# Appendix F: Vibration

# APPENDIX F-1

# AMBIENT VIBRATION MONITORING DATA

# 1 INTRODUCTION

Ambient vibrations measurements were made at 14 locations along the planned alignment. The vibration velocity levels were measured over a 24 hour period using a data logger using a slow rms detector. The vibrations were recorded using two methods, 1 second samples and 1 minute intervals. In general the vibration sensor was located in the building basement as near as possible to the planned alignment.

The 1 second sample data was used to identify train passes from existing rail traffic.

The 1 minute interval data was used to evaluate the overall vibration environment at each site. The interval data is presented in the accompanying figures. In the figures, L(99) is the vibration level that was exceeded 99% of the time in each interval, which is indicative of the background vibration levels (the levels that are usually present). L(50) is the vibration that is present 50% of the time. L(50) can be thought of as the average vibration level at the site. L(1) is the vibration level that is exceeded 1% of the time in each interval. L(1) is indicative of the greatest vibration levels that were measured during the interval.

These figures indicate that the vibration has a distinct day/night variation. Typically, the nighttime vibration levels are 5-10 dB lower than those measured during the daytime.

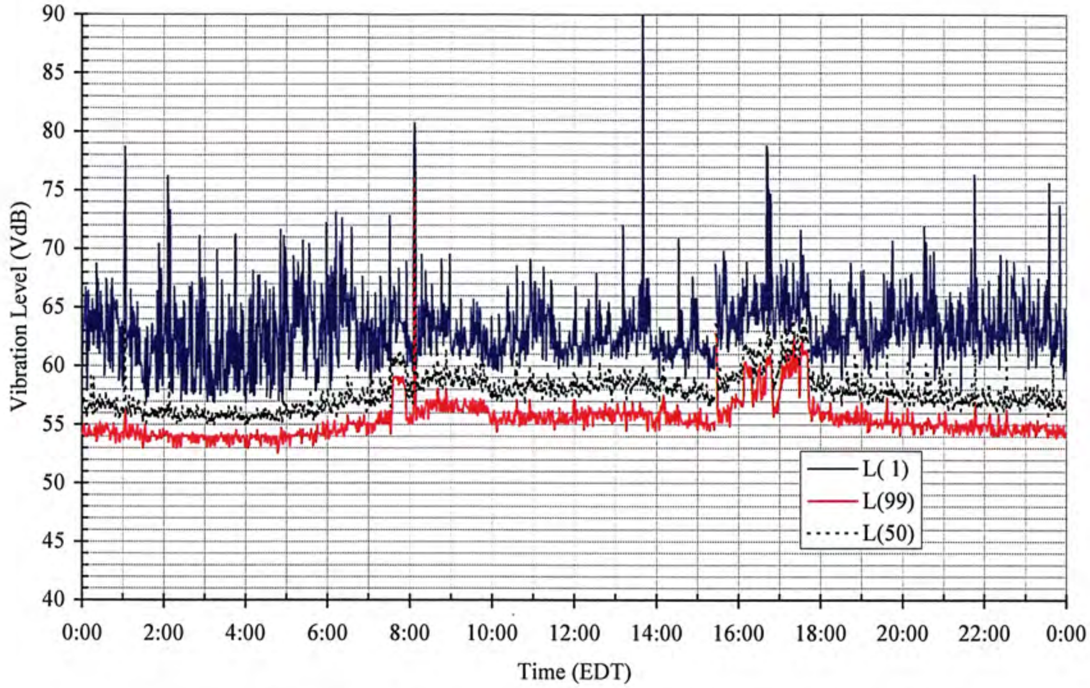


Figure A1: Ambient Vibrations - 466 Lexington Avenue - May 5-6, 1999

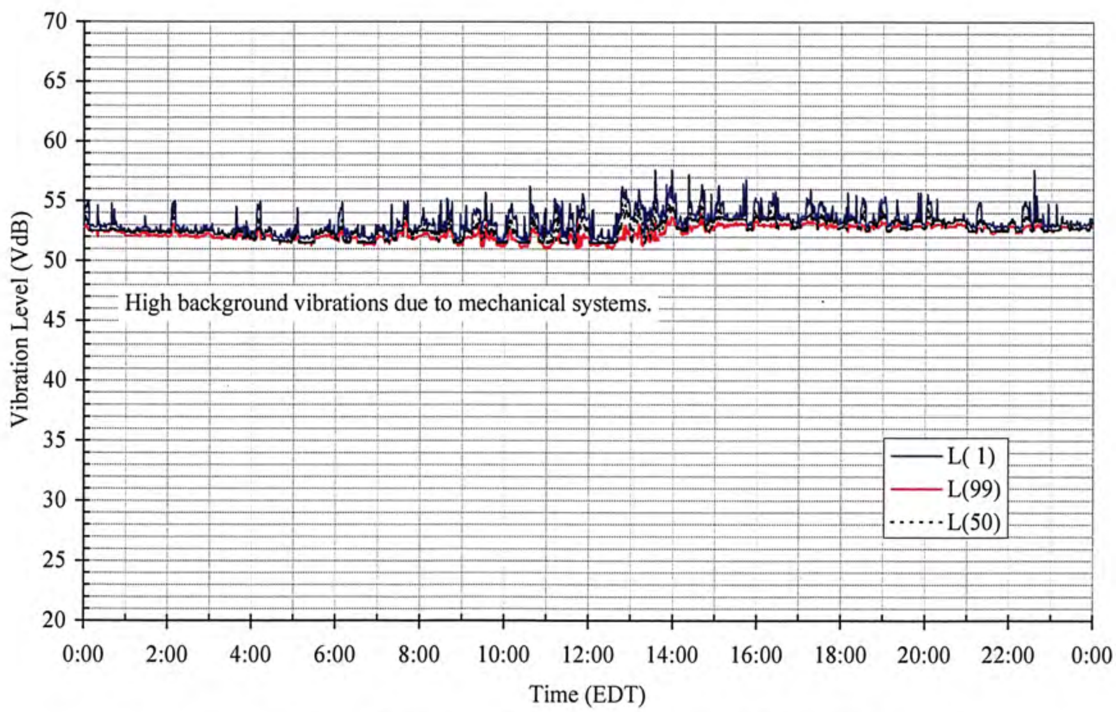


Figure A2: Ambient Vibrations - 270 Park Avenue - May 4-5, 1999

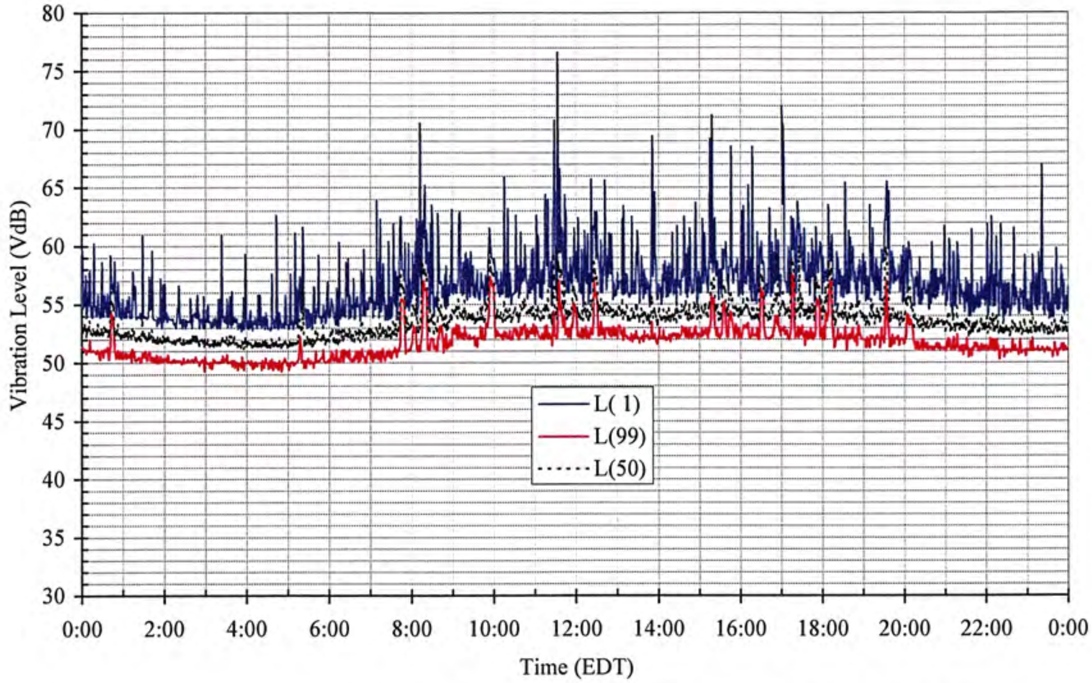


Figure A3: Ambient Vibrations - 301 Park Avenue (Waldorf Astoria) - July 27-28, 1999

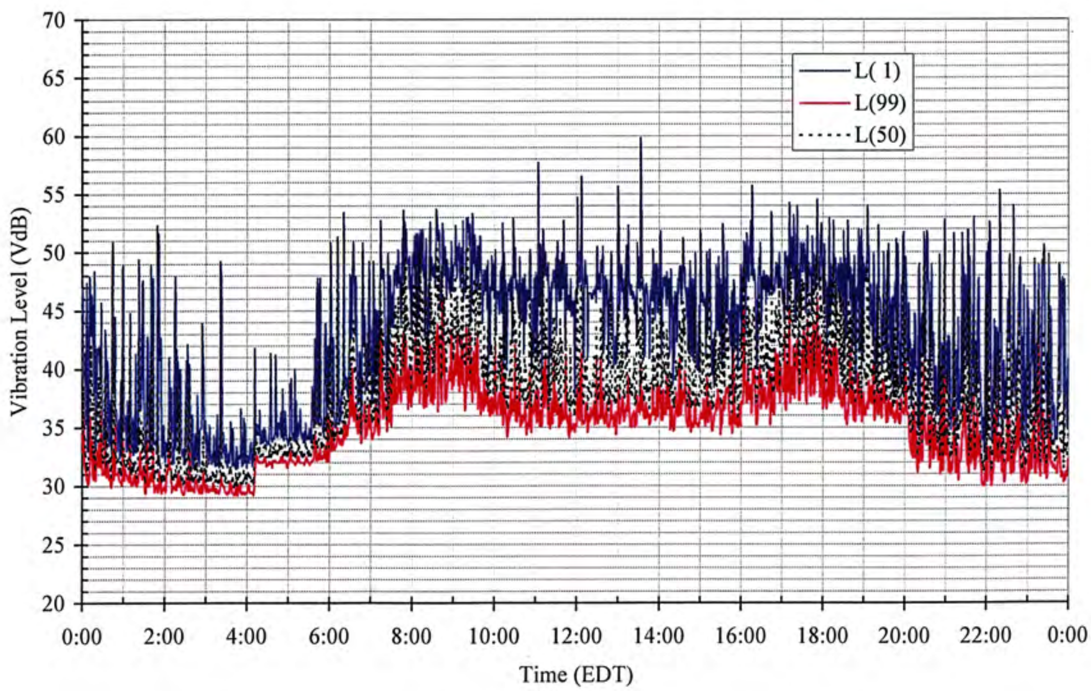


Figure A4: Ambient Vibrations - 350 Park Avenue - May 5-6, 1999

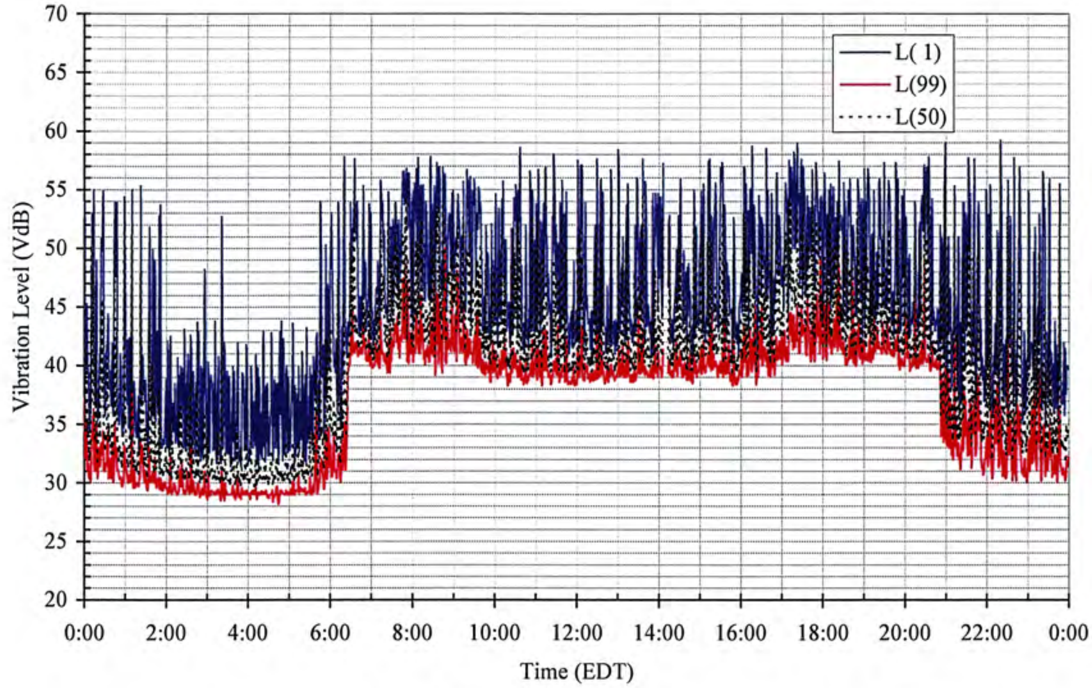


Figure A5 - Ambient Vibrations - 370 Park Avenue - May 5-6, 1999

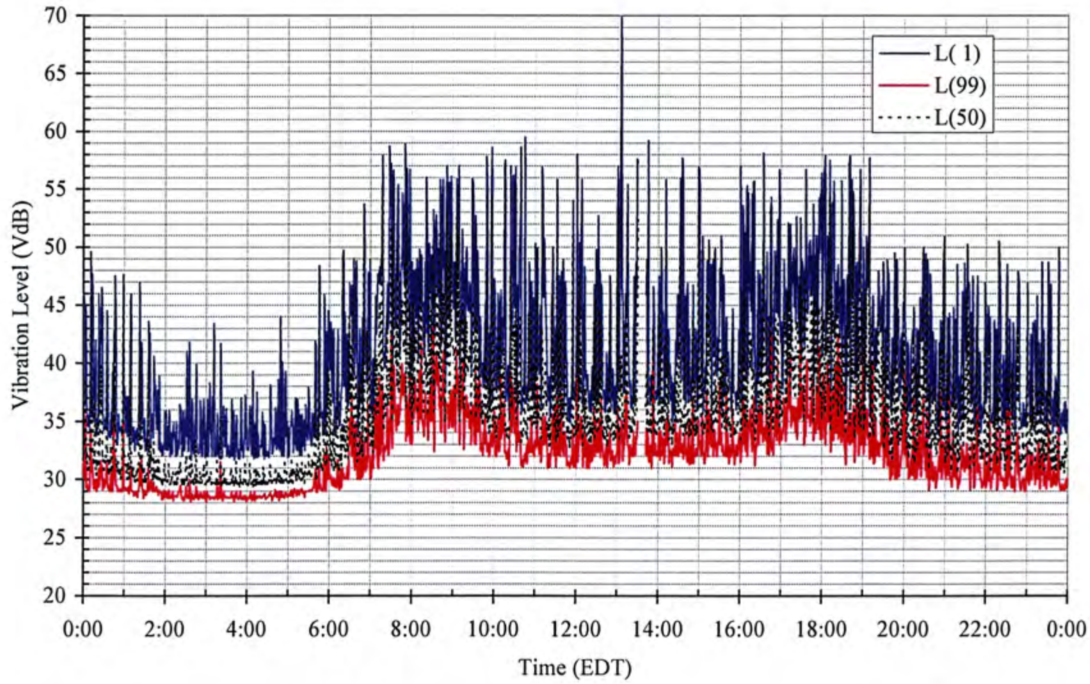


Figure A6: Ambient Vibrations - 390 Park Avenue (Lever House) - May 5-6, 1999

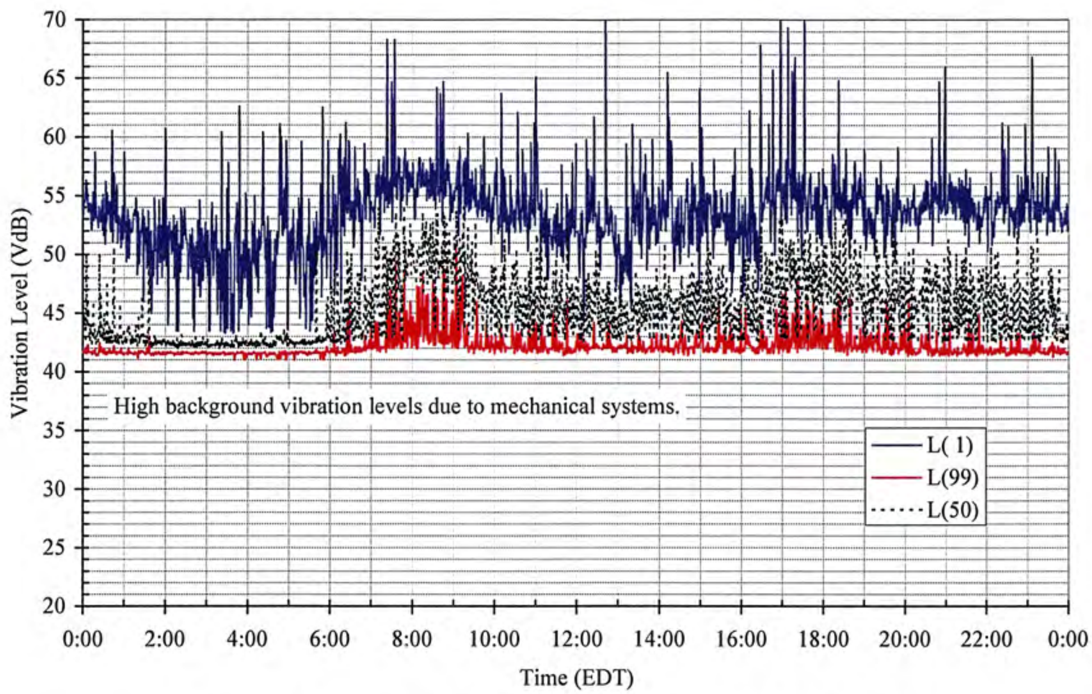


Figure A7: Ambient Vibrations - 425 Park Avenue - May 4-5, 1999

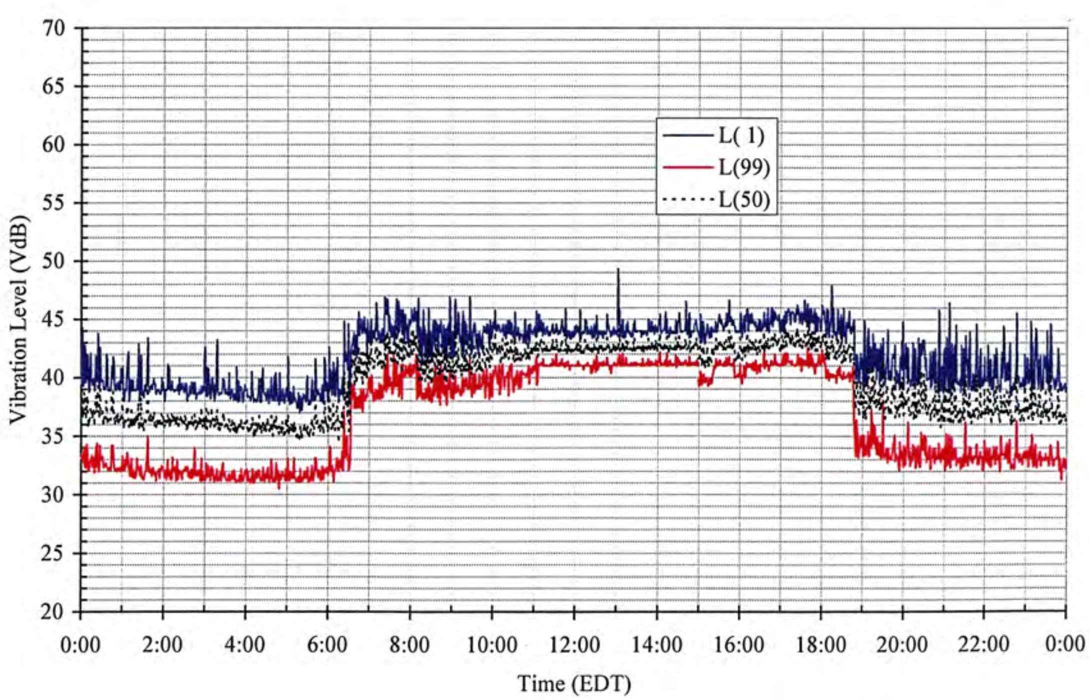


Figure A8: Ambient Vibrations - 500 Park Avenue - May 6-7, 1999

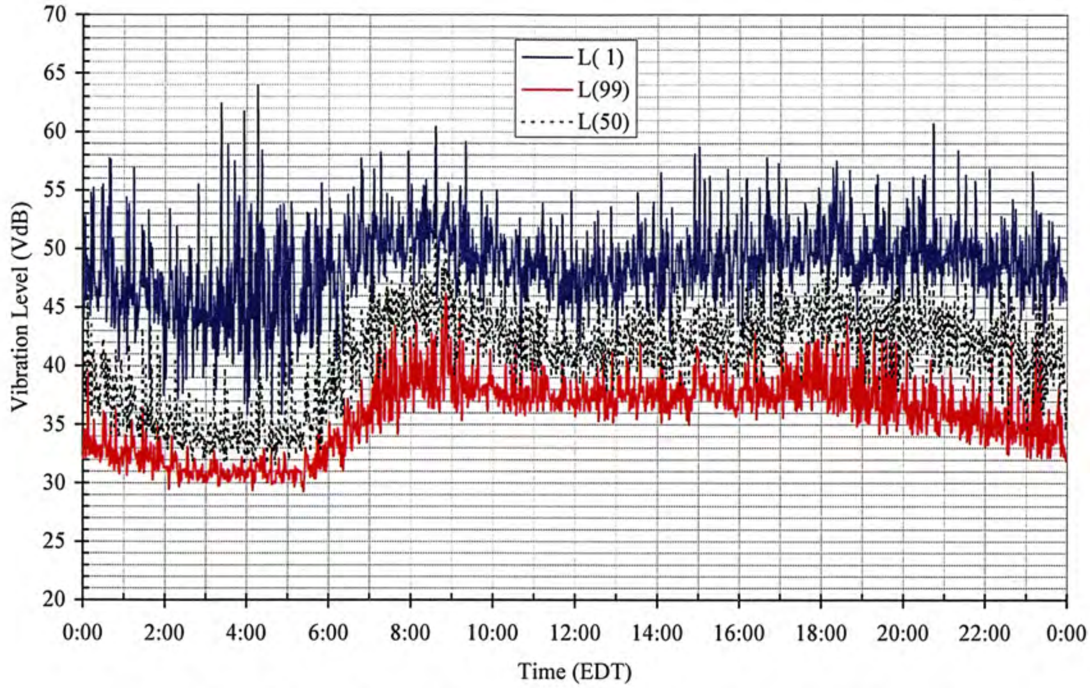


Figure A9: Ambient Vibrations - 521 Park Avenue - July 28-29, 1999

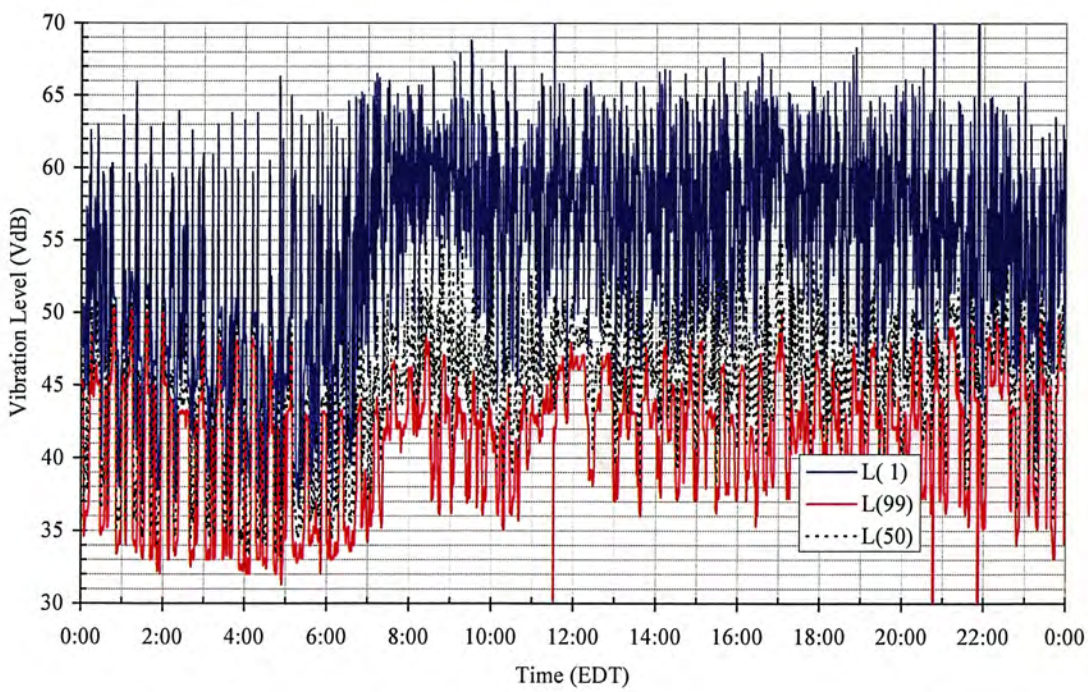


Figure A10: Ambient Vibrations - 786 Lexington Avenue - September 22-23, 1999

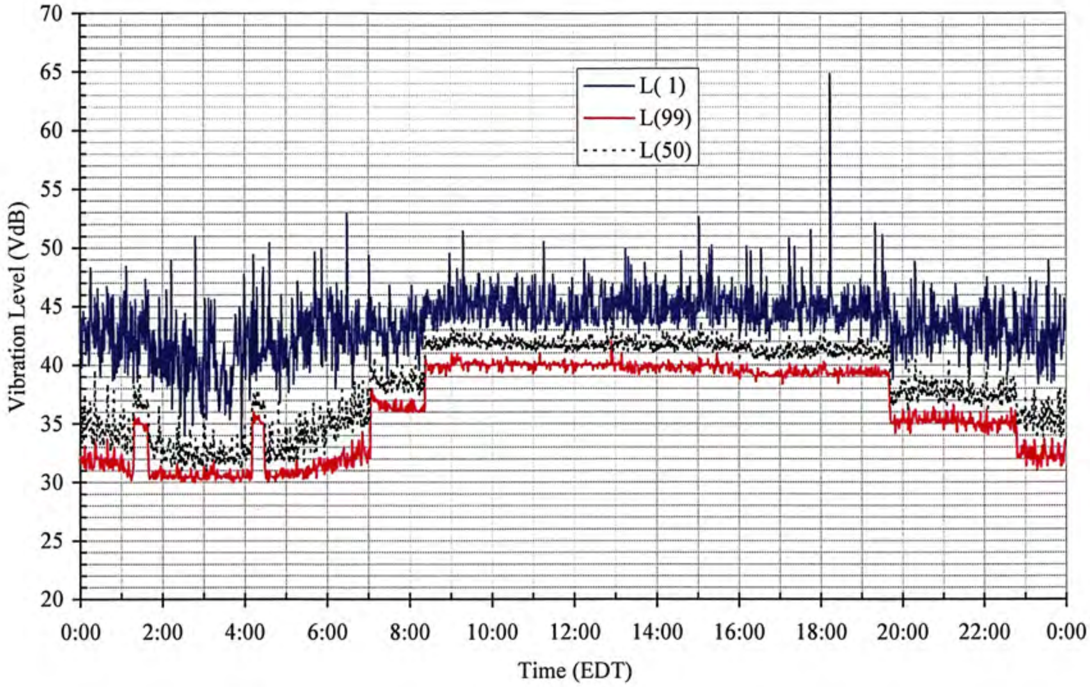


Figure A11: Ambient Vibrations - 166 East 63rd Street - May 6-7, 1999

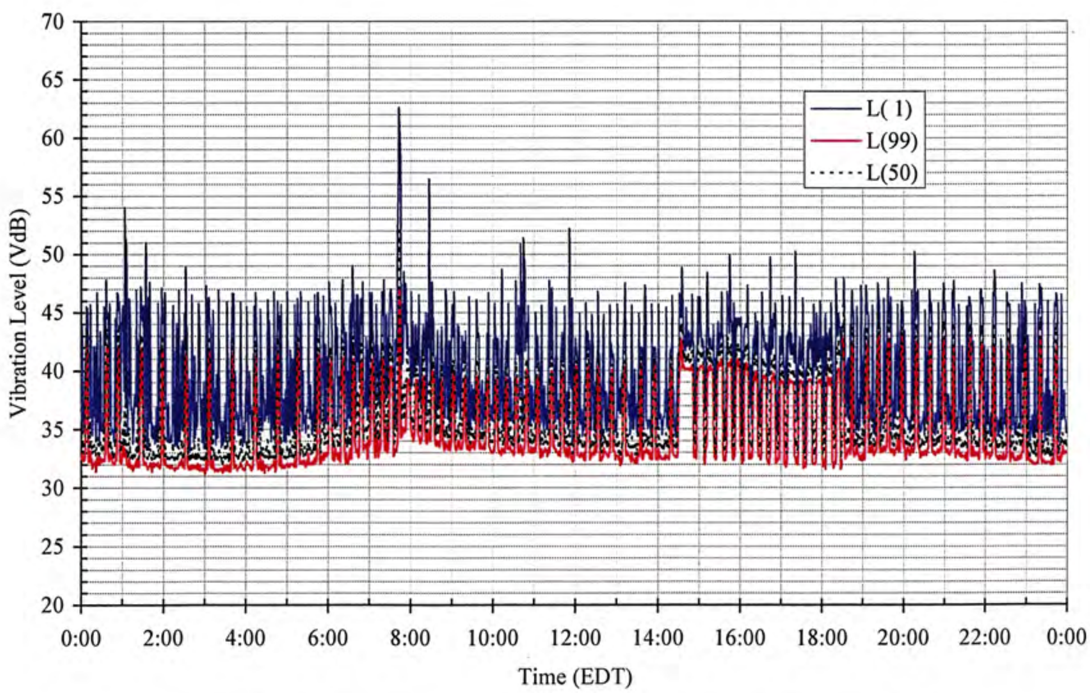


Figure A12: Ambient Vibrations - 250 East 63rd Street - May 6-7, 1999

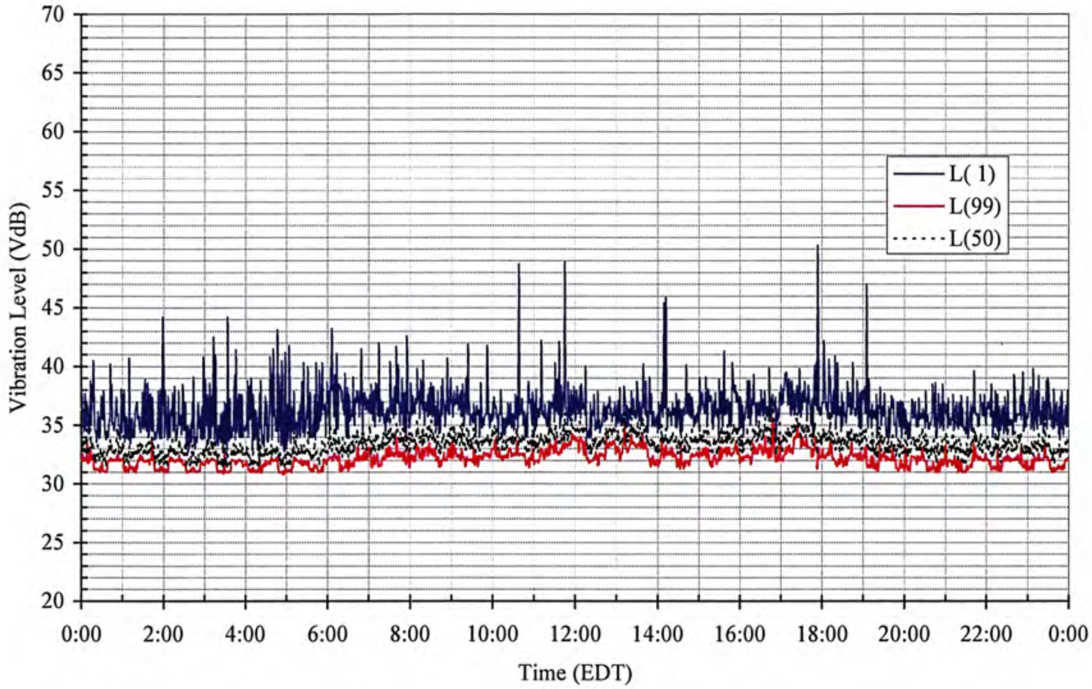


Figure A13: Ambient Vibrations - 201 East 62nd Street - May 6-7, 1999

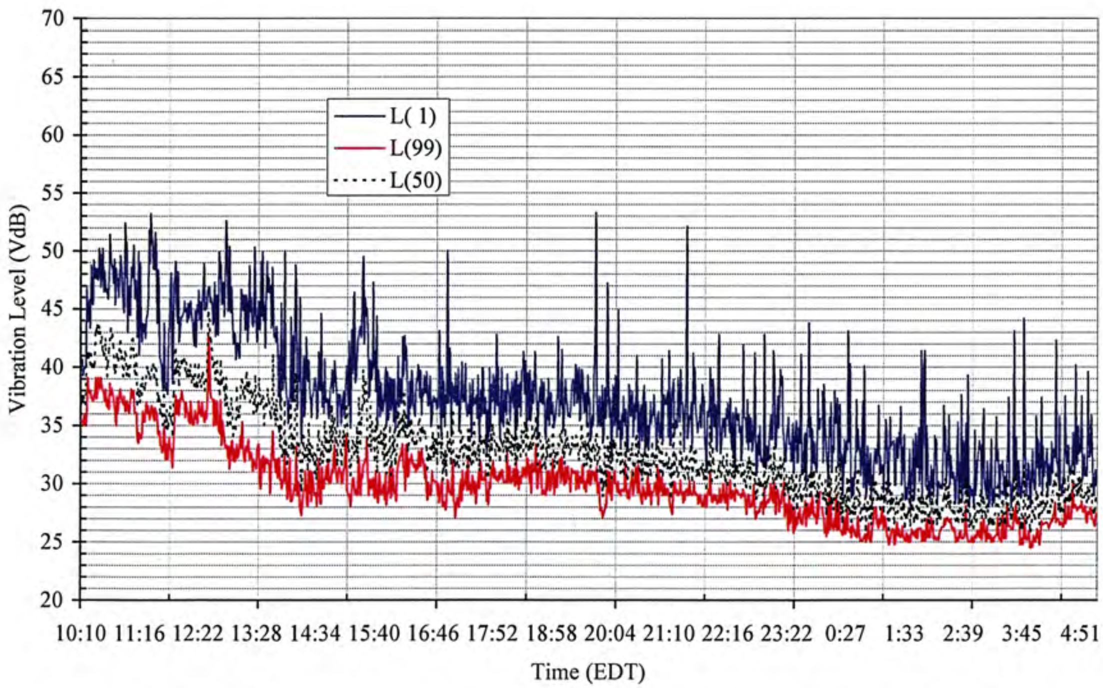


Figure A14: Ambient Vibrations - Newcomer High School - July 29-30, 1999

# APPENDIX F-2

## VIBRATION PREDICTIONS USING THE TRANSFER MOBILITY METHOD

# 1 INTRODUCTION

The propagation of vibration through the ground is a complex phenomenon that is affected by a number of factors, including the soil type, moisture content, location of the water table, soil layering, discontinuities such as trenches or caverns, and topography. In cases where only rough estimates of transmitted vibration are required, simple models can be used to predict propagation through the ground. The FTA general vibration assessment is an example of such a simple model. However, in cases where more precise estimates are required, or where the ground conditions preclude the use of simple models, a more rigorous approach is needed. In the present study, the complex subterranean structure on Manhattan consisting of myriad tunnels, building foundations and utility lines, suggested a rigorous approach to vibration prediction, even at the EIS stage.

Transfer mobility testing is an empirical method for measuring the vibration characteristics of the ground at a specific location. In the transfer mobility method, the vibration propagation characteristics of the ground are measured using a calibrated vibration source and an array of vibration sensors. Having determined the vibration propagation characteristics, it is then possible to predict the vibrations produced by other sources simply by comparing the new source to the calibrated source.

The improved accuracy of the transfer mobility method comes from the fact that the test vibrations travel over the same path as do the vibrations of the real vibration source, in this case, a train in a tunnel.

The transfer mobility method is described in general in Section 11 of the FTA manual. The purpose of this Appendix is to describe in detail the method and assumptions that were used in this study.

# 2 BACKGROUND

Most people are familiar with a time domain representation of vibration. For example, during an earthquake, the needle on a seismograph oscillates back and forth across the paper giving a time history of the magnitude of the vibrations in the ground. From a time history plot, one can readily observe the duration of the earthquake and determine the greatest magnitude of the vibrations. However, it is difficult to determine the frequency character of the vibration energy; that is, whether or not the vibration energy is comprised of slowly oscillating motions or of high frequency rapid oscillations.

Frequency domain analysis is a method used to break down the time signal into its principal frequency components. In the frequency domain, for example, it is very easy to see whether the vibration energy is predominantly low frequency, high frequency, or something in-between.

Frequency domain analysis is the backbone of the transfer mobility method. In effect, the transfer mobility measurement determines to what extent vibrations of different frequencies propagate through the ground. In fact, one way to measure transfer mobility is to simply vibrate the ground at a known frequency and measure the response. By changing the frequency of the vibrator, it is possible to obtain the ground propagation characteristics over a range of frequencies. In the present study, a large hammer was used to excite the ground. The hammer excites many frequencies at once, which speeds up the test process.

# 3 BASIC EQUATIONS AND DEFINITIONS

## *3.1 Point Source Transfer Mobility*

The source-path-receiver concept applies equally well to vibration as it does to airborne noise. In this case, the vibration source is a train or piece of construction equipment; the path is the ground; and, the receiver is the occupied space where the people and/or equipment reside who may be potentially affected by the vibration.

In the frequency domain, a point source, path and receiver are linked by the equation,

$$V(f) = Tm_{point}(f) * F_{point}(f), \qquad \text{(B1)}$$

where V is the vibration velocity in units of inches/second, $Tm_{point}$ is the transfer mobility (propagation) in units of inches/second/$lb_f$ and F is the vibrating force in units of pounds force ($lb_f$). The f in parentheses is meant to indicate that all three quantities are functions frequency. Equation B1 pertains to the point transfer mobility, that is the vibration that results from a point vibration source, such as a pile-driver. Similar expressions can be developed for other force distributions, such as a line-source which is used to model the vibrations produced by a train.

It is common to re-write Equation B1 using decibel notation, where the quantities are referenced to standard quantities. In decibel notation, Equation B1 becomes,

$$L_v(VdB) = TM_{point}(dB) + L_F^{point}(dB), \qquad \text{(B2)}$$

where, $L_v = 20 \log(V/V_{ref})$ is the vibration velocity level. $V_{ref}$, the reference velocity level is equal to$10^{-6}$ inches/second. The units of velocity level are denoted VdB to avoid confusion with acoustic decibels. $TM_{point}$ is the point transfer mobility level in decibels referenced to $10^{-6}$ inches/second/$lb_f$. $L_F^{point}$ is the force level in decibels referenced to 1 $lb_f$.

### 3.2 Line Source Transfer Mobility and Force Density

The point source transfer mobility is used to predict the vibration velocity due to a point excitation. A similar approach can be used to predict the vibration velocity due to a line source like a train. In decibel notation, the line source transfer mobility is given by,

$$L_v(VdB) = TM_{line}(dB) + L_F(dB) + C(dB)\,, \qquad \text{(B3)}$$

where $TM_{line}$ is the line source transfer mobility level in decibels, referenced to $10^{-6}$ inches/second/($lb_f$/ft) and $L_F$ is the force density level in decibels referenced to 1 $lb_f$/ft. C is a correction term used to account for factors like the building/soil coupling loss and track fixation method.

In the form presented in Equation B3, the transfer mobility and force density are used to predict the vibration level. Equation B3 can also be rearranged in order to estimate the force density of a line source based on measured propagation and vibration data,

$$L_F(dB) = L_v(VdB) - TM_{line}(dB)\,. \qquad \text{(B4)}$$

## 4 TEST and ANALYSIS EQUIPMENT

Figure B4.1 shows a schematic representation of the test equipment used to measure transfer mobility and force density in the present study. Each component is described in detail in the following sections.

Seismic Hammer

The seismic hammer imparts a force pulse to the ground. The hammer was fashioned out of a "safety hammer" that is commonly used for soil sampling tests. The hammer consists of a 300 $lb_m$ steel mass that is dropped approximately 30 inches onto a steel anvil. A mechanical winch and quick release hook are used to lift and drop the mass. The force pulse is measured using four strain gages, configured in a full bridge arrangement that is designed to give bending and temperature compensation.

The strain gages are connected to a signal conditioning box that provides a voltage signal proportional to the applied force.

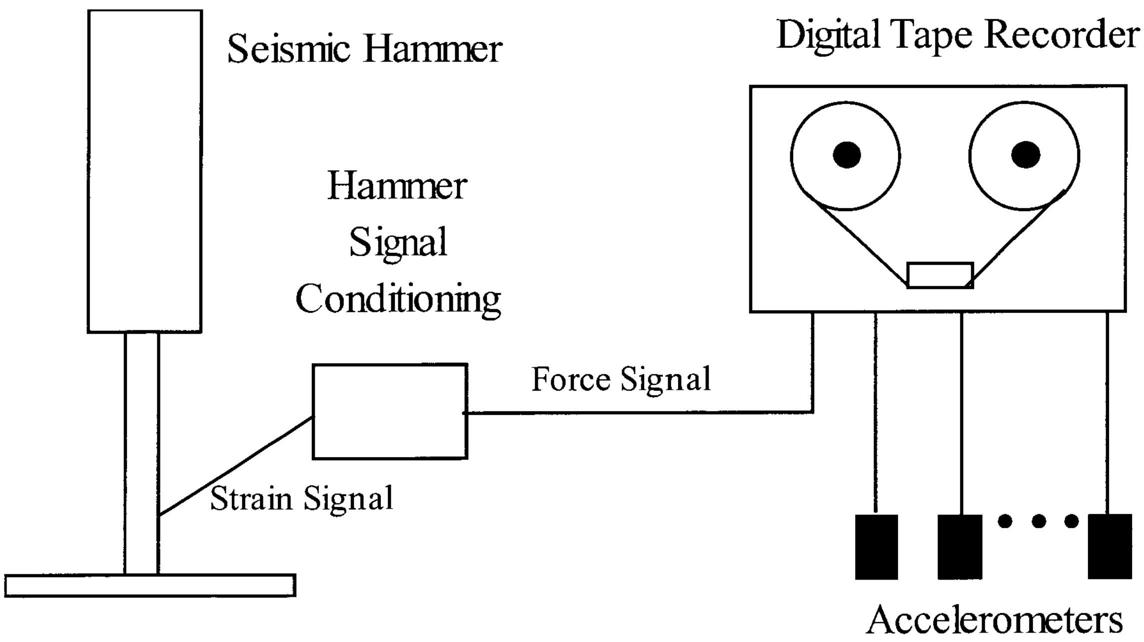


Figure B4.1: Data Acquisition Setup

Accelerometers

The ground vibration acceleration is measured using an array of accelerometers. The acceleration data is converted to velocity as required during a post processing operation.

Digital Tape Recorder

The hammer force signal and accelerometer response signals were recorded using a 16 channel digital tape recorder.

# 5 AT GRADE FORCE DENSITY TEST

The force density of a 6 car LIRR M3 train was measured on March 27, 1999. The measurements were made in a storage yard near the Belmont Park racetrack on Long Island. At this location, the alignment has 4 parallel tracks, all supported by tie on ballast. The measurements were done on Track #4.

## *5.1 Point Source Transfer Mobility*

The point transfer mobility was measured from Track #4 to seven vibration sensors located at distances of 25', 50', 75', 100' 200' and 300' from the track centerline. The impact hammer was located on a tie, centered between the rails. The vibration data was recorded as vibration acceleration, measured in the vertical direction.

Figure B5.1 shows a sample force pulse and the vibration response measured at the 50' sensor. In this case, the vibration pulse took approximately 50 milliseconds to reach the sensor.

Approximately 40 impacts were averaged to determine the acceleration/force transfer function. All of the data was tape recorded.

The force/response transfer functions were evaluated with a narrow band signal analyzer. The transfer functions were initially determined as the ratio of the measured acceleration to the applied force and then converted to narrow band velocity/force (transfer mobility). The narrow band transfer mobility transfer functions were then condensed into 1/3 octave bands by a suitable combination of the narrow band data.

Figure B5.2 shows the narrow band and 1/3 octave band point transfer mobility for the 100' sensor position. Here, the most efficient vibration transmission occurred between about 15 Hz and 40 Hz.

Coherence

The third trace on Figure B5.2 is the coherence of the narrow band transfer function. Coherence gives an indication of the quality of the measured data. By using artificial random noise superimposed on the recorded data, it was determined that good estimates of the transfer function were possible with coherence values as low as 0.2 (with 40 averages). As can be seen from this figure, the measured coherence was generally above 0.75, even at high frequencies. This indicates that the seismic hammer has adequate high frequency energy content and, further, that the high frequency portion of the transfer function has a high level of confidence associated with it. (When impacting on soft surfaces like soil, it is often difficult to obtain sufficient high frequency content in the impact pulse.)

## *5.2 Point Source Transfer Mobility – Attenuation with Distance*

Generally, the vibrations induced by the hammer decrease with increasing distance from the source. This is caused both by geometric spreading and by energy absorption in the soil.

Figure B5.3 shows the variation of the 100 Hz point transfer mobility component with distance. As the figure shows, the point transfer mobility data has a linear dependence on the logarithm of the distance from the track. The slope of the curve is equivalent to a 9 dB drop for each doubling of distance. This is approximately 6 dB more than the theoretical 3 dB attenuation rate for surface Rayleigh waves (with no soil dissipation).

A linear curve fit was used to model the point transfer mobility data for each 1/3 octave band. (In cases where the coherence of the transfer function was poor at a given frequency, the curve fit parameters from an adjacent frequency band were used in the model.)

The linear curve fit coefficients for the Long Island point source transfer mobility data are shown in Table B5.1.

**Table B5.1 -** Point Source Transfer Mobility Model Coefficients for Long Island

| 1/3 Octave Band Center Frequency (Hz) | $a_0$* | $a_1$* |
|---|---|---|
| 8 | 28 | -14 |
| 10 | 34 | -14 |
| 12.5 | 58.61941 | -25.00174 |
| 16 | 68.89712 | -28.9118 |
| 20 | 76.34807 | -32.42563 |
| 25 | 43.10594 | -12.77196 |
| 31.5 | 43.10594 | -12.77196 |
| 40 | 57.446 | -23.1388 |
| 50 | 38.63559 | -17.12976 |
| 63 | 38.63559 | -17.12976 |
| 80 | 17.8855 | -9.533762 |
| 100 | 48.37664 | -29.74355 |
| 125 | 28.28073 | -22.50879 |
| 160 | 32.99259 | -30.7296 |
| 200 | 46.79834 | -40.39494 |
| 250 | 34.96992 | -38.60573 |
| 315 | 23.9208 | -33.95278 |
| 400 | 21.31648 | -32.83701 |
| 500 | 10.60994 | -27.64251 |

* $TM_{point} = a_0 + a_1 * \log_{10}[d(ft)]$

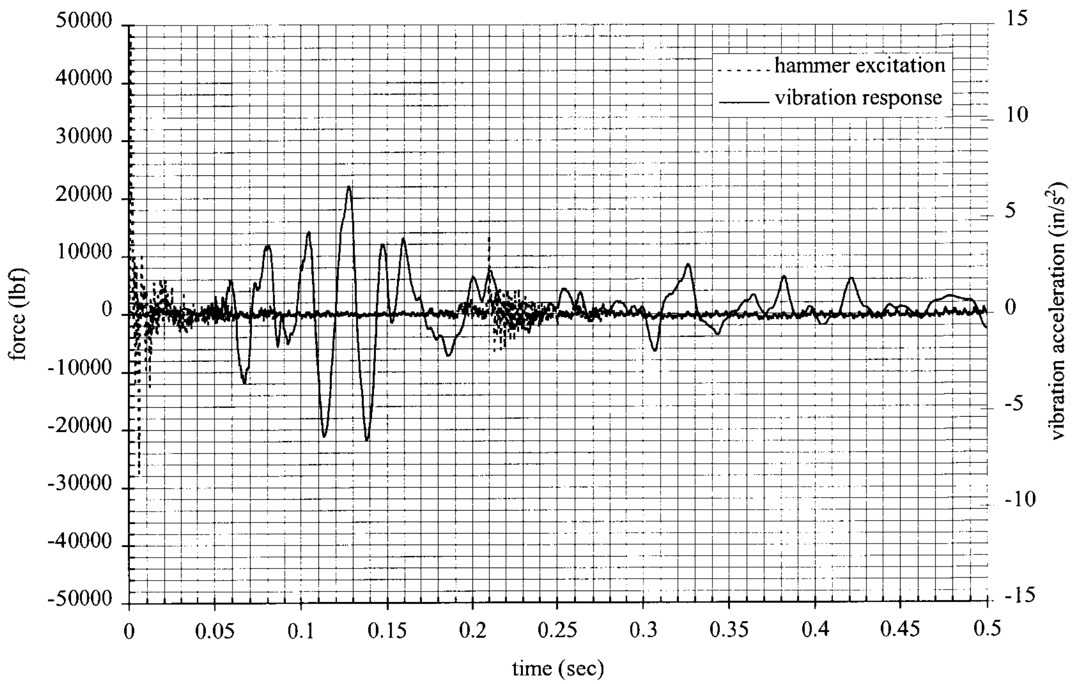


Figure B5.1: Hammer Induced Vibration Waveform at 50' Sensor

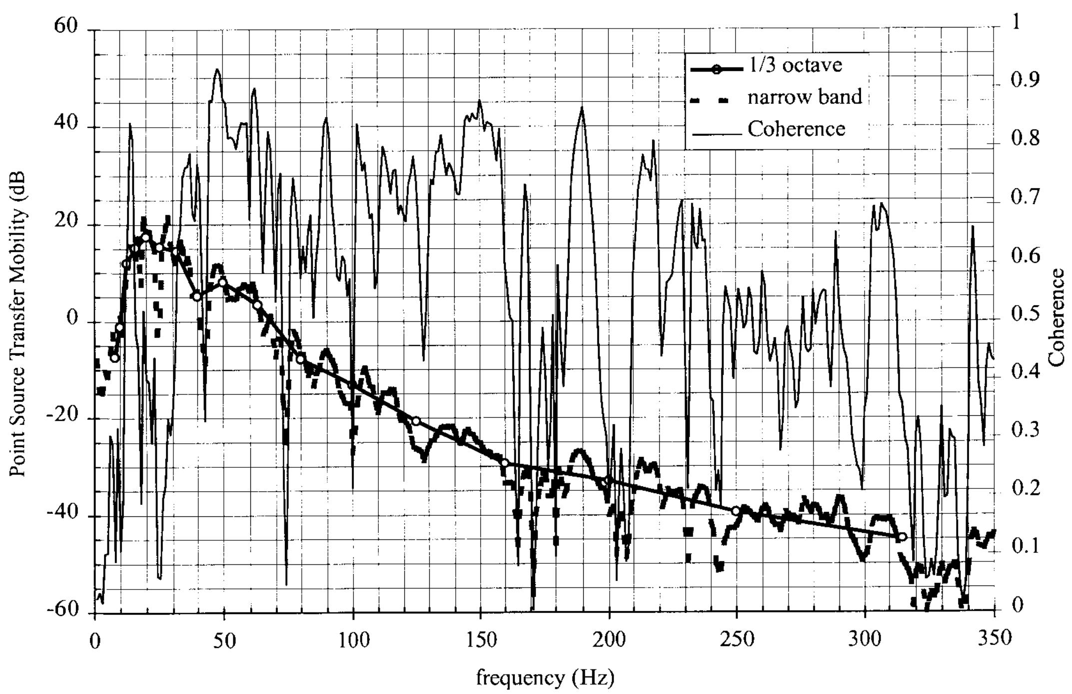


Figure B5.2: Point Source Transfer Mobility at 100 ft

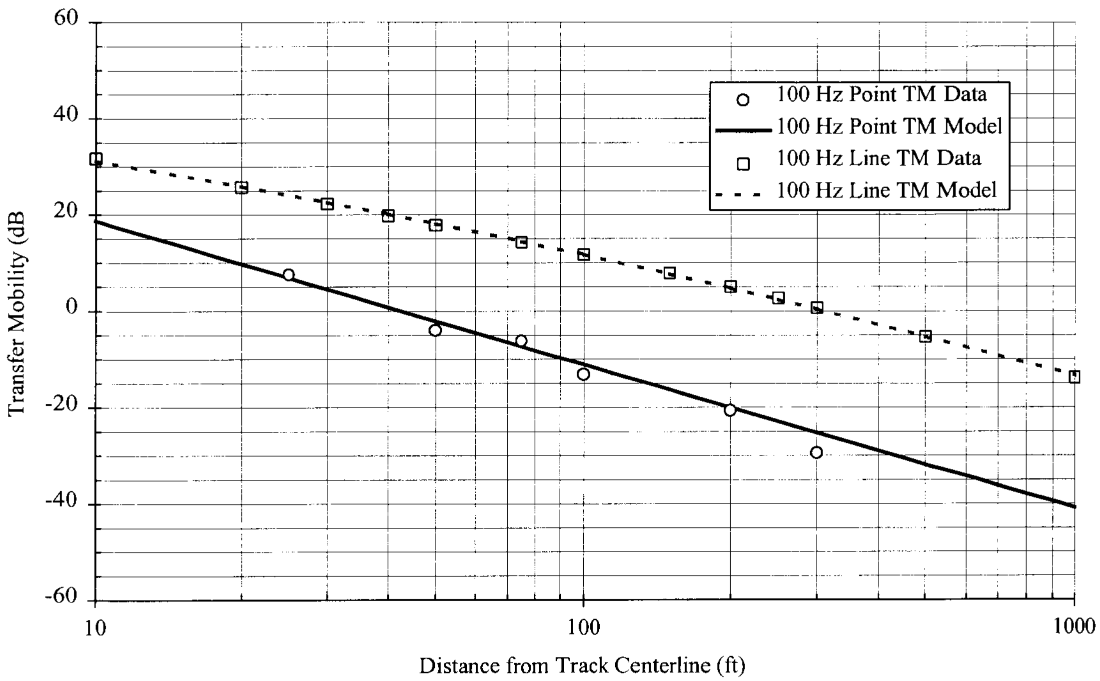


Figure B5.3: Variation of 100 Hz Transfer Mobility Component with Distance

### 5.3 *Line Source Transfer Mobility*

The six car train for the Long Island force density test was 510 ft long. Numerical integration was used to determine the line source transfer mobility from the point source model. The line source transfer mobility, evaluated at a perpendicular distance $y_0$, is given by the line integral,

$$TM^2_{line}(y_0) = \int_{-L/2}^{L/2} TM^2_{point}(y_0, x)\, dx, \qquad \text{(B5)}$$

where the point source transfer mobility is used in its dimensional form,

$$TM^2_{point}(y_0, x) = TM^2_{ref} * 10^{\frac{a_0 + a_1 \log[(y_0^2 + x^2)^{1/2}]}{10}}, \qquad \text{(B6)}$$

where x is the distance along the track from the center of the train, $a_0$ and $a_1$ are the linear curve fit coefficients for the point source transfer mobility, and $TM_{ref} = 10^{-6}$ in/s/lbf. Once the line source transfer mobility is calculated it can be converted to decibel notation using,

$$TM_{line}(dB) = 10 \log(TM^2_{line}) - 20 \log(TM_{ref}), \qquad \text{(B7)}$$

where $TM_{ref} = 10^{-6}$ in/s/(lbf/ft).

The line source transfer mobility, calculated at discrete distances, $y_0$, from the track centerline is shown on Figure B5.3 for the 100 Hz 1/3 octave band. To facilitate the calculations, a quadratic curve fit was used to model the calculated line source data.

### *5.4 Vibrations due to Train Passes*

After the transfer mobility tests were done, the track was cleared and the test train was run by the test site at 15 mph, 30 mph, 45,mph and 50 mph. At each speed, four passes were recorded, two in each direction. The train direction had no significant effect on the measured vibrations.

The 1/3 octave vibration spectra were measured at each accelerometer location for each train pass. The spectra were measured using the peak hold function in the spectrum analyzer. In peak hold mode, the analyzer records the maximum vibration level that occurred in each 1/3 octave band during the passby. Figure B5.4 shows the vibration spectra measured at the 100' sensor position during four train passes at 30 mph. The solid curve represents the average spectrum that was used for further analysis.

Figure B5.5 shows the average spectra for a 30 mph train speed at each measurement distance. As one would expect, the vibrations decrease with increasing distance from the track. Also, one can see that the high frequency components attenuate with distance at a faster rate than do the low frequency vibrations.

Figure B5.6 shows the average vibration spectra measured at the 100' sensor for various train speeds. Interestingly, the vibration spectra are similar at frequencies between 63 Hz and 200 Hz. The greatest difference in the spectra occurs at frequencies around 20 Hz.

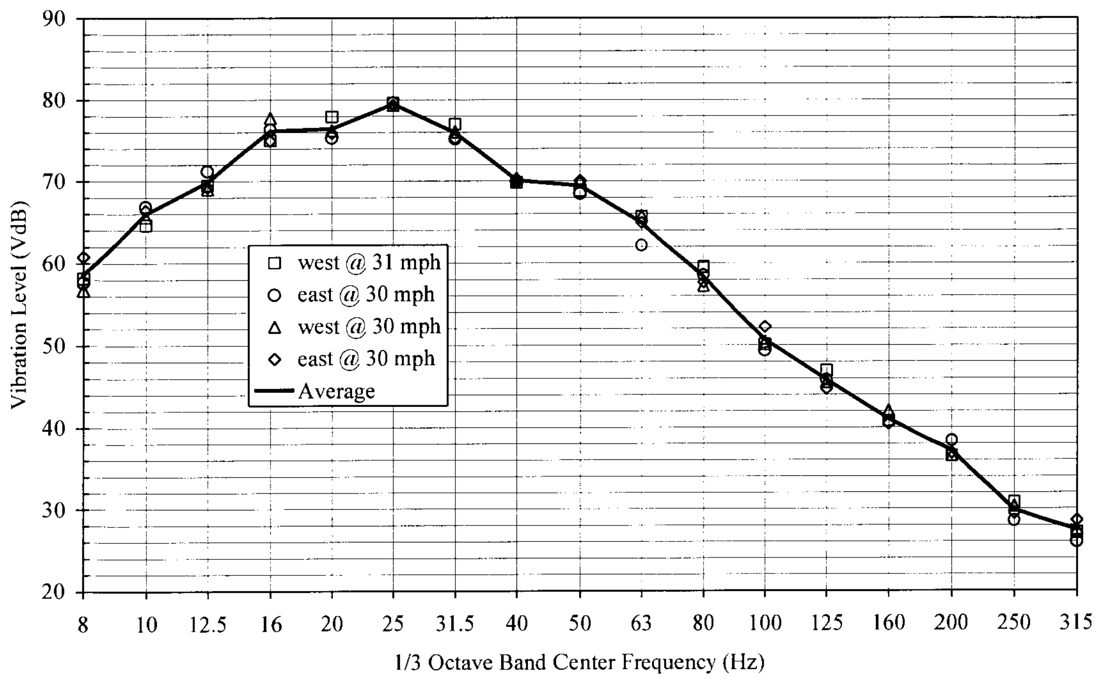


Figure B5.4: Vibration Spectra due to Train Passages at 30 mph - 100 ft Sensor

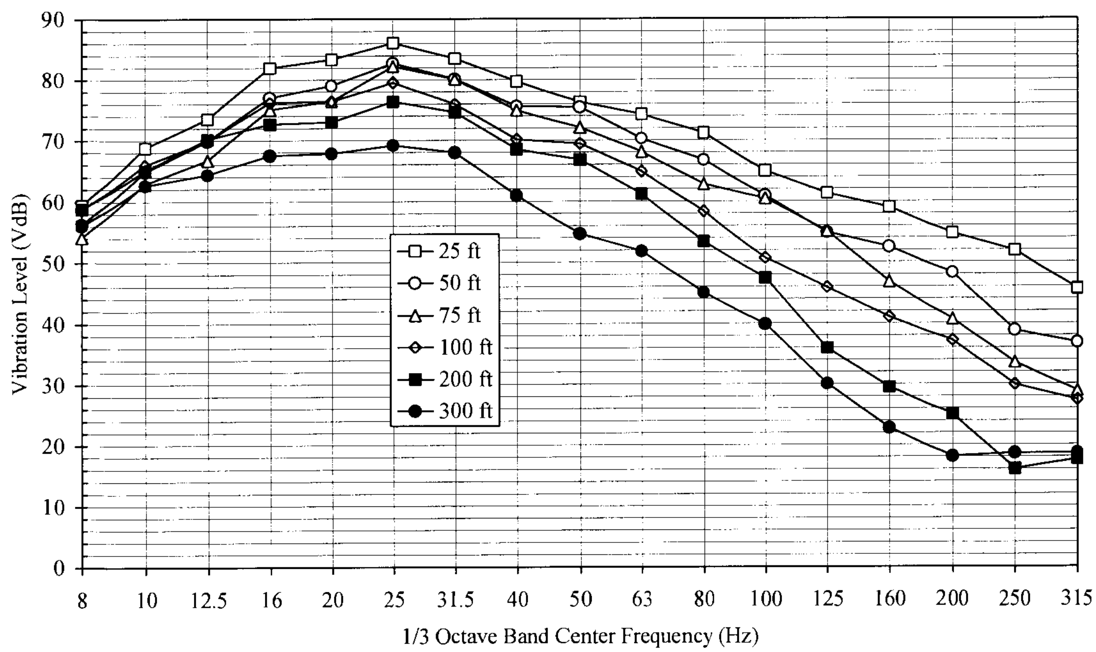


Figure B5.5: Variation of Average Vibration Spectra with Distance
for 30 mph Train Passes

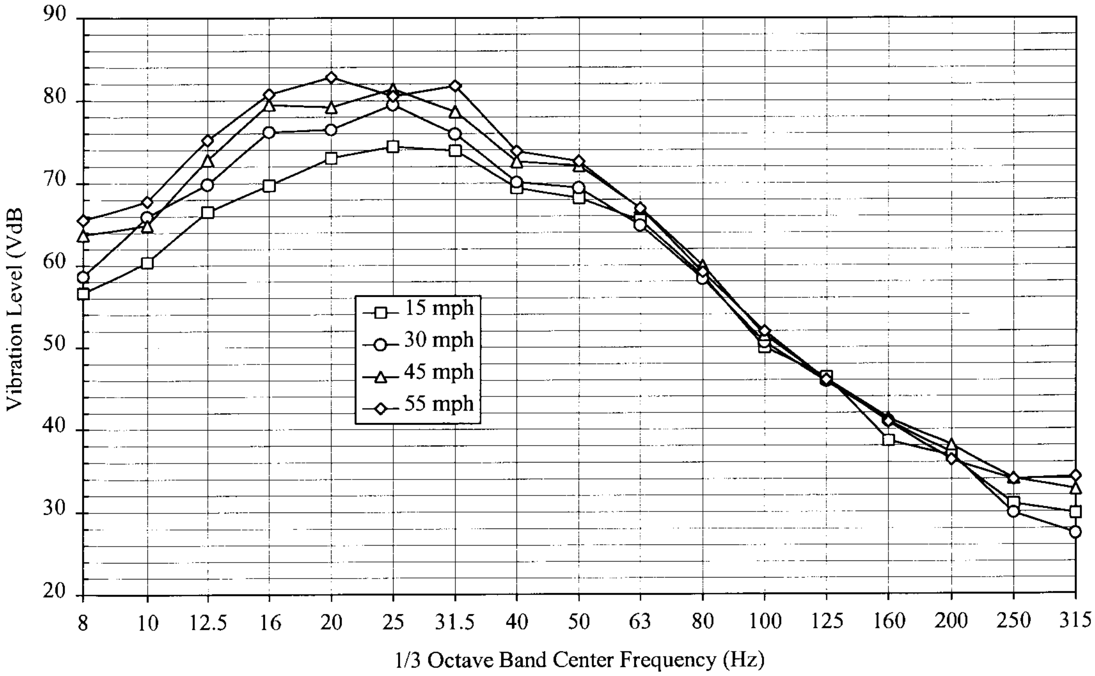


Figure B5.6: Average Train Induced Vibration Spectra - 100' Sensor

## 5.5 *Force Density*

Given the line source transfer mobilities (derived from the point source transfer mobility measurements) and the train induced vibration spectra, the line source Force Density Level (FDL) can be calculated using Equation B4.

The FDL is based on the train induced vibrations and transfer mobility at each measurement point. Because the same train is responsible for the induced vibrations, the FDL's from each measurement distance should be similar. Figure B5.8 shows the calculated FDL's from the 25', 50', 75', 100', 200' and 300' measurement distances for a 30 mph train speed. While there is generally good agreement between these data sets, the FDL spectra from the shorter distances (<100') are more closely grouped together. This is due primarily to higher quality (better coherence) transfer functions at the shorter distances. The average FDL was determined by a power average of the FDL's from the 25', 50', 75' and 100' sensors.

Figure B5.9 shows the average FDL calculated for the four test train speeds, 15 mph, 30 mph, 45 mph and 55 mph. In general, the FDL increases with train speed, although in the frequency band between 63 Hz and 123 Hz, the FDL's are all very similar.

Comparison of FDL to other Data

In the present project, the FDL's were based on a transfer mobility measurement referenced to the top of the tie. Other researchers reference FDL to the ground; that is they measure the transfer mobility by impacting the ground beside the alignment. Each method is equally valid, provided the FDL's are used correctly. At low frequencies (typically below the characteristic resonance of the wheel truck on the track support) both methods will predict the same FDL. However, at high frequencies, the tie based method will give a higher FDL than will the ground referenced method. This effect can be shown using relatively simple lumped parameter models. Therefore, it is reasonable that the FDL's shown here have more high frequency content than those determined using a ground based approach. Again, the final answers (the predicted vibration level at the location of the proposed alignment) should be the same, provided the data is used correctly.

# 6 PREDICTED VIBRATION LEVELS

The vibration levels in Manhattan and Queens can be predicted according to Equation B3 using the force density levels and the measured transfer mobility data for Manhattan and Queens.

## *6.1 Point Source Transfer Mobility Locations*

The point source transfer mobility was measured at 5 locations on Manhattan; 52$^{nd}$ Street near Park Avenue (May 17, 1999); 47$^{th}$ Street near Lexington Avenue (loop track area, May 18, 1999); the Manhattan end of the 63$^{rd}$ Street tunnel near 2$^{nd}$ Avenue (June 3, 1999); 61$^{st}$ Street near Park Avenue (July 28, 1999); and, 57$^{th}$ Street near Park Avenue (September 17 & 18, 1999). The measurements at 52$^{nd}$ Street and the Loop track were done on existing track structure. The 63$^{rd}$ Street tunnel measurements were done on the existing tunnel invert (there are no tracks at the present time). The measurements at 61$^{st}$ Street and 57$^{th}$ Street were made using boreholes; the 61$^{st}$ Street borehole test was done at a 125' depth and the 57$^{th}$ Street test was done at two depths, 52' and 114'.

In Queens, the transfer mobility was measured at the Queens end of the East River tunnel near the ventilation shaft at Vernon Boulevard (June 2, 1999).

No data were obtained at the 63$^{rd}$ Street tunnel in Manhattan due to very poor signal to noise ratios. The tunnel is approximately 156' deep at this point.

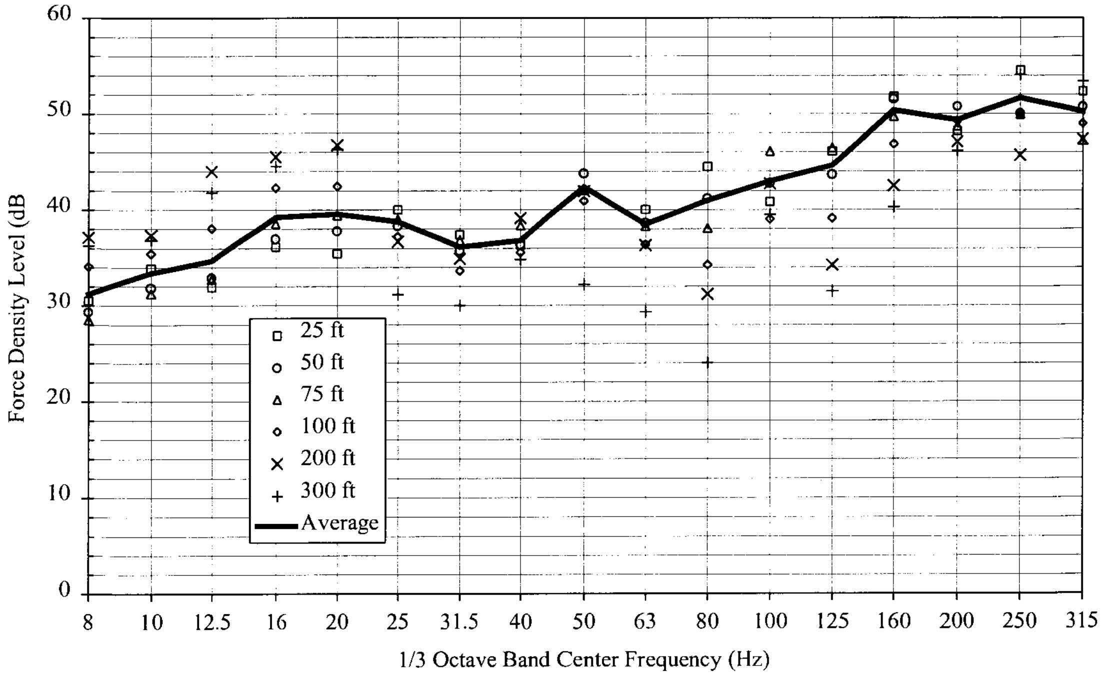


Figure B5.8: Calcualted Force Density Level at 30 mph

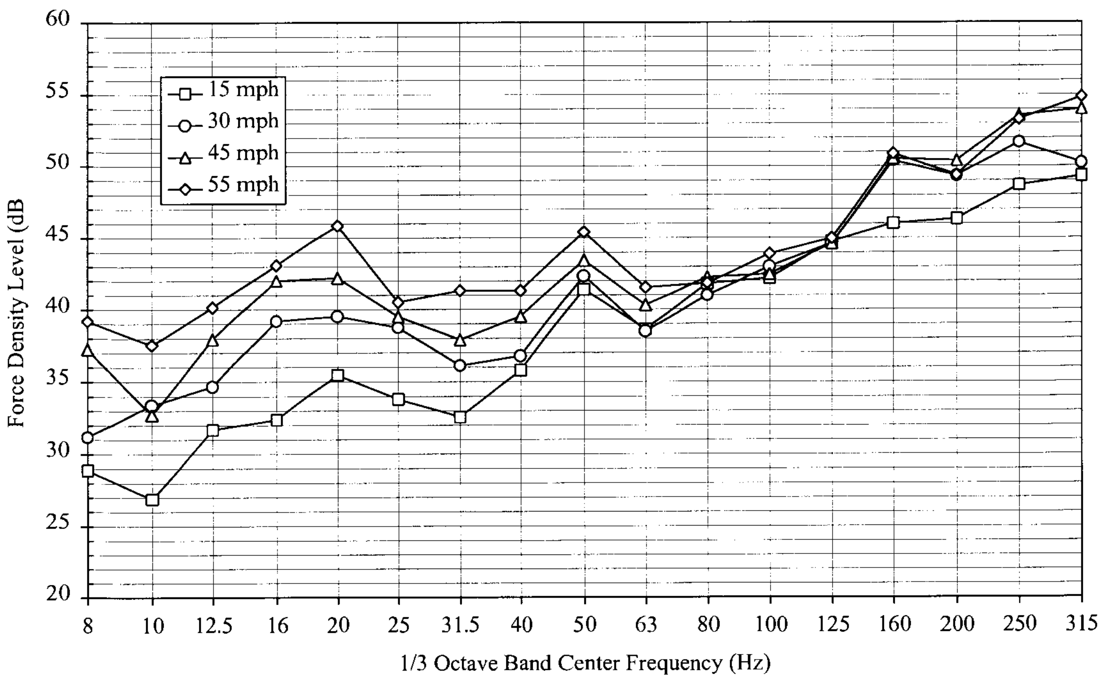


Figure B5.9: Variation of Force Density Level with Speed

## 6.2 Point Transfer Mobility Test Method

At the three borehole sites (61st Street, 57th Street - 2 depths) a downhole force sensor was used to measure the force imparted to the ground at the bottom of the borehole. The sensor was attached to the end of the drill stem and lowered to the bottom of the hole. The seismic hammer was attached to the top of the drill stem and was used to impart the force excitation. The transfer functions were based on the force signal from the downhole sensor, although the force signal from the seismic hammer was also recorded. The cable from the downhole sensor passed through the center of the drill stem which minimized cable abrasion during testing. For the borehole tests, the drill rig was used to lift and drop the 300 lbm seismic hammer weight. Approximately 150 impacts were recorded during each borehole test. The transfer functions were based on the best 100 impacts.

The full seismic hammer rig with gantry and electric winch (to lift the weight) was used in the other locations.

## 6.3 Point Source Transfer Mobility Data

In general, the quality of the transfer mobility measurements was not as high in Manhattan and Queens as it was on Long Island, due to the depth of the impact point and the relatively high ambient vibrations levels. The same difference in propagation that will cause the below-grade trains to be less intrusive than trains at-grade (at the same slant distance from the track) also makes it more difficult to measure the transfer mobility transfer function.

Figure B6.1 shows the transfer mobility that was measured at the 57th Street borehole (52' depth) at a distance of 88' (102' slant). The coherence was generally not as good as it was on Long Island, although between 130 Hz and 170 Hz it approached 0.7, which is remarkable given the high ambient vibration levels in New York City. The transfer mobility expressed in 1/3 octave bands is also shown on the figure.

Figure B6.2 shows the variation in transfer mobility at the 57th Street borehole with slant distance. As with Long Island, a linear model accurately fits the data. The line source TM for a 12 car train is also shown on the figure.

Linear polynomials were also sufficient to model the point source data for the other Manhattan test locations. In Queens, however, a quadratic model was required to reproduce the relatively low TM directly above the tunnel.

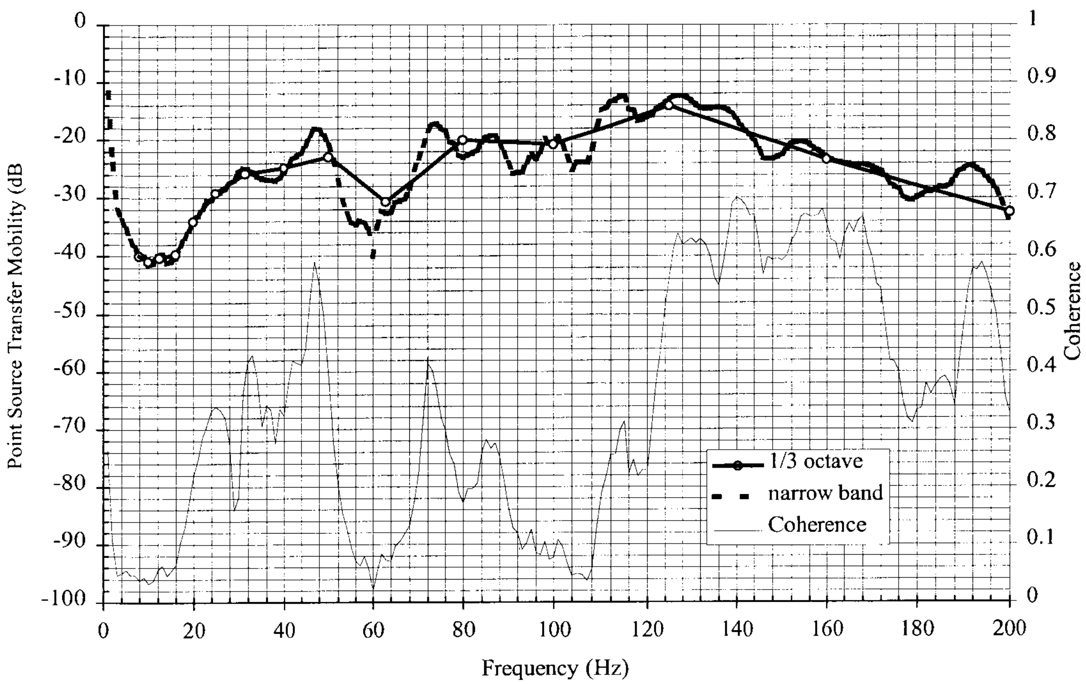


Figure B6.1: Point Transfer Mobility at 88' - 57th Street Borehole, 52' Deep

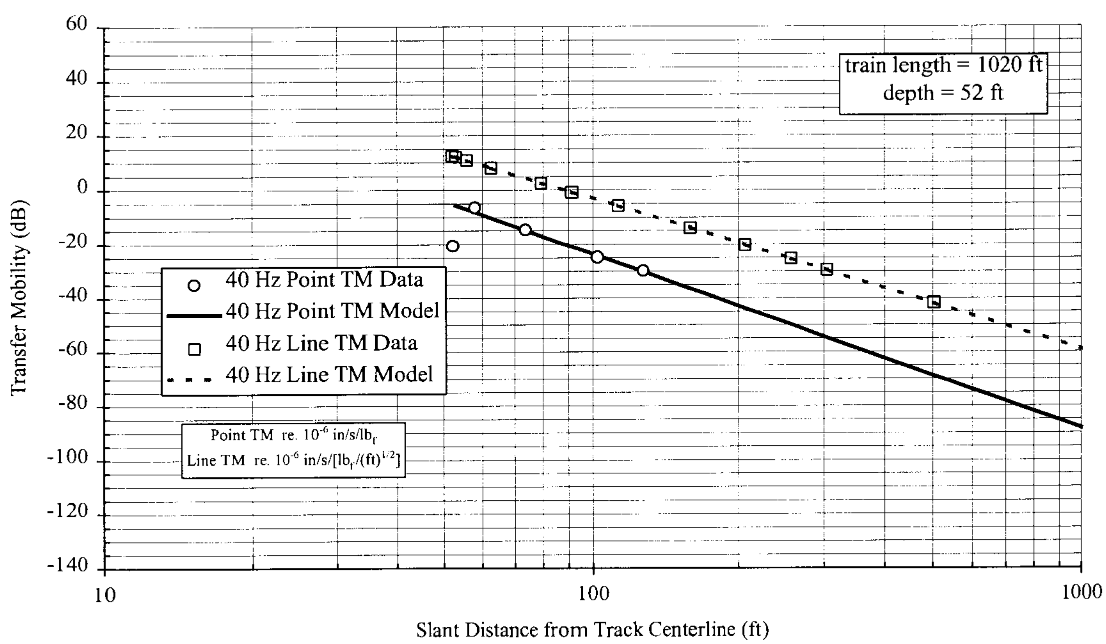


Figure B6.2: Line Source and Point Source Transfer Mobility
57th St. Borehole 52' Deep

The general form of the polynomial curve fit to the point source TM data is,

$$TM_{point}(dB) = a_0 + a_1 \log(d_{slant}) + a_2 *[\log(d_{slant})]^2 , \qquad \text{(B8)}$$

where $d_{slant}$ is the slant distance from the impact point to the measurement point on the surface, in feet. The curve fit coefficients for the various test locations are summarized in Table B6.1.

When performing the curve fits, where the coherence was poor for a given 1/3 octave-band frequency, the coefficients from an adjacent band were used instead.

The point source transfer mobility models were used in a numerical integration routine to calculate the line source transfer mobility at a given distance from the track, for each 1/3 octave band frequency. Again, to facilitate the prediction procedure, a quadratic polynomial was then used to model line source TM as a function of slant distance from the track. A 12 car train (1020') was used to calculate the line source TM.

Figure B6.3 shows the 40 Hz line source transfer mobilities models for each test location. The figure shows a number of interesting aspects about the TM models:

1) The highest TM levels (and most efficient vibration propagation) were recorded on Long Island. This would be expected since vibration sources located on the surface generate Rayleigh waves which propagate efficiently.

2) There is a dramatic difference in the 52nd Street, Loop Track and 57th Street borehole models, even though all three tests were done at approximately the same depth below the surface. The differences can be attributed to the extensive underground structure that was present at 52nd Street and the Loop track. The underground structure creates a unique and complicated path for the vibration energy. Because of this effect from the underground structure, it was decided that the 52nd Street and Loop track data would not be used for predictions. It was felt that a more conservative approach would be to use the borehole data, even for these locations.

3) The TM attenuation rate with distance increases as the test point gets deeper.

4) The deeper hole does not necessarily produce lower TM at the same slant distance. Consider the 57th Street borehole for example, the TM directly above the impact point for the 114' deep hole is higher than the TM for the 52' deep hole, 101' away (same slant distance). This suggests that, at this frequency at least, horizontal distance from the impact point is more important than depth for vibration attenuation.

## *6.4 Track Support Correction to the Force Density Level*

The wheel/rail interaction is responsible for the vibration forces that propagate through the rail, the rail trackbed and then into the ground. The forces produced by the wheel/rail interaction are primarily dependent on the quality of the running surface where the wheel meets the rail. Smooth wheels and rails produce much less vibration than wheels with flat spots running over

**Table B6.1** - Point Source Transfer Mobility Curve Fit Coefficients for the Entire Project

| Frequency (Hz) | $52^{nd}$ Street depth = 46.5' | | $47^{th}$ Street (Loop) depth = 45' | | $61^{st}$ Street depth = 125' | | $57_{th}$ Street depth = 52' | | $57^{th}$ Street depth = 114' | | Queens depth = 84' | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $a_0$ | $a_1$ | $a_0$ | $a_1$ | $a_0$ | $a_1$ | $a_0$ | $a_1$ | $a_0$ | $a_1$ | $a_0$ | $a_1$ | $a_2$ |
| 8 | -19.022 | -12.553 | -6.375 | -14.109 | 260.675 | -128.474 | 75.0 | -55.314 | 123.0 | -70.0 | -142.136 | 133.024 | -36.241 |
| 10 | 40.330 | -43.617 | -6.375 | -14.109 | 260.675 | -128.474 | 75.0 | -55.314 | 123.0 | -70.0 | -142.136 | 133.024 | -36.241 |
| 12.5 | 41.938 | -42.370 | -6.375 | -14.109 | 260.675 | -128.474 | 75.0 | -55.314 | 123.0 | -70.0 | -142.136 | 133.024 | -36.241 |
| 16 | 23.111 | -29.810 | -6.375 | -14.109 | 260.675 | -128.474 | 76.0 | -55.314 | 123.0 | -70.0 | -142.136 | 133.024 | -36.241 |
| 20 | 25.820 | -28.577 | -6.375 | -14.109 | 256.228 | -126.542 | 80.0 | -55.314 | 128.0 | -70.0 | -142.136 | 133.024 | -36.241 |
| 25 | -8.853 | -9.852 | -6.375 | -14.109 | 256.228 | -126.542 | 85.129 | -55.314 | 132.0 | -70.0 | -142.136 | 133.024 | -36.241 |
| 31.5 | -9.096 | -8.555 | -6.375 | -14.109 | 256.228 | -126.542 | 125.276 | -73.272 | 138.0 | -70.0 | -142.136 | 133.024 | -36.241 |
| 40 | 12.273 | -13.434 | -6.375 | -14.109 | 256.228 | -126.542 | 106.152 | -64.848 | 135.0 | -70.0 | -142.136 | 133.024 | -36.241 |
| 50 | 11.865 | -10.629 | -6.375 | -14.109 | 124.806 | -70.509 | 61.004 | -40.340 | 135.0 | -62.62 | -142.136 | 133.024 | -36.241 |
| 63 | 29.601 | -20.928 | 3.142 | -19.673 | 98.044 | -61.225 | 69.0 | -44.121 | 116.0 | -62.62 | -313.593 | 284.317 | -68.560 |
| 80 | 2.109 | -10.622 | 22.651 | -31.141 | 98.044 | -61.225 | 69.0 | -44.121 | 116.0 | -62.62 | -486.816 | 437.464 | -99.710 |
| 100 | 24.458 | -25.503 | 20.686 | -29.597 | 219.944 | -120.249 | 71.953 | -44.121 | 118.0 | -62.62 | -353.389 | 323.065 | -75.272 |
| 125 | 57.408 | -47.914 | 22.472 | -30.101 | 186.370 | -105.942 | 71.953 | -44.121 | 112.0 | -62.62 | -353.389 | 323.065 | -75.272 |
| 160 | 94.230 | -67.135 | 28.596 | -33.709 | 186.370 | -105.942 | 41.296 | -31.763 | 106.406 | -62.62 | -484.662 | 406.119 | -90.667 |
| 200 | 132.851 | -91.117 | 28.779 | -34.281 | 186.370 | -105.942 | 42.853 | -36.963 | 106.406 | -62.62 | -200.258 | 166.050 | -41.731 |

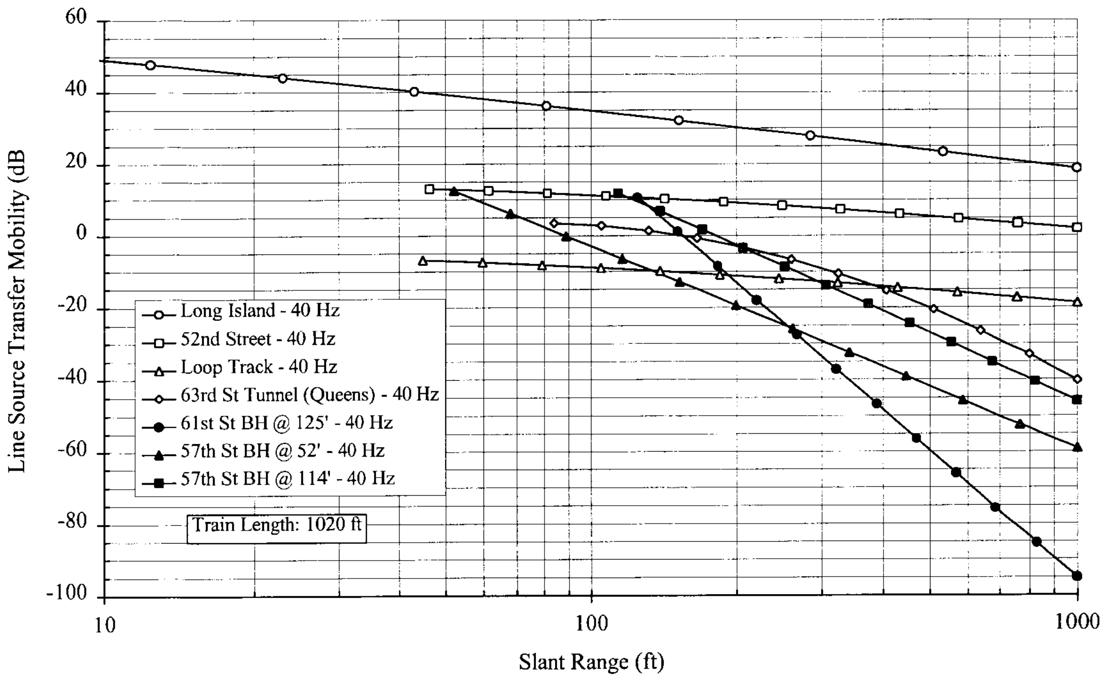


Figure B6.3: Comparison of Line Source Transfer Mobility Models - 40 Hz

jointed track, for example. Another important factor that affects the vibration level is the track support system. Rails that are rigidly supported produce more vibration than those with resilient track supports. Reference 3 states that groundborne vibrations are directly proportional to the track support modulus, so the difference in the vibration level (and hence the force density level) between two track support conditions is,

$$\Delta FDL\ (dB) = 20\ \log(\frac{k_1}{k_2}), \qquad \text{(B9)}$$

where $k_1/k_2$ is the ratio of the two support moduli.

Because the Long Island force density test was done with a tie on ballast support system, while the project will use direct fixation on concrete, a track support correction was introduced to account for the differences in the track support modulus. According to Reference 3, the difference between direct fixation and tie on ballast track supports is approximately 17 dB. However, recent test data from the Bay Area Rapid Transit system (BART) has indicated that tie on ballast is stiffer than first thought and a 7 dB correction is more appropriate. A 7 dB correction has been used for the present project.

A simple analytical model can be used to show that the relationship of Equation B9 only holds above the primary resonance associated with the wheel truck mass and the driving point impedance of the rail. The BART data suggests that this characteristic frequency is around 20 Hz. In the present study, 7 dB has been added only for frequencies of 20 Hz and above.

### 6.5 Building Vibration Response Corrections

The Manhattan and Queens transfer mobility measurements were made with respect to vibration levels at street level, not in specific buildings. A building's response to vibration depends on three principal factors; 1) how efficiently ground vibration is transferred to the building foundation (termed the coupling loss), 2) amplification due to structural resonances of the floor, walls and ceiling, and 3) vibration attenuation for higher floors in the building.

The FTA[1] manual provides standard building coupling loss factors that are based on the size of the building and the frequency of the vibration. Figure B6.4 shows the FTA coupling loss factors that are appropriate for buildings in the present study. The FTA factors are specified for buildings founded in soil, which is appropriate for the buildings in Queens and for smaller buildings on Manhattan. A zero coupling loss has been used for buildings on Manhattan that are five or more stories high, because, generally such buildings are founded in rock.

The floors, walls and ceilings in a building all have a characteristic resonant frequency. For wood frame buildings, the primary floor resonance will typically range from 15 Hz to 20 Hz. For concrete slab floor, the resonance will typically range from 20 Hz to 30 Hz. At frequencies near the fundamental resonance, the vibrations in the center of the floor can actually be higher than those near the supporting walls. The FTA manual recommends that 6 dB be added to the predicted vibration level in the frequency bands where a resonance is likely to occur. Because the construction methods in the study area differ, the 6 dB correction has been added to the predicted vibration spectrum between 10 Hz and 31 Hz, this is shown in Figure B6.4.

It has been conservatively assumed that the lowest occupied level of the building is on the 1st floor, hence, a floor to floor attenuation factor has not been used to adjust the predicted vibration spectra.

### 6.6 Groundborne Noise

The vibrating floors, walls and ceilings in a building radiate noise much like giant loudspeakers. The noise in a room can be estimated knowing the vibration velocities of the radiating surfaces and the amount of sound absorption in the room. The FTA manual states that a 0 dB radiation adjustment is appropriate for typical rooms.

Because people's perceptions of loudness depends on the frequency of the noise, an additional adjustment is made (the A weighting factor) to account for the response of the human ear. The A weight noise corrections are shown on Figure B6.4. The FTA manual gives the following formula to predict the 1/3 octave band noise levels in a room based on the vibration levels,

$$L_A = L_V + K_{A-wt}, \qquad \text{(B10)}$$

where $L_A$ is the noise level, $L_V$ is the vibration level and $K_{A-wt}$ is the A weighting factor.

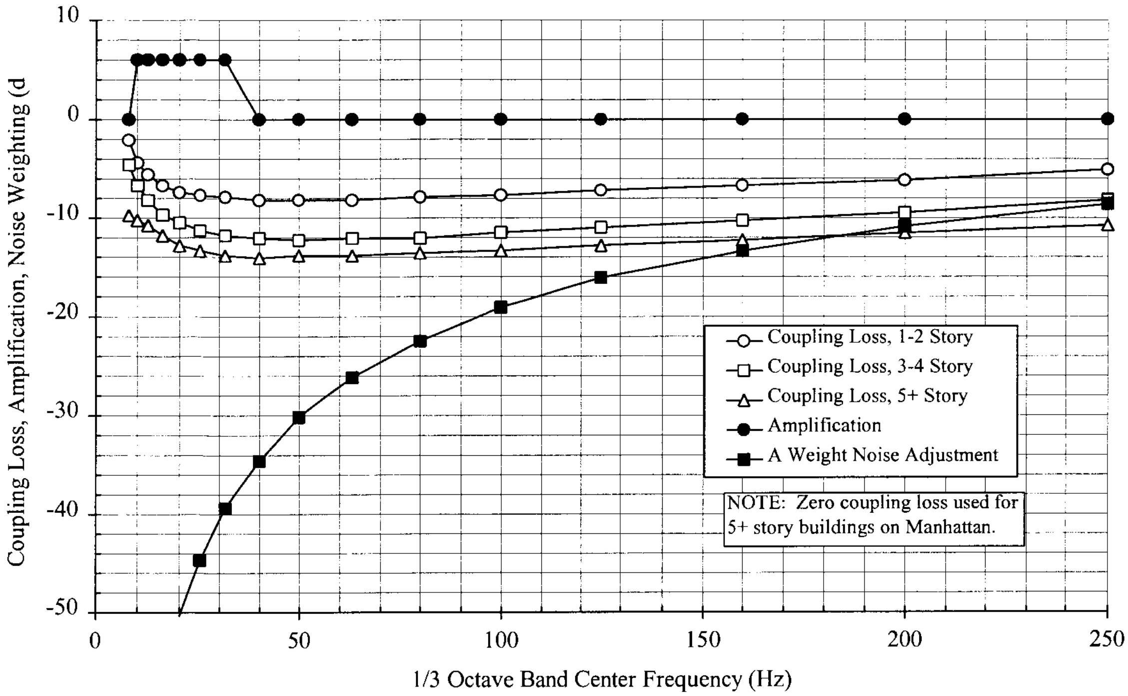


Figure B6.4 - Building Coupling, Ampliciation and Noise Weighting Factors

## 6.7 Overall Vibration and Noise Levels

A vibration and noise spectrum is predicted for each building in the study area. The overall vibration and noise levels are found by adding all of the 1/3 octave vibration and noise components. The addition is done as a power sum according to the formula,

$$L_{V,A}^{total} = 10\ Log\Big( \sum_{1/3\ octave\ bands} 10^{0.1 * L_{V,A}^{i}} \Big), \qquad \text{(B11)}$$

where $L^{i}_{V,A}$ is the vibration and noise level in the $i^{th}$ 1/3 octave band.

## 6.8 Track Depth Corrections

On Manhattan, borehole transfer mobility data was collected for test depths of 52' (57th Street), 114' (57th Street) and 125' (61st Street). For each building, the vibration and noise level was predicted for a tunnel depth equal to each of the three reference depths. A linear interpolation procedure was then used to predict the vibrations for the actual track depth. For depths greater than 125', the data at 125' was used for the prediction. For depths shallower than 52', the linear interpolation between 52' and 114' was projected past 52'.

In Queens, only 1 test depth was measured, 84'. To extrapolate to other depths, an adjustment factor of -0.07 dB/ft was used. This factor was determined based on the predicted vibration levels in Manhattan at 52' and 114' depth, directly above the alignment (0' map range). The -0.07 dB/ft adjustment factor corresponds reasonably well to the theoretical attenuation rate of -0.17 dB/ft for Rayleigh waves in an elastic half-space.

## 6.9 Multiple Tracks

For Manhattan Option 1, the vibration and noise predictions were done for each track in the alignment (5 main tracks and loop track). The greatest vibration and noise levels were then used to characterize that property. In Queens and for Manhattan Option 2, a single line down the center of the alignment was used to calculate the distance from the building to the track.

## 6.10 Special Trackwork Corrections

The FTA manual recommends adding 10 dB to the vibration predictions for special trackwork such as crossovers. Reference 3 indicates that the 10 dB correction is appropriate for a slant distance of 30' from the track. For distances greater than 30', a $r^{-1}$ attenuation referenced to 30' was used, where r is the slant distance.

## 6.11 Worn Wheels/Rails

No specific adjustment was used for worn wheels and rails. However, the peak hold spectral analyses for the Long Island test typically gave total vibration levels that were 5 dB higher than the corresponding RMS values. This 5 dB "safety factor" was retained in the analysis to account for future worn wheels/rail.

## 6.12 Prediction Procedure Flow Chart

Figure B6.5 depicts the steps that were taken to generate the estimated vibration and noise levels.

Building Data

In the GIS database, a point was placed at the approximate geometric center of each building in the study area. This point was used to calculate the distances to each of the tracks and to the trackwork locations. Each point carried the unique property ID associated to it in the database. The unique ID was used to lookup the number of stories and the building classification in the GIS database.

**Track Iteration Loop**

The following steps were taken for each track in the database. This was particularly necessary in Manhattan because of the complex routing of the alignment for Option 1.

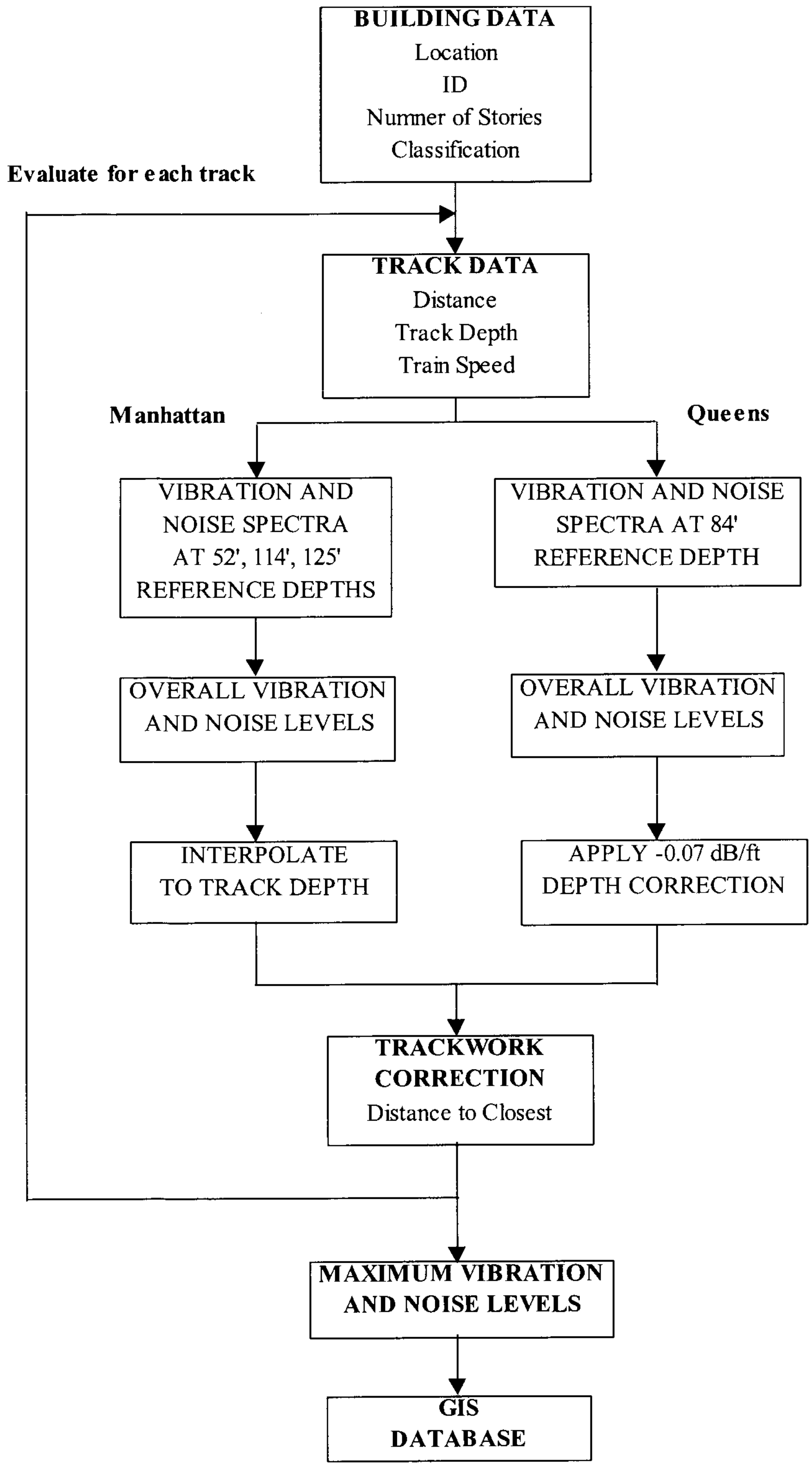


**FIGURE B6.5:** Groundborne Vibration and Noise Prediction Procedure

Track Data

The track routings in the database were first broken up into small segments where each segment was assigned a depth and train speed. The GIS program was then used to calculate the map distance to the closest track segment for the particular track being analyzed. The GIS program also recorded the track depth and the train speed.

Vibration Level

The predicted ground vibration spectrum was calculated using the line source transfer mobility models and the force density spectrum corresponding to the train speed.

On Manhattan, the vibration spectra were calculated for the three reference depths (52', 114' and 125') using the calculated map range from the GIS. The vibration spectra were corrected for building coupling and amplification. The noise spectra were calculated from the vibration spectra using the A weighting factors. The overall vibration and noise levels were then calculated for each reference depth by summing the contributions from the individual 1/3 octave bands. The vibration and noise levels for the property (for the actual track depth) were then calculated by interpolating between the reference levels. For track depths less than 114', the vibration and noise levels at 52' and 114' were used for the interpolation; for depths between 114' and 125', the levels at 114' and 125' were used; and, for depths greater than 125', the vibration and noise levels at the 125' depth were used.

In Queens, the vibration and noise spectra were calculated for an 84' track depth using the map range from the GIS. The 1/3 octave band levels were then combined into overall vibration and noise levels which were then corrected by –0.07 dB/ft to account for the difference between the track depth and the reference depth.

Trackwork Correction

The locations of special trackwork were identified in the GIS as points. The GIS program was then used to calculate the map distance to the closest trackwork site for each property. Based on the map distance to the trackwork and the depth of the track, an adjustment was made based on +10 dB at a 30' reference distance.

Maximum Vibration Level

For each of the tracks in the alignment, the greatest vibration and noise levels were selected as the overall groundborne vibration and noise levels for the property.

GIS Database

The groundborne vibration and noise predictions were re-attached to the GIS database for presentation.

# 7 COMPARISON - PREDICTED VIBRATION LEVELS AND MEASURED DATA

During the transfer mobility testing in Queens, the vibrations from a number of subway passes were recorded. At the Queens test location, the subway tracks are supported on the roof of the LIRR tunnel.

Figure B7.1 shows the predicted vibration spectrum directly above the tunnel using the LIRR model. The spectrum corresponds to a tunnel depth of 84' and a train speed of 30 mph. No corrections were made for building coupling. The second curve is the actual vibration spectrum that was measured when a subway passed the Queens test location. This spectrum was measured by the 0' sensor that was located directly above the tunnel. The predicted and measured vibration levels are comparable, however, the measured data has more low frequency energy. This is most likely an artifact of the support structure. The subway structure has a characteristic resonance, at which the subway train vibrations are actually amplified. Above the resonance, the structure tends to attenuate the vibrations. The third curve on Figure B7.1 shows the vibration spectrum that was measured near the MBTA's Red Line in Boston. This spectrum was measured for a comparable train speed, at a comparable tunnel depth. As can be seen from this figure, the MBTA data has much more high frequency content, which supports the premise that the lack of high frequency energy in the Queens subway spectrum is likely caused by the track support structure. Comparison of the MBTA spectrum with the TM Model predictions indicates good agreement up to about 150 Hz, lending credence to the LIRR predictions.

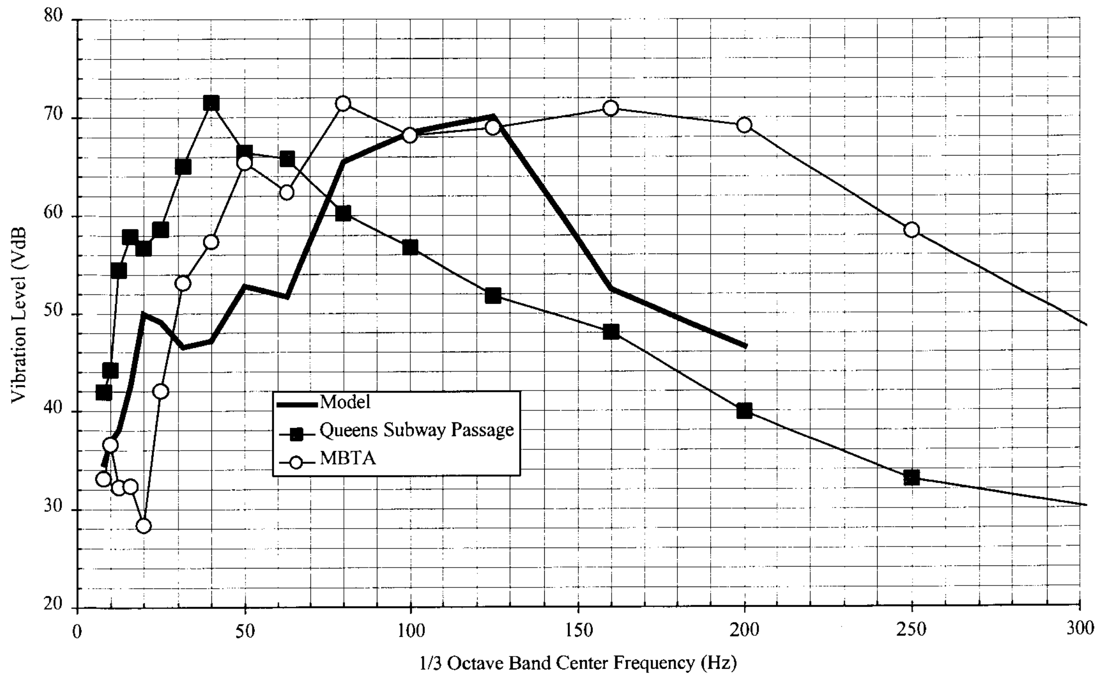


Figure B7.1: Predicted and Measured Vibration Spectra in Queens