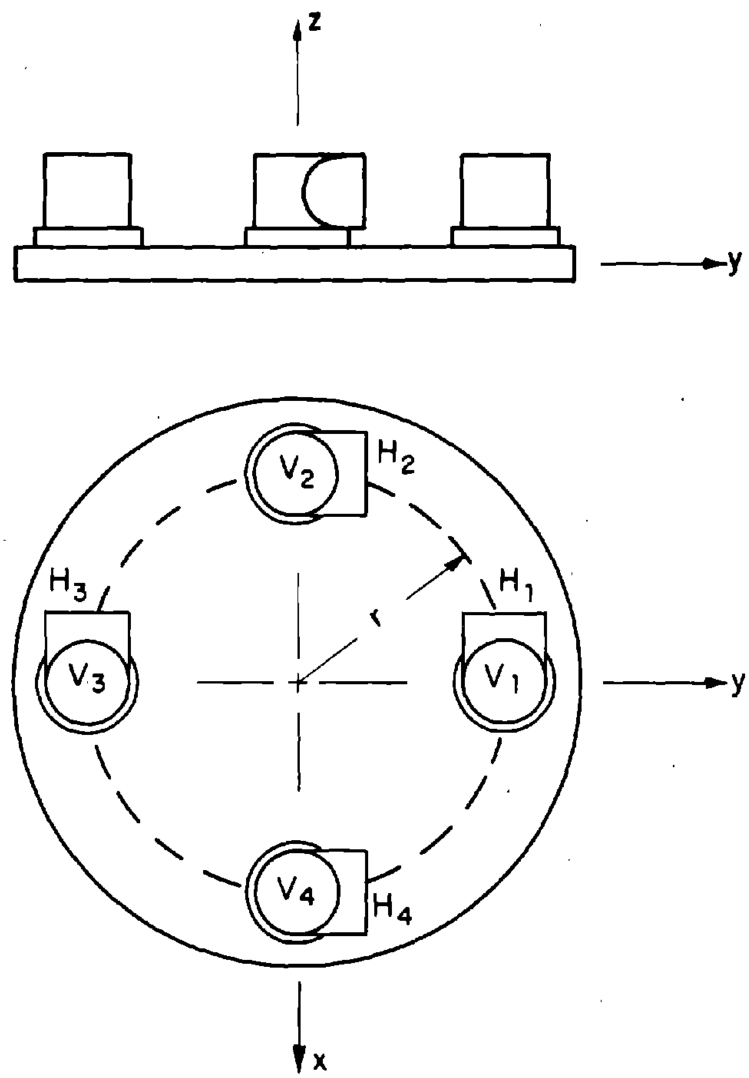
○ - MEASURED VALUES REF. [123]

△ - PREDICTION FROM EQ. D-9

FIG. D-11 COMPARISON OF PREDICTED ONE-THIRD OCTAVE SOUND PRESSURE LEVELS IN A CELLAR WITH MEASURED LEVELS on the surface of the soil, prior to driving in such a stake, and the motion on the surface of the soil, prior to driving in such a stake, and the motion which results at the free end of the stake after it has been driven into the ground. The transduction problem for soil motion is much more difficult than for sound pressure in an acoustic field. A rigid element in the soil such as a stone or a transducer package has, in general, six degrees of freedom. Six independent measures must be taken to completely define the local state of motion.

The only geometrical element for which complete response information is presently available, when it is in contract with a soil surface, is a rigid disk. It is, therefore, proposed that a rigid disk be used as a basis for a transducer for measuring soil surface vibrations. The general form of such a transducer is sketched in Fig. D-12. Although in principle only six accelerometers are required to determine the six independent motions, the slightly redundant system of eight accelerometers shown makes possible a simpler means of separating out the three translational and three rotational signals.

In order to serve as a useful transducer the disk should be large enough to permit intimate bonding to the soil without being unduly sensitive to local small scale inhomogeneities in the soil. At the same time the disk should be small enough so that its diameter is small in comparison with the wavelength of the shortest surface waves to be measured. In addition, the local magnification of soil motion due to the presence of the disk should be small and accurately known so that measurements can be corrected for the presence of the transducer. In this respect it would be desirable if the frequency response of the transducer were flat over the frequency range of interest.



OUTPUT SIGNALS

TRANSLATION		ROTATION	
VERTICAL - Z	$1/4(V_1+V_2+V_3+V_4)$	TORSIONAL - Z	$1/4r\,(H_1-H_2-H_3+H_4)$
HORIZONTAL - X	$1/2\,(H_1+H_3)$	ROCKING - X	$1/2r\,(V_1-V_3)$
HORIZONTAL - y	$1/2\,(H_2+H_4)$	ROCKING - y	$1/2r\,(V_2-V_4)$

FIG. D-12 SUGGESTED TRANSDUCER FOR DYNAMIC SOIL SURFACE MEASUREMENTS

With these thoughts in mind we have completed a preliminary design for the transducer disk of Fig. D-12. If the disk is made of aluminum alloy and has a diameter of 6 in (15.2 cm) and a thickness of 1/4 in (0.635 cm) it would make an acceptable transducer for surface waves in soils in the frequency range from 0 to 250 Hz. The disk would remain rigid in this range while at the same time it would have flat frequency response with negligible influence on the soil motion.

While the complete state of motion requires 6 independent measurements, there are many cases where less information may be required. For example, it may often be only necessary to obtain the vertical component of the free surface motion. In this case, only a single accelerometer placed in the center of the disk in Fig. D-12 would be required.

APPENDIX E GROUND VIBRATION LEVELS DUE TO SURFACE OPERATIONS

Only a limited amount of data is available giving ground vibration levels for operation on at-grade tie and ballast track. In all cases, the measurement technique was to imbed a metal or concrete rod in the ground and to measure acceleration levels on top of the rod. As discussed in Appendix D, this technique can be inaccurate due to the occurrence of resonances of the mass of the rod with the compliance of the soil. We have tried to eliminate data in which a resonant condition was believed to occur. This elimination was very difficult, however, because in most cases the details of the measurement device are not given. Therefore, the validity of the data presented below is open to question. However, the agreement between data taken by different people at different sites supports the collective validity of the results.

Ground vibration measurements were taken at distances of 9, 30 and 50 ft (2.75, 9.15, 15.25 meters) from the centerline of a tie and ballast track on the BART test track [147]. The observed vertical acceleration levels have been converted to velocity levels and are shown in Fig. E-1, where they can be compared with data from other rail systems.

Based in part on data from the BART test track, Wilson has plotted a typical range of levels to be expected at a distance of 50 ft (15.25 meters) from the track for operation of 8 car trains at 60 to 70 mph (96 to 113 km/h) [148]. To form a basis of comparison we have used Fig. 4.3, also taken from reference [148], to find the expected range of levels at 25 ft (7.5 meters). This

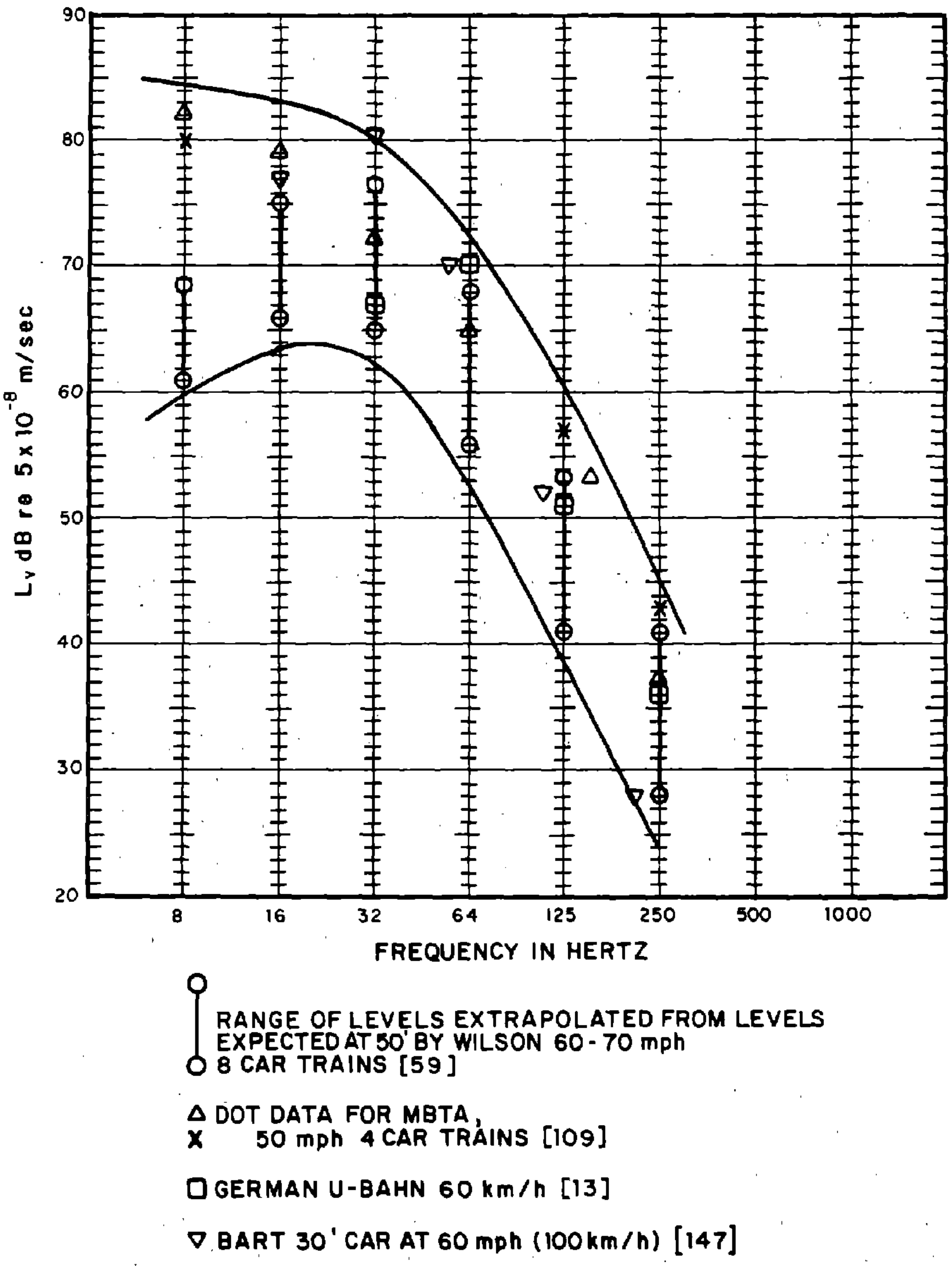


FIG. E.1 GROUND VIBRATION LEVELS 25 FT (7.5 m) FROM THE CENTERLINE OF AT-GRADE TIE AND BALLAST TRACK range is shown in Fig. E-1. It is in reasonable agreement with other data, but tends to be approximately 5 dB lower.

Ground vibration data from the Boston MBTA have been taken by the Transportation Systems Center staff [149]. Measured levels at 25 ft (7.5 meters) for operation of 4 car trains at 50 mph (80 km/h) are shown in Fig. E-1. These levels are comparable to other data, but are higher than Wilson's range of levels in the 8 and 16 Hz octave bands. Note, however, that the MBTA data may be for cars with wheel flats.

Finally, we show data reported for a German U-Bahn at 37 mph (60 km/h) [150].

All data in Fig. E-1 are for operations on tie and ballast track with continuously welded rail. The data are also for operation of mass transit type vehicles. Data for locomotives show higher levels of ground vibration due in part to the different axle load and in part due to the different suspension. Data on jointed track or for vehicles with wheel flats will be higher than that shown in Fig. E-1. However, little quantitative data exists for surface operations. We can refer to the increase in tunnel wall vibration levels that occurs for jointed track or with wheel flats and assume the same increase in level for at-grade operation.

APPENDIX F TUNNEL WALL VIBRATION DATA

To establish an empirical technique to predict tunnel wall vibration we have gathered reported data from various transit systems.

The collected data are for operation at 60 km/hr (37mph) on jointless rail. Data for both ballasted and direct fastener rail are considered. However, data for operation on floating slab trackbeds are not included.

The importance of rail fastener stiffness and tunnel wall thickness is known. However, when data from different tunnels are compared there is not a direct correlation of level with these parameters. Therefore, in presenting the data in Fig. F-1, we make no distinction as to fastener stiffness or tunnel wall thickness. However, it should be mentioned that levels toward the bottom of the range are for systems with soft rail fasteners.

All data in Fig. F-1 are for earth-based rectangular tunnels. As discussed in Chapter 4, levels in rock-based tunnels or in tube tunnels might be somewhat different.

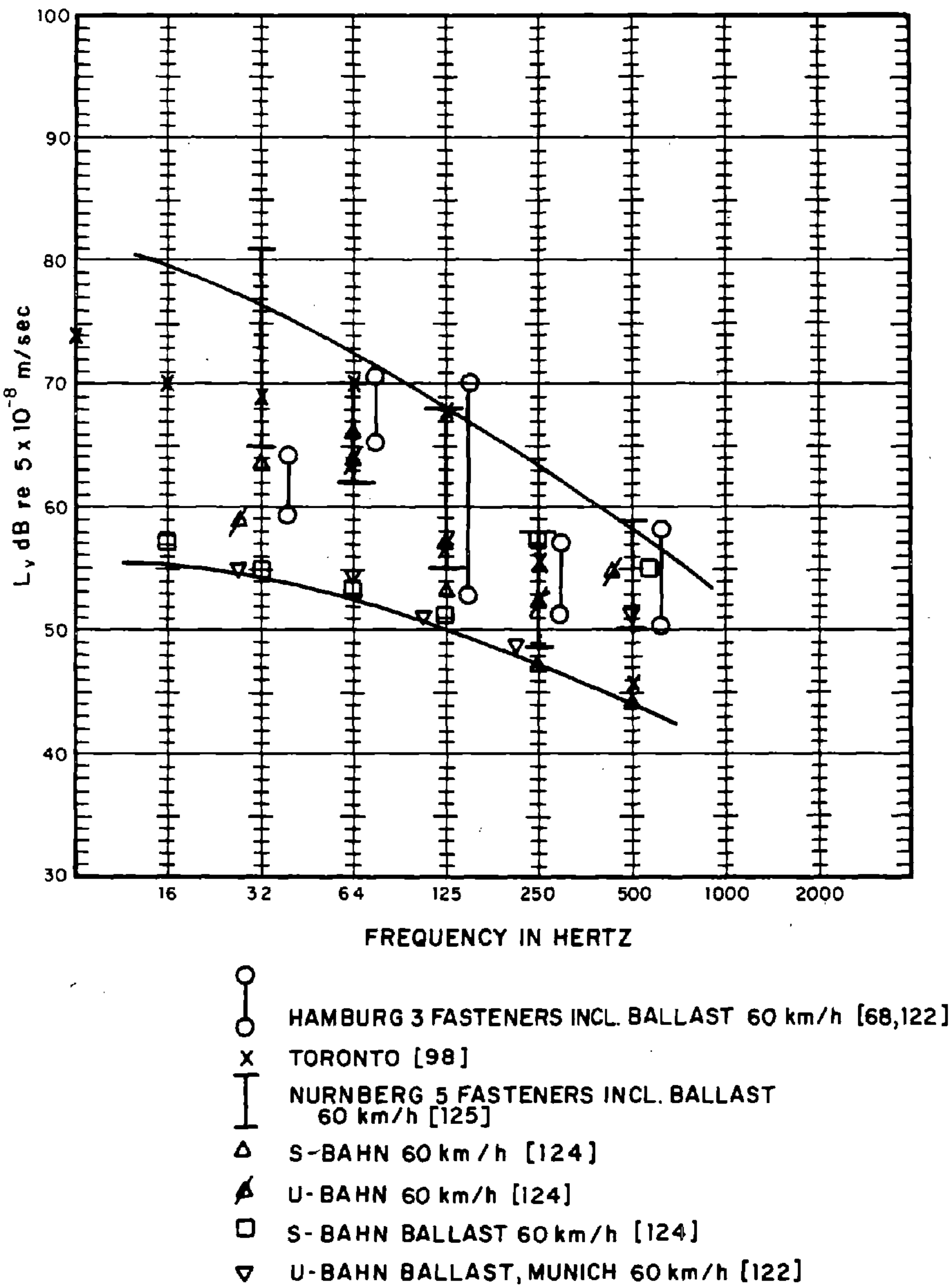


FIG. F–1 TUNNEL WALL VIBRATION

APPENDIX G REPORT OF INVENTIONS APPENDIX

This report contains a comprehensive review of reported work on rail transit noise and vibration. After a diligent review of the work performed under this contract it was found that no new inventions, discoveries, or improvements of inventions were made.

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18. The dependence of wheel/rail noise on each track design parameter has not yet been determined. However, many of the important parameters such as rail weight, tie spacing, and axle load have no direct influence on noise (note, there may be an indirect effect due to the influence of these parameters on wheel and rail wear and the development of corrugations).

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23. Specifications for a new series of cars for Chicago Transit Authority are reported in ref. [20].

24. See, for example, the results of measurements reported in ref. [17], also see ref. [20].

25. See, for example, data reported in ref. [20].

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28. J.M. Rapin, "Le Bruit au Voisinage des Voies de Chemin de Fer," (Noise in the Vicinity of Rail Lines), Cahiers du Centre Scientifique et Technique de Batiment, No. 132, Cahier 1130.

29. When an observer is near a building the sound waves reflected off the building add to levels directly from the source. Very close to the building a 6 dB(A) increase is observed — pressure doubling. At a distance of approximately 4 ft from the building the increase will be 3 dB(A) and will be less than 3 dB(A) for larger distances.

30. The subject of urban noise propagation is complex. However, as an approximation one can assume that urban noise levels will be well below open terrain levels when the observer is "behind" a building and above open terrain levels when a line of sight exists because of reverberation between the buildings.

31. Bonded joints or "dove tailed" joints tend to reduce impact at the rail joint and may represent an alternative to continuously welding the rail.

32. Use of pneumatic shock absorption and car aprons are believed to be the reasons that new S-Bahn cars are quieter than inter-city trains, see ref. [13].

33. Limited tests on wheel skirts have been carried out by JNR, see ref. [22].

34. Ref. [13] reports the wayside noise levels for track on concrete ties to be 2 dB(A) less than levels for track on wood ties, no explanation is given.

35. See, for example, data reported in ref. [20].

36. "Highway Noise — A Design Guide for Highway Engineers," National Cooperative Highway Research Program Rept. 116, 1971.

37. E. Buchta, "Gerauschabstrahlung von Hochbühnen in der vertikalen Ebene," (Noise radiation from elevated roads in the vertical plane), Uni Dusseldorf, Inst. fur Larmforschung, 1971.

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41. Data reported in ref. [20].

42. Data reported by JNR, see fre. [22].

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44. ORE D 87/RP 6, "Nichtklassischer Oberbau. Durch nichtklassischer Oberbau verursachte Larmabstrahlung und Schwinguugen," (Nonstandard roadbed. Sound radiation and vibrations caused by nonstandard roadbed), 1973.

45. See data reported in ref. [40].

46. Structure-Borne Sound, L. Cremer and M. Heckl, translated and revised by E.E. Ungar, Springer-Verlag, New York, 1973.

47. See, for example, results of tests carried out in Rotterdam and briefly described by E. Bender and M. Heckl, "Noise Generated by Subways Above Ground and in Stations," prepared for U.S. Department of Transportation as Technical Report OST-ONA-70-1, 1970.

48. C. Stüber, "Versuche zur körperschalldammenden Lagerung von Eisenbahnschienen," (Tests on rail support attenuating solid-conducted sound), VDI Report No. 113, pp. 143-150, 1967.

49. ORE D 105/RP 2, "Lärmbekampfung an Brucken. Gerauschmessungen an der Brucke Rosenheim, " (Noise abatement on bridges. Noise measurements on the Rosenheim Bridge), 1966.

50. Details of the Rotterdam fastener are given by Deenik and Eisses in Eisenbahningenieur, Vol. 17, page 209, 1966.

51. See ref. [21].

52. See ref. [22].

53. See Chapter 25 of ref. [9].

54. An intruding noise can just be heard when its level is equal to that of the background noise.

55. D.E. Goldman, "A Review of the Subjective Responses to Vibratory Motion of the Human Body in the Frequency Range 1 to 70 cps," Rept. 1, Project NM 004 001, Naval Medical Research Institute, Bethesda, Md., 1948.

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57. See, for example, C. Stüber, G. Hauck, and L. Willenbrink, "Körperschallmessungen an unterirdischen und oberirdischen Eisenbahnstrecken," (Solid-conducted sound measurements on underground and aboveground railroad stretches), Tagung Akustik und Schwingungstechnik Stuttgart, 1972, VDE-Verlag, pg. 382-385.

58. See, for example, ref. [13] or ref. [57].

59. "Noise and Vibration Characteristics of High Speed Transit Vehicles," prepared by Wilson, Ihrig and Associates, Incorporated for U.S. Department of Transportation as Rept. OST-ONA-71-1, June 1971, see page 25.

60. See Fig. 7 of ref. [59].

61. "BARTD Prototype Car 107 Noise Tests with Standard, Damped and Resilient Wheels," G.P. Wilson, Wilson, Ihrig and Associates, Inc. Report, June 1972.

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66. See page 48 of ref. [59].

67. R.J. Murray, A.D. Hunt, and D.W. Mair, "Noise and Vibration Studies, Track Fastenings," Toronto Transit Commission, Rept. RD 106, May 1967.

68. Based on measurements taken in Munich with 6 tons per axle and 12.5 tons per axle loading reported by G. Hauck, L. Willenbrink, and C. Stüber, "Körperschall — und Luftschallmessungen an unterirdischen Schienenbahnen. Teil 1," (Measurements of solid and air-conducted sound on underground railways. Part 1), Eisenbahntechnik Rundschau 21, pp. 289 - 300, 1972.

69. Based on measurements taken in Munich for cars with Megi-suspension of car body and pneumatic suspension, see ref. [68].

70. Information on the effect of rail fastener stiffness on tunnel wall vibration for the range above 20,000 lbs/in/in was not found. We surmise, however, that in this range the stiffness of the rail support is governed by the stiffness of the tunnel floor so that rail fastener stiffness has no effect.

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72. See Fig. 5 of ref. [56].

73. Although further work is needed on this topic, it is believed that the minimum fastener stiffness that can be used is 3000 lb/in/in, see ref. [59].

74. Measurements were conducted in Munich for ballast bed depths of 30 cm, 50 cm and 70 cm under the lower surfaces of the ties. The measurement point and other conditions were the same for each measurement, see ref. [68].

75. Measurements were conducted in earth-based rectangular tunnels in Hamburg, 44 cm average wall thickness; Frankfurt, 44 cm thick; Munich, 71 cm thick; and Cologne, 67 cm thick, see ref. [68], Table 5.

76. See Fig. 14 of ref. [59].

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