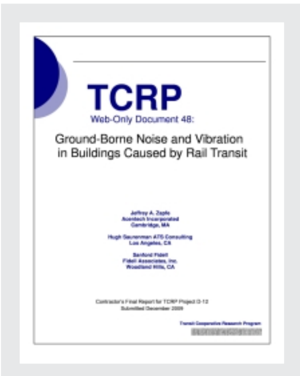

Ground-Borne Noise and Vibration in Buildings Caused by Rail Transit

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Contractor's Final Report for TCRP Project D-12
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Dr. Jeffrey A. Zapfe, Director of the Noise and Vibration Group at Acentech, was the principal investigator. The other authors of this report are Dr. Hugh Saurenman from ATS Consulting, and Dr. Sanford Fidell from Fidell Associates.

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ABSTRACT

Ground vibration produced by rail transit systems can be annoying to nearby building occupants when they perceive some combination of feelable vibration, re-radiated sound, and vibration-induced rattling of household paraphernalia. Community response to rail-induced ground vibration has not been extensively researched. While the well-known Schultz dosage-response curve is routinely used to predict the prevalence of annoyance produced by airborne transportation noise, no similar relationship has gained widespread acceptance for noise and vibration due to ground vibration. The principal goal of the present research was to develop a dosage-response relationship useful for predicting community annoyance due to ground vibration produced by rail transit systems.

This report documents the research conducted under the Transit Cooperative Research Program D-12 project, including a literature review, development of the study design, conduct of telephone interviews and vibration measurements, and data reduction and analyses. Telephone interviews were conducted with 1306 individuals in five North American cities: New York, Sacramento, Dallas, Toronto and Boston. Field measurements were made in each city to estimate vibration and noise exposure at each interview location.

The work produced several dosage-response relationships between vibration/noise exposure and annoyance. When compared to the current noise and vibration criteria specified by the Federal Transit Administration (FTA), the dosage-response analysis predicted a probability of 0.05 to 0.10 that a D-12 respondent would be highly annoyed by vibration and noise at the current FTA criterion levels.

SUMMARY OF FINDINGS

The objective of TCRP Project D-12 was to develop proposed criteria for acceptable levels of rail-transit-generated, ground-borne noise and vibration in buildings.

The vibration generated by steel-wheel trains operating on steel rails is referred to as "ground-borne vibration." The vibration travels through the ground and into buildings adjacent to the rail system. The resulting building vibration may cause annoyance to building occupants through several different mechanisms:

- Perceptible vibration: Building occupants feel the vibrations in the building's structure or furnishings (floors, walls, chairs, etc.).
- Rattle: The vibration can cause a variety of secondary rattling and buzzing noises from the vibration of items on shelves, pictures or other items hanging on walls, and loose-fitting windows.
- Radiated noise: The vibrating room surfaces radiate sound pressure waves much like giant loudspeakers. If the vibration is in the audible frequency range and is of sufficient amplitude, it can be perceived by room occupants as a low-frequency rumble noise. This rumble is referred to as "ground-borne noise."

The major components of the study included a literature review, a survey of North American rail transit systems to document their experience with complaints related to ground-borne vibration, a social survey consisting of telephone interviews with 1306 people living near rail transit lines, and measurements to estimate the exposure of the survey respondents to ground-borne vibration. The results of the social survey and the measurements were used to develop relationships between the levels of ground-borne vibration/noise and annoyance. Information developed during this study was also compared to criteria that are currently used in the United States to evaluate impacts from ground-borne vibration/noise.

The following sections provide an overview of the results of each phase of this study.

Literature Review

The literature review examined international standards that include limits on the levels of ground-borne vibration/noise, as well as the published literature related to human response to building vibration. Some of the major findings of the literature review are:

- In the frequency region of interest for rail transit systems, almost all standards are effectively based on a measure of overall vibration velocity level. Most standards specify a weighting curve that de-emphasizes vibrations that occur at low and high frequencies (typically below 16 Hz and above 80 Hz). Since the greatest vibrations generated by most rail systems typically occur between 16 Hz and 100 Hz, the weighted vibration levels rarely differ from the un-weighted vibration velocity level by more than a few decibels.
- National standards for acceptable levels of ground-borne vibration in residences vary over a 20 dB range. The current FTA (7) impact threshold is at the lower end of this range.
- All of the national standards reviewed base the limits for acceptable vibration on indoor vibration levels. This means that indoor vibration measurements must be performed to verify compliance.

- National standards for ground-borne noise typically express the limits in terms of A-weighted sound pressure level. The current FTA (7) impact threshold lies about at the middle of a 30 dB range of stated criteria.
- Relatively little information has been published concerning the relationship between the number and duration of vibration events, and annoyance. Most national standards are stated in terms of either the average, or maximum passby vibration level; rarely are adjustments included to account for the number and duration of vibration events. One exception is British Standard BS 6841 (6), which states a criterion based on total vibration exposure.
- Laboratory studies that have investigated human sensitivity to vibration provide only limited support for the weighting curves that are used in US (ANSI) and International (ISO) standards.

Survey of Transit Systems

The goal of the transit system survey was to obtain an indication from the operator's perspective of the extent and severity of problems caused by ground-borne vibration. An online service was used for the survey. An e-mail was sent to representatives of all rail transit systems that were members of the American Public Transportation Association (APTA), which represents most North American rail transit systems. The e-mail included a description of the D-12 project with a link to an online questionnaire that consisted of 18 questions. Survey responses were received from 30 of the 53 transit systems that were contacted.

Some key trends from the survey were:

- Of the 30 responses, 17 reported no vibration complaints in the past year, 10 reported 1 to 5 complaints, 2 reported 6 to 10 complaints, and one system reported more than 50 complaints. In general, most transit systems reported only limited complaints concerning ground-borne vibration and noise. All systems that reported complaints had received at least some of the complaints through informal channels. Community annoyance may therefore be underreported due to a lack of formal complaint procedures.
- No clear pattern was evident relating the number of complaints and the physical characteristics of the systems.
- The most common resolution to vibration-related issues was the development of, or intensification of, maintenance programs.

Field Survey and Measurement Program

Five transit systems were selected for field testing: New York City, Toronto, Boston, Sacramento, and Dallas. Sacramento and Dallas were at-grade light rail systems with ballast and tie track. The other three systems were rapid transit subway systems.

Test areas were selected in each city based on discussions with agency personnel. Ideal test areas had a history of complaints, a large number of potential respondents, and a wide range of exposure to rail transit vibration.

After a test area was selected, a telephone questionnaire was administered to a simple random sample of residential households within the survey area. The survey was designed so that it could be completed in approximately 5 to 10 minutes. A total of 1306 respondents completed a telephone interview: 582 in Toronto, 281 in New York, 304 in Boston, 103 in Dallas, and 36 in

Sacramento. The final survey question asked whether the respondent would consider allowing measurements to be made inside their home. A portion of respondents who agreed were re-contacted to arrange field measurement appointments. The field measurements consisted of:

- Noise and vibration measurements inside the residence, in a room where the resident thought that the vibration/noise was most noticeable.
- Vibration measurements on the ground immediately outside the residence.
- A simultaneous vibration measurement at a fixed outdoor reference position near the alignment. The same reference position was used for all residences in the same area. The reference measurements were used to adjust for any differences in the fleet vibration characteristics.

Because it was not practical to measure inside all 1306 surveyed homes, measurements were made at selected residential locations. The residence measurements were supplemented with a series of grid measurements made at locations distributed throughout each test area. The grid measurements were used to estimate the exposure at respondent locations where field tests were not conducted. In total, vibration measurements were made at 41 residences and 100 grid locations at the five systems.

Results of Field Measurements

Indoor vs. outdoor vibration

The test program included simultaneous indoor and outdoor measurements at 41 residences. The average difference between the indoor vibration and the outdoor vibration was close to zero, both for the entire population of test residences and for the residences specific to each transit system. However, substantial variation (on the order of ±5 decibels) was observed in the residential data. No clear pattern to the variation was apparent. Indoor vibration levels varied by as much as 10 decibels between two adjacent residences of the same apparent design. For the D-12 data set:

- on average, the indoor vibration level equaled the outdoor level, and
- the indoor vibration exceeded the outdoor vibration by less than 5 decibels more than 95% of the time.

Indoor vibration vs. indoor noise

The approach recommended in the FTA Guidance Manual (7) for predicting ground-borne noise is to assume that the vibration velocity level of a representative surface in the room (typically the floor) is a good predictor of sound pressure level in the room:

$$L_p \text{ (dB re } 20\mu\text{Pa)} = L_v \text{ (VdB re } 1\mu\text{in/s)},$$

which is based on the assumption that the sound pressure, p, radiated from a vibrating room surface can be approximated by the plane wave radiation formula,

$$p = \rho\, c\, v,$$

where, ρ is the air density, c is the speed of sound, and v is the vibration velocity of the surface.

If reverberant buildup is ignored, the relationship using decibel references of 1 μin/s for vibration velocity and 20 μPa for sound pressure is:

$$Lp = Lv – 5.7 \text{ dB.}$$

A -5 dB adjustment is consistent with data collected during the D-12 study. In the frequency range where train-induced ground-borne noise was loudest (31.5 Hz to 100 Hz), the average measured difference between vibration level and sound pressure level was about –5 decibels, with a range of ±5 decibels. Because of the limited amount of data collected, and the uncertainties caused by measuring vibration at just one location in the room, it is not clear what the correct adjustment should be.

Correlation between indoor vibration and noise

The correlation between the indoor vibration and indoor noise was only slightly greater than the correlation between outdoor vibration and indoor noise. Again, based on the D-12 data, this implies that reasonable estimates of indoor ground-borne noise can be obtained with measurements of exterior vibration, and that the additional expense of indoor vibration measurements offers only a slight improvement in the accuracy of the estimated indoor sound.

Vibration frequency spectra

Although differences were observed between vibration levels and frequency spectra measured at the five transit systems, the frequency spectra for all of the systems peaked in the 40 Hz to 80 Hz 1/3 octave frequency bands.

Vibration frequency weightings

The frequency weighting methods that are used in a number of national standards were used to determine vibration exposure. However, because the greatest vibration levels at the five D-12 test systems were generally between 40 Hz and 80 Hz, the weightings were effectively equivalent to vibration velocity level over this frequency range. Vibration levels derived using the various frequency weightings were highly correlated with each other, and none were more than marginally better at predicting annoyance than any of the others. Unfortunately, because the vibration spectra from the D-12 transit systems peaked in the same general range, it was not possible to obtain any fresh insight into how vibration frequency might be related to annoyance.

Vibration exposure

In selecting the transit systems for field testing, an effort was made to obtain a broad spectrum of exposure in terms of the vibration amplitudes and the number of events. One goal was to obtain data that would provide some insight into whether annoyance scales with the number of vibration events and/or the event durations. Among the five D-12 test systems, the total daily exposure (the product of the number of events and average event duration) varied by a factor of 10. The two systems with the greatest exposures were the rapid transit systems in Toronto and New York. The two with the lowest exposure were the light rail systems in Sacramento and Dallas. However, because only eight respondents in Sacramento and Dallas reported high annoyance due to ground-borne vibration or noise, no useful statistical conclusions could be drawn about the effects of exposure.

Relationships among noise and vibration measures

More than 200 noise and vibration metrics were considered as potential predictor variables for the dosage-response analysis. Most of these metrics proved to be so highly correlated (r = 0.9 or greater) with one another that for practical purposes, they differed only by a scale factor and/or a constant. Such high correlation among measures indicates that most of the derived measures were, in effect, only trivially variant measures of the underlying physical quantities.

A factor analysis was unable to identify physically interpretable subsets of vibration metrics that were both closely related to one another and, at the same time different from other subsets. The very high correlation among vibration measures implies that, for purposes of predicting community response to train-induced vibration at the five test systems, custom, convenience, and cost are as reasonable a basis for selecting a vibration metric as any statistically-derived criterion. Since, essentially, any metric was as good as any other in predicting annoyance, a set of commonly used vibration and noise measures were used to develop dosage-response relationships.

Social Survey Findings

The methods employed in the social survey yielded satisfactory interview completion rates and orderly and interpretable questionnaire responses. For example, the severity of noise and vibration effects generally decreased with distance from the alignment, and the same respondents who reported annoyance by one effect of train passbys (*e.g.*, shaking) also reported others (*e.g.*, rumbling noises). Most respondents were long-term residents of the test areas.

Only small numbers of respondents spontaneously mentioned rail-related noise or vibration as the least-favored aspect of neighborhood living conditions, or were consequentially affected by train passbys. For example, less than 6% of respondents living near surface tracks and less than 4% of those living above subway tracks described themselves as highly annoyed by low rumbling sounds created by trains; less than 12% of all respondents reported shaking or vibration when trains passed by their homes; less than 7% reported awakening due to train passbys; and only slightly more than 3% had complained to the local transit system about train-induced noise, rumble, rattle, shaking or vibration in their homes.

Several of the dosage-response relationships inferred from the D-12 data accounted for nearly a quarter of the variance in the relationships between vibration measures and questionnaire responses. Although such relationships leave much variance unaccounted for, they account for about as much variance as the relationship between community noise and annoyance that are relied upon to make decisions about noise mitigation for transportation projects (36). Not unexpectedly, it thus appears that measures of ground-borne noise and vibration that can be practically made, are unlikely to account for more than a minority of the variance in community response. Individual differences, adaptation over time and self-selection of residents for tolerance to vibration are three of the reasons why it is unrealistic to expect a closer relationship between vibration levels and annoyance.

Application of Study Results

The dosage-response relationships were cast in terms of the sound and vibration metrics that are currently used in the United States. At the FTA's residential vibration limit for frequent service (72 VdB), the D-12 dosage-response relationship predicts a 5% to 10% chance of high annoyance. This is similar to the prevalence of annoyance adopted for public policy purposes in similar (non-rail) applications. FAA's selection of L_{dn} = 65 dB as a threshold with regard to aircraft noise impacts, for example, is based on a predicted annoyance prevalence rate of 12.3% (36).

At the corresponding residential limit for A-weighted ground-borne noise (35 dB), the dosage-response relationships predict that only 3% to 6% of the D-12 respondents would report high annoyance. The D-12 data show that, on average, sound levels inside residences were about 5 dB lower than the vibration levels.

Duration of residency in community

At the time of interviewing, more than 95% of the D-12 respondents had lived in their homes for longer than a year. Hence, their opinions regarding annoyance reflect their long-term familiarity with the exposure conditions, rather than transient reactions to a novel exposure. More adverse reaction might be expected if a transit system were suddenly "turned on" in an otherwise quiet community. The D-12 data were obtained at systems that have been in the community for many years. If one considers the D-12 result as an asymptotic value, then it would be expected that short term adverse community reaction associated with the start of operations by a new transit system would diminish with time as people acclimatize to the noise and vibration.

Potential under-reporting of community annoyance

According to the transit agency survey, few agencies receive more than occasional noise and vibration complaints. According to the D-12 data, however, the prevalence of high annoyance in the surveyed communities varies from about 2% to 13%. This suggests either that few annoyed people complain to transit agencies, or that some agencies do not have comprehensive procedures for logging complaints.

Vibration measurement location

Noise and vibration criteria are typically applied at the receiver location inside the building. This approach can be costly and potentially inaccurate if there is ever a need to verify compliance with criteria. In the present study, large variations in indoor vibration level were observed among seemingly identical homes that were exposed to similar levels of ground vibration.

Given appreciable house-to-house variation, a measurement in one house does not necessarily lead to a reliable prediction of the vibration in the house next door. Thus, unless one were to measure in every house in the potentially affected community, exterior vibration levels could provide as useful an indication of expected vibration levels as a limited number of interior residential measurements.

The present data are not comprehensive enough to conclusively justify this reasoning. Nonetheless, the compelling logistical reasons for exterior-based vibration measurements are apparent; exterior measurements obviate the need for access to people's homes, and reduce the cost and complexity of field measurements. This is one area where future research could yield a large payback in simplifying the analysis of transit-related noise and vibration in communities.

Low-frequency limitations

The FTA manual distinguishes between the effects of feelable vibration and radiated noise. The systems selected for the D 12 sample had similar vibration characteristics with much of the vibration energy concentrated at audible frequencies. For this reason, vibration and noise measures used in the D-12 study were all well correlated because they were essentially measuring the same thing (vibration at audible frequencies.) The D-12 data are not sufficiently wide-ranging to support clear distinctions between the effects of feelable vibration and radiated noise. This is another area in which future research would be valuable.

1. INTRODUCTION

This document is the final report for Transportation Cooperative Research Program (TCRP) Project D-12, "Ground-Borne Noise and Vibration in Buildings Caused by Rail Transit." The overall goal of the study was to develop dosage-response relationships between train-induced vibration and community annoyance.

Three specific objectives of Project D-12 were to:

- Summarize the experience of transit agencies regarding complaints about train-generated vibration.
- Synthesize published information on rail-induced vibration and similar low-frequency noise and vibration effects.
- Develop one or more dosage-response curves that reflect the prevalence of annoyance in communities due to vibration produced by rail transit systems. The dosage-response curve(s) would be similar to the Schultz (1) curve that is used to predict annoyance from exposure to various sources of community noise.

1.1 Background

For most rail transit systems, at distances greater than 100 m from the alignment, the train-induced ground vibrations are considerably lower than the threshold of human perception. Even in dense urban areas like Manhattan with its multiple subway lines, most residences are far enough from subway tunnels that occupants do not notice the vibrations created by passing trains. The difficulty in solving railway vibration problems, and the costs for installing preventive measures when new systems are constructed, make it important to improve our understanding of how various characteristics of transit-induced vibration are related to the annoyance of residents living nearby.

The D-12 project is concerned with the train-related vibration that travels through the ground to nearby buildings. This *ground-borne vibration* is caused by the interaction of the steel wheels and rails, which causes vibration in the ground beneath the track. The vibration spreads through the ground in a manner similar to the waves created when a stone is thrown into a pond. When the ground waves reach nearby buildings, the interaction with the building structure creates vibration within the building.

Building occupants may perceive train-induced vibration in three ways:

- Occupants may feel vibration through parts of their bodies in contact with vibrating surfaces while standing, sitting or recumbent.
- The vibration of walls, ceilings and floors in a room may re-radiate audible sound. The audible sound is referred to as *ground-borne noise*. It is important to clearly distinguish between noise caused by ground-borne vibration and conventional noise that reaches the receiver through an airborne path.
- Building vibration can also cause secondary noises such as rattling of windows, items on shelves, and items hanging on walls. Rattling sounds may call attention to otherwise unnoticed vibration and exacerbate its annoyance.

People may not fully distinguish among these mechanisms and may simply find passing trains intrusive and annoying. Airborne noise from transit systems, such as train horns and grade crossing warning bells, may also influence overall reactions to train operations. The D-12 project was concerned only with phenomena caused by ground vibration. Measures, such as site selection, were taken to avoid situations in which annoyance was most likely to be related to airborne sources.

The overall goal of the study was to derive one or more dosage-response curves to relate the vibrations produced by rail transit systems to the annoyance of people living near the alignment. The data that were used to develop the dosage-response curves included 1) telephone interviews conducted in neighborhoods near North American rail transit systems, and 2) subsequent measurements of the levels of ground-borne vibration and noise in these neighborhoods.

1.2 Project Scope

The D-12 study was conducted in two phases. Phase 1 included background research and planning. Phase 2 included field testing, community surveys, and analyses to develop dosage-response relationships. The detailed project phases are described below.

Phase 1

Task 1. Literature Review: Criteria for rail-induced ground-borne noise and vibration were reviewed, as were published studies related to human response to ground-borne vibration and noise.

Task 2. Survey North American Rail Transit Systems: North American transit agencies were surveyed to determine 1) the prevalence of complaints related to ground-borne vibration, 2) how complaints have been handled, and 3) what, if any, corrective action has been taken.

Task 3. Identify Transit Systems for Field Studies: Twenty one transit systems were identified as candidates for community surveys and field measurements.

Task 4. Develop Field Survey and Measurement Program: This task included the development of protocols for field measurements, development of a telephone questionnaire, and the identification of quality control procedures for data collection and analysis.

Task 5. Draft Interim Report #1: This report was submitted in June of 2006.

Task 6. Revised Interim Report #1: This report was submitted in December of 2006.

Phase 2

Task 7. Field Data Collection: Community annoyance was assessed using telephone interviews. Vibration exposure was determined using outdoor and indoor field measurements of vibration and noise.

Task 8. Derive Community Response Curve: The results of the field measurements and the community survey were processed to develop dosage-response relationships.

Task 9. Draft Final Report: The draft final report was submitted for review in May of 2009.

Task 10. Final Report: The present report which was submitted in December of 2009.

1.3 Vibration Reference Quantities

A common challenge with interpreting ground vibration measurements is a lack of standardization of units. The most common vibration metrics are peak particle velocity (PPV), root mean square (RMS) vibration in units of micro-inches/second or millimeters/second, and RMS vibration in units of decibels using one of three common reference quantities. Unless otherwise specified, vibration amplitudes in this report are expressed in terms of RMS vibration velocity level using a decibel reference of 10^{-6} in/sec (1 µin/sec). As has become customary in the United States, the abbreviation "VdB" is used to denote vibration velocity levels expressed in units of decibels. Table 1 facilitates conversions among some of the more common vibration velocity units.

Table 1: Vibration Velocity Conversion Table

Decibels		Absolute Units	
VdB (ref =1µin/sec)	Metric decibels (ref =5×10^{-8}m/s)	US Units µin/sec	Metric Units mm/s
100	94	100,000	2.54
90	84	32,000	0.803
80	74	10,000	0.254
72	66	4,000	0.100
70	64	3,200	0.080
60	54	1,000	0.025
50	44	320	0.008
40	34	100	0.003

1.4 Evaluation of Rail Transit Noise and Vibration in the United States

The current document used in the United States to assess potential impact due to ground-borne noise and vibration from rail transit systems is published by the Department of Transportation's Federal Transit Administration (FTA) and is entitled *Transit Noise and Vibration Impact Assessment* (7).

Table 2 shows the matrix that the FTA uses to evaluate the impact of rail transit-related ground-borne vibration and ground-borne noise. The FTA's noise and vibration criteria are based on building occupancy and frequency of service. As a point of reference, ANSI standard S3.29-1983 (4) states that a vibration level of 72 VdB is approximately equal to the threshold of perception for the most sensitive humans.

The FTA also provides criteria for special buildings such as concert halls, theaters and recording studios, as shown in Table 3.

Table 2: FTA Ground-Borne Vibration (GBV) and Ground-Borne Noise (GBN) Impact Criteria for General Assessment

Land Use Category	Ground-Borne Vibration Impact Levels (VdB re 1 µ in/s)			Ground-Borne Noise Impact Levels (dB re 20 µ Pa)		
	Frequent Events[1]	Occasional Events[2]	Infrequent Events[3]	Frequent Events[1]	Occasional Events[2]	Infrequent Events[3]
Category 1: Buildings where vibration would interfere with interior operations.	65 VdB[4]	65 VdB[4]	65 VdB[4]	N/A[5]	N/A[5]	N/A[5]
Category 2: Residences and buildings where people normally sleep.	72 VdB	75 VdB	80 VdB	35 dBA	38 dBA	43 dBA
Category 3: Institutional land uses with primarily daytime use.	75 VdB	78 VdB	83 VdB	40 dBA	43 dBA	48 dBA

1. "Frequent Events" is defined as more than 70 vibration events per day. Most rapid transit projects fall into this category.
2. "Occasional Events" is defined as between 30 and 70 vibration events of the same source per day. Most commuter trunk lines have this many operations.
3. "Infrequent Events" is defined as fewer than 30 vibration events per day. This category includes most commuter rail branch lines.
4. This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. Vibration-sensitive manufacturing or research would require detailed evaluation to define the acceptable vibration levels. Ensuring lower vibration levels in a building often requires special design of the HVAC systems and stiffened floors.
5. Vibration-sensitive equipment is not sensitive to ground-borne noise.

Table 3: FTA Ground-Borne Vibration Noise Impact Criteria for Special Buildings

Type of Building or Room[3]	Ground-Borne Vibration Impact Levels (VdB re 1 µ in/s)		Ground-Borne Noise Impact Levels (A-weighted dB re 20 µ Pa)	
	Frequent Events[1]	Occasional or Infrequent Events[2]	Frequent Events[1]	Occasional or Infrequent Events[2]
Concert Halls	65 VdB	65 VdB	25 dB	25 dB
TV Studios	65 VdB	65 VdB	25 dB	25 dB
Recording Studios	65 VdB	65 VdB	25 dB	25 dB
Auditoriums	72 VdB	80 VdB	30 dB	38 dB
Theaters	72 VdB	80 VdB	35 dB	43 dB

1. "Frequent Events" is defined as more than 70 vibration events per day. Most transit projects fall into this category.
2. "Occasional or Infrequent Events" is defined as fewer than 70 vibration events per day. This category includes most commuter rail systems.
3. If the building will rarely be occupied when the trains are operating, there is no need to consider impact. As an example, consider locating a commuter rail line next to a concert hall. If no commuter trains will operate after 7 PM, the trains should rarely interfere with the use of the hall.

2. LITERATURE REVIEW

The goals of the literature review were to 1) identify other national standards related to ground-borne vibration and noise, and 2) review research pertaining to the sensitivity of humans to noise and vibration.

National vibration standards pertaining to ground-borne vibration and ground-borne noise are summarized in Appendix D. In addition to listing the specific articles and standards cited in this report, the reference list at the end of the report includes articles that were reviewed during the study.

The following are the general observations and inferences that were drawn from the literature review:

- **Descriptors of ground-borne vibration:** A variety of units, reference values, metrics and weighting schemes are commonly used to describe ground-borne vibration. The most common weighting schemes are effectively equivalent to RMS vibration velocity over the frequency range from 15 Hz to 80 Hz. The use of different units and weighting factors greatly complicates direct comparisons of the national standards.
- **Vibration standards:** Although international standards for measuring and evaluating vibration and noise exist, guidelines that put limits on noise and vibration have to date been established by individual countries. When converted to RMS velocity level, other national criteria for acceptable levels of residential vibration exposure extend over a 20 dB range, from approximately 68 VdB to 88 VdB. The current FTA criteria lie at the lower end of this range.
- **Descriptors of ground-borne noise:** Almost all national standards for train-related noise are stated in units of A-weighted sound pressure level. A-weighting de-emphasizes low-frequency components which contribute significantly to ground-borne vibration and noise. Alternative weighting schemes have been suggested by several researchers.
- **Ground-borne noise standards:** Not all national standards include limits for ground-borne noise. Those that do, almost always express the limits in terms of A-weighted sound pressure level. The residential A-weighted limits range from 20 dB to 49 dB. The current FTA residential limit lies in the middle of this range.
- **Effect of amplitude and number of events:** The relationship between annoyance and the magnitude and number of vibration events has been investigated. As would be expected, annoyance is generally found to increase with the number and duration of vibration events. Some research suggests that annoyance is not simply proportional to the number of events, but is proportional to the fourth power of vibration amplitude (*e.g.*, annoyance $\propto NV^4$, where N is the number of events per day and V is a measure of the vibration amplitude). For example, if the number of trains over a given time period increased by a factor of 16, the vibration amplitude would need to be reduced by a factor of 2 ($=16^{1/4}$) in absolute units, or by about 3 dB, for annoyance to remain constant. Relatively little attention has been paid to the effect of the duration of the vibration event (train length) on annoyance. This would be an important issue, for example, when assessing vibration from long freight trains.
- **Social surveys and dosage-response relationships:** Social surveys performed in Norway, Sweden, and Scotland had similar goals to the D-12 study (*i.e.*, development of dosage-

response relationships). These surveys showed 1) that a large number of respondents are needed to develop reasonable dosage-response relationships, 2) that community annoyance from vibration can be skewed by prior negative experiences with the transit system, and 3) that ground vibration is among the least annoying aspects associated with the presence of a rail transit system in the neighborhood.

- **Vibration perception:** Several laboratory studies of human sensitivity to vibration provide estimates of the human threshold of perception as a function of frequency. Both U.S. standard ANSI S3.29-1983 (4) and International Standard ISO 2631-2 (5) include "perception threshold" curves for three orthogonal body axes. Over the range of frequencies that is typically most troublesome with regard to rail-induced ground vibration (16 Hz to 80 Hz), these curves may be approximated by a constant vibration velocity. However, few of the human perception thresholds measured under laboratory conditions are consistent with those presented in the ANSI and ISO standards. This suggests that weighting curves based on the ANSI and ISO standards may not accurately reflect true vibration perception in residential exposure circumstances.

- **Combined ground-borne vibration and airborne noise:** No consensus exists about the combined effect of airborne noise and ground vibration on annoyance. Most research indicates that annoyance due to airborne noise is greater when accompanied by vibration. However, by acting as a distraction, airborne noise may also reduce the likelihood that ground-borne vibration will be noticed. If this is the case, it is possible that steps taken to reduce airborne noise levels, such as installing sound walls, could actually lead to increased sensitivity to ground-borne vibration. Current published vibration limits do not depend on the amount of concurrent airborne noise.

- **Rattle:** Little is known about the degree to which rattle induced by rail-induced ground-borne vibration is associated with annoyance. Recent research on low-frequency sideline noise from commercial aircraft indicates that rattle can be an important factor in residential annoyance.

2.1 Vibration Descriptors

2.1.1 Vibration Weighting Curves

Before discussing criteria in more detail it is useful to summarize the different metrics that are used to describe ground-borne vibration and noise. Although it may not be clear from the manner in which data are presented, ground vibration is almost always specified in terms that are equivalent to velocity within the frequency ranges of greatest relevance to rail transit systems. The metrics may be referred to as weighted acceleration or weighted velocity, and may be expressed in terms of absolute units or decibels using a variety of decibel references.

National standards typically express vibration limits in terms of an overall weighted vibration amplitude, usually acceleration in units of m/s^2. The weighting factors are typically applied on a 1/3 octave band basis, then the spectral levels are summed to yield an overall vibration amplitude. Although different terms are used for the weighting function, in many cases the weighting is based on the whole-body response curve of ISO 2631-2 (5).

The acceleration weighting curves used in various standards are shown in Figure 1. The quantities shown in the figure are:

- W_m (KB): Weighting curve defined in ISO 2631-2 (5) for characterizing whole-body vibration for arbitrary directions. This is also referred to as the "whole-body" or "KB" weighting curve. In some cases, guidelines are listed according to a KBF_{max} value rather than the RMS acceleration. KBF_{max} is the maximum value observed during the evaluation time and is similar to an Lmax or peak particle velocity measure. The maximum RMS acceleration value is referred to as KB_{FTm}. A measure of total vibration energy received over a given time period is expressed as KB_{eq}.
- W_k: Weighting curve defined in ISO 2631-1 (5) for seated or standing humans exposed to vertical vibration.
- W_d: Weighting curve defined in ISO 2631-1 (5) for seated or standing humans exposed to horizontal vibration.
- ANSI: Weighting curve provided in ANSI S3.29-1983 (4) for characterizing whole-body vibration for arbitrary directions.
- BS 6841(z): Weighting curve from British Standard 6841 (6) for vertical vibration.
- BS 6841(x/y): Weighting curve from British Standard 6841 (6) for horizontal vibration.

Figure 1 shows that acceleration weighting functions differ by as much as 20 dB at some frequencies.

Figure 2 displays the acceleration weighting curves transformed into velocity. (A decibel reference value of 1µg has been used for acceleration and 2.54×10^{-8} m/s (1µin/sec) for velocity.) Other reference values would change the vertical scale, but not the relative positions of the curves. If the curves are normalized so that the arithmetic average value from 25 Hz to 63 Hz is zero, then the weighting curves all converge over the frequency range of 16 Hz to 80 Hz, as shown in Figure 3.

Note that the ANSI and BS 6841 curves are undefined above 80 Hz, and W_m, W_d, and W_k are identical above 16 Hz. Thus, even though different standards rely on different weighting curves, the convergence of the weighting curves between 16 Hz and 80 Hz, the region in which rail-induced vibration is typically most severe, means that all of the curves are equivalent to an un-weighted vibration velocity, the measure that is currently used in the United States.

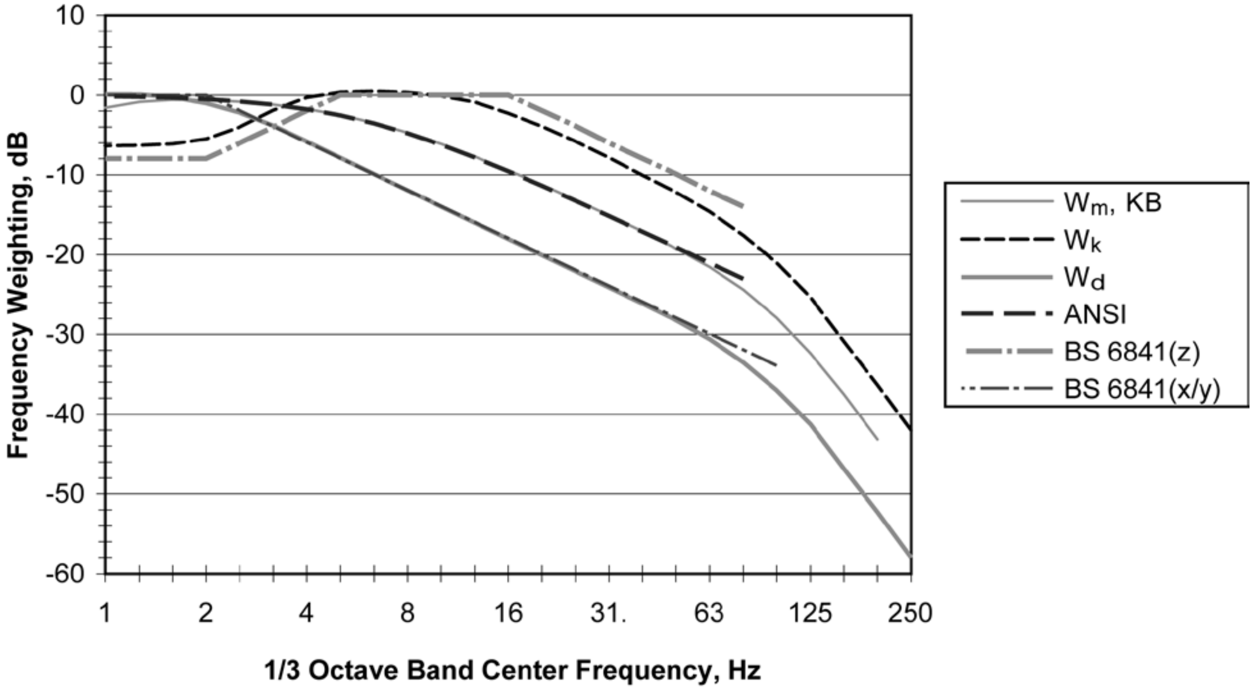


Figure 1: Acceleration Weighting Curves

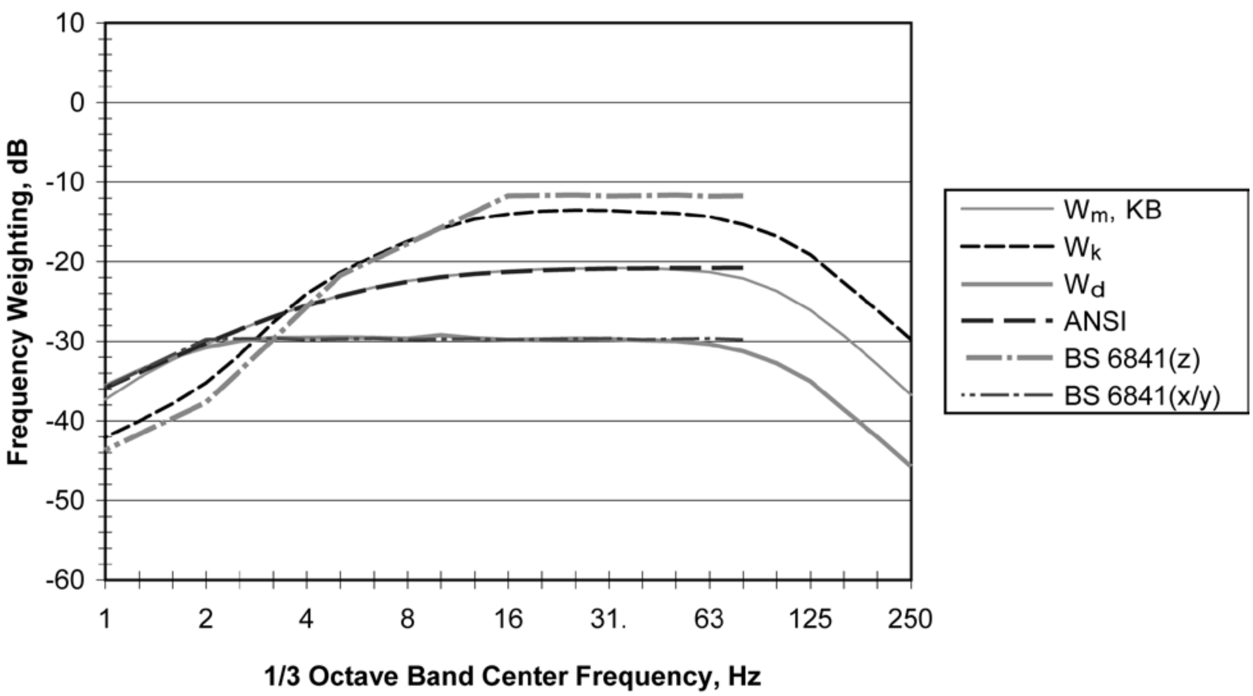


Figure 2: Weighting Curves in Terms of Velocity

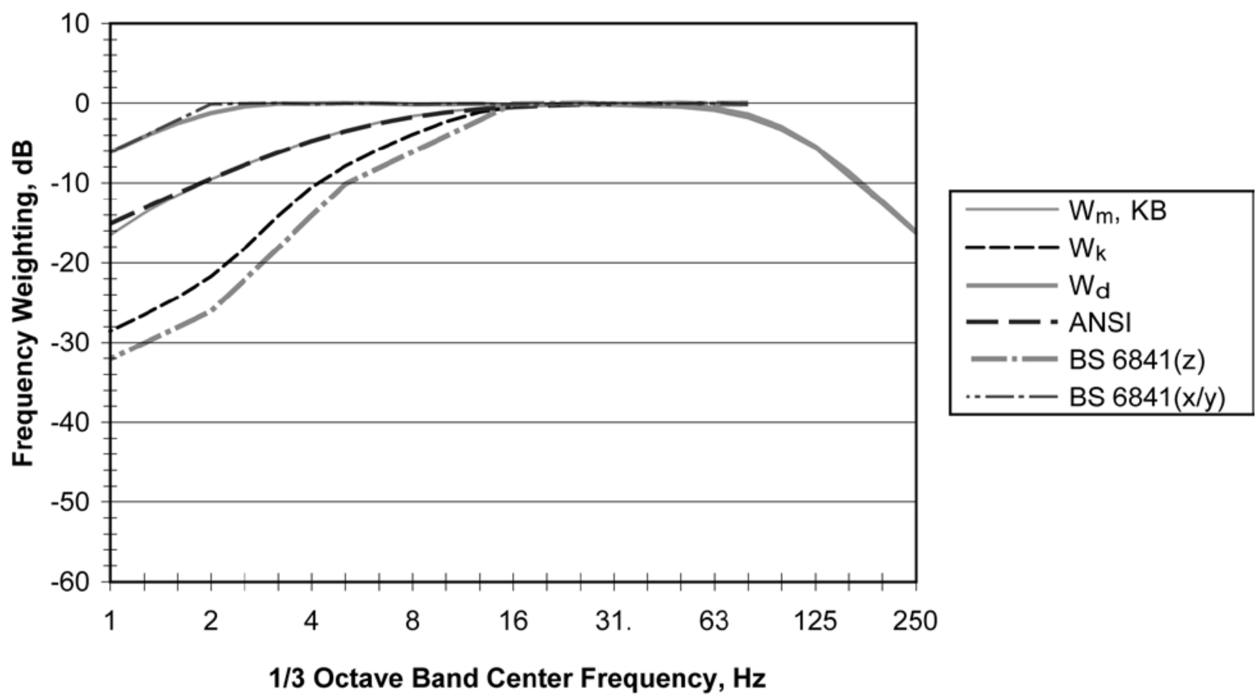


Figure 3: Normalized Velocity Weighting Curves

The commonality of the weighting curves raises the question as to how much difference the weighting curves make in evaluating typical train-induced ground vibration spectra. Several typical train vibration spectra are shown in Figure 4. The spectra include:

- **Spectrum 1**: Heavy rail rapid transit with highest spectral levels in the 16 Hz to 31.5 Hz 1/3 octave bands.
- **Spectrum 2**: Diesel locomotive powered commuter rail with highest spectral levels in the 12.5 Hz to 31.5 Hz 1/3 octave bands.
- **Spectrum 3**: Freight train with a more broadband spectrum and highest levels in the 16 Hz to 50 Hz 1/3 octave bands.
- **Spectrum 4**: A simulated vibration spectrum with energy concentrated at lower frequencies where the different weighting curves start to diverge. This is the commuter rail spectrum (Spectrum 2) shifted to the left by two 1/3 octave bands. After frequency shifting, the highest spectral levels are in the 8 Hz to 20 Hz bands.

The overall vibration velocity and acceleration levels using no weighting and the W_m, W_k, ANSI and BS 6841 weighting curves are shown in Table 4. For each spectrum, Table 4 shows:

- Row 1: The un-weighted velocity level and the weighted acceleration levels using the W_m, W_k, ANSI and BS 6841 weighting curves.
- Row 2: The normalization factors to convert to weighted velocity level.
- Row 3: The weighted velocity levels after normalization.
- Row 4: The difference between the un-weighted and weighted vibration velocity level.

Table 4 shows that, except for the simulated very low-frequency spectrum, the variation between weighted and un-weighted levels after normalization is negligible (less than 0.5 dB). The only time that the weighting curves will have more than a marginal effect is when the vibration has substantial amounts of energy at frequencies below 20 Hz. In the latter case, as illustrated by the simulated example of spectrum 4, the weighted velocity levels can be 0.9 to 3.4 decibels lower than the overall un-weighted velocity level.

It follows from this analysis of representative train spectra that:

- Since human sensitivity to vibration is largely confined to frequencies between 8 Hz and 80 Hz, the weighting method used generally does not make a meaningful difference in determining whether a vibration level exceeds an impact threshold, and
- Even in unusual situations where ground vibration is dominated by frequencies below 20 Hz, one would only expect to overestimate the potential for annoyance by a few decibels even if no weighting curve is used.

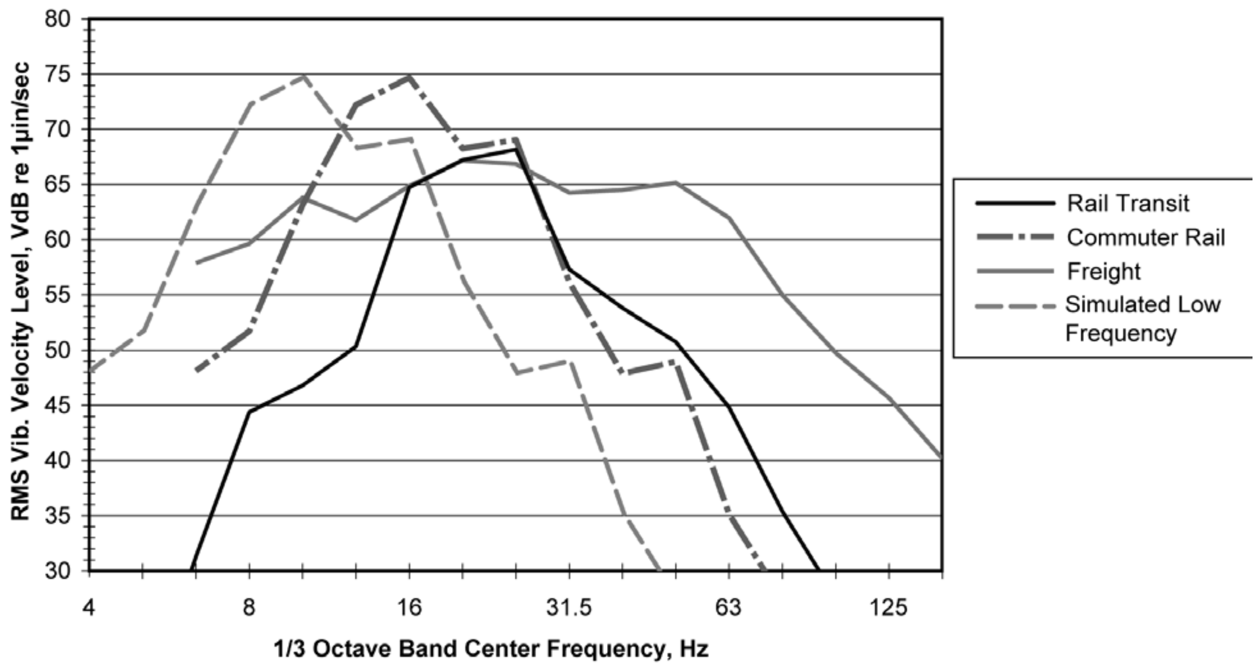


Figure 4: Typical Vibration Spectra from Train Operations

Table 4: Weighted Acceleration Metrics for Representative Train Spectra

Spectrum	Velocity VdB[1]	Weighted Acceleration Levels, dB[2]			
		Wm	Wk	ANSI	BS 6841
1. Rapid Transit					
Un-normalized	72.0	51.0	58.3	50.9	60.3
Normalization Factor	0.0	21.0	13.9	20.9	11.8
Normalized Value	72.0	72.0	72.2	71.8	72.0
Difference	--	0.0	0.2	-0.2	0.0
2. Commuter Rail					
Un-normalized	78.0	56.8	63.8	56.7	65.7
Normalization Factor	0.0	21.0	13.9	20.9	11.8
Normalized Value	78.0	77.8	77.7	77.6	77.5
Difference	--	-0.2	-0.3	-0.4	-0.5
3. Freight					
Un-normalized	74.7	53.4	60.5	53.4	62.4
Normalization Factor	0.0	21.0	13.9	20.9	11.8
Normalized Value	74.7	74.5	74.4	74.4	74.2
Difference	--	-0.2	-0.3	-0.3	-0.5
4. Simulated very low-frequency vibration					
Un-normalized	78.0	56.1	62.2	56.0	62.8
Normalization Factor	0.0	21.0	13.9	20.9	11.8
Normalized Value	78.0	77.1	76.1	76.9	74.6
Difference	--	-0.9	-1.9	-1.1	-3.4

1. The vibration velocity levels are in decibels relative to 1 μin/sec.
2. The un-normalized weighted acceleration levels are all in decibels relative to 1 μg.

2.1.2 Vibration Metrics

RMS (root-mean-square): Most standards are based on either a weighted or un-weighted vibration velocity in absolute units or decibels. The most common unit is the maximum RMS vibration level obtained using a one-second time constant (commonly known as a slow RMS detector). Typically, the maximum vibration level (Lmax) that occurs during a passby is tabulated, from which an "average-maximum" level is calculated using a linear decibel average, energy decibel average, or a direct linear average of the maximum levels from a number of train passages. The various averages are usually within 0.5 dB to 1 dB of one another as long as there are no significant outliers. This average-maximum level is then used to characterize vibration exposure at the measurement site.

The average RMS vibration level over the duration of a train passby, equivalent to an energy average (Leq) in acoustics, is sometimes used in place of Lmax. Using the passby average to characterize the train vibration yields more consistent estimates of the exposure, particularly with longer trains, however, it does require some judgment with respect to the event start and stop times.

Most RMS detectors used in sound and vibration analyzers perform an exponential running average of the RMS sound or vibration level. The exponential time weighting for the running average is defined as:

$$p(t)_{RMS} = \left[\frac{1}{\tau} \int_0^t p^2\,(\xi)\, e^{-(t-\xi)/\tau}\, d\xi \right]^{1/2}$$

where t is the observation time, $p(t)_{RMS}$ is the exponentially averaged quantity, τ is the time constant, and $p^2(\xi)$ is the square of the instantaneous quantity. The values of τ are 0.125 second and 1.0 second for the FAST and SLOW settings on standard sound level meters, respectively. The FAST setting corresponds roughly to the time constant of the human ear.

In the United States, SLOW time averaging is typically used to characterize ground-borne vibration. The SLOW detector setting was developed many years ago when analog meters were used to measure sound levels. Modern instrumentation uses digital processing to calculate both true RMS averages (no exponential averaging) as well as running exponential averages for a variety of time constants.

Statistical Maximum: The "Statistical Maximum" velocity or acceleration (v_{w95} and a_{w95}) is a variant on the average-maximum vibration level. The values of these quantities are determined from the mean and standard deviation of the individual event weighted RMS velocities (or accelerations) at a specific location as follows:

$$v_{w95} = \overline{v_{w,mean}} + 1.8\,\sigma$$

$$a_{w95} = \overline{a_{w,mean}} + 1.8\,\sigma$$

where $v_{w,mean}$ and $a_{w,mean}$ are the mean weighted RMS velocity and acceleration and σ is the standard deviation of the measured quantities. The interpretation of this is that there is a 95% probability that a measurement of train vibration will fall below the v_{w95} and a_{w95} levels. Table 5 shows the calculated statistical maximum levels for sample train vibration data. The measurements in Table 5 were performed above a subway on the BART system in the San Francisco Bay Area at horizontal distances ranging from 0 m to 30 m from the track centerline. Figure 5 shows the BART data measured at 7.6 m graphically. This example illustrates that the statistical maximum level is typically 1.5 to 3 dB greater than the average-maximum vibration level for similar trains operating at similar speeds. The difference would be greater for a mixture of transit modes (*e.g.*, light rail and freight trains in the same corridor), or in the case of a large variation in train speeds.

Table 5: Comparison of v_{95} and Average Vibration Level for Typical Transit Vibration Levels

Train	Measured Vibration Levels, BART Train Passbys, VdB						
	0 m	**3.8 m**	**7.6 m**	**11.4 m**	**15.2 m**	**22.9 m**	**30.5 m**
Train 1	71.8	68.5	69.9	64.4	70.6	68.3	66.4
Train 2	71.2	67.7	69.4	64.3	70.3	68.1	65.7
Train 3	71.2	67.9	69.5	64.2	70.2	68.0	65.8
Train 4	72.5	69.2	70.4	65.3	70.6	68.2	66.0
Train 5	71.0	67.8	69.3	63.9	69.9	67.5	65.4
Train 6	72.6	71.0	73.1	62.1	71.3	70.1	67.8
Train 7	72.5	71.0	73.1	61.9	71.1	69.8	67.5
Train 8	67.8	65.2	66.3	59.4	67.6	66.0	63.8
Train 9	73.0	71.9	73.2	58.0	69.6	68.7	67.5
Train 10	73.0	71.9	74.0	61.4	70.8	69.5	67.3
Train 11	72.9	71.1	73.0	63.4	71.8	70.6	68.2
Averages							
Decibel[1]	72.0	69.8	71.6	63.0	70.4	68.8	66.7
Linear[2]	71.9	69.6	71.3	62.8	70.4	68.7	66.6
L_{v95}[3]	74.0	72.7	74.7	65.9	72.1	70.8	68.6
Difference[4]	2.0	2.9	3.1	2.9	1.7	2.0	1.9

1. Energy average of decibel values.
2. Linear average after converting decibels to µin/sec.
3. In absolute units, $v_{95} = v_{avg} + 1.8\sigma$.
4. Difference between L_{v95} and decibel average.

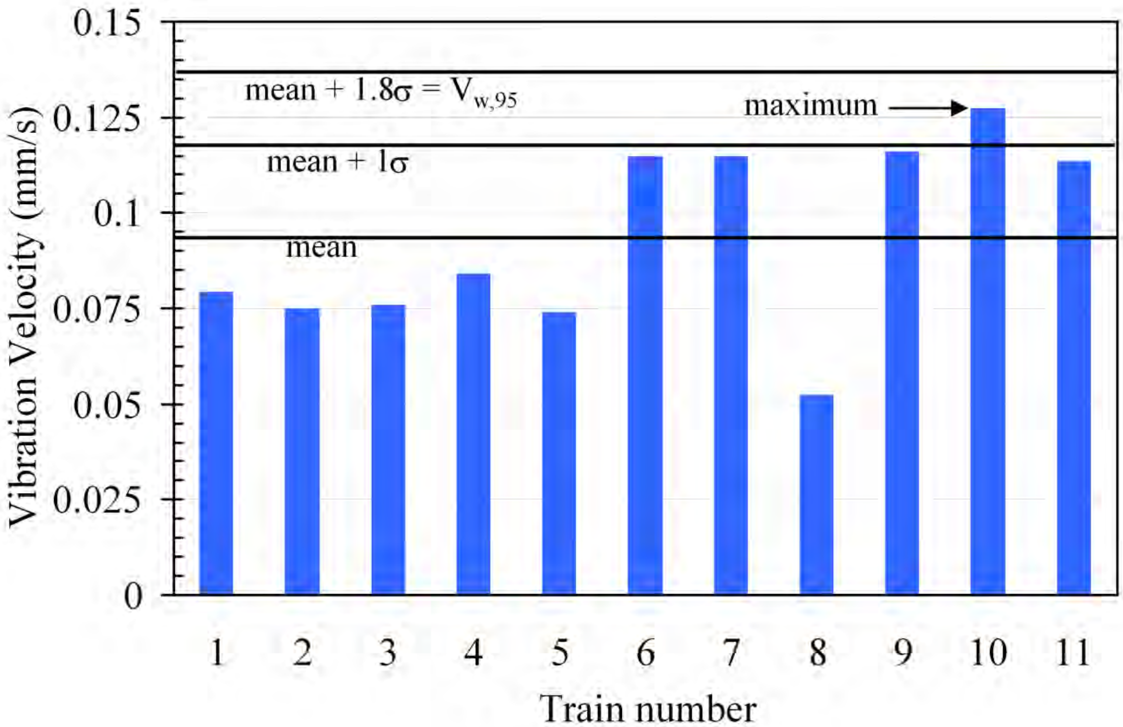


Figure 5: Example of Statistical Maximum Velocity (BART data at 7.6 m)

Vibration Dose Value (VDV) and Root Mean Quad (RMQ): The root mean quad and fourth-power vibration dose value are the most notable exceptions to RMS vibration to characterize human exposure. They are defined as:

$$a_{RMQ} = \left\{ \frac{1}{T} \int_0^T [a_w(t)]^4 \, dt \right\}^{\frac{1}{4}}$$

$$VDV = \left\{ \int_0^T [a_w(t)]^4 \, dt \right\}^{\frac{1}{4}}$$

where a_w is the weighted acceleration using the BS 6841 (6) z-axis weighting curve, a_{RMQ} is the root mean quad vibration amplitude, *VDV* is the vibration dose value, and *T* is the duration of the vibration event. The vibration dose is based on work done at the Institute of Sound and Vibration Research (ISVR) by Howarth and Griffin (8)(9)(10). VDV is not an RMS-like average, but rather an exposure quantity, similar to the sound exposure level (SEL) used to characterize sound energy. SEL values are normalized to one-second periods, and hence effectively compress all of the acoustic energy measured during an event into a one-second period. The vibration dose increases as the duration, number, and amplitude of vibration events increase. For multiple events, the vibration dose value can be calculated by increasing the integration time to reflect the increase in vibration exposure. Or, equivalently, the individual VDV's can be summed as follows,

$$VDV_{total} = \left[\sum_i VDV_i^4 \right]^{\frac{1}{4}}$$

It is important to note that the frequency weighting scheme used with Vibration Dose Values is the BS 6841(z) (6) curve, not the W_m/KB curve that is used by a number of other standards.

Although Howarth and Griffin's research supports the use of the VDV metric to characterize human response to building vibration, it is an awkward metric to calculate and is confusing to apply. The unconventional units of $m/s^{1.75}$ result from the integration of the fourth power of acceleration over time (e.g., acceleration^4×time), which yields units of $[m^4/sec^7]^{0.25}$ or $m/s^{1.75}$. If the metric were normalized to a hypothetical one-second duration, as with SEL (effectively compressing all of the fourth power energy into a 1-second period), the equation would become:

$$VDV_{EquivSEL} = \frac{1}{T_0} \left\{ \int_0^T [a_w(t)]^4 \, dt \right\}^{\frac{1}{4}}$$

where T_0 is 1 second, and the units would be m/s^2.

The rationale for reliance on VDV for characterizing exposure to vibration is based on the findings of a few laboratory studies. However, given that VDV and RMQ are not calculated by most vibration measurement equipment, specialized computer programs would generally be required to obtain either RMQ or VDV from a recorded vibration file. It is questionable whether the potential for a slight improvement in the correlation between the vibration measure and annoyance is worth the considerable added complexity of the measurement procedure.

2.2 Noise Descriptors

The central characteristic of rail-generated ground-borne noise is the dominance of low-frequency energy that is often experienced as a low-frequency rumble. The A-weighted sound level is the most common descriptor used to assess the annoyance of common environmental noise sources. Unfortunately, because A-weighting de-emphasizes low-frequency sound, it is often inappropriate for noise sources that contain considerable amounts of low-frequency energy.

Several frequency-weighting functions have been proposed for quantifying low-frequency sound levels (cf. the G1, G2, LSL, and LSPL functions noted by Tokita et al. (19)). These and the more familiar A- and C-weighting functions are summarized in Table 6. All but one of these functions (LSPL), are characterized by a spectral peak with steep roll offs on either side. The sharp peaks suggest targeted resonant frequency responses, either structural or physiological. According to Tokita et al. (19), these functions are all meant to address a combination of structural response effects such as rattle, as well as "feelings of oppression and vibration," presumably in differing proportions for different weighting functions.

Neither Tokita *et al.* (19) nor Tokita and Nakamura (18) provide detailed rationales for the shape of each weighting function, but they do argue in the former citation that the LSL curve provides a superior account of subjective response. A commonly noted resonant frequency for wood-frame residential structures is on the order of 20 Hz, so to the extent that vibration-induced rattle affects annoyance, weighting functions sensitive in this frequency range may address this particular issue.

Table 6: Standardized Frequency-Weighted Sound Levels

Sound Level Weighting	Source	Description
A	ANSI 1.4-1983 (R2006)	Nominal equal-loudness at low sound levels
B	ANSI 1.4-1983 (R2006)	Nominal equal-loudness at moderate sound levels
C	ANSI 1.4-1983 (R2006)	Nominal equal-loudness at higher sound levels
G	ISO 7196:1995	20 Hz peak, high roll off either side. No justification provided for curve shape provided in standard.
G1	Tokita *et al.* (19)	20 Hz peak, and eventually adopted as the G curve, above.
G2	Tokita *et al.* (19)	20 Hz peak very similar to G1, but with less attenuation of the low frequencies than G1.
LSL	Tokita *et al.* (19)	50 Hz peak with spectral shape very similar to G1.
LSPL	Tokita *et al.* (19)	Broad, flat response from 2 to 50 Hz, with steep roll off on either side.

Although A-weighting is insensitive to low-frequency noise, a study by Walker and Chan (11) showed that some frequency weighting is appropriate. The authors conducted laboratory studies of human response to low-frequency noise with two different peak frequencies (50 Hz and 80 Hz). When A-weighting adjustments were included, the correlation between annoyance and the noise descriptors was significantly improved. The Walker and Chan study examined how the presence of broadband masking noise affected annoyance from low-frequency noise. It is not clear whether their conclusions about frequency weighting are applicable when rattle is a significant source of the annoyance.

Annoyance due to rattle is a factor that has been investigated with regard to low-frequency aircraft noise. Low-frequency sideline noise produced by large commercial jets during ground operations shares much of the low-frequency characteristics of ground-borne noise produced by rail transit systems. A panel of experts on aircraft noise, structural response to vibration, and human response to transportation noise recently published an extensive literature review and report of its findings concerning low-frequency noise effects on residential populations near Minneapolis-St. Paul International Airport (MSP) (12). After considering a number of methods to characterize low-frequency noise, the panel recommended adoption of the Low-Frequency Sound Level (LFSL) because of its high correlation with secondary noise emissions (rattle) and annoyance. LFSL is a single-event noise metric that sums the maximum 1/3 octave band sound levels from 25 Hz to 80 Hz that occur during the course of an individual aircraft passby. The frequency bands used to calculate LFSL compared to A and C weighting are shown in Figure 6.

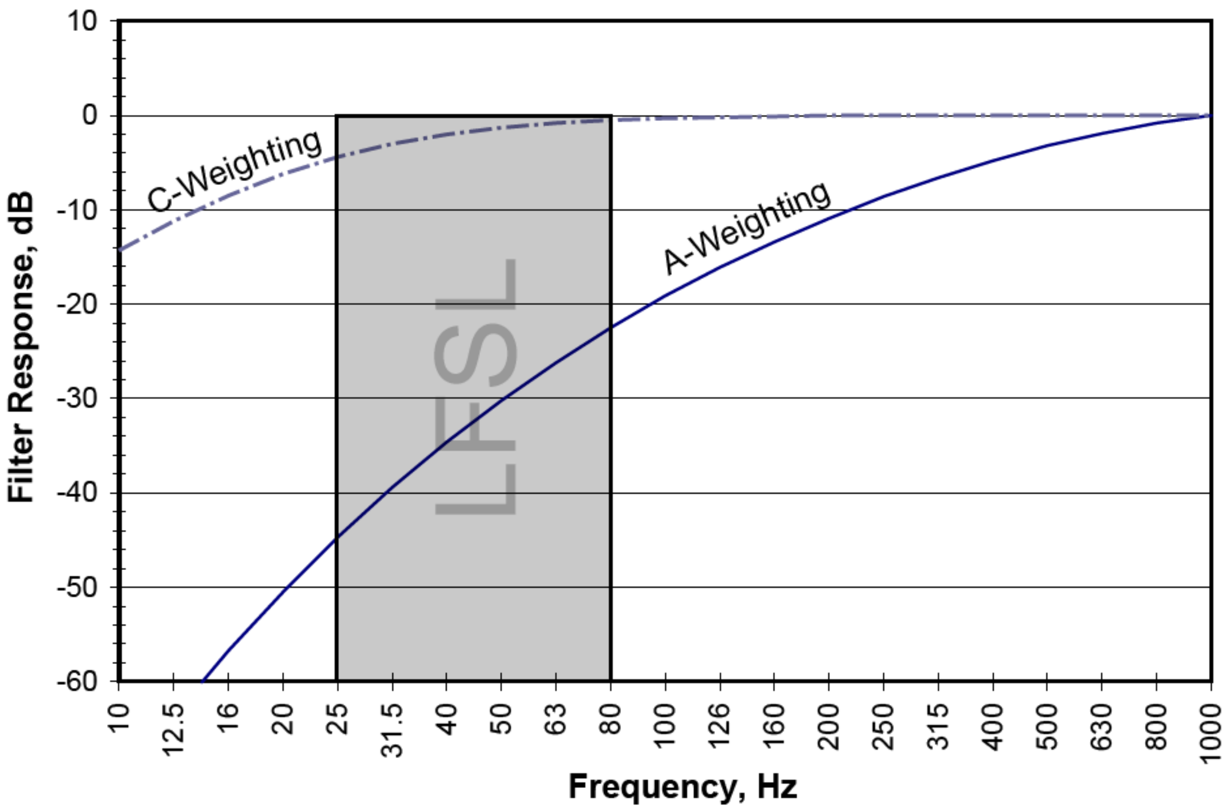


Figure 6: Common Weighting Networks Used for Assessing Airborne Sound Impacts

Some of the more relevant conclusions of the MSP expert panel include the following:

- Loudness level contours (such as those of Stevens (13)) provide a reliable indication of the loudness, noise rating, and direct annoyance of sounds in the low-frequency range of interest. However, the primary effect of low-frequency noise on residential populations is annoyance due to "secondary emissions": rattling noises and vibration of windows, doors, and household paraphernalia.
- A laboratory study in which test subjects judged the annoyance of recorded samples of low-frequency aircraft noise confirmed that:
  - a) Low-frequency sideline noise was more annoying than aircraft overflight noise heard at the same A-weighted sound level.
  - b) The additions of even minor amounts of rattle increased annoyance.
  - c) Reductions in the low-frequency content of the noise proportionally decreased the annoyance of non-rattling test sounds.
- LFSL was identified as the preferred predictor of the prevalence of rattle-induced annoyance in communities exposed to low-frequency aircraft noise.
- LFSL was defined as a short-term, single-event noise measure, rather than as a long-term, cumulative, or time-weighted average metric, because it was intended primarily as a direct

predictor of rattle, not of long-term annoyance. It has subsequently been shown empirically to function well as a predictor of the annoyance engendered by rattle.

- Annoyance due to low-frequency aircraft noise is strongly related to LFSL values. Figure 7 summarizes the relationship between low-frequency aircraft noise levels near MSP and LAX airports, and annoyance. Noise metrics based on A-weighting were of little value for the purposes of predicting community response to low-frequency noise because A-weighted measurements cannot distinguish between sounds of vastly different low-frequency content which also contain substantial energy at higher frequencies.

Perhaps the key conclusion of the MSP study is that annoyance correlates with rattle, and the LFSL is the noise metric that best correlates with rattle, and hence with annoyance.

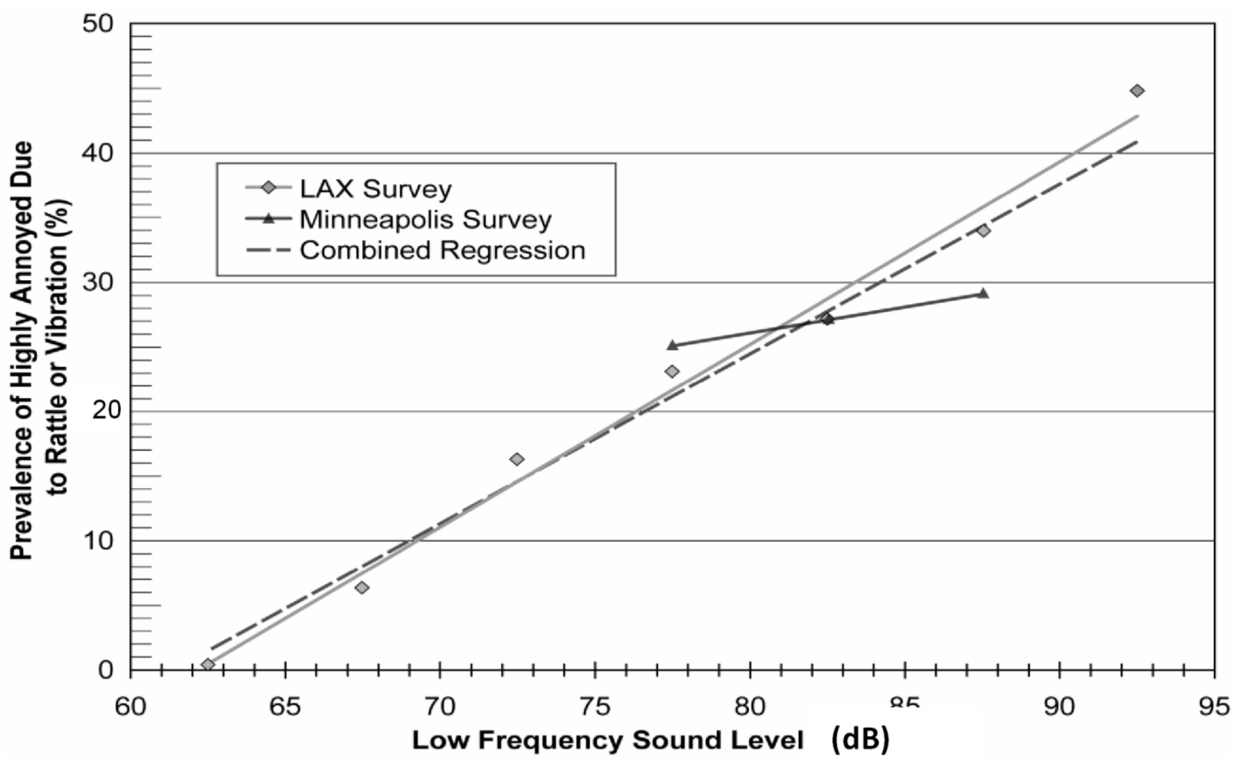


Figure 7: Noise Levels and Percentages Highly Annoyed in MSP and LAX Surveys

2.3 Standards for Vibration and Noise

Many countries have adopted standards for acceptable levels of ground-borne vibration generated by rail traffic. A few also have standards for ground-borne noise. These standards are summarized in Appendix D. Most standards are based on single number measures of indoor vibration, typically a weighted vibration level that is equivalent to vibration velocity over the frequency range of 16 Hz to 80 Hz. The weighting curves are usually based on the response curve for whole-body vibration of ISO 2631-2(5). Although the standards vary somewhat in how the vibration weighting curves are defined at frequencies below 16 Hz and above 80 Hz, these frequency ranges generally have little effect on overall vibration levels associated with typical rail transit operations.

It is difficult to directly compare the vibration limits adopted by different countries because many standards measure vibration differently. Figure 8 shows the approximate limits (in VdB) for nine vibration standards, assuming residential exposure and rail transit operations consisting of approximately 100 train passbys per day, each lasting approximately 10 seconds. The exact wording varies between standards, but generally, when the predicted or measured vibration exceeds the applicable threshold, vibration mitigation must be considered.

Figure 8 shows that the acceptable nighttime vibration level for residential setting ranges from 68 VdB to 84 VdB. The majority of the standards fall between 72 VdB and 78 VdB. Note that the language and units for the standards vary, and some interpretation was necessary to prepare the comparison in Figure 8, however, the figure still gives a general sense of how standards used in various countries compare. Note also that the criteria used in the United States do not specifically distinguish between daytime and nighttime exposure. For comparison purposes, the nighttime limit shown in Figure 8 corresponds to the FTA's residential limit and the daytime limit corresponds to FTA's threshold for institutional facilities with primarily daytime use. Figure 8 shows general consistency between the vibration standards that are used worldwide, although some countries allow substantially higher vibration levels than others.

Only a few of the national standards include specific limits for ground-borne noise. The general indication seems to be that achieving the standard for vibration will automatically result in acceptable levels of ground-borne noise. Walker and Chan (11) include a table with ground-borne noise standards from The American Public Transportation Association (APTA), London Underground and an unspecified German standard. (The APTA limits formed the basis for the FTA ground-borne noise impact thresholds, and the FTA guidelines had not been published at the time that the Walker and Chan paper was written.) The current FTA limits for A-weighted ground-borne noise in residential buildings is 43 dB for infrequent events (<30 events/day), 38 dB for occasional events (30-70 events/day), and 35 dB for frequent events (>70 events/day). The A-weighted limits shown in the Walker and Chan paper are 40 dB for the London Underground and 35 dB for the German standard.

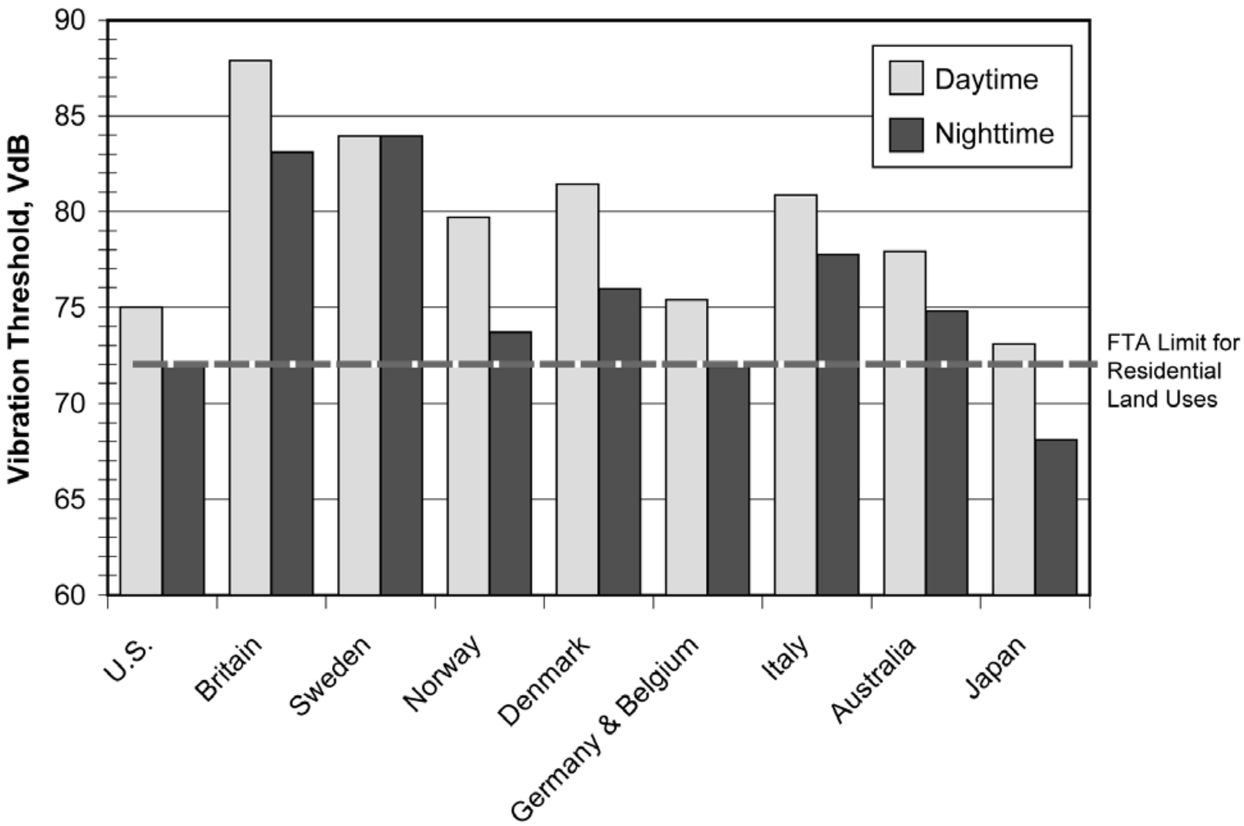


Figure 8: National Limits for Rail Transit Vibration

2.4 Research on Human Response to Vibration

A variety of laboratory and field studies of human response to vibration have been published. The research ranges from ride quality studies, to hand-arm vibration due to work tools, to whole body vibration. The studies relevant to ground vibration from rail transit include those that have considered human response to low level vibrations that are near the threshold of perception.

Some of the research particularly relevant to the D-12 study is highlighted in this section. This includes the laboratory studies of the threshold of human perception and equal vibration perception contours, the combined effects of broadband noise and ground-borne vibration, the relationship between annoyance and the number of events, and social survey studies of community annoyance.

2.4.1 Threshold of Perception and Equal Perception Contours

Most limit criteria have been developed under the premise that vibration begins to annoy people at levels only slightly greater than the perception threshold. If this is the premise, then it is important to accurately describe the level at which vibration becomes perceptible to people.

Figure 9 compares the perception threshold as estimated by several researchers. This figure was adapted from a figure presented by Bellman *et al.* (25) that was given in terms of acceleration. Also shown in Figure 9 is the base response curve from ANSI S3.29 (4), which is described as the threshold of perception for the most sensitive humans. It is clear from the figure that the experimentally derived perception thresholds are generally higher than those stated in ANSI S3.29 (4) particularly at frequencies below 20 Hz.

Figure 10 shows the perception threshold based on laboratory tests reported in Bellman *et al*. (25) along with equal perception contours. The results are shown in terms of both velocity and acceleration. Although Bellman's work used a limited number of subjects, it suggests that alternate weighting curves may more accurately reflect human response, particularly the threshold of perception, which Bellman's work indicates is equal to an acceleration level of 65 dB to 70 dB across the frequency range of 8 Hz to 80 Hz.

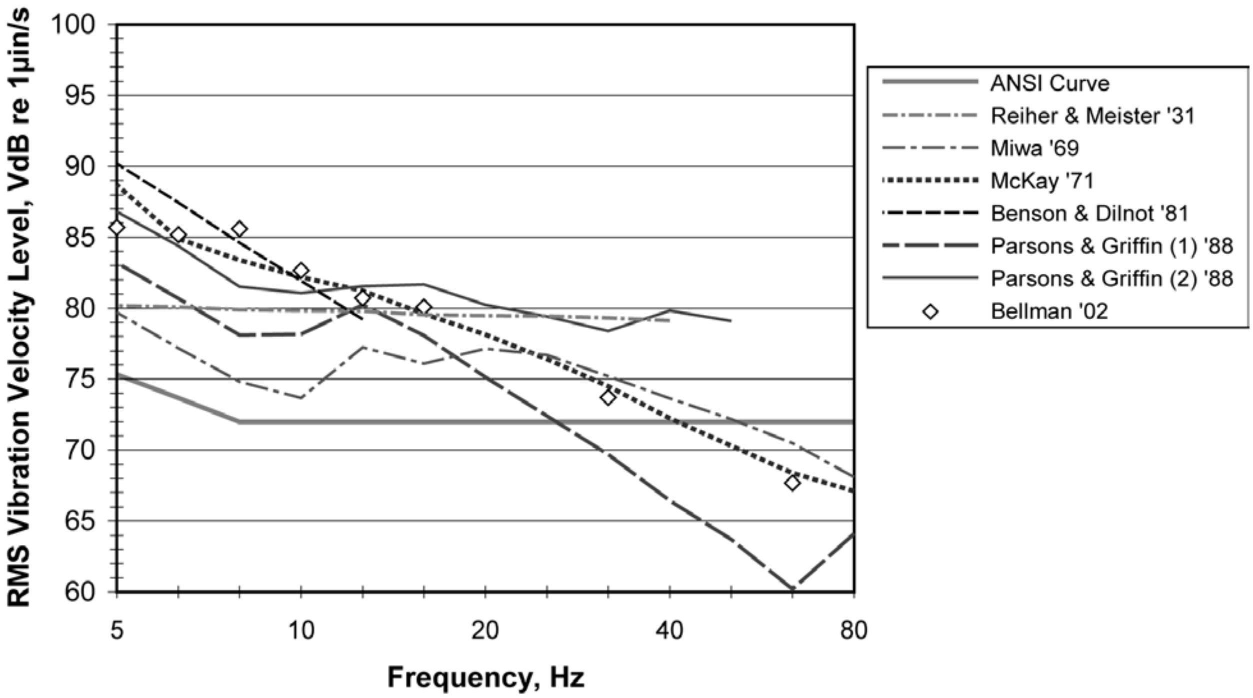


Figure 9: Results of Experimental Measurements of Perception Threshold
(Adapted from Bellman et al, 2004 (25))

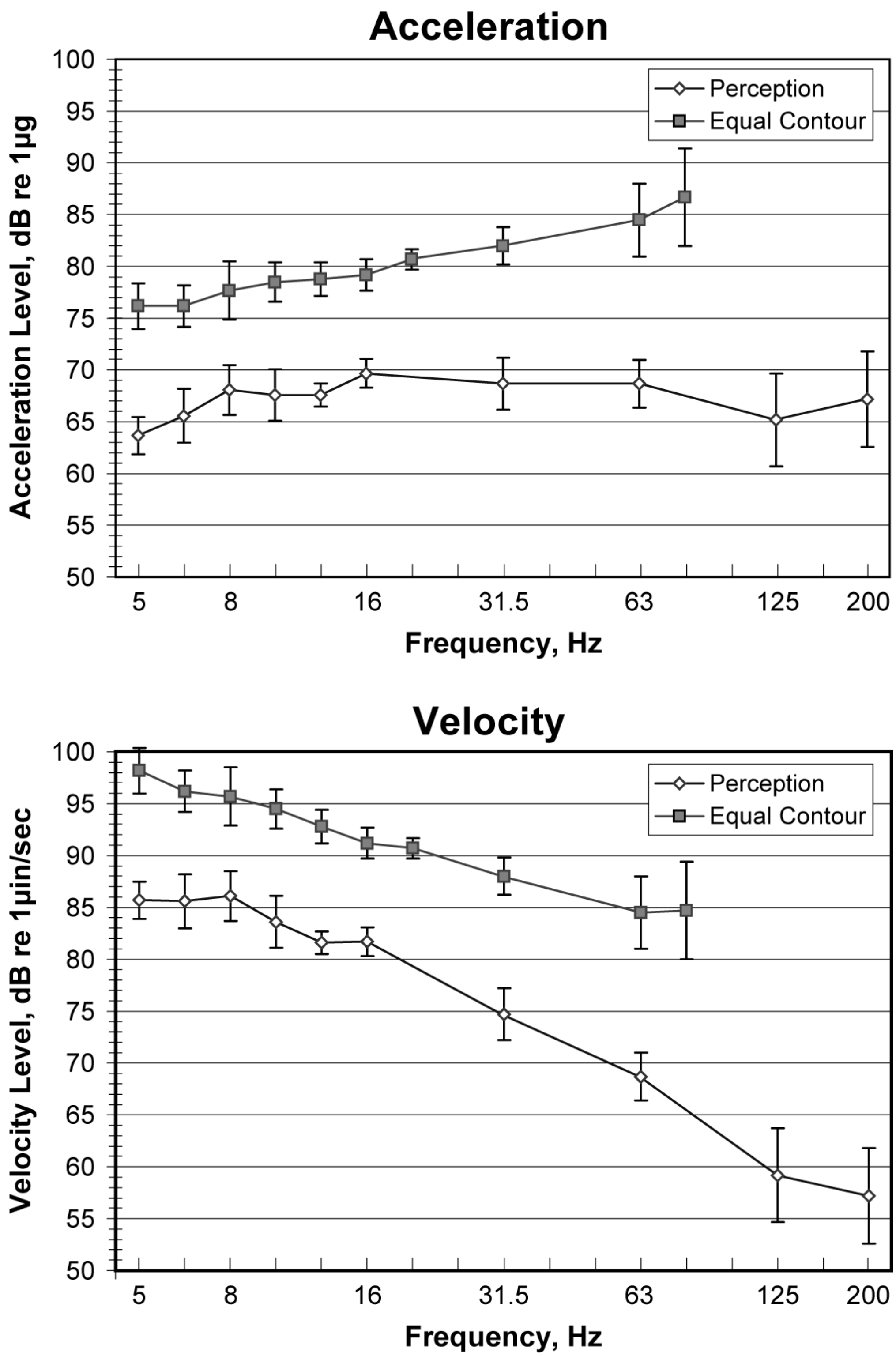


Figure 10: Equal Vibration Perception Contours Compared to Perception Threshold
(Adapted from Bellman et al, 2004 (25))

2.4.2 Combined Effects of Broadband Noise and Ground-Borne Vibration

The consensus of a small body of research on the combined annoyance of noise and vibration is that noise is more annoying when accompanied by vibration. For example, in an evaluation of noise and vibration near railways in Sweden, Öhrström and Skånberg (26) concluded that annoyance responses were much more frequent in areas where there were substantial vibrations, particularly at low levels of noise. They defined weak vibration as less than 1 mm/s (92 VdB) and strong vibration as greater than 2 mm/s (98 VdB). Both of these levels are relatively high, so it is not surprising that they generated greater annoyance than just noise alone.

The laboratory work of Howarth and Griffin (9) led to similar conclusions. Preferences for reducing the level of either noise or vibration were used to develop equivalences between them. Noise was found to be more annoying than vibration in the sense that test subjects preferred to reduce noise levels more often than they did vibration levels.

In a laboratory study of the effect of combined noise and vibration, Paulsen and Kastka (27) also demonstrated that vibration influenced the evaluation of noise annoyance. However, their results suggest a shallower gradient than that determined by Howarth and Griffin (9). Paulsen and Kastka found that annoyance judgments depended on how the questions were presented to subjects, and that noise had very little effect on judgments of annoyance due to vibration.

Another study by Howarth and Griffin (10) developed a method for predicting total annoyance due to combined noise and vibration. The authors developed an annoyance index value, ψ, which depended on the vibration dose value and the sound exposure level:

$$\psi = 22.7 + 243\,\phi_v^{1.18} + 0.265\,\phi_s^{0.036}$$

where φ_v is the vibration dose value and φ_s is the sound exposure level (where $\log_{10} \varphi_s = L_{AE}$, normalized to one second). The annoyance index is a relative one and has no absolute meaning outside the context of the study. Thus, the relationship developed by Howarth and Griffin simply describes a rate of growth of relationship between annoyance and noise/vibration, but does not attempt to relate this annoyance to that found in field studies. The authors concluded that in laboratory judgments, the combined effect of noise and vibration is a more useful predictor of total disturbance than either effect alone.

Several contradictory findings on the effects of background noise on the perception of vibration have also been published. Bellman *et al*. (25) concluded that A-weighted broadband background noise at 69 dB had no effect on the vibration perception threshold. However, Paulsen and Kastka (27) found that when subjects were exposed to 60 dB of A-weighted noise, fewer subjects could perceive mild, 0.05 mm/s (66 VdB) vibration. Zeichart *et al*., as described by Knall (28), also made observations that suggested that high noise levels can have a masking effect on the perception of vibration.

The implications of possible masking of vibration by noise are 1) that ground-borne vibration phenomena could be more annoying for subways than for at-grade and elevated systems, and 2) in some situations steps taken to mitigate airborne noise may lead to more noticeable ground-borne vibration.

Relationship Between Annoyance and Number of Events

It is commonly believed that annoyance due to building vibration increases as the duration and number of vibration events increase. In the United States, frequency of service is categorized as frequent (>70 events/day), occasional (30-70 events/day), and infrequent (<30 events/day). Most urban transit systems (rapid transit and light rail) fit into the frequent category, while most commuter rail systems fall into the occasional or infrequent category.

Howarth and Griffin (8) performed a laboratory study to determine how annoyance is affected by the number of vibration events. The authors developed the following relationship for equivalent annoyance:

$$N\,V^{3.7} \propto annoyance$$

where N is the number of trains and V is the vibration magnitude. According to this relationship, 200 trains at 70 VdB would produce the same level of annoyance as 25 trains at 75 VdB. This relationship was used to develop the fourth-power vibration dose value (VDV) that is described in the British Standard (6). Note that if annoyance is only proportional to NV^2 (as is assumed for community noise), then 200 trains at 70 VdB would produce the same level of annoyance as 64 trains at 75 VdB.

Öhrström (29) also examined the effect of the number of train passages on vibration-induced annoyance. Table 7 summarizes the survey responses in two areas with similar vibration levels but different numbers of operations per day. The responses were compared by mean annoyance rating (on a five point scale), and by the percentage of respondents describing the railway as “rather“ or “highly“ annoying. Although annoyance ratings were generally higher for greater numbers of train passbys, the research was designed only to study the effect of vibration on noise-induced annoyance, and was unable to derive a quantitative relationship between vibration and the number of events. Note that these were also relatively high vibration levels, which could limit the generalization of the findings.

Table 7: Comparison of Annoyance Response Based on Numbers of Trains

Area	# of Trains	Unweighted Vibration (mm/s) (VdB)	% Rather and Highly Annoyed			
			Maximum Noise Level, Lmax (A-weighted dB)			
			70-75	76-80	81-85	86-90
Saffle	20	0.3-8.0 (81-110 VdB)	3.2%	11.0%	26.4%	32.3%
Partille	160	1.3-3.1 (94-102 VdB)	8.1%	10.7%	29.6%	53.3%
Source: Öhrström, 1997 (29)						

Field Surveys of Annoyance due to Rail Vibration

The literature contains several field surveys of ground-borne vibration from rail operations. Woodroof and Griffin (30) performed a study intended to estimate the number of people in Scotland who notice, and are annoyed by, ground-borne vibration from railways. The study included interviews of 459 respondents, of whom 160 noticed railway-induced building vibration. Vibration data was collected in 52 of the surveyed residences where the occupants had reported feelable vibrations from trains. In each residence, the vibrations were measured in three orthogonal directions over a 24-hour period. Train events were separated from the background vibration, and a number of different vibration metrics were calculated including the Vibration Dose Value, as well as overall levels using W_b and W_g weighting curves. The metric that was found to be best correlated with annoyance was the number of trains per day that produced perceptible vibration. Perhaps the most striking conclusion of the study was: "These data suggest that vibration is among the least annoying aspects of a railway's presence in a neighborhood." Another important conclusion of the study was that vertical vibration was typically most severe and that there was no need for detailed analysis of the horizontal vibration. Although the study included measurements from across Scotland, the vibration levels were relatively low (the highest reported average vibration level was only 72 VdB).

Table 7 shows that vibration levels in Öhrström and Skånberg's Swedish studies (26)(29) were substantially higher than those observed in the Scottish study (30). The stated aim of the Öhrström and Skånberg study was "…not to study vibration in detail but only to compare annoyance to noise in combination with strong vibration levels with annoyance to noise alone." The study included a sufficient number of questions about vibration that an effort was made to pool the data with the results of a Norwegian study reported by Klæboe *et al.* (31). To quote the Klæboe study:

> "The exposure-effect relationships for each of the Swedish areas differed, as did the exposure-effect relationship based on the pooled Norwegian data set. One problem with using the previously existing measurements was that they often were obtained from buildings where inhabitants had complained about vibrations. The measurements might therefore not be representative for other buildings in the area. There were also concerns that there might be differences in the scaling of the measurement values. Lacking the resources to secure new measurements according to the new standard NS 8179 in these areas, a decision was made to proceed without these data."

A third study was performed in Norway by Klæboe *et al.* (31)(32)(33). The authors conducted a large-scale field study to determine the relationship between rail-related vibration levels and community annoyance. They developed a new term to describe vibration characteristics – the previously described statistical maximum value "v_{95}." The study included telephone interviews with 1503 respondents exposed to vibration levels between 0 and 3 mm/s (imperceptible vibration to over 100 VdB).

The survey questionnaire was similar to that of the present study. The vibration levels were determined for each respondent using a semi-empirical prediction model that had been verified through measurements throughout Norway.

Figure 11 shows the overall responses of respondents to perception and annoyance due to train vibration. These annoyance responses were used to determine predicted response curves based on the statistical weighted velocity level as shown in Figure 12. No effort was made to separate the source of annoyance as perceptible vibration, audible structure-radiated noise, or rattle. However, the authors successfully developed curves of annoyance as a function of vibration amplitude. At a vibration level of 72 VdB, Figure 12 predicts that 30% of people would notice the vibration and about 5% would be highly annoyed.

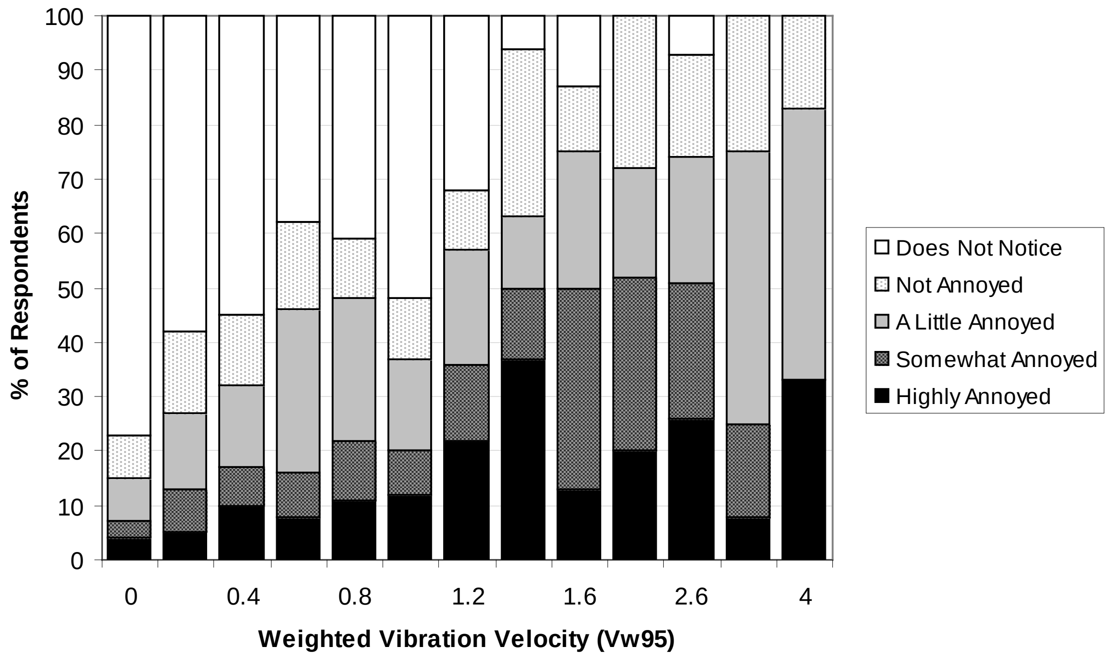


Figure 11: Annoyance Response of Survey Respondents

Source: Klæboe *et al.* (31)

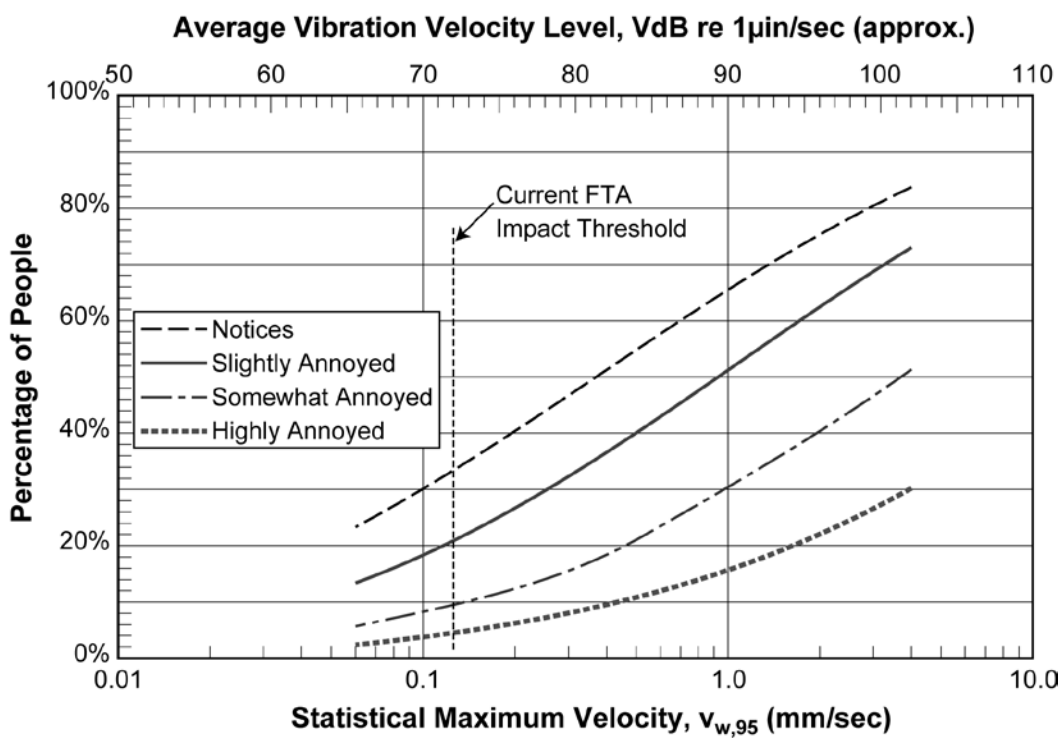


Figure 12: Estimated Cumulative Degrees of Annoyance

Source: Klæboe *et al.* (31) Norwegian survey. Top scale is average maximum vibration velocity level, which, based on analysis of several sets of train passby data, is approximately 2 decibels less than the statistical maximum velocity.

A recent study (34) was commissioned by the Department for Environment Food and Rural Affairs (DEFRA) in the United Kingdom to investigate the human response to vibration in residential environments. The work was intended as a pilot study to develop field measurement and survey techniques that would eventually be used in a broader study of dosage-response relationships. The methods developed for the DEFRA study were strikingly similar in many respects to those of the present D-12 study. Some of the notable similarities include:

- use of indoor and outdoor measurements at selected test sites,
- use of a reference location to characterize the fleet,
- use of grid measurements to estimate levels in surveyed houses where no measurements were made,
- observation of considerable measurement variability for seemingly identical buildings,
- use of digital flash-card recorders to record waveforms for later post-processing.

The DEFRA questionnaire included 58 items and was administered in person. The questionnaire was judged to be too long and repetitive for further use, however.

The only field study reviewed that specifically investigated the annoyance of ground-borne noise was performed by Vadillo, Herreros, and Walker (35). The survey was conducted to determine the extent to which subjects were able to distinguish between ground-borne noise and ground-borne vibration as the source of their annoyance. The maximum train-induced vibration levels ranged from 58 VdB to 74 VdB. The authors concluded that residents were never bothered by noise and vibration when the A-weighted ground-borne noise level was less than 32 dB, sometimes bothered at levels between 32 dB and 42 dB, and always bothered at levels greater than 42 dB. In fact, all residents exposed to maximum A-weighted noise levels greater than 42 dB complained strongly about noise and vibration levels, and reported that the vibration was more annoying than the noise. The authors also found that residents exposed to low levels of street traffic noise were more annoyed by train-induced ground-borne noise than were people who lived in houses where the traffic noise was louder.

3. TRANSIT SYSTEM SURVEY

North American rail transit agencies were surveyed to investigate the extent and severity of problems caused by rail-induced ground-borne vibration. The transit agencies' responses also helped to identify transit systems for field survey and measurement.

3.1 Transit System Types

North American rail transit systems are typically categorized as heavy rail, light rail, and commuter rail. Unfortunately, the definitions tend to overlap. For the purposes of this study, the three principal rail transit system types are classified as:

- Heavy Rail (rapid transit): Dedicated guideway rapid transit with frequent service by trains with as many as 10 cars.
- Commuter Rail: Transit operations focused on the morning and evening commuter periods, most commonly locomotive powered, often sharing tracks with freight operations.
- Light Rail: One to four car trains sometimes sharing the right of way with street traffic.

3.2 Survey Design

The goal of the transit system survey was to document agency experience with community annoyance from rail vibration. The survey was designed so that it could be completed in about 10 minutes. The principal questions of interest were:

- Has the transit system experienced complaints related to ground vibration?
- How many complaints have been received, if any?
- How are the complaints handled?
- Does the transit system include design features to mitigate vibration?

The survey consisted of an e-mail introduction with a link to an online questionnaire consisting of 18 questions. Following the introductory material, the first series of questions asked for general information in multiple-choice and yes/no formats. The subsequent questions were presented as being optional and consisted of more open-ended questions that probed for details about system design features, the specific nature of vibration problems and/or complaints, and the results of any measurements and mitigation efforts. The cover e-mail and survey questions can be found in Appendix E.

Survey respondents who were reluctant to be completely forthcoming about their problems due to public disclosure and possible litigation were assured that the survey results would be disseminated in summary form only.

The survey was sent to representatives of all members of the American Public Transportation Association (APTA) that operate rail transit systems. This list of agencies and contacts was provided by APTA. An online service (www.surveymonkey.com) was used to distribute and process the surveys. Once the questionnaire was designed and tested, an e-mail with a link to the survey was sent to a representative of each rail transit system. A list of the agencies that were contacted can be found in Table 8.

The contact list was reviewed prior to sending the survey to identify any representatives who did not appear to be appropriate for the survey (*e.g.*, someone in the legal office of the agency). In such cases, the transit system was contacted directly to identify an appropriate representative.

3.3 Survey Findings

The main findings of the survey are summarized in Table 9. Responses were received from 57% (30 of 53) of the transit systems that were contacted. Responses were received from 50% of the commuter rail systems, 56% of the heavy rail transit systems, and 67% of the light rail systems. (Note that a number of transit agencies operate multiple vehicle types.)

Non-responding agencies were re-contacted by telephone and email over a period of several months. Only one agency explicitly refused to provide any information and contact persons were never identified for several of the systems.

Given that the goal was to obtain a general picture of agency experience with vibration problems, no attempt was made to develop any weighted statistics based on system size or to apply statistical analysis to draw conclusions. Some of the trends observed were as follows:

- Few systems reported more than minor, intermittent vibration problems. Of the 30 responses, 17 (57%) reported no vibration complaints in the past year, 10 (33%) reported 1 to 5 complaints, 2 (7%) reported 6 to 10 complaints, and one system reported more than 50 complaints. Complaints were not concentrated within any particular system type (commuter/heavy/light rail).
- No clear pattern was evident relating the type of system, mitigation features, and geography to vibration complaints.
- All systems that reported complaints had received at least some of them through informal channels. Community annoyance may therefore be underreported at systems that do not have a formal complaint procedure.
- Four out of five systems with jointed rail reported at least minor problems with vibration.
- Of the systems with complaints/problems, 73% had extensive sections of subway. Of the systems that reported no complaints or problems related to ground vibration, only 33% had significant sections of subway. This may indicate that subway track is more likely to cause vibration complaints than at-grade or elevated track, or could reflect the fact that subways are usually located in more densely populated areas.
- No obvious association was observed between vibration mitigation features employed by the transit system and vibration complaints.
- A large number of agencies believed that complaints were correlated to a particular factor, such as proximity of the homes to the rail system, or rail corrugation.
- At most systems where vibration was perceived to be a problem, measurements of vibration and noise had been performed (note that this data was not obtained or used as part of the D-12 study).
- Seven of 14 systems reported that vibration-related complaints were addressed through the development of, or intensification of, maintenance programs.

Table 8: Transit Agency Survey Recipients

State/Prov	Name	Type of Rail Operations					
CA	Altamont Commuter Express (ACE)	CR					
CA	Los Angeles County Metropolitan Transportation Authority		HR	LR			
CA	North San Diego County Transit District (NCTD)	CR					
CA	Peninsula Corridor Joint Powers Board (PCJPB)	CR					
CA	Sacramento Regional Transit District (Sacramento RT)			LR			
CA	San Diego Trolley, Inc.			LR			
CA	San Francisco Bay Area Rapid Transit District (BART)		HR				
CA	San Francisco Municipal Railway (MUNI)			LR	CC		
CA	Santa Clara Valley Transportation Authority (VTA)			LR			
CA	Southern California Regional Rail Authority (Metrolink)	CR					
CO	Denver Regional Transportation District (RTD)			LR			
CT	Connecticut Department of Transportation (CDOT)	CR					
DC	Washington Metropolitan Area Transit Authority (WMATA)		HR				
FL	Hillsborough Area Regional Transit Authority (HART)			LR			
FL	Jacksonville Transportation Authority (JTA)					AG	
FL	Miami-Dade Transit (MDT)		HR			AG	
FL	South Florida Regional Transportation Authority (TRI-Rail)	CR					
GA	Metropolitan Atlanta Rapid Transit Authority (MARTA)		HR				
IL	Chicago Transit Authority (CTA)		HR				
IL	Northeast Illinois Regional Commuter Railroad Corporation (Metra)	CR					
IN	Northern Indiana Commuter Transportation District (NICTD)	CR					
MA	Massachusetts Bay Transportation Authority (MBTA)	CR	HR	LR			
MD	Maryland Transit Administration (MTA)	CR	HR	LR			
MI	City of Detroit Department of Transportation (DDOT)			LR			
MO	Bi-State Development Agency (METRO)			LR			
NJ	New Jersey Transit Corporation (NJTransit)	CR		LR			
NJ	Port Authority Trans-Hudson Corporation (PATH)		HR				
NJ	Port Authority Transit Corporation (PATCO)		HR				
NY	Metro-North Commuter Railroad Company (MTA-MNCR)	CR					
NY	MTA Long Island Rail Road (MTA-LIRR)	CR					
NY	MTA New York City Transit (NYCT)		HR				
NY	Niagara Frontier Transportation Authority (NFT Metro)			LR			
NY	Staten Island Rapid Transit Operating Authority (SIRTOA)		HR				
OH	The Greater Cleveland Regional Transit Authority (GCRTA)		HR	LR			
OR	Tri-County Metropolitan Transportation District of Oregon (Tri-Met)			LR			
PA	Port Authority of Allegheny County			LR			
PA	Southeastern Pennsylvania Transportation Authority (SEPTA)	CR	HR	LR			
TN	Memphis Area Transit Authority (MATA)			LR			
TX	Dallas Area Rapid Transit (DART)	CR		LR			
TX	Fort Worth Transportation Authority (The T)	CR					
TX	Island Transit (Galveston)			LR			
UT	Utah Transit Authority (UTA)			LR			
VA	Virginia Railway Express (VRE)	CR					
WA	Central Puget Sound Regional Transit Authority (ST)	CR		LR			
WA	City of Seattle - Seattle Center Monorail Transit						MO
WA	King County Department of Transportation - Metro Transit Division			LR			
WI	Kenosha Transit (KT)			LR			
Alberta	Calgary Transit (Light Rail)			LR			
Alberta	Edmonton LRT (Light Rail)			LR			
BC	Translink - Greater Vancouver Transportation Authority (Skytrain)			LR			
BC	West Coast Express (Vancouver)	CR					
Ontario	Greater Toronto Transit Authority (GO Transit)	CR					
Ontario	Toronto Transit Commission		HR	LR			
Quebec	Societe de Transport de Montreal (Subway)		HR				

Codes: CR = Commuter Rail; HR = Heavy Rail (Rapid Transit); LR = Light Rail;
CC = Cable Car; AG = Automated; Guideway; MO = Monorail

Table 9: Transit Agency Survey Findings

Agency Responses:	**Number:**	**Percentage:**
Total No. of Surveys Distributed	53	
Total No. of Responses Received	30	
Overall Response Rate		57%
No. of Commuter Rail Systems Surveyed	20	
No. of Commuter Rail System Responses	10	
No. of Commuter Rail Systems with Problems (Major or Minor)	5	
% of Commuter Rail System Responses with Problems		50%
No. of Heavy Rail Systems Surveyed	16	
No. of Heavy Rail System Responses	9	
No. of Heavy Rail Systems with Problems (Major or Minor)	5	
% of Heavy Rail System Responses with Problems		56%
No. of Light Rail Systems Surveyed	28	
No. of Light Rail System Responses	15	
No. of Light Rail Systems with Problems (Major or Minor)	10	
% of Light Rail System Responses with Problems		67%
No. of Other Systems Surveyed	4	
No. of Other System Responses	2	
No. of Other Systems with Problems (Major or Minor)	0	
% of Other System Responses with Problems		0%
Vibration Complaints:	**Number:**	**Percentage:**
None	17	57%
1-5	10	33%
6-10	2	7%
21-50	0	0%
More than 50	1	3%
Have a Formal System for Complaints		61%
Have Received Informal Complaints		45%

4. SOCIAL SURVEY DESIGN

4.1 Approach to Social Survey

When the D-12 study was first conceived, the plan was to interview 120 subjects (six at each of 20 agencies) and to measure the transit-related noise and vibration in each residence. During the literature review, it became clear that a sample of 120 people was simply not enough to yield a statistically significant result. Similar studies of annoyance were based on interviews numbering in the thousands.

In Phase 1, the project team proposed to change the approach to interviews and field testing that would:

- significantly increase the number of interviews (the goal was 2000),
- reduce the number of agencies where testing would be performed (from 20 to 5), and
- not measure in every interviewed residence, rather measure in a sample of residences and use surface grid measurements to estimate the vibration exposure at each interview location.

The proposed change in approach was approved by the D-12 panel.

4.2 Survey Cities

Five transit agencies were selected for interviews and field measurements. The interview/field test program started in November of 2006 and was completed in August of 2007. A total of 1306 individuals completed telephone surveys.

Community interviews and vibration measurements were undertaken at five transit system locations,

1. Metropolitan Transportation Authority (MTA), New York City (Brooklyn)
2. Dallas Area Regional Transit (DART)
3. Sacramento Regional Transit
4. Toronto Transit Commission (TTC)
5. Massachusetts Bay Transportation Authority (MBTA), Boston

A survey program was also initiated at the San Francisco Municipal Transportation Agency (Muni), but was halted at the request of Muni. No further interviews or field measurements were undertaken in San Francisco.

4.3 Overview of Test Program

Interviewing areas were selected that had reports of, or the potential for, relatively high ground-borne vibration levels. Distance from the rail alignment was the chief means of ensuring a range of low-exposure data, simply by conducting interviews with respondents who lived relatively far from the alignment. Interviews were thus conducted at three of the oldest transit systems in North America; New York, Boston and Toronto.

In June of 2006, Mr. Martin Schroeder, Senior Program Manager of Rail Programs at the American Public Transportation Association (APTA) sent letters to 21 Directors/General

Managers of the major transit agencies in North America, requesting their support. Telephone follow-ups yielded points of contact at 10 of the agencies.

Internet-based aerial photography was used to screen potential sites for suitable rail alignments and housing density. Agencies were contacted after the screening to discuss potential interviewing areas. In some cases, site visits were made to obtain street-level assessments of potential interviewing areas.

Telephone interviews and sound and vibration measurements were conducted at:

1. **New York City Transit (NYCT):** The testing was performed in the Brooklyn neighborhood of Park Slope. The tracks are in a tunnel that runs predominantly under city streets.
2. **Dallas Area Rapid Transit (DART):** The testing was performed along the Red Line in the West Oak Cliff area southwest of Dallas and along the Blue Line northeast of Dallas. This is a surface system.
3. **Sacramento Regional Transit (SacRT):** The testing was performed in East Sacramento and Rancho Cordova along the Gold Line and in South Sacramento along the Blue Line. These are also surface alignments.
4. **Toronto Transit Commission (TTC):** The TTC measurements were performed along the Bloor-Danforth subway line east of downtown Toronto. The Toronto alignment is underground and runs predominantly along city streets.
5. **Massachusetts Bay Transportation Authority (MBTA, Boston):** Testing was done along the Southwest Corridor tunnel in the Back Bay section of Boston. The tunnel contains the MBTA Orange Line subway, MBTA Commuter Rail trains and Amtrak inter-city trains. Testing was also done in East Boston near the MBTA Blue Line that is also in a tunnel.

In all cases, transit agency personnel were consulted to identify suitable survey areas.

Table 10 summarizes the operational parameters for each of the test systems and gives the approximate locations of the test areas. Table 11 shows the approximate number and length of the trains operating on each system for both daytime and nighttime hours. The ratios of daytime operations to nighttime operations range between 3.7 and 5.0 for the rapid transit systems (Toronto, New York, and Boston) and between 3.2 and 3.9 for the light rail systems in Dallas and Sacramento. This range is insufficient to draw any inferences about the relative annoyance of daytime and nighttime operations.

The amount of time that each system creates ground-borne vibration at a site depends on the number of trains per day, the average length of the trains, and the train speed. The right two columns in Table 11 are an approximation of the relative exposure to vibration at each of the systems. The calculation assumes an average vehicle length and speed at each of the systems. Table 11 shows that the relative exposures at the two light rail lines (Dallas and Sacramento) were quite similar and that the exposures for the rapid transit lines in Toronto, New York, and Boston Back Bay were 8 to 10 times greater. One of the goals in selecting systems was to have a range of operating conditions, and this was achieved.

Vibration and sound measurements were made inside and outside of selected residences. Table 12 summarizes the numbers of interviews and residential measurements at each of the test areas.

Further details about each of the test areas may be found in Appendix A.

Table 10: Test System Operational Parameters

Agency	System	Approximate Test Area Location	Mode	Alignment
MTA (New York)	F Line	Brooklyn, Park Slope	Heavy Rail	Underground
DART (Dallas)	Red Line Blue Line	S. Hampton & W. Illinois E. Mockingbird & Abrams	Light Rail Light Rail	Surface Surface
Sacramento	Blue Line Gold Line Gold Line	35th Ave and 28th St. Trujillo & Starfire Mills Tower & Mills Park	Light Rail and Freight	Surface (corridor shared with freight)
TTC (Toronto)	Bloor - Danforth	Coxwell & Strathmore	Heavy Rail	Underground
MBTA (Boston)	Orange Line Commuter Rail Amtrak	Back Bay, east of Massachusetts Ave., north of Columbus Ave.	Heavy Rail Commuter Rail Inter-city	Underground (shared corridor)
MBTA (Boston)	Blue Line	Chelsea & Maverick	Heavy Rail	Underground

Table 11: Number of Trains per Day during Daytime and Nighttime Hours

System	Number of Trains		Average Number of Vehicles		Ratio, Day to Night[3]	Relative Exposure[4]	
	Day[1]	Night[2]	Day[1]	Night[2]		Multiplier	Decibels
Toronto	530	143	6	6	3.7	11.4	10.6
New York	306	81	8	8	3.8	8.8	9.4
Boston, Back Bay	375	71	6	6	5.3	7.6	8.8
Boston, Blue Line	264	66	4	4	4.0	3.7	5.7
Dallas Blue Line	117	40	2.3	2.1	3.2	1.0	0.0
Dallas, Red Line	133	39	2.3	2.1	3.7	1.1	0.4
Sacramento, Blue Line	107	26	3	3.2	3.9	1.1	0.6
Sacramento, Gold Line	107	30	3	3.2	3.3	1.2	0.7

1. “Day” is defined as 7 AM to 10 PM.
2. “Night” is defined as 10 PM to 7 AM.
3. (Number day trains × Average length day trains)÷ (Number night trains × Average length night trains).
4. Total number of transit vehicles during a 24 hour period is a measure of the vibration exposure. “Multiplier” is normalized to the system with the fewest number of vehicles (Dallas Blue Line). “Decibels” is $10log_{10}$(Multiplier).

Table 12: Interview and Measurement Summary				
System	**Interviewing Dates**	**Number of Completed Interviews**	**Field Measurement Dates**	**Number of Test Houses/Grid Points**
Toronto	5/17/07-5/21/07	582	6/25/07-6/28/07	13 / 22
MTA (New York)	11/9/06-11/14/06	281	1/15/07-1/18/07	11 / 19
MBTA (Boston)	6/21/07-6/24/07	304	8/20/07-8/24/07	13 (5 exterior only) / 26
DART (Dallas)	2/22/07-2/25/07	103	3/21/07-3/23/07	4 / 14
Sacramento	4/19/07-4/22/07	36	5/21/07-5/23/07	5 / 19
Totals		**1306**		**41 / 100**

4.4 Site Selection and Definition

After agency contacts helped to define general areas of interest, specific alignment segments were selected. A sampling polygon extending approximately 100 m to either side of the tracks was then defined with respect to latitude and longitude coordinates of the vertices of the polygon. Figure 13 shows a sample polygon for the Blue Line in Boston. Maps of the interviewing areas in all five cities may be found in Appendix A.

Figure 13: Test Area for MBTA Blue Line (Boston)

4.4.1 Construction of Sampling Frames

Sampling frames of potential respondents were created at each site by exhaustively listing published numbers of telephone-subscribing households within the polygonal areas. The polygons were initially identified by examination of aerial photography, defined by vertices in latitude/longitude units (rather than as street address ranges), and refined as necessary by site visits. The sides of the polygons were generally parallel to the track alignment, at distances of approximately 100 meters to either side of the alignment centerline. Potential respondents were selected for interview by simple random sampling from these frames at the time of interviewing. As many as ten contact attempts (callbacks) to each selected household were scheduled at the time of interviewing.

Names and addresses of respondents have not been published to preserve confidentiality.

4.4.2 Questionnaire

A structured questionnaire with standardized wording was prepared along the lines of prior questionnaires addressing the annoyance of transportation noise (*e.g.,* Fidell *et al.* (37), Klæboe *et al.* (31), Öhrström and Skånberg (26), and Woodruff and Griffin (38)). The questionnaire was optimized for telephone administration, with predominantly closed response category items. Response scales for annoyance-related items utilized the same scale and response categories as many other studies of transportation noise-induced annoyance. Respondents were constrained to describe degrees of annoyance as “not at all annoying,” “slightly annoying,” “moderately annoying,” “very annoying,” or “extremely annoying.”

Appendix B contains the wording of the questionnaire items. The wording of individual items varied slightly from site to site to accommodate names of local transit systems, and to adjust for differences between underground and surface running systems.

The interview was introduced as a study of neighborhood living conditions. Preliminary items qualified potential respondents as *bona fide* adult residents of the target household, and inquired about the most and least favored aspects of neighborhood living. This order of questioning permitted spontaneous mention of rail noise and vibration as the least favored aspects of neighborhood living prior to any mention of noise-related matters.

Eligible respondents who were not annoyed, did not notice, and did not experience any effects of rail noise and vibration were asked only eleven questions, and were able to conclude the interview in about two minutes. Those who were annoyed to some degree by airborne or ground-borne noise, noticed vibration, or were awakened by rail noise and vibration required about another three minutes to complete the interview. The questionnaire focused on annoyance, sleep disturbance, and complaints as the primary effects of interest.

The final interview question asked whether the respondent would consider allowing noise and vibration measurements to be made in their home. Field test locations were selected from the group of people who responded affirmatively to this question. To avoid skewing the survey results, responses to all of the substantive questionnaire items were obtained before respondents were asked about their willingness to permit access to their homes.

5. FIELD MEASUREMENTS

5.1 Measurement Overview

The overall goal of the field measurements was to estimate the exposure of each survey respondent to ground-borne vibration and noise using a wide variety of exposure metrics. The approach taken was to focus on obtaining a sufficient number of responses to the social surveys so that valid statistical inferences could be drawn from the data. There were 1,306 respondents to the social survey; clearly it was not feasible to measure noise and vibration inside the residence of each respondent. Instead, measurements were made at 41 residences, and ground-surface measurements were made at an additional 100 locations (the system-by-system breakdown is given in Table 12). Grid measurements were interpolated to estimate vibration levels at each interview location based on its position along the alignment, and perpendicular distance from the alignment. The calculated exterior vibration levels were then adjusted to estimate the vibration and noise levels inside each residence, based on the exterior and interior measurements at the 41 residential measurement sites.

At each system, the field measurements were performed over a three to five day period. For residential test locations, appointments were made allowing approximately one hour for the measurements plus sufficient time to set up and remove the equipment.

The following general approach was used to select measurement sites, and to acquire and analyze the vibration and noise data.

Field Measurements

1. Sensor Orientation: All vibration measurements were made with the sensor oriented in the vertical direction. Previous research has shown that the vertical vibration in residential structures tends to be the most severe, and also that people are most sensitive to vertical vibration.

2. Measurement Sites: Residential test locations were selected from the list of people who indicated in the telephone survey that they would be willing to have measurements made in their home. An attempt was made to select residences distributed over the study area.

3. Residential Measurements: At the appointed time, the measurement equipment was set up in the room where the resident indicated that the ground-borne noise and vibration was most noticeable. This was generally a living room, bedroom or basement family room. A vibration measurement was also made outside at the approximate setback distance from the alignment.

4. Grid Measurements: Measurements of ground-surface vibration were performed in a grid arrangement to characterize the ground vibrations over the entire survey area. The purpose of the grid measurements was to provide a means to estimate vibration exposure at all survey locations. The grid measurements were distributed throughout the study area and were typically made on street curbs or sidewalks next to the alignment. Outdoor residence measurement sites were also used as grid points for interpolation purposes.

5. Reference Position: During the residence and grid measurements, simultaneous vibration measurements were also made at one fixed reference position. The reference data provided a way to confirm that the trains that passed the residence/grid location were typical of the fleet.

6. Perpendicular Measurements: At least one measurement series was performed at various distances along a perpendicular to the alignment. These data were used to develop distance attenuation relationships for each test area.
7. All vibration measurements were made using seismic accelerometers with a nominal sensitivity of 1 V/g or 10 V/g. Sound measurements were made using 12.7 mm (½”) microphones. The vibration and sound waveforms were recorded in the field using digital flash card recorders.

Data Analysis

1. Initial Processing: The recorded data was processed using MATLAB to calculate a variety of sound and vibration metrics.
2. Indoor-Outdoor Levels: The residential measurements were used to characterize the relationships between indoor vibration, indoor sound and outdoor vibration.
3. Adjustments: Data pertaining to specific grid and residential locations were adjusted if the measured sample of trains was not typical of the fleet (as determined by the large number of measurements at the reference position).

Vibration Predictions

The following procedure was used to estimate the ground-borne vibration and noise levels inside each respondent’s residence:

1. Position along the alignment: The linear position of the residence along the alignment was calculated. The two closest grid points that bracketed the residential position were identified.
2. Distance attenuation: The distance of the residence from the alignment was calculated and the distance-attenuation relationships were used to adjust the levels at the bracketing grid points to this distance. The exterior ground vibration level at the residence was then estimated by linear interpolation of the distance-adjusted grid levels. All interpolations were made based on logarithmic (decibel) levels.
3. Outdoor to indoor: The indoor vibration levels were estimated based on an average outdoor-to-indoor adjustment.
4. Vibration to sound: The indoor vibration levels were used to estimate the indoor sound levels, based on an average adjustment determined from the measured residential data.

Interpolation calculations were performed on a 1/3 octave band basis, resulting in estimates of indoor sound and vibration at each of the 1306 residences where telephone surveys were conducted.

5.2 Residential Measurement Location Selection

The final interview question asked whether respondents would consider allowing measurements to be made inside their home. Homes suitable for vibration measurements were selected from respondents who answered “yes” to this question. Attempts were made to select homes throughout the interviewing area, although this was not always possible given the limited number of people willing to permit access.

Willing residents were contacted by telephone to arrange appointments. Reminder letters were mailed about two weeks before the planned test date, and follow-up telephone calls were made the week prior to the scheduled visit. Cooperation was generally very good. In the case of the few no-shows, it was possible to make measurements in a nearby neighbor's residence. Typically, three to four residential measurements were done per day, with grid measurements being performed between residential visits, where possible.

The approximate latitude and longitude of the dwelling façade closest to the alignment was determined using aerial mapping software. Figures showing the location of each interview location may be found in Appendix A. For surface systems, the latitude and longitude of discrete points along the alignment centerline were determined through aerial mapping software. For sub-surface systems, the agencies provided the necessary plans and information to locate the alignment centerline. The alignments were digitized at 30 cm intervals and the digitized models were used to calculate 1) the distance from each residence to the alignment centerline, and 2) the position of the residence along the alignment (from a starting reference point usually just outside the test area). Figures showing the alignment in each test city may be found in Appendix A.

In addition to the specific residential measurements, grid measurements were also made to determine the vibration gradients along, and perpendicular to, the alignment. The grid points were selected to provide an indication of the vibration distribution throughout the test area. Figure 14 shows the grid point distribution used for the New York test area. One measurement point per short block and two points per long block were used. Note that the blank area in the southeast of Figure 14 is a park. In addition to the grid points along the alignment, measurements were made along a line perpendicular to the alignment. The perpendicular measurements were used to calculate vibration attenuation with distance. Where appropriate, exterior residence measurements were used as additional grid points.

The locations of grid points were identified according to visible landmarks (street intersections, buildings). Aerial mapping software was used to calculate latitude and longitude coordinates of the grid points. The grid locations for all test cities are shown in Appendix A.

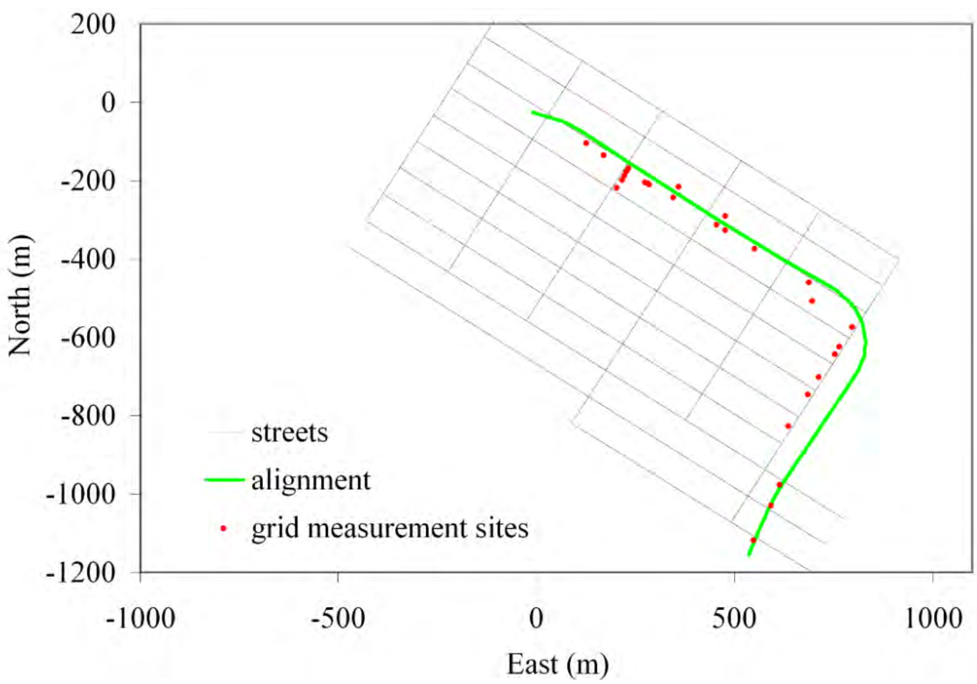


Figure 14: New York Grid Measurement Points

5.3 Field Measurement Procedures

5.3.1 Instrumentation

All data collected in the field was recorded using Rion Model DA-20, four-channel digital recorders. The DA-20 systems record data as WAV files on compact flash cards. Table 13 summarizes the instrumentation that was used during the study. All vibration data was acquired as acceleration.

Table 13: Instrumentation Summary

TYPE	SENSOR / INSTRUMENT	PREAMPLIFIER	SIGNAL CONDITIONER
Data Recorder	Rion DA-20	n/a	n/a
Vibration	Wilcoxon 731A accelerometer	n/a	Wilcoxon P31
Vibration	PCB 393A03 accelerometer	n/a	PCB 480E09 (1 channel) PCB 480B21 (3 channel)
Vibration Calibrator	Hardy Instruments HI 823	n/a	n/a
Vibration Calibrator	PCB Model 394C06	n/a	n/a
Sound	B&K 4189 12.7 mm microphone	PCB 426E01	PCB 480E09
Sound	Norsonic 1225 12.7 mm microphone	Norsonic Model 1201	n/a
Acoustical Calibrator	B&K 4220 Pistonphone	n/a	n/a

5.3.2 Measurement Approach

Figure 15 shows a schematic of the field test configuration. The measurements consisted of:

1. Residential interior measurement: Sound and vibration were measured inside a normally occupied room that the resident identified as a location where the transit noise and vibration was most noticeable, usually a living room, bedroom, or basement family room. An accelerometer was affixed to the floor near the middle of the room, and a microphone on a tripod was placed near the accelerometer. The microphone was set at a height of about 150 cm (5 ft) above the floor. Figure 16 shows a typical residential measurement installation. The indoor residential measurements were designed to be completed in approximately one hour to minimize the inconvenience to the resident. Most measurements were performed during daytime hours.
2. Residential exterior measurement: Ground vibration was measured immediately outside the residence. Exterior sound was also measured when the tracks were at-grade in order to determine whether the indoor noise levels were confounded by airborne noise from trains. The exterior residential measurement point was generally at the approximate setback distance of the structure from the alignment. Figure 17 shows a typical exterior measurement. The alignment was to the right in this photograph.
3. Grid measurement: Grid measurements were typically made on street curbs or sidewalks next to the alignment. Interpolation of the grid data was used to estimate exterior vibration levels at each interview location. Figure 18 shows a photo of a typical grid measurement location.

The data recorder is the blue instrument at the bottom of the photograph. The instrument in the middle of the photo is the accelerometer signal conditioner.

4. Perpendicular measurement: The perpendicular measurements were typically made on the curb of a cross street that was perpendicular to the alignment. The perpendicular data were used to estimate vibration attenuation with distance from the alignment. The perpendicular measurements generally consisted of four to five positions at distances up to 75 m from the alignment.

5. Reference position: Simultaneous measurements were made at one common reference location for each cluster of grid/residential measurements. A large number of train events were captured at the reference location, which made it possible to characterize the fleet, statistically. The data from the grid/residence locations (typically 10-20 trains) could then be checked to see that the sample was typical of the fleet; if not the data was adjusted accordingly. Figure 19 shows a reference location that was used in New York City. The sensor was on the curb and the recorder and signal conditioner were inside the vehicle. Because the vibrations from trains were usually most easily detected at the reference site, the member of the test crew at this location was responsible for logging train events. The log of event times simplified identification and confirmation of train passages during data post-processing.

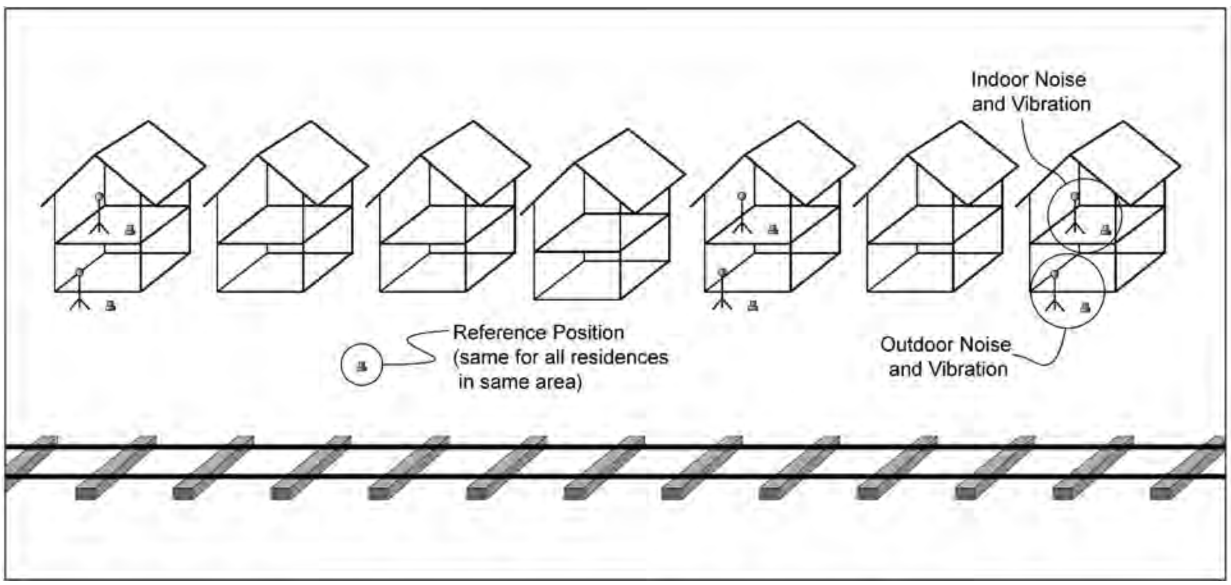


Figure 15: Configuration of Field Measurements

Figure 16: Typical Residential Measurement Setup

Figure 17: Typical Exterior Measurement Setup

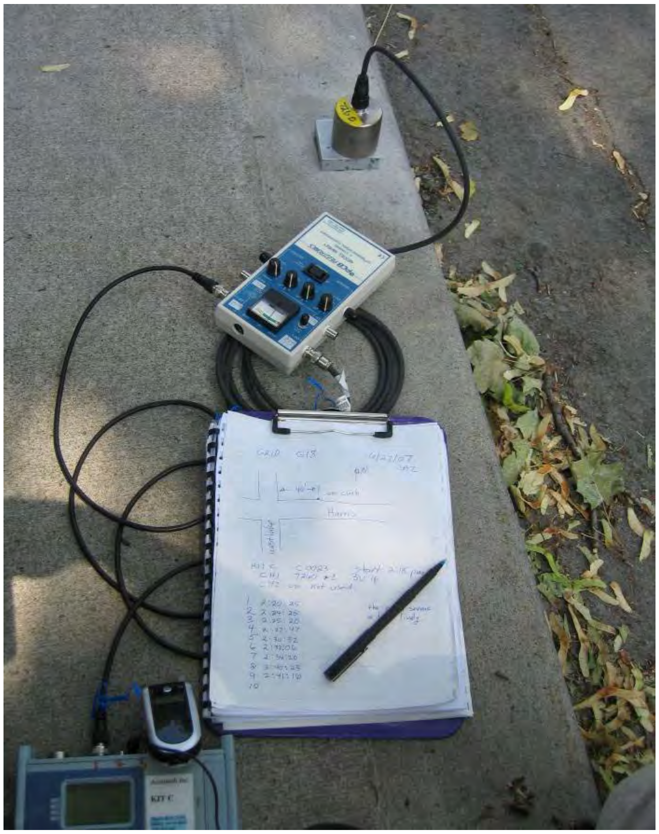


Figure 18: Typical Grid Measurement Setup

Figure 19: Typical Reference Measurement Setup

5.3.3 Field Log Sheets and Field Crew

Field log sheets were prepared for each type of measurement; reference, residence interior, residence exterior and grid point. Samples of the log sheets may be found in Appendix C. The typical field crew consisted of three people who communicated via mobile phone. For a residential measurement, one person was stationed at the reference location, while the other two were responsible for measurements inside and outside the residence. For grid measurements, one person was stationed at the reference location while the other two went to separate grid locations.

5.4 Data Analysis Procedures

5.4.1 Initial Processing

The overall goal of the measurements and analysis was to obtain useful descriptors of the vibration and noise environment inside each residence for correlation with the questionnaire responses. Many different descriptors were calculated because it was not known beforehand which one(s) would correlate best with questionnaire responses. Processing and storage of reduced field measurements were accomplished in a manner that made it possible to compute additional descriptors as necessary. The field recordings were analyzed using MATLAB. The steps in the analysis were:

1. The recorded calibration signals were analyzed to determine sensor scale factors.
2. Each data file was analyzed to calculate 1/3 octave band spectra at 250 ms intervals (RMS averaging). Acceleration spectra were converted to velocity in the frequency domain using the appropriate 1/3 octave center frequencies. All 1/3 octave band spectra were stored as ASCII text files.
3. The 250 ms data were analyzed to identify train events at interior, exterior, and reference locations. Although the recorder clocks were synchronized to within ±1 second, there was often a time shift when the reference position was not at the same track location as the grid/residence measurement (the train arrived at the reference before it arrived at the residence, for example). Any time-offsets were accounted for to ensure that the same train produced the sound/vibration at each of the measurement sites. Once the data records were synchronized, train passage events were identified using the field log sheets and by visual inspection of the vibration time histories. There were many examples where the events were evident only at the reference position because the residential levels were masked by the background sound/vibration.
4. Train passage events were verified by reviewing the vibration time histories and the 1/3 octave band spectra for each measurement site. Events that were corrupted by sound/vibration from other sources were removed. An example of corrupted vibration data is shown in Figure 20.
5. The 1/3 octave band spectra starting approximately 10 seconds before the event and continuing until approximately 10 seconds after the event were stored for subsequent calculation of noise and vibration metrics for each event, and for calculation of various exposure metrics at each site.

One step that was not taken was to group the events. For example, at many sites it would have been possible to identify which track the train was using based on the frequency spectra and arrival times. For example, Figure 21 shows the data from a site where the inbound and outbound trains had clearly different vibration characteristics. Trains were not separated into groups because 1) residents usually would be unable to distinguish which track the train was using, and 2) because the concern for this project was the overall exposure to vibration, not the characteristics of individual events.

Likewise, in cases where there was a mix of commuter rail and rail transit operating in the same right of way, no attempt was made to distinguish between the two. For two of the test systems, however, freight and transit operations shared the same right of way. In these cases, the vibration from freight trains was ignored because 1) the freight trains were so infrequent it was not practical to obtain measurements at all residential/grid sites within the time available, and 2) the number of survey respondents exposed to mixed freight and transit traffic was less than 30, which was insufficient to draw statistical inferences.

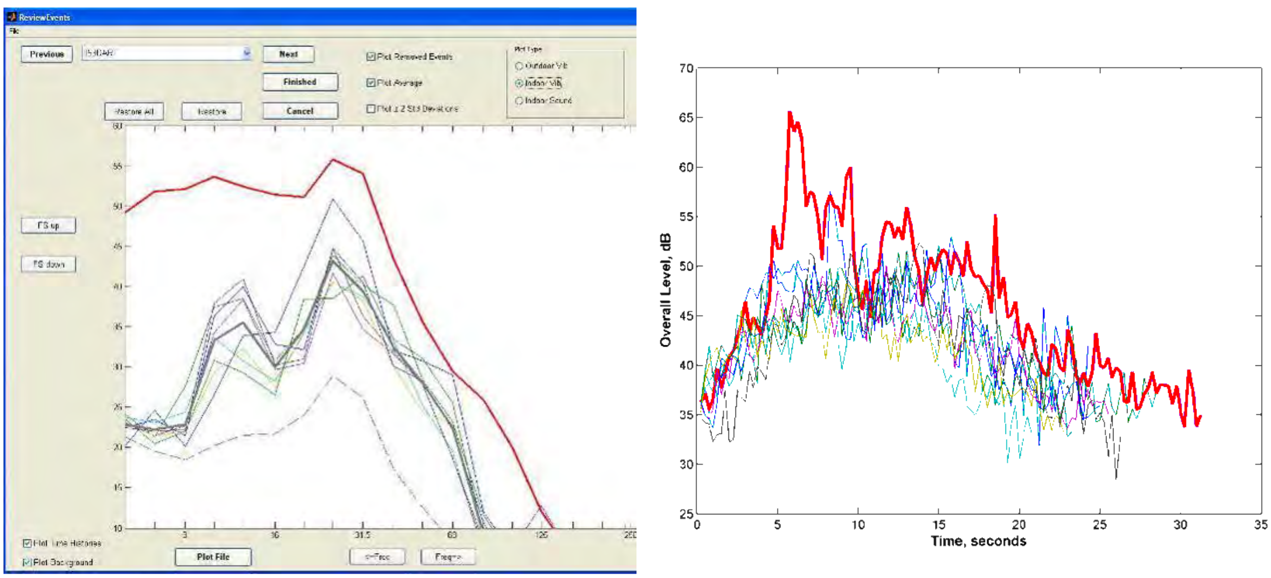


Figure 20: Example of Event Screening for Corrupted Data

The left plot shows the 1/3 octave band vibration levels measured inside a residence in Dallas for all of the apparent train passages. The gray dashed line shows the ambient (no trains) vibration spectrum and the heavy gray line shows the linear average of the train-induced spectra. The right plot shows the corresponding vibration time histories. The highlighted event (in red) does not appear to have been caused by train vibration. The abrupt increase and decrease in vibration at about 5 seconds clearly is inconsistent with the other train passages and was likely to have been caused by something inside the home. This event was subsequently removed from the analysis.

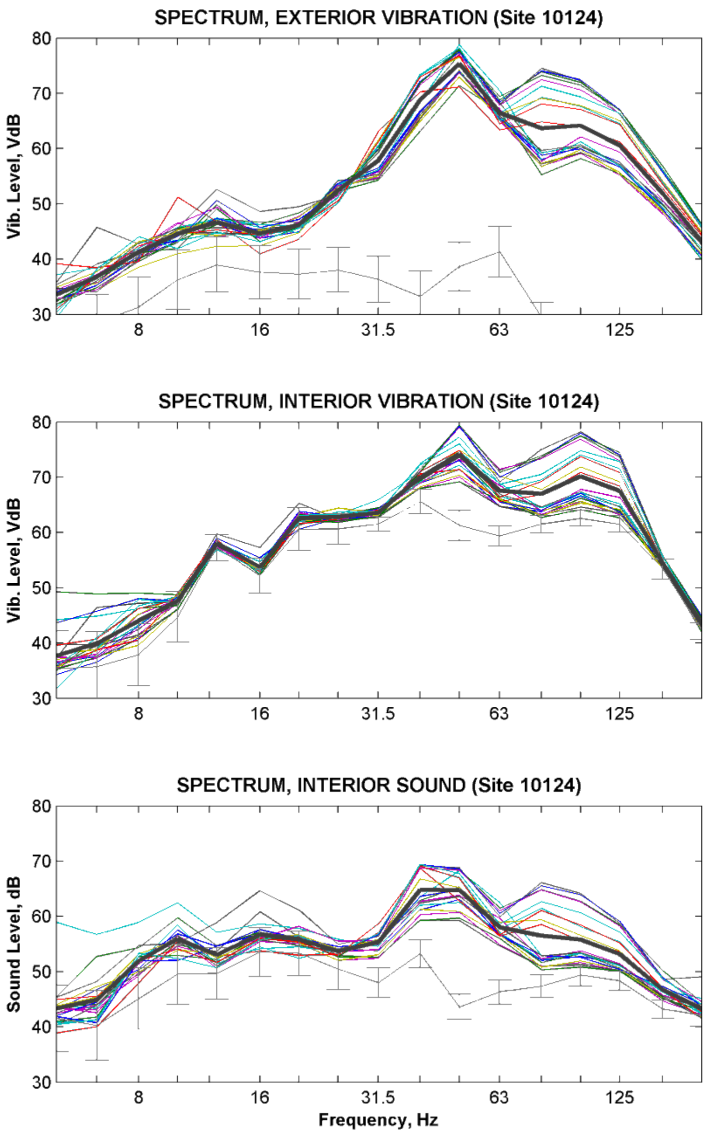


Figure 21: Example of Direction-Dependent Vibration Spectra

This is an example where vibration from inbound and outbound trains had consistently different characteristics. Trains on the closer track exhibited higher levels between 80 Hz and 100 Hz. The heavyweight black line is the linear average and the lightweight gray line is the background (no trains). The error bars are the average background plus and minus one standard deviation. Train events and spurious noise (e.g., people talking) were removed before calculating the average background level.

This also is an example where the train vibration was well above the background vibration at the outdoor position, but the vibration and noise were only marginally above the background at the indoor position.

5.4.2 Secondary Processing

The 250 ms 1/3 octave band data formed the basis for subsequent calculations of event metrics and summary metrics for each site. Once the train events had been identified, the 250 ms data were used to calculate the following metrics on a 1/3 octave band basis for each train event:

- Lmax: the maximum RMS vibration level using RMS 250 ms, 1 second and 5 second duration averages,
- Leq: the RMS average over the event duration defined by the 3 decibel down points from the 1 second Lmax,
- SEL: the total RMS energy over the event duration defined by the 10 decibel down points (from the 1 second Lmax), normalized to a 1 second period.

Note that the terms Leq, SEL and Lmax describe the characteristics of the passby, and can be in terms of either sound or vibration.

In addition, the duration of each event was calculated and stored. (The duration was defined as the time between the 3 dB down points that were used for calculating Leq.) The analysis frequency range extended from 5 Hz to 200 Hz (1/3 octave band center frequencies). To allow maximum flexibility, the 250 ms data for each train event were also stored so that additional metrics could be calculated.

The Leq, SEL and Lmax values for each event were then averaged to obtain the following quantities that were used to calculate different measures of vibration and noise exposure:

Average Leq: The linear average of the Leq decibel levels and the standard deviation,

Average Lmax: The linear average of the Lmax decibel levels and the standard deviation,

Average SEL: The linear average of the SEL decibel levels and the standard deviation,

RMS Average SEL: The root mean square average of the event SEL values using the following equation,

$$SEL_{abs} = 10^{SEL/20}$$

$$SEL_{RMS\_Avg} = 10 \times \log_{10}\left(\frac{1}{N}\sum_{i=1}^{N} SEL_{abs}(i)^2\right)$$

RMQ Average SEL: The root mean quad average of the event SEL values using the following equation,

$$SEL_{RMQ\_Avg} = 5 \times \log_{10}\left(\frac{1}{N}\sum_{i=1}^{N} SEL_{abs}(i)^4\right)$$

Average Event Duration: The average time between the 3 dB down points.

The effects of the different averaging methods (linear, RMS and RMQ) can best be shown with an example. Consider the five decibel levels of 70, 75, 80, 85 and 100. The averages using the three different averaging methods, with and without the 100 dB level, are:

Averaging	with 100 dB	without 100 dB	Difference
Linear:	82.0 dB	77.5 dB	-4.5
RMS:	93.2 dB	80.6 dB	-12.6
RMQ:	96.5 dB	82.2 dB	-14.3

The 100 dB level dominates the RMS and RMQ averages. Removing the 100 dB level reduces the RMS and RMQ averages by 13 and 14 decibels respectively but reduces the linear average by only 4.5 decibels. It is commonly expected that human annoyance with noise and vibration is associated with the loudest (highest vibration/noise) events and therefore an RMS or RMQ average will provide a better measure of potential annoyance than a linear average.

The average Leq, Lmax, and SEL were then used to calculate the site metrics listed in Table 14. The metrics include the average vibration level and several measures of the 24-hour vibration exposure. For the Leq, Lmax and SEL velocity metrics, the mean level plus two standard deviations was also calculated. (Klaeboe (31) showed that the mean plus 1.8 standard deviation level (v_{w95}) was a good approximation for the loudest trains in a fleet.)

Table 14: Summary of Site-Level Measurement Metrics

Measure	Number of Related Measures	Description
Passby Duration	1	Based on 3 dB down points from 1 second Lmax.
Leq, Velocity and Sound	20*	Energy average based on 3 dB down points.
Lmax, Velocity and Sound	20*	Maximum using an RMS averaging time of 1 second.
SEL, Velocity and Sound	20*	Energy normalized to 1 second using the 10 dB down points.
Velocity Exposure RMS	20*	24-hour exposure to vibration based on the sum of the RMS average SEL values.
Velocity Exposure RMQ	20*	24-hour exposure to vibration based on the sum of the RMQ average SEL values.
Acceleration	7**	Acceleration calculated from the 1/3 octave band spectra of the Leq, Lmax and SEL.
A-weighted Velocity and Sound	7**	Overall level calculated from the 1/3 octave band spectra of the Leq, Lmax and SEL with A-weighting applied.
Wm-weighted Velocity	7**	Overall level calculated from the 1/3 octave band spectra of the Leq, Lmax and SEL velocity with Wm weighting applied.
LFSL Velocity and Sound	7**	LFSL (low-frequency sound level) calculated from the 1/3 octave band spectra of Leq, Lmax and SEL.

* Overall plus each 1/3 octave band from 5 Hz to 200 Hz

** Overall level for Leq, Lmax, SEL (linear, RMS and RMQ averages), and exposure (RMS and RMQ)

5.4.3 Quality Assurance/Quality Control

A substantial amount of noise and vibration data was collected during the field measurement phase of this project. A key component in the design of the data collection and analysis procedures was to ensure that the data obtained was generated by trains and not corrupted by background vibration and noise. The following steps were taken to ensure data quality:

1. The MATLAB routines for processing the WAV files were verified by comparing the results to those obtained independently by playback through a commercial spectrum analyzer. This validation of the MATLAB procedures was performed prior to fully processing the field test data.
2. Sound and acceleration calibration signals were recorded in the field using acoustical calibrators for the microphones and portable vibration shakers for the accelerometers. The calibration levels were verified prior to processing the data files.
3. The field log sheets were scanned and saved as PDF files so they could be readily referenced during the data analysis process.
4. Simultaneous measurements were made at a reference position during all of the grid/residential measurements. The times when trains passed the reference site were noted, which helped to identify which vibration events were caused by trains, and which were caused by other vibration sources.
5. Both the time history and the 1/3 octave band spectra for each possible train event were inspected for each measurement position. Events that were clearly not caused by trains were

eliminated from the analysis. Note that trains that caused unusually high vibration and/or noise levels were retained in the analysis because these trains were part of the residents' vibration exposure. One useful way to determine whether a vibration event was caused by a train was to verify that the event occurred simultaneously at each of the measurement positions (interior, exterior, reference).

6. The background vibration (no trains) was also calculated at each site. The background was determined from the linear average vibration level (in decibels) with train events excluded as well as any unrepresentative vibration events, such as people walking in the building. Displaying the background vibration along with the train-related spectra helped to identify spurious events. Since the data was recorded, it was also possible to listen to the appropriate section of original WAV file to verify that the vibration was produced by a train and not something else.

5.5 Measurement Overview

Although this study was focused on determining human response to building vibration generated by rail transit operations, the field measurements represent a valuable body of information on the characteristics of the ground-borne vibration and noise found at five North American rail transit systems. The measurement results have potential application to the methods that are currently used to predict ground-borne vibration from proposed new transit systems, and when responding to complaints about ground-borne vibration and/or noise.

The following sections present some important details of the measurement results including 1) the average relationships between outdoor vibration and indoor vibration/noise, 2) the relationships between several different metrics for characterizing ground-borne vibration/noise, and 3) the system-to-system variation in the observed vibration levels.

5.5.1 Relationships between Indoor Sound, Indoor Vibration and Outdoor Vibration

The average overall vibration and noise levels measured at each of the residential test sites are summarized in Table 15. The values in the table represent average RMS levels, based on the 3 dB down points (referred to as Leq in this report). Table 15 shows the average levels from the three standard residential measurement positions: 1) outdoor vibration, 2) indoor vibration, and 3) indoor sound. For all three measurement locations, the un-weighted overall levels and the A-weighted levels are shown. The calculation of the overall levels was limited to the 1/3 octave bands from 5 Hz to 200 Hz.

The uppermost plot in Figure 22 shows the relationship between indoor vibration and outdoor vibration. Although there is considerable spread in the data (up to ±10 decibels), the best-fit line is very nearly given by,

$$Lv(\text{Indoors}) = Lv(\text{Outdoors}),$$

which means that, on average, the vibration level inside the residence was equal to the vibration level outside the residence. The relationship between indoor and outdoor vibration is determined by the coupling loss at the foundation/soil interface, the attenuation as vibration propagates from the building foundation into occupied spaces, and building structural resonances that amplify the vibration (floor resonances in particular). The data in Figure 22 suggests that these effects tend to cancel out for the residences tested in the D-12 study and, on average, the indoor vibration equals the outdoor vibration. This applies to single story slab-on-grade residences in Sacramento and

Dallas, brownstones in New York and Boston, and two story duplexes with full basements in Toronto and Boston.

The middle two graphs in Figure 22 show the relationships between indoor sound and outdoor vibration, and indoor sound and indoor vibration, respectively (all with no weighting applied). The lower two graphs show the same data with A-weighting applied to both vibration and sound. The best-fit linear curve fits and the correlation coefficients (R^2) are also shown on the figures.

In predicting the structure-borne sound in a room, it is commonly assumed that the sound pressure level is equal to the vibration velocity level of a representative surface (in VdB). Figure 22, however, shows that Lp = Lv is not necessarily a good model for the D-12 data. In fact, the present study suggests that Lp = Lv− 5 dB is a better model for the relationship between sound pressure and floor vibration.

Some additional observations from the data summarized in Table 15 and Figure 22 are:

- The outdoor vibration level was nearly as good a predictor of indoor sound level as was the indoor vibration level.
- The correlation between sound and vibration improved when both were A-weighted.
- The majority of the locations where the indoor A-weighted noise levels exceeded 40 dB were in Toronto. The indoor A-weighted noise level exceeded 40 dB at eight of the 11 residences measured in Toronto. Of all the other residences in Boston, Dallas, New York, and Sacramento, in only one residence in Boston and one residence in Sacramento did the indoor A-weighted sound level exceed 40 dB.
- The difference between indoor sound level and indoor vibration velocity level increased as the sound level increased. For example, referring to the best-fit line in the lower two graphs in Figure 22, the average difference between the vibration level and the sound level was 2 dB when the A-weighted vibration level was 30 dB, and 9 dB when the A-weighted vibration level was 50 dB. This could be related to the influence of the ambient sound/vibration when the trains were reasonably quiet.
- Forcing the slope of the best-fit curves of A-weighted sound level as a function of A-weighted vibration level to be unity, the relationship is approximately:

$$L_{PAwt} = L_{VAwt} - 5$$

Table 15: Overall Vibration and Noise Levels Measured at Residences

Transit System	Survey Label	Dist. from Track CL (m)	Measured Overall Levels[1,2] (dB)					
			Outdoor Vibration		Indoor Vibration		Indoor Sound	
			Linear	A-Weight	Linear	A-Weight	Linear	A-Weight[3]
Toronto	10086	18.6	75.4	51.2	74.0	50.4	68.6	**44.0**
	10124	16.8	77.3	51.1	78.1	55.3	69.4	**43.1**
	10126	15.2	71.6	43.4	74.1	43.9	72.3	**43.1**
	10230	5.8	74.8	51.9	82.2	64.5	69.7	**52.7**
	20073	27.7	73.3	47.9	63.9	42.0	63.4	**42.0**
	20088	19.8	70.1	50.6	76.4	54.1	64.5	**42.5**
	20012	3.4	78.4	48.9	82.4	52.1	67.2	**40.8**
	Opp[4]	15.5	80.8	56.9	73.6	49.1	67.8	**43.8**
	70053	39.6	66.2	35.7	67.7	39.0	65.3	31.1
	70068	83.5	55.8	32.3	61.6	39.5	56.8	37.3
	70079	39.3	64.7	38.0	68.1	39.7	57.0	30.1
	70106	19.8	76.7	50.6	79.7	48.6	70.5	**41.1**
New York	Opp[4]	16.2	65.3	35.9	61.0	30.2	64.5	35.5
	00040	16.2	66.5	40.1	75.3	40.8	71.9	28.8
	00057	63.7	66.0	35.5	65.4	23.4	57.4	19.2
	00110	16.2	64.9	33.6	70.1	28.0	72.6	30.9
	00116	19.8	71.3	42.2	79.4	49.2	67.2	37.1
	00207	14.0	67.5	38.7	69.9	33.0	65.4	27.8
	00240	18.9	74.3	47.6	67.9	37.4	66.8	34.8
	00254	26.8	74.4	43.9	70.6	41.3	65.4	33.3
	00269	19.5	74.5	44.0	80.2	48.7	67.4	37.2
	00272	56.7	61.1	31.0	68.4	40.5	64.6	33.2
Boston	20031	83.2	53.7	13.3	50.6	7.4	51.4	-1.1
	20078	83.2	51.3	6.7	57.2	12.0	57.4	7.5
	70134	57.3	62.1	7.2	58.2	2.1	67.5	22.4
	70148	82.0	55.1	19.5	56.1	12.0	51.4	13.3
	20000	15.2	70.1	37.6	80.8	50.8	70.3	**43.0**
	70007	32.0	66.0	35.7	68.0	35.4	62.6	27.7
	70080	103.0	63.2	33.5	63.8	33.2	51.6	19.5
Dallas	00053	89.0	43.6	13.5	46.2	5.6	55.4	20.7
	00061	16.5	58.2	23.3	65.1	25.2	63.0	29.3
	00065	11.6	59.3	29.9	53.3	26.4	--[5]	--[5]
Sacramento	00003	11.3	60.1	18.2	56.8	16.9	--[5]	--[5]
	00010	11.6	43.5	8.3	46.7	9.0	45.8	6.5
	00011	16.5	74.5	42.8	69.4	36.7	61.9	35.4
	00026	89.6	69.6	36.1	67.4	35.2	64.6	**45.5**
	00029	16.8	73.3	39.1	69.4	36.0	80.4	32.5

1. Levels are train passby Leq. The Lmax (1 second duration) levels were 1 to 2 decibels higher.
2. Overall levels for 5 to 200 Hz 1/3 octave bands.
3. Levels in bold exceed an A-weighted level of 40 dB.
4. Test of opportunity, occupant of intended test house was not home.
5. Indoor sound measurements were not performed at these residences because resident was not home. The indoor vibration measurement was performed on an open porch.

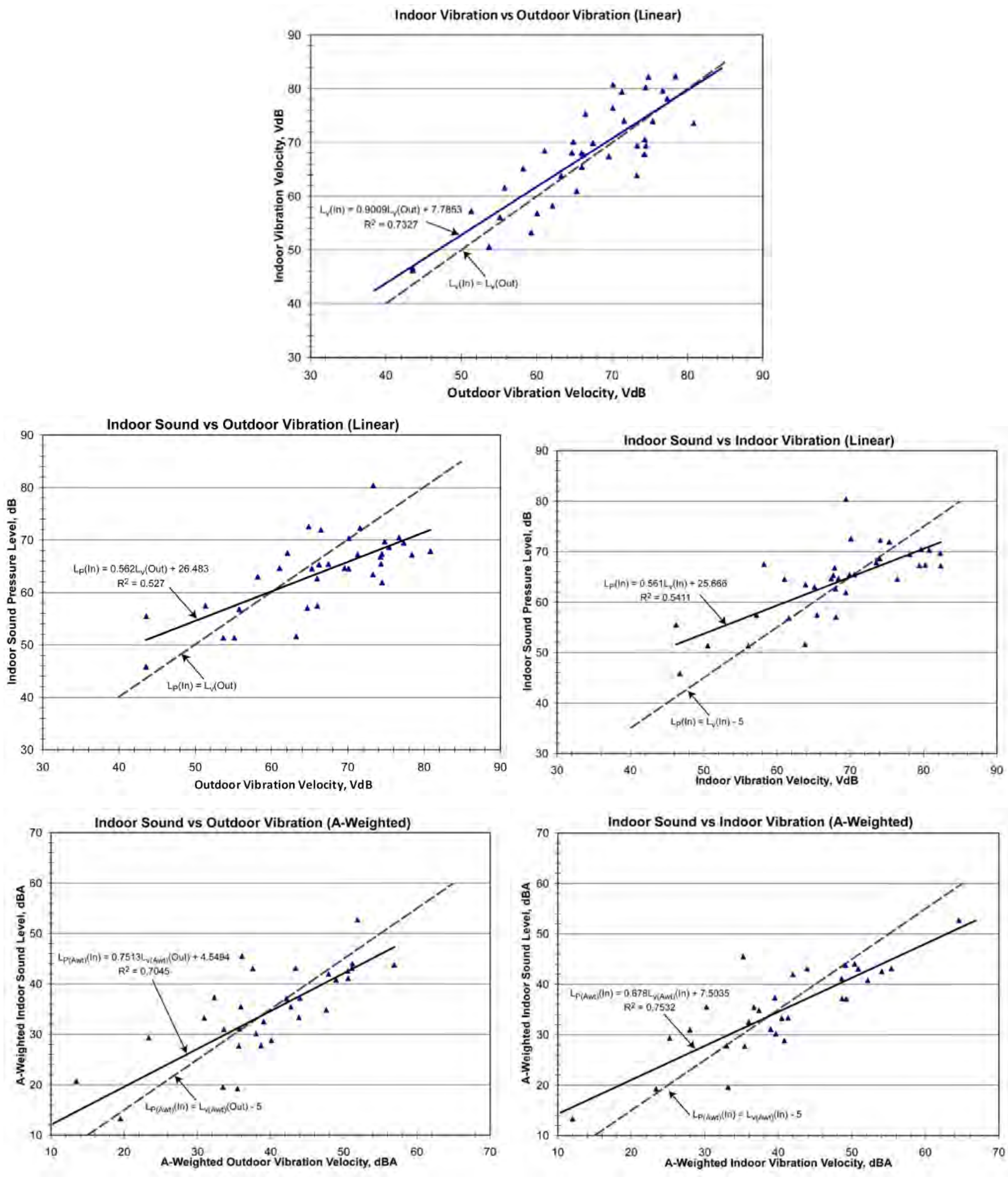


Figure 22: Relationships between Indoor and Outdoor Measurements

5.5.2 Relationships between Metrics

As discussed earlier, a number of different measures have been used or considered for characterizing human response to ground-borne vibration and noise generated by rail transit operations. A goal of this study was to investigate which measures were best correlated with human response to the vibration/noise. The two basic categories of metrics are 1) metrics based on average train vibration levels and, 2) metrics based on cumulative measures of exposure to vibration. These metrics include a number of different weighting curves (see Figure 1 and Figure 2), most of which are equivalent to vibration velocity level over the 16 Hz to 80 Hz frequency range.

The steps in the data analysis procedure consisted of analyzing the measurements, calculating average and exposure levels at each measurement position on a 1/3 octave band basis, and then using interpolation to estimate the outdoor vibration levels at each respondent's residence. The different metrics were then calculated using the interpolated 1/3 octave band levels.

As a first step in investigating the relationships between different metrics, a factor analysis was performed on the interpolated data. A factor analysis is a multivariate statistical technique that seeks to create a small number of analytic "dimensions" that identify subsets of variables that are closely related to one another, but not to other subsets of variables. The practical utility of a factor analytic solution depends on the physical interpretability of the resulting dimensions. If the various dimensions with which variables are associated cannot be readily described in useful terms, the factor-analytic solution is of no assistance in distinguishing among variables. Metrics used in the factor analysis consisted of the different measures of overall vibration level, cumulative exposure metrics, and the levels in each 1/3 octave band.

The factor analysis was unable to identify physically interpretable subsets of vibration metrics that were both closely related to one another and at the same time different from other subsets. The very high correlation among measures implies that, for purposes of predicting community response to train-induced vibration levels in homes, custom, convenience, and cost are as reasonable a basis for selecting a vibration metric as any statistically-derived criterion. This observation is specific to the data collected for this study and may or may not be applicable to systems with substantially different vibration characteristics. However, it is clear in the present data set that any number of metrics would be equally effective at predicting annoyance. Since any metric was essentially as good as any other at predicting community response, it seemed prudent to select a series of metrics for the detailed dosage-response analysis that were familiar to the noise and vibration community and did not require specialized instrumentation. An effort was also made to the extent possible to choose variables for detailed analysis that were less-well correlated with one other.

The metrics considered were:

Overall Velocity: Most common methods for characterizing passby train vibration are equivalent to either the RMS average vibration velocity over the duration of the passby, or the maximum vibration velocity level measured during the passby. Figure 23 shows the relationship between the RMS average over the 3 decibel down points (Leq) and the Lmax using a 1 second averaging time. As can be seen in Figure 23, the two measures are highly correlated and, consequently, either would be equally effective at predicting annoyance.

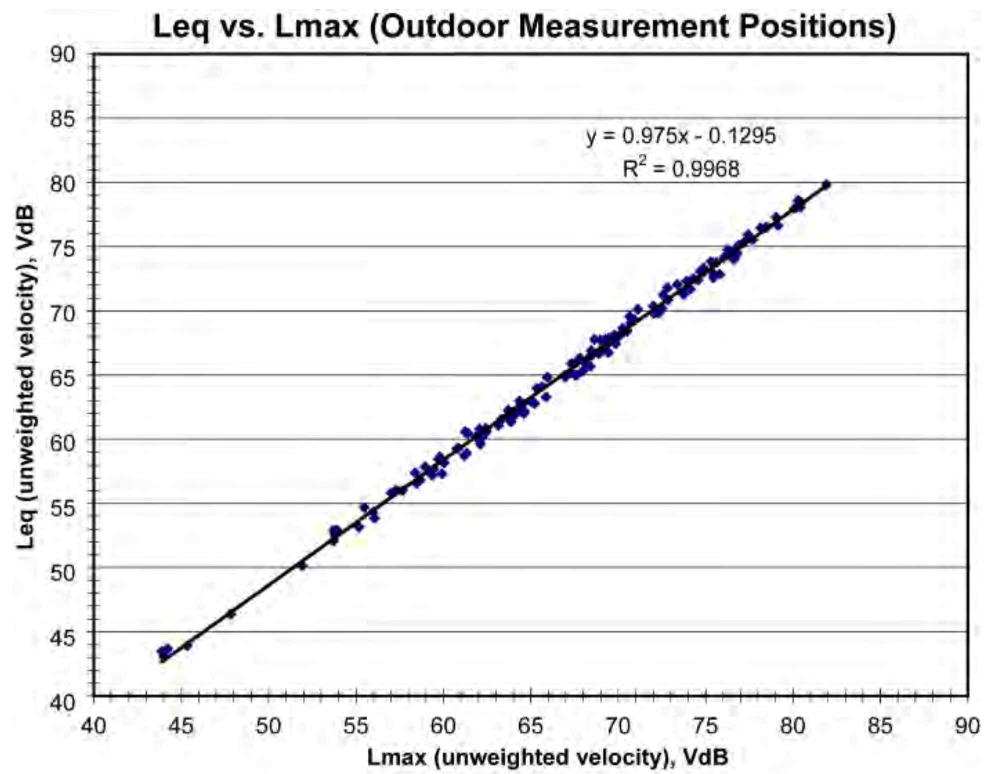


Figure 23: Relationship between Site Average Outdoor Lmax and Leq

Lmax is the maximum passby level using a 1 second RMS average. Leq is average level over the 3 dB down points.

Weighted Velocity: Figure 24 shows the relationships between un-weighted and weighted vibration velocity level using representative weighting curves. The figure clearly shows that these metrics are highly correlated with each other. Consequently, any of the weighted velocity levels would be as good a predictor of annoyance as any other.

Acceleration: Although few standards for ground-borne vibration are defined in terms of the vibration acceleration level, it was considered in this study because it has a different spectrum weighting than velocity (acceleration places more emphasis on high-frequency vibrations). Figure 25 shows the relationship between Leq velocity (average between 3 dB down points) and Leq acceleration. From the figure it can be seen that even when using these two relatively dissimilar measures, the correlation is quite high (R^2=0.91).

A-Weighting: A-weighting is relevant because current standards for ground-borne noise are typically expressed in terms of the indoor A-weighted sound level. It is commonly assumed that the sound pressure level inside a room is proportional to the vibration velocity level of the vibrating room surfaces. Therefore, A-weighted vibration velocity should also be a relatively good predictor of A-weighted ground-borne noise. Figure 26 shows the relationship between the A-weighted velocity level and the un-weighted velocity level. The correlation between the two metrics is high ($R^2 = 0.80$), although not as high as the correlation between un-weighted Leq and Lmax. Variables that are not well-correlated are desirable because they can be tested in the dosage-response analysis with the hope that one may be a better predictor of annoyance than the other. If the variables are highly correlated, by definition they will account for the same percentage of the observed variance.

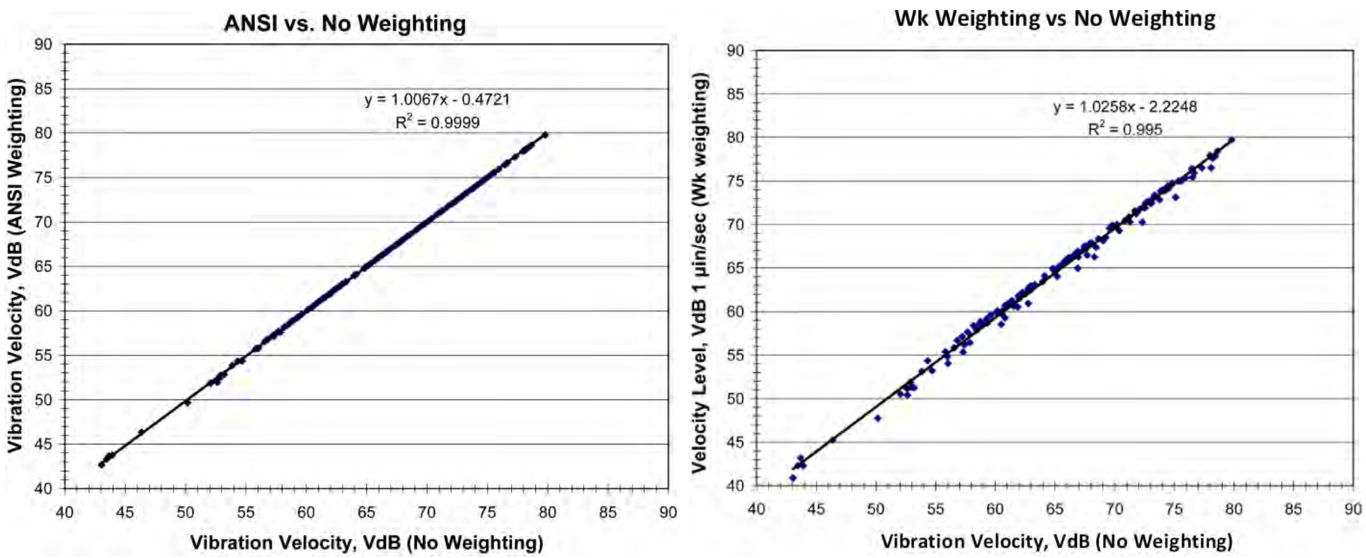


Figure 24: Relationship between Un-weighted and Weighted Velocity Levels

Both graphs compare weighted vibration velocity to the un-weighted velocity. The left plot uses ANSI weighting, which rolls off at frequencies lower than 8 Hz. The right plot shows Wk weighted velocity.

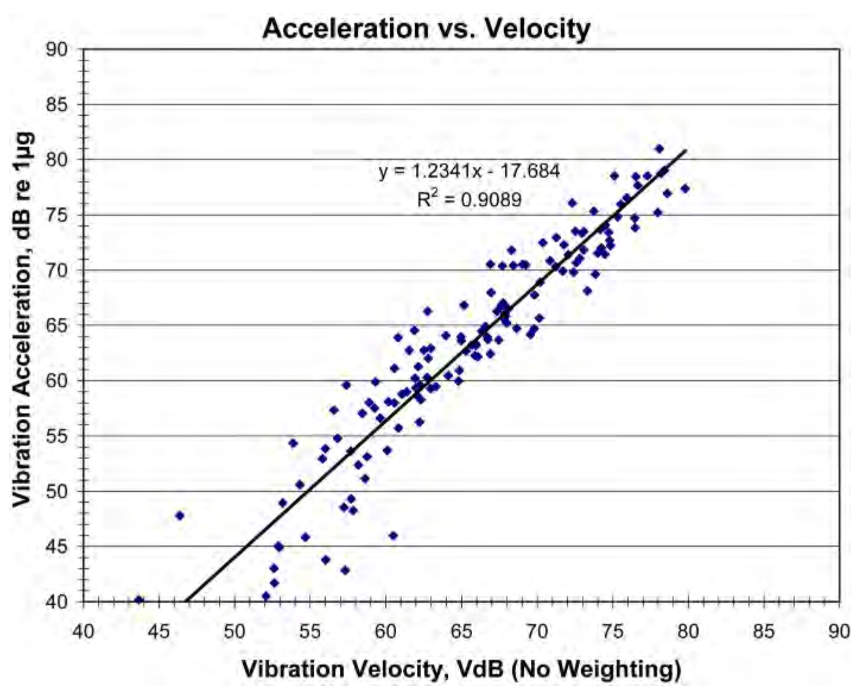


Figure 25: Relationship between Leq Acceleration and Velocity Levels

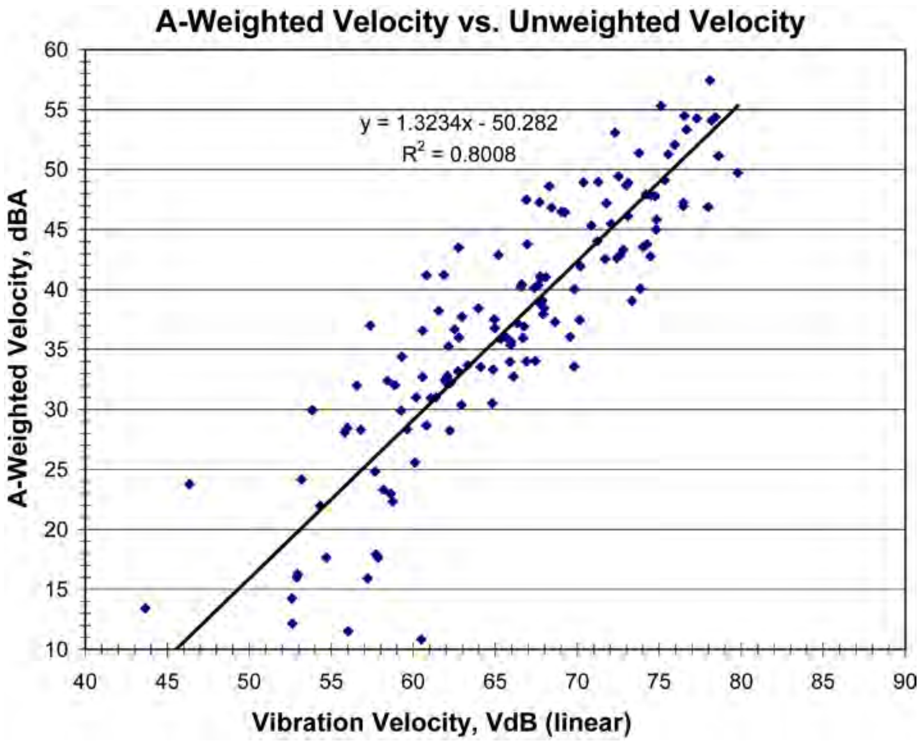


Figure 26: Relationship between A-weighted and Un-weighted Velocity Level

Measures of Exposure: A potential shortcoming associated with most current ground-borne vibration standards is they are based on the absolute train vibration level, and have little ability to account for the number of events per day, or the duration of a typical event. It seems reasonable that longer trains would be more annoying than shorter trains, and that annoyance would increase with the frequency of service in general, and nighttime service in particular. Table 11 summarizes the relative levels of exposure for the five transit systems tested in the D-12 study. The table shows that when the maximum levels of train vibration were the same, there was approximately an 11 dB difference between the exposure in Toronto (the greatest exposure) and the exposure at the light rail lines in Sacramento and Dallas. Table 16 summarizes the average event duration for the five test systems. The average durations were consistent with the typical numbers of cars in the consist (see Table 11).

Table 16: Average Event Duration

Transit System	Duration, seconds[1]			
	Average	Standard Deviation	Minimum	Maximum
Toronto	9.4	1.6	5.2	13.5
New York	14.6	3.1	8.8	19.7
Boston	9.0	2.8	5.8	16.9
Dallas	4.0	0.8	3.0	5.7
Sacramento	5.5	1.6	3.4	10.1
1. Average time between 3 dB down points.				

The exposure metrics most familiar to the acoustics community are based on the equivalent sound level (Leq) over a period of time, most commonly 24 hours or one hour. For example, many impact criteria for noise are based on the Day-Night Average Sound Level (abbreviated as Ldn or DNL). Ldn is a 24-hour Leq with a +10 decibel penalty applied during nighttime hours to account for the increased sensitivity of people at night. As shown in Table 11, the ratio of daytime-to-nighttime trains did not vary significantly among the five transit systems. This is not surprising since, presumably transit agencies plan service around the conventional work day. Because there is no real variation in the day/night exposure metrics, it is not possible to gain any insight into the relative importance of daytime versus nighttime exposure to vibration. Consequently, the exposure metrics used to investigate dosage-response relationships do not include nighttime adjustments.

RMQ is a metric that the British have proposed to characterize exposure. As discussed earlier, laboratory studies by Howarth and Griffin (8) indicate the following relationship between annoyance, number of events (*N*), and vibration amplitude (*V*):

$$NV^{3.7} \propto annoyance$$

This relationship was used in developing the fourth-power vibration dose value (VDV) used in the British Standard (6), which is essentially an RMQ exposure metric. To calculate VDV as defined in the British Standard would have required analyzing the raw vibration data to obtain RMQ averages along with RMS averages. Although this would have been possible using MATLAB, the potential benefits of the additional processing were not sufficient to justify the considerable effort that would have been required to re-analyze the data. Rather, an approximate method was used to investigate the correlation between RMS and RMQ exposure using average SEL at each exterior measurement site. Figure 27 shows the relationship between the average SEL using RMS velocity and the average SEL using RMQ velocity. The two metrics are highly correlated (R^2=0.986) with only a few locations where the variance from the best fit line is more than 1 dB. The average difference between the RMQ and RMS averages is approximately 1 dB. It was decided that the computational effort in calculating VDV did not justify the small potential benefit in accounting for slightly more of the observed variance.

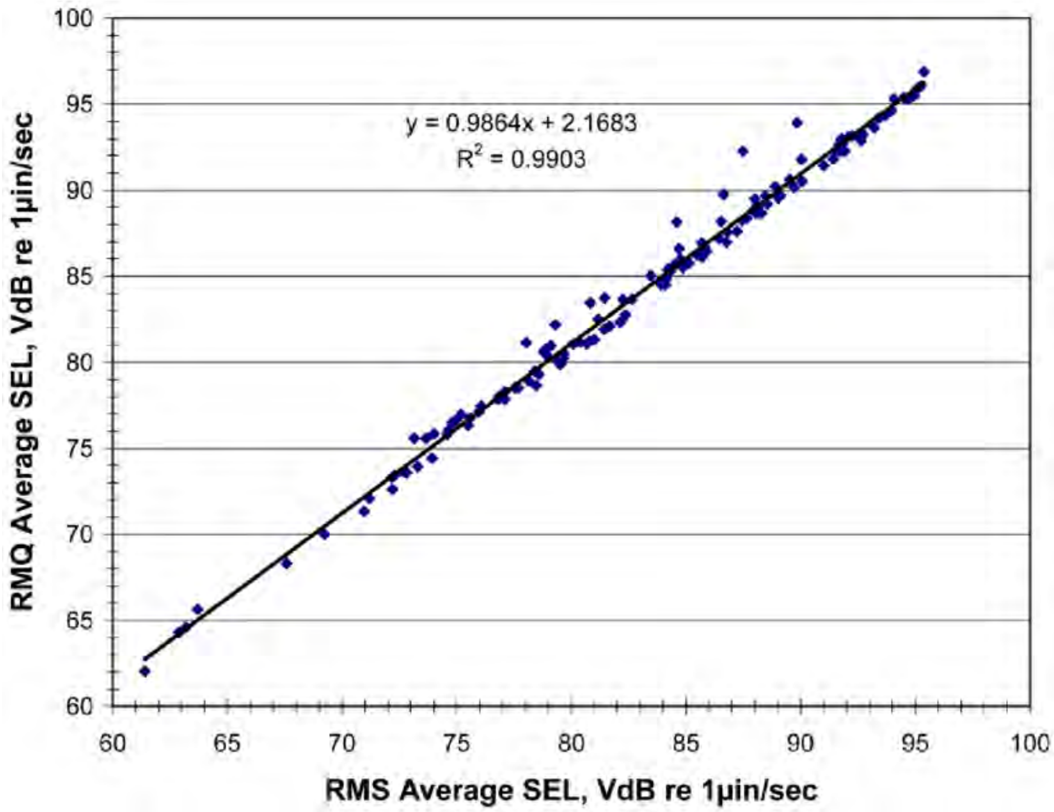


Figure 27: Comparison of RMQ and RMS Exposure

Comparison of site average SEL calculated using RMS and RMQ averaging for all exterior measurement positions. SEL is the total energy of the event normalized to 1 second.

5.5.3 Vibration Spectra

The frequency character of the vibration can be equally as important as the absolute level. This section presents an overview of the measurement results in terms of the 1/3 octave band spectra. The outdoor vibration levels are used for the comparison and the metric used is the RMS average over the 3 dB down points (Leq).

5.5.3.1 Comparison of Vibration Spectral Shapes

Figure 28 through Figure 33 show the average vibration spectra obtained at each of the outdoor measurements locations (residence plus grid), at each of the transit systems. The upper plot in each figure shows the measured vibration spectrum at each site, along with a line corresponding to 72 VdB for comparison. The lower plot shows the spectra after being normalized such that the overall vibration level is 72 VdB. The purpose of showing the normalized spectra is to highlight the frequency characteristics of each system.

The following observations can be made regarding the data shown in Figure 28 through Figure 33:

- The Toronto data have a distinct peak at 50 Hz that is evident in all but a few of the vibration spectra (Figure 28). None of the other systems exhibited such distinct peaks, particularly ones that that were so consistent. The fact that this peak shows up in the results for most of the measurement sites could be an indication that it is a characteristic of the Toronto situation (track, tunnel, rolling stock, soil conditions).

- A second, less distinct, peak shows up in the Toronto data in the 80 Hz to 100 Hz range. Both of the Toronto peaks are in the audible frequency range, and it is likely that these peaks are perceived inside buildings as audible noise. The absolute Toronto levels also exceeded 72 VdB at a number of locations, and it is expected that these would be perceptible by most people. The combined effect of audible noise and perceptible vibration could contribute to a higher level of annoyance in Toronto than at other systems where noise was more prevalent.
- The vibration spectra measured in New York (Figure 29) had a consistent shape with a broad peak in the 40 Hz to 80 Hz range.
- The maximum spectral levels near the Boston Blue Line (Figure 30) typically occurred in the 40 Hz to 60 Hz range. At the Blue Line, the vibration levels above 30 Hz decreased more rapidly with increased distance than did the vibrations below 30 Hz. This effect causes a low-frequency distortion that is evident in the normalized data.
- The Boston Back Bay spectra (Figure 31) fall into two distinct groups; Group 1 with maximum levels in the 60 Hz to 100 Hz range, and Group 2 that peaks around 20 Hz and then rolls off at higher frequencies. Further investigation showed that most of the Group 1 sites were located to the south of the rail right of way. The right of way is shared by commuter rail and Orange Line rapid transit trains. The Orange Line, which is located along the north side of the right of way, has a floating slab trackbed. It can be inferred from the measurements that the floating slab is effectively attenuating vibration at frequencies greater than 20 Hz.
- The vibration spectra at the Dallas sites (Figure 32) tended to be broadband, with maximum levels in the 30 Hz to 80 Hz range. The spectral levels were relatively low compared to the other transit systems.
- The vibration spectra from the Sacramento sites (Figure 33) generally had maximum levels in the 30 Hz to 60 Hz range. An interesting characteristic of the Sacramento data is a peak at 20 Hz that shows up in the results at some of the sites. Because the 20 Hz vibration levels are relatively low at the sites where this peak occurred, it does not have much influence on the overall vibration level, however, it is quite prominent in the normalized spectra. The Sacramento residence with the greatest measured vibration level was located near a crossover. In Figure 33 this corresponds to the red curve with solid red diamonds.
- Note that few of the measured outdoor vibration levels shown in Figure 28 through Figure 33 would exceed 72 VdB in any 1/3 octave band. There were a few sites in Toronto and New York, three at the Boston Blue Line, one in Sacramento, and none at either Boston Back Bay or Dallas. This indicates that most of the locations where vibration measurements were performed during the D-12 study would not be a considered to be “impacted” according to feelable vibration criteria used in the United States. Of course, this does not mean the sites would not be impacted based on ground-borne noise criteria.

Figure 34 shows the energy averaged outdoor spectra measured at each transit system (sometimes referred to as “decibel averaging”). The top graph in Figure 34 shows the average spectra while the bottom graph shows the spectra normalized to an overall level of 72 VdB. The Toronto average spectrum is the only one that has appreciable energy above 60 Hz. It is also clear that Toronto is the only system where the maximum level occurs at a distinct peak in the vibration spectrum. As discussed above, the 50 Hz peak in the Toronto vibration spectrum occurred at most of the measurement locations.

Based on the average curves and the current criteria for ground-borne vibration, Toronto would be expected to have the highest level of community annoyance closely followed by the Boston Blue Line. On a 1/3 octave band basis, the maximum vibration levels in New York were about 5 decibels lower than those in Toronto, indicating that a lower level of annoyance would be expected in New York than in Toronto.

The vibration levels at residences in the Boston Back Bay, Dallas, and Sacramento were generally sufficiently low that limited levels of community annoyance would be expected, again based solely on a feelable vibration criterion.

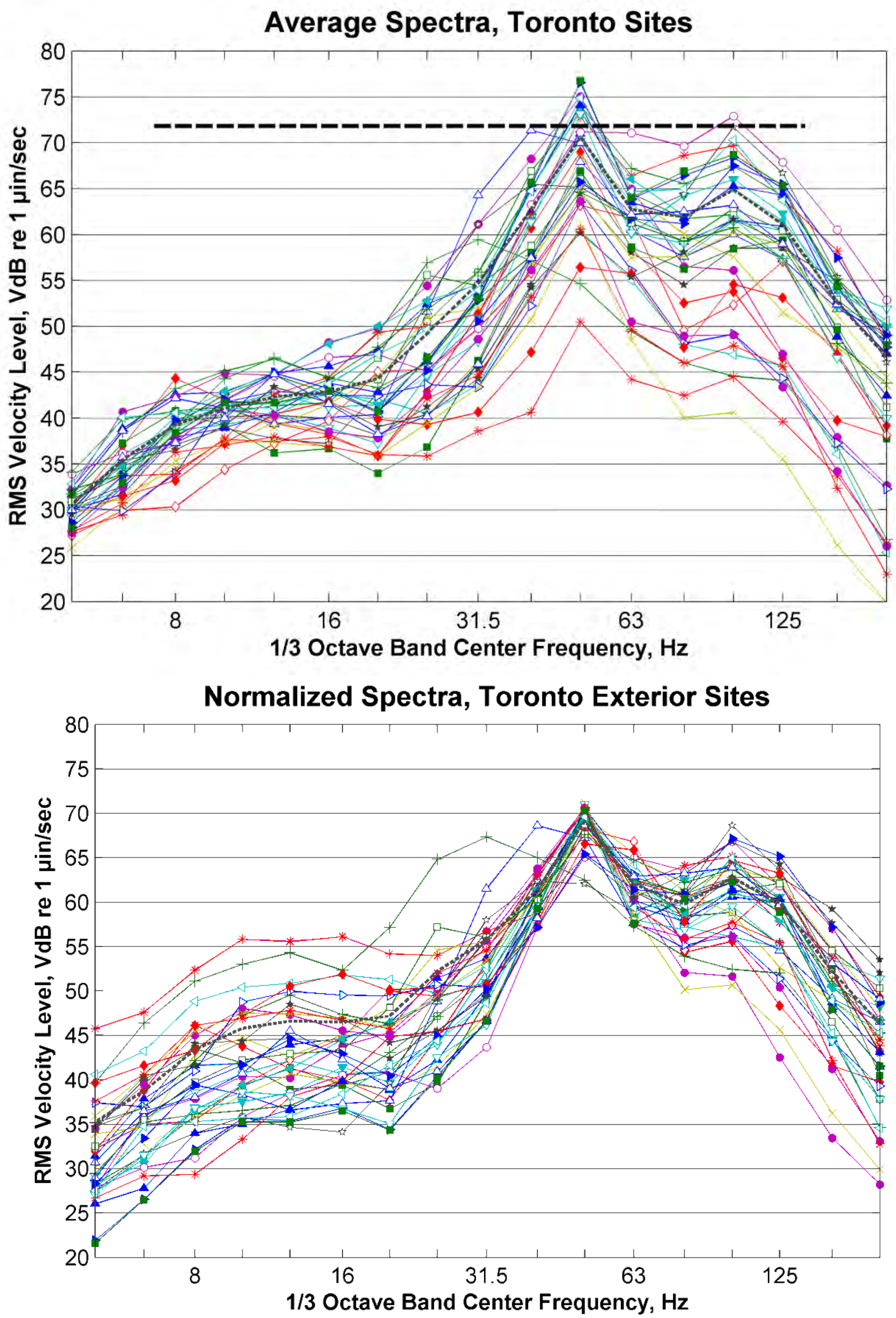


Figure 28: Average Vibration Velocity Spectra, Toronto Outdoor Measurement Sites

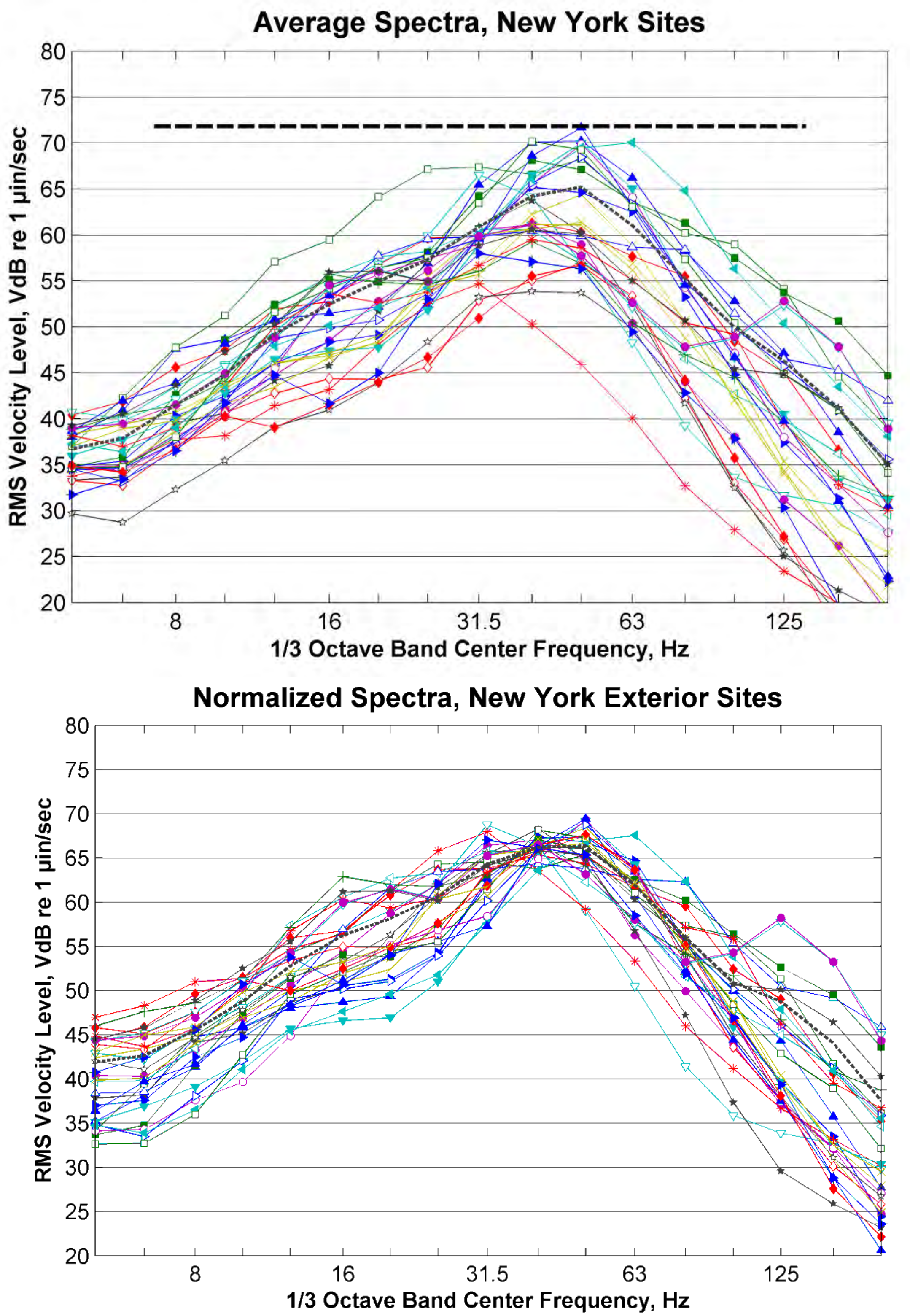
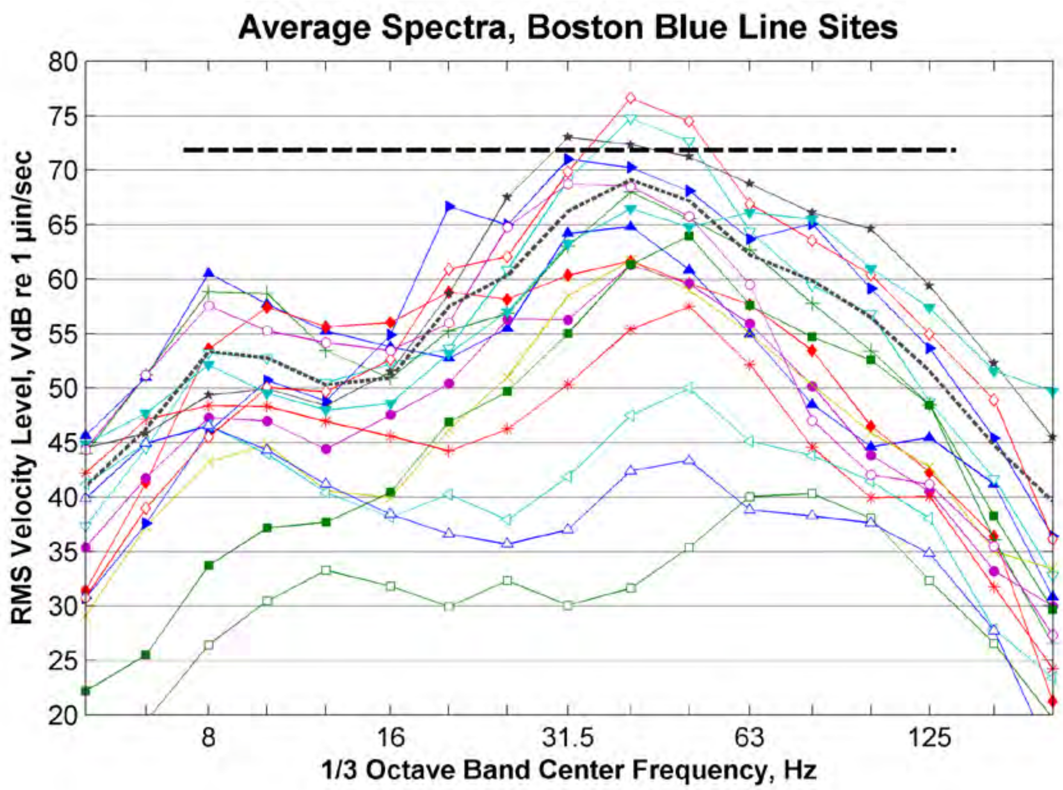


Figure 29: Average Vibration Velocity Spectra, New York Outdoor Measurement Sites



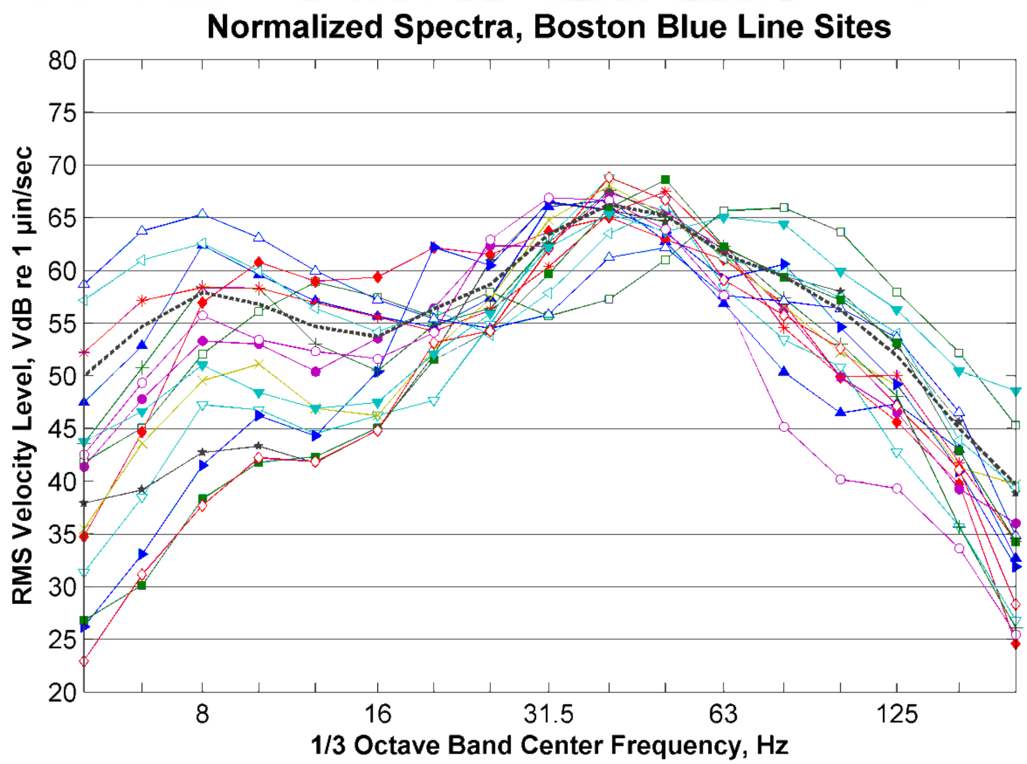


Figure 30: Average Vibration Velocity Spectra, Boston Blue Line Outdoor Sites

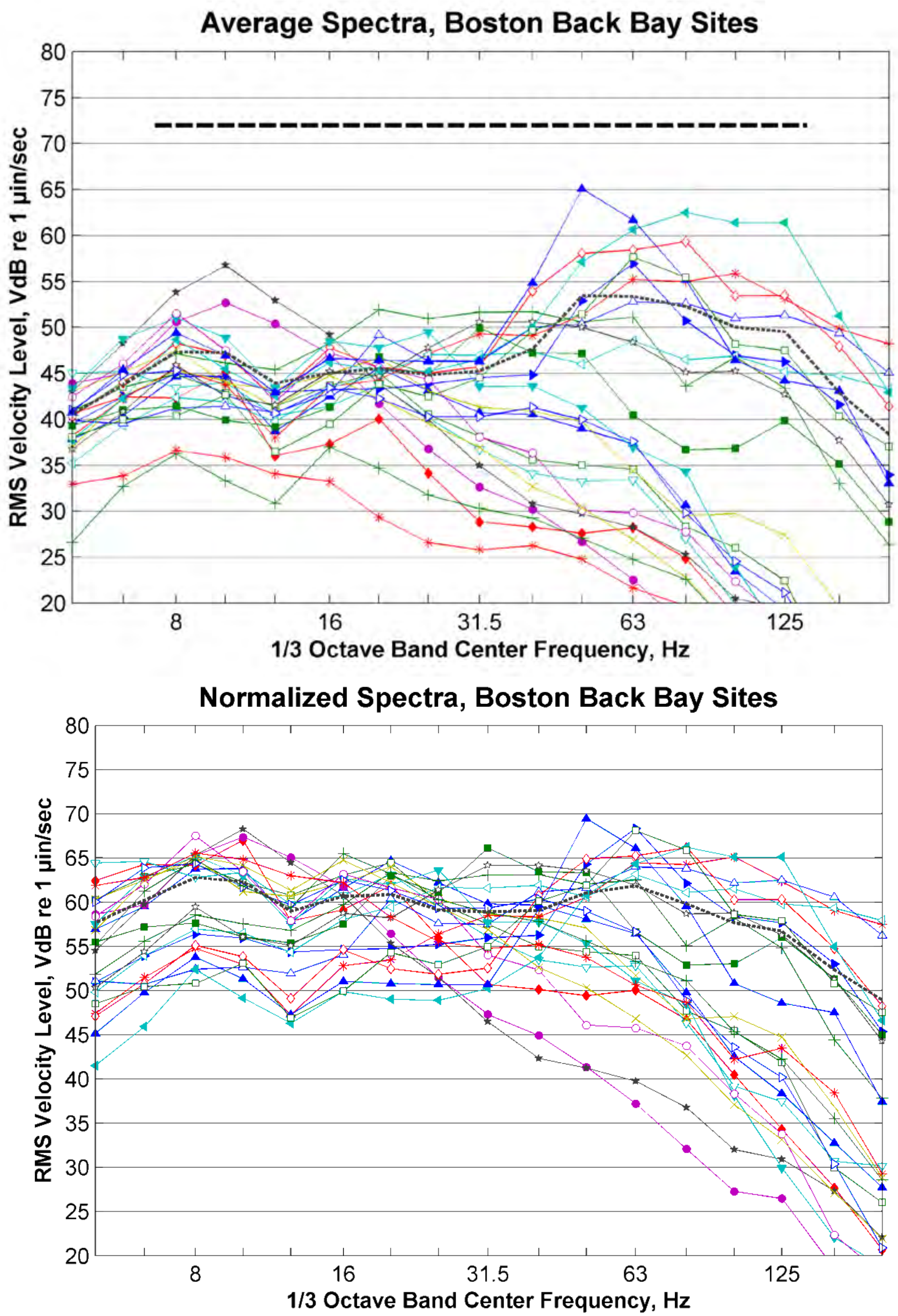


Figure 31: Average Vibration Velocity Spectra, Boston Back Bay Outdoor Sites

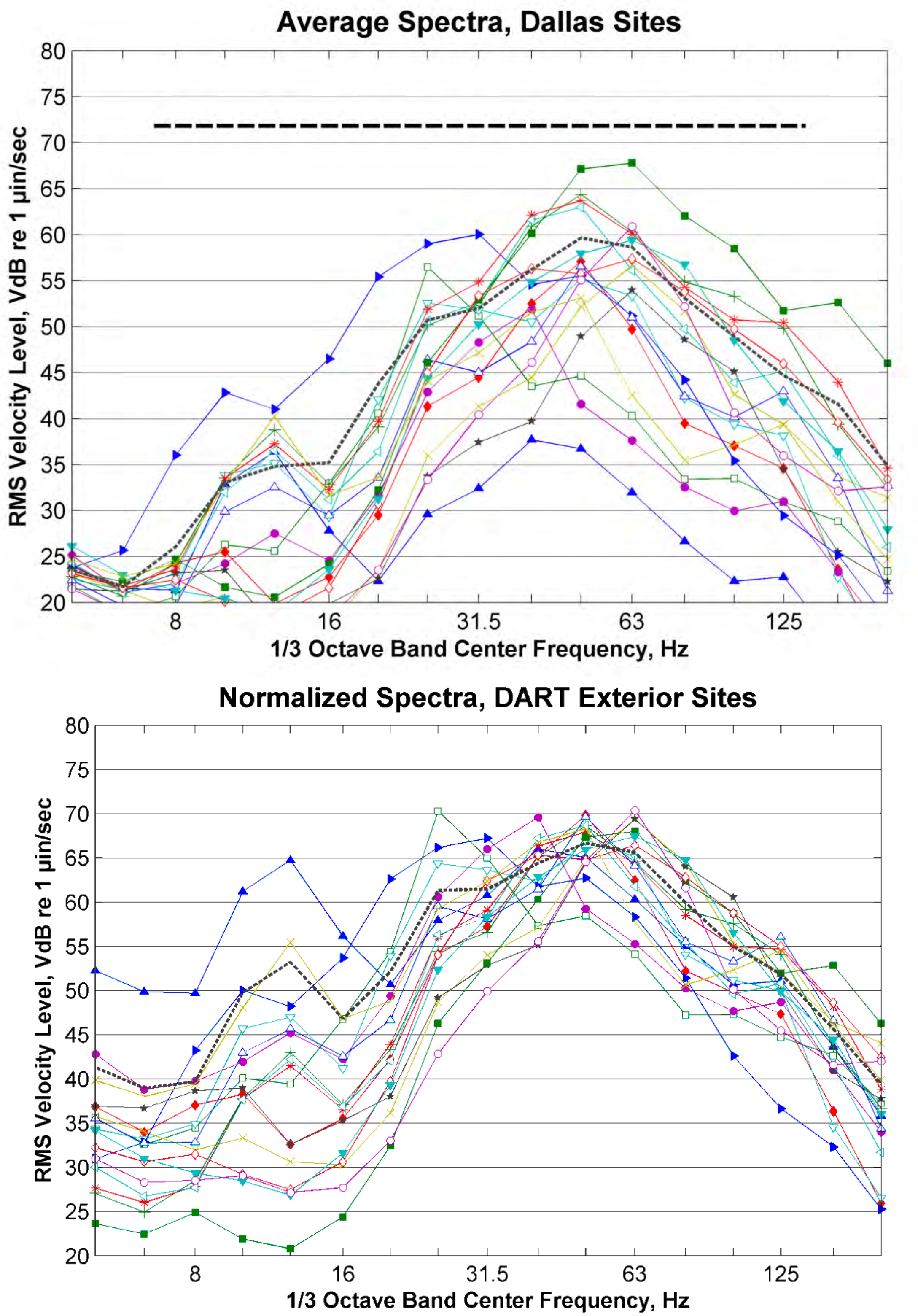


Figure 32: Average Vibration Velocity Spectra, Dallas Outdoor Measurement Sites

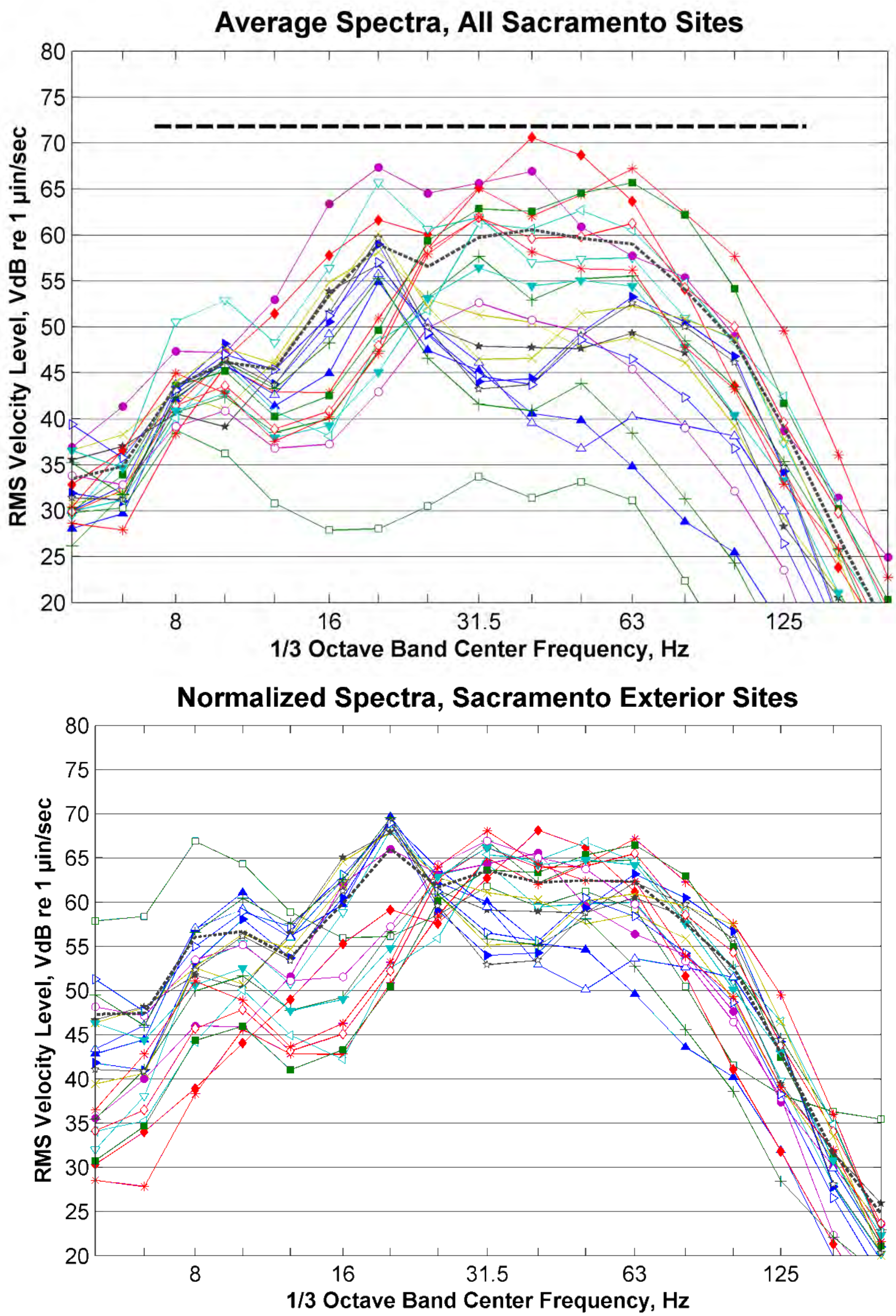


Figure 33: Average Vibration Velocity Spectra, Sacramento Outdoor Measurement Sites

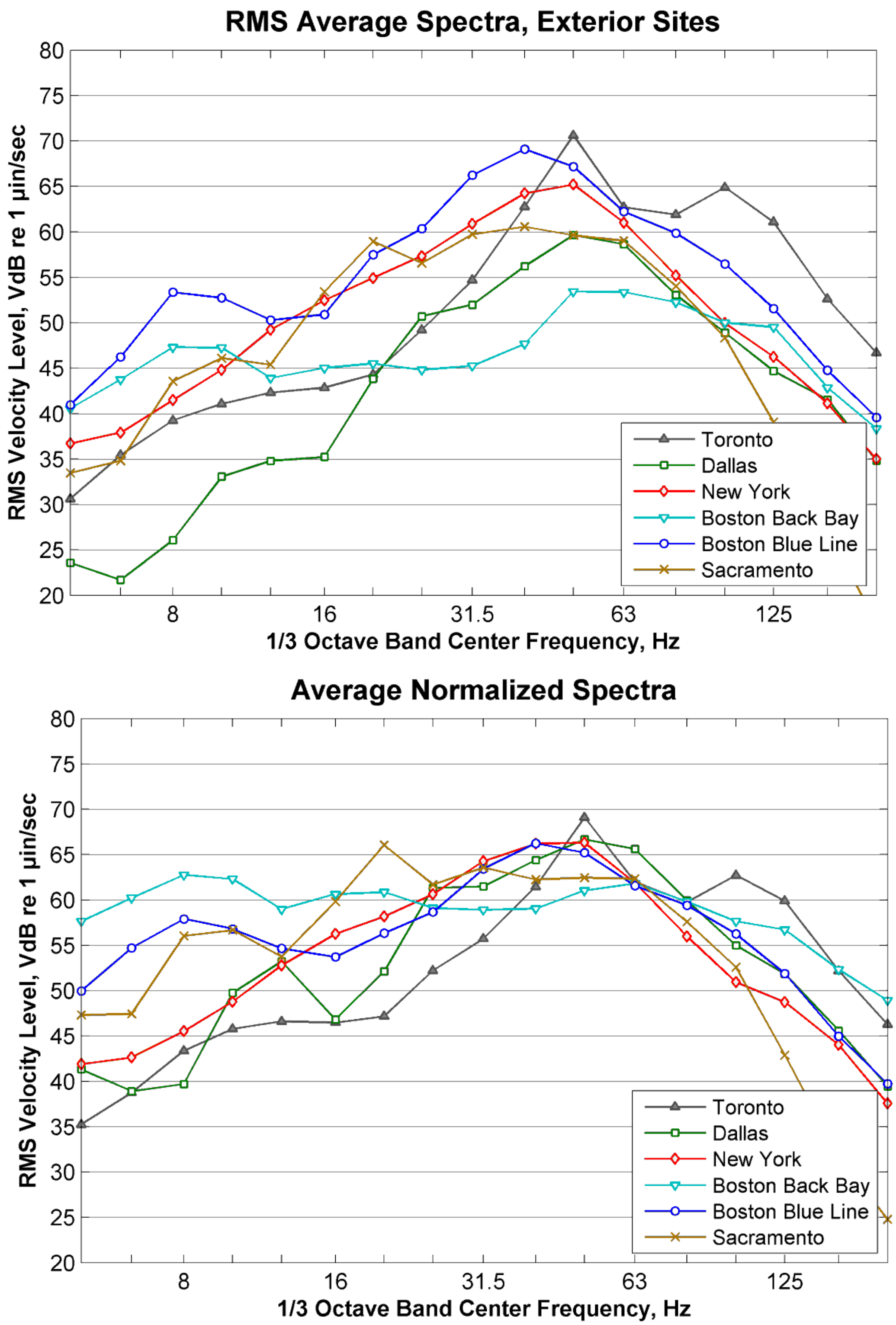


Figure 34: Average Vibration Velocity Spectra, Outdoor Measurement Sites

5.5.3.2 Outdoor to Indoor Adjustments

At each of the residential test locations, the vibrations were measured simultaneously inside and outside of the residence. Noise was also measured inside the residence.

Figure 35 through Figure 39 show the measured differences in the 1/3 octave band, indoor and outdoor spectra measured at each site. The RMS average vibration and sound levels over the 3 dB down points (Leq) were used for this analysis. The differences were calculated for each train event at each site and then presented as a site average. The upper plot in each figure shows the difference between the indoor vibration level and the outdoor vibration level (indoor– outdoor). The middle plot shows the difference between indoor sound and indoor vibration and the lower plot shows the difference between indoor sound and outdoor vibration. In the presentation of the data, any 1/3 octave band levels that were not at least two standard deviations greater than the background were excluded to avoid skewing due to the background levels.

Figure 40 shows the average differences for all of the test sites. Figure 41 shows the average differences for each transit system, along with the overall average (all systems combined).

Some observations and conclusions that can be drawn from these figures are:

- There is a large house-to-house variation in the D-12 data. In most cases the standard deviation is around 5 dB, with a tendency to increase with frequency.
- The average difference between indoor and outdoor vibration was nearly zero. The average for Toronto is within ±2 dB of zero over the entire frequency range. The New York average decreased with frequency at a rate of approximately 3 decibels per octave. (There were too few data points from Boston, Dallas and Sacramento to draw conclusions.)
- When all indoor vibration minus outdoor vibration data were combined (Figure 40), the average difference was effectively zero over the entire frequency range.
- Because the average indoor vibration was approximately equal to the average outdoor vibration, the curves of indoor sound minus indoor vibration and indoor sound minus outdoor vibration are similar.
- There is a consistent pattern of indoor sound being 3 to 5 decibels lower than indoor vibration over a frequency range from 31.5 Hz to 100 Hz. The differences are somewhat less for higher and lower frequencies. The 3 to 5 dB difference is consistent with the observed difference between A-weighted indoor/outdoor vibration and A-weighted indoor sound which was about 5 dB (see Section 5.5.1).
- There are no clear patterns based on the type of residence or the transit system. Almost all of the test residences were wood-frame construction. The residences in Toronto were primarily two story duplexes with basements, the residences in New York were three to five story brownstones and apartment buildings, the residences in Dallas and Sacramento tended to be single story slab-on-grade construction, and the residences in Boston were primarily two story duplexes, four to five story brownstones, or apartment buildings.
- An important factor to recognize in considering these results is that the indoor sound levels measured during train events were often near the background sound levels. In fact, only in Toronto did the indoor noise levels consistently exceed the background.

Figure 42 shows the combined average curves obtained using different acceptance criteria in terms of the amount that a data point must exceed the background to be included in the average. The acceptance criteria range from no data points being excluded, to excluding all data points that do not exceed the average background level by at least three standard deviations. The following observations follow from this analysis:

- Indoor vibration minus outdoor vibration: The data acceptance criteria have virtually no effect on the average.
- Indoor sound minus indoor vibration: As the threshold for accepting data increases, the average difference drops. This effect increases with frequency.
- Indoor sound minus outdoor vibration: Because the average difference between indoor vibration and outdoor vibration is close to zero over the entire frequency range, the curves of indoor sound minus indoor vibration and indoor sound minus outdoor vibration are similar. The acceptance threshold has less of an effect on the indoor sound minus outdoor vibration than on the indoor sound minus indoor vibration.

From the outdoor-to-indoor analysis it can be concluded that, for the D-12 data, the indoor vibration spectrum is effectively equal to the outdoor spectrum. Consequently, the exterior vibration levels are a very good predictor of the indoor levels, on average.

While the indoor and outdoor vibration levels were comparable on average, there was a considerable variation when comparing specific houses. To illustrate this, consider three seemingly identical, adjacent brownstone buildings in New York. Figure 43 shows the average indoor vibration and sound spectra that were measured in each of the houses. The measurements were all made in the living room which faced the street (and the subway). The indoor sound levels were very similar, yet the vibration in one of the brownstones was 15 dB lower than was observed in the other two. The difference in vibration was likely due to a unique structural element or some other hidden peculiarity of the sensor position, however, the important thing to note is that there was no way to know by inspection of the exteriors which of the residences would have lower, or higher vibration levels.

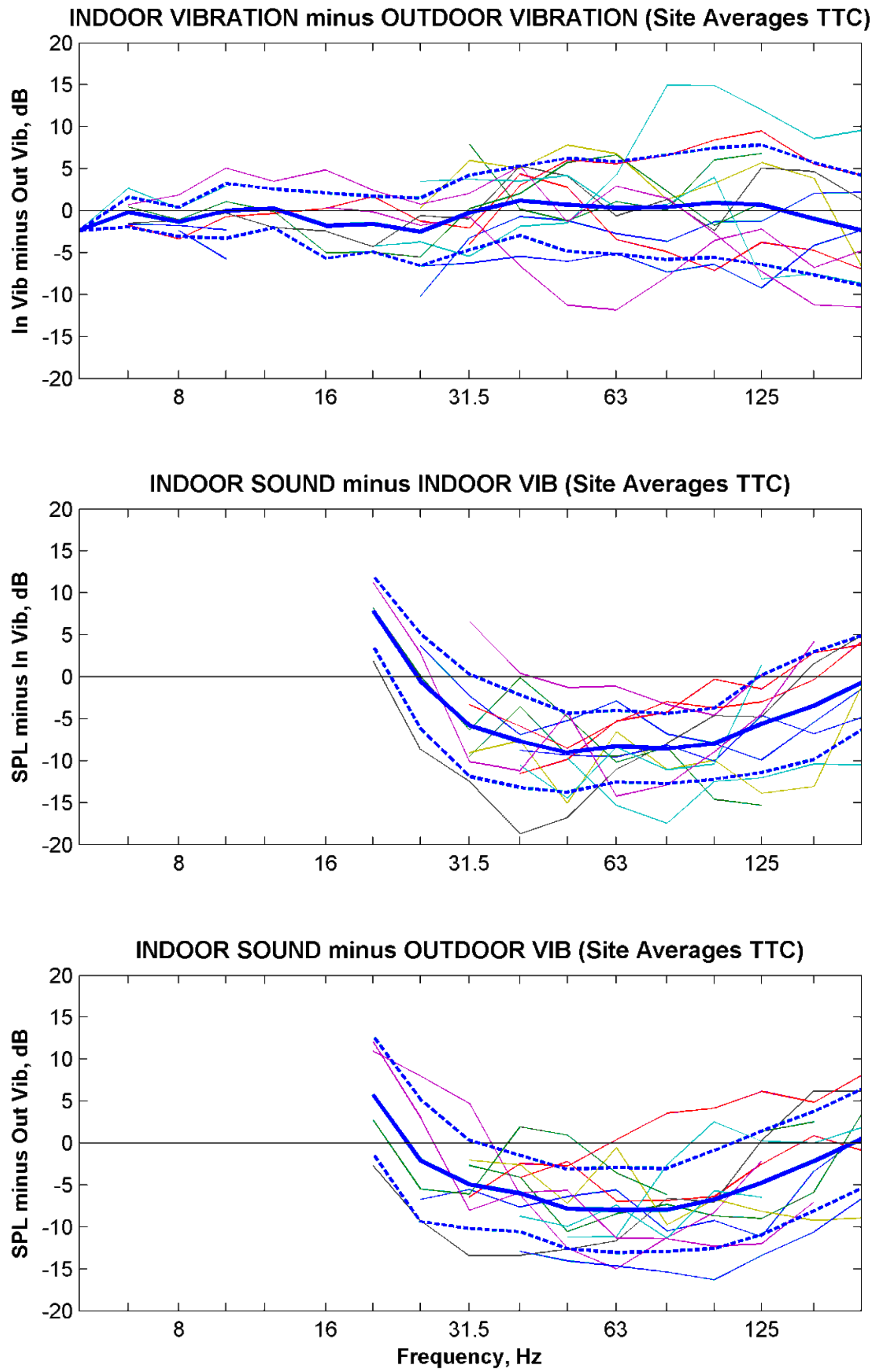


Figure 35: Average Outdoor-to-Indoor Differences, Toronto

Solid blue line is average of all sites, dashed blue lines are ± 1 standard deviation. Only levels that were more than 2 standard deviations greater than background levels were included in the calculation of average differences.

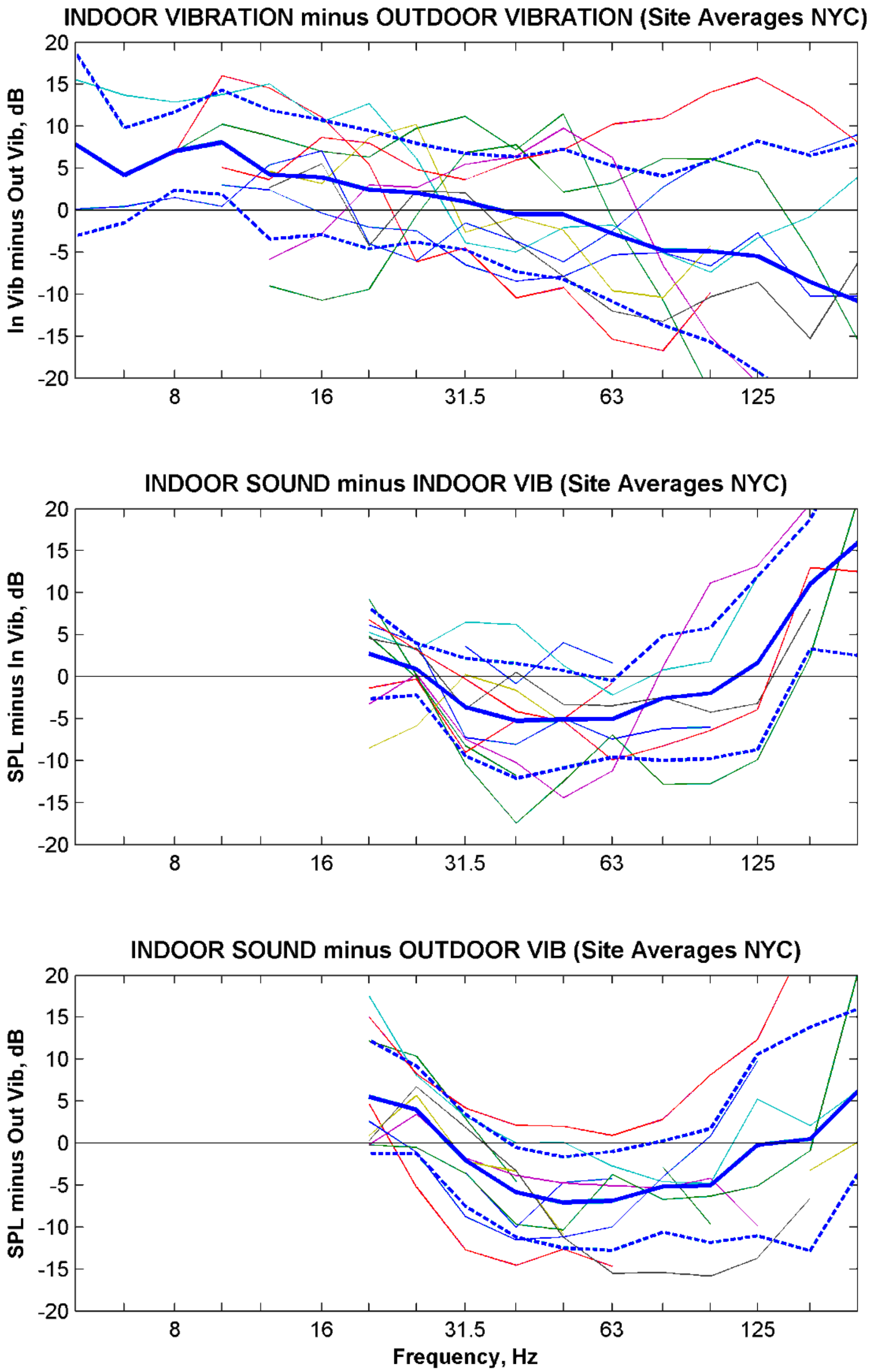


Figure 36: Average Outdoor-to-Indoor Differences, New York

Solid blue line is average of all sites, dashed blue lines are ± 1 standard deviation. Only levels that were more than 2 standard deviations greater than background levels were included in the calculation of average differences.

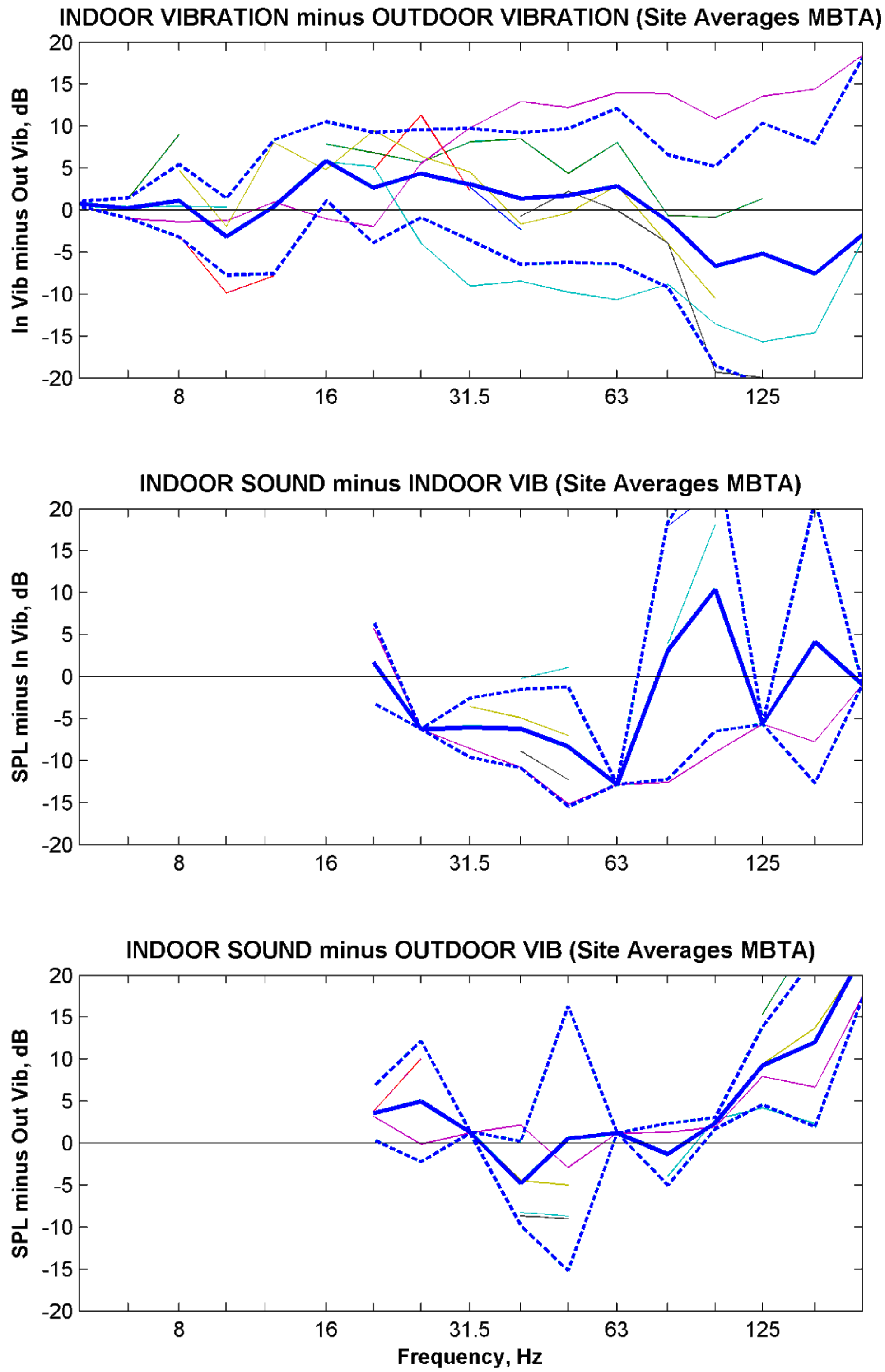


Figure 37: Average Outdoor-to-Indoor Differences, Boston

Solid blue line is average of all sites, dashed blue lines are ± 1 standard deviation. Only levels that were more than 2 standard deviations greater than background levels were included in the calculation of average differences.

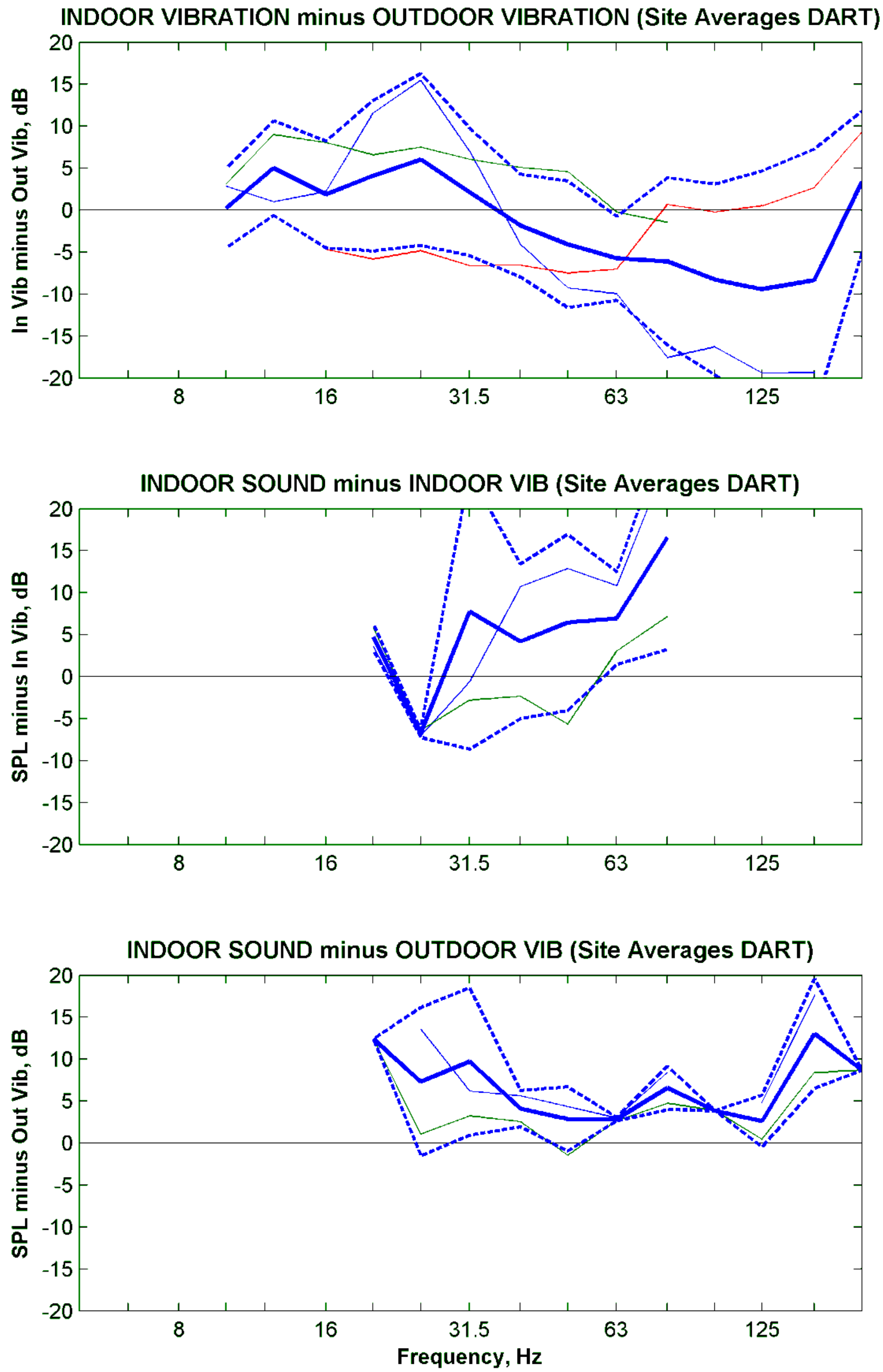


Figure 38: Average Outdoor-to-Indoor Differences, Dallas

Solid blue line is average of all sites, dashed blue lines are ± 1 standard deviation. Only levels that were more than 2 standard deviations greater than background levels were included in the calculation of average differences.

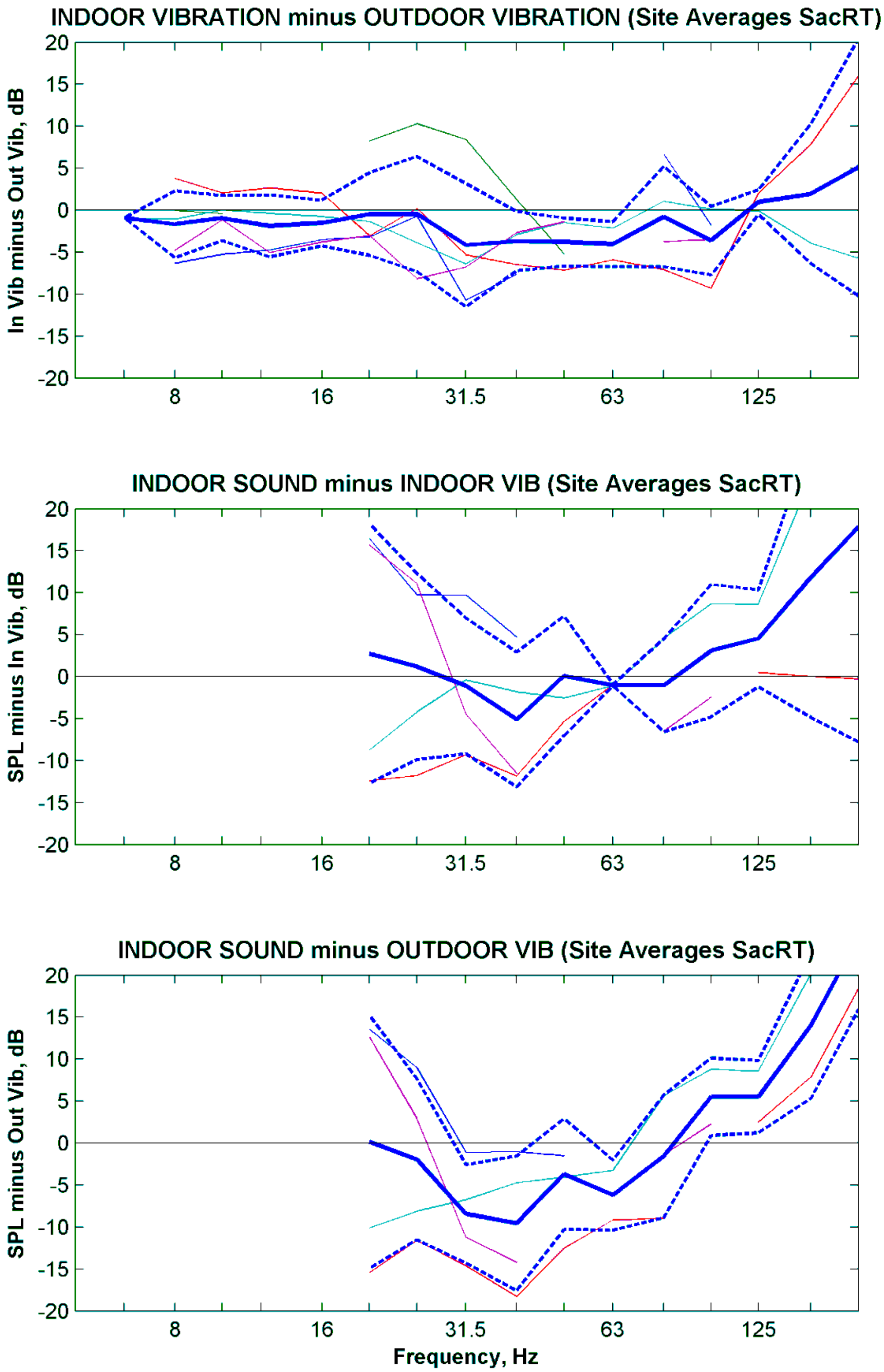


Figure 39: Average Outdoor-to-Indoor Differences, Sacramento

Solid blue line is average of all sites, dashed blue lines are ± 1 standard deviation. Only levels that were more than 2 standard deviations greater than background levels were included in the calculation of average differences.

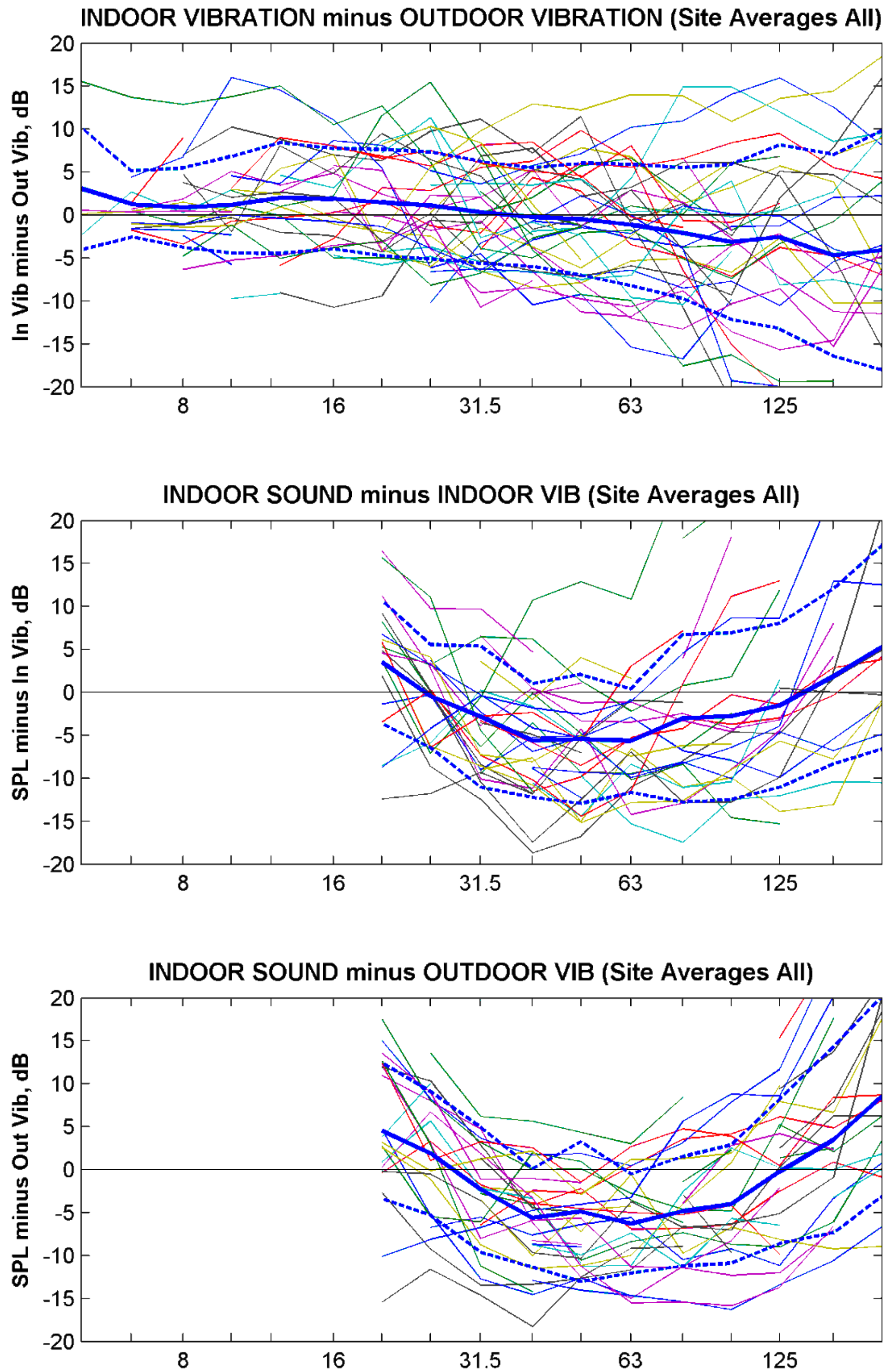


Figure 40: Average Outdoor-to-Indoor Differences, All Sites

Solid blue line is average of all sites, dashed blue lines are ± 1 standard deviation. Only levels that were more than 2 standard deviations greater than background levels are included in the calculation of average differences.

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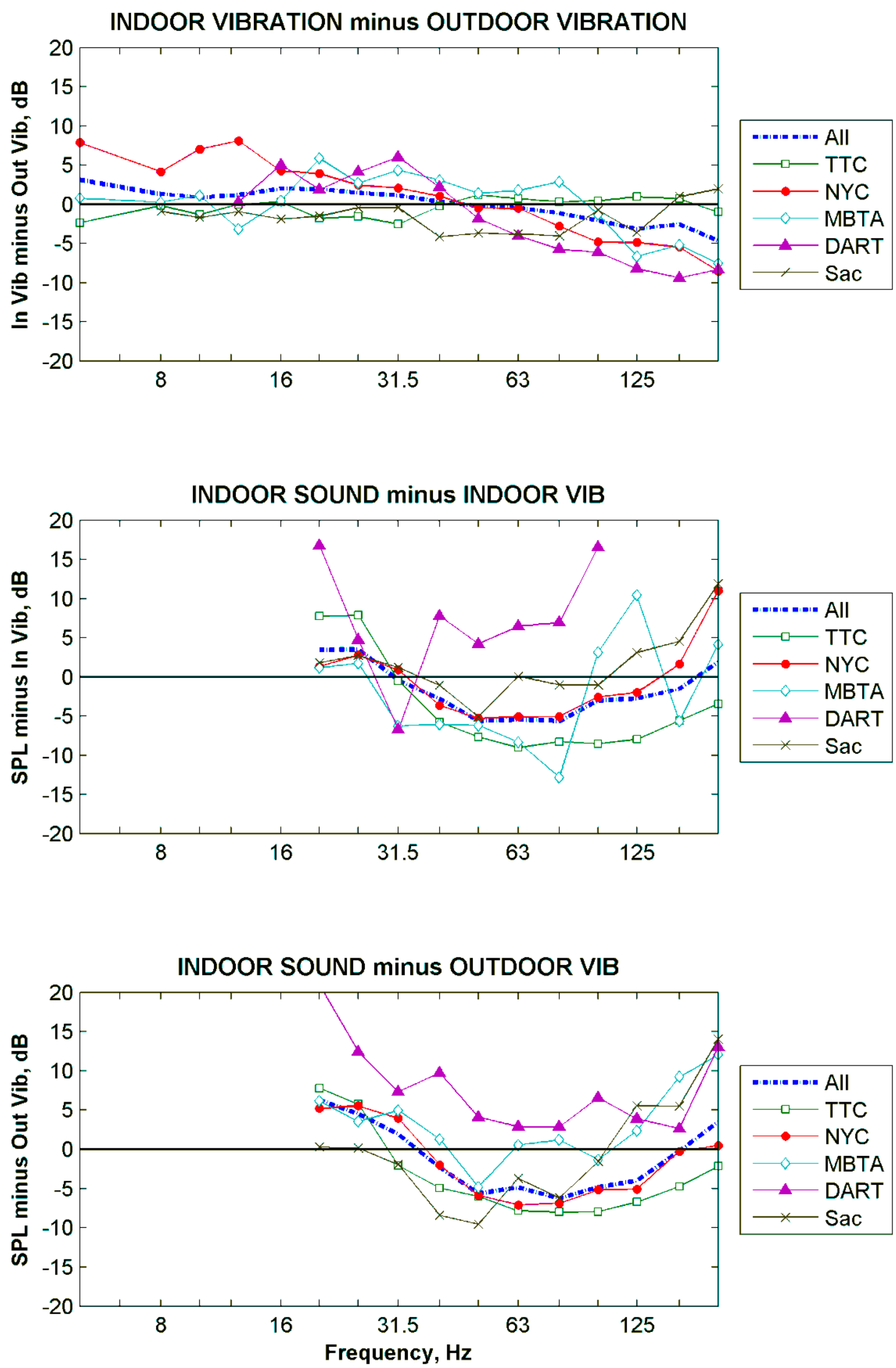

Figure 41: Average Outdoor-to-Indoor Differences for Each Transit System

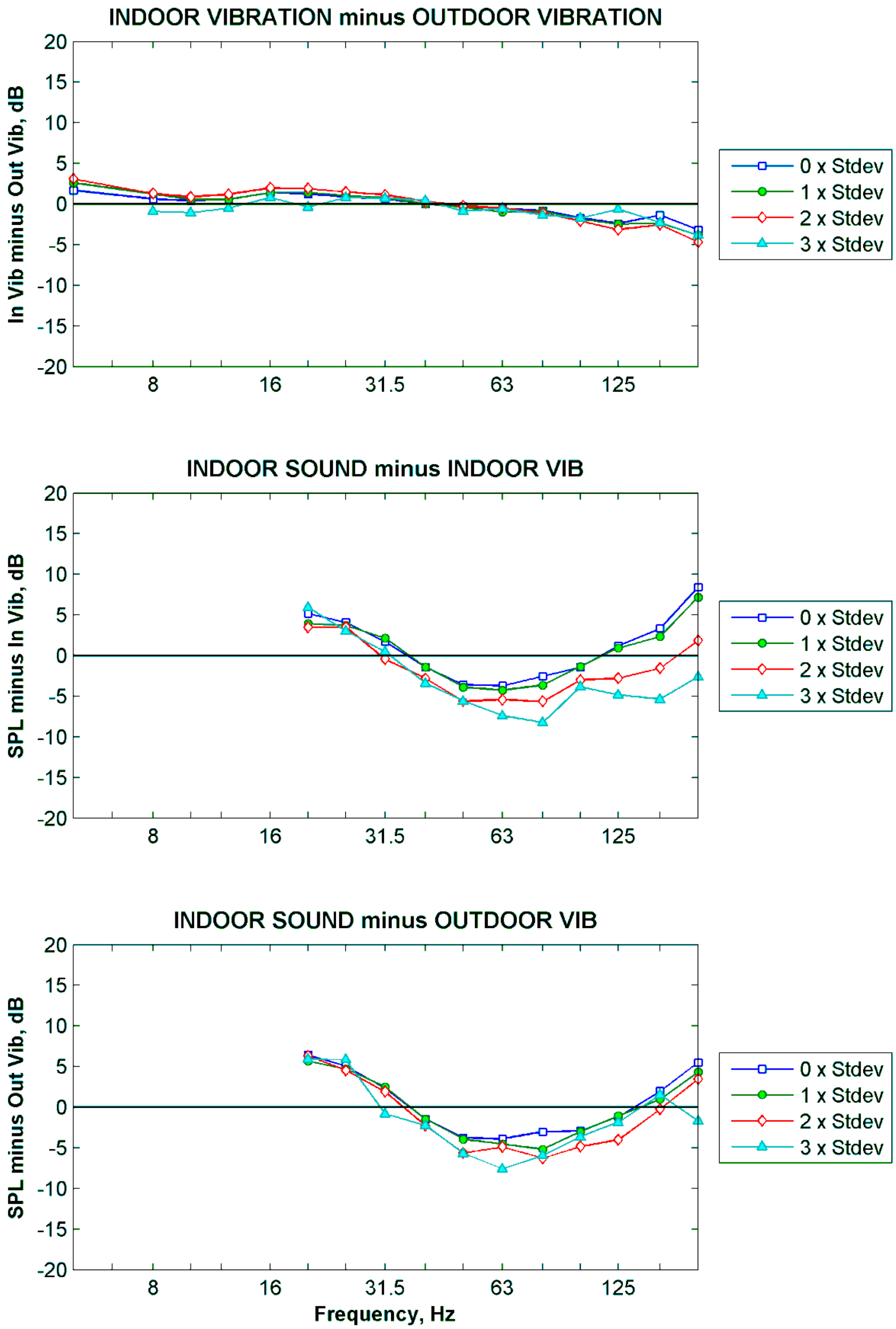

Figure 42: Comparison of Average Outdoor-to-Indoor Differences, using Different Data Thresholds

"N x Stdev" indicates that only levels that exceeded the background level by at least N times the standard deviation were included in the average.

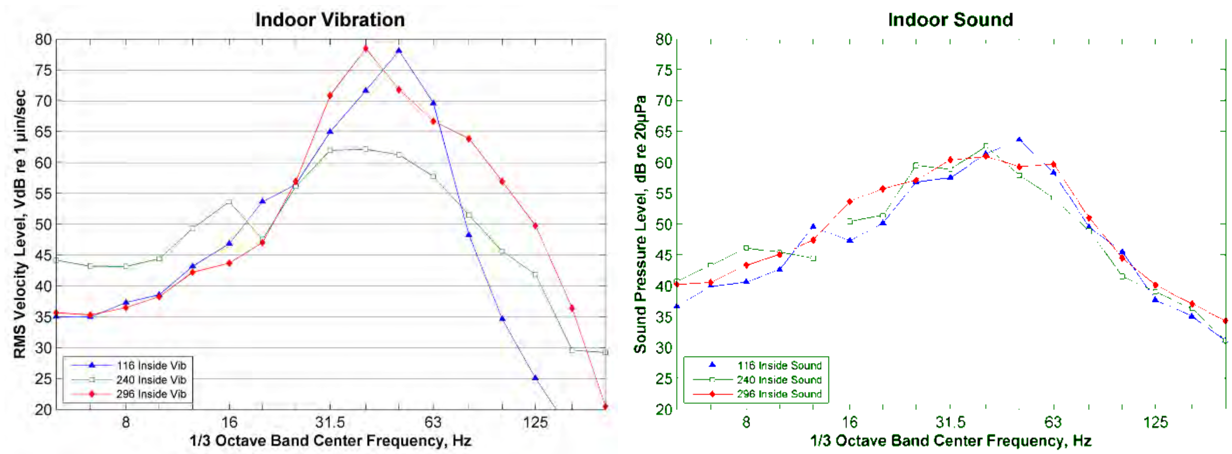

Figure 43: Comparison of Indoor Vibration and Sound in Three New York Residences
The three brownstone residences were adjacent to each other and appeared to be of similar construction and vintage. All three measurements were made in the living room on the first floor. There was a full basement below.

5.6 Interpolation Procedure

The purpose of the field measurement program was to provide estimates of the indoor levels of ground-borne vibration/noise at the residences of all 1306 telephone survey respondents. Because it was unrealistic to measure inside 1306 residences, an interpolation scheme was used to predict the vibration and noise based on measurements at a number of grid points distributed over the test area. The process was two-fold, first to estimate the exterior vibration levels at the receiver using the grid measurements, and second to adjust the exterior levels to predict the sound and vibration inside the receiver location.

The exterior vibration levels were calculated using linear interpolation based on the closest neighboring grid points (some exterior residence locations were also used as grid points). Separate interpolations were done along the length of the alignment and perpendicular to the alignment. Figure 44 shows a sample interpolation calculation. The following steps formed the basis of the interpolation process:

1. The alignment was first represented as a series of straight line segments approximately 30 cm long. The latitude and longitude of each segment were calculated using aerial mapping software. For sub-surface systems, the agencies provided the necessary details to locate the centerline of the alignment.

2. Using the position of the residence, the closest point of approach (CPA) to the alignment was calculated, along with the coordinates of the CPA on the alignment. In Figure 44 for example, the residence was 76.7 m to the north of the alignment. The closest façade facing the alignment was used to identify the residence position. Residence locations were determined using aerial mapping software.

3. The closest grid points along the alignment were then determined based on the CPA point. In Figure 44, the closest grid points were G3 to the east and 70018 to the west. The position of the CPA with respect to the grid points was then calculated. In this case the CPA was closer to the western grid point and was 10.6% of the distance from 70018 to G3. (For a 50% ratio, the estimated vibration would be an average of the two nearest grid points.)

4. The vibration levels at the two neighboring grid points were then adjusted to the same setback distance of the residence using a linear interpolation between the perpendicular grid points. In this case, the residence was 76.7 m from the alignment, which placed it between perpendicular grid points G16 (47.7 m) and G20 (84 m). The relative position ratio was then calculated based on the grid points. In this example the ratio was 79.9%, which meant the residence was closer to G20. The vibration levels at the neighboring grid points were then adjusted for distance based on this ratio. Once, the grid point levels were adjusted, the residence level was calculated based on the "along the alignment" interpolation ratio, determined from the previous step.

As shown in Figure 44, G3 (4 m) was the closest perpendicular grid point to the alignment. To prevent unexpected interpolation results in the event that a residence was closer to the alignment than G3, an artificial grid point, D=0, was created at the center of the alignment. The D=0 point was given the same attenuation parameters as G3, preventing any singularities in the interpolation routine. (In essence, any residences that were closer to the alignment than G3 were given the same attenuation parameters as G3.) Similar artificial grid points were used at each end of the alignment, and at a suitably large perpendicular distance from the alignment. In each case, the artificial grid point was assigned the parameters of the closest real grid point.

The interpolation procedure was used to estimate the exterior vibration level at each residence on a 1/3 octave band basis.

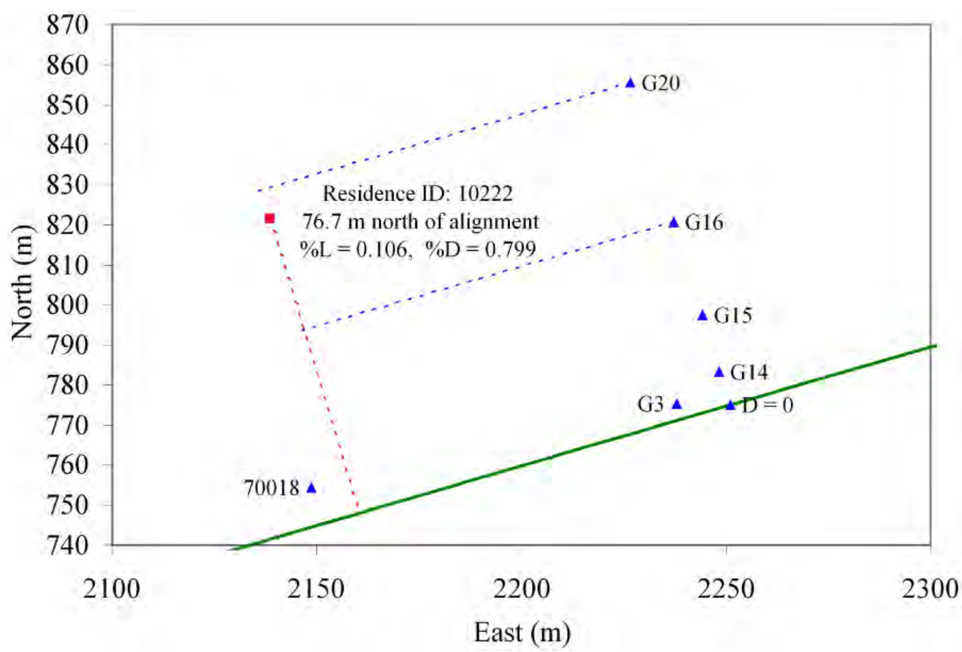

Figure 44: Sample Residence Interpolation Calculation

5.7 Summary of Measurement Observations

The following points summarize the key observations regarding the D-12 field measurement data.

- The 1/3 octave band vibration spectra at most sites were greatest between 20 Hz and 80 Hz. Because most weighting curves used in national standards are effectively flat over this frequency range, the resulting overall vibration levels differ only by a constant. Consequently, the D-12 data does not have the necessary frequency range to permit a full comparison of the effectiveness of the different weighting curves at predicting annoyance.
- A-weighted velocity was less well-correlated to overall velocity than many of the others considered. Consequently, this metric had the potential to explain more (or less) of the community response variance.
- The average difference between outdoor and indoor vibration in the D-12 data was essentially zero. The standard deviation of the difference was approximately 5 dB, which reflects a wide building-to-building variation in the response to vibration.
- The average difference between the measured sound level and the indoor vibration level was about −5 dB for the audible frequency bands where the vibration was most severe.
- The correlation between indoor sound and indoor vibration was only slightly better than the correlation between indoor sound and outdoor vibration. This suggests that outdoor vibration was almost as good a predictor of indoor sound as was indoor vibration.
- Of the 34 residences where indoor measurements were performed, 11 had A-weighted ground-borne noise levels that exceeded 40 dB. Nine of the residences were in Toronto, one was in Boston near the Blue Line, and one was near a crossover on the Sacramento Regional Transit Gold Line.
- The experience from this project is that measuring noise and vibration inside of a residence is much more difficult and time consuming than measuring the vibration levels immediately outside the residence. The extra effort and time is primarily related to obtaining the necessary approvals from property owners, scheduling appointments with built in time buffers, and set up and removal of the equipment. Also, the field crew has to be larger to accommodate indoor and outdoor measurements.
- Assuming equal average vibration levels, there would be approximately a 10 decibel spread in measures of 24-hour exposure at the different transit systems. Because of longer and more frequent trains, vibration exposure in Toronto, Boston and New York would be 8 to 10 decibels greater than in Dallas and Sacramento. This effect is illustrated in Figure 45. The figure compares the calculated 24-hour exposure at each D-12 residence to the average train vibration at each residence. For an average train vibration level of 65 VdB, for example, the 24-hour exposure was approximately 43 VdB in Dallas and Sacramento, 50 VdB in Boston, and 52 to 54 VdB in New York and Toronto.

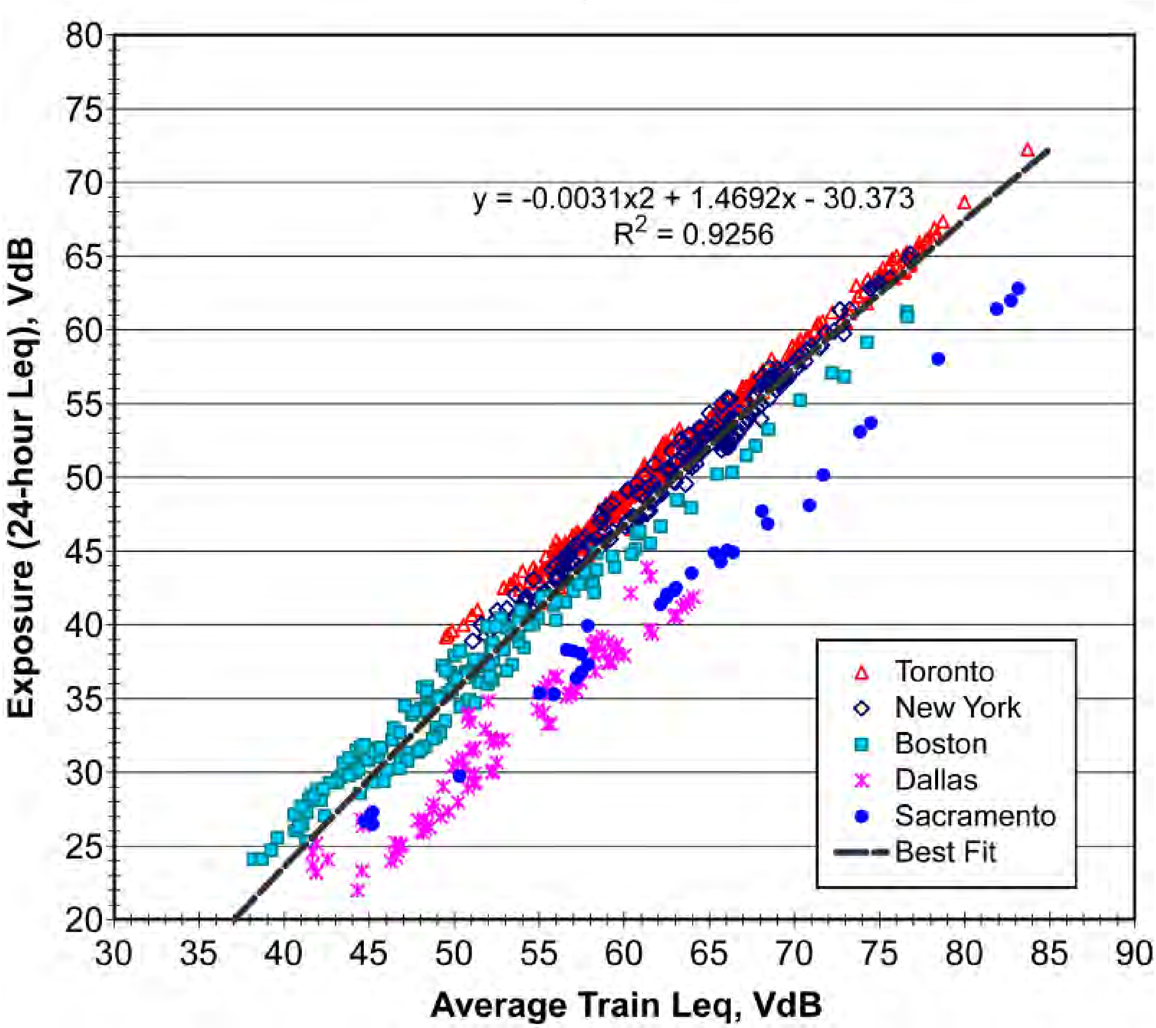

Figure 45: Calculated Vibration Exposure at D-12 Residences based on Vibration Level

Train Leq is the RMS average vibration over the 3 decibel down points.
"Exposure" is the equivalent vibration level from train traffic distributed over 24-hours (analogous to Leq(24) used to evaluate community noise).

6. ANALYSES OF QUESTIONNAIRE RESPONSES

A primary goal of this study was to develop a dosage-response curve, or curves, to relate the annoyance of people living near rail transit lines to ground-borne vibration and noise that is generated by rail operations.

In the 30 years since the pioneering work of Schultz (1), the percentage of all respondents at an interviewing site who describe themselves as highly annoyed has become the customary measure of community response to transportation-related noise. Figure 46 shows the dosage-response curve derived by Schultz on the left and a comparison of the Schultz curve with additional data that was assembled by Fidell and Silvati (67). One of the notable features of these curves is the amount of spread in the responses. These curves provide an indication of the degree to which any measure of a physical quantity, in this case noise, can predict when an individual will find the quantity highly annoying. This is one of the reasons that large numbers of respondents are required to draw statistically significant conclusions from social surveys.

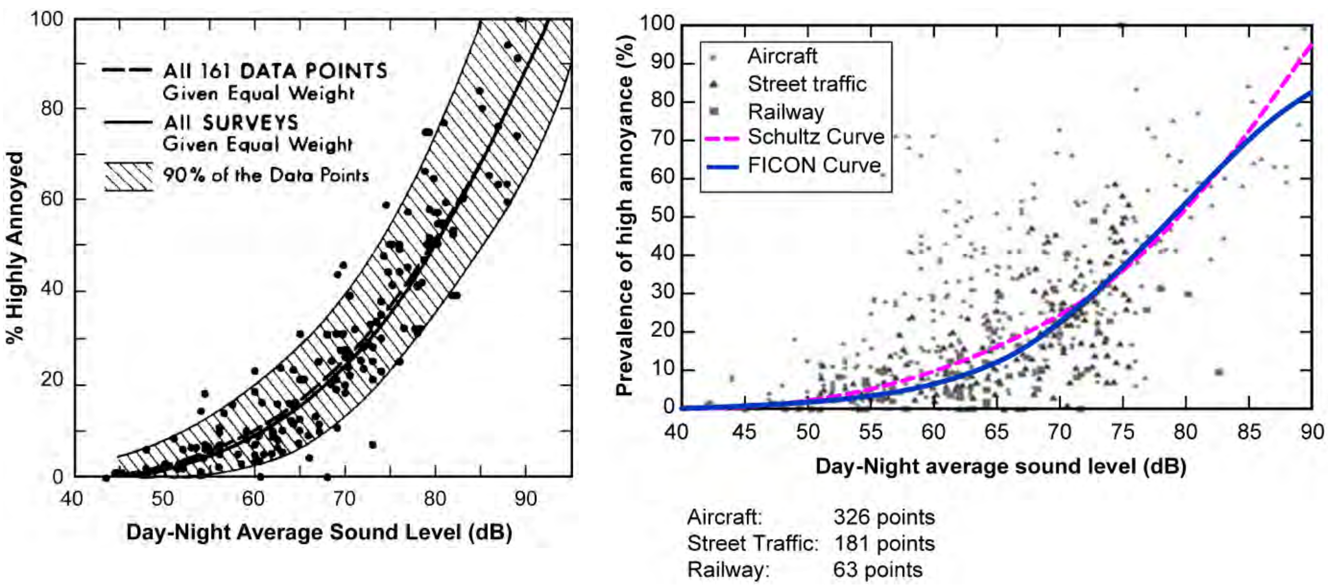

Figure 46: Dosage-Response Relationships for Noise

Figure on left is from the original Schultz synthesis of social surveys on noise annoyance (1) and the figure on the right is from a recent analysis by Fidell and Silvati (67) of alternative approaches to characterizing annoyance due to aircraft noise.

6.1 Narrative Account of Findings of Social Survey

Interviews were completed with 1306 adult respondents at five sites: 1167 homes were near subway tracks, and 139 homes were near surface tracks. Among the respondents residing in homes near subway tracks, 582 were in Toronto, 304 in Boston, and 281 in New York. For respondents living near surface transit system tracks, 103 were interviewed in Dallas, and 36 in Sacramento.

The interview completion rate is the ratio of completed interviews to the total number of identified telephone numbers, minus those numbers that were unreached after 10 callbacks, or ineligible because of language difficulties, or because the telephone number was a fax machine or business. The interview completion rate varied from a high of 91% (in Dallas) to a low of 45% (in New York). The weighted average completion rate in all cities other than New York was 70%. The high refusal rate in New York reduced the five-city, weighted average completion rate to 62%. About 57% of all respondents were women.

Responses to questionnaire items were consolidated across sites in the following subsections. (Percentages may not sum to 100% due to exclusion of “don’t know,” “not ascertained,” and intentionally skipped or otherwise missing responses, and because of rounding.)

Duration of Residence (Item 1)

As shown in Table 17, nearly half of the respondents had lived at their current addresses for ten or more years. Only 44 (3.5%) had lived at their present addresses for less than one year.

Table 17: Duration Respondents had Lived at Present Address (Item 1)

Duration of Residence	Percent of Respondents	Cumulative Percent of Respondents
Less than one year	3.5	3.5
Between one and two years	7.1	10.6
Between two and five years	22.4	33.0
Between five and ten years	19.4	52.4
Ten or more years	47.6	100.0

Least favored aspect of neighborhood living conditions (Item 3)

Although noisy neighborhood conditions (including traffic and aircraft noise, emergency vehicle sirens, loud nighttime street noise, etc.) were fairly commonly cited in response to this open-ended question, explicit mentions of rail noise were rare. Only 2.1% of all respondents specifically mentioned rail-related or “subway” noise as the least favored aspect of neighborhood living conditions. A few allusions to crossing bells at sites in Dallas and Sacramento were categorized as rail-related as well.

Annoyance due to street traffic noise (Items 4/4a)

A little more than a quarter (27%) of all respondents reported annoyance to any degree due to street traffic while at home during the year prior to interviewing. Only 8.3% had been very or extremely annoyed by street traffic noise in the year prior to the interview.

Notice/annoyance of passing trains (Items 5/5a)

Respondents living near surface tracks were asked if they had been bothered or annoyed by sounds made by passing trains, while those living above subway tracks were asked whether they could tell in any way when trains passed under their homes. Of the 139 respondents living near surface tracks in Dallas and Sacramento, only 16% reported bother or annoyance to any degree due to passing trains. Among all respondents in Dallas and Sacramento, only 6.5% described themselves as being highly (“very” or “extremely”) annoyed by sounds made by passing trains

Among respondents living near subway systems in Toronto, New York and Boston, 38.2% reported that they noticed (could “tell in any way”) when trains passed under their homes.

Notice/annoyance of rumbling, rattling, shaking and vibration

Questionnaire items 6, 7 and 8 inquired whether respondents noticed low rumbling sounds, rattling sounds, and shaking and vibrations in their homes when trains passed by. About a third (32.2%) of the respondents reported noticing at least one of these effects. As noted below, low rumbling sounds were more commonly noticed than rattling and vibrations.

Notice/annoyance of low rumbling sounds (Items 6/6a)

Of the 1306 respondents at all sites, 29.8% (26.3% at the surface sites and 30.3% at the subway sites) reported noticing low rumbling sounds created by passing trains. Overall, 3.9% of all respondents (5.7% at the surface sites and 3.6% at the subsurface sites) reported that they were highly annoyed by such low rumbling sounds.

Rattling (Items 7/a,b)

Rattling sounds in their homes when trains passed by were reported by 14.2% of all respondents. Those who reported hearing rattling sounds were asked how often they heard rattling: 17.4% reported hearing rattle about once a week, 19.3% reported hearing rattle about once a day, 34.2% reported hearing rattle several times a day, and 29.2% reported hearing rattle many times a day.

Shaking (Items 8/a,b,c,d at underground sites; Items 9/a/b/c at surface sites)

In-home shaking or vibration when trains passed by was felt by 11.5% of all respondents. Those who reported feeling shaking or vibration were asked how often they experienced shaking or vibration. About one sixth (16.7%) reported feeling shaking or vibration about once a week; 21.3% reported feeling shaking or vibration about once a day; 37.3% reported feeling shaking or vibration several times a day, and 24.7% reported feeling shaking or vibration many times a day.

Among those who noticed vibrations or rattling sounds from passing trains, only 2.4% had tried to reduce them, and only about a third of those thought the vibrations or rattling had been lessened by their efforts.

Awakening due to train passbys (Items 9/9a at subway sites)

Awakenings in the year prior to interviewing due to rumble, rattle, or vibrations from train passbys were reported by 6.6% of all those interviewed. About a quarter (24%) of those who reported awakening were awakened less often than once a week. Another 24% reported awakening at least one night per week; 9% reported awakening at least two nights per week; 12% reported awakening on at least three nights per week; 8% reported awakening 4 nights per week; 6% reported awakening at least five nights per week, and 17% reported awakening 6 or 7 nights a week Among those who were awakened, 44% were highly annoyed by the sleep disturbance.

Complaints (Item 10)

Only 3.2% of the 1306 respondents reported that they had complained to the local agency about any form of noise, rumble, rattle, shaking or vibration in their homes due to train passbys. Among those who had complained, 59.5% were highly annoyed, and 42.9% had been awakened by train passbys.

Floor of residence (Item 11 at subway sites, 12/13 in Dallas/Sacramento)

A third of the respondents lived either in a single story home or in a below-grade apartment. Another 19% of the respondents lived in apartments on the second floor, 11% on the third floor, 8% on the fourth floor, and 10% on the fifth floor or higher. (The remainder lived in quarters that spanned more than one floor, or did not provide an answer to this questionnaire item). Of the 111 respondents who were moderately or more greatly annoyed by any of the effects of train passbys, 68 (61%) lived at or below-grade, while 43 (39%) lived on the second floor or higher.

6.2 Overview of Reports of Annoyance

Table 18 summarizes the number of respondents from each transit system that reported various degrees of annoyance. The columns to the left summarize the total number of respondents reporting annoyance from the entire population of respondents, the columns to the right include only the respondents whose residences were less than 37 m (120 ft) from the transit alignment. The data from Table 18 are presented in graphical form in Figure 47. The four categories of annoyance were:

- None
- Any or Higher: All respondents who reported any level of annoyance.
- Moderate or Higher: The respondents who reported a moderate or higher level of annoyance.
- Highly Annoyed: The respondents who reported that they were "very" or "extremely" annoyed.

The combined annoyance data in Table 18 shows that people who lived closest to the alignment were more likely to be annoyed. Of the 1306 total respondents, 345 lived within 37 m of the transit alignment. Of these 345 people, 38 (11%) reported being highly annoyed (for any reason) by passing trains. For the 961 residents who lived farther away than 37 m, only 29 (3%) reported being highly annoyed. Of the people living within 37 m, Toronto had the highest number of highly annoyed (25); the next highest number was four in Sacramento and New York. Of the 67 people in the study who reported being highly annoyed, 43 (64%) lived in Toronto.

At the other end of the annoyance spectrum; of 1306 total respondents, 992 (76%) reported no level of annoyance whatsoever. Of the 345 respondents within 37 m, 172 (50%) reported no level of annoyance. So, even at distances relatively close to the tracks, where 11% of the people reported high annoyance, 50% of the people were not bothered at all by the transit system.

Table 19 summarizes the number of respondents who reported that they had been awakened by passing trains in the previous year. Of the 345 people who lived within 37 m, 52 reported being awakened by trains. But, almost as many (34) reported being awakened by trains even though they lived farther away than 37 m; it is possible that the trains were blamed even though something else caused the resident to be awakened.

Referring to the bar graph in Figure 47, the percentage of respondents within 37 m of the alignment who noticed ground-borne noise or vibration was highest in New York (64%), followed by Sacramento (56%), and Toronto (52%). Some caution should be used when interpreting the data from Sacramento because only 16 respondents lived within 37 m of the transit alignment. The percentage of respondents within 37 m who were highly annoyed was greatest in Sacramento (25%, 4 out of 16) followed by Toronto (15%, 25 out of 163).

Table 18: Number of Survey Respondents Reporting Annoyance

System	All Respondents					Respondents within 37 m of Alignment				
	Total	None	Any or Higher	Moderate or Higher	Highly Annoyed	Total	None	Any or Higher	Moderate or Higher	Highly Annoyed
Annoyance from Rattle										
Toronto	582	506	76	53	33	163	112	51	36	21
New York	281	258	23	11	3	99	84	15	8	1
Boston	304	291	13	8	5	38	31	7	3	1
Dallas	103	97	6	4	2	29	26	3	2	1
Sacramento	36	32	4	3	3	16	14	2	2	2
Total	1306	1184	122	79	46	345	267	78	51	26
Annoyance from Perceptible Vibration										
Toronto	582	498	84	56	28	163	111	52	36	19
New York	281	256	25	13	3	99	80	19	10	2
Boston	304	294	10	7	5	38	32	6	3	1
Dallas	103	99	4	3	2	29	26	3	2	1
Sacramento	36	28	8	5	4	16	10	6	4	3
Total	1306	1175	131	84	42	345	259	86	55	26
Annoyance from Rumble										
Toronto	582	445	137	63	30	163	92	71	34	18
New York	281	185	96	16	6	99	38	61	9	4
Boston	304	281	23	13	7	38	30	8	5	3
Dallas	103	83	20	5	3	29	21	8	2	2
Sacramento	36	23	13	5	5	16	9	7	4	4
Total	1306	1017	289	102	51	345	190	155	54	31
Composite (maximum of annoyance rating for rattle, perceptible vibration and rumble)										
Toronto	582	431	151	77	43	163	84	79	43	25
New York	281	183	98	21	7	99	36	63	14	4
Boston	304	276	28	16	9	38	25	13	6	3
Dallas	103	81	22	5	3	29	20	9	2	2
Sacramento	36	21	15	6	5	16	7	9	5	4
Total	1306	992	314	125	67	345	172	173	70	38

Table 19: Number of Respondents Reporting being Awakened in Previous Year

System	All Respondents			Respondents within 37 m of Alignment		
	Total	No	Yes	Total	No	Yes
Toronto	582	532	50	163	128	35
New York	281	267	14	99	89	10
Boston	304	291	13	38	35	3
Dallas	103	99	4	29	28	1
Sacramento	36	31	5	16	13	3
Total	1306	1220	86	345	293	52

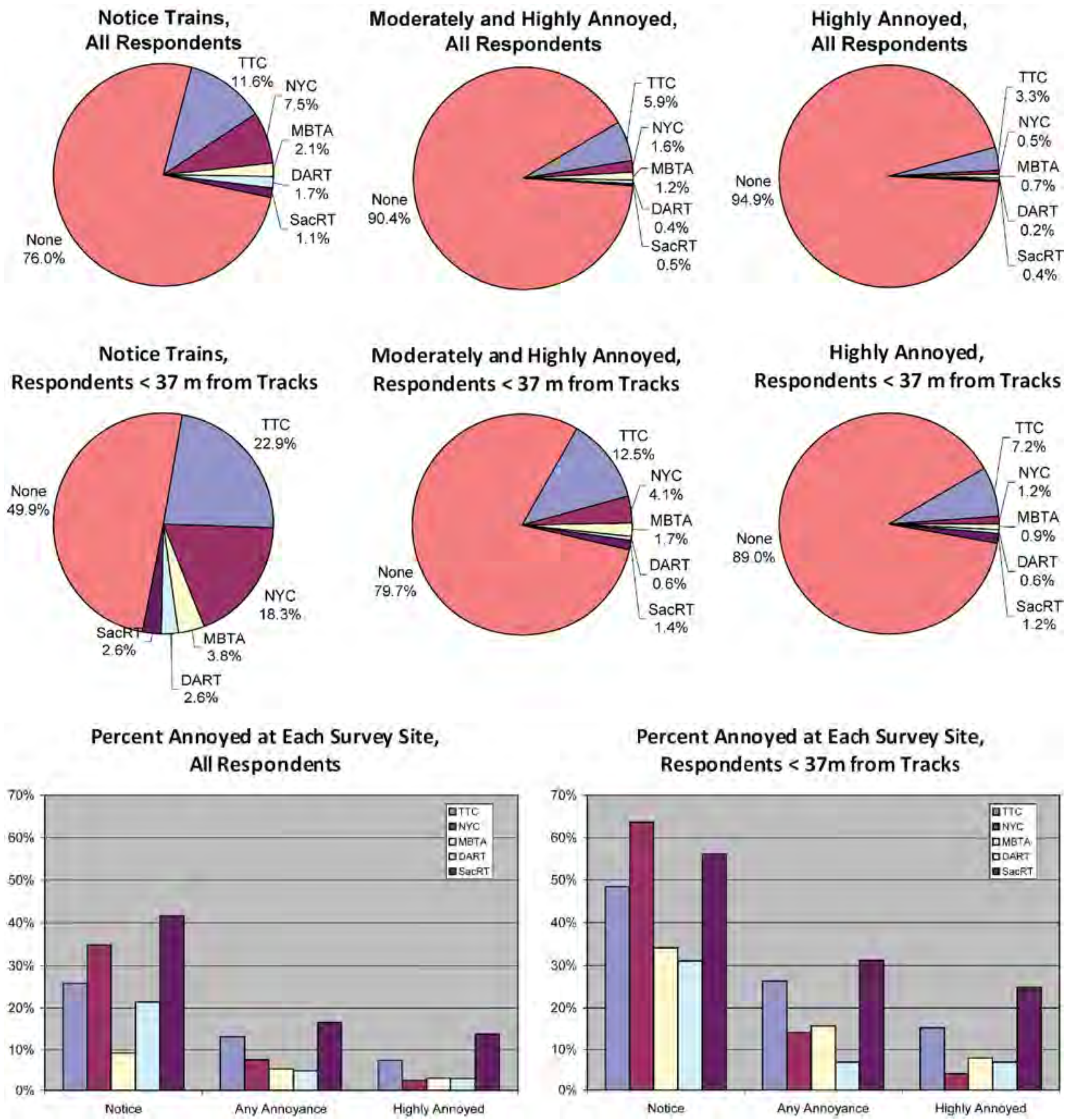

Figure 47: Percentages of Respondents Reporting Annoyance

Figure 48 through Figure 55 present a graphical summary of the approximate respondent locations at each transit system, along with those residents who reported being highly annoyed. Respondents were classified as "highly annoyed" if they described themselves as "very," or "extremely" annoyed by train-related vibration, low-frequency rumble, or rattle.

Figure 48 shows the New York respondent locations relative to the alignment. As would be expected, respondents reporting high annoyance generally lived closest to the subway.

Figure 49 and Figure 50 show the locations of highly annoyed residents near the Sacramento Gold and Blue lines, respectively. It is interesting to note that next to the one Gold Line resident who was highly annoyed, was a neighbor who was not annoyed.

Figure 51 and Figure 52 show the highly annoyed residents of Dallas who lived near the Blue and Red line, respectively. The highly annoyed residents generally lived closest to the alignment.

Figure 53 shows the residents in Toronto who were highly annoyed. Generally, the highly annoyed respondents lived close to the alignment. A few people reported high annoyance even though they lived on parallel streets a considerable distance (80 m) from the subway. It is possible that these people mis-attributed the intrusive noise and vibration to the subway, when it was caused by some other source, like street traffic for example. As with the other sites, for the highly annoyed people who lived near the subway, there were equal or larger numbers who were not highly annoyed, but lived equally close to the alignment.

Figure 54 and Figure 55 show the location of highly annoyed respondents in the Back Bay area of Boston, and near the Blue Line, respectively. As with the other four cities, the highly annoyed respondents tended to live near the alignment.

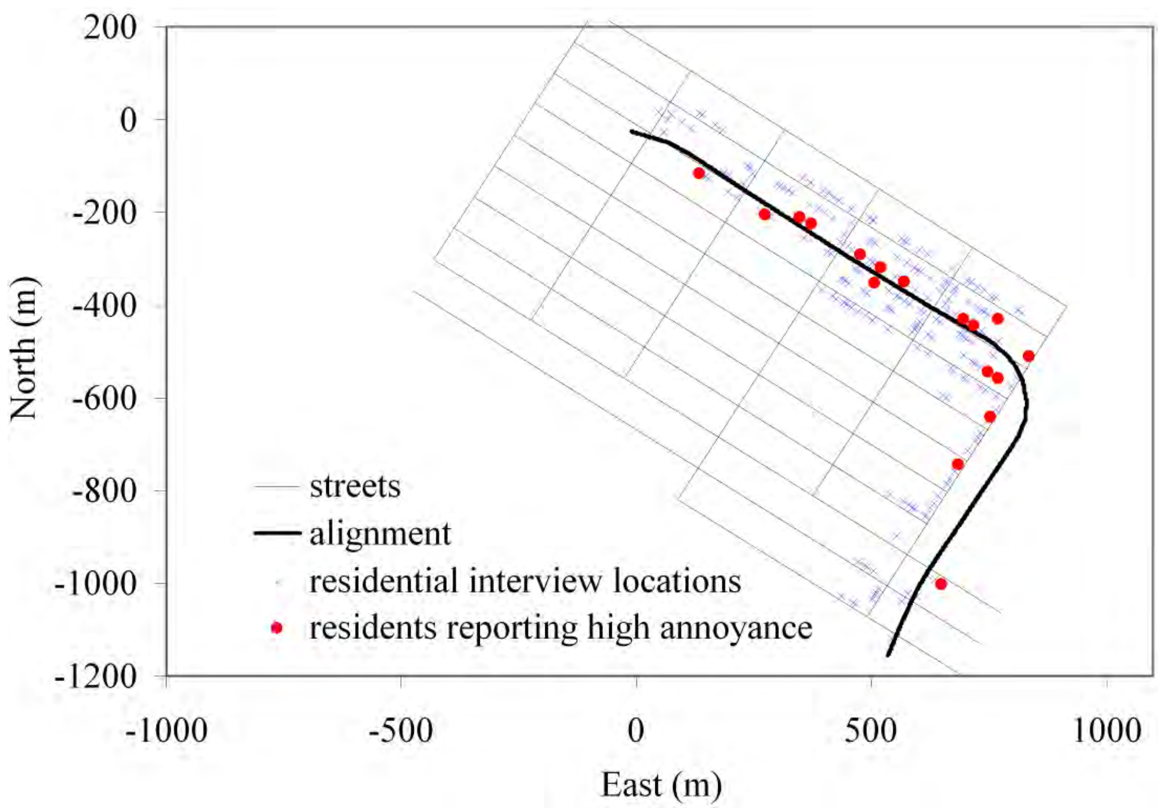

Figure 48: New York Respondents Reporting High Annoyance

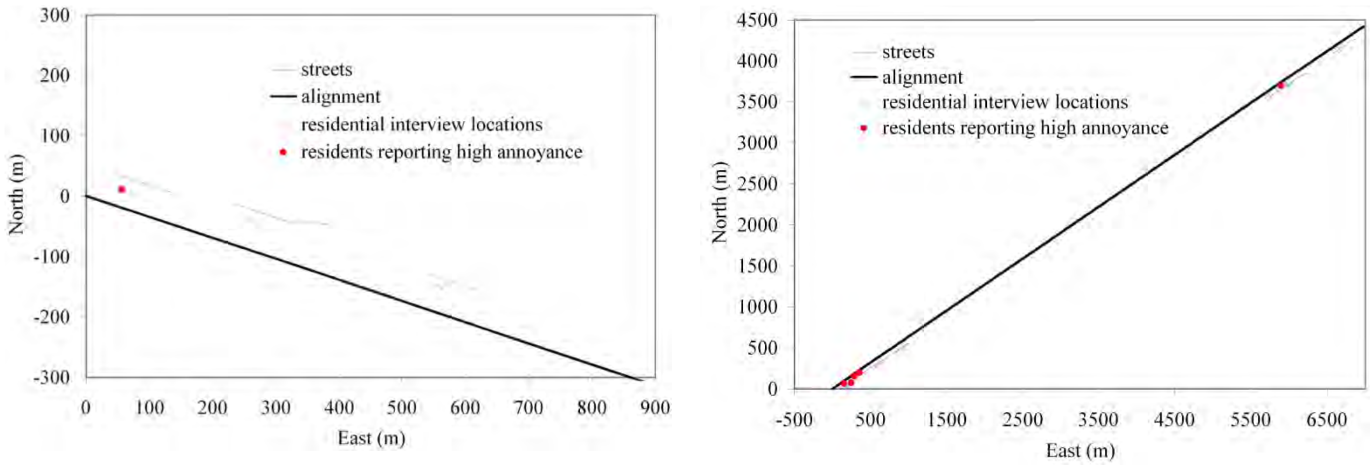

Figure 49: Sacramento Gold Line Respondents Reporting High Annoyance

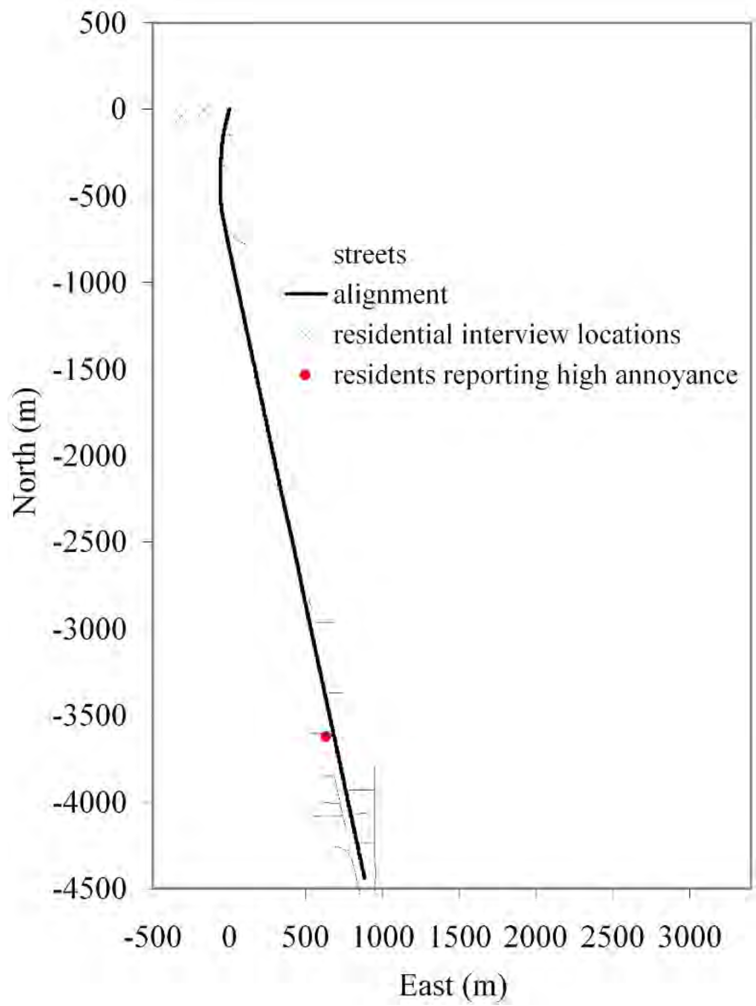

Figure 50: Sacramento Blue Line Respondents Reporting High Annoyance

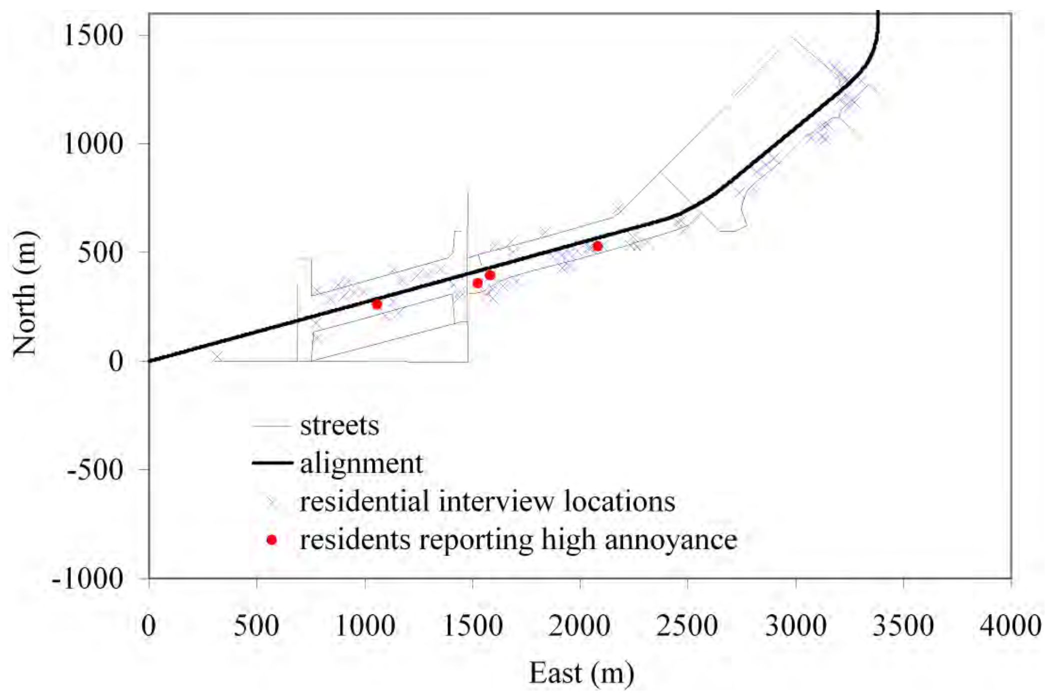

Figure 51: Dallas Blue Line Respondents Reporting High Annoyance

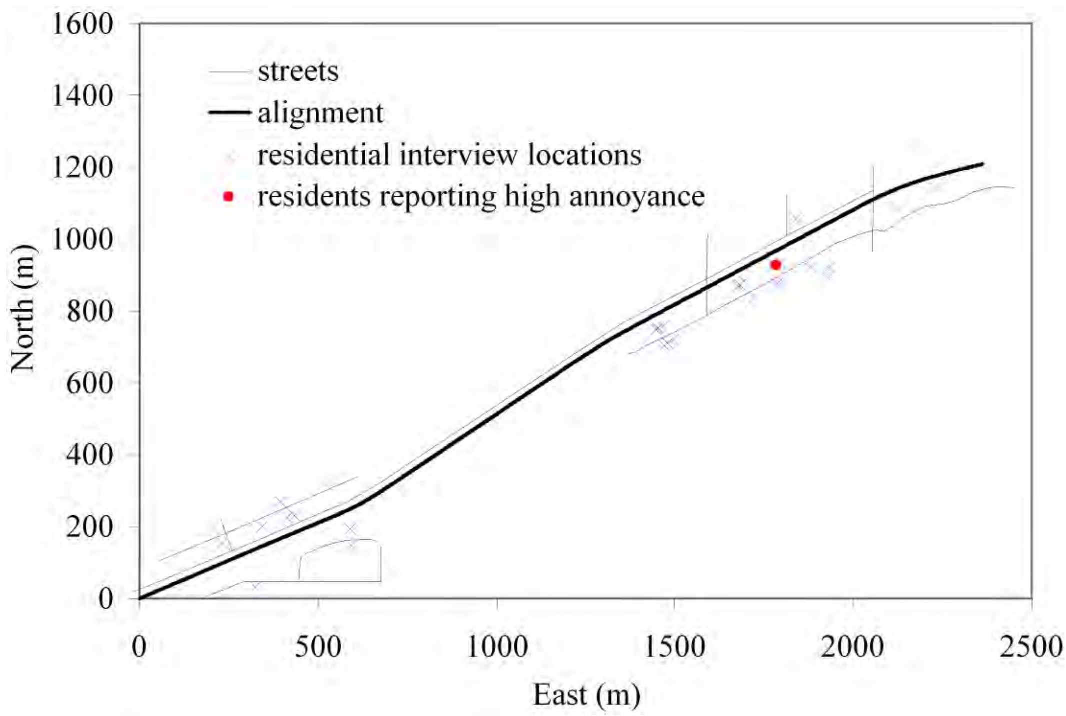

Figure 52: Dallas Red Line Respondents Reporting High Annoyance

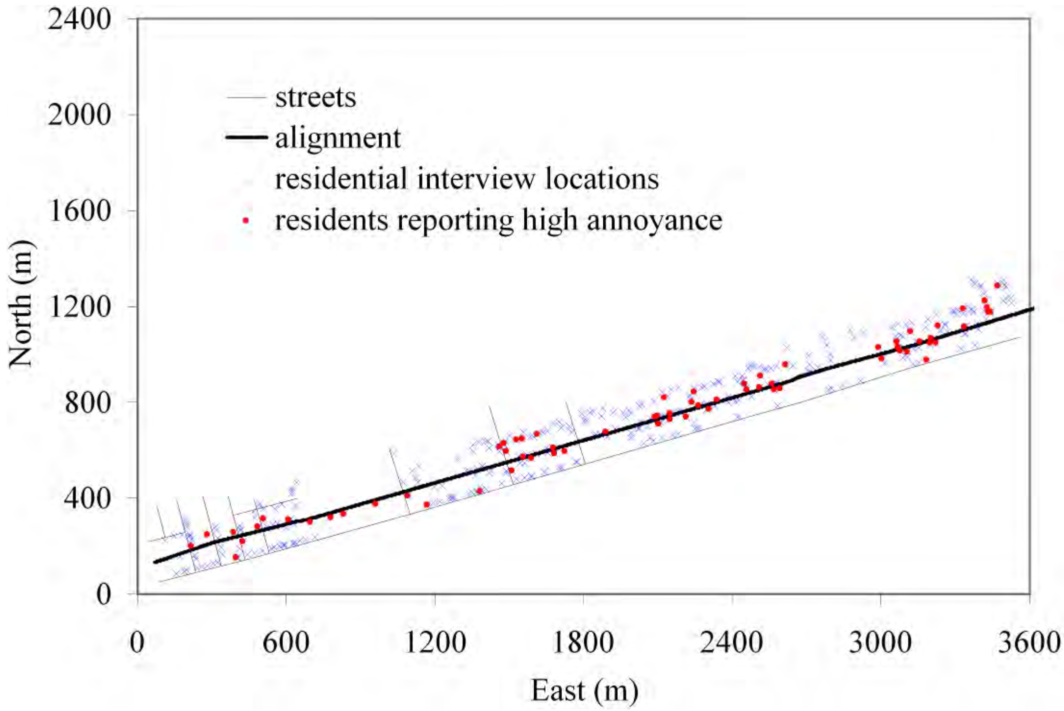

Figure 53: Toronto Respondents Reporting High Annoyance

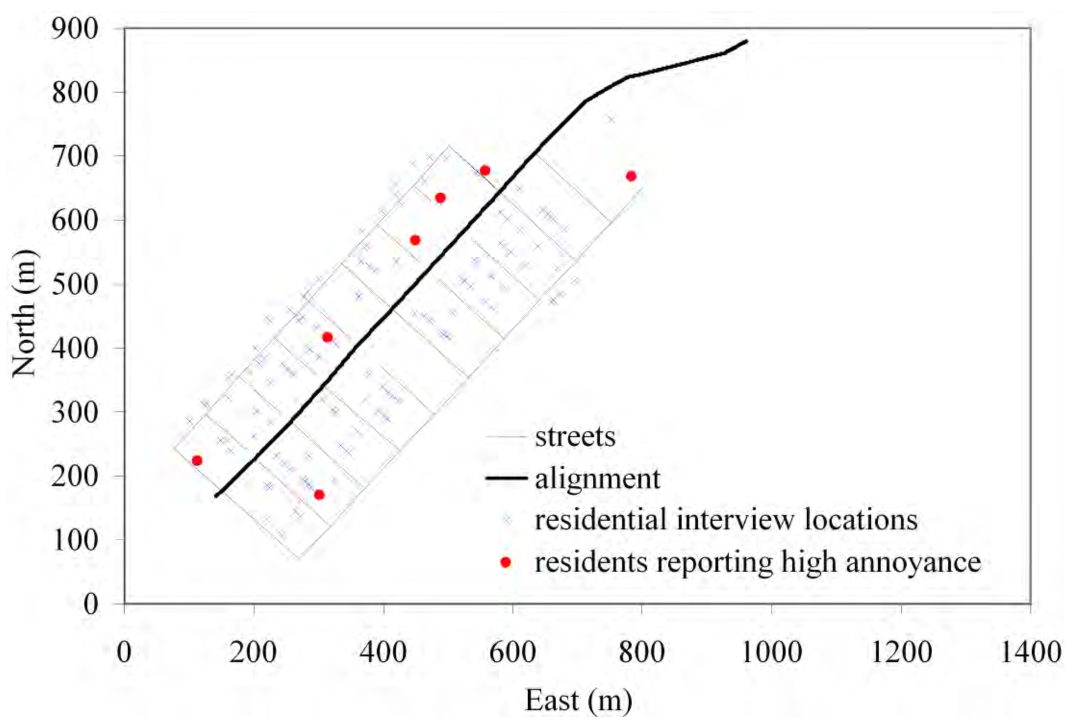

Figure 54: Boston Back Bay Respondents Reporting High Annoyance

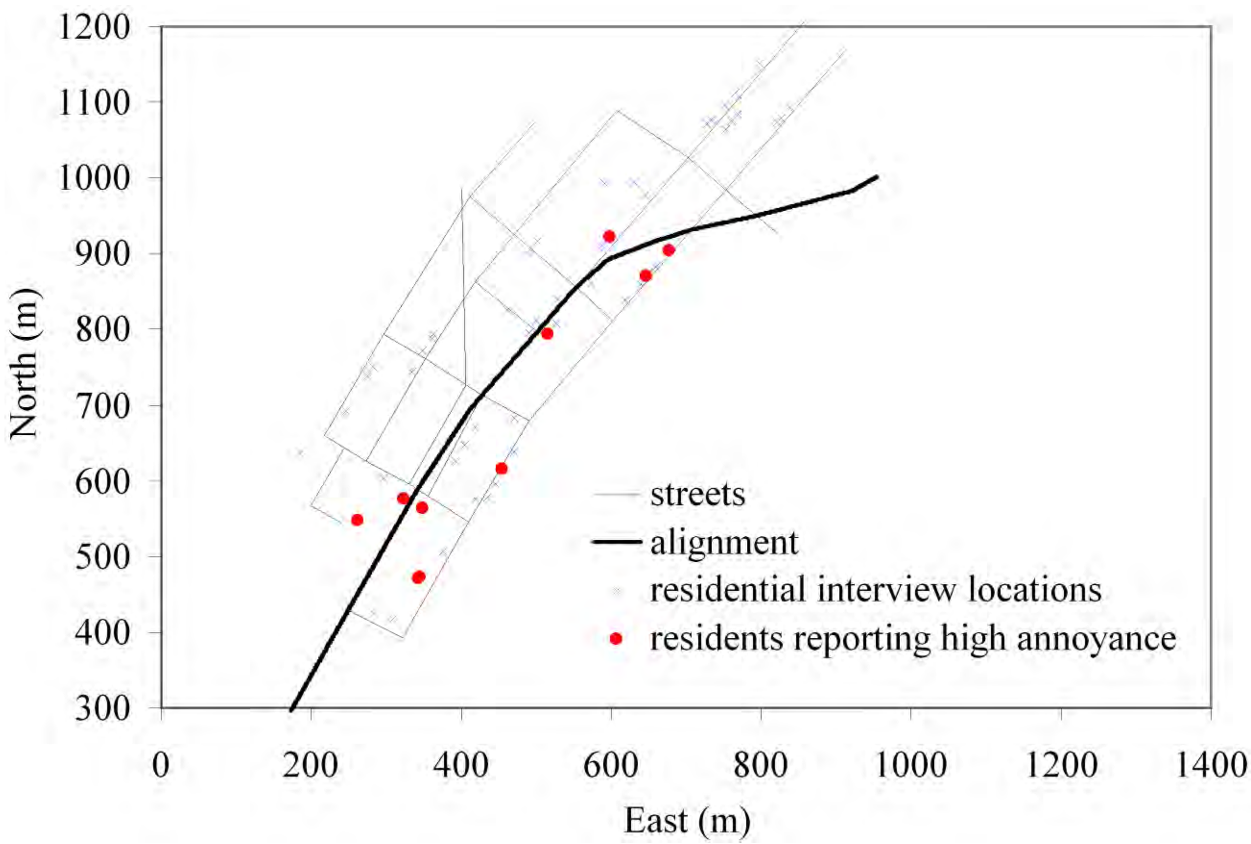

Figure 55: Boston Blue Line Respondents Reporting High Annoyance

6.3 Relationship between Vibration Levels and Questionnaire Response Items

Cumulative histograms were prepared in 3 dB-wide intervals for the questionnaire items concerning 1) notice of rail-induced rumble, rattle, or vibration, 2) annoyance due to rumble, rattle, and vibrations induced by the passage of trains, 3) awakening, and 4) complaints. The horizontal scale on the histograms is the RMS average vibration velocity level over the 3 decibel down points (Leq). The data are shown for Leq with flat weighting and with A-weighting. As discussed previously, the average difference between indoor and outdoor vibration was effectively zero, hence the un-weighted Leq is also a reasonable approximation of the indoor vibration level. The A-weighted vibration level is a good approximation of the indoor A-weighted sound level plus or minus a constant.

The relationships are plotted in cumulative form to facilitate identification of vibration and noise levels associated with respondent reports of different levels of annoyance. Note that these histograms do not represent the opinions of all respondents, but only of those who answered the questionnaire items as described. The histograms are thus useful as indications of vibration levels associated with annoyance, not for estimating affected population proportions.

Figure 56 shows the relationship between the vibration level and the number of respondents that noticed trains passing and Figure 57 shows the relationship for the number of respondents who expressed any annoyance with the vibration. Figure 58 and Figure 59 show the histograms for respondents who reported being moderate or highly annoyed, and highly annoyed, respectively.

Altogether, 24% of all respondents were at least slightly annoyed by low rumbling sounds, rattling sounds or vibrations (or by more than one of these) produced by passing trains; 9.6% were moderately or more annoyed; and only 5.1% of respondents were highly (“very” or “extremely” annoyed) annoyed.

Figure 60 shows the cumulative histogram for the respondents who indicated that they had been awakened by train operations. Fewer than 7% (86) of all respondents (1306) reported that they had been awakened in the year prior to interviewing by rumble, rattle, or vibrations due to train passbys. Among those who were awakened, 92% were also at least slightly annoyed, 64% were moderately or more annoyed, and 44% were highly annoyed.

Figure 61 shows the cumulative histogram of the respondents who had complained to the transit system about vibration or noise. Of the 1306 respondents, only 3.2% had complained about the noise and vibration produced by train passbys. Of these, 95.2% were at least slightly annoyed, 76.2% were at least moderately annoyed, 59.5% were highly annoyed, and 42.9% had been awakened by train passbys.

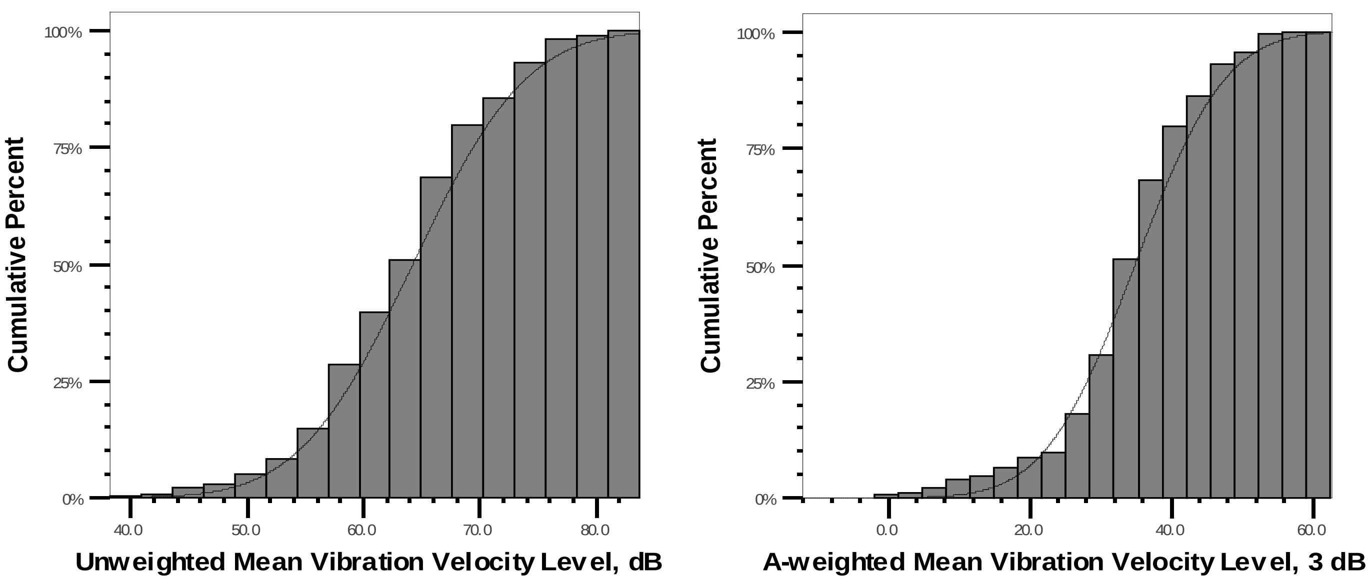

Figure 56: Vibration Levels for 421 Respondents who Noticed Train Passbys

Relationships between estimated vibration levels in the homes of respondents who noticed rumble, rattle, vibration or shaking due to train passbys (*i.e.*, by responding positively to one or more of questionnaire items 6, 7 or 8)

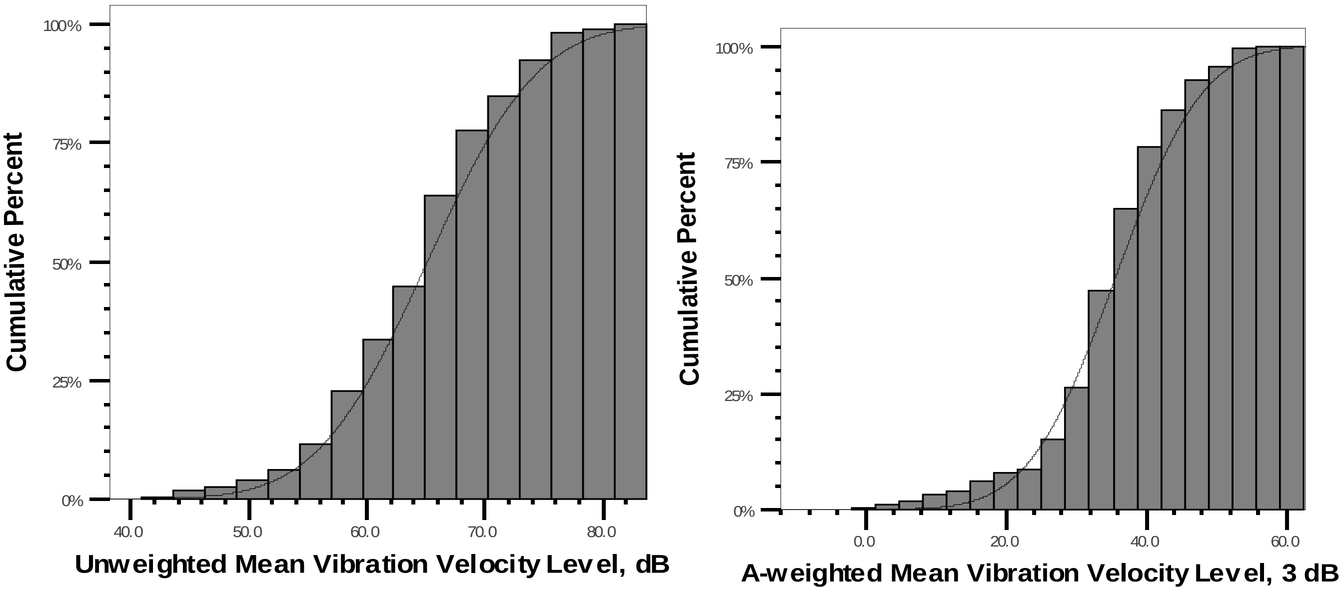

Figure 57: Vibration Levels for 314 Respondents Annoyed to Any Degree by Train Passbys

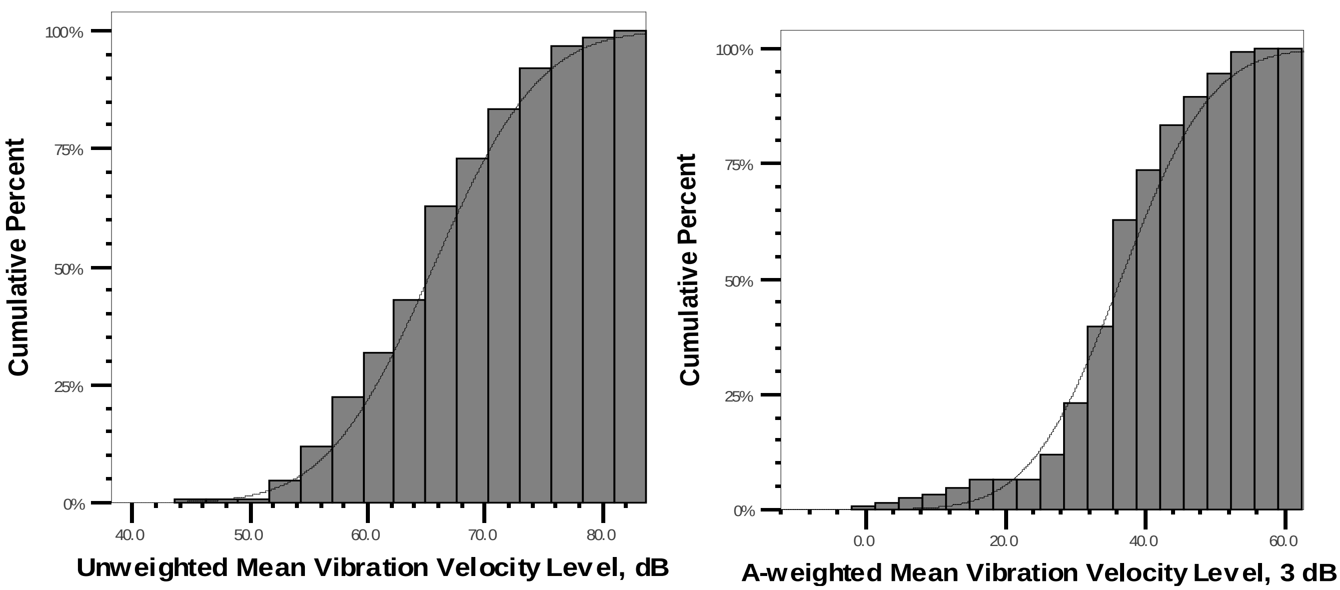

Figure 58: Vibration Levels for 125 Respondents Moderately or More Greatly Annoyed by Train Passbys

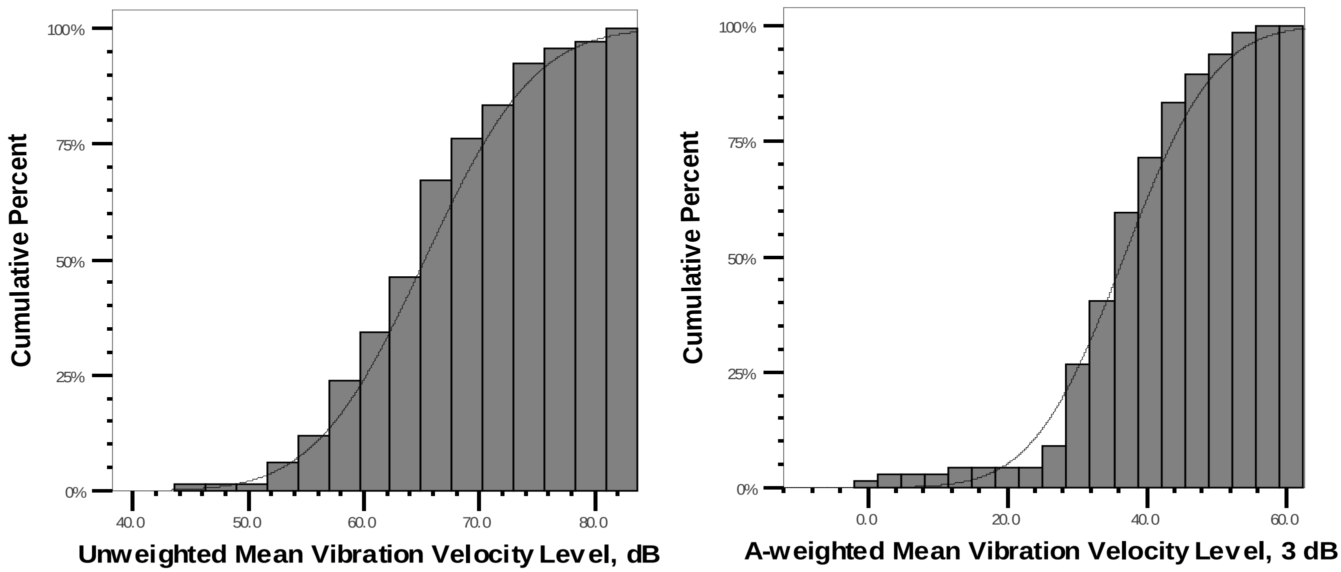

Figure 59: Vibration Levels for 67 Respondents Highly Annoyed by Train Passbys

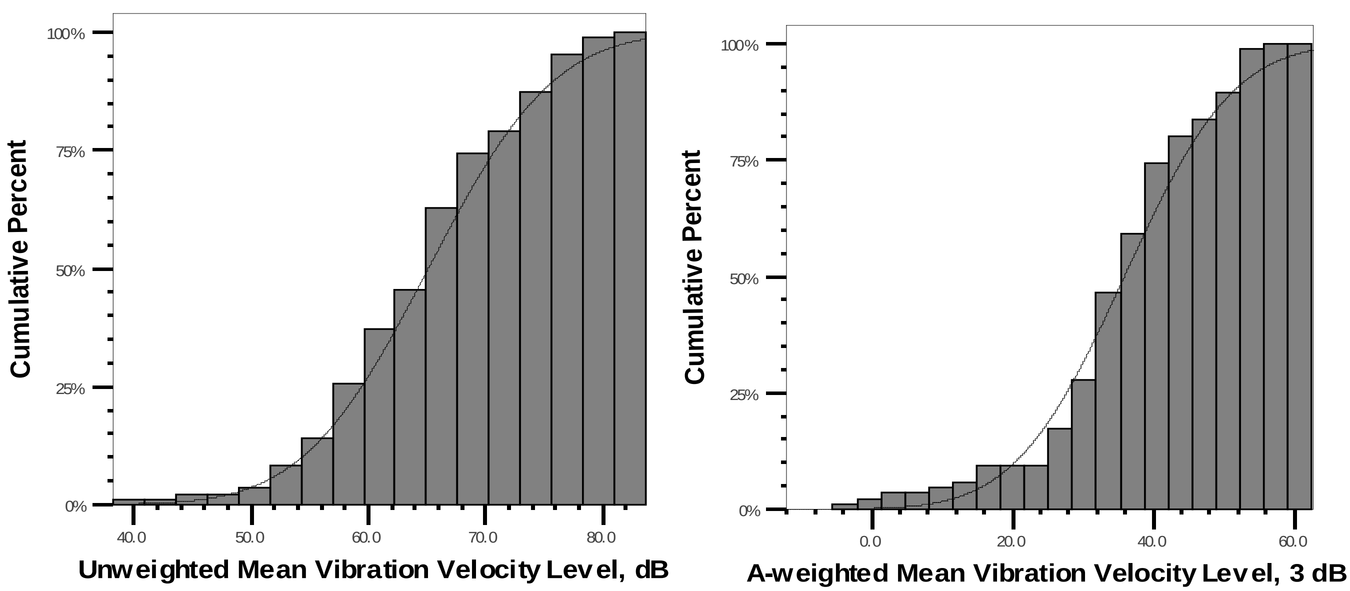

Figure 60: Vibration Levels for 86 Respondents Awakened by Train Passbys

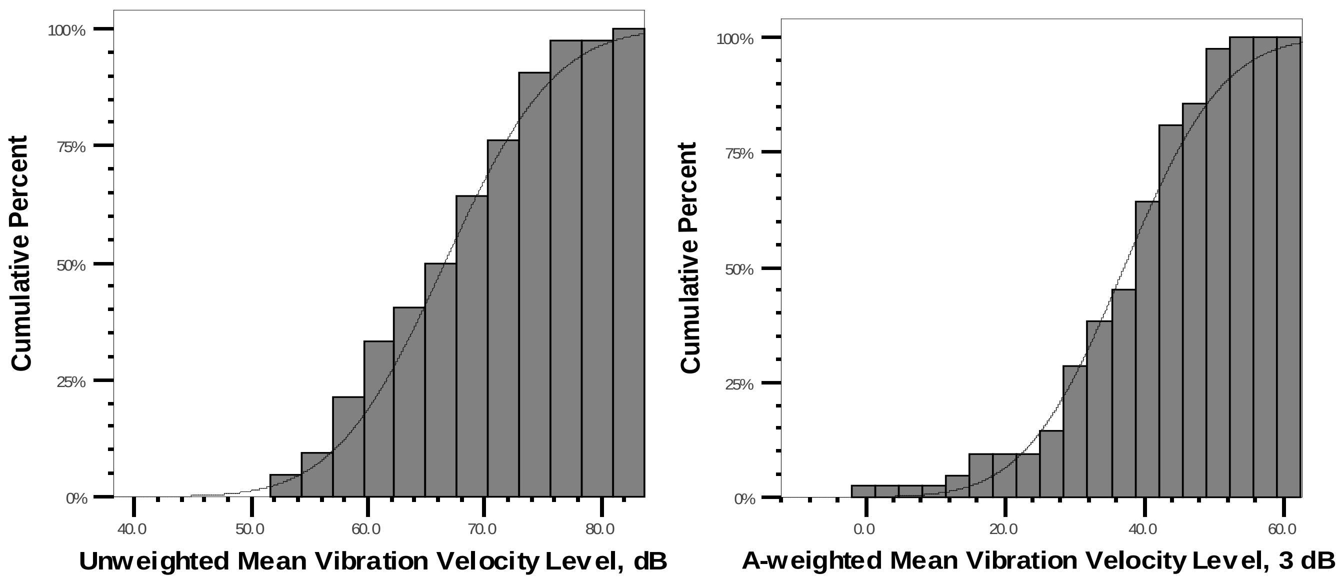

Figure 61: Vibration Levels for 42 Respondents who had Complained about Train Passbys

6.4 Estimating Vibration Levels in the Homes of Varying Percentages of Respondents Affected by Rail Vibration

The Gaussian distributions fitted to the histograms plotted in Figure 56 to Figure 61 can be used to estimate vibration velocity levels in homes of various percentages of respondents in the current sample who reported various effects of train passbys. Table 20 shows the means and standard deviations of these fitted distributions of un-weighted and A-weighted vibration velocity levels.

Table 20: Means and Standard Deviations of Vibration Velocity Levels for Respondents Reporting Various Effects of Train Passbys

	Un-weighted Leq (VdB)		A-weighted Leq (dB)	
	Mean	**SD**	**Mean**	**SD**
Notice	64.2	7.7	34.9	10.0
Annoyance				
Slightly	65.1	7.4	35.6	9.8
Moderately, very or extremely	65.6	7.2	36.6	10.2
Very or Extremely	65.3	7.5	36.8	10.3
Awakening	65.1	8.5	35.9	12.3
Complaint	66.6	7.4	37.1	11.2

Table 21 shows how these values may be used to estimate the vibration levels in the homes of varying percentages of the respondents who noticed, were annoyed in varying degrees, awakened, and complained about train passbys at the five interviewing sites. The percentage is first converted into a Z-score (as shown in Table 22), then multiplied by the standard deviation of the fitted continuous Gaussian distribution, and finally added to the mean value.

Table 21: Equations for Estimating Percentages of the Current Sample Reporting Various Effects of Train Passbys

	Unweighted Leq, dB	A-weighted Leq, dB
Notice	64.2 + 7.7 Z%	34.9 + 10.0Z%
Annoyance		
Slightly	65.1 + 7.4 Z%	35.6 + 9.8 Z%
Moderately, very or extremely	65.6 + 7.4 Z%	36.6 + 10.2 Z%
Very or extremely	65.3 + 7.5 Z%	36.8 + 10.3 Z%
Awakening	65.2 + 8.4 Z%	35.9 + 12.3 Z%
Complaint	66.6 + 7.4 Z%	37.1 + 11.2 Z%

Table 22: Z-scores Corresponding to Cumulative Percentages of Cases (areas under the Gaussian distribution up to the tabled percentage)

% of cases	Z score
10%	-1.28
20%	-0.84
30%	-0.52
40%	-0.25
50%	0.00
60%	0.25
70%	0.52
80%	0.84
90%	1.28

For example, the calculation that estimates the un-weighted vibration velocity level in the homes of 10% of those respondents who noticed train passbys is:

$$64.2 \text{ VdB} + 7.7*(-1.28) = 54.3 \text{ VdB}$$

Put another way, the un-weighted mean vibration velocity level of train passbys in the homes of 90% of the respondents who noticed train passbys was greater than 54.3 VdB.

6.5 Logistic Regression Models to Predict Response Due to Train Passbys

Logistic regressions were conducted in which distances to respondents' homes from the alignment, average durations of train passbys, and vibration velocity levels were used to predict responses to interview questions concerning notice, annoyance, awakening and complaints due to train passbys. These regressions were conducted on the responses of all questionnaire respondents, not merely those affected in some manner by train passbys (as in the histogram analyses described above).

As has been mentioned, many of the metrics that were initially considered were highly correlated with each other and, therefore were equally good dosage-response predictors. In order to limit the computationally intensive dosage-response calculations to a reasonable number, a subset of metrics was selected for detailed analysis. In selecting these metrics, in addition to the correlations, the familiarity with the noise and vibration community and compatibility with commercial measurement equipment was considered. A set of metrics that are not well-correlated offers the best chance to find a particular dosage metric that explains the largest proportion of the variance in the response variable. Table 23 summarizes the nine primary metrics that were used to develop dosage-response relationships.

Table 23: Primary Vibration Metrics used for Logistic Regression Prediction Equations

Metric Name	Description
D	Distance from the alignment centerline
LeqF	Average un-weighted passby* Leq** velocity level
LeqF+2σ	LeqF plus 2 standard deviations (approximates the "loudest" train)
LeqFmax	Maximum 1/3 octave band velocity, un-weighted
LeqFmax+2σ	LeqFmax plus 2 standard deviations
LeqA	Energy averaged A-weighted velocity level over passby*
LeqA+2σ	LeqA plus 2 standard deviations
LeqAmax	Maximum 1/3 octave band velocity, A-weighted
LeqAmax+2σ	LeqAmax plus 2 standard deviations

* Passby duration defined by 3 dB down points from passby maximum

** Energy-averaged vibration level over passby duration

The general form of the logistic-regression equation is

$$p = \frac{e^{A+Bx}}{1+e^{A+Bx}}$$

where p is the probability (of annoyance in this case), x is the vibration metric and A and B are constants derived from the logistic-regression analysis. A more detailed discussion of logistic-regression analysis can be found the text by Tabachnick and Fidell (69).

6.5.1 Probability of Notice

The most reliably predictable effect of train passbys was simple notice. A respondent was considered to have "noticed" the passage of trains if he or she responded "Yes" to any of the following questionnaire items:

- Item 6 - "Do you notice low rumbling sounds inside your home when … trains pass by"?
- Item 7 - "Do you ever hear rattling sounds from windows, doors, wall hangings, or other items in your home when … trains pass by"?; and
- Items 8 or 9 "Do you ever feel your home shake or the floors, walls, counters, or furniture vibrate when … trains pass by"?

Among the 1306 respondents, only about a third (421) reported notice of one or more of these aspects of train passages. Proximity to the tracks, as well as RMS vibration velocity levels, accounted for nearly a quarter of the variance in notice of train passbys.

Logistic regression analyses were performed using distance from the tracks, un-weighted velocity level and weighted velocity level as the exposure metrics. Table 24 summarizes the logistic regression coefficients that resulted from these analyses.

Table 24: Logistic Regression Coefficients to Predict Probability of Notice

Metric (units)	Logistic Regression Coefficients A	Logistic Regression Coefficients B	Variance Accounted For
D (m)	0.921	-0.0295	22%
LeqF (VdB)	-7.985	0.120	22%
LeqA (dB)	-3.554	0.093	22%

The logistic regression model predicting notice of train passbys based on the distance of respondents' homes from the tracks was statistically significant ($\chi^2_1 = 226.5$), and accounted for 22% of the variance in the relationship, as estimated by Nagelkerke's definition (3). The regression model correctly classified 74% of the cases: 87% of the respondents who did not notice the passage of trains were correctly classified, while 46% of those who noticed the passage of trains were correctly classified. Figure 62 plots the relationship between distance of the respondent's home from the alignment and the predicted likelihood of noticing train passbys. Note that the quantity plotted is the probability of notice among all respondents as predicted by the logistic regression model; individual respondents reported either that they did or did not notice train passbys. The probability decreases as distance increases, as would be expected. At a distance of 30 m (100 ft), the odds were even that D-12 respondent would or would not notice train passages.

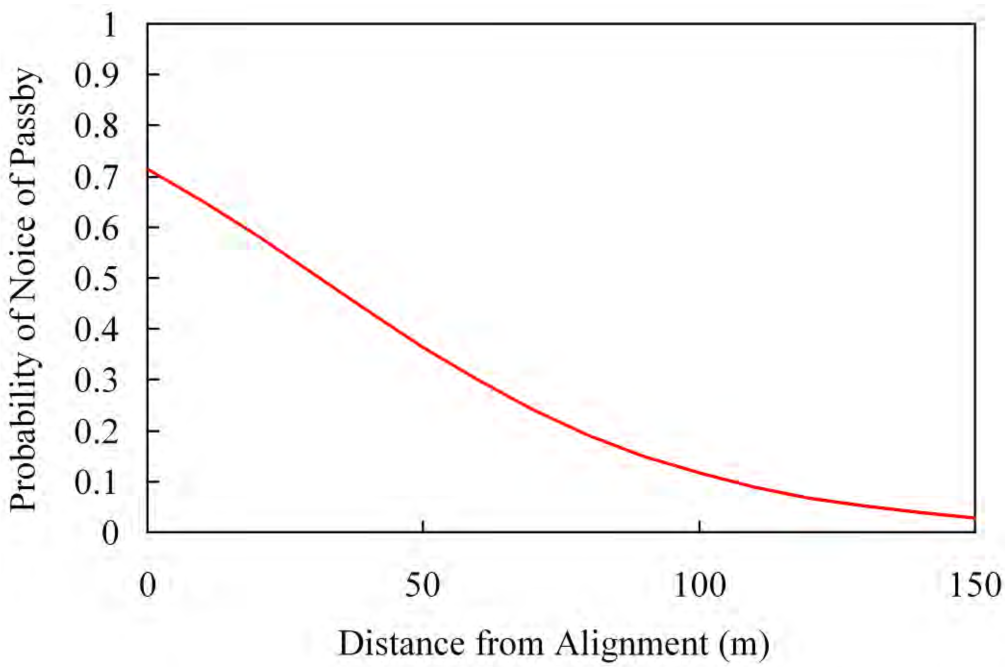

Figure 62: Predicted Probability of Noticing a Train Passby as a Function of Distance from the Alignment

The logistic regression model predicting notice of trains from un-weighted mean vibration velocity levels (Leq based on 3 dB down points) in respondents' homes was statistically significant ($\chi^2_1 = 226.5$), and accounted for 22% of the variance in the relationship. Overall, 72% of the cases were correctly classified, with 90% of the cases that did not notice the passage of a train correctly classified and 34% of those who noticed the passage of a train correctly classified.

The logistic regression model predicting notice of trains based on A-weighted vibration velocity levels in respondents' homes was statistically significant ($\chi^2_1 = 235.9$), and accounted for 22% of the variance in the relationship by Nagelkerke's definition (3). Overall, 73% of the cases were correctly classified, with 92% of the cases that did not notice the passage of a train correctly classified and 34% of those who noticed the passage of a train correctly classified.

Figure 63 plots the relationship between the un-weighted and A-weighted vibration velocity levels and the probability of noticing train passbys. According to the D-12 data, at a vibration level of 72 VdB the chance that a respondent would report noticing vibration was 67%. At an A-weighted noise level of 35 dB there was a 43% probability that a D-12 resident would have noticed a train passby.

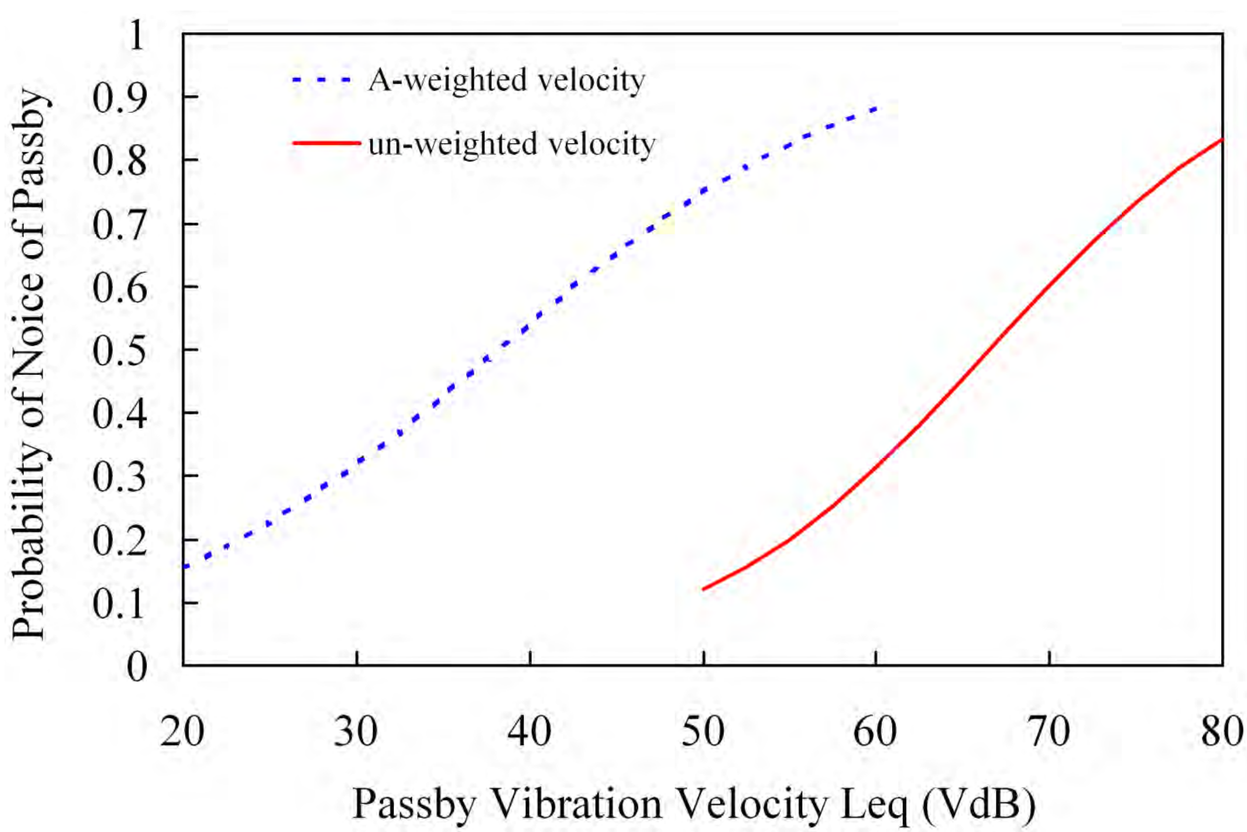

Figure 63: Probability of Notice Based on A-weighted (LeqA) and Un-weighted Passby Vibration Velocity Level (LeqF)

6.6 Predicting Moderate or Greater Annoyance with Train Passbys

The survey questions associated with annoyance due to a train passby were as follows:

- Item 6A: “Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by low rumbling sounds inside your home as …trains pass by”?
- Item 7B (or 8B): “Would you say that you are not at all, slightly, moderately, very or extremely annoyed by rattling sounds in your home caused by…trains”?
- Item 8B (or 9B): “Would you say that you are not at all, slightly, moderately, very or extremely annoyed by shaking or vibrations in your home when a…train passes by”?

Reactions to questionnaire items soliciting reactions to vibration, noise, and rattle were highly correlated. Among the respondents who noticed and reacted strongly to any of these effects, few respondents reported only one. Construction of composite annoyance variables provided greater statistical power for the dosage-response analyses.

A composite variable was created such that a respondent was said to be moderately or more greatly annoyed by the passage of a train if he or she responded “moderately annoyed,” “very annoyed,” or “extremely annoyed” to any of the three questions. Among the 1306 respondents, 125 (9.6%) were moderately or more greatly annoyed by one or more features of the passage of a train.

A second composite variable was created to represent high annoyance with the passage of trains. Respondents were coded as “highly annoyed” if they answered “very annoyed,” or “extremely annoyed” to any of items 6A, 7/8B, or 8/9B. Among the 1306 respondents, 67 (5.1%) were highly annoyed by one or more features of the noise or vibration associated with the passage of trains.

Table 25 summarizes the logistic regression coefficients for the eight variables selected for detailed analysis. The percentage of the variance that each metric accounts for is also shown in the table. As Table 25 shows, A-weighted velocity level (LeqA) accounted for the greatest proportion of the variance (10%) in people who reported high annoyance.

Figure 64 plots predictions from un-weighted passby vibration (LeqF) of the logistic regression models for the probability that a D-12 respondent reported “high annoyance” or “moderate or greater annoyance” due to train vibration. The probabilities of annoyance in both degrees increase with increased vibration level. Of necessity, the probability of reporting moderate or greater annoyance for any given exposure level exceeds the probability of reporting high annoyance.

The blue dots and open red squares in Figure 64 represent discrete values calculated by aggregating responses within 5 dB-wide vibration ranges. For example, 93 people were exposed to LeqF vibration levels between 72.5 VdB and 77.5 VdB. Of these 93 people, 7 (7.5%) reported high annoyance, while 16 (17.2%) reported moderate or high annoyance. The simple calculations within intervals of un-weighted passby Leq vibration (LeqF) agree quite well with the logistic regression predictions for these variables.

Table 25: Logistic Regression Coefficients to Predict Probability of High Annoyance and Moderate or Greater Annoyance

Metric	Logistic Regression Coefficients					
	Highly Annoyed			Moderate + Highly Annoyed		
	A	B	% Variance Accounted For	A	B	%Variance Accounted For
LeqF (VdB)	-8.475	0.089	8	-8.607	0.103	12.5
LeqF+2σ (VdB)	-8.753	0.085	7	-8.894	0.097	11
LeqFmax (VdB)	-7.870	0.084	8	-7.865	0.096	12.5
LeqFmax+2σ (VdB)	-7.711	0.072	6	-8.137	0.088	11
LeqA (VdB_A)	-5.470	0.078	10	-4.900	0.082	13
LeqA+2σ (VdB_A)	-6.131	0.078	8	-5.678	0.084	11
LeqAmax (VdB_A)	-4.925	0.071	8	-4.351	0.076	11
LeqAmax+2σ (VdB_A)	-5.398	0.067	6	-4.951	0.074	9

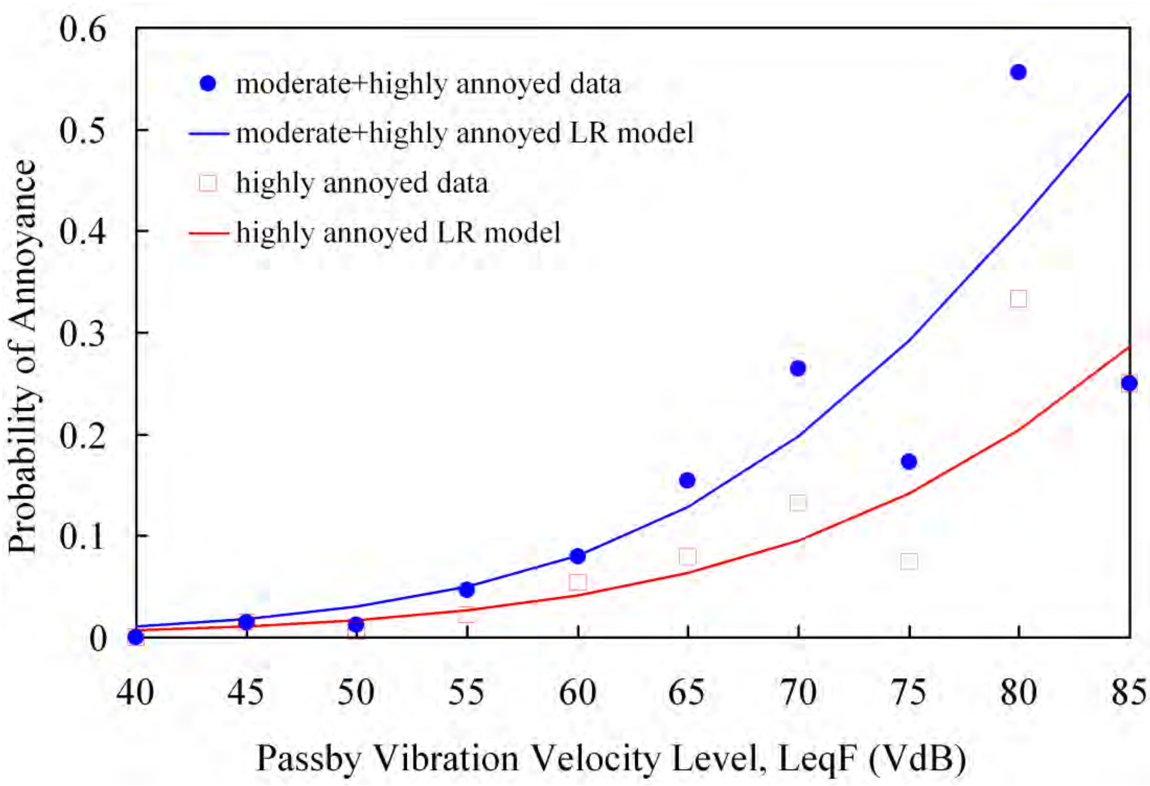

Figure 64: Probability of Annoyance Based on Un-weighted Passby Vibration Velocity Level (LeqF)

7. STUDY IMPLICATIONS RELATED TO CURRENT NOISE AND VIBRATION CRITERIA

The guidelines of the Federal Transit Administration (FTA) manual (7) represent current standard practice in the United States for assessing ground-borne noise and vibration due to rail transit operations. In this section, the findings of the current study are discussed in the context of the metrics used in the FTA manual.

7.1 Study Limitations

Although the present study was extensive (more than 1300 telephone interviews were conducted in five cities, and noise and/or vibration measurements were made at more than 140 locations), some practical limitations nonetheless affect the way the findings should be used.

1. The frequency of service of all of the transit systems tested in the present study exceeded 70 events per day. This limits discussion to the FTA's “frequent” service category.
2. The cities where the greatest numbers of interviews were conducted (New York, Toronto, and Boston) were served by predominantly heavy rail, sub-surface transit systems where structure-borne noise tends to be more prevalent than feelable vibration. Relatively little information was collected at residences in which low-frequency, feelable vibration was the dominant source of annoyance.
3. The selected exposure metrics were based on the vibration level measured on the ground, outside of the residence. In cases where simultaneous indoor and outdoor measurements were taken, no clear pattern that would allow a reasonable adjustment of outdoor levels to estimate indoor levels was evident. Indoor vibration levels at seemingly identical houses with similar exterior vibration levels differed by as much as 10 dB. For all homes in which vibration measurements were made, the average adjustment from outdoor to indoor measurements was 0 dB.
4. At most, exposure measures accounted for a tenth of the “highly-annoyed” variance in the present sample. Thus, far more variability in individual annoyance judgments is attributable to factors *other than* vibration than to vibration alone. This implies a need for caution in considering major changes to established criteria.

7.2 Vibration Measures

A vibration signal may be measured and characterized in many ways. More than 200 individual vibration metrics, drawn from accepted practice, publications in the technical literature, and the experience of the project team, were considered in the current study. Nearly all of these metrics proved to be only slightly variant measures of the same underlying physical quantity, and hence, highly correlated with each other. This finding implies that most metrics serve about as well as any other as a statistical predictor of annoyance due to rail vibration.

In the absence of a compelling statistical rationale for preferring one vibration metric over others as a predictor of annoyance, custom, convenience, and cost are reasonable alternative bases for selecting a vibration metric for detailed analyses. Un-weighted velocity level and A-weighted velocity level are two metrics familiar to general acoustics and vibration practitioners that can be measured with conventional instrumentation.

A-weighted velocity level is preferred to sound pressure level as a predictor variable for two additional reasons:

1. The sound pressure in a room produced by train-induced ground-borne vibration, p, is readily predictable from the floor vibration velocity, v, because to a good approximation, v is related to p by the acoustic impedance of air,

$$p = \rho\, c\, v\,,$$

   where ρ is the air density and c is the speed of sound. Hence, the sound pressure level in the room can be accurately and reliably estimated from the measured floor vibration.

2. Direct measurements of sound pressure levels in field settings are often confounded by non-rail sources (such as sounds of street traffic and household activity), whereas vibration measurements are less susceptible to such confounding. Train-induced vibrations are generally easily distinguished from background vibration levels. It is therefore simpler to unambiguously measure vibration events than sound events in typical field settings.

In the FTA manual, un-weighted velocity level and A-weighted sound level are defined in terms of a 1-second, true-RMS average train passby maximum level. Note that in prior sections of this report, the dosage-response relationships were based on the average passby levels defined by the 3 dB down points. To facilitate direct comparisons with the FTA criteria, a transform based on the very high intra-variable correlations was used to express the dosage-response curves identified earlier, in terms of passby maximum levels. Specifically, the following transformations were used:

$$LF_{OA}\Big|_{passby\,\max} = 1.0193\, LeqF + 0.0873, \quad (R^2 = 0.9968)$$

$$LF_{BM}\Big|_{passby\,\max} = 1.0148\, LeqF + 1.3457, \quad (R^2 = 0.9944)$$

$$LA_{OA}\Big|_{passby\,\max} = 1.02666\, LeqA + 0.49, \quad (R^2 = 0.9976)$$

where LF_{OA} is the passby maximum, un-weighted overall vibration level; LF_{BM} is the passby maximum, un-weighted vibration in any single 1/3 octave band; and LA_{OA} is the passby maximum A-weighted overall vibration level. As the equations show, the three sets of transformed variables were nearly perfectly correlated with the base metrics. Table 26 summarizes the logistic regression coefficients for the transformed FTA-equivalent variables.

Table 26: FTA-equivalent Logistic Regression Coefficients to Predict Probability of High Annoyance and Moderate or Greater Annoyance

Metric	Highly Annoyed		Moderate + Highly Annoyed	
	A	B	A	B
LF_{OA}, mean (VdB)	-8.522	0.087	-8.661	0.101
LF_{OA}, mean +2σ (VdB)	-9.354	0.089	-9.580	0.102
LF_{BM}, mean (VdB)	-7.981	0.083	-7.992	0.095
LF_{BM},mean +2σ (VdB)	-8.385	0.078	-8.961	0.095
LA_{OA}, mean (dB)	-5.507	0.076	-4.939	0.080
LA_{OA}, mean +2σ (dB)	-6.276	0.077	-5.834	0.083

7.3 Relationship to Current Vibration Criteria

Figure 65 shows the dosage-response relationships expressed in terms of the passby maximum vibration level (1-second true RMS average). The solid curves in the figure represent the opinions of people who described themselves as being highly annoyed (questionnaire response of “very” or “extremely” annoyed) by train vibration for any reason (rumble, rattle or shake). The dotted curves represent people who described themselves as moderately or more greatly annoyed by the train vibration.

Vibration exposure is defined in two ways: 1) the mean of the passby maximum levels (that is, the energy average vibration level over all observed passbys), and 2) the mean vibration level plus two standard deviations (mean+2σ). For a normal distribution, the probability that a train would exceed the mean+2σ level is 5%, so this level would correspond to the “loudest” trains that passed by the site, and hence, is the more appropriate measure if it is believed that people are more likely to be disturbed by the loudest trains in the fleet, rather than the fleet-average train.

The FTA's 72 VdB limit for frequent service (>70 events/day) and residential occupancy is also shown in Figure 65. The probability of high annoyance due to train vibration at the FTA limit of 72 VdB varied by a factor of two (from about 0.05 to 0.10), depending on whether the prediction is based on the mean level or the mean level plus two standard deviations.

The policy positions of the Federal Aviation Administration and other federal agencies with interests in transportation noise are explicitly based on FICON’s 1992 (36) dosage-effect relationship, illustrated in Figure 66. According to FICON’s dosage-effect relationship, 12.3% of the population would be highly annoyed at the exposure level (L_{dn} = 65 dB) at which federal participation in funding noise impact mitigation programs is believed to be warranted. The probability of annoyance with rail vibration at FTA’s currently recommended level of 72 VdB thus appears generally consistent with the policy positions adopted by other federal agencies concerning acceptable population-level impacts of transportation noise.

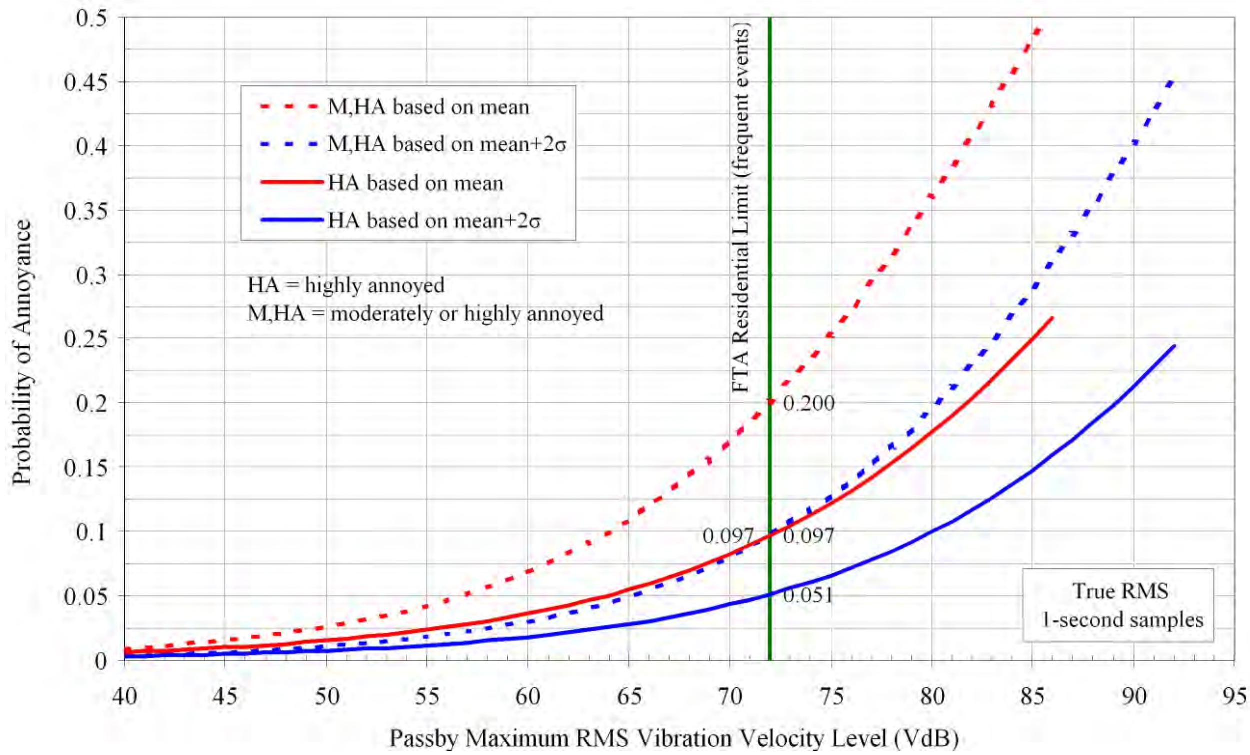

Figure 65: Probability of Annoyance Based on Passby Maximum Vibration Velocity Level

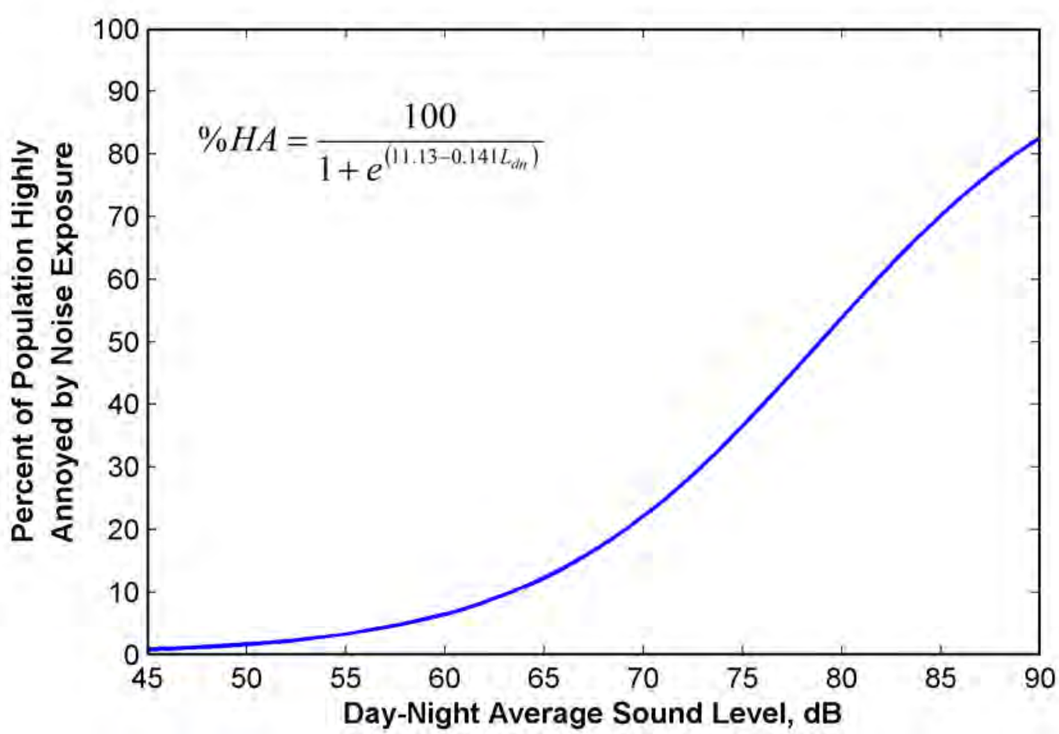

Figure 66: FICON's (36) Dosage-Effect Relationship

The FTA manual also specifies detailed vibration impact criteria based on the band-maximum vibration levels (the greatest vibration in any 1/3 octave frequency band). Figure 67 shows the present findings in terms of the band-maximum vibration level, along with the FTA's 72 VdB residential limit. Figure 67 shows that the probability of high annoyance with rail vibration at the current FTA band-maximum level varied from about 0.06 to 0.117. As discussed above, the current FTA band-maximum criterion appears generally consistent with the policy positions adopted by other federal agencies concerning acceptable population-level impacts of transportation noise.

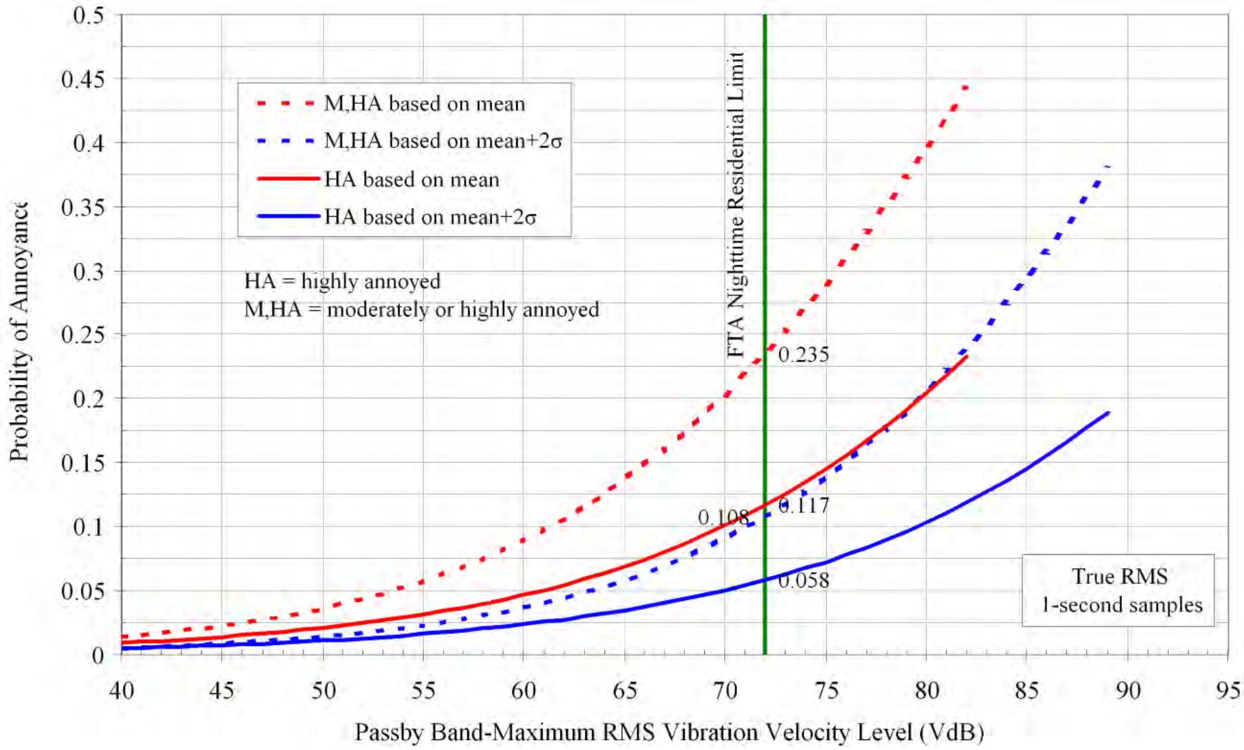

Figure 67: Probability of Annoyance Based on Passby Band-Maximum Vibration Velocity Level

7.4 Relationship to Current Ground-Borne Noise Criteria

Since the rail-induced sound pressure in a room can be reliably estimated from the floor vibration, it follows that the A-weighted vibration level can reliably predict the A-weighted sound pressure level. The FTA manual states that, for typical residential rooms, the sound pressure level in dB is approximately equal to the floor vibration velocity level in VdB. In the subsequent discussion, A-weighted velocity level (dB) and sound level (in units of A-weighted decibels) are used interchangeably.

Figure 68 shows the D-12 dosage-response relationships based on the passby maximum A-weighted velocity level as the exposure metric. The FTA's 35 dB A-weighted limit for residential occupancy (and frequent events) is also shown on the figure. At 35 dB (A-weighted), the probability that a D-12 respondent would have reported high annoyance from train passbys varied from about 0.03 to about 0.06, depending on whether the prediction was based on the mean exposure level or the mean +2σ level. The figure also shows that the mean A-weighted level at which the probability of high annoyance reaches 0.12 is about 42 dB. Consequently, if a probability of 0.12 of high annoyance is taken as a reasonable impact threshold, then the present information can be interpreted to suggest that either the current 35 dB A-weighted criterion is too stringent, or alternatively, that the conversion from velocity to sound is overly conservative.

The latter explanation is more strongly supported by the present data. For plane wave sound radiation from a surface, the near-field sound pressure is related to the surface velocity by ρc, where ρ is the density of air and c is the speed of sound. Dividing by the appropriate reference quantities and maintaining consistent units, the sound pressure level and vibration velocity level are related by,

$$Lp(dB) = Lv(VdB) - 5.5$$

Thus, the radiated sound pressure level should be 5.5 dB lower than the surface velocity level. In D-12 study homes where both vibration and noise were measured, the data suggest that the radiated sound pressure level was about 5 dB lower than the vibration level, rather than equal to the vibration level. If the curves in Figure 68 are shifted to the left by 5 dB, then the probability of high annoyance would increase to 5.6% to 11%, closer to the nominal prevalence of high annoyance (12%) implied by FICON's criterion.

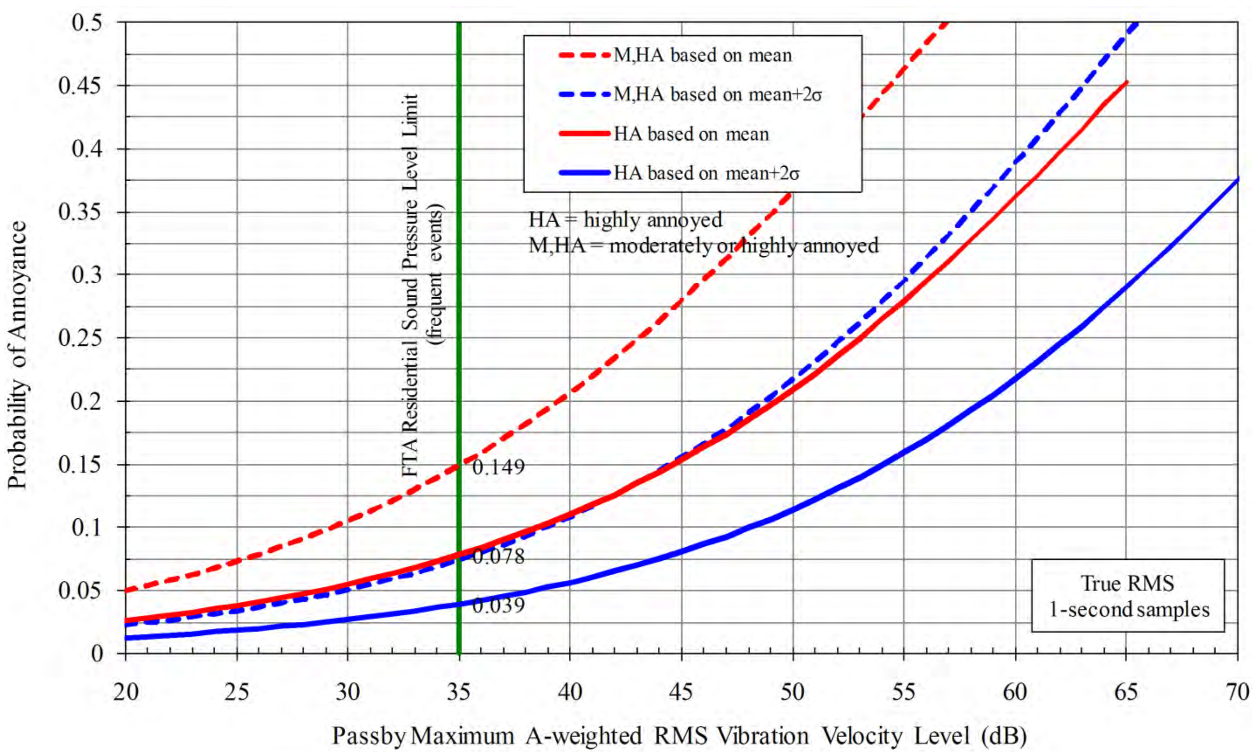

Figure 68: Probability of Annoyance Based on Passby Maximum A-weighted Vibration Velocity Level

7.5 Location of Application of Criteria

The current FTA criteria are based on the calculated vibration/noise exposure at the receiver's position. In the FTA procedure, ground vibrations are adjusted to account for soil/foundation coupling, floor-to-floor attenuation, and resonant amplification of floors, walls and ceilings. In the present study, the measured data supported a net 0 dB adjustment to predict the indoor vibration levels based on the outdoor vibrations. This adjustment is not very different from that recommended in the FTA manual for wood frame houses (-5 dB for soil/foundation coupling + 6 dB for floor amplification = +1 dB net adjustment).

The present measurements do not support any factors that are different from those presently considered in the FTA manual.

7.6 Summary of Study Findings with Respect to Current Criteria

At the current FTA limit of 72 VdB for frequent rail service, the study results show that the probability that a resident would be highly annoyed by train passbys is roughly 10%, a probability that is generally consistent with interpretive criteria adopted by other federal agencies for other forms of transportation noise impacts.

The study also suggests that if a -5 dB vibration-to-noise adjustment was applied to the FTA adjustments to predict sound pressure level from vibration, the resulting annoyance predictions at 35 dB (A-weighted) would also be about 10% highly annoyed.

7.7 Criteria for Sensitive Equipment

A transit alignment need not pass through an exclusively residential area to affect a community. Many vibration sensitive facilities can be adversely affected by the ground vibration produced by rail transit operations. Examples of such facilities include university laboratories, animal research facilities, bio-technology labs, hospitals, semiconductor and nano-technology facilities.

7.7.1 Vibration Criteria for Sensitive Equipment

Many pieces of commercially available vibration-sensitive equipment have clearly defined criteria for acceptable levels of floor vibration. Most pieces of research equipment do not have criteria, primarily because this equipment tends to be custom made. In cases where specific vibration criteria do not exist, or the specific equipment involved are not known, generic criteria are available for various types of facilities. The generic criteria are commonly known as "Vibration Criteria Curves" ("VC" curves). These were developed in the 1980s at Bolt Beranek and Newman. The VC curves were first introduced in 1990 (56) and have appeared in various references and design guides since (57)(58). Figure 69 shows the family of VC curves that apply to a wide range of vibration sensitive facilities.

The generic criterion curve applies to the RMS floor vibration velocity spectrum, measured in 1/3 octave frequency bands. Generally, a criterion is considered to be exceeded if the velocity level in any 1/3 octave band exceeds the VC level.

The VC criterion curves do not extend to frequencies above 80 Hz because 1) high-frequency vibrations produce comparatively small displacements and thus tend to interfere relatively little with equipment function, 2) the structural components and housing of an equipment item tend to isolate the sensitive parts of the item from externally acting vibrations, and 3) readily available isolation means can provide considerable attenuation at high frequencies. The criterion curves do not extend below 4 Hz, in recognition of the fact that most instruments are not overly sensitive to low-frequency vibration. (In the presence of low-frequency vibrations, items move essentially as rigid bodies, with only minor relative displacements of the type that would interfere with functionality.) For pneumatically isolated equipment it is common practice to extend the “flat portion” of the curves to 1 Hz to account for the amplification effect that occurs at an isolation system's natural frequency.

The vibration criterion curves in Figure 69 are often defined by a single letter or number corresponding to the flat portion of the curve (8 Hz to 80 Hz). The lettering convention is not consistent in the industry, so to avoid confusion it is preferable to identify the curves by their numerical value in micro-inches per second, as in Figure 69. Typical facility and equipment usages for the various VC criterion levels are listed in Table 27. Note that the VC curves define vibration levels that are considerably lower than the 72 VdB that is used in the United States for human exposure in residential settings.

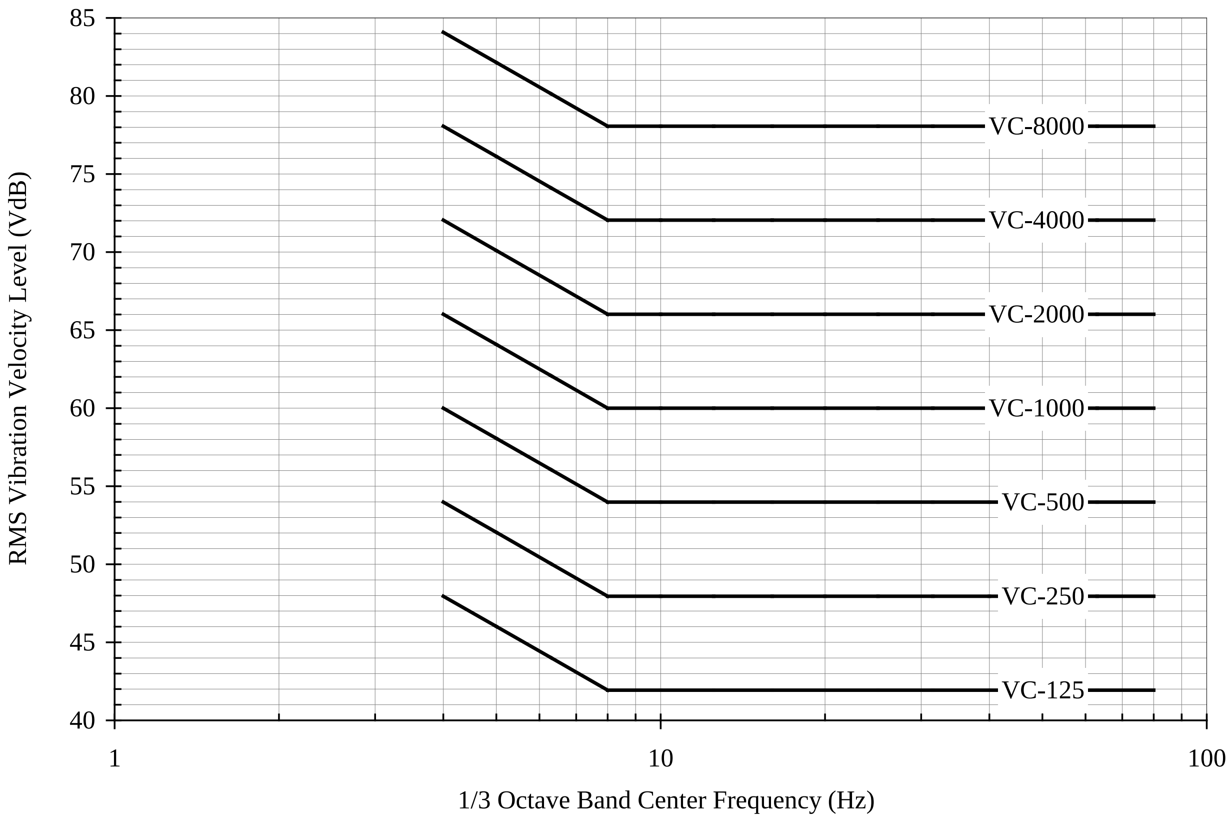

Figure 69: Generic Vibration Criterion Curves

Table 27: Generic Vibration Criteria for Sensitive Equipment and Facilities

Criterion	Velocity (μm/s)	Equipment or Facility Use
VC-8000	200	Computer Equipment
VC-4000	100	Operating Rooms, Surgery, Bench Microscopes up to 100X magnification, Laboratory Robots
VC-2000	50	General Laboratory, Bench Microscopes up to 400X magnification, Precision Balances, Metrology, Animal Research
VC-1000	25	Micro and Neuro-Surgery, Bench Microscopes greater than 1000X magnification, Optical Equipment on Isolation Tables, Semiconductor Equipment for Line Widths to 3 μm
VC-500	12	Electron Microscopes up to 30,000X magnification, MRI, Mass Spectrometers, Semiconductor Equipment for Line Widths to 1 μm
VC-250	6	Electron Microscopes greater than 30,000X magnification, Cell Implant Equipment, Semiconductor Equipment for Line Widths to 0.5 μm
VC-125	3	Unisolated Optical Equipment, Semiconductor Equipment for Line Widths to 0.25 μm

Section 8.2.1 of the FTA manual (7) describes the generic criteria in terms of vibration decibels rather than micro-meters/per second, but the categories are the same. These descriptions are consistent with current industry practice.

In many cases new transit alignments will pass by vibration sensitive facilities with existing equipment already in place and functioning. This equipment will likely have specific vibration criteria that have been provided by the manufacturer. In cases like these, it is important that the actual instrument criteria are considered, rather than the generic categories. This is the best way to ensure that future neighbors of the new alignment are not adversely impacted by vibration. Note that in some cases, it may not be possible to adequately mitigate the rail vibration at the source to achieve sufficiently low levels inside nearby facilities. In such cases, additional mitigation measures in the form of specialized vibration isolation systems may have to be employed at the equipment item itself.

7.7.2 Acoustic Criteria for Sensitive Equipment

No generic acoustic criteria for sensitive equipment (such as that described in Figure 69 and Table 27) exist, because most vibration sensitive instruments do not have corresponding acoustical criteria. Electron microscopes, which have stringent requirements for vibration and acoustic noise, are a notable exception.

Figure 70 shows the acoustic criteria for two electron microscopes, a JEOL JEM 2100/2200 and a FEI Tecnai 20 F. (The actual criteria are given in terms of un-weighted sound pressure level, which have been converted to A-weighted SPL to facilitate direct comparison to data presented elsewhere in this report.) Note that the JEOL criterion extends to frequencies below 20 Hz, which would not normally be a concern for the impact assessment of a proposed rail transit project. For systems with characteristic spectral peaks in the 31.5 Hz band, the allowable A-weighted sound pressure level could be as low as 15 dB. Such instruments could easily be the most noise-sensitive adjacencies to a new transit alignment.

Since no generally accepted generic noise criteria exist for sensitive equipment, an analyst considering the possible impact of a new transit system should rely on actual criteria if available, or if actual criteria are not available, on representative criteria for similar systems.

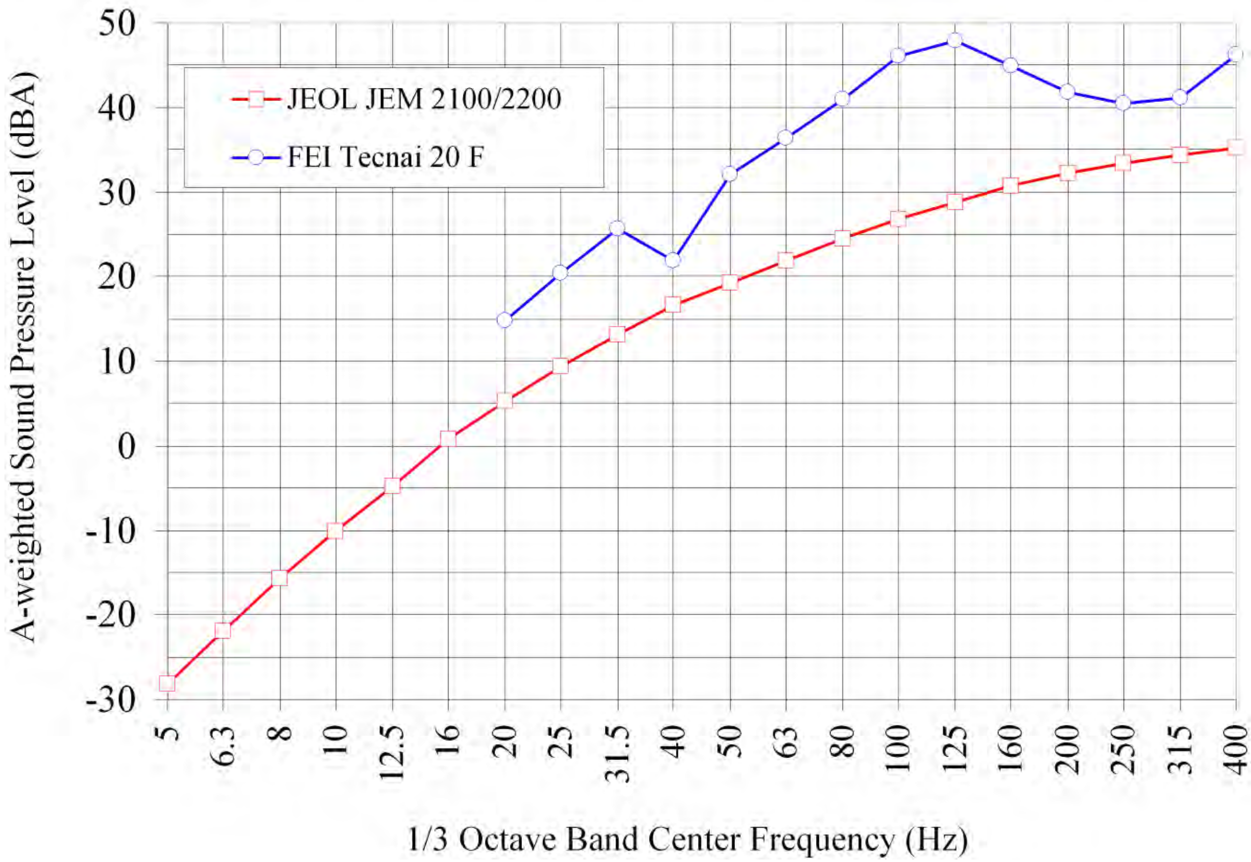

Figure 70: Acoustical Criteria for JEOL and FEI Electron Microscopes

7.8 Implementation Plan

For this study to be beneficial to the transit community, its results must be known, accepted and eventually integrated into the procedures used to determine when ground-borne vibration mitigation measures are needed.

TRB and APTA conferences and committee meetings offer the best opportunities to present current and developing research to regulators, agency representatives, and consultants. Presentations on progress and preliminary conclusions of the D-12 project have been made at every TRB annual meeting since January 2006. Presentations have also been made at meetings of the APTA Track, Noise and Vibration Technical Forum since March 2006. Acceptance of the research by the wider acoustics and vibration community is best obtained through peer-reviewed journals.

The following steps are envisioned to publicize the results of the D-12 study,

- Present the results of the D-12 study at the TRB Annual meeting in 2010.
- Present the results to the APTA Track Noise and Technical Forum
- Present the results of the D-12 study at an international conference such as InterNoise.
- Prepare a paper or series of papers for publication in a peer-reviewed journal such as the *Journal of the Acoustical Society of America* or the *Journal of Sound and Vibration*.
- Prepare an article to be published in a rail community trade magazine such as *Railway Track and Structures* or *Progressive Railroading*.

The D-12 study did indicate that additional data could help clarify adjustments that are currently cited in the FTA manual. Two areas have been identified as areas where future research would be beneficial in helping to strengthen the methods currently used to predict and assess rail vibration.

8. SUGGESTED ADDITIONAL WORK

Additional research would be particularly valuable in two areas. The first is for the study of exposure to vibration generated by rail service characterized by higher axle loads, longer trains, and less frequent service than for a typical urban rail transit system. Examples of this type of service include many commuter rail systems, high speed passenger trains, and freight rail lines.

The second area is prediction of ground-borne vibration from rail systems. Wide variations in the predictions developed by different vibration consultants are possible, even though both are following guidelines provided by the Federal Transit Administration. Considerable judgment is required to develop detailed predictions, and several areas are evident in which refinements of the current predictions are possible. A useful goal would be to clarify prediction procedures so that anyone who follows the guidelines would produce similar predictions, and that the predictions would be reasonably accurate.

Each of these topics would be beneficial to the rail community and could be performed as stand-alone programs. The topics presented as detailed TCRP-formatted problem statements are included in Appendix F.

REFERENCES

1. Schultz, T. J., "Synthesis of Social Surveys on Noise Annoyance," *Journal of the Acoustical Society of America*, Vol. 64, No. 2, (1978), pp. 377-405.

2. Fidell, S., "The Schultz curve 25 years later: a research perspective," *Journal of the Acoustical Society of America*, 14(6), December, 2003, pp. 3007-3015.

3. Nagelkerke, N. J. D. (1991), "A note on a general definition of the coefficient of determination," *Biometrika*, 78, 691-692.

4. ANSI S3.29-1983 (R2001), "American National Standard Guide to the Evaluation of Human Exposure to Vibration in Buildings," American National Standards Institute.

5. IS0 2631, "Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration," IS0 2631-1 (1997): "Part 1: General requirements," ISO 2631-2 (2003): "Part 2: Continuous and shock-induced vibrations in buildings (1 to 80 Hz)."

6. BS 6841 (1987): "Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock," British Standards Institution.

7. Federal Transit Administration, "Transit Noise and Vibration Impact Assessment," Report FTA-VA-90-1003-06 (May 2006).

8. Howarth, H.V.C., and Griffin, M.J. (1988) "Human Response to Simulated Intermittent Railway-Induced Building Vibration," *Journal of Sound and Vibration*, Vol. 120(2), pp. 413-420.

9. Howarth, H.V.C., and Griffin, M.J. (1990) "The Relative Importance of Noise and Vibration from Railways," *Applied Ergonomics*, Vol. 21.2, pp. 129-134.

10. Howarth, H.V.C., and Griffin, M.J. (1991) "The Annoyance Caused by Simultaneous Noise and Vibration from Railways." *Journal of the Acoustical Society of America*, Vol. 89(5), pp. 2317-2323.

11. Walker, J.G., and Chan, M.F.K. (1996) "Human Response to Structurally Radiated Noise Due to Underground Railway Operations," *Journal of Sound and Vibration*, Vol. 193(1), pp. 49-63.

12. Fidell, S., Harris, A., and Sutherland, L. (2000) "Findings of the Low-Frequency Noise Expert Panel of the Richfield-MAC Noise Mitigation Agreement of 17 December, 1998."

13. Stevens, S.S. (1936), "A scale for the measurement of a psychological magnitude: loudness," *Psychol. Rev.* 43, 405-416.

14. Broner, N. and Leventhall, H.G. (1983) "Low Frequency Noise Annoyance Assessment by Low Frequency Noise Rating (LFNR) Curves," *Journal of Low Frequency Noise and Vibration*, Vol. 2, pp. 20-28.

15. Broner, N. and Leventhall, H.G. (1984) "The Annoyance, Loudness, and Unacceptability of Lower Level Low Frequency Noise," *Journal of Low Frequency Noise and Vibration*, Vol. 3, pp. 154-166.

16. Andresen, J. and Møller, H.(1984) "Equal Annoyance Contours for Infrasonic Frequencies," *Journal of Low Frequency Noise and Vibration*, Vol. 3(3), pp. 1-9.

17. Møller, H., (1987) “Annoyance of Audible Infrasound,” *Journal of Low Frequency Noise and Vibration*, Vol. 6, pp. 1-17.

18. Nakamura, S., and Tokita, Y. (1981) “Frequency characteristics of subjective responses to low frequency noise,” *Inter-Noise*, pp. 735-738

19. Tokita, Y., Oda, A., and Shimizu, K. (1984) “On the frequency weighting characteristics for evaluation of infra and low frequency noise,” *Proc. Inter-Noise 84*, pp. 917 – 920.

20. Goldstein, M. and Kjellberg, A. (1985) “Annoyance and Low Frequency Noise With Different Slopes of the Frequency Spectrum,” *Journal of Low Frequency Noise and Vibration*, Vol. 4, pp. 43-51.

21. ANSI S12.9, part 4 (R1996), “Quantities and Procedures for Description and Measurement of Environmental Sound – Part 4: Noise Assessment and Prediction of Long-Term Community Response,” American National Standards Institute.

22. ISO 7196 (1995): “Frequency-weighting characteristic for infrasound measurements,” International Organization for Standardization.

23. Kelley, N.D. (1987) “A Proposed Metric for Assessing the Potential of Community Annoyance from Wind Turbine Low-Frequency Noise Emissions,” Colorado Solar Energy Research Institute, U.S. Department of Energy.

24. AWEA Tier 1 – Standard 2.1 (1989) “Procedure for Measurement of Acoustic Emissions from Wind Turbine Generator Systems,” American Wind Energy Association.

25. Bellman, M., Mellert, V., Remmers, H., and Weber, R. (2004) “Influence of Frequency and Magnitude on Perception of Vertical Whole-body Vibration,” CFA/DAGA Joint Congress.

26. Öhrström, E., and Skånberg, A.-B. (1996) “A Field Survey on Effects of Exposure to Noise and Vibration from Railway Traffic – Part I: Annoyance and Activity Disturbance Effects,” *Journal of Sound and Vibration*, Vol. 193(1), pp. 39-47.

27. Paulsen, R., and Kastka, J. (1995) “Effects of Combined Noise and Vibration on Annoyance,” *Journal of Sound and Vibration*, Vol. 181(2), pp. 295-314.

28. Knall, V. (1996) “Railway Noise and Vibration: Effects and Criteria,” *Journal of Sound and Vibration*, Vol. 193(1), pp. 9-20.

29. Öhrström, E., (1997) “Effects of Exposure to Railway Noise – A Comparison Between Areas With and Without Vibration,” *Journal of Sound and Vibration*, Vol. 205(4), pp. 555-560.

30. Woodroof, H.J., and Griffin, M.J. (1986) “A Survey of the Effect of Railway-induced Building Vibration on the Community.” University of Southampton, ISVR Technical Report to British Rail Technical Centre, Derby.

31. Klæboe, R., Turunen-Rise, I.H., Hårvik, L., and Madshus, C. (2003) “Vibration in Dwellings from Road and Rail Traffic – Part II: Exposure-effect Relationships Based on Ordinal Logit and Logistic Regression Models,” *Applied Acoustics*, Vol. 64, pp. 89-109.

32. Turunen-Risem I.H., Brekke, A., Hårvik, L., Madshus, C., and Klæboe, R. (2003) “Vibration in Dwellings from Road and Rail Traffic – Part I: A New Norwegian Measurement Standard and Classification System,” *Applied Acoustics*, Vol. 64, pp. 71-87.

33. Klæboe, R., Öhrström, E., Turunen-Rise, I.H., Bendtsen, H., and Nykanen, H. (2003) “Vibration in Dwellings from Road and Rail Traffic – Part III: Towards a Common Methodology for Socio-Vibrational Surveys,” *Applied Acoustics*, Vol. 64, pp. 111-120.

34. "Human Response to Vibration in Residential Environments," NANR172, Department for Environment, Food and Rural Affairs, London, UK, March 2007.

35. Vadillo, E.G., Herreros, J., and Walker, J.G. (1996) “Subjective Reaction to Structurally Radiated Sound from Underground Railways: Field Results,” *Journal of Sound and Vibration*, Vol. 193(1), pp. 65-74.

36. FICON 1992. “Federal Agency Review of Selected Airport Noise Analysis Issues,” Federal Interagency Committee on Noise (FICON), August 1992.

37. Fidell, S., Pearsons, K., Silvati, L., and Sneddon, M. (2002) “Relationship between low-frequency aircraft noise and annoyance due to rattle and vibration,” *Journal of the Acoustical Society of America*, Vol. 111(4), pp.1743-1750.

38. Woodroof, H.J., and Griffin, M.J. (1986) “A Survey of the Effect of Railway-induced Building Vibration on the Community.” University of Southampton, ISVR Technical Report to British Rail Technical Centre, Derby.

39. ANSI S3.18-2002, “Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole Body Vibration – Part 1: General Requirements,” American National Standards Institute.

40. AS 2670.2 (1990): “Evaluation of human exposure to whole-body vibration - Continuous and shock-induced vibration in buildings (1 to 80 Hz).” Council of Standards Australia.

41. Renzo Tonin & Associates Consulting (2004). “Technical Note 4: Managing Noise and Vibration on Construction Sites.”

42. NBN B03-003 (2002): “Déformations des structures – Valeurs limites de déformation – Bâtiments. (Criteria of State Limits with Regards to Vibration in Buildings.” Federal Scientific Policy, Belgium).

43. Information No. 9/1997 (1997): “Orientering om lavfrekvent støj, infralyd og vibrationer i eksternt miljø.” Danish Environmental Protection Agency (Danish Ministry of the Environment).

44. NT ACOU-082 (1991): “Buildings: Vibration and Shock, Evaluation of Annoyance.” Nordtest (Nordic Strategy Group on Quality and Metrology).

45. Jacobsen, J. (2003) “Danish Guidelines on Environmental Low Frequency Noise, Infrasound and Vibration,” *Noise Notes*, Vol. 2(2), pp. 10-18.

46. DIN 4150-2 (1999): “Erschütterungen im Bauwesen - Teil 2: Einwirkungen auf Menschen in Gebäuden (Vibrations in Buildings – Effects on Persons in Buildings).” Deutsches Institut für Normung (German Institute for Standardization).

47. UNI-9614:1990 (1990) "Misura delle vibrazioni negli edifici e criteri di valutazione del disturbo (Vibration Measurement in Buildings and Annoyance Evaluation)." Ente Nazionale Italiano de Unificazione (Italian National Standards Body).

48. Breccolotti, M. and Materazzi, A. (2005) "Ambient Vibration Analysis and Mitigation in the Site of Villa Ruffo in Rome," Proceedings of Eurodyn 2005, Paris, France.

49. Vibration Regulation Law (1994): "Cabinet Order for the Implementation of the Vibration Regulation Law." Ministry of the Environment.

50. Annual Report (White Paper): "Quality of the Environment in Japan" (2003) Ministry of the Environment.

51. NS 8176 (1999): "Vibration and shock – measurement of vibration in buildings from land based transport and guidance to evaluation of its effects on human beings." Norwegian Council for Building Standardization

52. SOSFS (1996) 7/E: "General guidelines issued by the Swedish National Board of Health and Welfare: 7/E Indoor Noise and High Sound-Levels." Socialstyrelsen (Swedish National Board of Health and Welfare).

53. DNR.S02-4235/SA60 (2002): "Buller och Vibrationer, Fran Sparburen Linjetrafik." Banverket (Swedish Railway Administration).

54. ERM Group, Inc (2004). "EARL: Noise and Vibration Briefing Note."

55. RPS Planning Transport & Environment (2005). "Brighton and Hove Wastewater Treatment Works Environmental Statement."

56. Ungar, E. E., Sturz, D. H., and Amick, C. H., "Vibration Control Design of High Technology Facilities," *Sound and Vibration*, July 1990, pp.20-27.

57. "AISC Steel Design Guide No. 11," Chapter 6, Design for Sensitive Equipment, 1997, pp. 45-46.

58. "1999 ASHRAE Handbook," Chapter 46, Sound and Vibration Control, p. 43.

59. Hessler, G. (2004) "Proposed Criteria in Residential Communities for Low-Frequency Noise Emissions from Industrial Sources," *Noise Control Engineering Journal*, Vol. 52(4), pp. 179-185.

60. Bellman, M. (2002) "Perceptions of Whole-Body Vibrations: From basic experiments to effects of seat and steering-wheel vibrations on the passenger's comfort inside vehicles," Doctoral Dissertation, University of Oldenberg.

61. Degen, K.G., Behr, W., and Grutz, H-P. (2004) "Investigations and Results Concerning Railway-induced Vibrations at Deutsche Bahn," *ISVR Eighth International Workshop on Railway Noise,* Vol. 1, pp. 357-365.

62. Morihara, T., Sato, T., Yano, T., (2004) "Comparison of Dose-Response Relationships Between Railway and Road Traffic Noises: The Moderating Effect of Distance," *Journal of Sound and Vibration*, Vol. 277, pp. 559-565.

63. Nelson, James T. (1997) "TCRP Wheel/Rail Noise Control Manual," National Academy Press, Washington DC, 1997.

64. Persson, K, and Bjorkman, M. (1988) "Annoyance Due to Low Frequency Noise and the Use of the dB(A) Scale," *Journal of Sound and Vibration*, Vol. 127(3), pp. 491-497.

65. Schomer, P. (2004) "The Importance of Proper Integration and of Emphasis on the Low-Frequency Sound Energies for Environmental Noise Assessment," *Noise Control Engineering Journal*, Vol. 52(1), pp. 26-39.

66. Fidell, S., Horonjeff, R., Schultz, T., and Teffeteller, S. (1983) "Community Response to Blasting," *Journal of the Acoustical Society of America*, 74(3), pp. 888-893.

67. Fidell, S. and Silvati, L. "Parsimonious alternatives to regression analysis for characterizing prevalence rates of aircraft noise annoyance," *Noise Control Eng. J.*, 52 (2), 2004 Mar–Apr.

68. "Human Response to Vibration in Residential Environments," Department of Environment, Food and Rural Affairs, UK, March 2007.

69. Tabachnick, B., and Fidell, L. "Using Multivariate Statistics," Allyn and Bacon, Fifth Edition, 2007.

APPENDIX A

INTERVIEW AREAS
AND
MEASUREMENT LOCATION SUMMARY

A.1. INTRODUCTION

Community interviews and vibration measurements were done at five transit system locations,

1. Metropolitan Transportation Authority (MTA), New York City (Brooklyn)
2. Dallas Area Regional Transit (DART)
3. Sacramento Regional Transit
4. Toronto Transit Commission (TTC)
5. Massachusetts Bay Transportation Authority (MBTA), Boston

A.1.1 New York City (Brooklyn)

Agency:	Metropolitan Transportation Authority (New York City Transit)
System:	F Line
Mode:	Heavy Rail
Alignment:	Underground tunnel, cut and cover
Train Service:	8/10-car consists (180 m), approximately 390 events per day
Interview Area:	Park Slope area of Brooklyn. See Figure A-1.
Interview Sites:	281, see Figure A-2.
Measurement Locations:	11 residential, see Figure A-3.
	19 grid, see Figure A-4.
Building Type:	Predominantly 3-4 story brownstone. Some small apartment buildings. See Figure A-5.

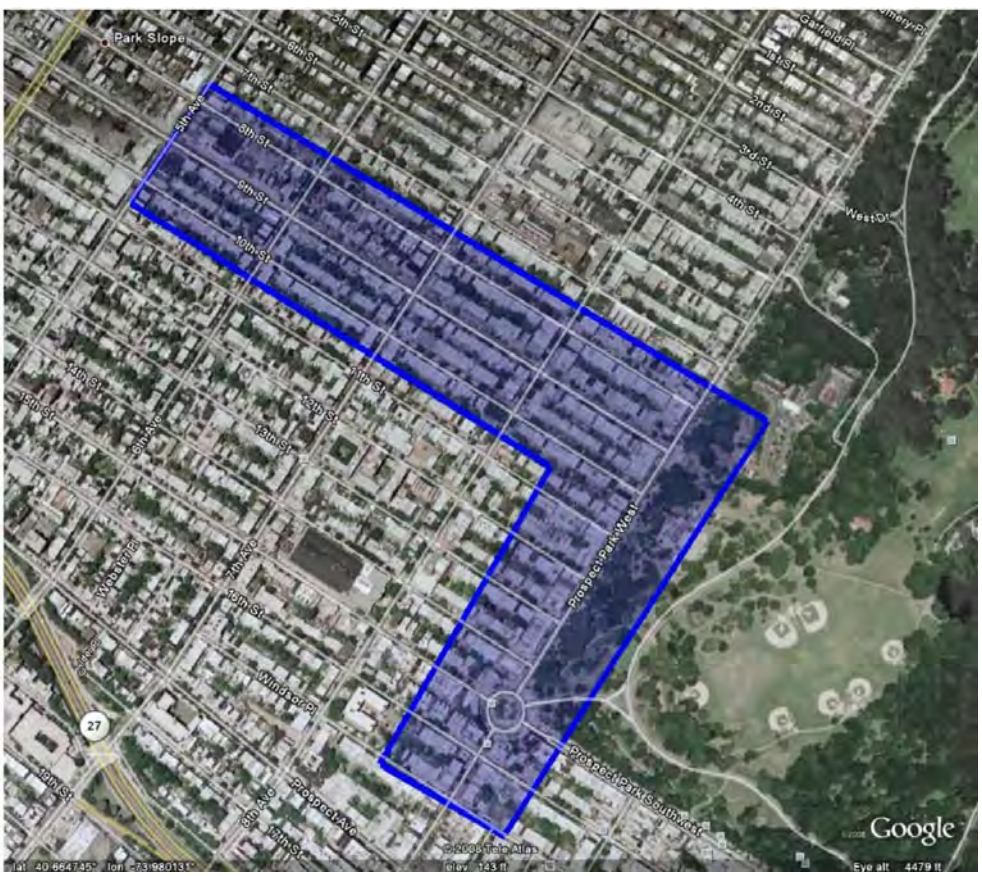

Figure A-1: New York Interview Area

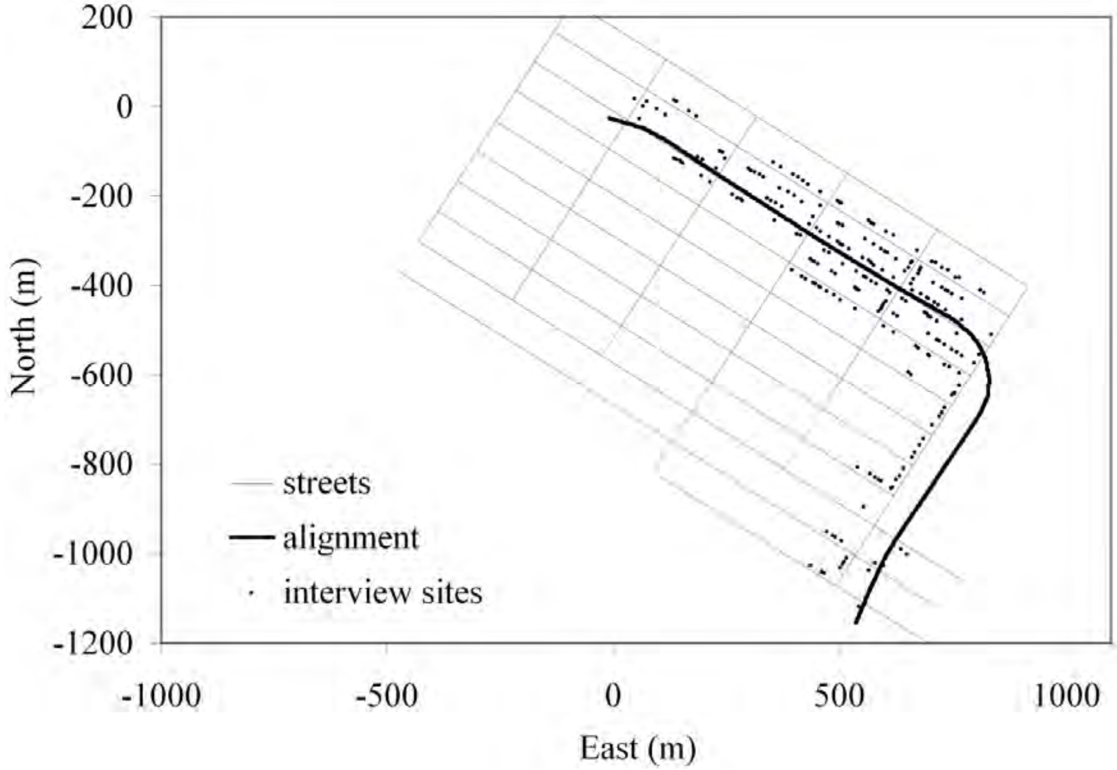

Figure A-2: New York Interview Sites

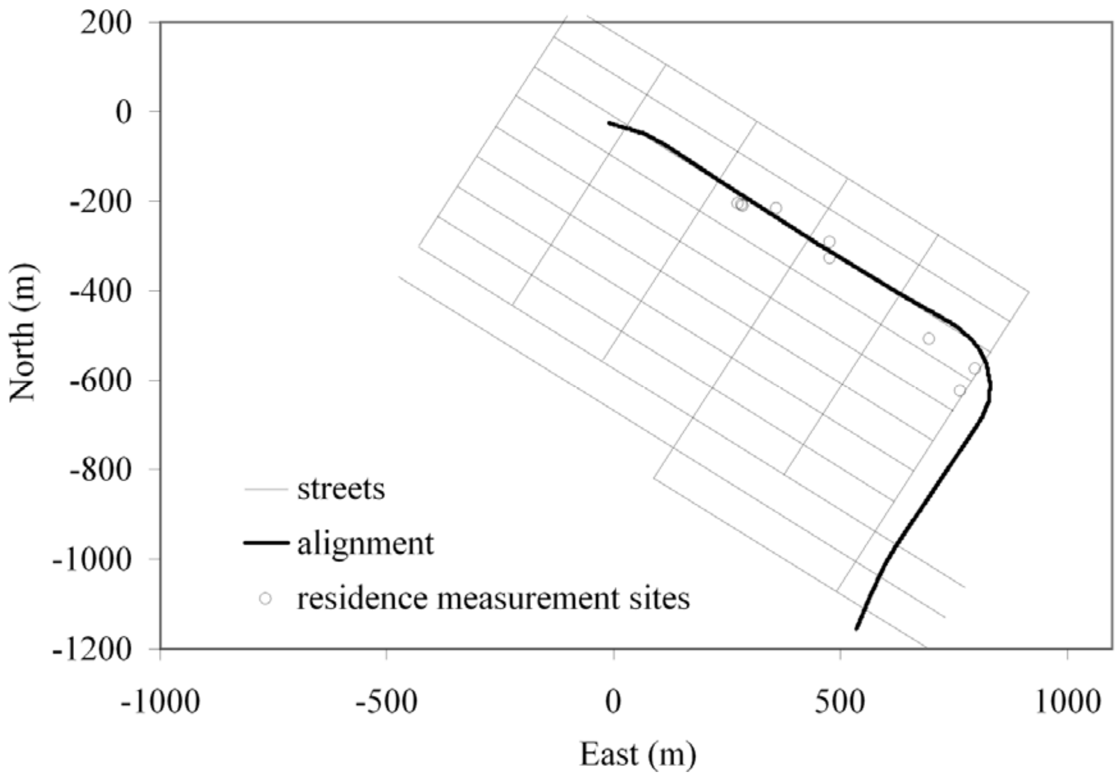

Figure A-3: New York Residence Measurement Locations

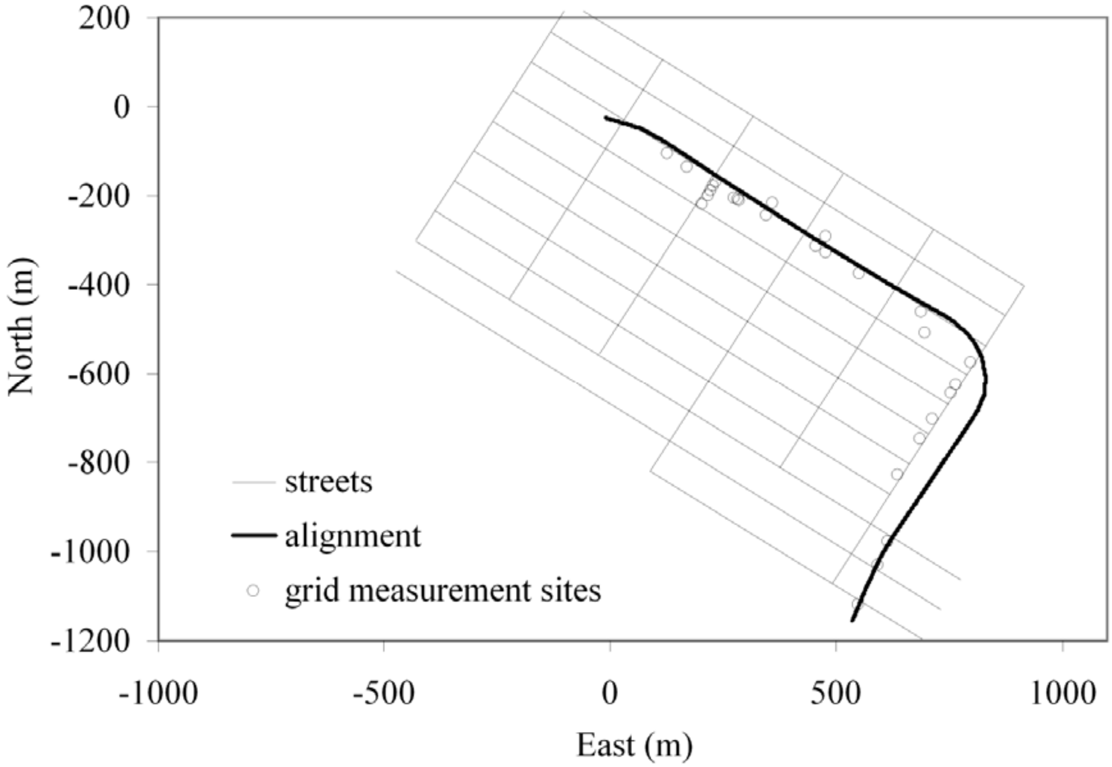

Figure A-4: New York Grid Measurement Locations

Figure A-5: New York Typical Residential Construction

A.1.2 Dallas Area Regional Transit (DART)

Agency:	Dallas Area Regional Transit (DART)
System:	Red Line, Blue Line
Mode:	Light Rail
Alignment:	Surface
Train Service:	1-3 car consists (22 m - 69 m) events/day 170 Red, 160 Blue
Interview Area:	Red Line: Southwest Dallas near W. Illinois Ave, and S. Hampton Rd. See Figure A-6.
	Blue Line: Northeast Dallas near E. Mockingbird Ln. and Abrams Rd. See Figure A-7.
Interview Sites:	Red Line: 33, see Figure A-8.
	Blue Line: 70, see Figure A-9.
Measurement Locations:	Red Line: 1 residential, 6 grid, see Figure A-10.
	Blue Line: 3 residential (1 measurement of opportunity with no survey), 8 grid, see Figure A-11.
Building Type:	Predominantly single family detached, one story, wood frame. See Figure A-12.

Figure A-6: DART Red Line Interview Area

Figure A-7: DART Blue Line Interview Area

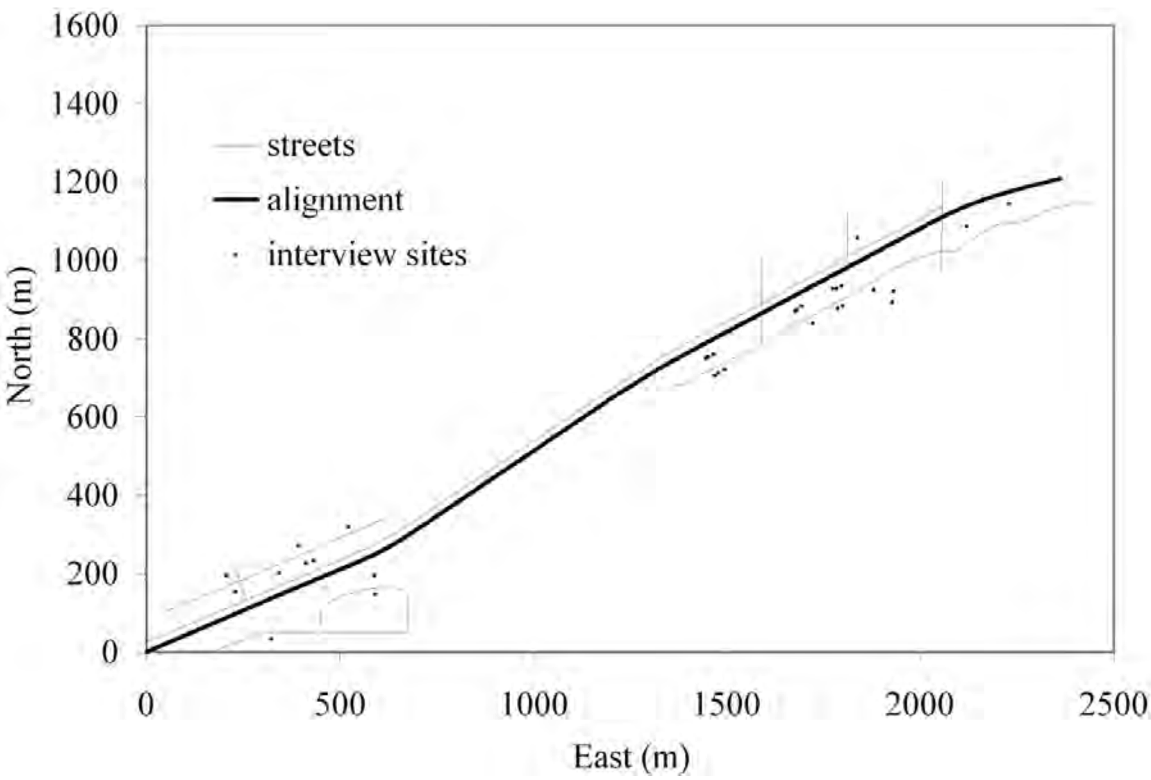

Figure A-8: DART Red Line Interview Sites

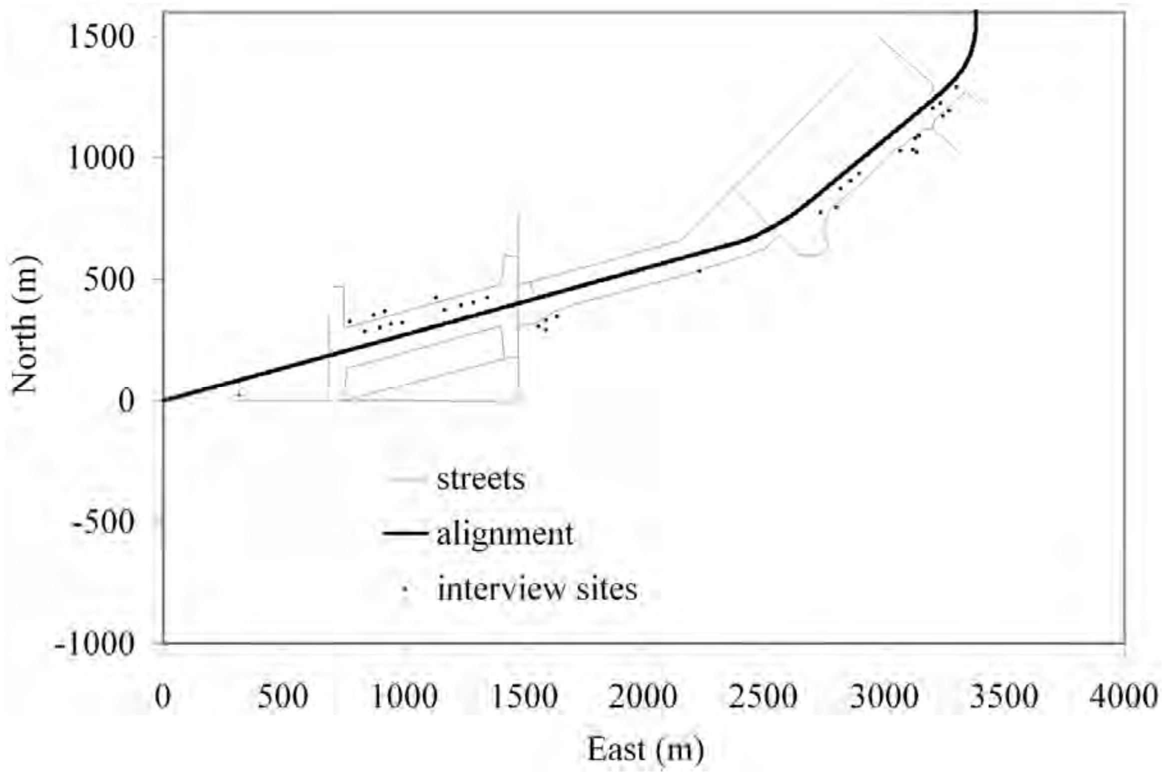

Figure A-9: DART Blue Line Interview Sites

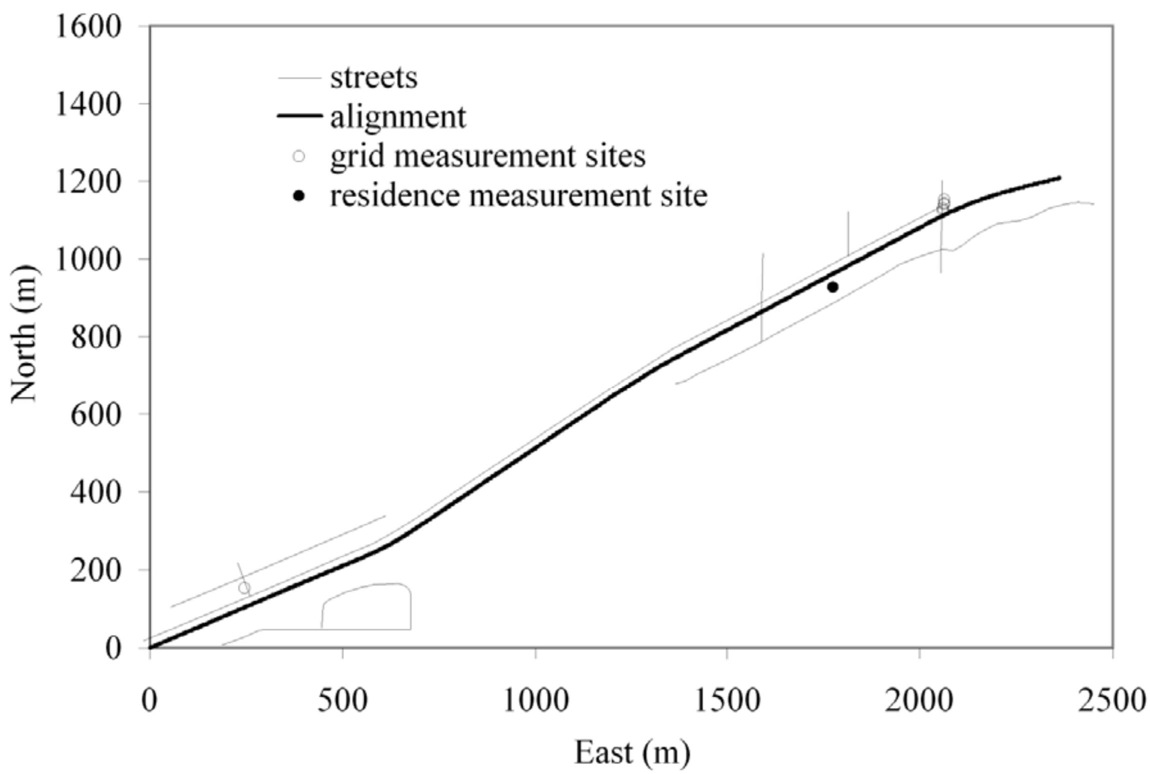

Figure A-10: DART Red Line Grid and Residence Measurement Locations

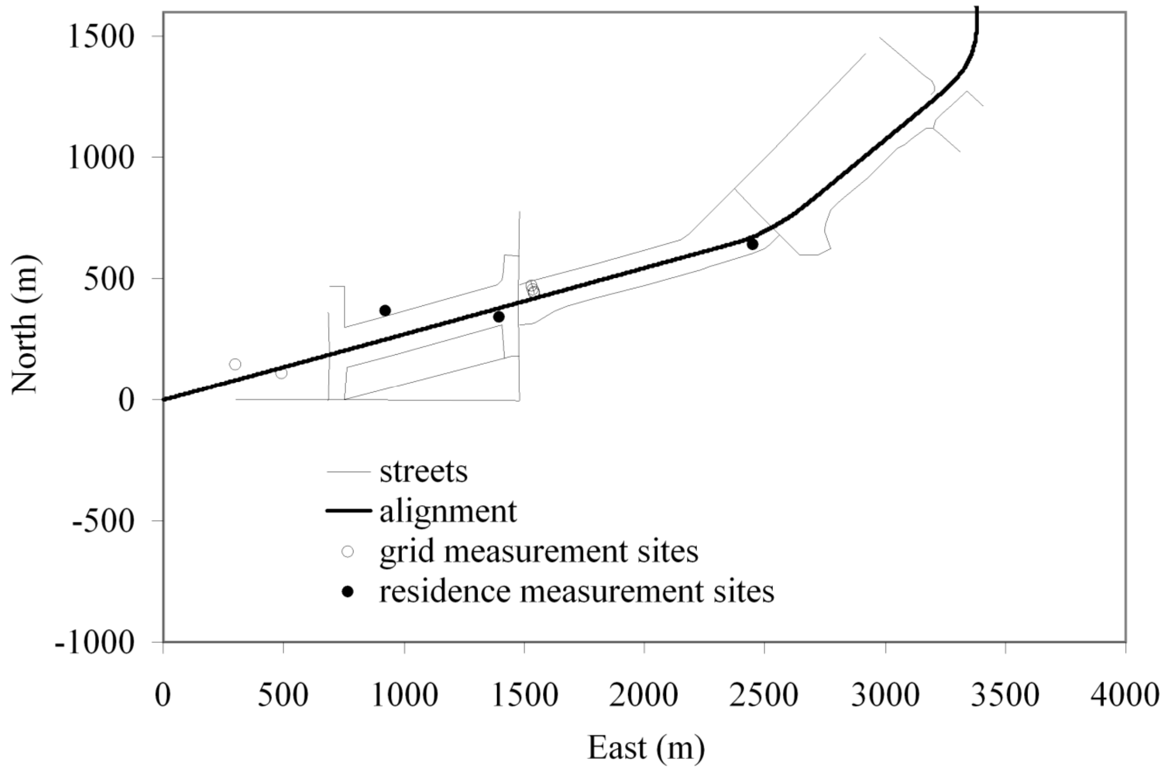

Figure A-11: DART Blue Line Grid and Residence Measurement Locations

Figure A-12: DART Typical Residential Construction

A.1.3 Sacramento RT

Agency:	Sacramento Regional Transit
System:	Blue Line, Gold Line
Mode:	Light Rail, Freight Rail
Alignment:	Surface
Train Service:	2-4 car consists (25 m - 50 m), events/day: 130 Blue, 140 Gold
	Infrequent freight service.
Interview Area:	Blue Line: South Sacramento, 35th Ave. and 28th St. See Figure A-13.
	Gold Line Area #1: East Sacramento, Q St. and 48th St. See Figure A-14.
.	Gold Line Area #2: East Sacramento, Trujillo Way and Starfire Dr. See Figure A-15.
	Gold Line Area #3: East Sacramento, Olson Dr. and Mills Park Dr. See Figure A-16.
Interview Sites:	Blue Line: 9, see Figure A-17.
	Gold Line: 27, see Figure A-18 and Figure A-19.
Measurement Locations:	Blue Line: 3 residential, 9 grid, see Figure A-20.
	Gold Line: 2 residential, 10 grid, see Figure A-21 and Figure A-22.
Building Type:	Predominantly single family detached, one story, wood frame. See Figure A-23.

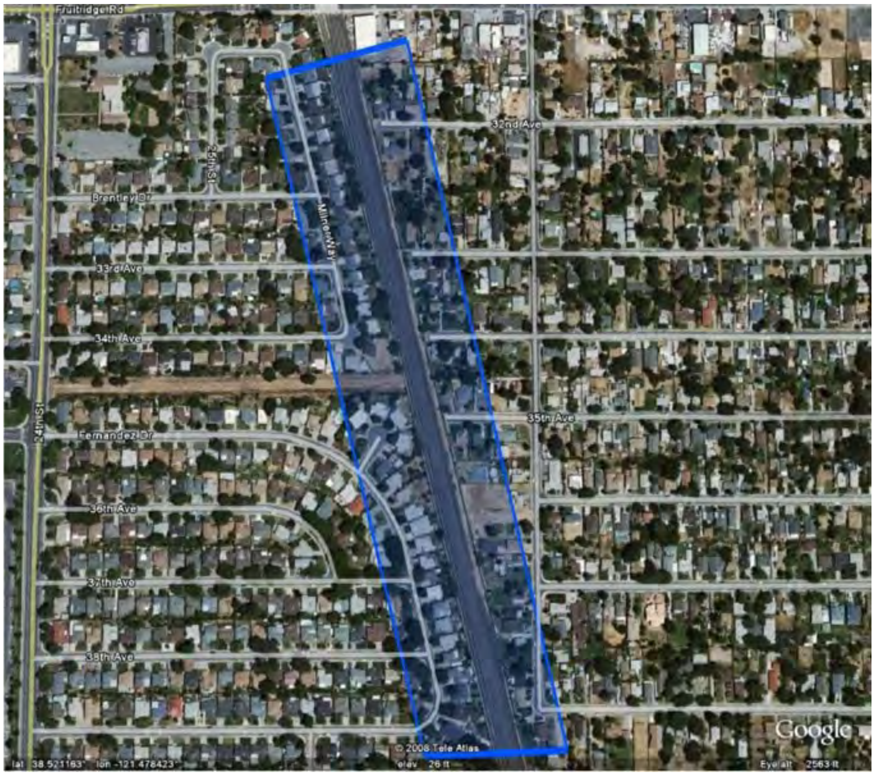

Figure A-13: Sacramento RT Blue Line Interview Area

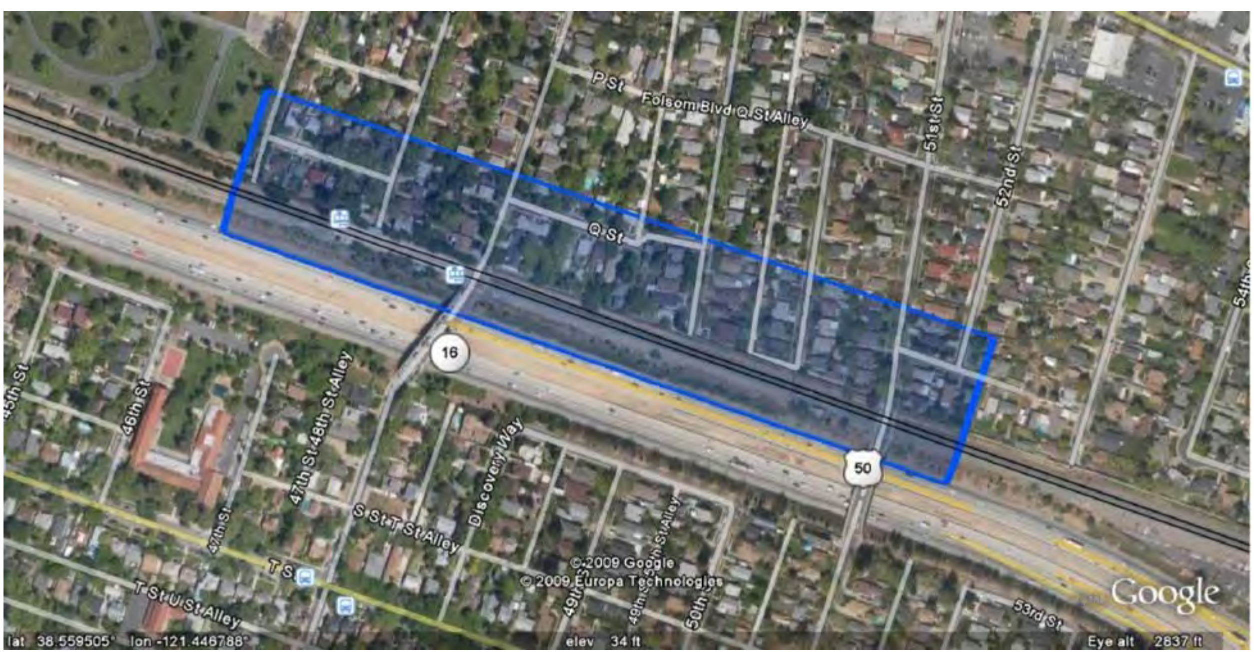

Figure A-14: Sacramento RT Gold Line Interview Area #1

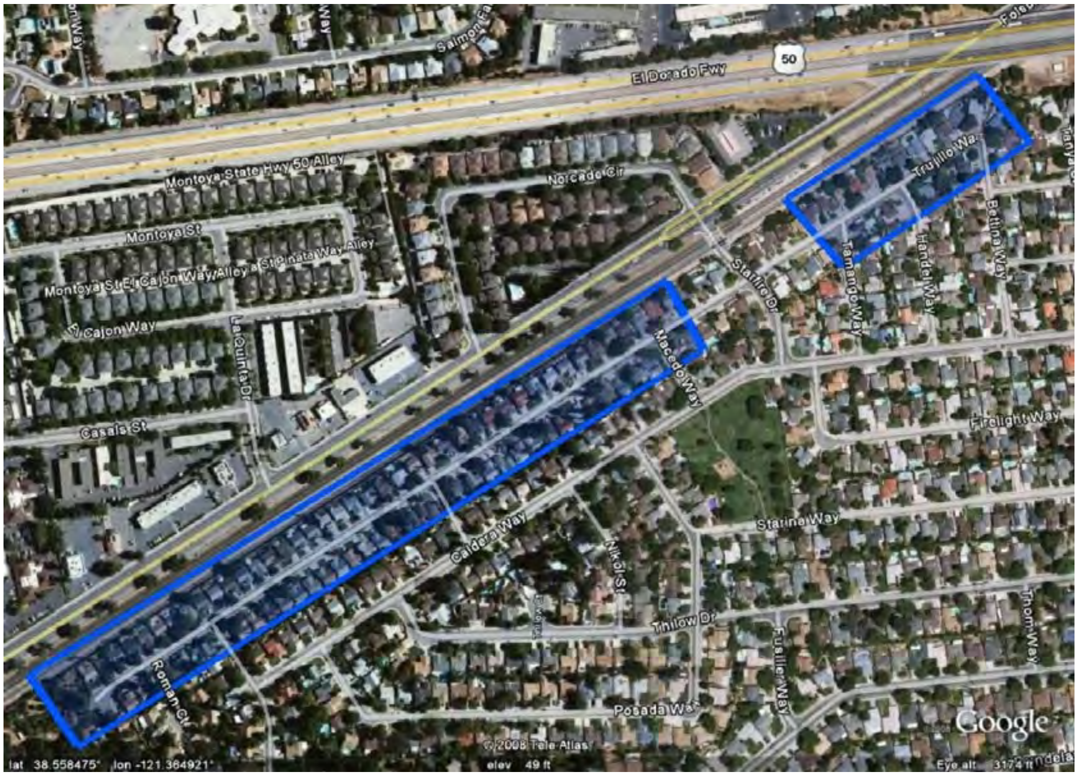

Figure A-15: Sacramento RT Gold Line Interview Area #2

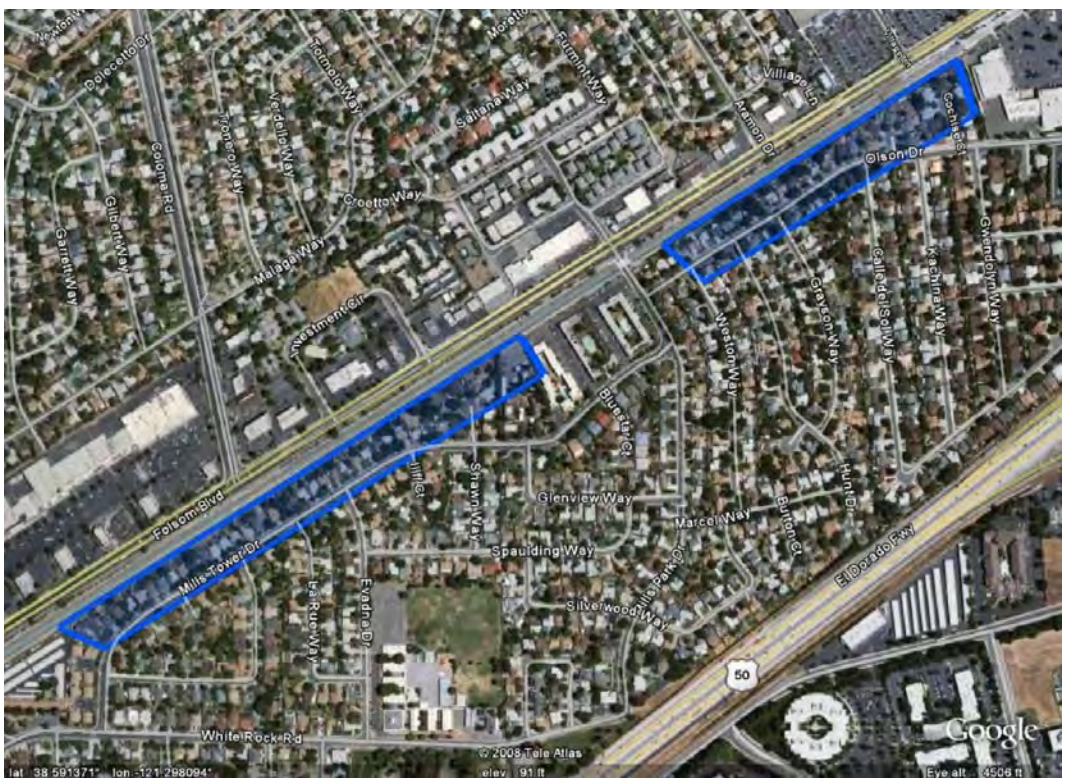

Figure A-16: Sacramento RT Gold Line Interview Area #3

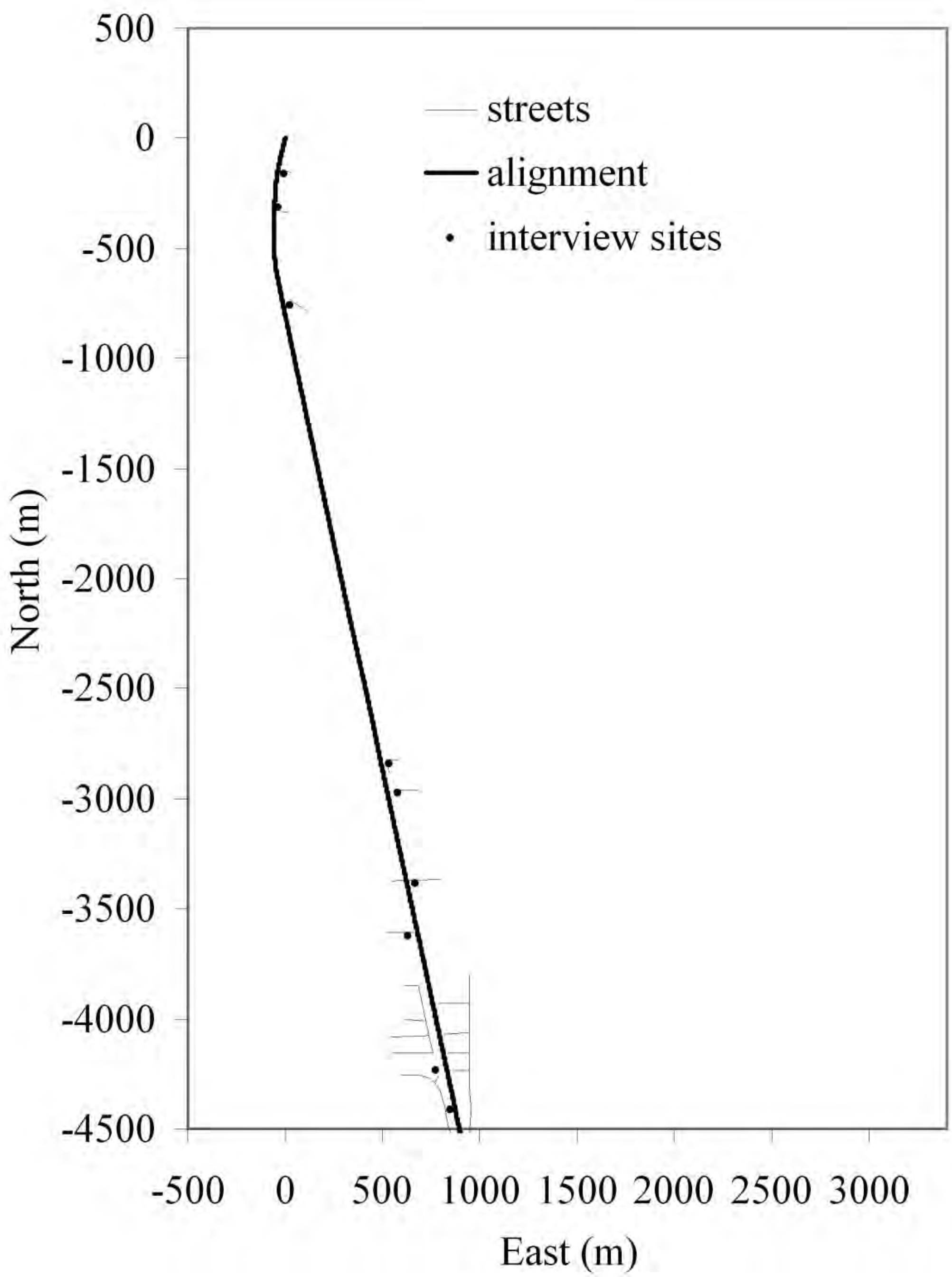

Figure A-17: Sacramento RT Blue Line Interview Sites

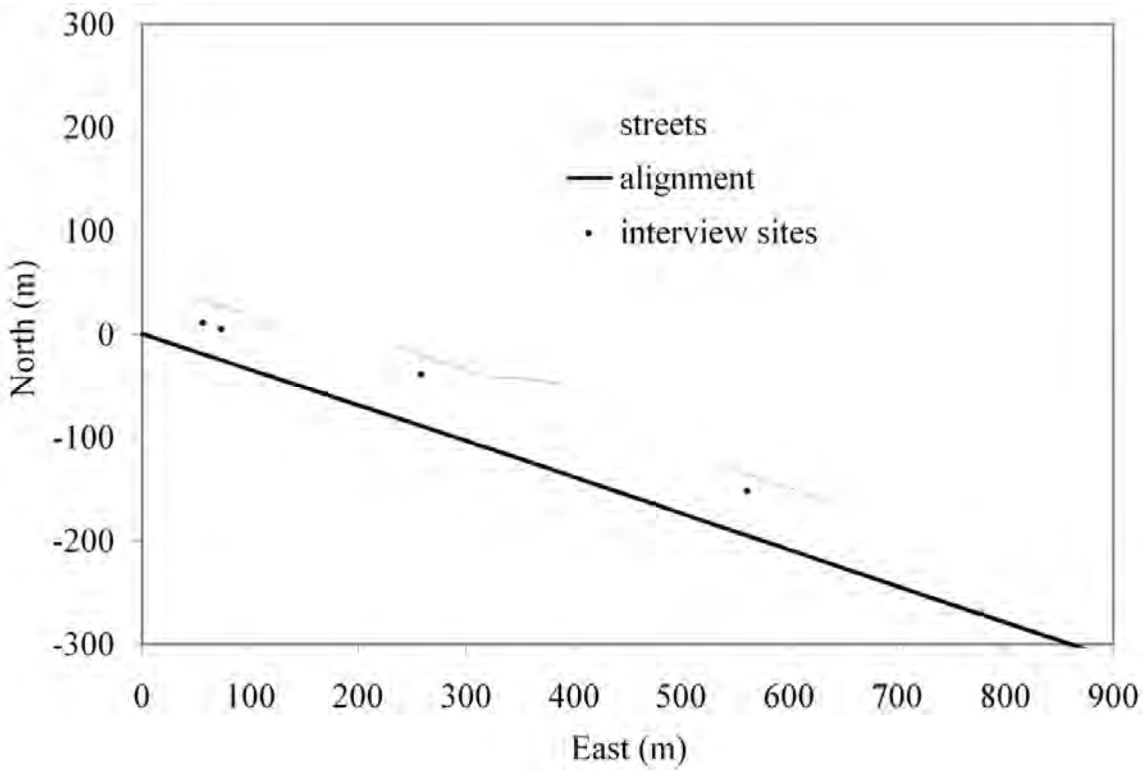

Figure A-18: Sacramento RT Gold Line Area #1 Interview Sites

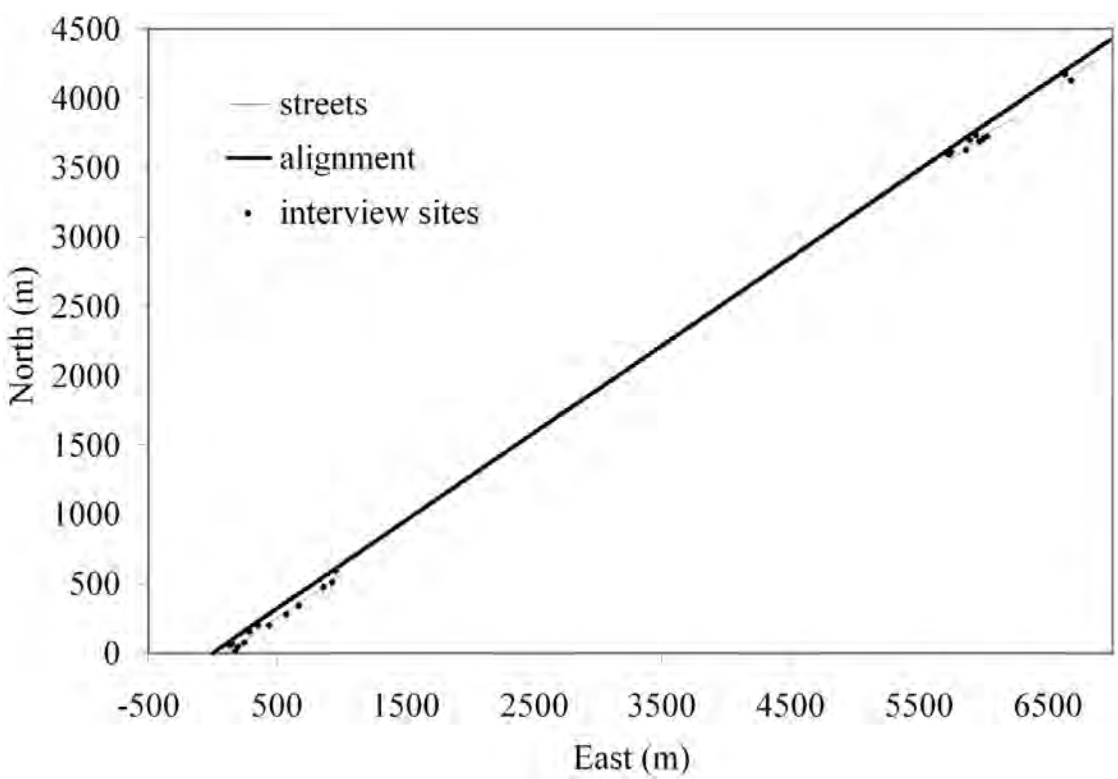

Figure A-19: Sacramento RT Gold Line Area #2, #3 Interview Sites

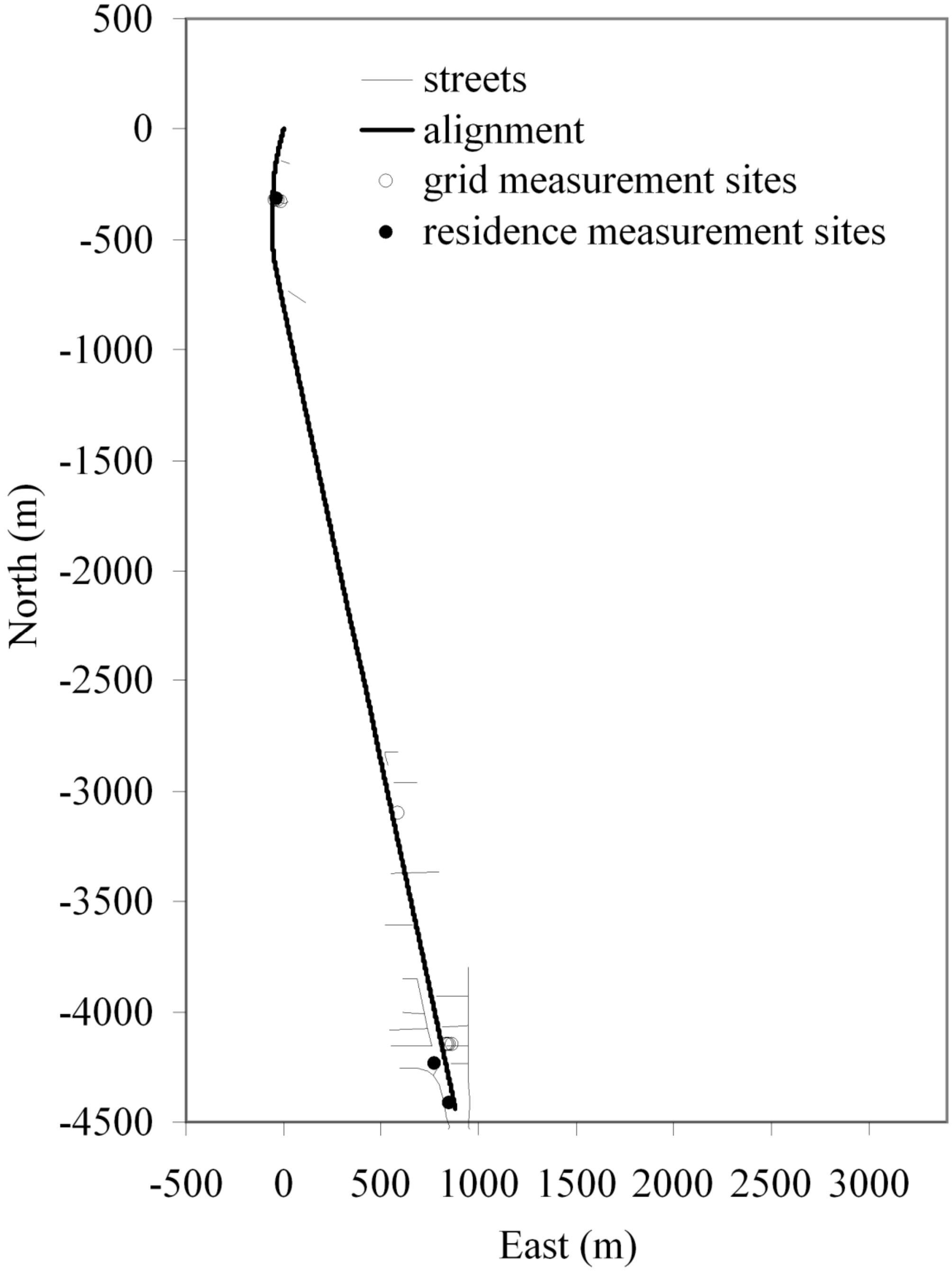

Figure A-20: Sacramento RT Blue Line Grid and Residence Measurement Locations

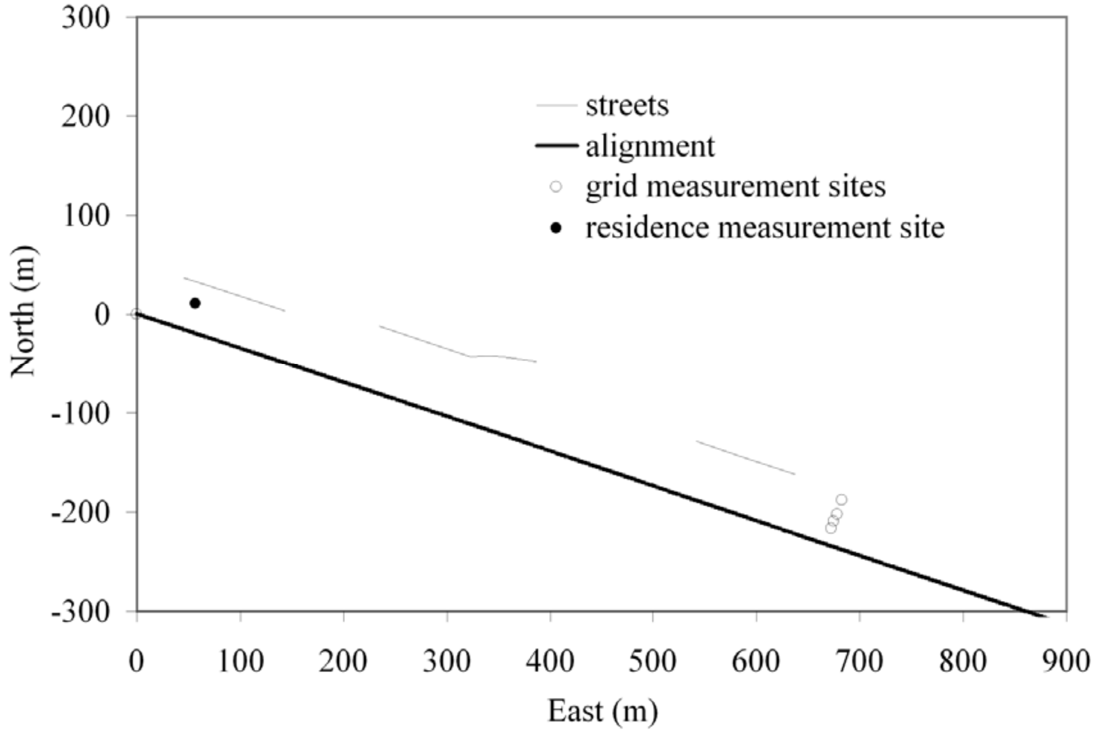

Figure A-21: Sacramento RT Gold Line Area #1 Grid and Residence Measurement Locations

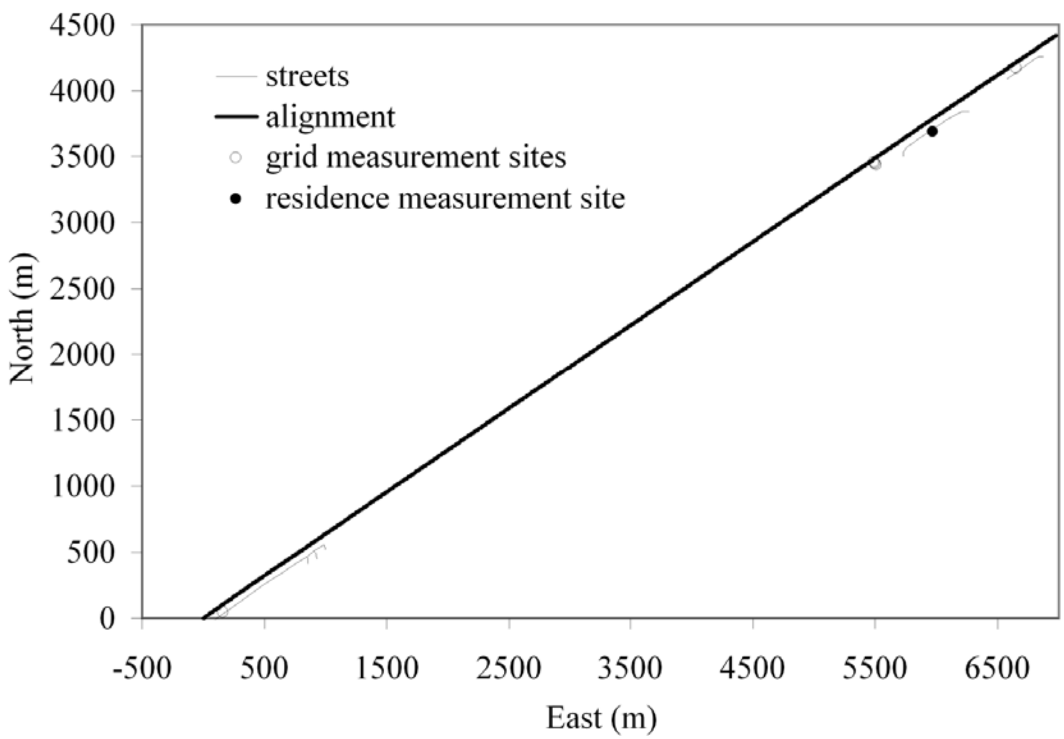

Figure A-22: Sacramento RT Gold Line Area #2, #3 Grid and Residence Measurement Locations

Figure A-23: Sacramento RT Typical Residential Construction

A.1.4 Toronto TTC

Agency:	Toronto Transit Commission (TTC)
System:	Bloor/Danforth Line
Mode:	Heavy Rail
Alignment:	Underground tunnel, cut and cover
Train Service:	6-car consists (140 m), approximately 660 events per day
Interview Area:	East Toronto, north of Danforth Ave. from Pape Ave. to Main St. See Figure A-24.
Interview Sites:	582, see Figure A-25.
Measurement Locations:	13 residential, see Figure A-26.
	22 grid, see Figure A-27.
Building Type:	Predominantly 1-2 story wood frame, one and two-family. Some large apartment buildings. See Figure A-28.

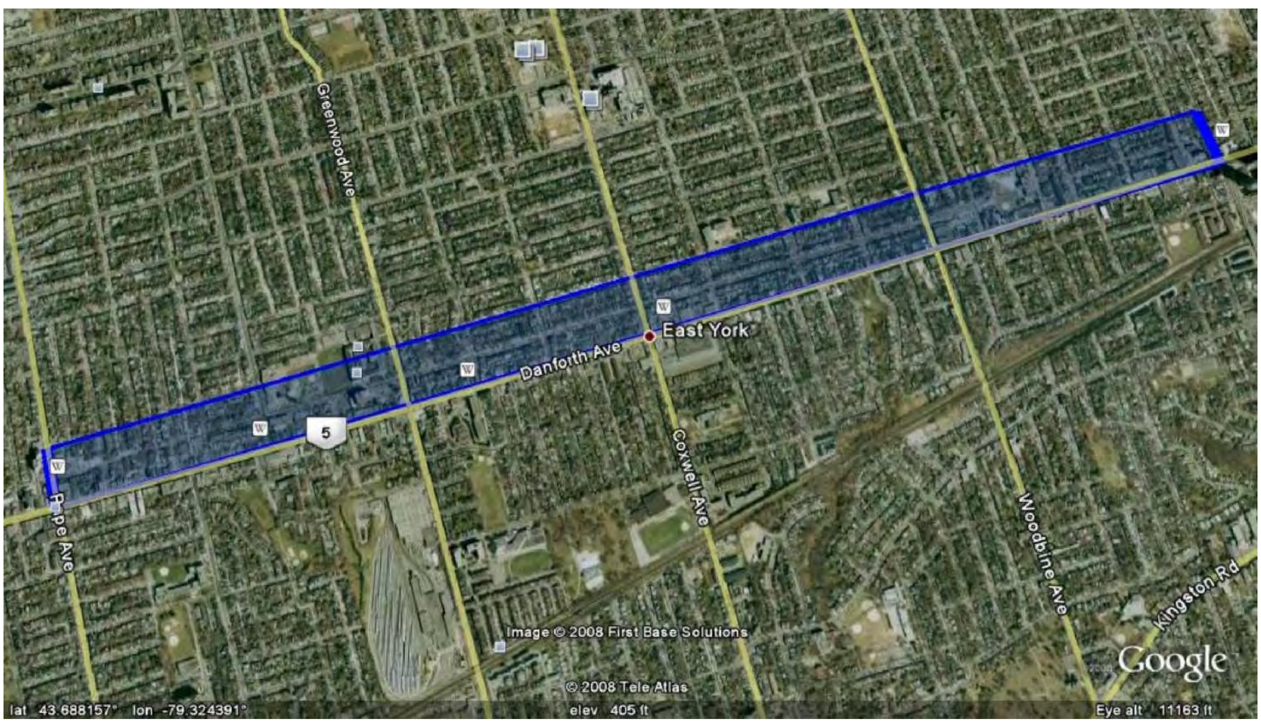

Figure A-24: Toronto Interview Area

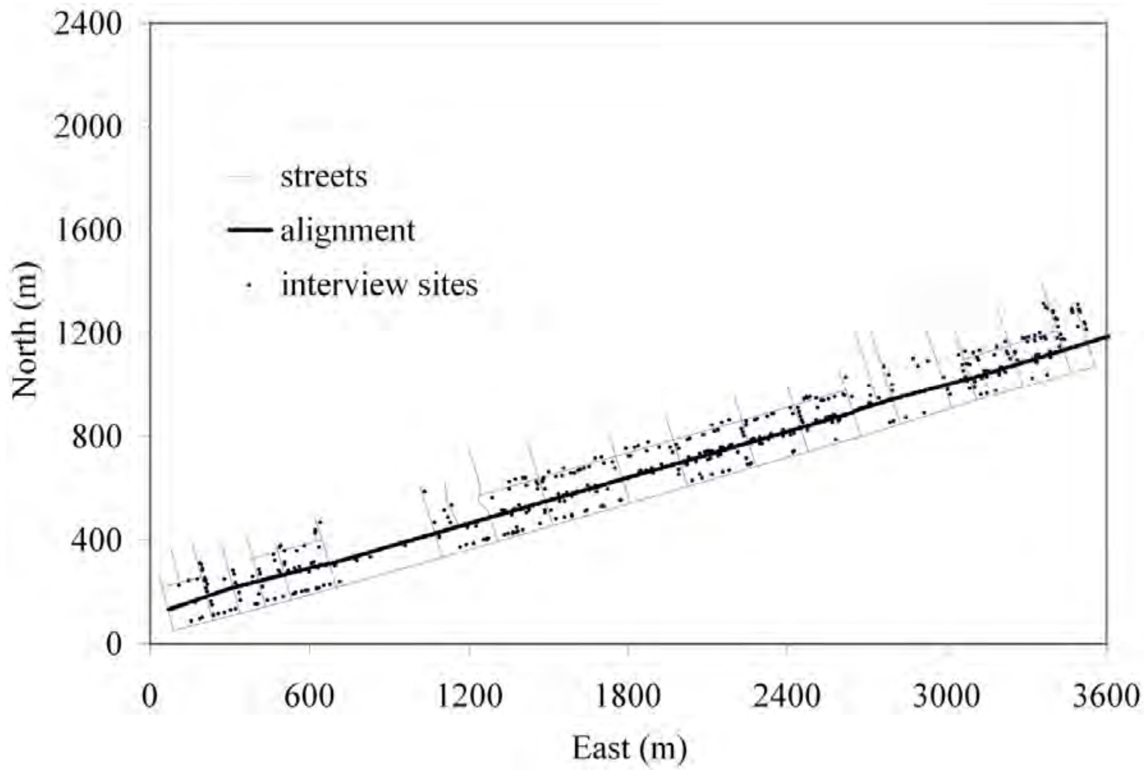

Figure A-25: Toronto Interview Sites

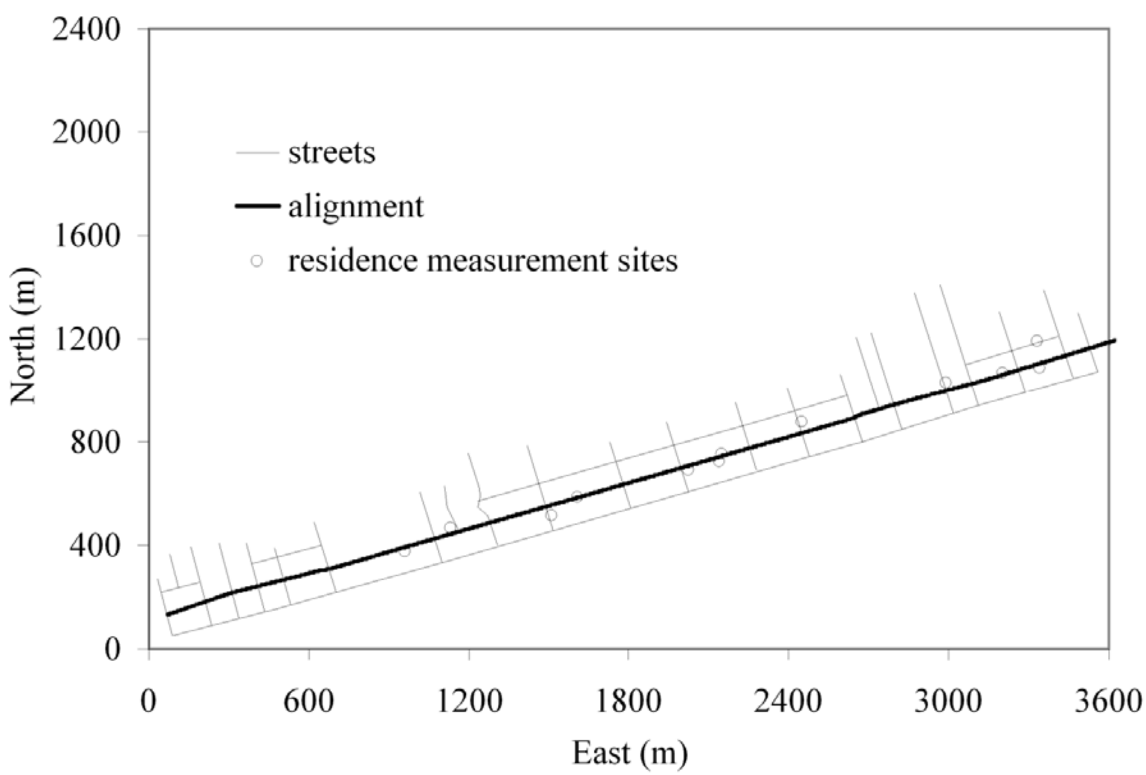

Figure A-26: Toronto Residence Measurement Locations

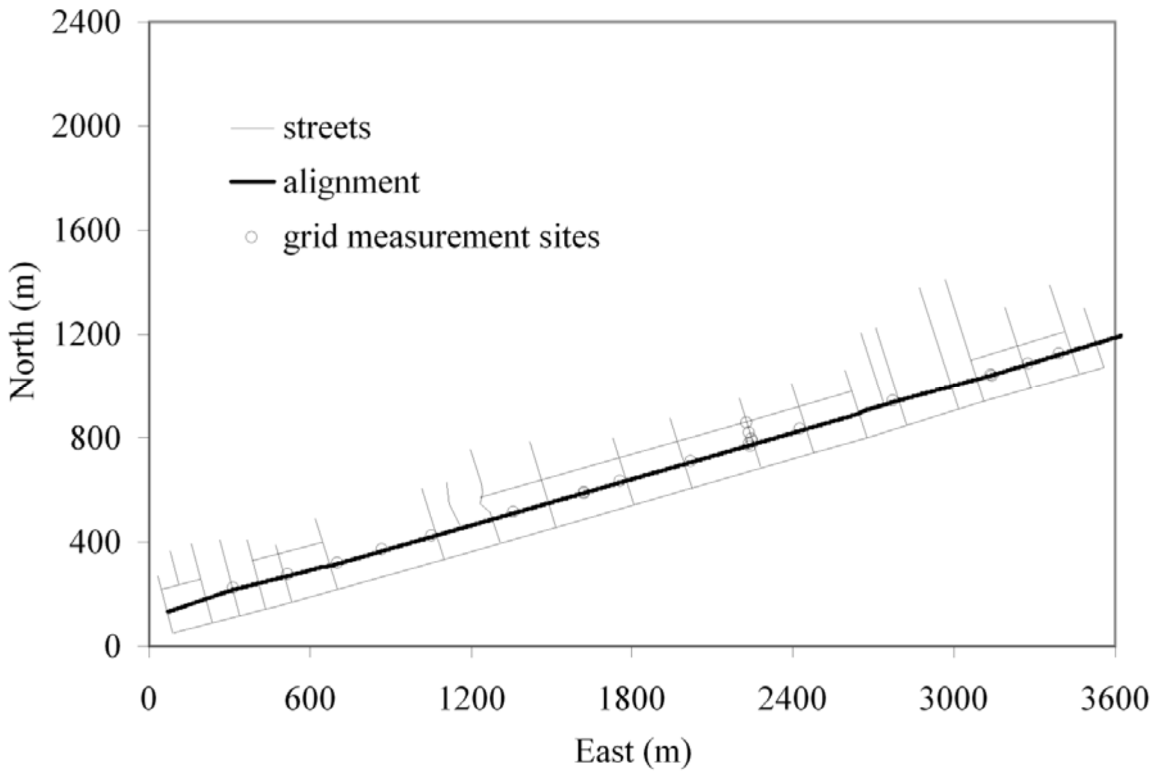

Figure A-27: Toronto Grid Measurement Locations

Figure A-28: Toronto Typical Residential Construction

A.1.5 Boston

Agency:	Massachusetts Bay Transportation Authority (MBTA)
System:	Orange Line, Commuter Rail, Amtrak, Blue Line
Mode:	Heavy Rail, Commuter Rail, Inter-city Passenger Rail
Alignment:	Underground tunnel, cut and cover
Train Service:	Orange Line: 6 car consists (120 m), 280 events/day Commuter Rail/Amtrak, (variable length), 170 events/day Blue Line: 4 car consists (60 m), 350 events/day
Interview Area:	Orange/Commuter Rail/Amtrak: Southwest Corridor, Back Bay section of Boston, east of Massachusetts Ave. and north of Columbus Ave. See Figure A-29. Blue Line: East Boston, Maverick St. and Chelsea St. See Figure A-30.
Interview Sites:	Orange Line/Commuter/Amtrak: 216, see Figure A-31. Blue Line: 88, see Figure A-32.
Measurement Locations:	Orange Line/Commuter/Amtrak: 7 residential, 16 grid, see Figure A-33 and Figure A-34. Blue Line: 6 residential, 10 grid, see Figure A-35 and Figure A-36.
Building Type:	Orange Line/Commuter/Amtrak : Predominantly 3-4 story brownstone, small apartment buildings, large apartment buildings. See Figure A-37. Blue Line: 2-3 story detached wood frame, some small apartment buildings. See Figure A-38.

Figure A-29: Boston Orange Line/Commuter Rail/Amtrak Interview Area

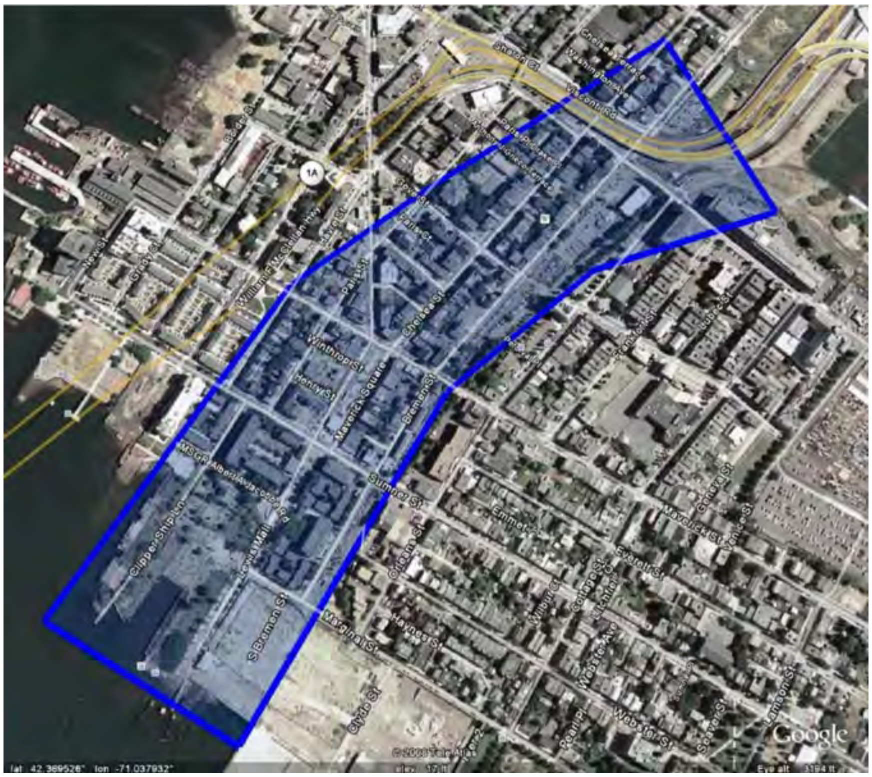

Figure A-30: Boston Blue Line Interview Area

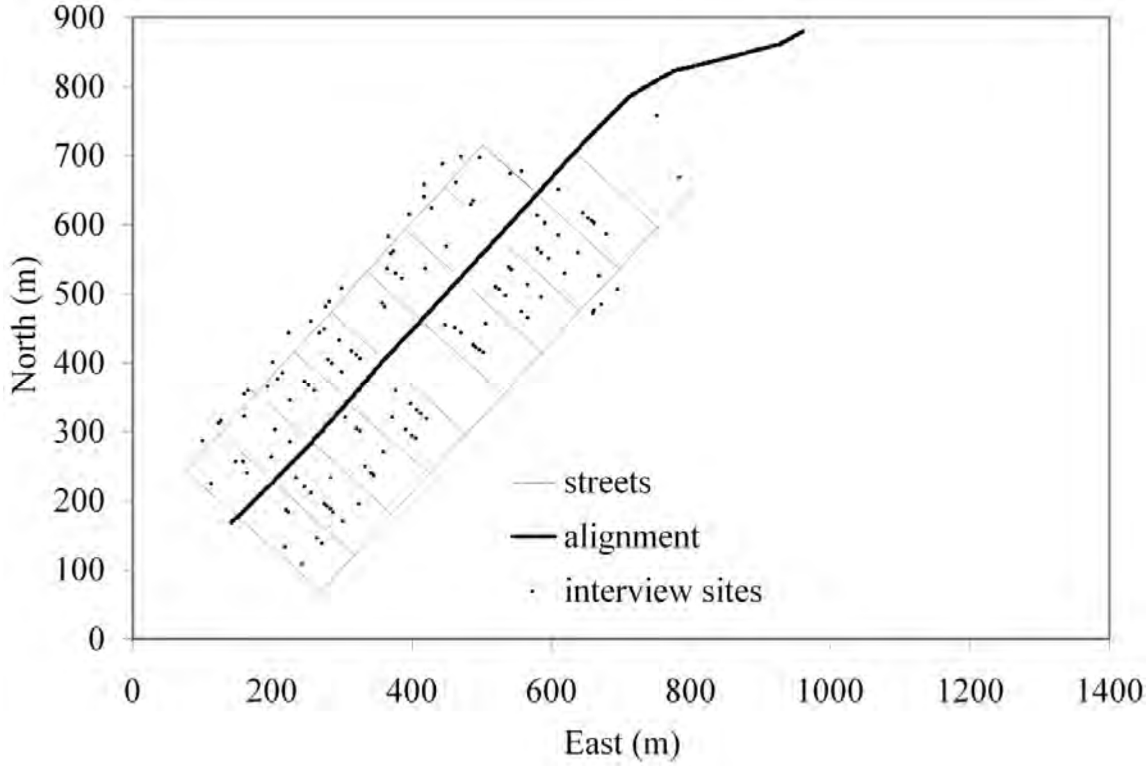

Figure A-31: Boston Orange Line/Commuter Rail/Amtrak Interview Sites

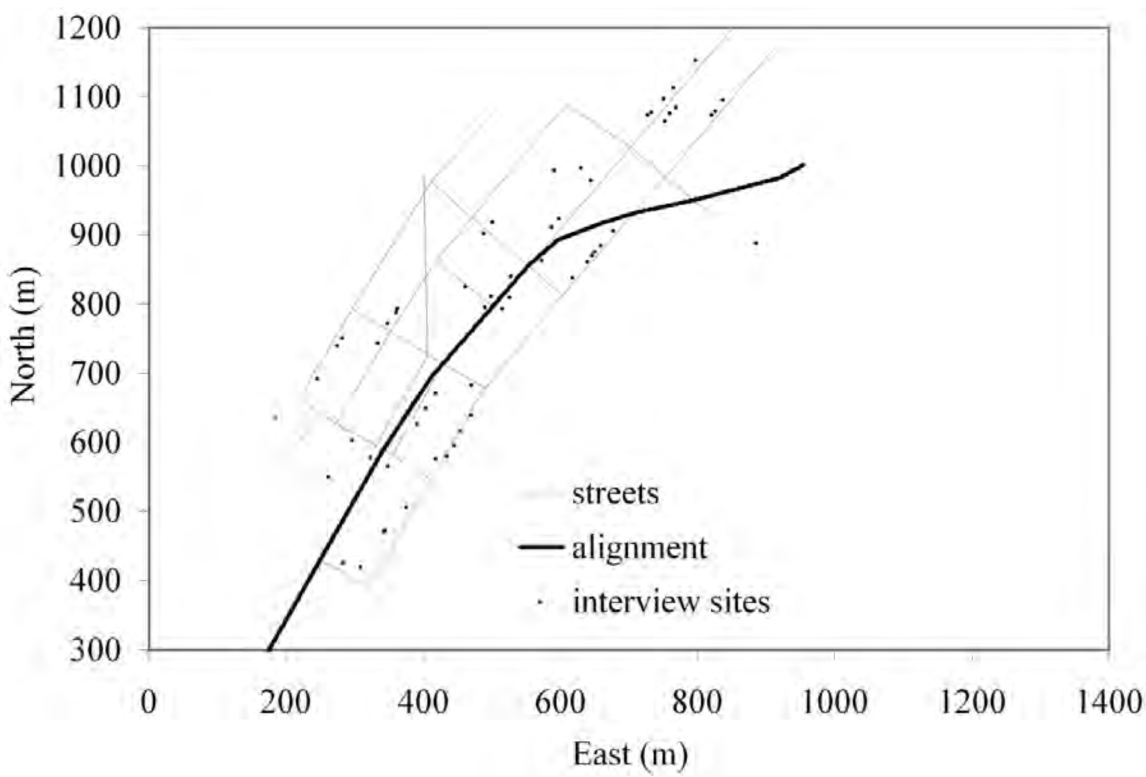

Figure A-32: Boston Blue Line Interview Sites

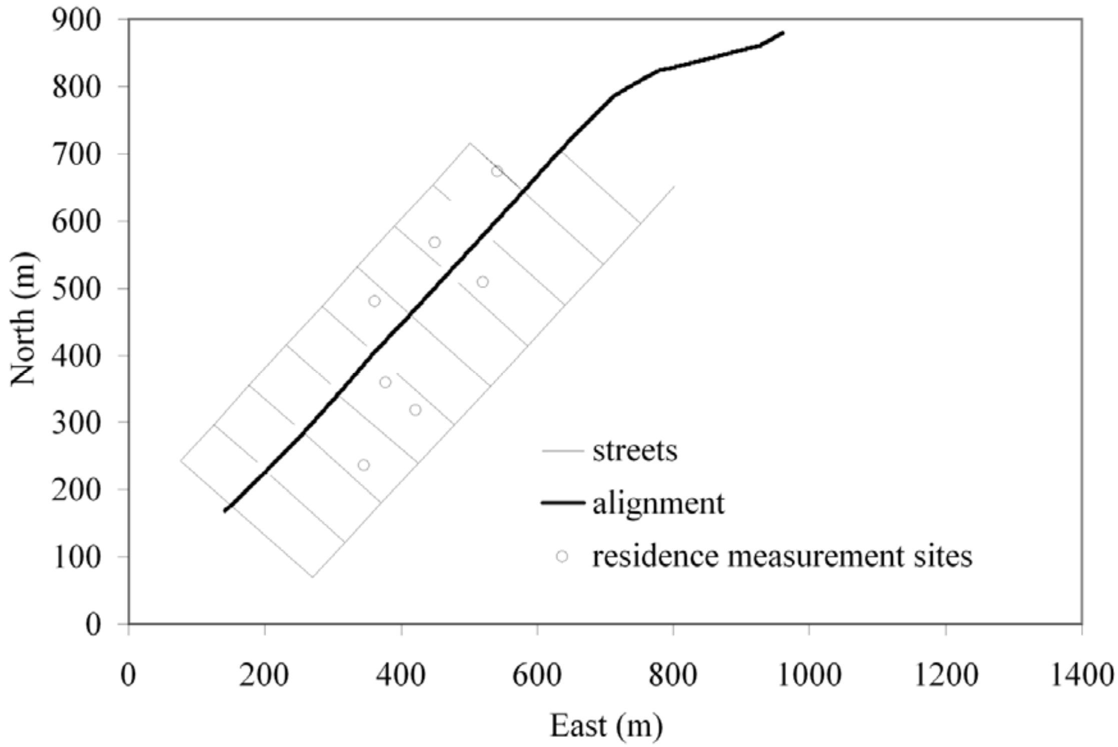

Figure A-33: Boston Orange Line/Commuter Rail/Amtrak Residence Measurement Locations

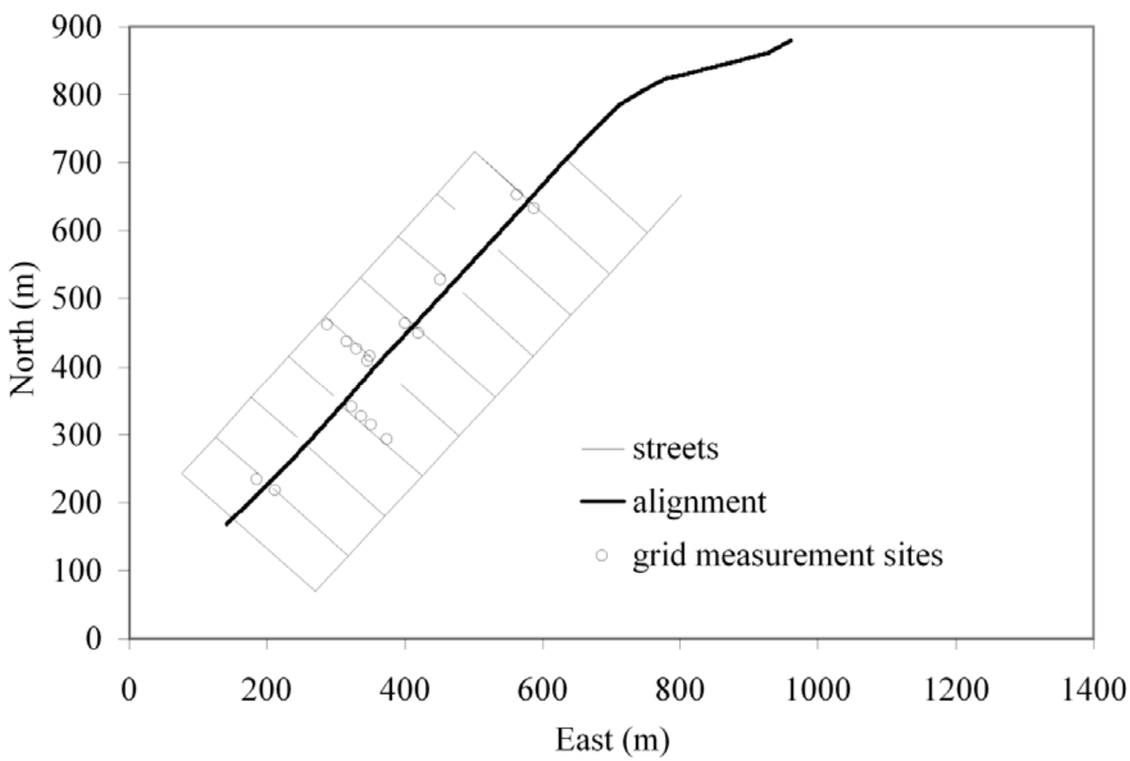

Figure A-34: Boston Orange Line/Commuter Rail/Amtrak Grid Measurement Locations

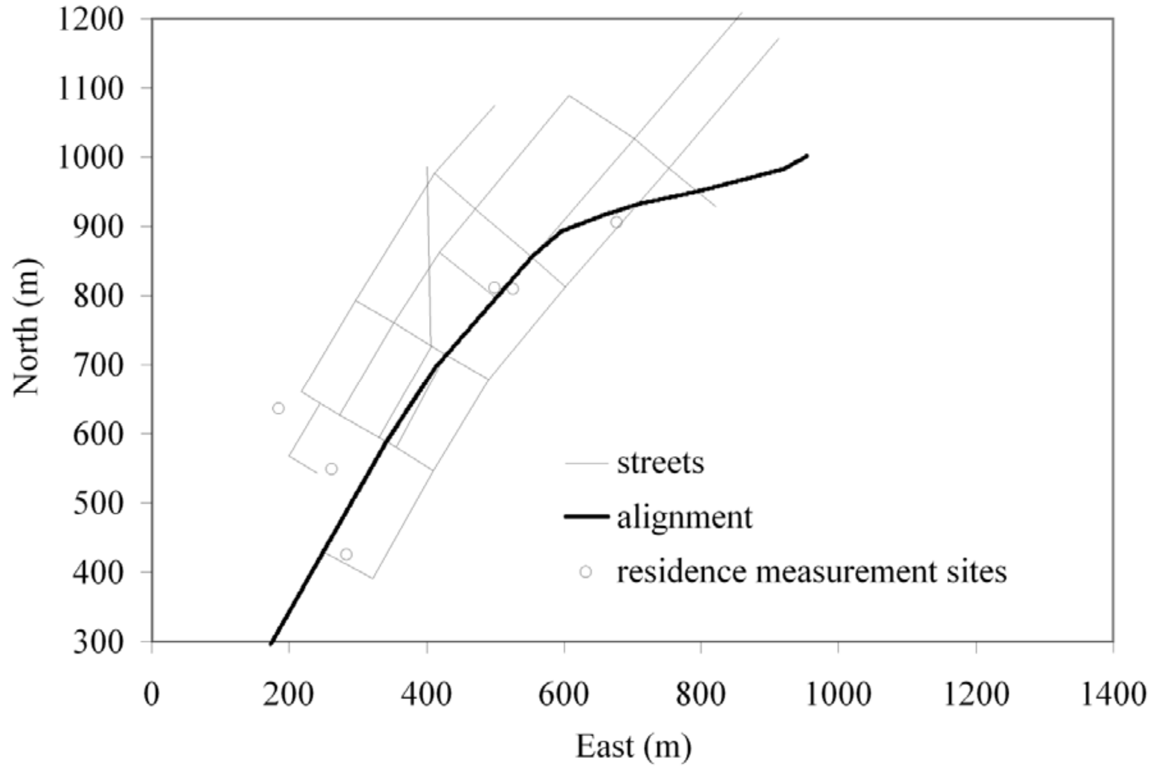

Figure A-35: Boston Blue Line Residence Measurement Locations

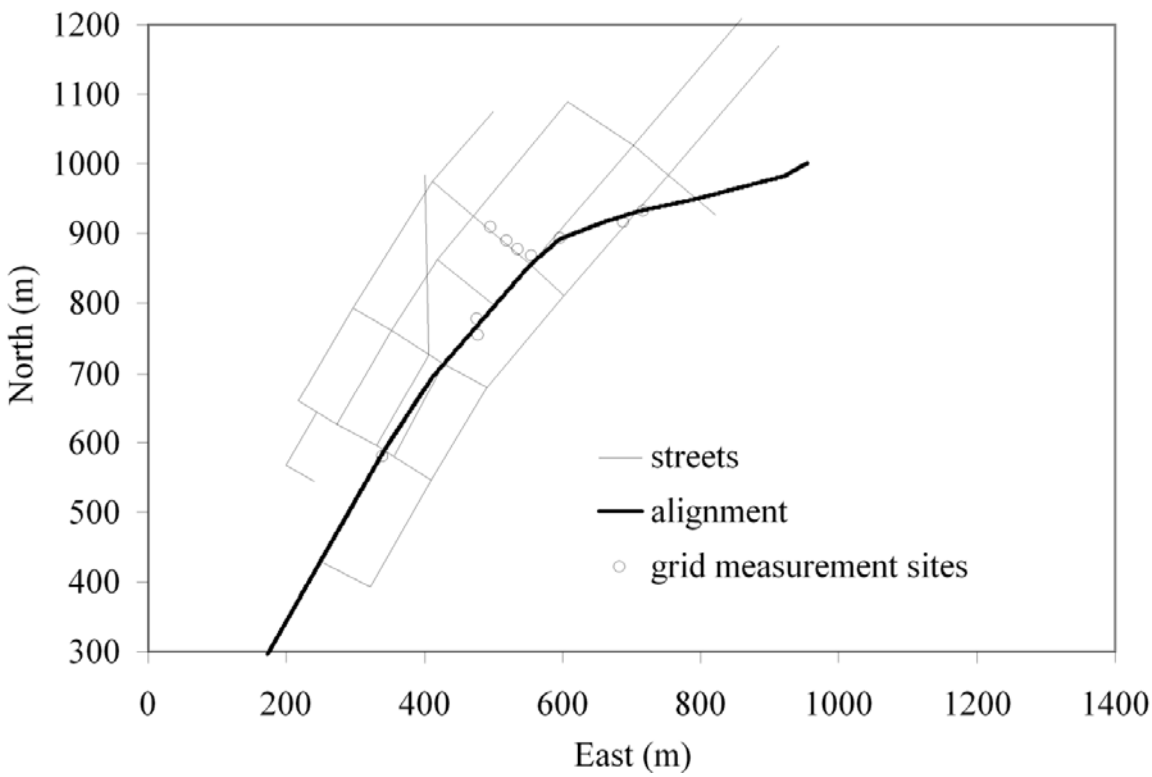

Figure A-36: Boston Blue Line Grid Measurement Locations

Figure A-37: Boston Orange Line/Commuter Rail/Amtrak Typical Residential Construction

Figure A-38: Boston Blue Line Typical Residential Construction

APPENDIX B

INTERVIEW QUESTIONNAIRE ITEMS

ITEM	NYC (BROOKLYN)	DALLAS	SACRAMENTO	TORONTO	BOSTON
1	Can you please tell me how long you have lived at (street address)?	Can you please tell me how long you have lived at (street address)?	Can you please tell me how long you have lived at (street address)?	Can you please tell me how long you have lived at (street address)?	Can you please tell me how long you have lived at (street address)?
2	What do you like most about living conditions in your neighborhood?	What do you like most about living conditions in your neighborhood?	What do you like most about living conditions in your neighborhood?	What do you like most about living conditions in your neighborhood?	What do you like most about living conditions in your neighborhood?
3	What do you like least about living conditions in your neighborhood?	What do you like least about living conditions in your neighborhood?	What do you like least about living conditions in your neighborhood?	What do you like least about living conditions in your neighborhood?	What do you like least about living conditions in your neighborhood?
4	While you’ve been at home over the past year, have you been bothered or annoyed by street traffic noise? (IF NO, SKIP TO ITEM 5)	While you’ve been at home over the past year, have you been bothered or annoyed by street traffic noise? (IF NO, SKIP TO ITEM 5)	While you’ve been at home over the past year, have you been bothered or annoyed by street traffic noise? (IF NO, SKIP TO ITEM 5)	While you’ve been at home over the past year, have you been bothered or annoyed by street traffic noise? (IF NO, SKIP TO ITEM 5)	While you’ve been at home over the past year, have you been bothered or annoyed by street traffic noise? (IF NO, SKIP TO ITEM 5)

ITEM	NYC (BROOKLYN)	DALLAS	SACRAMENTO	TORONTO	BOSTON
4A	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by street traffic noise while you've been at home over the past year?	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by street traffic noise while you've been at home over the past year?	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by street traffic noise while you've been at home over the past year?	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by street traffic noise while you've been at home over the past year?	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by street traffic noise while you've been at home over the past year?
5	While you’ve been at home over the past year, can you tell in any way when subway trains pass by underground? (IF NO, SKIP TO ITEM 11)	While you’ve been at home over the past year, have you been bothered or annoyed by the sounds that DART Rail trains make as they pass by outside your home? (IF NO, ASK ITEM 6 NEXT.)	While you’ve been at home over the past year, have you been bothered or annoyed by the sounds that Sacramento Light Rail trains make as they pass by outside your home? (IF NO, ASK ITEM 6 NEXT.)	While you’ve been at home over the past year, can you tell in any way when TTC subway trains pass by underground? (IF NO, SKIP TO ITEM 11)	While you’ve been at home over the past year, can you tell in any way when [Orange/Blue] line subway trains pass by underground? (IF NO, SKIP TO ITEM 11)

ITEM	NYC (BROOKLYN)	DALLAS	SACRAMENTO	TORONTO	BOSTON
5A	n/a	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by sounds made by DART Rail trains while you've been at home over the past year?	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by sounds made by Sacramento Light Rail trains while you've been at home over the past year?	n/a	n/a
6	Do you notice low rumbling sounds inside your home when subway trains pass by? (IF NO, SKIP TO ITEM 7)	Do you notice low rumbling sounds inside your home as DART Rail trains pass by outside? (IF NO, SKIP TO ITEM 8)	Do you notice low rumbling sounds inside your home as Sacramento Light Rail trains pass by outside? (IF NO, SKIP TO ITEM 8)	Do you notice low rumbling sounds inside your home when subway trains pass by? (IF NO, SKIP TO ITEM 7)	Do you notice low rumbling sounds inside your home when line subway trains pass by? (IF NO, SKIP TO ITEM 7)

ITEM	NYC (BROOKLYN)	DALLAS	SACRAMENTO	TORONTO	BOSTON
6A	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by low rumbling sounds inside your home when subway trains pass by?	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by low rumbling sounds inside your home as DART Rail trains pass by?	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by low rumbling sounds inside your home as Sacramento Light Rail trains pass by?	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by low rumbling sounds inside your home when subway trains pass by?	Would you say that you have been slightly annoyed, moderately annoyed, very annoyed, or extremely annoyed by low rumbling sounds inside your home when subway trains pass by?
7	Do you ever hear rattling sounds from windows, doors, wall hangings, or other items in your home when subway trains pass by? [IF NO, SKIP TO ITEM 8)	While you’ve been at home over the past year, have you ever been awakened by low rumbling sounds, rattling, shaking, or vibration inside your home when DART Light Rail trains pass by? (IF NO, SKIP TO ITEM 8)	While you’ve been at home over the past year, have you ever been awakened by low rumbling sounds, rattling, shaking, or vibration inside your home when Sacramento Light Rail trains pass by? (IF NO, SKIP TO ITEM 8)	Do you ever hear rattling sounds from windows, doors, wall hangings, or other items in your home when subway trains pass by? (IF NO, SKIP TO ITEM 8	Do you ever hear rattling sounds from windows, doors, wall hangings, or other items in your home when subway trains pass by? [IF NO, SKIP TO ITEM 8)

ITEM	NYC (BROOKLYN)	DALLAS	SACRAMENTO	TORONTO	BOSTON
7A	About how often do you hear rattling sounds in your home when subway trains pass by?	In a typical week during the past year, on about how many nights have low rumbling sounds inside your home awakened you one or more times?	In a typical week during the past year, on about how many nights have low rumbling sounds inside your home awakened you one or more times?	About how often do you hear rattling sounds in your home when subway trains pass by?	About how often do you hear rattling sounds in your home when subway trains pass by?
7B	Would you say that you are not at all, slightly, moderately, very, or extremely annoyed by rattling sounds in your home when subway trains pass by?	n/a	n/a	Would you say that you are not at all, slightly, moderately, very, or extremely annoyed by rattling sounds in your home when subway trains pass by?	Would you say that you are not at all, slightly, moderately, very, or extremely annoyed by rattling sounds in your home when subway trains pass by?
8	Do you ever feel your home shake or the floors, walls, counters, or furniture vibrate when subway trains pass by? (IF NO, SKIP TO ITEM 9)	Do you ever hear rattling sounds from windows, doors, wall hangings, or other items in your home when DART Light Rail trains pass by? (IF NO, SKIP TO ITEM 9)	Do you ever hear rattling sounds from windows, doors, wall hangings, or other items in your home when Sacramento Light Rail trains pass by? (IF NO, SKIP TO ITEM 9)	Do you ever feel your home shake or the floors, walls, counters, or furniture vibrate when subway trains pass by? (IF NO, SKIP TO ITEM 9)	Do you ever feel your home shake or the floors, walls, counters, or furniture vibrate when subway trains pass by? (IF NO, ASK ITEM 9 NEXT)

ITEM	NYC (BROOKLYN)	DALLAS	SACRAMENTO	TORONTO	BOSTON
8A	About how often do you feel shaking or vibrations in your home when subway trains pass by?	About how often do you hear rattling sounds in your home when DART Light Rail trains pass by your home?	About how often do you hear rattling sounds in your home when Sacramento Light Rail trains pass by your home?	About how often do you feel shaking or vibrations in your home when subway trains pass by?	About how often do you feel shaking or vibrations in your home when subway trains pass by?
8B	Would you say that you are not at all, slightly, moderately, very or extremely annoyed by shaking or vibrations in your home when subway trains pass by?	Would you say that you are not at all, slightly, moderately, very or extremely annoyed by rattling sounds in your home caused by DART Light Rail trains?	Would you say that you are not at all, slightly, moderately, very or extremely annoyed by rattling sounds in your home caused by Sacramento Light Rail trains?	Would you say that you are not at all, slightly, moderately, very or extremely annoyed by shaking or vibrations in your home when subway trains pass by?	Would you say that you are not at all, slightly, moderately, very or extremely annoyed by shaking or vibrations in your home when subway trains pass by?
8C	Have you tried to do anything in your home to reduce vibrations or rattling sounds from subway trains? (IF NO, N/A, DK, or REF, SKIP TO ITEM 9)	n/a	n/a	Have you tried to do anything in your home to reduce vibrations or rattling sounds from subway trains? (IF NO, N/A, DK, or REF, SKIP TO ITEM 9)	Have you tried to do anything in your home to reduce vibrations or rattling sounds from subway trains? [IF NO, N/A, DK, or REF, SKIP TO ITEM 9)
8D	Have the vibrations or rattling sounds from subway trains been lessened by anything you've been able to do in your home?	n/a	n/a	Have the vibrations or rattling sounds from subway trains been lessened by anything you've been able to do in your home?	Have the vibrations or rattling sounds from subway trains been lessened by anything you've been able to do in your home?

ITEM	NYC (BROOKLYN)	DALLAS	SACRAMENTO	TORONTO	BOSTON
9	While you've been at home over the past year, have you ever been awakened by low rumbling sounds, rattling, shaking, or vibration inside your home when subway trains pass by? (IF NO, SKIP TO ITEM 10)	Do you ever feel your home shake or the floors, walls, counters, or furniture vibrate when DART Light Rail trains pass by? (IF NO, SKIP TO ITEM 10)	Do you ever feel your home shake or the floors, walls, counters, or furniture vibrate when Sacramento Light Rail trains pass by? (IF NO, SKIP TO ITEM 10)	While you've been at home over the past year, have you ever been awakened by low rumbling sounds, rattling, shaking, or vibration inside your home when subway trains pass by? (IF NO, SKIP TO ITEM 10)	While you've been at home over the past year, have you ever been awakened by low rumbling sounds, rattling, shaking, or vibration inside your home when subway trains pass by? (IF NO, SKIP TO ITEM 10)
9A	In a typical week while you've been at home during the past year, on about how many nights have low rumbling sounds, rattling, shaking or vibration from subway trains awakened you?	About how often do you feel shaking or vibrations in your home when DART Light Rail trains pass by?	About how often do you feel shaking or vibrations in your home when Sacramento Light Rail trains pass by?	In a typical week while you've been at home during the past year, on about how many nights have low rumbling sounds, rattling, shaking or vibration from subway trains awakened you?	In a typical week while you've been at home during the past year, on about how many nights have low rumbling sounds, rattling, shaking or vibration from subway trains awakened you?
9B	n/a	Would you say that you are not at all, slightly, moderately, very or extremely annoyed by shaking or vibrations in your home caused by DART Light Rail trains?	Would you say that you are not at all, slightly, moderately, very or extremely annoyed by shaking or vibrations in your home caused by Sacramento Light Rail trains?	n/a	n/a

ITEM	NYC (BROOKLYN)	DALLAS	SACRAMENTO	TORONTO	BOSTON
9C	n/a	Have you tried to do anything in your home to reduce vibrations or rattling sounds made by DART Light Rail trains? [IF NO, N/A, DK, or REF, SKIP TO ITEM 10 NEXT)	Have you tried to do anything in your home to reduce vibrations or rattling sounds made by Sacramento Light Rail trains? [IF NO, N/A, DK, or REF, SKIP TO ITEM 10 NEXT)	n/a	n/a
9D	n/a	Have the vibrations or rattling sounds made by DART Rail trains been lessened by anything you've been able to do in your home?	Have the vibrations or rattling sounds made by Sacramento Light Rail trains been lessened by anything you've been able to do in your home?	n/a	n/a
10	Have you ever complained to New York City Transit about noise, rumble, rattle, shaking, or vibration in your home made by subway trains?	Have you ever complained to DART about noise, rumble, rattle, shaking, or vibration in your homemade by DART Rail trains?	Have you ever complained to Sacramento Regional Transit about noise, rumble, rattle, shaking, or vibration in your home made by Light Rail trains?	Have you ever complained to the Toronto Transit Commission about noise, rumble, rattle, shaking, or vibration in your home made by subway trains?	Have you ever complained to the MBTA about noise, rumble, rattle, shaking, or vibration in your homemade by [Orange/Blue] line subway trains?
11	What floor of your building do you live on?	Can you see DART Rail trains from any window of your home?	Are you bothered or annoyed by the sounds of warning bells at street crossings by train tracks?	What floor of your building do you live on?	What floor of your building do you live on?

ITEM	NYC (BROOKLYN)	DALLAS	SACRAMENTO	TORONTO	BOSTON
12	Would you be willing to speak with someone about the possibility of measuring noise and vibration in your home?	Do you live in a single-family home or in an apartment building?	Can you see Sacramento Light Rail trains from any window of your home?	Would you be willing to speak with someone about the possibility of measuring noise and vibration in your home?	Would you be willing to speak with someone about the possibility of measuring subway noise and vibration in your home?
12A	n/a	Does your home have more than one story?	n/a	n/a	n/a
12B	n/a	Does your home have a full basement?	n/a	n/a	n/a
12C	n/a	What floor of your building do you live on?	n/a	n/a	n/a
12D	n/a	Does your apartment building have a full basement?	n/a	n/a	n/a
13	n/a	Would you be willing to speak with someone about the possibility of making measurements of noise and vibration in your home?	Do you live in a single-family home or in an apartment building?	n/a	n/a
13A	n/a	n/a	Does your home have more than one story?	n/a	n/a
13B	n/a	n/a	n/a	n/a	n/a

ITEM	NYC (BROOKLYN)	DALLAS	SACRAMENTO	TORONTO	BOSTON
13C	n/a	n/a	What floor of your apartment building do you live on?	n/a	n/a
14	n/a	n/a	Would you be willing to speak with someone about the possibility of making measurements of noise and vibration in your home?	n/a	n/a

APPENDIX C

FIELD LOG SHEETS

TCRP D-12 PROJECT DATA SHEET - REFERENCE

SITE ID #	TECHNICIAN NAME:	DATE:
ADDRESS/COORDINATES:		

SITE SKETCH:

Approximate Distance from Measurement Site to Tracks: ______________________

Notes:

EQUIPMENT INFORMATION

Recording Device:	
FILE ID:	

Vibration Sensor	Serial #		Notes
(acceleration, vertical)	Location		

Calibration	Channel			
calibrator serial #	cal level (grms)	gain	file ID	recorder i/p range (V)

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TCRP D-12 PROJECT DATA SHEET - REFERENCE

SITE ID #	ADDRESS/COORDINATES:	DATE:

TRANSIT SYSTEM DETAILS

System Name: MBTA - Boston

Type of Train: ______ Number of Trains Per Day: ______

Track Structure at Site: SUBWAY AT-GRADE ELEVATED OTHER: ______

Track Type at Site: BALLAST AND TIE DIRECT FIXATION EMBEDDED OTHER: ______

EQUIPMENT INFORMATION

Recording Device: ______ Serial #: ______

Sensor Details:

Location	Channel	Serial #	Gain	Notes

RECORDING DETAILS

Time Started: ______ Time Ended: ______ Duration: ______

Events (Trains, etc.):

Event	Time	Notes

TCRP D-12 PROJECT DATA SHEET - EXTERIOR

SITE ID #	TECHNICIAN NAME:	DATE:
ADDRESS/COORDINATES:		
SITE SKETCH:		

Approximate Distance from Measurement Site to Tracks: ______________________

Notes:

EQUIPMENT INFORMATION

Recording Device:	
FILE ID:	

Vibration Sensor	Serial #		Notes
(acceleration, vertical)	Location		

Calibration	Channel			
calibrator serial #	cal level (grms)	gain	file ID	recorder i/p range (V)

EXTERIOR TEST LOCATION DETAILS

Measurement Location: SIDEWALK ALLEY OTHER: ____________

Measurement Surface: CONCRETE ASPHALT OTHER: ____________

Approximate Street Width: ____________ No. of Traffic Lanes: ____________

Notes:

Pedestrian Activity: LIGHT MODERATE HEAVY

Traffic Levels: LIGHT MODERATE HEAVY

RECORDED DATA

Start Time:		Notes:	
File ID:			
Vibration Sensor Gain:		recorder i/p range (V):	

Events (Trains, etc.):

Event	Time	Notes

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TCRP D-12 PROJECT DATA SHEET - INTERIOR

SITE ID #	TECHNICIAN NAME:	DATE:
ADDRESS/COORDINATES:		
SITE SKETCH:		

Approximate Distance from Measurement Site Track Centerline:

EQUIPMENT INFORMATION

Recording Device: Serial #:

Vibration Sensor	Serial #			Notes:
(acceleration, vertical)	Location			
Calibration	Channel			
calibrator serial #	cal level (grms)	gain	file ID	recorder i/p range (V)

Acoustic Sensor	Serial #			Notes:
	Location			
Calibration	Channel			
calibrator serial #	cal level (dB)	gain	file ID	recorder i/p range (V)

INTERIOR TEST LOCATION DETAILS

Building Type (circle one):	SINGLE FAMILY	MULTIPLE-FAMILY	OTHER:	______
Building Construction:	______			
Foundation (circle one):	SLAB-ON-GRADE	SUSPENDED	OTHER:	______
Basement (circle one):	YES	NO		
Number of Floors:	______		Measurement Floor:	______
Room Type:	______			
Floor Covering (circle one):	CARPET	HARDWOOD	OTHER:	______
Acoustical Absorbtion:	HIGH	NORMAL	LOW	

Vibration Noticeable: YES NO	Audible Rumble: YES NO	Audible rattling: Yes No

RECORDED DATA

Start Time:		Notes:	
File ID:			
Vibration Sensor Gain:		recorder i/p range (V):	
Acoustic Sensor Gain:		recorder i/p range (V):	

Events (Trains, etc.):

Event	Time	Notes

TCRP D-12 PROJECT DATA SHEET - GRID

SITE ID #	TECHNICIAN NAME:	DATE:
ADDRESS/COORDINATES: channel 1 and channel 2		
SITE SKETCH:		

Approximate Distance from Measurement Site Track Centerline:

EQUIPMENT INFORMATION

Recording Device: Serial #:

Accel - channel 1	Serial #			Notes:
(acceleration, vertical)	Location			
Calibration	Channel			
calibrator serial #	cal level (grms)	gain	file ID	recorder i/p range (V)

Accel - channel 2	Serial #			Notes:
	Location			
Calibration	Channel			
calibrator serial #	cal level (dB)	gain	file ID	recorder i/p range (V)

TCRP D-12 Final Report

GRID MEASUREMENTS

RECORDED DATA

Start Time:		Notes:	
File ID:			
Accel Gain (channel 1):		recorder i/p range (V):	
Accel gain (channel 2):		recorder i/p range (V):	

Events (Trains, etc.):

Event	Time	Notes

APPENDIX D

SUMMARY OF STANDARDS FOR GROUND-BORNE NOISE AND VIBRATION

A number of different national and international standards have been adopted for predicting the impact of vibration and noise of all types, and to limit levels in residential settings. A brief summary of each country's guidelines are presented below.

International Organization for Standardization: ISO 2631-2 (D2) is the current international standard dealing with the comfort and annoyance of building occupants due to whole-body vibration and shock. It specifies measurement and evaluation methods and defines a frequency weighting (W_m/KB-weighting scheme) over the range of 1 Hz to 80 Hz. Guidance on acceptable magnitudes of vibration is omitted, assigning this judgment to individual countries.

Federal Transit Administration: The vibration standard currently used in the United States for the assessment of noise and vibration impacts from transit projects is the FTA manual (D4). Buildings are classified using three categories. Impact thresholds are specified for frequent (>70 events/day), occasional (30-70 events/day) and infrequent (<30 events/day) exposure. Impact criteria are also specified for "special buildings" such as concert halls, TV and recording studios, auditoriums, and theaters, where lower limits are essential for interior operations. The FTA guidelines for ground-borne noise and vibration are summarized in Table D1.

Table D1: FTA Ground-Borne Vibration and Noise Impact Criteria

Land Use Category	Vibration Impact Levels (VdB re 1 micro inch/sec)			Noise Impact Levels (dB re 20 micro Pascals)		
	Frequent Events[1]	Occasional Events[2]	Infrequent Events[3]	Frequent Events[1]	Occasional Events[2]	Infrequent Events[3]
Category 1: Buildings where vibration would interfere with interior operations.	65 VdB[4]	65 VdB[4]	65 VdB[4]	n/a[5]	n/a[5]	n/a[5]
Category 2: Residences and buildings where people normally sleep.	72 VdB	75 VdB	80 VdB	35 dBA	38 dBA	43 dBA
Category 3: Institutional land uses with primarily daytime use.	75 VdB	78 VdB	83 VdB	40 dBA	43 dBA	48 dBA

1. More than 70 vibration events of the same source per day. Most rapid transit projects fall into this category.
2. Between 30 and 70 vibration events of the same source per day. Includes most commuter rail trunk lines.
3. Fewer than 30 vibration events of the same source per day. This includes most commuter rail branch lines.
4. This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. Vibration sensitive manufacturing or research will require detailed evaluation to define the acceptable vibration levels.
5. Most vibration-sensitive equipment is not sensitive to noise.

Source: FTA Manual, 2006 (D4)

ANSI: Human response to vibration is also treated by ANSI S3.29-1983 (R2001) (D1). This standard defines a vibration perception threshold and recommends acceptable levels of vibration for various occupancies. This standard was used as a basis for the FTA guidelines. The ANSI base response curves, which are intended to correspond to the approximate threshold of perception for the most sensitive people, are shown in Figure D-1. Laboratory studies of human response to vibration do not seem to provide much support for the ANSI defined "perception thresholds." In all fairness, it is important to point out that the perception thresholds defined in ANSI S3.29 are similar to those specified in ISO and other international standards and that the preamble to ANSI S3.29 notes the "existing shortage of applicable data." The frequency-weighting characteristics shown in Figure D-1 were established in ANSI 3.18-2002 (D6).

ANSI S3.29-1983 (R2001) suggests evaluation of the following factors:

- Type of excitation: steady state, intermittent, and impulsive vibration.
- Frequency and direction of the vibration (1 Hz to 80 Hz, in x, y, z axes).
- Occupied space usage; for example, workshop, office, residential, hospital operating room.
- Time of day.
- Vibration acceptability.

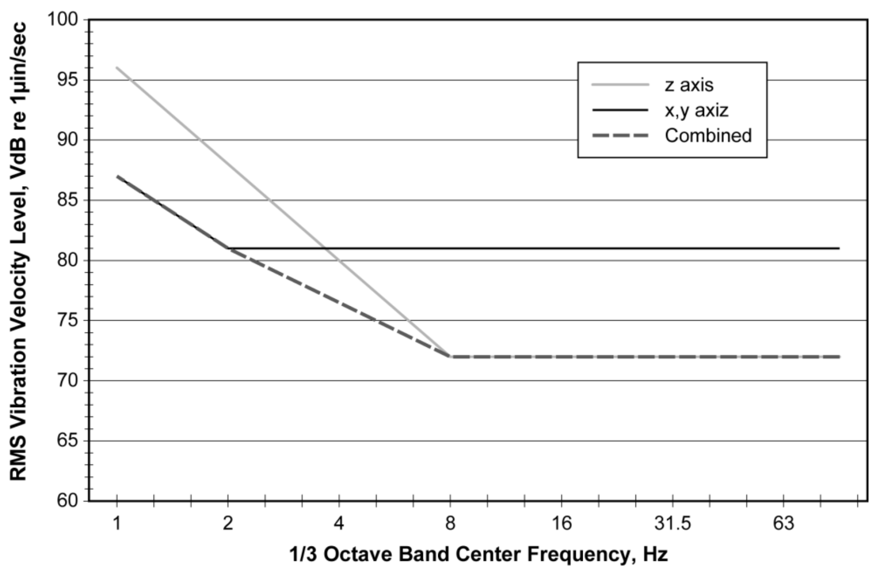

Figure D-1: ANSI S3.29-1983 Base Response Curves in Decibels

An appendix to the standard, which is for information only and is not part of the standard, provides guidance on estimating occupant response to building vibration. This is done by applying multiplying factors to the base curves based on the conditions of interest. The site multiplying factors given in the appendix to ANSI 3.29-1983 are summarized in Table D2.

The appendix also includes a factor for addressing the number of vibration events per day:

$$F_n = 1.7 \times N^{-0.5}$$

where N is the number of events per day ($N > 3$).

In addition, an event duration factor is recommended for discrete events with durations exceeding one second,

$$F_d = T^{-1.2} \text{ for concrete floors}$$

$$F_d = T^{-0.32} \text{ for wood floors}$$

where T is the event duration in seconds.

Table D2: Site Multiplying Factors

Occupancy	Time, hours	Continuous and intermittent vibration and repeated impulsive shock	Impulsive shock excitation with few occurrences per day (three or less)
Hospital operating room and critical working areas[1]	All	0.7-1	1
Residential (good environmental standard)	0700-2200	1.4 to 4	90
	2200-2400	1 to 1.4	1.4
	0000-0700	1 to 1.4	1.4
Office[2]	All	4	128
Workshop[2,3]	All	8	128

1. Magnitudes of impulsive vibration in hospital operating rooms and critical working places pertain to periods of time when surgical operations are in progress or critical work is being performed. At other times, vibration magnitudes as high as are recommended for residences may be allowed provided there is prior agreement and warning.
2. Impulsive vibration magnitudes in offices and workshop areas should not be increased without considering the possibility of significant disruption in work activity.
3. Vibration in workshops from certain industrial processes (such as drop forging or crushing) may be in a separate category. Vibration values specified in ANSI S3.18-2002 should then apply.

Source: Appendix to ANSI S3.29-1983 (D1)

Australia: The standard currently used in Australia is AS 2670.2-1990: Evaluation of human exposure to whole-body vibration - Continuous and shock-induced vibration in buildings (1 Hz to 80 Hz) (D7). This standard is identical to, and was reproduced from, ISO 2631-2 (D2).

Guidelines for acceptable vibration are determined by regional environmental agencies. Table D3 shows the limits set forth in New South Wales. The velocity values in the table refer to the maximum level allowable in any one-third octave band.

Table D3: New South Wales EPA Vibration Limits to Protect Human Comfort

Place	Time	Weighted Vibration Velocity			
		Continuous (mm/s)	Intermittent (mm/s)	Continuous (VdB)	Intermittent (VdB)
Residential	Day	0.2	6.0	78	107
	Night	0.14	2.0	75	98
Offices	Day	0.4	12.7	84	114
	Night	0.4	12.7	84	114
Workshops	Day	0.8	12.7	90	114
	Night	0.8	12.7	90	114

Source: Renzo Tonin & Associates Consulting, 2004 (D8).

Belgium: Belgian Standard NBN B03-003: "Criteria of State Limits with Regards to Vibration" (D9) specifies that the guidelines from the German standard DIN 4150-2 (D13) are to be used. Recently some modifications to the standard have been proposed, specifically suppressing the A_u requirement and using A_r as a basis for evaluating vibration impacts.

Denmark: A set of Danish guidelines for the measurement and assessment of environmental low frequency noise, infrasound and vibration was published in 1997 (D10). These specify recommended measurement methods and limit values for noise and vibration. The measurement procedures specified in Nordtest method NT ACOU-082 (D11) are also used.

Table D4 shows the recommended vibration and noise limits for the Danish standard. For vibration, the standardized "whole body" (KB) weighting, described according to ISO 2631-2 (D2), is used. In addition, the frequency is limited to the range from 1 Hz to 80 Hz. The maximum RMS level is used as the basis for the assessment. When setting limits that reflect environmentally acceptable vibration levels, only tactile vibration is considered. Re-radiated noise that often accompanies vibration is assessed as low frequency noise. For low frequency noise, the A-weighted level over the frequency range of 10 Hz to 160 Hz is considered, the symbol used is $L_{pA,LF}$. The recommended limits are 5 dB to 15 dB lower than the ordinary noise limits. Secondary phenomena, such as rattling windows, are not considered.

Table D4: Guidelines Specified by Danish Environmental Protection Agency

Building Type	Weighted acceleration level, L_{aw}	Weighted acceleration, a_w	Corresponding weighted velocity, v_w	Vibration Velocity (VdB)	Low-frequency noise limit LpA,LF
Dwellings in residential areas (day and night) or in mixed areas (evening and night), institutions	75 dB	5.6 mm/s^2	0.16 mm/s	76	20 dBA
Dwellings in mixed areas (daytime)	80 dB	10 mm/s^2	0.3 mm/s	81	25 dBA
Offices and Classrooms	80 dB	10 mm/s^2	0.3 mm/s	81	30 dBA
Other rooms in enterprises	85 dB	17.8 mm/s^2	0.5 mm/s	86	35 dBA
Source: Jakobson, 2003 (D12)					

Germany: The German standard for evaluating vibration effects in buildings is DIN 4150-2 (D13). This standard uses weighted RMS velocity values [adjusted according to the W_m/KB-weighting defined in ISO 2631-2 (D2)]. In DIN 4150-2, the fast-response root-mean-square velocity value is defined as $KB_F(t)$. The decision tree shown in Figure D-2 is employed using $KB_F(t)$ and the following additional parameters:

- KB_{Fmax} is defined as the maximum value (single or repeated) for the $KB_F(t)$ signal obtained during the evaluation period and which can be attributed to the vibration source being evaluated.
- KB_{FTi} is defined as the maximum $KB_F(t)$ signals obtained for each 30-second cycle, T, within the measurement period, where the subscript "i" is used to identify the cycle number.
- KB_{FTm} is the root-mean-square value for the KB_{FTi} signal.
- KB_{FTr} is the "vibration severity" which is calculated by weighting to account for nights and weekends. The value for KB_{FTr} is calculated as follows:

$$KB_{FTr} = \sqrt{\frac{1}{T_r}(T_{e1} \cdot KB_{FTm1}^2 + 2T_{e2} \cdot KB_{FTm2}^2)}$$

  where, T_r is the evaluation period, T_{e1} is the exposure period outside rest periods, T_{e2} is the exposure period during rest periods, KB_{FTm1} is the KB_F value outside rest periods, and KB_{FTm2} is the KB_F value during rest periods.

The acceptable levels of vibration for various land uses are summarized in Table D5.

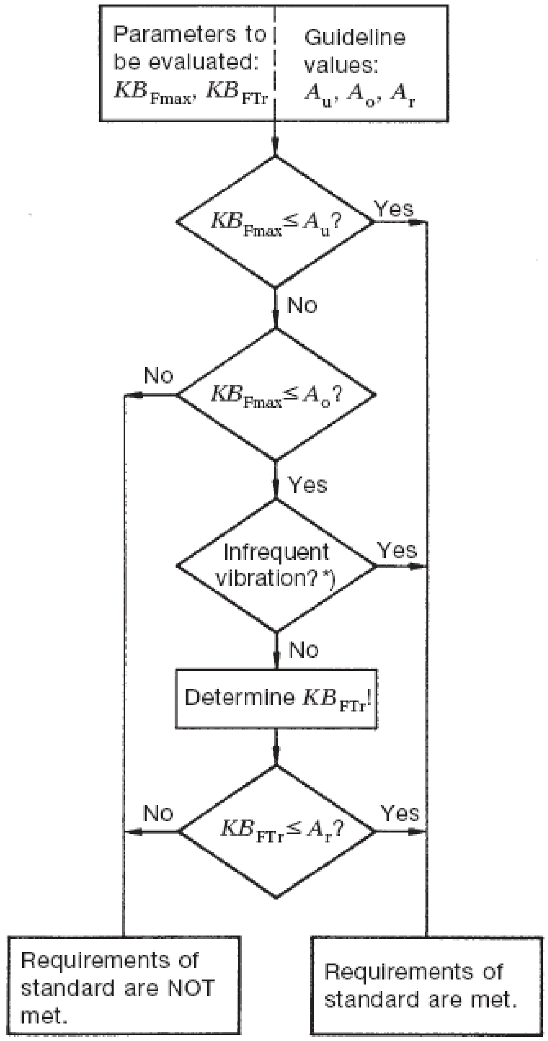

Figure D-2: Flow Chart for Evaluation Procedure as Presented in DIN 4150-2

Table D5: Guidelines Specified by German Standard DIN 4150-2

Class	Zone	KB-Weighted Velocity, mm/s					
		Day			Night		
		A_u	A_o	A_r	A_u	A_o	A_r
1	Exclusively Industrial	0.40	6	0.20	0.30	0.60	0.15
2	Principally Industrial	0.30	6	0.15	0.20	0.40	0.10
3	Mixed	0.20	5	0.10	0.15	0.30	0.07
4	Residential	0.15	3	0.07	0.10	0.20	0.05
5	Protected Areas	0.10	3	0.05	0.10	0.15	0.05
Values Adjusted to VdB							
Class	**Zone**	**KB-Weighted Velocity in VdB** (decibels using a reference of 1µin/sec)					
		Day			**Night**		
		A_u	A_o	A_r	A_u	A_o	A_r
1	Exclusively Industrial	84	108	78	81	87	75
2	Principally Industrial	81	108	75	78	84	72
3	Mixed	78	106	72	75	81	69
4	Residential	75	101	69	72	78	66
5	Protected Areas	72	101	66	72	75	66

Italy: The current guidelines for vibration levels in Italy are from the Technical Rule UNI-9614: Vibration Measurement in Buildings and Annoyance Evaluation (D14). The method is partially in concordance with ISO 2631-2 (D2), but also specifies the limits for acceptable vibration levels that are summarized in Table D6.

Table D6: Italian Standards: UNI-9614

Area	Vertical Movement		Transverse Movement	
	mm/s^2	VdB	mm/s^2	VdB
Critical Areas	5.0	74	3.5	71
Residential (Night)	7.0	77	5.0	74
Residential (Day)	10.0	80	7.2	77
Offices	20.0	86	14.0	83
Facilities	40.0	92	28.0	89
Source: Breccolotti, M. and Materazzi, A., 2005 (D15)				

Japan: Japanese vibration limits are established regionally (by prefectural governor) rather than by a national standard. The Japanese Ministry of the Environment has issued a cabinet order that specifies guidelines for factory-emitted and motor vehicle-emitted vibration. The Japanese standards are listed in Table D7 and Table D8.

It is unclear whether national limits have been set for railway vibration, but according to the Ministry of the Environment (D16), subsidies have been provided for vibration mitigation, and compensation has been offered for relocation in areas where vibration caused by high-speed trains exceeds 70 VdB.

Table D7: Regulatory Standards for Vibration Emitted from Specified Factories

Area	Time	
	Daytime	Nighttime
I: Areas where maintenance of quiet is particularly needed to preserve a good living environment and where quiet is needed as they are used for residential purposes.	60 – 65 dB	55 – 60 dB
II: Areas used for commercial and industrial as well as residential purposes where there is a need to preserve the living environment of local residents and areas mainly serving industrial purposes which are in need of measures to prevent the living environment of local residents from deteriorating.	65- 70 dB	60 – 65 dB
Source: Ministry of the Environment (Japan) (D17)		

Table D8: Request Limits for Motor Vehicle Vibration

Area	Time	
	Daytime	Nighttime
I. Areas where maintenance of quiet is particularly needed to preserve a good living environment and where quiet is needed as they are used for residential purposes.	65 dB	60 dB
II. Areas used for commercial and industrial as well as residential purposes where there is a need to preserve the living environment of local residents and areas mainly serving industrial purposes which are in need of measures to prevent the living environment of local residents from deteriorating.	70 dB	65 dB
Source: Ministry of the Environment (Japan) (D17)		

Norway: The current method used in Norway for measuring vibration in buildings is Nordtest Method NT ACOU-082, "Buildings: Vibration and Shock, Evaluation of Annoyance" (D11). The method specifies instrumentation, frequency range and weighting curve (the W_m/KB curve specified by ISO 2631-2 (D2)), calibration details, and measurement procedures to determine weighted acceleration levels. The method also includes a process for estimating vibration levels in buildings.

Norwegian Standard NS 8176, Vibration and Shock – Measurement of Vibration in Buildings from Land Based Transport and Guidance to Evaluation of its Effects on Human Beings" (D18) describes a new method for measuring the velocity or acceleration and establishes guidelines for tolerable vibration. The standard uses statistical 95 percentile values of maximum weighted velocity or acceleration. Buildings are classified according to four different categories (A-D) based on vibration sensitivity, and corresponding limits are set. The categories and levels cited in the Norwegian standard are summarized in Table D9.

Table D9: Classes Used in Norwegian Standard NS 8176 (1999)

Building Classification	Statistical Maximum Value for Weighted Acceleration, $a_{w,95}$	Statistical Maximum Value for Weighted Velocity, $v_{w,95}$	Equivalent Vibration Velocity (VdB)
Class A: High vibration comfort – only a few people will perceive vibrations.	3.6 mm/s^2	0.1 mm/s	72 VdB
Class B: Fairly high vibration comfort – People will to some degree perceive vibrations.	5.4 mm/s^2	0.15 mm/s	75 VdB
Class C: Recommended limit for vibrations in new buildings and when new railway or road transportation lines are planned. Approximately 15% of the people subject to vibrations according to class C will be disturbed by the vibrations.	11 mm/s^2	0.3 mm/s	81 VdB
Class D: Recommended limit for existing buildings. Approximately 25% of the people subject to vibrations according to class D will be disturbed by the vibrations.	21 mm/s^2	0.6 mm/s	87 VdB
Source: Turunen-Risem et al (Part 1), 2003 (D5)			

Sweden: The guidelines for vibration from railroads in Sweden have been issued by Banverket, the Swedish Railway Administration (D20). It is presumed that the vibration values are weighted according to the W_m/KB-weighting scale, and maximum RMS velocity values are used as limits. In areas with existing track, areas experiencing vibration levels greater than 1.0 mm/sec are investigated and mitigation measures are considered. In areas where new track is built or tracks are reconstructed, the limits are more stringent. Vibration values greater than 2.5 mm/sec (100 VdB) are considered unacceptable and the railway administration offers measures (typically, buying and demolishing houses) wherever such levels are experienced. The Swedish vibration limits are given in Table D10.

The Swedish standards for low-frequency noise are set according to guidelines issued by Socialstyrelsen (The National Board of Health and Welfare): SOSFS 1996: 7/E "Indoor Noise and High Sound-Levels."(D19) The limit for indoor noise is given as 30 dBA. The guidelines do not provide explicit limits on low-frequency noise but rather offer guidance in assessing whether noises with a low-frequency character will be found to be objectionable based on a receptor's decreasing sensitivity to noises at lower frequencies. These guidelines are summarized in Table D11.

Table D10: Swedish Vibration Limits for New and Reconstructed Railroads

Type of Construction	Normal Value		Limit Value	
	mm/s	VdB	mm/s	VdB
New or Reconstructed Railroads	0.4	84	0.7	89
Existing Railroads	0.4	84	1.0	92
Source: DNR.S02-4235/SA60, 2002 (D20)				

Table D11: Recommendations for Assessment of Low-Frequency, Equivalent Noise as an Indoor Sanitary Nuisance

1/3 Octave Band, Hz	Equivalent Acoustic Pressure Level, dB
31.5	56
40	49
50	43
63	41.5
80	40
100	38
125	36
160	34
200	32
Source: SOSFS 7/E, 1996 (D19)	

United Kingdom: The limits in Great Britain are set according to the standard BS 6841 (1987) (D3). It is important to note that the current British Standard uses a weighting curve for vibration that is substantially different from both the W_m/KB-weighting curve and the ANSI weighting curve. The British standards rely on the *Vibration Dose Value* (VDV). Table D12 specifies VDV levels below which a low probability of adverse comment is expected. Table D13 specifies VDV levels above which adverse comment can be expected.

Assessment of ground-borne noise is similar to assessment of airborne noise, including the use of A-weighted measurements. The practice adopted in the case of noise from underground railways has been to use the L_{Amax} noise parameter. The threshold levels are given in Table D14.

Table D12: Vibration Dose Values Corresponding to a Low Probability of Adverse Comment					
Location	**Exposure Periods**				
	16 hr	**1 hr**	**225 sec**	**14 sec**	**0.9 sec**
Residential Buildings, Daytime	0.01 to 0.02	0.02 to 0.04	0.04 to 0.08	0.08 to 0.16	0.16 to 0.32
Source: EARL Noise and Vibration Briefing Note, 2004 (D21)					

Table D13: Vibration Dose Values Above Which Various Degrees of Adverse Comment may be Expected in Residential Buildings			
Place	**Low Probability of Adverse Comment**	**Adverse Comment Possible**	**Adverse Comment Probable**
Residential Buildings, 16 h of daytime	0.2 to 0.4	0.4 to 0.8	0.8 to 1.6
Residential Buildings, 8 h of nighttime	0.13	0.26	0.51
Source: EARL Noise and Vibration Briefing Note, 2004 (D21)			

Table D14: Noise from Underground Construction Sources – Threshold of Significant Effect in Dwellings and Schools / Colleges		
Effect Classification	**Noise Level dB ($L_{Amax,S}$)[1]**	
Low	35-39	Neutral
Medium	40-44	Significant Effect
High	45-49	
Very High	> 49	
1. Measured near the center of any dwelling room on the ground floor.		
Source: Brighton and Hove Wastewater Treatment Works Environmental Statement (D22)		

APPENDIX D REFERENCES

D1. ANSI S3.29-1983 (R2001), "American National Standard Guide to the Evaluation of Human Exposure to Vibration in Buildings," American National Standards Institute.

D2. ISO 2631, "Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration," IS0 2631-1 (1997): "Part 1: General requirements," ISO 2631-2 (2003): "Part 2: Continuous and shock-induced vibrations in buildings (1 Hz to 80 Hz)."

D3. BS 6841 (1987): "Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock," British Standards Institution.

D4. Federal Transit Administration, "Transit Noise and Vibration Impact Assessment," Report FTA-VA-90-1003-06 (May 2006).

D5. Turunen-Risem I.H., Brekke, A., Hårvik, L., Madshus, C., and Klæboe, R. (2003) "Vibration in Dwellings from Road and Rail Traffic – Part I: A New Norwegian Measurement Standard and Classification System," Applied Acoustics, Vol. 64, pp. 71-87.

D6. ANSI S3.18-2002, "Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole Body Vibration – Part 1: General Requirements," American National Standards Institute.

D7. AS 2670.2 (1990): "Evaluation of human exposure to whole-body vibration - Continuous and shock-induced vibration in buildings (1 Hz to 80 Hz)." Council of Standards Australia.

D8. Renzo Tonin & Associates Consulting (2004). "Technical Note 4: Managing Noise and Vibration on Construction Sites."

D9. NBN B03-003 (2002): "Déformations des structures – Valeurs limites de déformation – Bâtiments. (Criteria of State Limits with Regards to Vibration in Buildings." Federal Scientific Policy, Belgium).

D10. Information No. 9/1997 (1997): "Orientering om lavfrekvent støj, infralyd og vibrationer i eksternt miljø." Danish Environmental Protection Agency (Danish Ministry of the Environment).

D11. NT ACOU-082 (1991): "Buildings: Vibration and Shock, Evaluation of Annoyance." Nordtest (Nordic Strategy Group on Quality and Metrology).

D12. Jacobsen, J. (2003) "Danish Guidelines on Environmental Low Frequency Noise, Infrasound and Vibration," Noise Notes, Vol. 2(2), pp. 10-18.

D13. DIN 4150-2 (1999): "Erschütterungen im Bauwesen - Teil 2: Einwirkungen auf Menschen in Gebäuden (Vibrations in Buildings – Effects on Persons in Buildings)." Deutsches Institut für Normung (German Institute for Standardization).

D14. UNI-9614:1990 (1990) "Misura delle vibrazioni negli edifici e criteri di valutazione del disturbo (Vibration Measurement in Buildings and Annoyance Evaluation)." Ente Nazionale Italiano de Unificazione (Italian National Standards Body).

D15. Breccolotti, M. and Materazzi, A. (2005) "Ambient Vibration Analysis and Mitigation in the Site of Villa Ruffo in Rome," Proceedings of Eurodyn 2005, Paris, France.

D16. Vibration Regulation Law (1994): “Cabinet Order for the Implementation of the Vibration Regulation Law.” Ministry of the Environment.

D17. Annual Report (White Paper): “Quality of the Environment in Japan” (2003) Ministry of the Environment.

D18. NS 8176 (1999): “Vibration and shock – measurement of vibration in buildings from land based transport and guidance to evaluation of its effects on human beings.” Norwegian Council for Building Standardization

D19. SOSFS (1996) 7/E: “General guidelines issued by the Swedish National Board of Health and Welfare: 7/E Indoor Noise and High Sound-Levels.” Socialstyrelsen (Swedish National Board of Health and Welfare).

D20. DNR.S02-4235/SA60 (2002): “Buller och Vibrationer, Fran Sparburen Linjetrafik.” Banverket (Swedish Railway Administration).

D21. ERM Group, Inc (2004). “EARL: Noise and Vibration Briefing Note.”

D22. RPS Planning Transport & Environment (2005). “Brighton and Hove Wastewater Treatment Works Environmental Statement.”

APPENDIX E

TRANSIT AGENCY NOISE AND VIBRATION SURVEY QUESTIONS

The transit system survey consisted of a cover letter and a series of questions. Following is the cover e-mail sent with the request to fill out the survey, and the survey questions.

Cover E-Mail for Survey

Cover e-mail

Subject: TCRP D-12 Survey

Dear [FirstName],

Greetings! We are conducting this survey as part of the initial effort of TCRP Project D-12, " Noise and Vibration in Buildings Caused by Rail Transit." The objective of this project is to develop criteria for acceptable levels of rail-transit-generated noise and vibration in buildings.

Please complete this short 10-minute survey. The purpose of the survey is to document North American transit systems' experiences with ground vibration. It is important that we obtain responses from as many transit systems as possible, including those who have not had problems with vibration. The individual responses will be kept confidential and will only be discussed in aggregate.

We appreciate your help. Feel free to forward the survey on to others in your organization. If you have any questions, please contact Hugh Saurenman or Zack Dennis at ATS Consulting, (213) 488-7770 (hsaurenman@ATSConsulting.com or zdennis@ATSConsulting.com).

Here is a link to the survey: [SurveyLink]

Thank you for your participation,

Hugh Saurenman

Please note: If you do not wish to receive further emails from us, please click the link below, and you will be automatically removed from our mailing list.

[RemoveLink]

Online Survey Questions

Introduction: We are conducting this survey as part of the initial effort of TCRP Project D-12, "Noise and Vibration in Buildings Caused by Rail Transit." The objective of this project is to develop criteria for acceptable levels of rail-transit-generated noise and vibration in buildings. Vibration is transmitted from the tracks, through the ground to nearby buildings. The resulting building vibration can be intrusive to occupants because of the perceptible vibration or the rattling of windows and items on shelves. The vibration of room surfaces can also radiate noise; in essence the room surfaces act as large loud speakers. The audible noise is referred to as noise. Noise is thought to be more common for subways than for at-grade track and is usually perceived as a low-frequency rumbling noise coming from an unidentifiable source.

In the survey we use the term ***vibration*** to refer to all the effects of vibration, including perceptible vibration, noise, and any rattling or shaking noises caused by the vibration.

Instructions: The survey consists of 12 questions regarding the experience your rail transit system has had with vibration. Please answer all questions to the best of your knowledge. We encourage comments regarding your personal experience with vibration issues, complaints, or the survey itself. A separate section is provided at the end for this purpose. If the link to this survey was forwarded to you by someone else, please provide us with your contact information (name, e-mail, phone number) in the comments section at the end of the survey. Thank you for your help!

1. Please identify the transit mode where your district has had, or currently has, problems with vibration:

	No Problems	Minor Problems	Major Problems
Light Rail Transit	O	O	O
Heavy Rail (Rapid Transit)	O	O	O
Commuter Rail	O	O	O
Streetcar	O	O	O

1(a). Are there any other transit modes where vibration has been an issue (please specify transit mode and severity of problem)?

2. Please estimate the total number of vibration/ noise complaints that have been received in the last year.

    None
    1-5
    6-20
    21-50
    More than 50

3. Is there a formal system to receiving and responding to community complaints about noise and/or vibration?

    Yes
    No

3(a). If yes, please provide a brief description of the complaint system.

4. Have you become aware of problems through any other process? (*e.g.,* telephone calls from residents, residents talking to maintenance workers, comments to board members from constituents)

   Yes
   No

4(a). If yes, please describe briefly.

5. Have vibration complaints been system-wide or focused in one or more particular locations?

   Focused at one or more specific locations
   System-wide with no apparent pattern
   Infrequent or no complaints

Please answer the following questions with regard to ***all*** of the areas where vibration problems have occurred on your system. After completing this section you will be given the option of providing additional information about specific locations.

6. What types of track structures are used? (check all that apply)

   At-Grade
   Elevated
   Depressed (Trench)
   Cut and Cover Subway
   Bored Subway
   Other (please specify)

7. What types of track systems are used (check all that apply)

   Ballast and Tie
   Direct Fixation
   Embedded
   Other (please specify)

8. Are the rails welded or jointed?
   Welded
   Jointed

9. Do the complaints appear to be correlated with anything in particular (e.g., need for track maintenance, rail corrugation, seasonal, etc.)?

10. What mitigation features currently exist on the system? (check all that apply)

    None
    Floating slabs
    High resilience fasteners
    Ballast mats
    Tie isolation pads
    Other (please specify)

11. Have any measurements of vibration and/or noise been performed in response to complaints?

    Yes
    No
    Don't know

11(a). If yes, are the measurement results available?

    Yes
    No
    Don't know

12. How have the complaints been resolved? (check all that apply)

    Track maintenance
    Vehicle maintenance
    High resilience fasteners
    Litigation/settlement
    No resolution
    Other (please specify)

13. Would you like to fill in one or more forms describing particular areas where vibration has been a major concern?

    Yes, take me there now.
    No thank you.

This section is to describe, in detail, up to five areas where vibration has become an issue. Please fill out one form for each area you would like to describe.

14. Please describe the area in detail (transit mode, speed, headways, rolling stock, track type, any unusual features, geology, etc.).

15. Please describe the nature of the vibration problem (complaints about intrusion or cracks in foundations, litigation, etc.)

16. Have noise or vibration measurements been taken?

    Yes
    No
    Don’t know

16a. If yes, please describe the measurements.

17. Has the problem been resolved?

    Yes
    No
    Don’t know

17a. If yes, please describe the resolution:

18. Is there another area you would like to describe in detail?

    Yes, I would like to fill out another form.
    No, thank you.

APPENDIX F

PROBLEM STATEMENTS FOR POTENTIAL FUTURE WORK

1. TOPIC 1 - HUMAN SENSITIVITY TO GROUND-BORNE VIBRATION FROM HIGH AXLE LOAD TRAINS

1.1 RESEARCH PROBLEM STATEMENT

One goal of the TCRP D-12 research program, "Ground-Borne Noise and Vibration in Buildings Caused by Rail Transit" was to develop a relationship between rail transit-induced ground-borne vibration/noise exposure and community annoyance. An effort was made in the D-12 study to sample a variety of transit modalities, however most of the data collected corresponded to situations with either light rail or rapid transit operations in urban or suburban areas. Since heavier axle load vehicles tend to generate low-frequency vibration, it is likely that annoyance would be more likely associated with perceptible building vibration than audible noise. Unfortunately, only a small amount of the D-12 data applied to situations where the feelable vibration was sufficiently severe that it could be considered a likely source of annoyance.

The D-12 study included two locations where passenger or freight trains powered by diesel-electric locomotives operated in the same corridors as transit systems. However, the amount of data collected for such systems was not sufficient to identify the differences in the vibration characteristics of this type of traffic, or how these operations affected human annoyance.

The proposed research would be an extension of the D-12 project and would collect data specifically near alignments where intercity, locomotive powered trains are the predominant source of vibration, for example along the Northeast corridor from Boston to Washington, DC.

The additional data would augment the current D-12 data set, extending the type and range of exposure described by the dose-response relationships. The results of the study would help define human response to ground-borne vibration, particularly the relationships between annoyance and total exposure. The data also would assist in refining and standardizing predictions of ground-borne vibration for different types of rail traffic.

1.2 OBJECTIVES

The objectives of the research would be,

1) To obtain annoyance and vibration exposure data for a large sample of people who live near rights of way that carry predominantly locomotive powered passenger and freight trains.

2) To develop dose-response relationships for locomotive powered trains and compare these to the curves developed during the D-12 program.

1.3 RESEARCH PROPOSED

The goal of the research would be to obtain at least 1000 respondents to a community survey of annoyance, similar to the survey used in the D-12 program.

Task 1 - Identify Systems for Test

Identify 3-5 systems for survey and testing. Obtain the support of the Agencies involved, similar to what was done in the D-12 study.

Task 2 - Survey of Annoyance

Develop and administer a questionnaire to residents who live in the test areas.

Task 3 - Field Testing

Perform field measurements to characterize the vibration exposure at the homes of each of the survey respondents. Analyze the exposure data using the metrics that were developed during the D-12 program.

Task 4 - Dose-Response Analysis

Develop dose-response relationships using the survey results and the measured exposure. Compare the relationships to those obtained during the D-12 study. If appropriate, combine the data with the D-12 data to produce a unified dose-response relationship.

Task 5 - Report

Summarize the results in a final report to include discussions of the implications with respect to currently used criteria.

1.4 ESTIMATE OF THE PROBLEM FUNDING AND RESEARCH PERIOD

It is suggested that funding in the range of $250,000-$300,000 would be needed for this work, and the work could be done in 1.5-2 years.

1.5 URGENCY AND PAYOFF POTENTIAL

Currently, vibration mitigation is routinely employed in the design of new rail projects. Research in Europe[1] finds that annoyance from the predominantly low-frequency vibration associated with high axle load trains occurs at levels higher than the current FTA criteria. Consequently, it is possible that vibration mitigation measures are being needlessly used for new rail projects. With a planned high speed rail project in California, and with plans by Amtrak to introduce high-speed rail service in up to eleven existing corridors, the potential payoff in capital cost savings by reducing the need for vibration mitigation, could be significant.

This research would not be considered urgent in the sense that it has no safety or other critical implications. However, given recent economic challenges, it is now even more important to spend public money wisely.

[1] Klæboe, R., Turunen-Risem, I.H., Hårvik, L., and Madshus, C. (2003) “Vibration in Dwellings from Road and Rail Traffic – Part II: Exposure-effect Relationships Based on Ordinal Logit and Logistic Regression Models,” Applied Acoustics, Vol. 64, pp. 89-109.

1.6 RELATIONSHIP TO FTA STRATEGIC GOALS AND POLICY INITIATIVES and TCRP STRATEGIC PRIORITIES

The research would address the second FTA strategic goal, "Improving Capital and Operating Efficiencies," by potentially reducing the capital cost of vibration mitigation measures. This could also impact operating costs in terms of ongoing maintenance, and/or replacement of the mitigation means that would normally be necessary over the lifetime of a new rail line.

1.7 RELATED RESEARCH

The proposed research is a direct follow-on to the TCRP D-12 project, "Ground-Borne Noise and Vibration in Buildings Caused by Rail Transit." The survey, measurements and data analysis techniques that were developed during the D-12 project would be directly applicable to the proposed research.

1.8 PERSONS DEVELOPING THE PROBLEM

This research idea is proposed by the same team who performed the work associated with the D-12 study.

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1.9 PROCESS USED TO DEVELOP PROBLEM STATEMENT

The proposed work represents follow-on research to the TCRP D-12 project. The research would have a direct impact on the work that is conducted by members of the TRB ADC-40 Rail Noise and Vibration sub-committee and the American Public Transportation Association (APTA) Track Noise / Vibration Technical Forum.

1.10 DATE AND SUBMITTED BY

2. TOPIC 2 - VERIFICATION OF TRANSIT NOISE AND VIBRATION PREDICTIONS

2.1 RESEARCH PROBLEM STATEMENT

The current method to predict ground-borne vibration and noise from new transit projects is documented in the 2006 manual, "Transit Noise and Vibration Impact Assessment," published by the Federal Transit Administration (FTA). The detailed prediction methods use the transfer mobility (TM) method to estimate the vibration and noise exposure in communities near planned new rail alignments. Because the TM method uses vibration propagation tests to characterize the ground transmission properties, there is a relatively high degree of confidence that the attenuation of vibration with distance near measurement sites is accurate. However, there are a number of other areas where there is less confidence in the data and the assumptions used for ground-borne vibration predictions. Some of these areas include:

- Deriving force density levels from measurements. Experience is that there can be substantial differences in the force densities derived depending on where the measurements are performed.
- Vibration attenuation occurring when the vibration energy travels from the ground into the building foundation, commonly referred to as the “coupling loss.” Clearly this depends on the building construction.
- Attenuation of vibration as it propagates throughout the building structure, and amplification resulting from resonances of the floors and other structural elements. There are a number of different factors used by different consultants. The experience with measurements performed during the D-12 project is that the average effect of the coupling loss and amplifications for wood-frame residential structures is close to zero decibels; however, there can also be a large building-to-building variation for seemingly identical structures.
- The radiated noise efficiency is typically assumed to be 1. That is, the vibration velocity level of the floor is assumed to be equal to the resulting sound pressure level when using the decibel references of 1 µin/sec for vibration velocity and 20 µPa for sound. The data from the residences measured for the D-12 project suggest that a more appropriate adjustment would be -5 dB rather than 0 dB.
- In many cases, the resulting predictions are augmented with a factor of safety to account for these uncertainties. A uniform adjustment of 5 decibels is used by many consultants. Others used an undefined “design factor” as the adjustment. The goal is often stated as making sure that the predictions tend to be conservative. That is, the general approach is to make sure that it will be rare that vibration levels from train operations exceed the predicted levels.

The results of the D-12 project, “Ground-Borne Noise and Vibration in Buildings Caused by Rail Transit,” show that it is unlikely that more than a small percentage of the variance in human response to ground-borne vibration and noise will ever be explained by physical measures of the vibration amplitude. Extrapolating from the survey data, it appears that there always will be some people who report being highly annoyed by even the faintest vibration and others who are never highly annoyed by vibration regardless of how high the vibration levels are.

One conclusion that can be drawn from the results of the D-12 study is that basing decisions about expensive vibration mitigation measures on highly-conservative prediction procedures may not be justified. The goal of this study will be to provide information that can be used to standardize the vibration prediction procedures and can be used to develop consistent policy about how much "safety factor" should be included in the predictions. If the study can confirm the accuracy of the prediction procedures or suggest changes that will improve the accuracy, smaller factors of safety could be justified, which could substantially reduce the need for vibration mitigation. Also, analysis of post-build vibration levels could lead to less conservative assumptions about factors such as estimating radiated sound levels from predicted vibration levels. The overall goal would be to provide tools that would result in vibration mitigation being installed only where it is needed.

2.2 OBJECTIVES

The objectives of the research would be to,

1) Refine vibration prediction procedures.
2) Provide data that decision makers can use to justify the factor of safety used in vibration prediction studies.
3) Justify the adjustment factors that are used for building coupling loss, floor amplification, and for conversion from vibration level to radiated sound pressure level.

2.3 RESEARCH PROPOSED

Task 1 - Identify Transit Systems for Test

Identify a representative number (5-10) of new transit systems that have associated pre-build ground-borne vibration and noise predictions. In order to remove the confounding factor of mitigation, it is suggested that test areas be chosen where no track mitigation was installed. As part of the selection process, it should be determined that pre-build vibration/noise prediction data is available for use.

Task 2 - Select Test Locations

For each of the systems in Task 1, identify possible test buildings and contact the owners in order to obtain permission to make vibration and noise measurements. The goal would be to achieve 50 individual test locations.

Task 3 - Field Testing

Conduct vibration and noise measurements at each of the test sites. The noise and vibration would be measured simultaneously inside and outside the building for a sufficient number of train passages (typically 15-20). At a minimum, data should be acquired in 1/3 octave frequency bands.

Task 4 - Data Analysis

Compare the exterior vibration data to the pre-build estimates in order to determine the accuracy of the predictions. Compare the interior and exterior vibration data to determine the building coupling loss and compare this to the recommended adjustments in the FTA manual. Compare the interior noise level to the interior vibration level to determine the vibration-to-noise adjustment factor and compare this to the FTA method.

Task 5 - Report

Summarize the results in a final report to include recommendations related to the use of safety factors, building coupling loss and vibration-to-noise adjustments.

2.4 ESTIMATE OF THE PROBLEM FUNDING AND RESEARCH PERIOD

It is suggested that funding in the range of $400,000-$450,000 would be needed for this work, and the work could be done in 2-2.5 years.

2.5 URGENCY AND PAYOFF POTENTIAL

Currently, vibration mitigation is routinely employed in the design of new transit projects. If the vibration and noise predictions are overly conservative, then it is likely that mitigation is being specified unnecessarily. Depending on the required mitigation performance, the cost of mitigation could be $100-$500 per foot of track. Given that thousands of feet of track mitigation may be identified on a project, better predictions could represent significant cost savings.

This research would not be considered urgent in the sense that it has no safety or other critical implications. However, given recent economic challenges, it is now even more important to spend public money wisely.

2.6 RELATIONSHIP TO FTA STRATEGIC GOALS AND POLICY INITIATIVES and TCRP STRATEGIC PRIORITIES

The research would address the second FTA strategic goal, "Improving Capital and Operating Efficiencies," by potentially reducing the capital cost of vibration mitigation measures. This could also impact operating costs in terms of ongoing maintenance, and/or replacement of the mitigation means that would normally be necessary throughout the lifetime of a new transit line.

2.7 RELATED RESEARCH

The results from the TCRP D-12 program, "Ground-Borne Noise and Vibration in Buildings Caused by Rail Transit" have a direct bearing on the proposed research. The proposed research would be a natural follow-on to the work undertaken during the D-12 project.

2.8 PERSONS DEVELOPING THE PROBLEM

This research idea is proposed by the same research team that was awarded the D-12 study.

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2.10 DATE AND SUBMITTED BY