APPENDIX J4

VIBRATION

Date	Reference
December 19, 2008	Vibration Measurements and Predictions for Central Corridor LRT
N/A	Vibration Contour Figures

ATSConsulting
acoustics, transportation + strategy

MEMORANDUM

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Date: December 19, 2008

Subject: Vibration Measurements and Predictions for Central Corridor LRT Project

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DEFINITIONS OF ABBREVIATIONS AND ACRONYMS

This section presents brief definitions of the abbreviations and acronyms that are used in this report. The definitions are in alphabetical order.

1/3 octave bands: A method of characterizing the frequency characteristic of a sound or vibration signal. The term "octave" has been borrowed from music where it refers to a span of eight notes. The ratio of the highest frequency to the lowest frequency in an octave is 2:1. For a 1/3-octave band spectrum, each octave is divided into three bands where the ratio of the lowest frequency to the highest frequency in each 1/3-octave band is 21/3:1 (1.26:1). An octave consists of three 1/3 octaves.

A-weighting: The frequency weighting function used to approximate the frequency response of human hearing.

CCLRT: Central Corridor Light Rail Transit.

CCPO: Central Corridor Project Office

dB: Decibel. A decibel is defined as $20\times\log_{10}(V/V_{ref})$ where V is the amplitude of the quantity and V_{ref} is a standard reference quantity. The standard decibel reference for sound is 20 µPa and for vibration velocity is 1 µin/sec. The symbol "µ" indicates 10^{-6} and "Pa" is the abbreviation for Pascals, which is a measure of pressure. 1 Pascal = 1 Newton/m^2.

dBA: The abbreviation used to indicate sound levels using A-weighting.

FDL: Force density level in decibels. FDL is used to characterize the vibration forces generated by light rail vehicles.

FTA: Federal Transit Administration.

Ground-Borne Noise: The noise that is generated by the vibration of room surfaces. Ground-borne noise and structure-borne are essentially equivalent. The term "ground-borne" is used to indicate that the ground is the source of the vibration.

Ground-Borne Vibration: Vibration of a building structure that is caused by vibration of supporting soil or rock,

Hz (Hertz): The abbreviation used for frequency. It is equal to the number of oscillations per second of a sound or vibration wave and was formerly referred to a cycles per second.

Leq: The equivalent sound or vibration level over a specified period of time. This term is normally applied to environmental sound. It is also applied to vibration signals in this study. The mathematical expression for calculating Leq is the same as for calculating an RMS average (see below).

L1%, L10%, L50%, L90%, L99%: These are the vibration levels exceeded for a percentage of the measurement period. The level exceeded 1% of the measurement period (L1%) represents typical maximum vibration levels from events such as buses passing while the L90% and L99% represent background levels when all transient vibration sources are quiescent.

LRT: Light rail transit.

LRV: Light rail vehicle.

LSTM: Line source transfer mobility. A measure of how the intervening soil and rock affects the propagation of vibration from a line vibration source such as a bus or LRV to a receiver position.

NMR: Nuclear Magnetic Resonance. A vibration sensitive research tool used to investigate the properties of molecules.

RMS: Root mean square. This is the square root of the average of the squared amplitudes and is a method of averaging sound and vibration signals in this report.

transfer mobility: Transfer mobility describes the relationship between a vibration source and the vibration at a receiver position. Coherence (defined above) provides a measure of how strongly related the vibration at the receiver is to the exciting force.

VC-A through VC-E: Curves commonly used to characterize the suitability of different vibration environments for research equipment. "VC" is an abbreviation for "vibration criteria."

VdB: Vibration decibels. The abbreviation "VdB" is used to avoid confusion with sound decibels.

Vibration velocity: Vibration is the oscillation about an equilibrium point. The amplitude of the oscillation can be described in terms of the displacement, velocity, or acceleration of the vibrating particles. The general consensus is that the response of humans and vibration sensitive equipment is best correlated to the velocity of a vibration. Therefore, it is fairly standard to describe vibration in terms of the velocity. It is straightforward to convert between displacement, velocity, and acceleration.

1. INTRODUCTION/BACKGROUND

This report presents the results of detailed analysis of potential vibration impacts on vibration-sensitive facilities from light rail transit (LRT) operations on the proposed Central Corridor Light Rail (CCLRT) project and possible mitigation strategies to address the impacts. It is an update of an earlier draft memorandum prepared by ATS Consulting dated July 29, 2008. This final memorandum includes a discussion of the results of supplementary testing conducted as part of refining the force density function, testing in additional laboratory spaces at the University of Minnesota where vibration sensitive research equipment is located, additional ambient vibration measurements at Minnesota Public Radio (MPR) and Church of St. Louis King of France, and vibration propagation testing at the McNally Smith College of Music in downtown Saint Paul.

The investigations included critical facilities identified by project staff and key stakeholders:

- University of Minnesota (U of M) research facilities near Washington Avenue.
- The KSTP television studio on University Avenue.
- A recording studio at 1951 University Avenue.
- The Minnesota Department of Health/Minnesota Department of Agriculture (MDH/MDA) Lab at 601 Robert Street N, Saint Paul.
- The Church of St. Louis King of France at 506 Cedar Street in Saint Paul.
- Central Presbyterian Church at 500 Cedar Street in Saint Paul.
- Minnesota Public Radio at 480 Cedar Street, Saint Paul.
- McNally-Smith College of Music at 19 Exchange St E, Saint Paul.

In addition, vibration measurements were made at four locations on the Hiawatha Light Rail Transit (HLRT) line to determine the vibration force generated by the existing light rail vehicles.

The testing was performed in three phases. The first phase took place between May 20 and May 24, 2008 and consisted of vibration propagation and ambient vibration testing at most of the locations listed above and force density tests at two HLRT locations. The second phase that was performed between September 29 and October 4, 2008 included supplementary force density measurements at two additional HLRT locations, several additional vibration propagation tests, and ambient vibration measurements. The third phase of testing consisted of ambient vibration measurements at 20 U of M laboratories and took place between October 13 and October 17, 2008.

Testing included existing ambient vibration in a number of sensitive spaces, vibration propagation tests, measurements of vibration generated by HLRT trains, and measurements of vibration generated by Metro Transit buses. The vibration propagation tests show how vibration attenuates as waves are transmitted from the source, through the ground, and into sensitive spaces within the buildings. The test procedure used follows Federal Transit Administration (FTA) (Ref. 1)[*] guidelines for a Detailed Vibration Assessment. The field testing consists of using a dropped weight to generate vibration pulses and measuring the response at the ground surface and at sensitive spaces inside buildings. The basic procedure is illustrated in Figure 1. Ideally, impacts are performed at 6 to 11 locations in a line at the approximate location where the light rail tracks would be located.

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[*] References are listed at end of report.

Digital signal analysis is used to analyze the field data and obtain the relationship between the impact force and the resulting ground vibration at the accelerometer positions (an accelerometer is a device that measures vibration). As shown in Figure 1, the accelerometers may be located at the ground surface or inside buildings. The relationship between the input force and the resulting vibration velocity is called the *transfer mobility*. The standard procedure is to average the results of 20 impacts at each of the impact locations to improve the signal-to-noise ratio. The final step in the analysis is to combine the results from the 6 to 11 impact test locations into the equivalent of a line-source transfer mobility (LSTM).

By performing a similar test at an existing light rail line and measuring the vibration generated by the light rail vehicles at the same location, it is possible to develop a force density function (FDL) that characterizes the vibration forces generated by the light rail trains. The FDL is used with the LSTM to predict the levels of ground vibration using the following relationship:

$$Lv = FDL + LSTM$$

where:

Lv = Vibration velocity level
LSTM = Line source transfer mobility at the receptor position
FDL = Measured force density level at an existing light rail line
(*all values are in decibels assuming a consistent set of units and decibel reference values)*

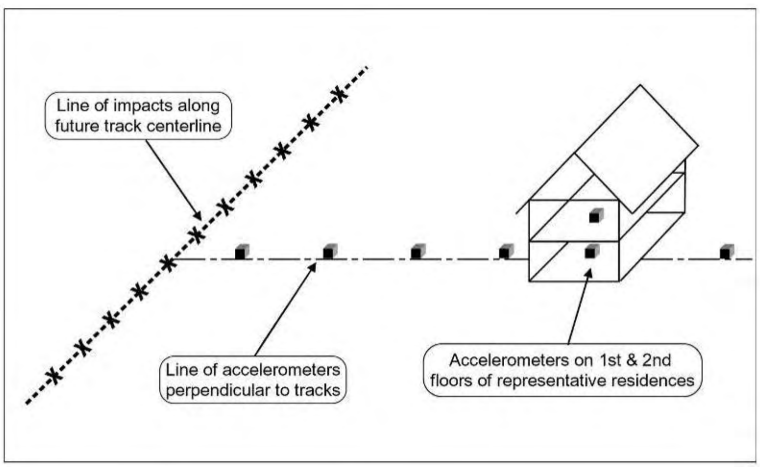


Figure 1: Schematic of Vibration Test Procedure

For these tests, the impacts were generated with a 45 lb weight dropped from a height of 4 feet onto a load cell. The vibration signals were measured with seismic accelerometers (PCB Model 393A03). The signals from the load cell and accelerometers were recorded on Rion Model DA-20 digital recorders. The raw WAV files from the recorders were analyzed using digital signal processing to obtain the narrowband transfer function relationships between each combination of impact location and accelerometer position. The basic steps in the processing are:

1. The force and response signals from each impact are visually inspected and an accept/reject decision made. Signals with excessive background vibration were rejected.

2. The impacts are digitally processed to obtain the narrowband transfer function with a 400 Hz frequency range and a 0.5 Hz resolution.
3. The narrowband transfer functions are converted to equivalent 1/3 octave band spectra by calculating the root-mean-square (rms) average over the frequency limits of each 1/3 octave band. The coherence is also converted to a 1/3 octave band spectrum using linear averaging.
4. The 1/3 octave band transfer function results for each test are used to calculate an equivalent line source transfer function (LSTM). In essence a numerical integration process is used to combine the point source transfer function results from 6 to 11 impact positions into the LSTM. An LSTM function is calculated for each accelerometer position.

2. SUMMARY OF RESULTS

This report is an update of the draft report prepared in July 2008. The changes that have been made since that time include:

- Additional FDL measurements were performed at two HLRT embedded track sections. These measurements eliminated the confusion about the appropriate FDL curve to use for the predictions.
- Vibration tests were performed with two Metro Transit buses at one of the embedded track test sections. These tests showed that the vibration from buses exceeds the vibration from the HLRT light rail vehicles at frequencies below 30 Hz.
- Three additional vibration propagation tests were performed at labs at the University of Minnesota campus where vibration sensitive research is being conducted.
- Ambient vibration was measured in 20 additional U of M laboratory spaces.
- Supplementary measurements of ambient vibration were performed in two of the Minnesota Public Radio facility on Cedar Street.
- A vibration propagation test was performed at one of the McNally Smith recording studios.

The predicted vibration impacts and locations where vibration mitigation is recommended are summarized in Table 1. The locations where vibration impact is predicted are only slightly different from the preliminary report. However, there have been changes in the degree of mitigation recommended.

Following is a summary of the locations where tests were performed, the resulting assessment of impact and potential mitigation strategies to address the impact:

- **Force Density Tests:** The force density tests on the HLRT embedded track show that the vibration from buses exceeds the LRV vibration at frequencies below 30 Hz and that there is potential for a substantial amount vibration at frequencies greater than 60 Hz.
- **University of Minnesota**: Based on the tests performed on the U of M campus, vibration mitigation is needed for Weaver Densford Hall, Amundson Hall, the NMR facility in the basement of Nils Hasselmo Hall, and the NMR facility in Kolthoff Hall. Sufficient mitigation can be achieved at all of these facilities with high-resilience track fasteners.
- **KSTP Studios**: The predicted ground-borne noise levels exceed the FTA impact threshold for ground-borne noise in the studios closest to University Avenue. If further tests confirm that the predicted levels of ground-borne noise exceed the background noise, use of high-resilience direct fixation fasteners will eliminate the impact.
- **Recording Studio at 1951 University Avenue**: The predicted ground-borne noise levels inside the recording studio exceed the FTA impact threshold. Even with the use of high-resilience track fasteners, the predicted ground-borne noise levels exceed the impact threshold. Alternative mitigation measures are to relocate the studio or to construct a vibration isolated room inside the existing studio. This is a relatively small, private recording facility, and relocation or construction of an isolated room would cost significantly less a track-based vibration mitigation measure.
- **MDH/MDA Labs**: No impacts are predicted at the laboratories in the MDH/MDA Labs building.

- **Church of St. Louis King of France and Central Presbyterian Church**: The predicted vibration levels are well below the threshold for damage and for human annoyance. However, the predicted ground-borne levels exceed the FTA impact threshold. Eliminating the predicted impact will require use of a floating slab trackbed or the equivalent. The predicted vibration levels at the Church of St. Louis pipe organ are vibration levels that occur when the pipe organ is being played. Therefore, the LRV vibration is not predicted to have any adverse effect on the pipe organ.
- **MPR Studios**: The predicted ground-noise levels inside several of the studios exceed the FTA impact threshold for recording studios. Eliminating the predicted impact will require the installation of a floating slab trackbed or the equivalent.
- **McNally Smith Recording Studios:** The predicted levels of ground-borne noise inside the tested recording studio exceed the FTA threshold applicable to recording studios. The vibration mitigation recommended for the two churches on Cedar Street and for the MPR building on Cedar Street will be sufficient to eliminate the impact.
- **Fitzgerald Theater:** The Fitzgerald Theater is approximately the same distance west of Cedar Street as the McNally Smith recording studios. As for the recording studios, the vibration mitigation recommended for the two churches on Cedar Street and for the MPR building on Cedar Street will be sufficient to eliminate the potential for impact.

Table 1: Summary of Vibration Mitigation

Location	**Station Numbers**	**Length, ft**	**Mitigation Options**
U of M, Washington Ave Kolthoff Hall Hasselmo Hall NMR Amundson Hall Weaver Densford Hall	1245+00 to 1263+00	1800	Resilient fasteners
KSTP Studio			Resilient fasteners, additional analysis of mitigation requirements
1951 University			Relocate recording studio or construct a vibration isolated room
MDH/MDA Labs	--	--	No mitigation required
Church of St. Louis King of France	1685+50 to 1692+50	700 ft	Float Slab or design equivalent
Central Presbyterian Church			
Minnesota Public Radio			
Fitzgerald Theater			
McNally Smith Recording Studios			

3. CRITERIA FOR ACCEPTABLE LEVELS OF GROUND VIBRATION

3.1 Federal Transit Administration Vibration Impact Criteria

The criteria for vibration impact used for the CCLRT Final Environmental Impact Statement are defined in the FTA Guidance Manual (Ref. 1). The version of the Guidance Manual released in 2006 extended the vibration impact criteria to include different forms of the criteria for a General Vibration Assessment and for a Detailed Vibration Assessment. The criteria for a General Assessment are based on land use and train frequency, as shown in Table 2. There are some buildings, such as concert halls, recording studios and theaters, which can be very sensitive to vibration but do not fit into any of the three categories listed in Table 2. Due to the sensitivity of these buildings, they usually warrant special attention during the environmental evaluation of a transit project. Table 3 gives the FTA criteria for acceptable levels of ground-borne vibration for various types of special buildings.

It should also be noted that Table 2 and Table 3 include separate FTA criteria for ground-borne noise—the "rumble" that can be radiated from the motion of room surfaces in buildings due to ground-borne vibration. Although expressed in dBA, which emphasizes the more audible middle and high frequencies, the criteria are set significantly lower than for airborne noise to account for the annoying low-frequency character of ground-borne noise. Because airborne noise often masks ground-borne noise for above-ground (i.e., at-grade or elevated) rail systems, ground-borne noise criteria are primarily applied to subway operations where airborne noise is not a factor.

Table 2: Ground-Borne Vibration and Noise Impact Criteria for General Assessment

Land Use Category	Ground-Borne Vibration Impact Levels (VdB re 1 micro inch/sec)			Ground-Borne 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 VdB	43 dBA
Category 3: Institutional land uses with primarily daytime use.	75 VdB	78 VdB	83 VdB	40 dBA	43 VdB	48 dBA

Notes:
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 truck 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.
Source: Federal Transit Administration, May 2006.

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

Type of Building or Room	Ground-Borne Vibration Impact Levels (VdB re 1 micro-inch/sec)		Ground-Borne Noise Impact Levels (dB re 20 micro Pascals)	
	Frequent Events[1]	Occasional or Infrequent Events[2]	Frequent Events[1]	Occasional or Infrequent Events[2]
Concert Halls	65 VdB	65 VdB	25 dBA	25 dBA
TV Studios	65 VdB	65 VdB	25 dBA	25 dBA
Recording Studios	65 VdB	65 VdB	25 dBA	25 dBA
Auditoriums	72 VdB	80 VdB	30 dBA	38 dBA
Theaters	72 VdB	80 VdB	35 dBA	43 dBA

Notes:
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 p.m., the trains should rarely interfere with the use of the hall.
Source: Federal Transit Administration, May 2006.

The FTA criteria for a Detailed Assessment are shown in Figure 2 and the FTA interpretation of the curves is given in Table 4. When using the curves in Figure 2, there is impact if any part of the predicted vibration spectrum exceeds the applicable curve. That is, as long as the entire 1/3 octave band spectrum is below the curve, vibration mitigation is not required. The sample spectrum shown in Figure 2 is the average vibration level measured at a distance of 25 feet from the tracks for train speeds of 50 mph, and is provided for illustration purposes only. This example exceeds the FTA threshold for impact at residences during nighttime hours but is below the threshold for daytime hours.

The VC curves in Figure 2 are intended to apply to spaces that accommodate vibration sensitive equipment such as some of the U of M research facilities. Note that the detailed criteria curves do not apply to frequencies greater than 80 Hz. For this assessment the curves have been extended to higher frequencies to ensure that potential adverse effects on sensitive equipment are not overlooked.

Table 4: Interpretation of Vibration Criteria for Detailed Analysis

Criterion Curve	Max Lv(1) (VdB)	Description of Use
Workshop	90	Distinctly feelable vibration. Appropriate to workshops and non-sensitive areas.
Office	84	Feelable vibration. Appropriate to offices and non-sensitive areas.
Residential Day	78	Barely feelable vibration. Adequate for computer equipment and low-power optical microscopes (up to 20X).
Residential Night, Operating Rooms	72	Vibration not feelable, but ground-borne noise may be audible inside quiet rooms. Suitable for medium-power optical microscopes (100X) and other equipment of low sensitivity.
VC-A	66	Adequate for medium- to high-power optical microscopes (400X), microbalances, optical balances, and similar specialized equipment.
VC-B	60	Adequate for high-power optical microscopes (1000X), inspection and lithography equipment to 3 micron line widths.
VC-C	54	Appropriate for most lithography and inspection equipment to 1 micron detail size.
VC-D	48	Suitable in most instances for the most demanding equipment, including electron microscopes operating to the limits of their capability.
VC-E	42	The most demanding criterion for extremely vibration-sensitive equipment.

Source, FTA 2006 (Ref 1)
Notes:
(1) The descriptors used for curves are the same as used in the standards "ANSI S3.29-1983 (ASA 48-1983),[2] and ISO -2361-2, 1989.[3]
(2) Maximum in any 1/3 octave band over the range of 8 to 80 Hz.

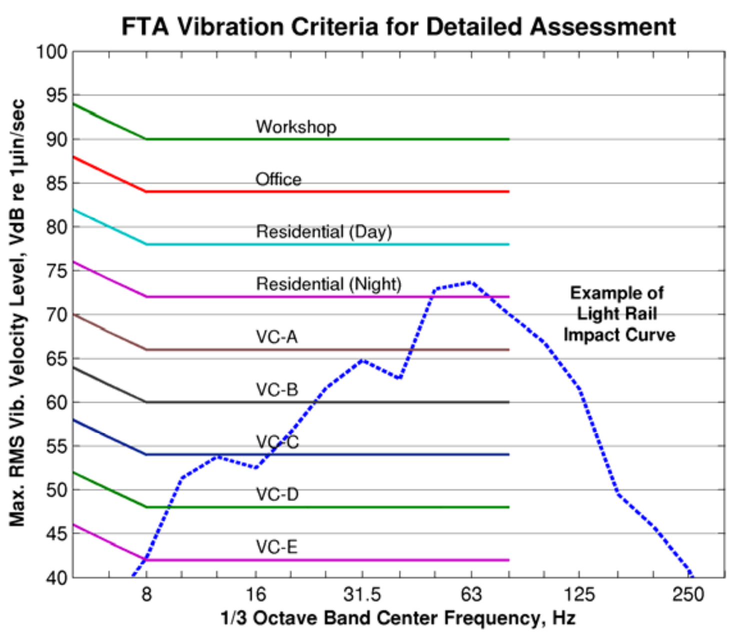


Figure 2: FTA Vibration Criteria for Detailed Assessment

The research equipment identified by the U of M as sensitive to vibration includes various models of electron microscopes (generically referred to as microscopy tools), x-ray crystallography and other spectroscopy equipment, and several Nuclear Magnetic Resonance (NMR) installations. Each of the microscopy tools and NMR installations has unique sensitivity to vibration. The VC curves shown in Figure 2 are often used for characterizing the suitability of spaces for vibration sensitive equipment when specific specifications are not available.

Varian Inc. manufactured some of the NMR equipment used at the NMR lab in Hasselmo Hall. Highly vibration-sensitive research equipment like NMR units have very low vibration tolerances and therefore very specific installation requirements. The U of M provided an excerpt from the Varian, Inc NMR System Installation Planning manual to more concisely convey the vibration tolerance limits to ATS staff. The installation manual states that "…the maximum allowable vibrations for the anti-vibration pistons" are the values listed in Table 5. The criteria are in terms of the peak acceleration amplitude. Converting the peak acceleration amplitude to equivalent rms velocity amplitude requires some interpretation. Shown in Table 5 are the equivalent Peak Particle Velocities (PPV) at specific frequencies and the equivalent root mean square (rms) levels assuming a crest factor of 4.[*] The equivalent rms values are compared to the VC-E curve in Figure 3. The Varian recommended limits are substantially lower than the VC-E curve at frequencies below 5 Hz and at frequencies above 25 Hz.

Example vibration criteria given in the installation manuals of several different microscopy tools are summarized in Table 6. As with the NMR criteria in Table 5, there is some uncertainty in translating the specifications for microscopy tools into the equivalent vibration velocity level that is used to characterize vibration in this report. All of the example electron microscope specifications reviewed for this analysis express vibration in terms of the displacement. Where not specified, the limits are assumed to be for the maximum peak-to-peak displacement because this gives a lower vibration limit than would be the case if the limits were assumed to be for the zero-to-peak or rms amplitude. The specifications are converted to equivalent rms displacement assuming a crest factor of 6 and then converted to equivalent vibration velocity level in VdB using a decibel reference of 1 µin/sec. The equivalent rms velocity levels are shown in Figure 4.

The electron microscope criteria indicate the many of these tools are most sensitive to low-frequency vibration and are relatively insensitive to vibration at frequencies above about 10 Hz. This is an indication that the manufacturers have incorporated vibration control elements into the tool design that reduces sensitivity at high frequencies. Further, at least for frequencies greater than 5 Hz, Figure 4 indicates that keeping LRT vibration levels at or below the VC-E curve is sufficient to protect most microscopy tools from interference from vibration.

[*] "Crest factor" is defined as the ratio of the peak vibration to the rms vibration. Experience is that the crest factor for trains is typically around 4.

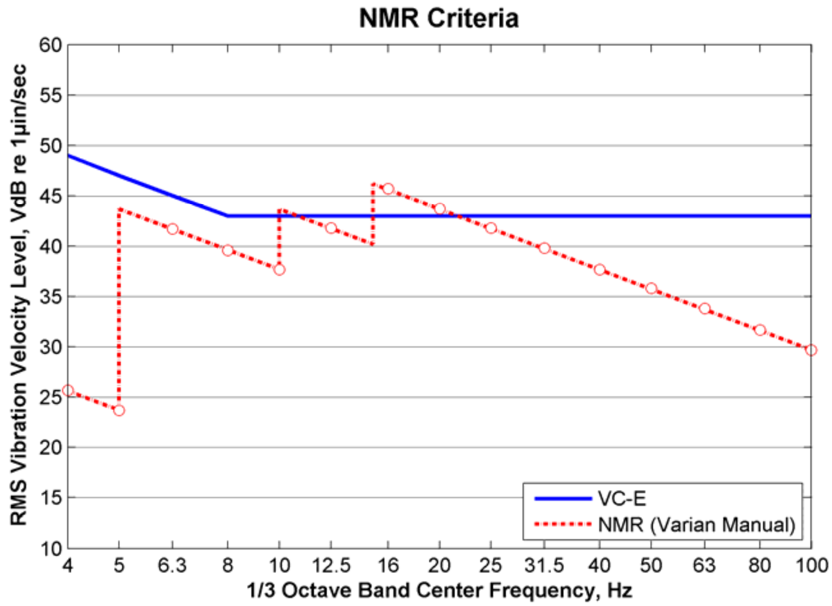


Figure 3: NMR Criteria Compared to VC-E Curve

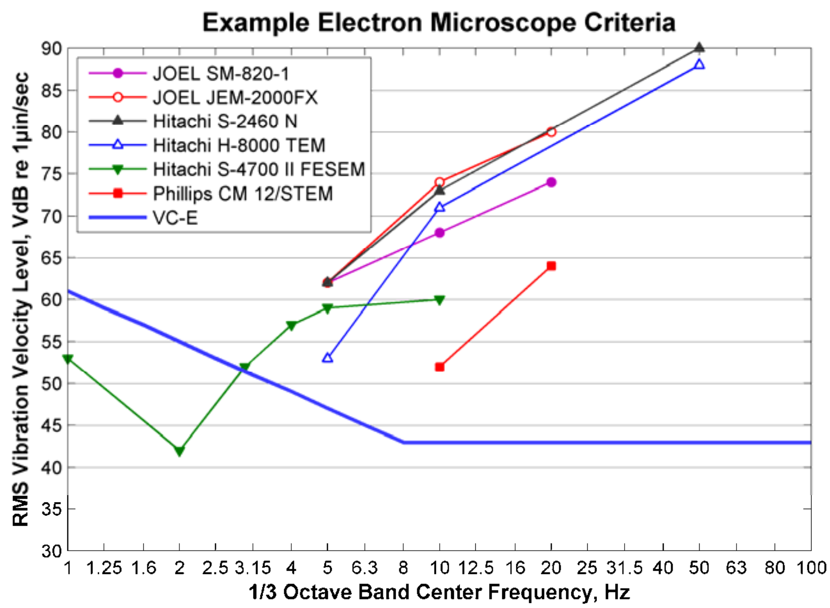


Figure 4: Example Vibration Criteria for Electron Microscopes

Table 5: Limits on Floor Vibration for NMR Systems

Frequency	Limit	Frequency, Hz	Equivalent PPV, in/sec	Equivalent rms[1], VdB
Greater than 15 Hz	No single peak greater than 200 µg	80	154	32
		15	819	46
10 to 15 Hz	No single peak greater than 100 µg	15	410	40
		10	614	44
5 to 10 Hz	No single peak greater than 50 µg	10	307	38
		5	614	44
Less than 5 Hz	No single peak greater than 5 µg	5	61	24
		1	307	38

Note:
1. Root mean square vibration velocity in decibels using a decibel reference of 1µin/sec.
Source: Varian, Inc. NMR Installation Manual

Table 6: Vibration Criteria from Manufacturer's Literature

Equipment	Frequency	Specification, Displacement, µm		Equivalent Velocity Level, VdB	Comments
		peak-peak	rms	rms	
1. JOEL SM-820-1					
	5 Hz	3	0.25	50	
	10 Hz	3	0.25	56	
	20 Hz	3	0.25	62	
2. JEOL JEM-2000FX					
	5 Hz	3	0.25	50	
	10 Hz	6	0.50	62	
	20 Hz	6	0.50	68	
3. Hitachi S-2460 N					
	5 Hz	3	0.25	50	
	10 Hz	5	0.42	60	
	50 Hz	7	0.58	77	
4. Hitachi H-8000 TEM					
	5 Hz	1	0.083	40	
	10 Hz	4	0.033	58	
	50 Hz	6	0.50	76	
5. Hitachi S-4700 II FESEM					
	1 Hz	5	0.42	40	The minimum of 0.7 µm at 2 Hz may correspond to a resonance in the vibration isolation system.
	2 Hz	0.7	0.058	29	
	3 Hz	1.6	0.133	40	
	4 Hz	2	0.17	44	
	5 Hz	2	0.17	46	
	10 Hz	1.1	0.092	47	
6. Phillips CM 12/STEM (specification in velocity, assume p-p, but may be rms)					
	10 Hz	0.5	0.041	40	Specification is 30 µm/sec
	20 Hz	0.9	0.075	51	Specification is 110 µm/sec

3.2 Vibration Criteria for Avoiding Damage

It is very rare for vibration generated by any rail system, even freight trains, to be of sufficient magnitude to cause damage to buildings, even minor cosmetic damage. Potential for vibration to damage buildings is mainly limited to construction activities such as blasting and pile driving or mining activities that require blasting. Vibration limits to avoid building damage are almost always expressed in terms of the peak particle velocity (PPV). The most common vibration limit is a PPV of 2 in/sec, which is largely based on studies performed by the U.S. Bureau of Mines.

A study reported on in USBM Bulletin 656 (1971) investigated the effect of blasting vibration on roadways, bridges, concrete structures, and residential structures. The results indicated that minor damage such as cracks in masonry, drywall, and plaster in old residential structures can occur at a vibration level above 5.4 in/sec. The “threshold of damage” limit recommended by the USBM was 4.0 in/sec, which was considered sufficient to avoid structural or cosmetic damage to residences. A recommendation of the US Office of Surface Mining is to use a limit of 0.75 in/sec to protect against growth of hairline cracks in weak residential structures including hairline cracks that may be too small to be seen without magnification.

In addition, there are several European standards that specify substantially lower limits to protect against damage to fragile historic structures. One example is Swiss Standard SN640312a (April 1992) from the Association of Swiss Highway Professionals, Committee VSS 272. The values from the Swiss Standard are shown in Table 7. Based on the definitions in the Swiss Standard, most structures in the project area would be categorized as “Average Sensitivity.” An exception would be the churches on Cedar Street in St. Paul that would be classified as “Particularly High Sensitivity.” The rate of occurrence would be considered “Frequent.” The Swiss Standard indicates that a vibration limit of between 0.12 and 0.24 in/sec (PPV) for vibration below 30 Hz would be appropriate for the sensitive historic structures. This is substantially lower than the vibration limits in most other standards.

Most vibration amplitudes in this report are root mean square (rms) averages expressed in decibels using a decibel relative to 1 micro-inch/second (μin/sec). The ratio of to PPV to rms is called the crest factor. The crest factor for train vibration is typically in the range of 4 to 6. Using the minimum vibration limit of the Swiss Standard of PPV=0.12 in/sec and a crest factor of 4, the equivalent rms vibration would be 0.03 in/sec, which is equal to 90 VdB. That is, based on the Swiss Standard a “Particularly High Sensitivity” building is safe from damage from a frequent event such as LRT operations is less than 90 VdB. If the vibration is at frequencies greater than 60 Hz, the equivalent threshold is 96 VdB.

The level of 90 VdB has been used as a screening for potential damage to sensitive buildings. As long as the predicted vibration levels do not exceed an overall vibration level of 90 VdB, there is no need to further investigate the potential for damage. This includes any type of damage from structural damage to cosmetic damage in the form of cracks in foundations and damage to stained glass windows. This is the same threshold that is recommended by the FTA guidance manual section on construction vibration (Ref. 1, page 12-13) for “Buildings extremely susceptible to vibration damage.”

Table 7: Guideline Values for Construction Vibration (Swiss Standard SN640312a)

Sensitivity Category	**Rate of Occurrence**	**Guideline Value (in/sec)**		
1. Very Low Sensitivity		Up to 3 times the values for Sensitivity Category 3		
2. Low Sensitivity		Up to 2 times the values for Sensitivity Category 3		
3. Average Sensitivity		< 30 Hz	30 to 60 Hz	> 60 Hz
	Occasional	0.59	0.79	1.18
	Frequent	0.24	0.31	0.47
	Permanent	0.12	0.16	0.24
4. Particularly High Sensitivity		Between 0.5 and 1 times the values for Sensitivity Category 3		

4. VIBRATION MITIGATION MEASURES

A number of different approaches have been used by rail transit systems to reduce the adverse effects of ground vibration. These measures range from very simple approaches such as placing felt pads under dishes that are rattling to the very expensive such as placing the entire track system on a concrete slab that is supported by springs (a floating slab) or constructing a building so that the entire building is supported by rubber or coil springs. The most common vibration mitigation measures used on rail systems consist of placing some sort of resilient layer between the track and the soil. Some approaches for installing standard vibration mitigation measures with embedded track (as would be used on the majority of the CCLRT system) are:

- **High-resilience boot:** A common embedded track system is to place the rails in a rubber “boot” and pour concrete around the boot. The rubber boot provides electrical isolation of the rails from the ground and provides enough resilience that movement of the rail during operations and movement resulting from thermal expansion and contraction does not cause the concrete to crack. In the standard configuration, the rail boot results in a fairly stiff track system. It is sometimes feasible to reduce the track stiffness by using a thicker and softer material for the boot. However, it is unlikely that a softer boot would provide sufficient vibration isolation except for segments where the predicted vibration levels exceed the impact threshold only at frequencies of 60 Hz and higher.
- **Resilient direct fixation track fasteners:** Direct fixation (DF) track fasteners are used to attach rails directly to a concrete slab. They are standard on the subways and aerial structures of most modern rail transit systems. The stiffness of a standard DF track fastener is around 150k lb/in. Reducing the stiffness to around 110k lb/in will increase the cost by a small amount. Going to a high-resilience DF track fastener (stiffness less than 60k lb/in) will cost approximately twice as much as a standard DF fastener. To use resilient fasteners with embedded track, the track would be constructed on top of a concrete slab and then concrete panels would be placed between and next to the rails. The design is similar to a typical rail/roadway grade crossing.
- **Ballast mat:** Ballast mats are designed to be placed under ballast and tie track. However, some embedded track designs have used ballast mat under a concrete slab as a vibration mitigation measure. In essence, the ballast mat is used to create a floating slab. This approach has the advantage of putting a continuous layer under the concrete slab, which reduces the potential for litter and other fouling material to get under the slab and short circuit the vibration isolation provided by the resilient layer.
- **Tire Derived Aggregate (shredded tires):** This approach consists of building the track on top of a layer of tire derived aggregate (TDA). This is an innovative approach for recycling old automobile tires. Although this approach has not been used for embedded track, it has been successfully used by light rail systems in Denver and San Jose to reduce vibration from sections of ballast and tie track. A 12 inch layer of TDA was used for both the Denver and San Jose installations and all indications are that those designs are functioning as intended.

  A concept for using a layer of shredded tires under embedded track is shown in Figure 5. The concept of this design is that standard embedded track would be constructed above a 12-inch layer of TDA. To perform as intended, there will need to be elastomer filled gaps between the track slab and any pavement that is in contact with adjacent buildings.

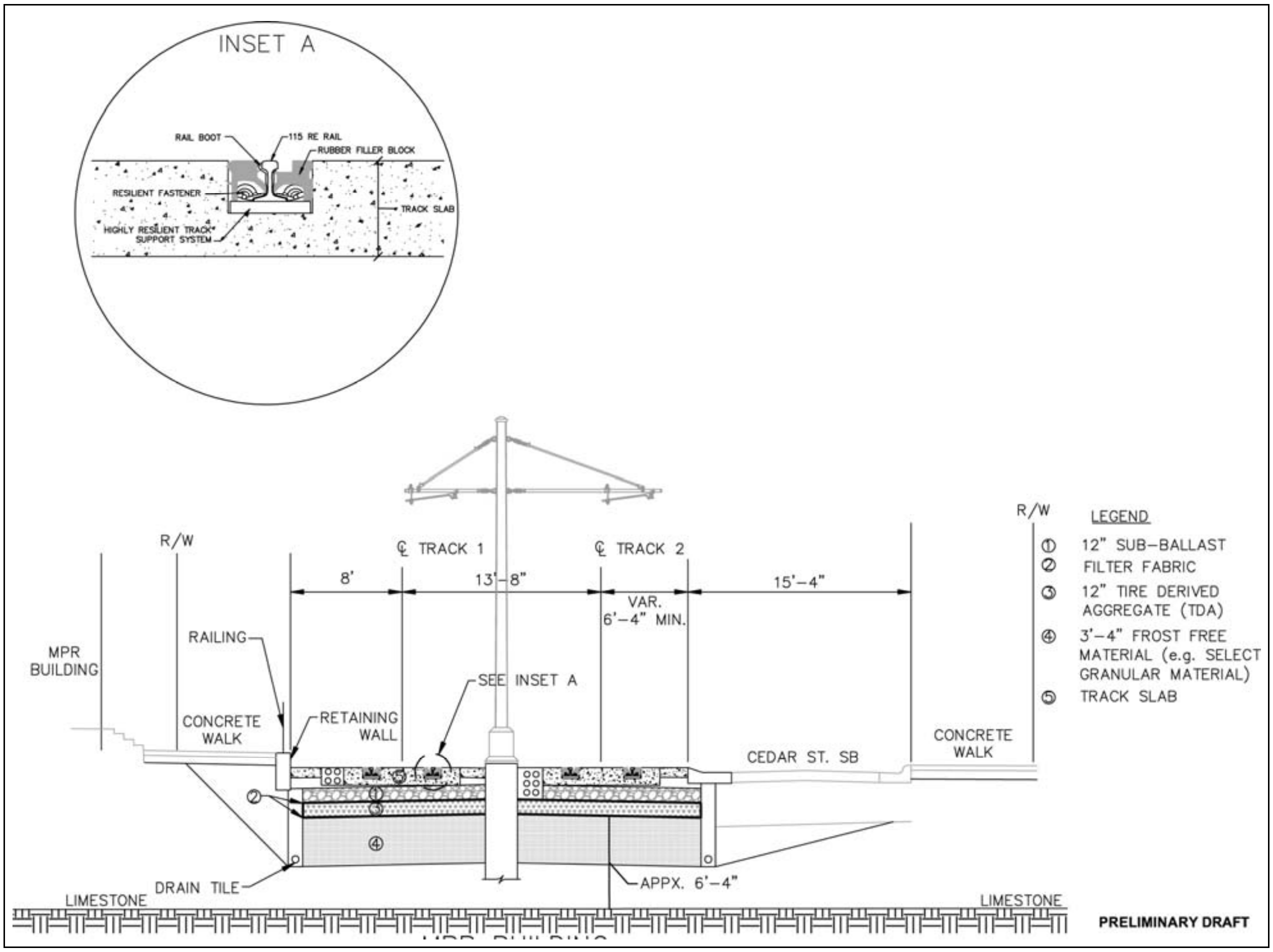


Figure 5: Concept for Using Tire Derived Aggregate for Vibration Isolation of Embedded Track
Source: DMJM+Harris/AECOM, December 2008

- **Floating slab track:** A floating slab consists of a concrete slab supported by elastomer or steel-coil springs. The track is attached directly to the concrete slab using DF fasteners and the springs are supported by a concrete foundation. The frequency range at which a floating slab is effective depends on the thickness of the slab and the stiffness of the springs. Most North American floating slab systems use rubber pads that are 12 to 18 inches in diameters supporting a concrete slab that is 12 to 24 inches thick. Floating slabs are very effective at reducing vibration levels; however, they are also very expensive. Potential problems with at-grade floating slabs in areas with a relatively severe climate such as Saint Paul are the effects of freeze-thaw cycles and the potential for foreign material to get into the gap under the floating slab and short circuit the vibration isolation.
- **Alternative approaches:** A number of alternative approaches have been proposed that may have applicability under specific circumstances. One example is underground barriers, something that several different Japanese rail systems have investigated recently. The basic concept is to use variations of an open trench or, when the propagation is through soft soils, a solid wall. Other

examples include increasing the thickness of the concrete under the track, specifying straighter rail, and, when the track will traverse sections of very soft soil, building the track on top of pile systems.

For most of the areas where vibration impacts are predicted for the CCLRT project it appears that use of high-resilience DF fasteners will provide sufficient vibration mitigation. Two DF fasteners that would be suitable choices are the Pandrol "Panguard" fastener (www.pandrol.com) and the Advanced Track Products "Egg" fastener (www.advancedtrack.com).

The left plot in Figure 6 shows the measured performance of two different floating slabs and the theoretical floating slab attenuation for a 10 Hz floating slab system. Experience is that a floating slab designed with a resonance frequency of 7 to 8 Hz will provide attenuation close to what is predicted by a simple spring-mass system vibration isolator with a 10 Hz resonance. The plot on the right shows the measured vibration attenuation of a tire derived aggregate system in San Jose and high resilience fasteners in Boston.

One factor to note is that these systems all have the potential to amplify vibration at frequencies near their resonance frequency. This could be an issue if floating slabs are used to attenuate vibration for an embedded track section that will carry both street traffic and light rail vehicles. If vehicular traffic will be operating on the same guideway as the light rail vehicles, the floating slab would be likely to amplify the vibration from vehicular traffic. This is because vibration from buses, trucks and other pneumatic tire vehicles tends to peak in the 10 to 16 Hz range.

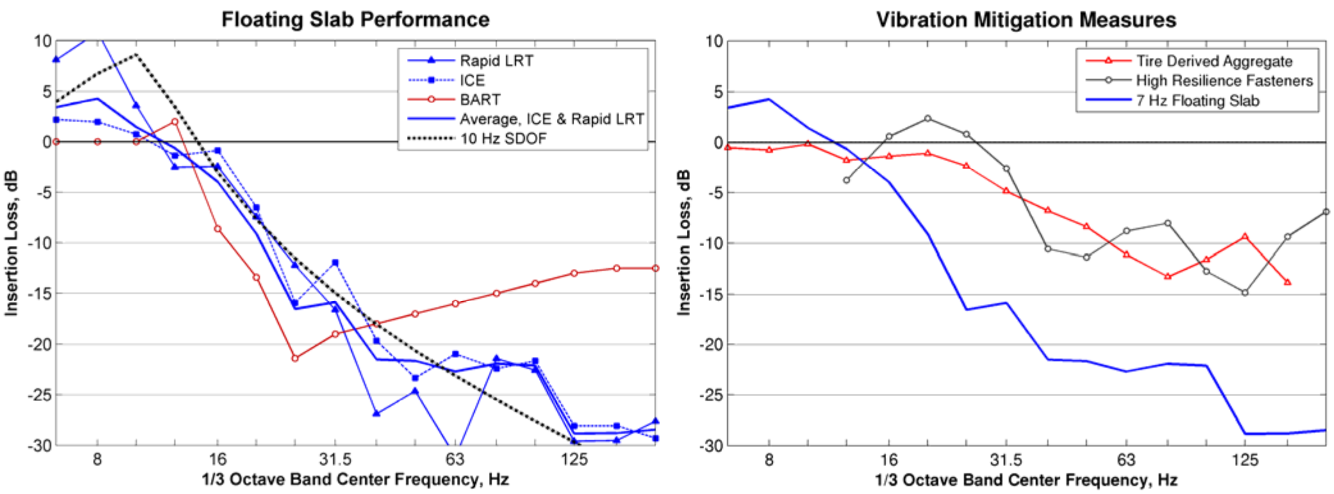


Figure 6: Performance of Different Vibration Mitigation Measures

The figure on the left shows floating slab performance measured at the BART system in the San Francisco Bay Area, measurements of a high speed train (ICE) and a rapid LRT train in Berlin, and the estimated vibration isolation using a 10 Hz resonance single-degree-of-freedom spring mass model. The BART floating slab was designed to have a resonance frequency of 8 Hz and the Berlin floating slab was designed to have a resonance of 7 Hz. The performance of the two floating slabs generally follows the theoretical curve for a 10 Hz single degree of freedom system. The attenuation of the BART floating slab drops off above 31.5 Hz probably because of the ambient vibration.

The figure on the right shows the floating slab attenuation curve used to evaluate the effectiveness of a floating slab track system and the measured attenuation of TDA and high resilience direct fixation fasteners.

Sources: BART Floating Slab Track, Ref. 4; Rapid LRT and ICE (Berlin) Floating Slab, Ref 5; High-resilience fasteners, Ref. 6; Tire Derived Aggregate, Ref. 7.

5. FORCE DENSITY MEASUREMENTS

Force Density Level (FDL) tests were performed at four locations on the Hiawatha Light Rail Transit (HLRT) line as a means of measuring the vibration forces generated by light rail vehicles. In addition, tests were performed with Metro Transit Buses at one of the test sites to determine the relative vibration levels of buses and light rail vehicles. The test locations were:

- **Test 1, Ballast and Tie Track**, Hiawatha Boulevard and 24th Street: Measurements were made at target train speeds of 20, 30, 40, and 50 mph using revenue service trains. The impact line was at the right-of-way fence, which is approximately 15 feet from the near track centerline.
- **Test 2, Embedded Track**, 5th Street and 5th Avenue: This location was in downtown Minneapolis. The impact line was along the sidewalk curb, which is approximately 10 ft from the centerline of the near track. As discussed in a memorandum summarizing preliminary testing (July 19, 2008), the results at this site were inconsistent and did not provide a good measure of the FDL. These measurements were limited to the standard operating speed of the revenue service trains, which is approximately 20 mph.
- **Test 3, Embedded Track**, 5th Street halfway between Portland Avenue and 5th Avenue: This site was 1/2 block east of where Test 2 was performed. The reason for the test was to determine whether the Test 2 measurements were valid. A two car test train was used for the measurements. Target speeds were 15, 25, and 35 mph. The impact line was along the centerline of the near track.
- **Test 4, Embedded Track**, 53rd Street and Minnehaha Avenue: The test was performed with revenue service trains at target speeds of 15, 25, and 35 mph. The impact line was at the centerline of the near track.
- **Test 5, Standard and Articulated Buses**, 53rd Street and Minnehaha Avenue: This measurement of bus FDL was performed at the same location as Test 4. Metro Transit provided two buses for the test; a standard 50-foot bus and an articulated bus. The buses were operated at target speeds of 10, 20, 30, and 40 mph and the impact line for the bus FDL was at the centerline of southbound Minnehaha Avenue.

The following sections present the data collection and analysis procedures and summarize the results of each of the FDL tests. See Appendix A for detailed results of the train and bus passby.

The overall approach in developing the FDL to use for the vibration predictions was to use a conservative approach to ensure that the predictions would tend to be on the high side. To this end, the predictions use the maximum of the embedded track FDLs and are based on the maximum rms vibration velocity level (1-second time constant) rather than the rms average over the period of a train passage. Also, although the measured FDLs are for two-car trains, the potential for higher vibration levels when three-car trains are operating has been included in the analysis. Some overall observations from the FDL tests are:

1. The FDLs measured at 5th Street and 5th Avenue (Test 2) during the May 2008 tests do not appear to be valid. These FDLs were not used for predicting ground-borne vibration.
2. The embedded track FDLs measured at 5th Street and Portland Avenue and at Minnehaha and 53rd were very consistent. The FDL measurement at 24th Street was typical of many FDL measurement results, but the results were less consistent than at 5th and Portland and Minnehaha and 53rd. The high consistency is likely to be the result of using an impact line at the track centerline for 5th Street and Portland and for Minnehaha and 53rd. The embedded track FDLs formed the basis of all predictions

in this report. The ballast and tie measurements were primarily used to estimate the effect of higher speeds on vibration levels.

3. The vibration energy from buses tends to be concentrated in the 8 to 30 Hz frequency range. Bus vibration exceeds LRV vibration in this frequency range assuming similar operating speeds. At higher frequencies LRV vibration is substantially higher than bus vibration.
4. For the two buses tested, the articulated bus generated vibration levels approximately 3 decibels higher than the single (non-articulated) bus.
5. At least in these tests, bus vibration tends to increase more rapidly with speed than LRV vibration. This may not be a universal trend because the LRV vibration on the Hiawatha Light Rail line varied less with speed than has been observed on other light rail systems.

5.1 Data Collection and Processing Procedures

Measuring the FDL of a vibration source consists of measuring the vibration of the source and performing a transfer mobility measurement at the same location. For this test the vibration source was either light rail vehicles or Metro Transit buses. The transfer mobility measurements were made from the centerline of the tracks or roadway whenever possible. The same procedure was used to measure transfer mobility for the FDL tests and for the tests along the CCLRT corridor. See the introduction (page 3) for a general description of the transfer mobility and force density test procedures.

Transfer mobility is measured using a dropped weight as the vibration source and ground-borne vibration from trains and buses is measured at the same site using seismic accelerometers attached to the ground surface. Point-source transfer mobility was measured at 11 points spaced at 15 ft intervals. These point-source transfer mobilities were combined to calculate an equivalent line-source transfer mobility (LSTM). Numerical integration using the rectangle method was used to convert the 11 point-source transfer mobilities measured at each accelerometer position into one line-source transfer mobility. The units for point transfer mobility are (μin/sec)/lb and the units for LSTM are (μin/sec)/(lb/√ft).

Assuming all values are expressed in decibels, the FDL is the difference between the measured train or bus vibration and the measured LSTM on a 1/3 octave band basis. FDL provides a measure of the vibration forces generated by trains or buses. A key assumption of this procedure is that FDL is largely independent of the local geologic conditions, which means that FDL should be independent of distance from the tracks. Typical FDL tests include measurements of LSTM and train vibration at three to eight distances from the tracks. Although there will always be variations in the FDLs derived from measurements at different distances, the variations tend to be on the order of ±1 to 3 decibels in the frequency range where the transfer mobility coherence is close to 1 and the train vibration is well above the background vibration. As discussed below, this was true for the FDL measurements at three of the four test sites. Large variations were observed in the data from the 5th Street and 5 Avenue test (Test 2), this data was not used to develop vibration predictions.

The analysis procedure consisted of determining average train vibration at each measurement position and then using the LSTM measured at the same position to calculate FDL at that position. It was not feasible to use an impact line at the track centerline for Tests 1 and 2. The impact line for Test 1 was at the right-of-way fence (shown in Figure 7) and the impact line for Test 2 was at the curb of 5th Street (shown in Figure 15). Linear or quadratic best-fit lines of LSTM vs. log(distance) for each 1/3 octave band were used to estimate the LSTM at the measurement distances for these tests.

The vibration from each train passby was analyzed to obtain the average vibration level over the period that the train passed the measurement position and the maximum vibration level during the train passage.

Root mean square (rms) averaging was used to obtain the average over the passby. The passby average is referred to as Leq in this report. The maximum level obtained was the maximum rms level using a 1-second time constant and is referred to as Lmax in this report. The averaging for Leq was between the 3 decibel down points in the overall vibration velocity level. That is, the averaging started when the vibration level was within 3 decibels of the maximum vibration level and stopped when the vibration level dropped to more than 3 decibels below the maximum level. Note that the FTA impact criteria for ground-borne vibration are based on Lmax.

The FDLs were all calculated using the Leq. Lmax was not used directly to calculate FDL because Leq tends to be a more consistent measure of train vibration than Lmax. Fairly short-term vibration fluctuations can have a substantial effect on Lmax even though the higher vibration levels may not last long enough to affect people's perception of the vibration or to affect vibration sensitive equipment. The difference between Lmax and Leq for the 2-car trains was almost always between 1 and 2 decibels and the average difference for all of the train passbys analyzed was 1.8 decibels. Therefore, the FDL curves derived with Leq have been adjusted up by 1.8 decibels before using the curves for predictions. All of the FDL curves shown in the body of this report are for predicting Lmax and all of the predicted levels are in terms of Lmax.

The same approach was used to calculate the bus FDLs. The difference between Lmax and Leq for the bus tests was generally between 2 and 3 decibels and the average difference for all of the bus passbys was 2.5 decibels.

Following is a summary of the steps used to obtain the average train/bus vibration levels at each accelerometer position:

1. The recorded vibration data was processed using Matlab® routines to calculate 1/3 octave band frequency spectra at 250 ms intervals.
2. The spectra were processed to select and separate the train and bus vibration events.
3. The Leq and Lmax 1/3 octave band spectra of the vibration acceleration were obtained for each train event at each accelerometer. The spectra were post-processed to convert to vibration velocity.
4. The data were carefully inspected to ensure that the results were valid and were not inordinately affected by other vibration sources. There was interference from background vibration for the tests at 24th Street (Test 1, ballast and tie track) and 5th Street and 5th Avenue (Test 2, embedded track). There were several events at 24th Street where tractor-trailer rigs were parking near the 100 foot position and corrupted the results at the 75 foot and 100 foot positions. At 5th Street and 5th Avenue, the vibration at frequencies below about 20 Hz appears to have been dominated by background vibration generated by vehicular traffic and building mechanical equipment.
5. The vibration spectra were graphed and carefully inspected to ensure data integrity. The graphs are included in Appendix A and graphs of the average spectra are included below in the discussions of each FDL test.
6. The average vibration spectra were used with the transfer mobility results to calculate FDLs at each accelerometer position. The measured LSTM functions and the final FDL curves are included in the discussions of each test. As discussed above, the basis of the FTA Detailed Vibration Prediction procedure is that FDL is independent of measurement distance. This was found to be consistent with the measurements with the exception of Test 2 at 5th Street and 5th Avenue, as discussed below).

5.2 FDL Test 1, 24th Street, Ballast and Tie Track

The ballast and tie track measurements were performed in an open area just south of 24th Street east of the HLRT. Figure 7, Figure 8, and Figure 9 are photographs of the test site. The train vibration measurements were performed at distances of 25, 50, 75 and 100 feet east of the centerline of the inbound track. The outbound track was approximately 15 feet further to the west. A representative from Metro Transit communicated with the train drivers to request specific speeds as the trains passed the measurement position. The tests were performed at target speeds of 20, 30, 40, and 50 mph. As seen in Figure 7, train speeds were measured with a radar speedometer.

The impact line was at the right-of-way fence and not at the track centerline. Best fit curves of the measured LSTM in each 1/3 octave band were used to adjust the LSTM to the measurement distances for train vibration.

The measured LSTM spectra are shown in Figure 11, the average train vibration levels are shown in Figure 12, and the measured FDL are shown in Figure 13. Both inbound and outbound trains were used for these measurements. The outbound track was 14 ft farther from the accelerometers than the inbound track. The train vibration data and the FDL curves at 39, 64, 89 and 114 ft are from operations on the outbound track. Referring to the FDL curves in Figure 13, no consistent difference in the vibration levels on the near and far tracks was observed.

The final FDL curves are shown in Figure 14. This includes both the measured FDL curves at speeds of 20, 30, 40 and 50 mph and the estimated FDL curves at other speeds. One observation from the FDL curves shown in Figure 14 is that the levels increase by 3 to 8 decibels as train speed increases from 20 to 50 mph. The increase in overall vibration level is at a rate of 10 to 15 log(speed), which is considerably less than the 20log(speed) factor recommended for use in the FTA Guidance Manual (Ref. 1).

Another observation is that at frequencies greater than 100 Hz the FDL values at the 75 ft and 100 ft accelerometers are 5 to 10 decibels lower than the FDL at the other measurement positions. This appears to be the result of low coherence at these frequencies. Therefore, the FDL levels at frequencies above 100 Hz at 75 and 100 ft have not been included in the average FDL calculations.

Figure 7: Photograph of 24th Street Site Looking South

Figure 8: Photograph of 24th Street Site Looking North

Figure 9: Photograph of 24th Street Site Looking West from 100 foot Position

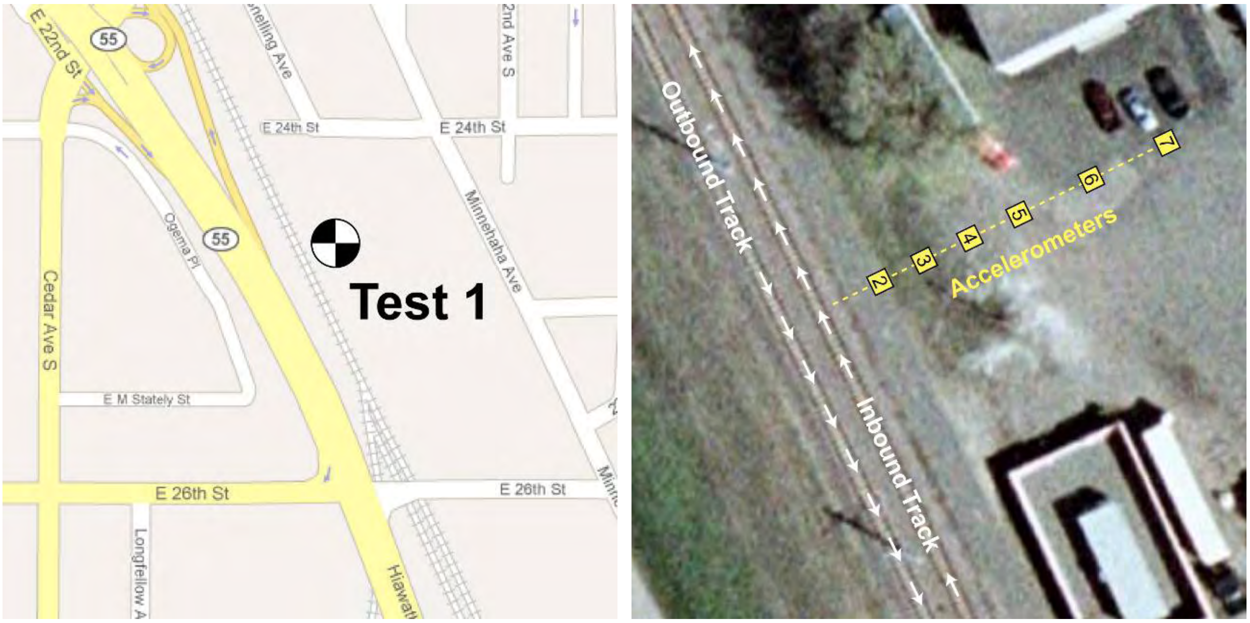


Figure 10: LRV FDL Measurement Location at 24th Street, Ballast and Tie Tracks
Accelerometer positions 3 and 7 (37.5 and 150 ft) were used for the LSTM measurements only.

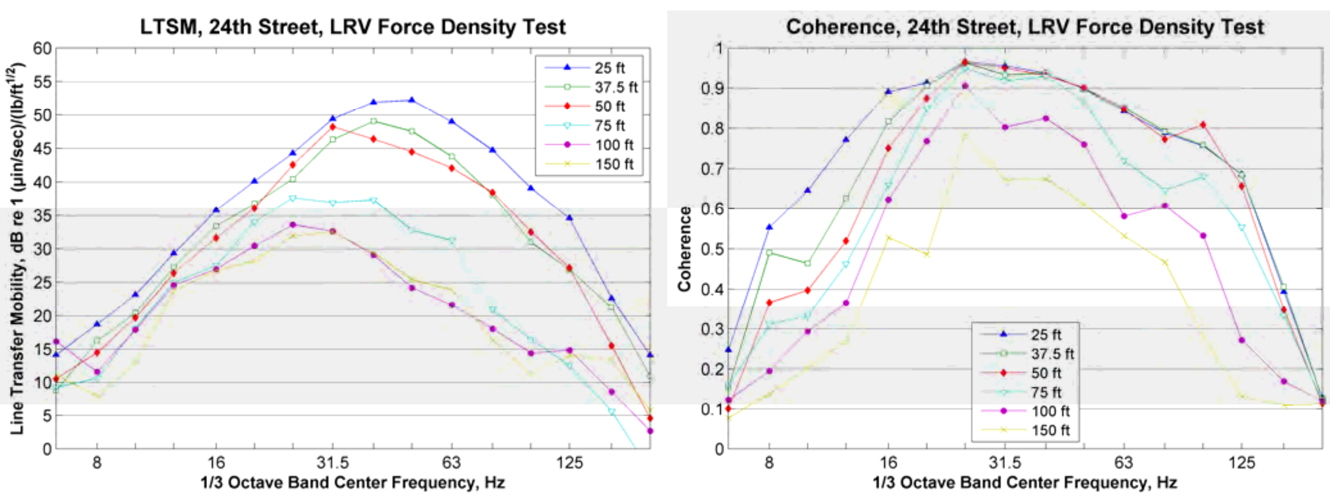


Figure 11: Measured Line Source Transfer Mobility, 24th Street FDL Test Site

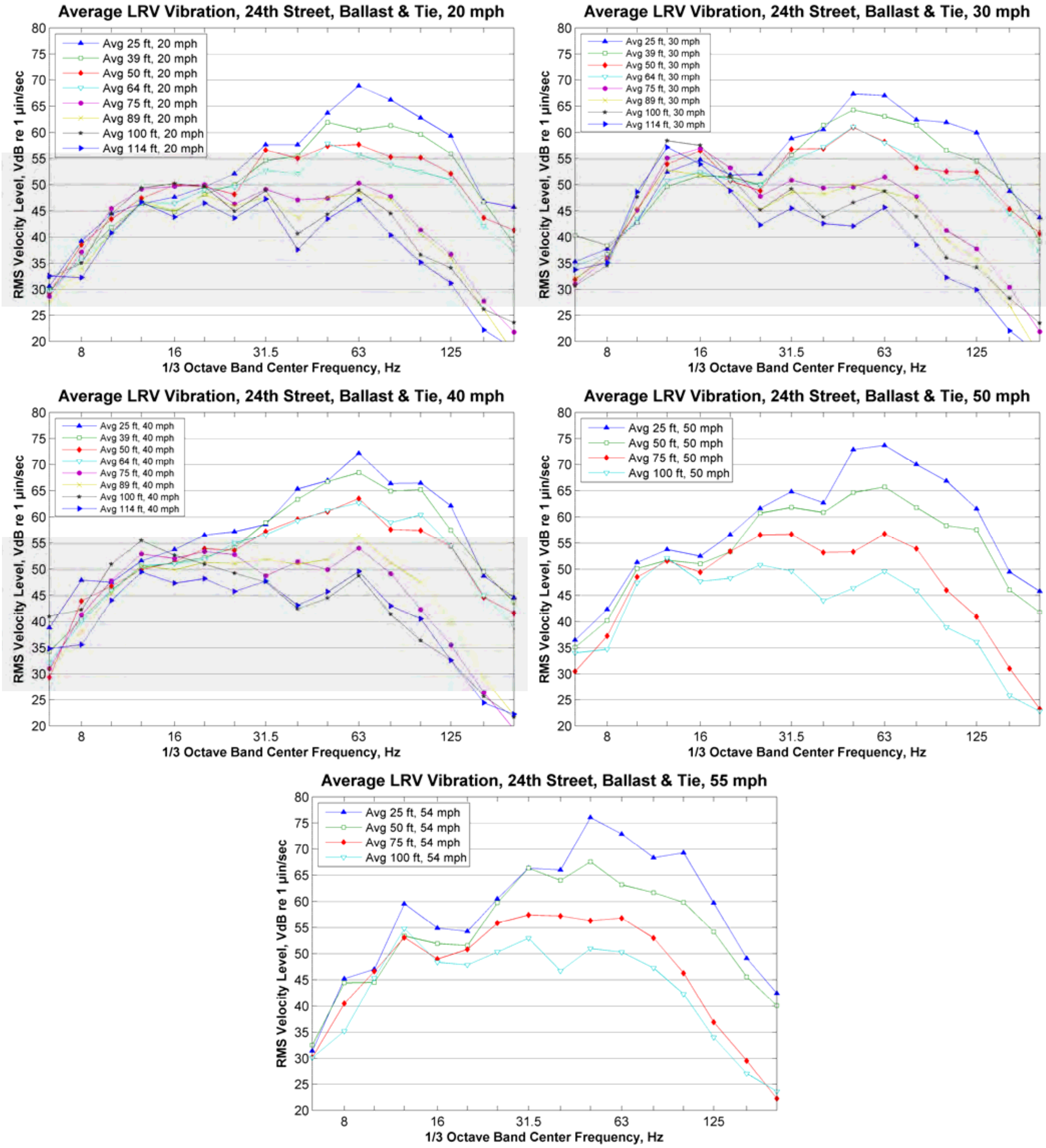


Figure 12: Average Train Vibration Levels, 24th Street Ballast and Tie Track

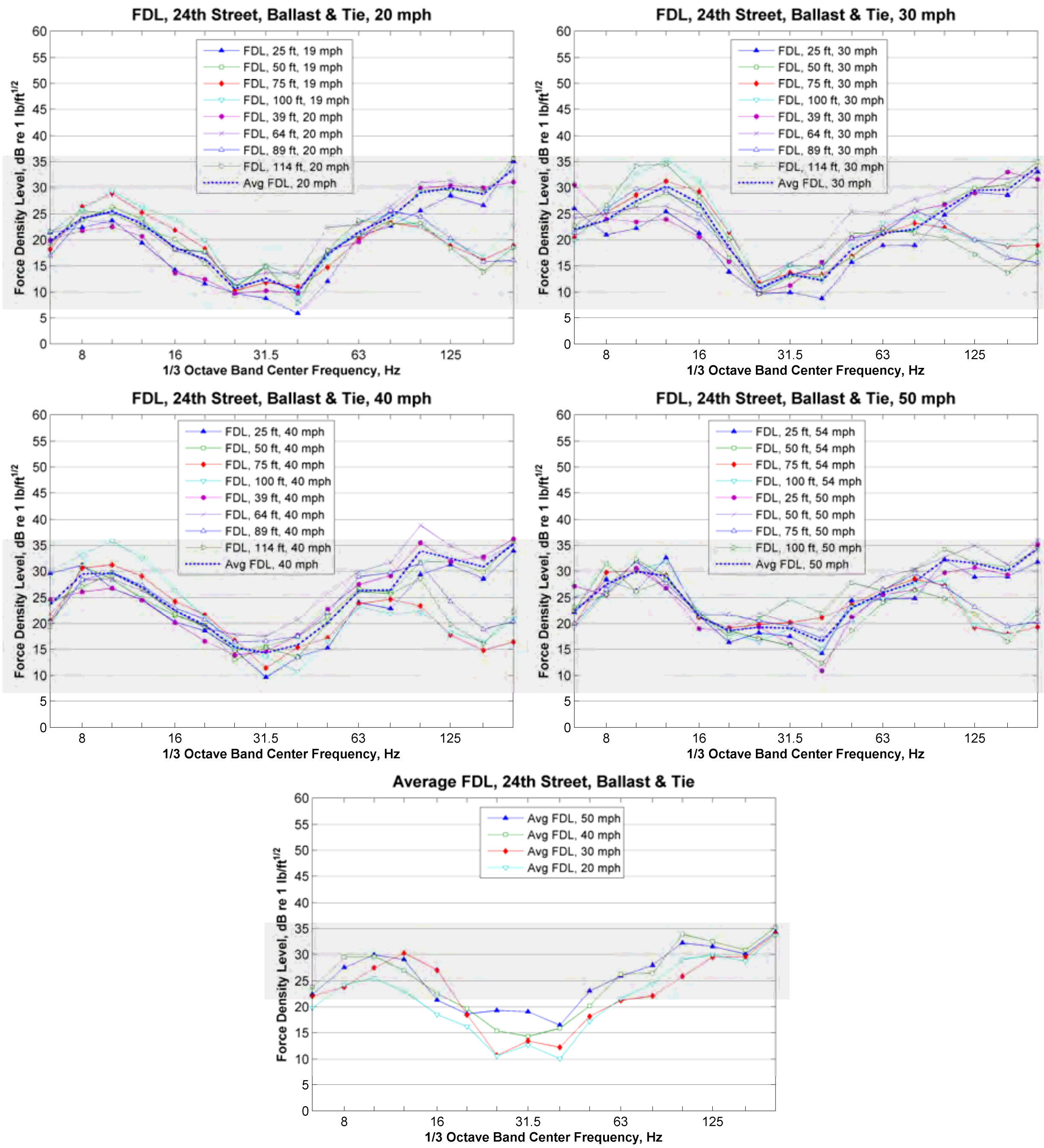


Figure 13: Force Density Levels, 24th FDL Test Site (Ballast and Tie Track)

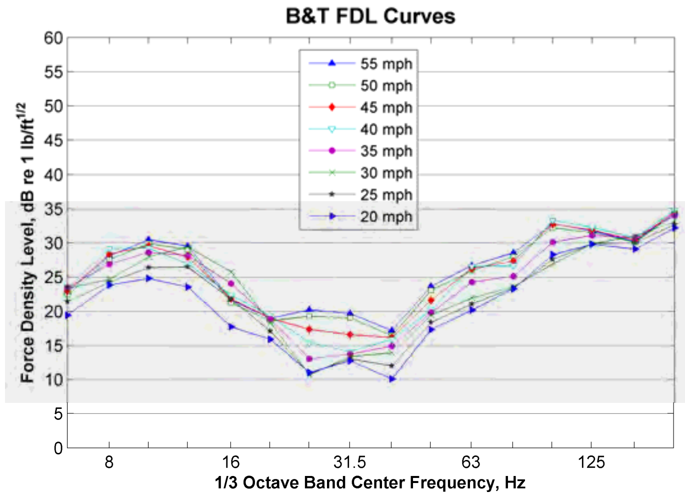


Figure 14: Derived FDL Curves for Ballast and Tie Track

Note that these curves are for predicting Lmax although they were derived from the train Leq values. The average difference between Lmax and Leq for the HLRT trains measured for this analysis was 1.8 dB. Therefore, 1.8 dB has been added to the Leq FDL curves to derive the Lmax FDL curves.

5.3 FDL Test 2, 5th Street and 5th Avenue, Embedded Track

The first embedded track measurement was performed at the intersection of 5th Street and 5th Avenue. As discussed below, there are several unexplained results with the 5th Street and 5th Avenue tests and the FDL curves do not converge to a single FDL curve. In order to seek convergent data, tests were performed at two additional embedded track sections (Test 3 and Test 4).

Figure 15 is a photograph looking east from 5th Avenue South where the measurements were performed. Figure 16 shows the accelerometer line on 5th Avenue running perpendicular to 5th Street in the northeast direction and Figure 17 is a street map and aerial photograph of the site. The train vibration measurements were performed at distances of 25, 50, 75 and 100 feet northeast of the centerline of the inbound track. The outbound track was approximately 12 feet further to the southwest. Of the five inbound and six outbound trains measured, several slowed for the intersection and three stopped because of a red light at 5th Avenue.

Train speed was not measured and all trains were assumed to be operating at 20 mph, consistent with Metro Transit standard operating procedures for this section of revenue-service track. The expectation was that train vibration levels would be different for inbound and outbound trains and for the trains that slowed or stopped at 5th Avenue. As seen in Figure 19, the vibration spectra are in two distinct groups plus one outlier (train 1). Surprisingly, the groups do not correspond to inbound versus outbound trains or slow and stopped trains versus through trains. Figure 19 shows the vibration spectra from the 25-foot measurement position; the data for the other three channels are shown in Appendix A.2.

Also shown in Figure 19 is the average ambient vibration during the train vibration measurements. Vibration levels were recorded continuously during the measurements and the train data extracted later. The ambient vibration is the rms average of the vibration when no trains were passing. As can be seen, at frequencies below 20 Hz the train vibration levels do not appear to have exceeded the background vibration. Potential sources of the background vibration include buses, trucks, automobiles, and mechanical equipment in nearby buildings. Based on the subsequent measurements of bus vibration at Minnehaha and 53rd Street (Test 5), the background vibration at frequencies below 30 Hz is likely to have been generated by buses and other vehicular traffic operating on nearby streets.

Another notable feature of the embedded track vibration is the strong high-frequency components for Channel 1 and to a lesser extent for Channels 2 and 3. This is illustrated in Figure 20. The left graph shows the average vibration spectra at 25 feet at 20 mph for Test 1 (24th Street, ballast and tie) and for Test 2. At frequencies of 80 Hz and greater the embedded track vibration is 15 to 20 decibels greater than the ballast and tie track vibration. The graph on the right presents the comparison at 50 feet. At this distance the embedded and ballast and tie data are within 5 decibels over the entire frequency range. The data suggests that there was a particularly efficient path for the high-frequency vibration to propagate from the tracks to the 25 foot position and that the efficiency of this path decreased rapidly beyond 25 feet.

The transfer mobility data from the 5th Street tests are shown in Figure 18 and the derived FDL curves are shown in Figure 21. As can be seen in the left side in Figure 21, the FDL functions vary widely above 63 Hz. With the benefit of the supplementary force density tests at embedded track (Test 3 and Test 4), the following observations and conclusions about can be drawn regarding the 5th Street and 5th Avenue results:

- The FDL at 25 feet is not valid. The problem appears to be due to the impact line for the transfer mobility tests being located 10 ft north of the tracks. Under normal circumstances where the subsurface conditions are relatively uniform, this small a path difference would not have much effect on the vibration levels. However, at this location the propagation path from the track centerline to the 25 ft accelerometer was much more efficient than the propagation path from the sidewalk curb to the 25 ft position. This could be caused by a subsurface structure of some sort. Subsequent to the tests, we learned that the Hennepin County Courthouse and Jail have subsurface facilities in this area. It is possible that these structures caused the anomalous result at the 25 ft accelerometer position.
- The 50 foot and 75 foot FDLs are consistent with the two subsequent FDL measurements. These two results were used to derive a "high range" FDL for the early draft report dated July 19, 2008.
- The FDL derived from the 100 foot accelerometer results does not appear to be valid. The 100 ft FDL was used as the "low-range" FDL in the early draft report dated July 19, 2008.

The FDL curves derived from the tests at 5th Street and 5th Avenue have not been used for any of the Central Corridor LRT predictions because of the unexplained anomalies discussed above.

Figure 15: Photograph of 5th Street and 5th Avenue Site Looking East

Figure 16: Photograph of 5th Street and 5th Avenue Site Looking North on 5th Avenue

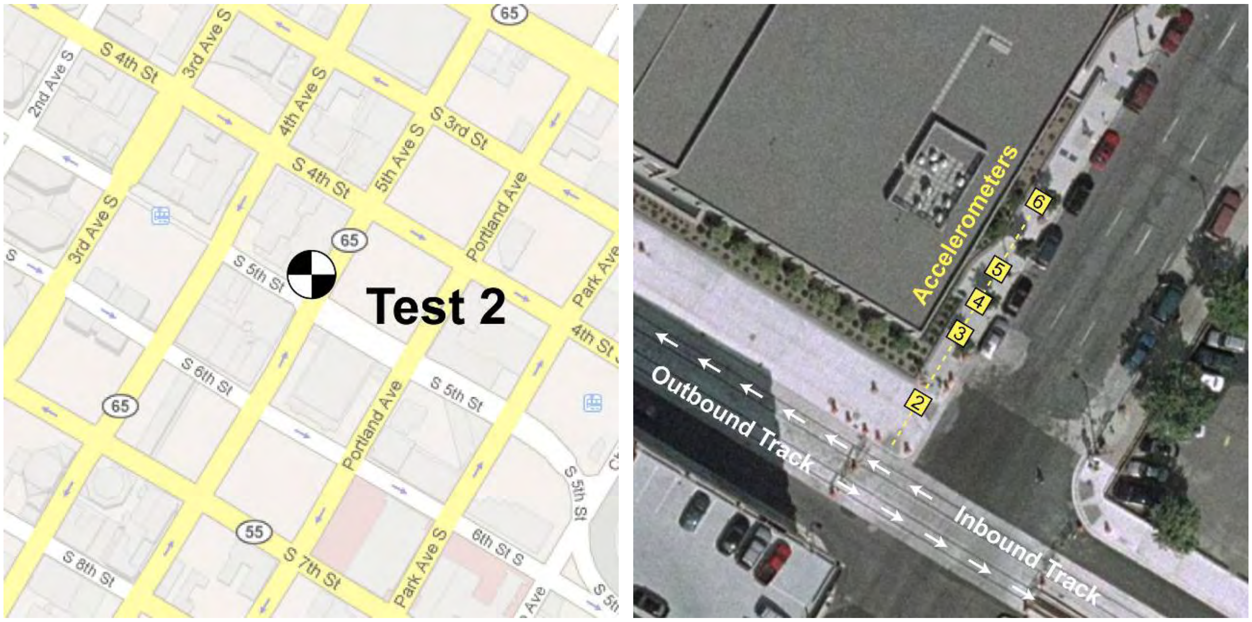


Figure 17: LRV FDL Measurement Location at 5th Street Portland Avenue

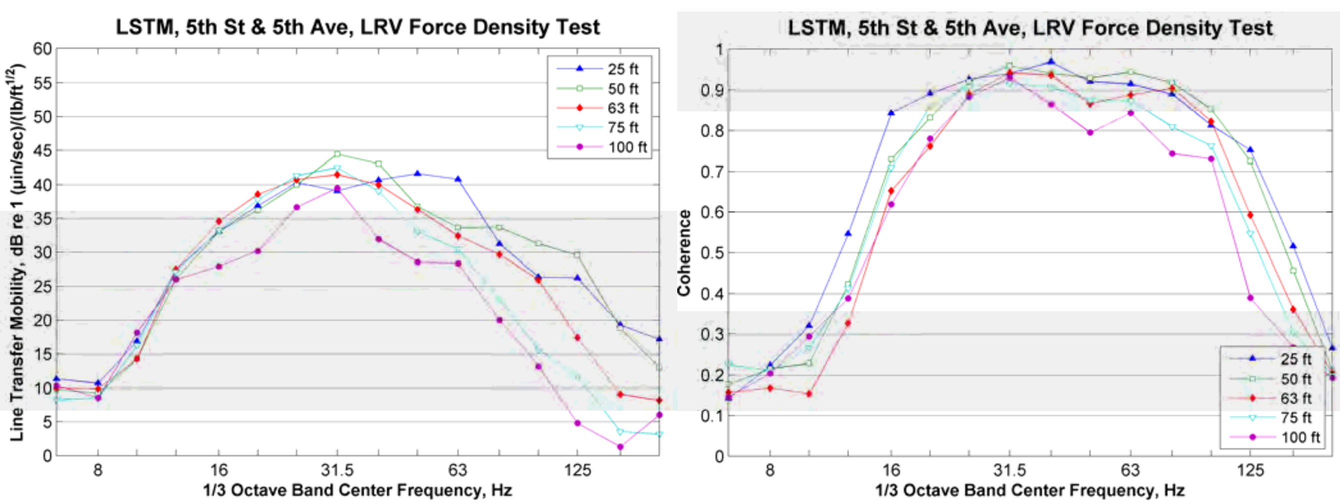


Figure 18: Line-Source Transfer Mobility, 5th St. and Portland Avenue Embedded Track

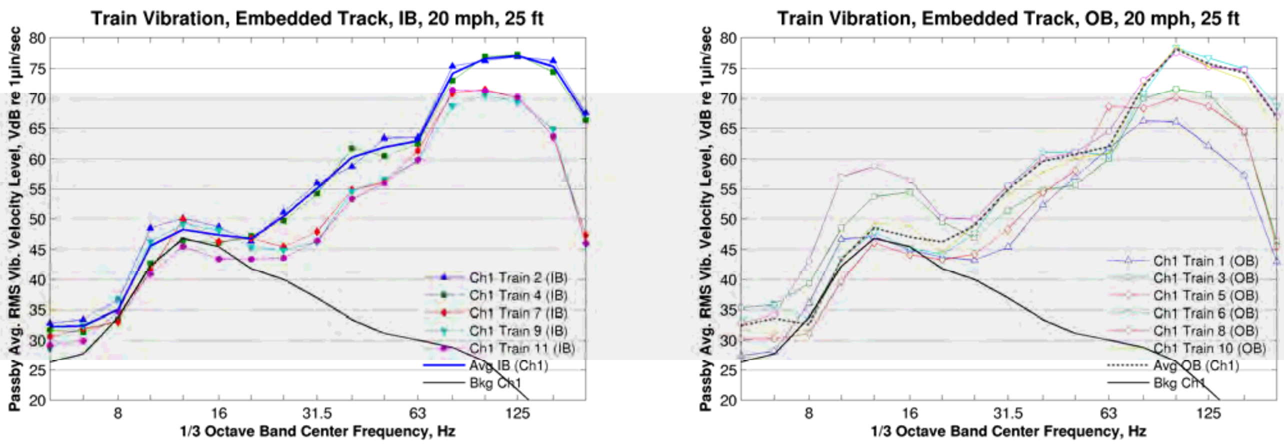


Figure 19: Train Vibration Levels, 5th Street and 5th Avenue Embedded Track, 20 mph 25 foot Accelerometer
(see Appendix A.2 for graphs of vibration spectra at 50, 75, and 100 feet)

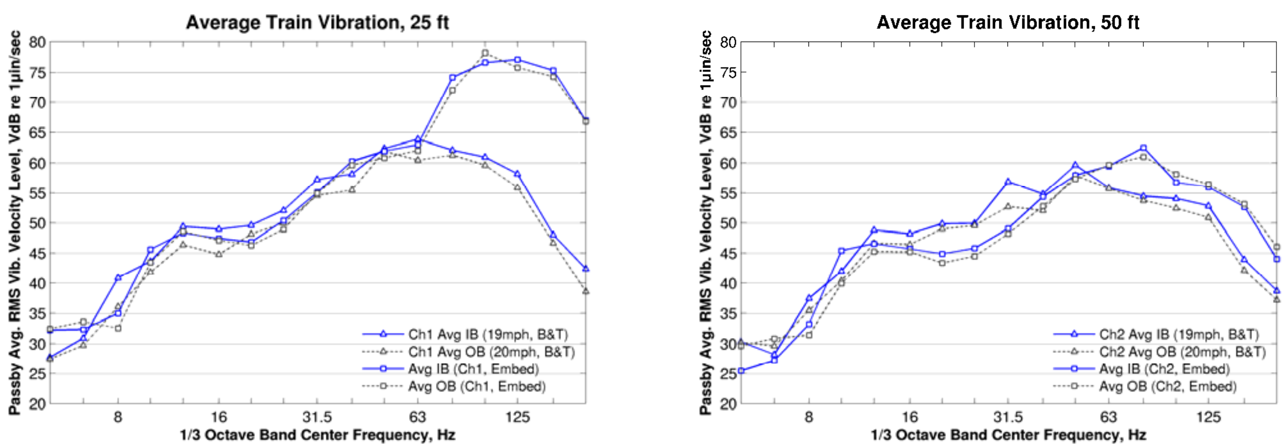


Figure 20: Comparison of HLRT Vibration Spectra, Tests 1 and 2

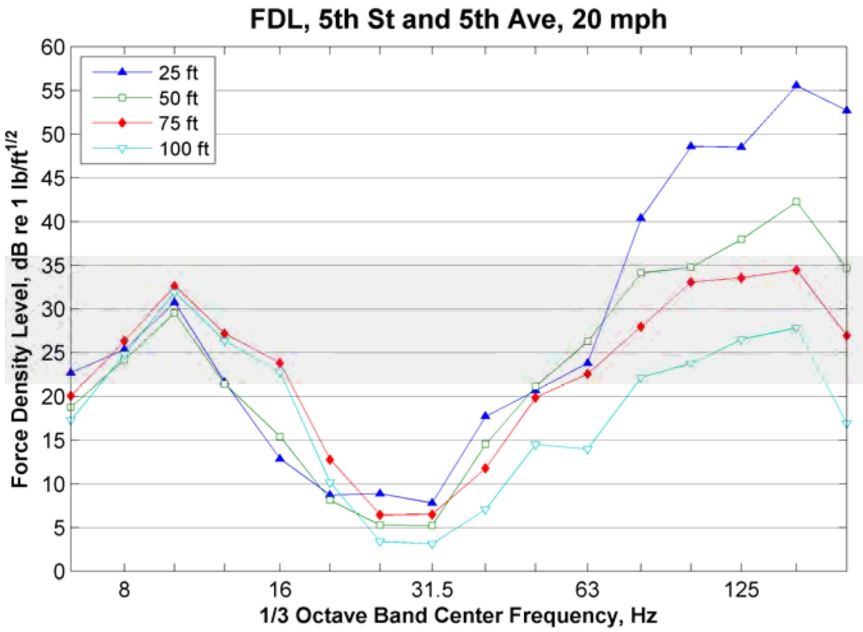


Figure 21: Measured FDL, Embedded Track, 5th Street and 5th Avenue, 20 mph

5.4 FDL Test 3, 5th Street and Portland Avenue, Embedded Track

This test was performed on a section of embedded track along 5th Street halfway between 5th Avenue and Portland Avenue on September 29, 2008 (see Figure 22). This location is one-half block east of the location where Test 2 was performed. The test was performed with a two-car test train late at night to minimize the effect of ambient vibration on the test results. The target speeds were 15, 20, and 25 mph and speed was measured with a radar gun. The tests were performed on the inbound track.

The impact line was at the centerline of the inbound track. A total of 19 train passbys were measured, 15 of which were included in the FDL calculations. The excluded trains were primarily revenue service trains that either stopped or were too slow at the measurement location. The details of train passby measurements are provided in Appendix A.

Figure 23 shows the measured LSTM and coherence of the impact test. The impact test showed excellent coherence between 12 and 160 Hz. Although the coherences for the test at 5th Street and 5th Avenue were relatively high, the coherences for this test were close to 1 over a wider frequency range. This is a reflection of the background vibration being lower. The background vibration was lower because the testing was performed late at night when activity was at a minimum and all street traffic, including buses, was diverted from 5th Street during the test. Comparing the background levels during Test 2 (Figure 19) to the background levels during Test 3 (Figure 24), it can be seen that background vibration was approximately 12 decibels lower during Test 3.

Another interesting feature is that the results for this test do not have the high-frequency components that showed up at the 25 ft position for the Test 2 measurements, which were one-half block to the northwest. Comparing the vibration levels at the 25 ft for Test 2 (Figure 19) to those from Test 3 (Figure 24) it can be seen that the maximum vibration for Test 2 was between 70 and 80 VdB and occurred at 100 to 125

Hz while for Test 3 the maximum vibration level was between 50 and 55 VdB. There was a 20 decibel difference between the two measurements at 25 ft.

The FDL curves derived from the 5th and Portland data are shown in Figure 25. The FDLs for the six measurement positions correspond very closely and are generally within a 2 to 3 decibel range. This is a reflection of having performed the measurements under well controlled conditions when the background vibration was at a minimum. The lower right graph in Figure 25 compares the FDL curves for average speeds of 14, 19, and 23 mph. The differences in the FDLs in most 1/3 octave bands is less than 5 decibels and is less than 2 decibels in several 1/3 octave bands. This shows that the levels of ground vibration are not strongly dependent on speed over the range of 14 to 23 mph.

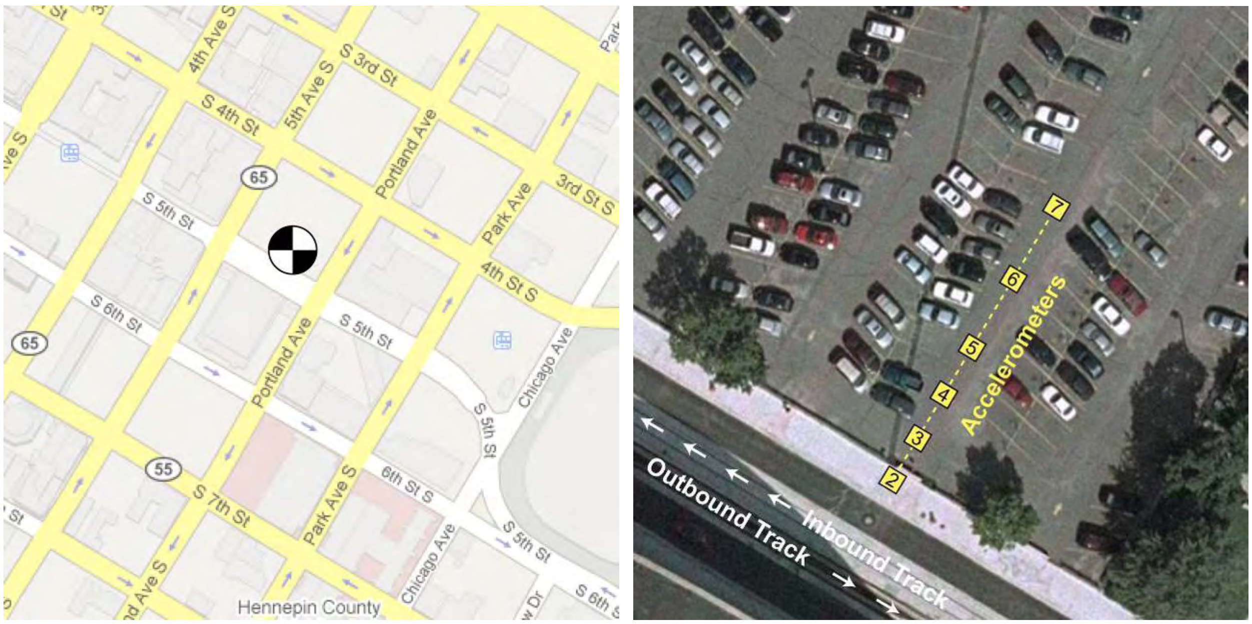


Figure 22: LRV FDL Measurement Location at 5th Street and Portland Avenue

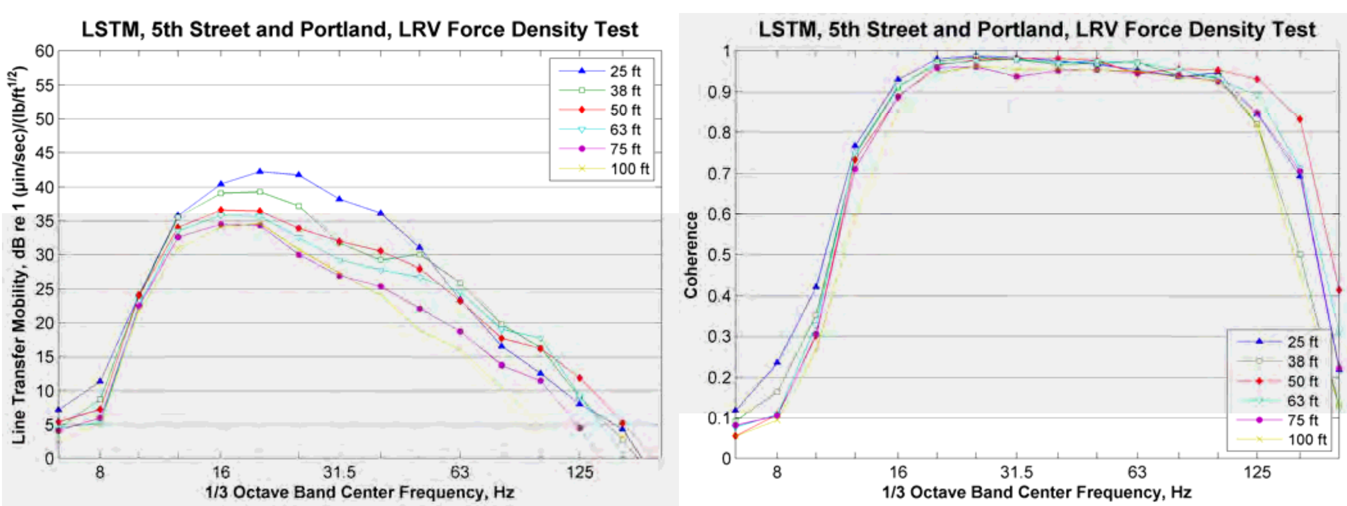


Figure 23: Line-Source Transfer Mobility, 5th St. and Portland Avenue Embedded Track

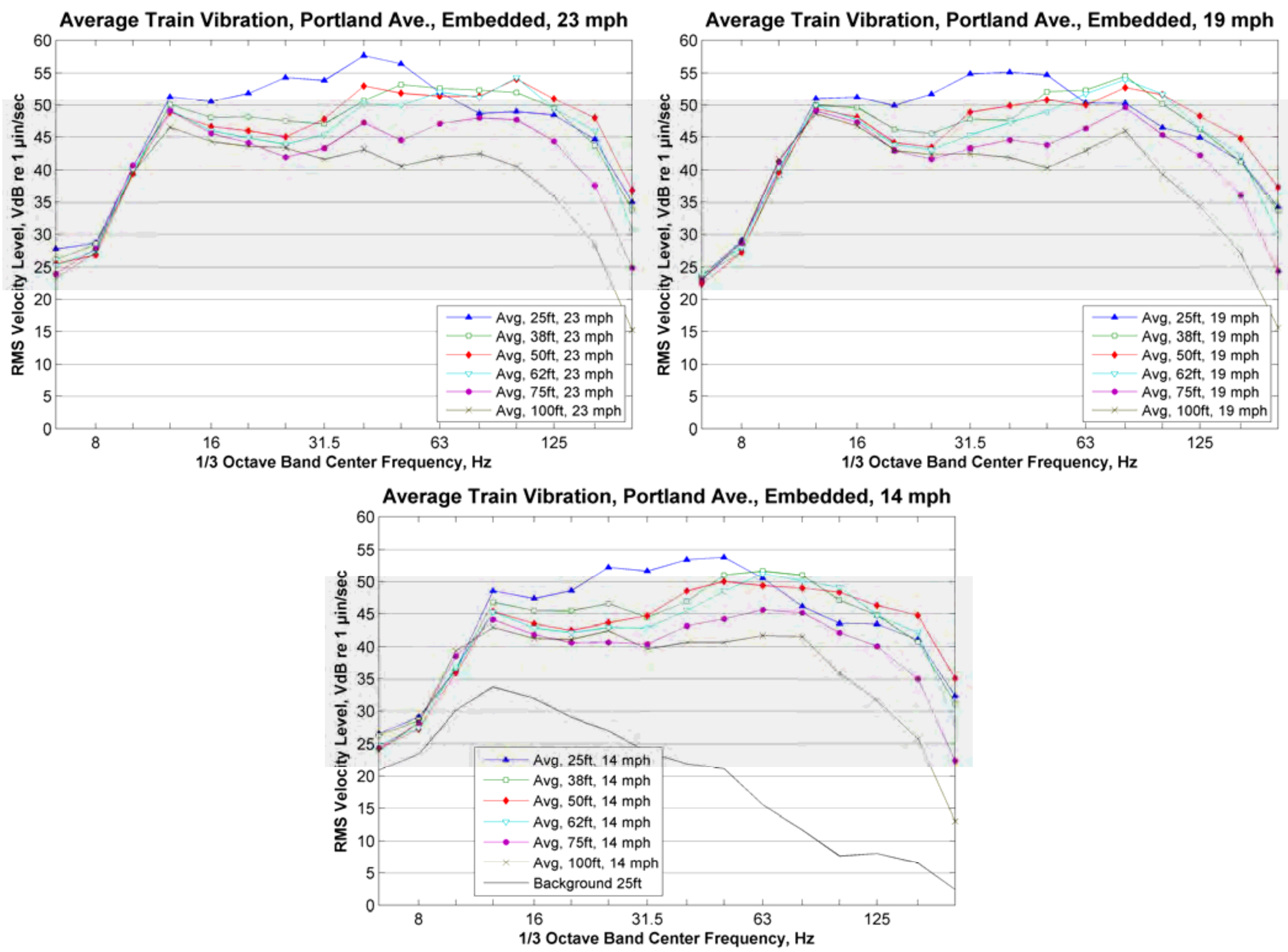


Figure 24: Average Train Vibration Levels, 5th Street and Portland Avenue Embedded Track

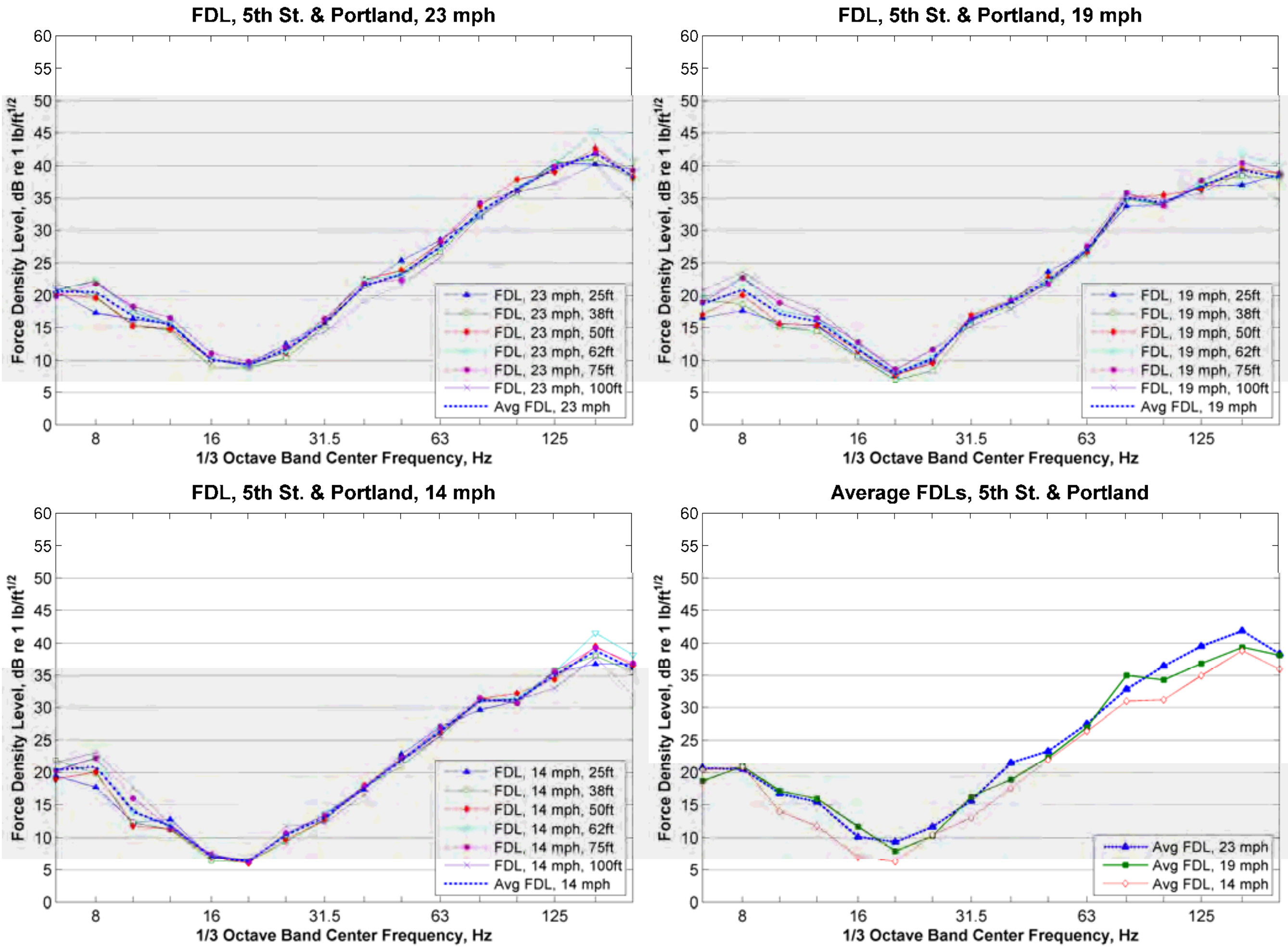


Figure 25: Force Density Levels, 5th Street and Portland Avenue Embedded Track

5.5 FDL Test 4, Minnehaha Avenue and 53rd Street, Embedded Track

This test was performed on a section of embedded track along Minnehaha Avenue (near the intersection of Minnehaha and 53rd Street) on October 2, 2008. An overview of the location for the test is shown in Figure 26. The same location was used for the measurements of bus vibration (Test 5).

Revenue service trains on the outbound tracks were used for the FDL tests and the impact line for the transfer mobility tests was at the centerline of the outbound track. The train speeds were controlled by a representative from Metro Transit and a radar gun was used to measure the speed. The target speeds for the tests were 15, 25, and 35 mph. A total of nine trains were measured and included in the FDL calculations. The average train speeds were 14, 23 and 33 mph. The detailed results of the train vibration measurements are presented in Appendix A.

The procedures used to analyze the train vibration data and to derive the force density function for Minnehaha Avenue and 53rd Street are the same as used for the other tests. Figure 27 shows the measured LSTM and coherence at this site. The measurements showed good coherence between 12.5 and 160 Hz.

The average train vibration levels at 14, 23 and 33 mph are shown in Figure 28. Graphs of the vibration spectra for all nine trains used for the FDL measurement are shown in Appendix A. Although this is not a complete sample of the entire HLRT fleet, it notable that none of the light rail vehicles observed in this test or any of the other tests for this study had audible wheel flats. This is an indication the Metro Transit pulls vehicles with flatted wheels out of service for maintenance soon after the flats develop, which is consistent with Metro Transit maintenance practices. The bottom graph in Figure 28 includes the background vibration level during the train vibration measurements. This graph illustrates that the train vibration was well above the background vibration at frequencies of 12.5 Hz and greater.

The FDL curves for each speed and accelerometer position are shown in Figure 29. Although the FDL curves are not as tightly clustered as for Test 3, with a few exceptions they are within a 5 decibel range. The average FDL curves for each speed are shown in the lower left graph in Figure 29. Although the FDL curves show somewhat more variation with speed than was observed in Test 3, over much of the frequency range there is relatively little increase in vibration levels as speed increases.

Figure 26: FDL Measurement Location at Minnehaha and 53rd Street

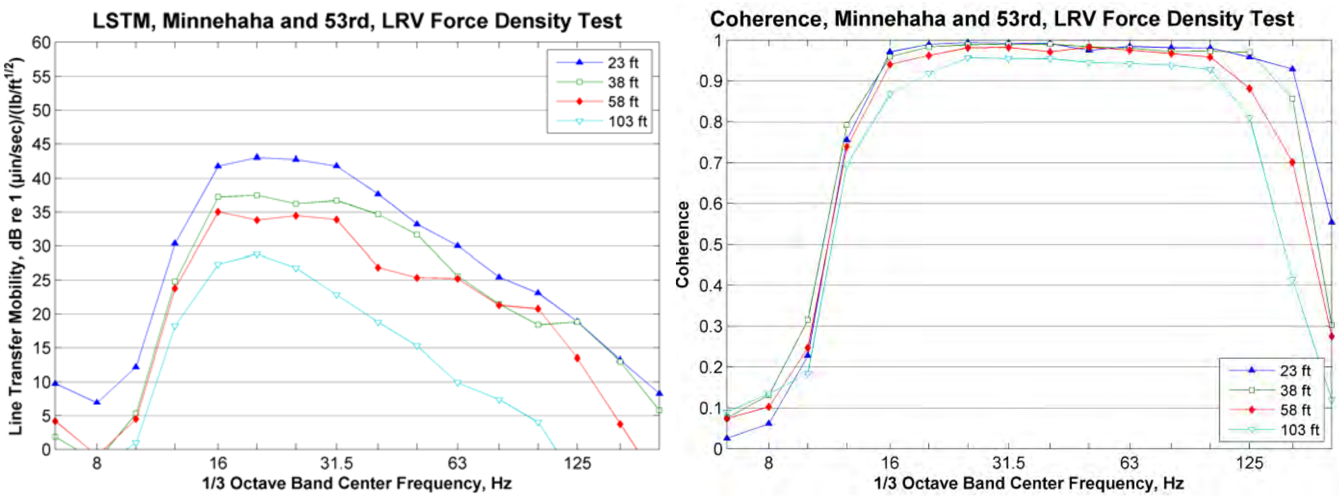


Figure 27: Line-Source Transfer Mobility, LRV FDL Test, Minnehaha & 53rd Street

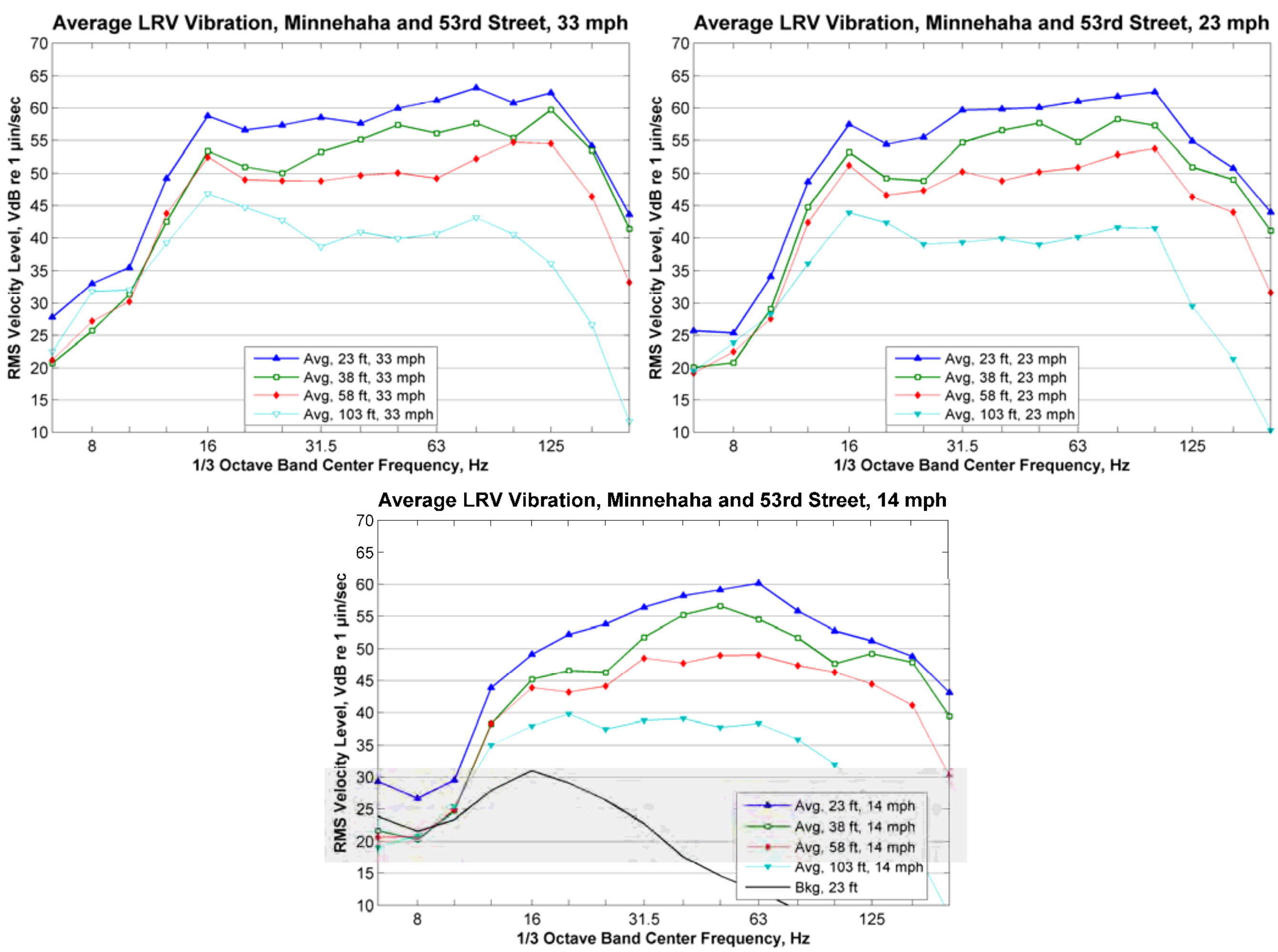


Figure 28: Average Train Vibration Levels, Minnehaha and 53rd Street, Embedded Track

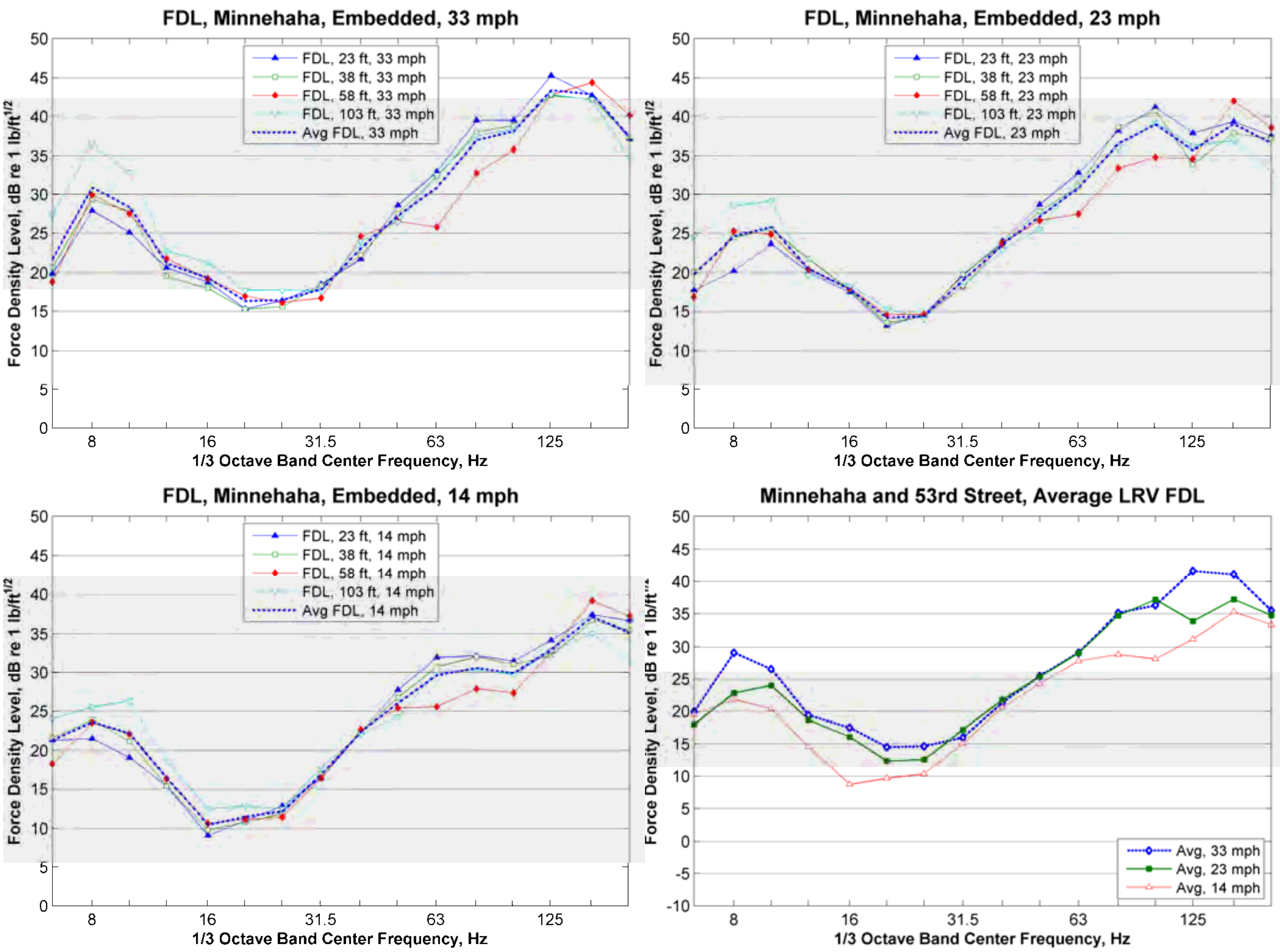


Figure 29: LRV Force Density Levels, Minnehaha and 53rd Avenue, Embedded Track

5.6 FDL Test 5, Minnehaha Avenue and 53rd Street, Bus FDL

Test 5 was performed on the southbound lane of Minnehaha Avenue near 53rd Street to determine the FDL of transit buses. This is the same location that Test 4 was performed. The accelerometer positions were the same as used for the LRV FDL tests. With respect to the transfer mobility tests, the only difference between the bus and LRV test is that the impact line was at the centerline of the southbound lane instead of the track centerline (see Figure 26).

Two Metro Transit buses were used for this test, one was an articulated bus and the other was a standard 50-foot bus. The target speeds were 10, 20, 30, and 40 mph and a radar gun was used to measure the speed. Figure 30 shows the average vibration levels for the standard bus and Figure 31 shows the average vibration levels for the articulated bus. As can be seen from comparing the two figures, the vibration from the articulated bus was approximately 3 decibels higher than that from the single bus. It can also be seen that the vibration energy from the buses peaks at 16 Hz compared to the LRV vibration spectra that was relatively flat from 20 Hz to 100 Hz.

The measured LSTM and the coherence are shown in Figure 32. As would be expected, the LSTM and coherence are very similar to what was measured for the LRV force density test at the same location. The differences are due to the impact line being 15 ft closer to the accelerometers for this test.

The FDL curves for each test position and bus speed are shown in Figure 33 for the single bus and Figure 34 for the articulated bus. The FDLs are not as closely grouped as the LRV FDLs, particularly at frequencies greater than 40 Hz. Interestingly, the bus vibration peaks at 16 Hz while the bus FDL peaks at 10 Hz. This is a result of the transfer mobility dropping off rapidly below 16 Hz.

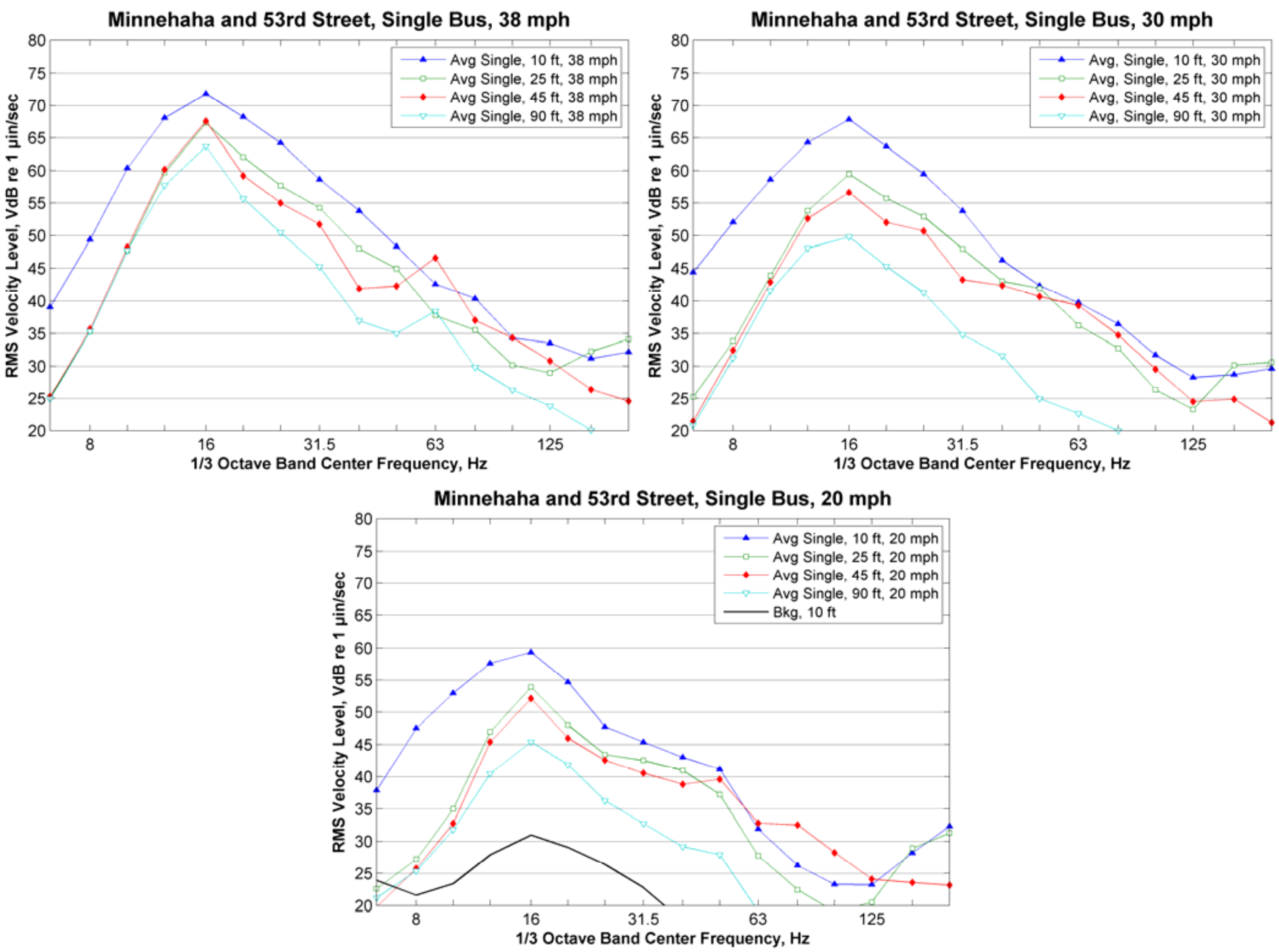


Figure 30: Average Single Bus Vibration Levels, Minnehaha and 53rd Street

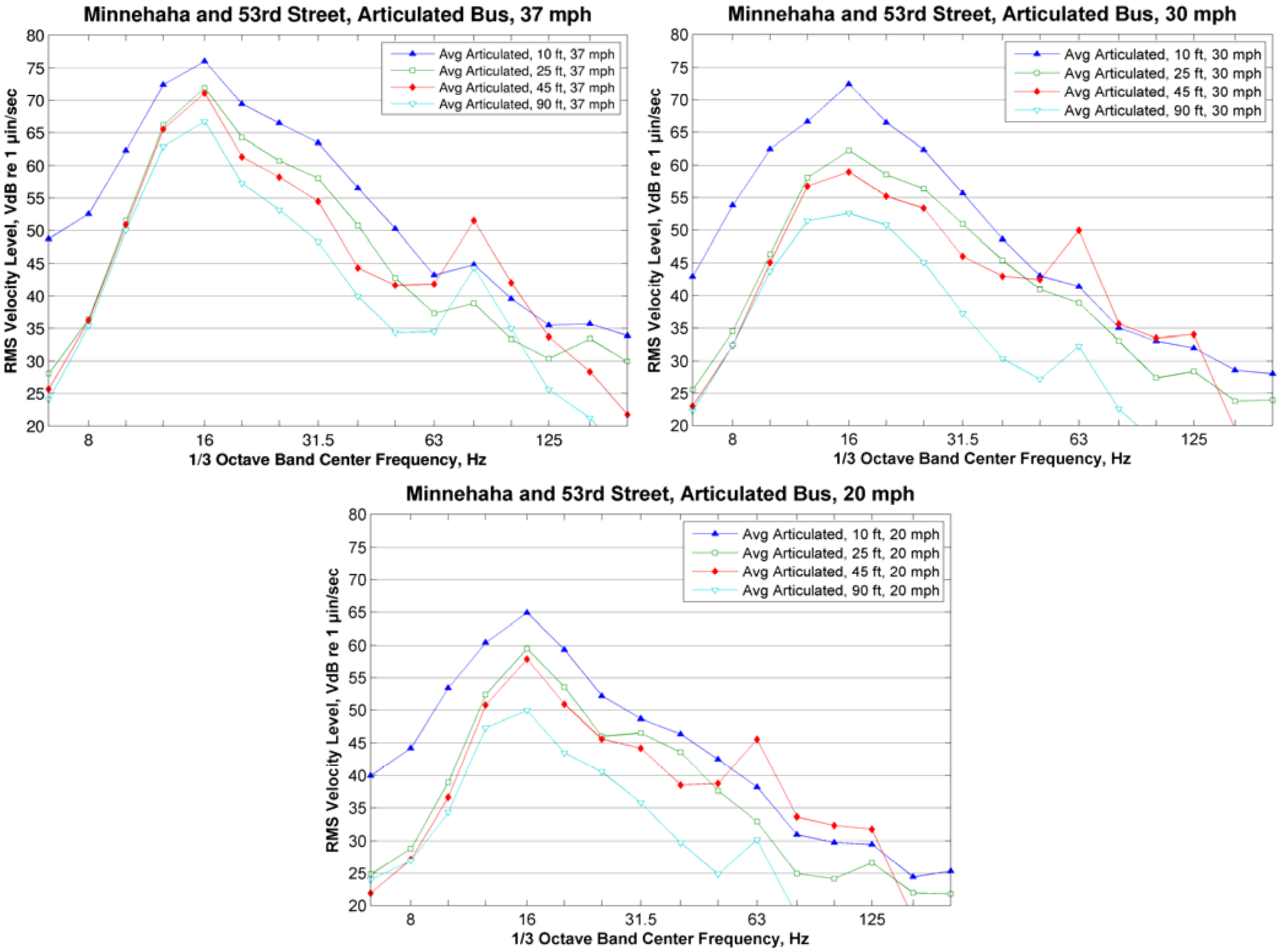


Figure 31: Average Articulated Bus Vibration Levels, Minnehaha and 53rd Street

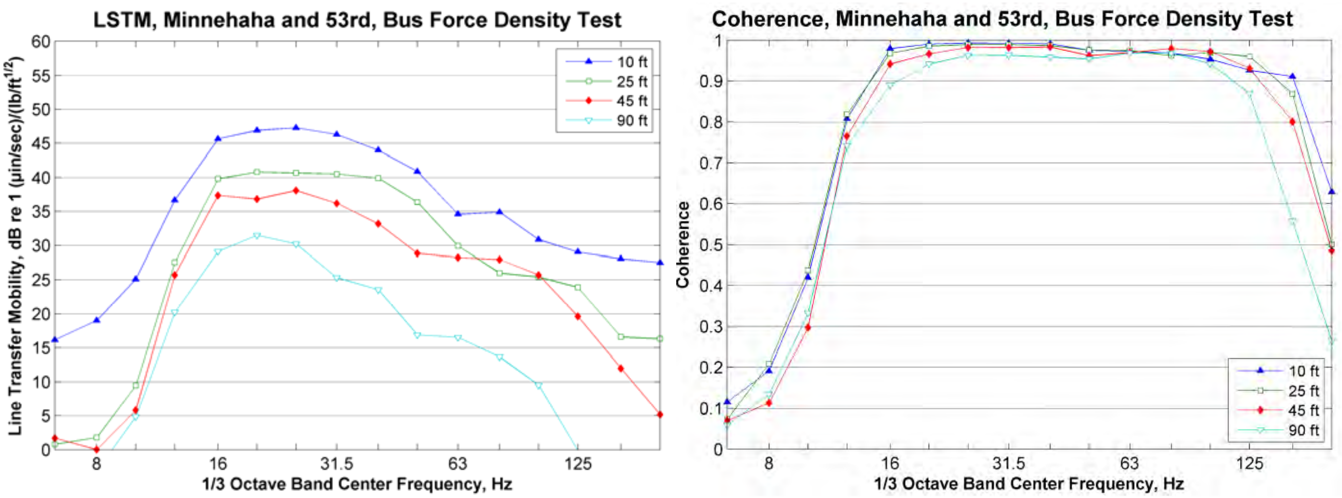


Figure 32: Line-Source Transfer Mobility, Bus FDL Test, Minnehaha & 53rd Street

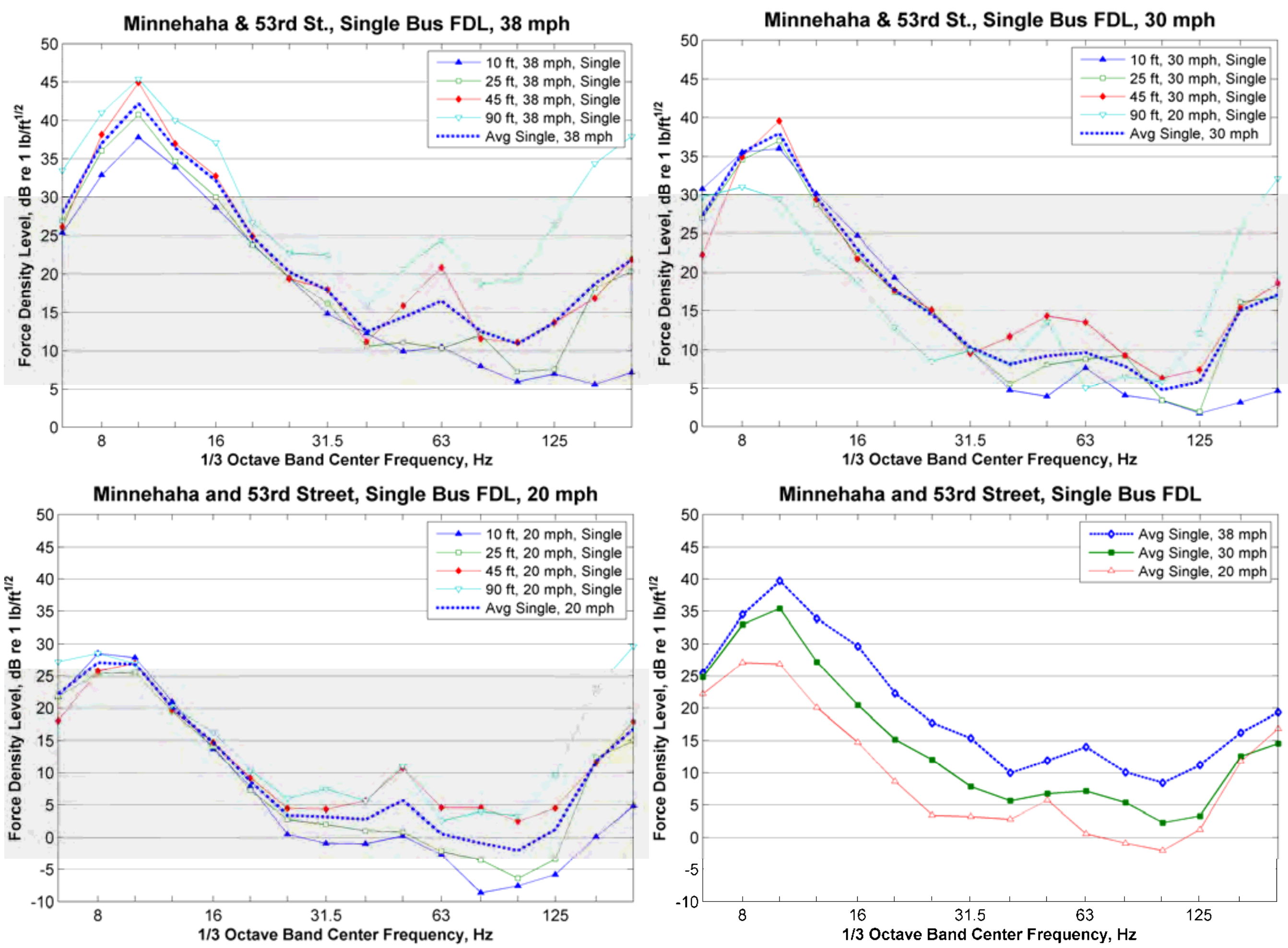


Figure 33: Single Bus Force Density Levels, Minnehaha and 53rd Street

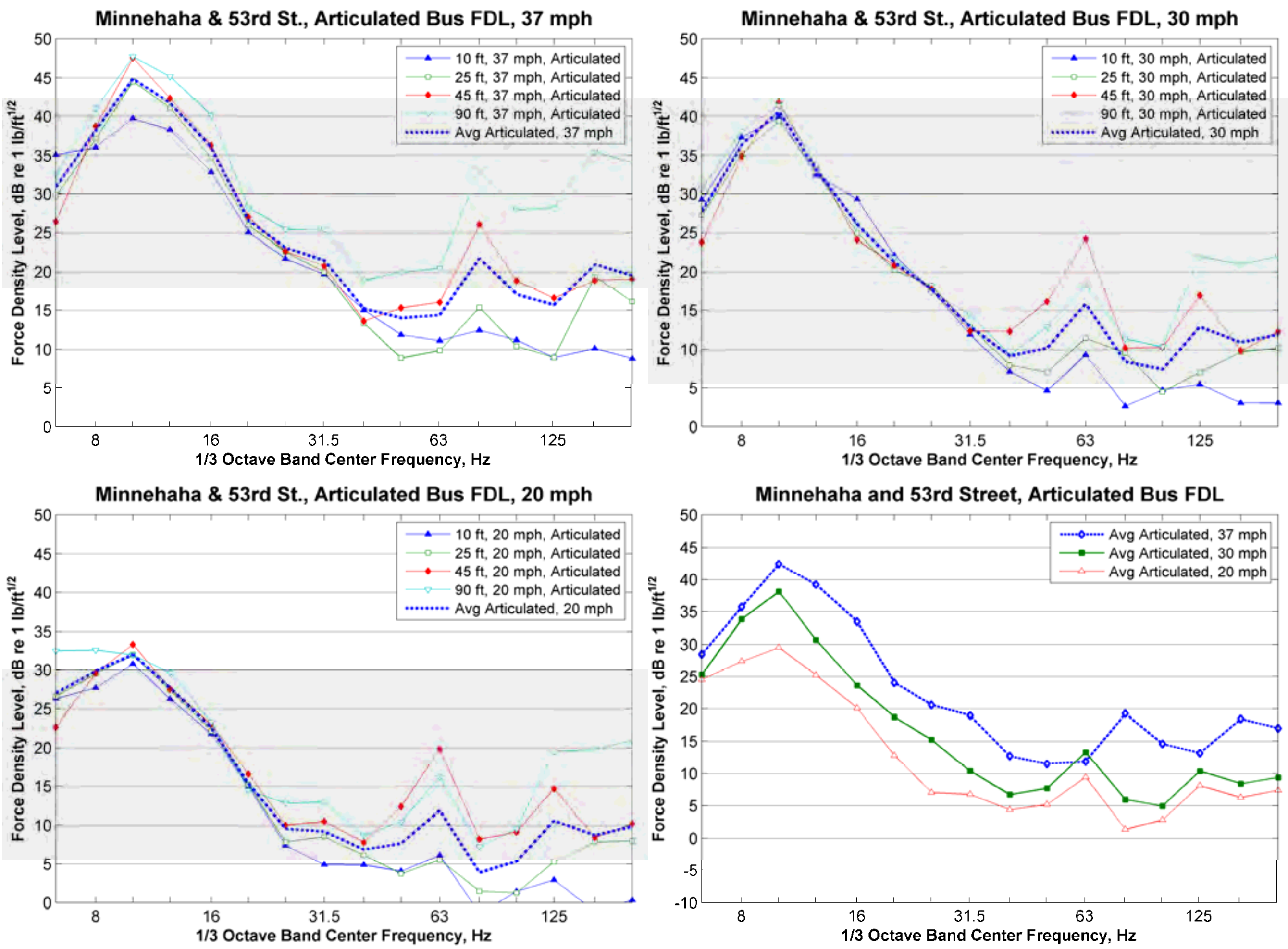


Figure 34: Articulated Bus Force Density Levels, Minnehaha and 53rd Street

5.7 Force Density Levels Used for Predictions

The FDL measurements at 24th Street and Hiawatha Boulevard (Test 1), 5th Street and Portland Avenue (Test 3), and Minnehaha Avenue and 53rd Street (Test 4), were used to develop the FDL curves that have been used for Central Corridor LRT vibration predictions. The steps in the analysis were:

Step 1: The 14 and 23 mph FDLs from Test 3 and Test 4 were combined by using the maximum level in each 1/3 octave band for the respective speeds. These two FDL curves along with the 33 mph FDL curve from Test 4 were used as the base FDL curves for the vibration predictions. The process of combining the curves is shown in Figure 35. The red line with solid squares is the 23 mph FDL from 5th Street and Portland (Test 3), the green line with open diamonds is the FDL from Minnehaha and 53rd (Test 4), and the black dashed line is the composite FDL used for the predictions. Also shown in Figure 35 is the FDL for ballast and tie track measured at 24th Street and Hiawatha Boulevard. Of interest is that the FDL for ballast and tie track shows notably different characteristics than the curves for embedded track. It is not clear what caused this difference – the FDL results from tests at ballast and tie and embedded track sections have been similar at other light rail systems, such as the Portland TriMet MAX light rail system. However, the embedded track measurements that formed the basis of the vibration predictions showed fairly good agreement with each other.

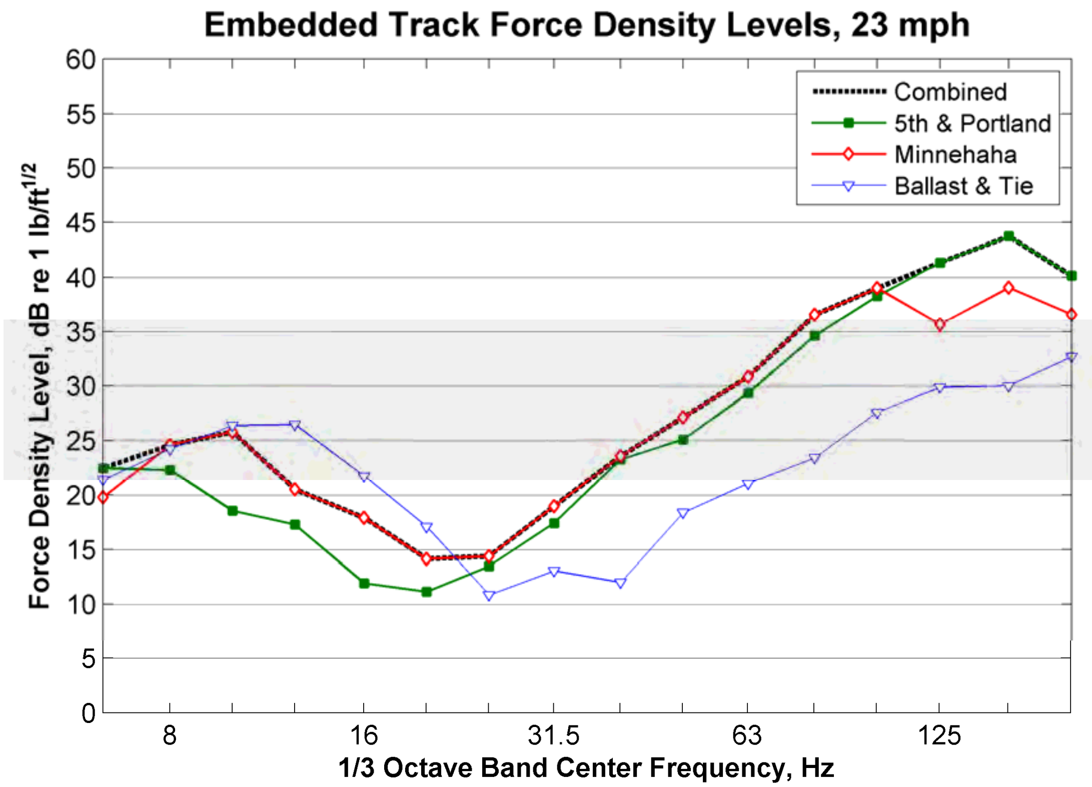


Figure 35: Measured and Composite FDL at 23 mph, Embedded Track

Step 2: The measured FDL from Minnehaha at 33 mph was extrapolated to 40 mph by adding the difference between the 33 and 40 mph FDLs measured at 24th Street.

Step 3: At this point there were FDL curves for speeds of 14, 23, 33 and 40 mph. The FDLs at intermediate speeds were estimated using linear interpolation based on log(speed).

Step 4: An adjustment factor +1.8 decibels was added to the FDL curves to account for the difference between Lmax and Leq. As discussed above, Leq was used to calculate the FDLs because it tends to be more stable than Lmax. The adjustment factor of 1.8 decibels is the average difference between overall Lmax and Leq for all train passbys at 24th Street and at Minnehaha and 5th and Portland. This adjustment is included in all the bus FDL graphs shown in this section.

The final FDL curves at speeds of 14 to 40 mph are shown in Figure 36. The equivalent curves for buses derived from the 53rd and Minnehaha tests are shown in Figure 37. The FDL curves are for predicting the Lmax vibration level.

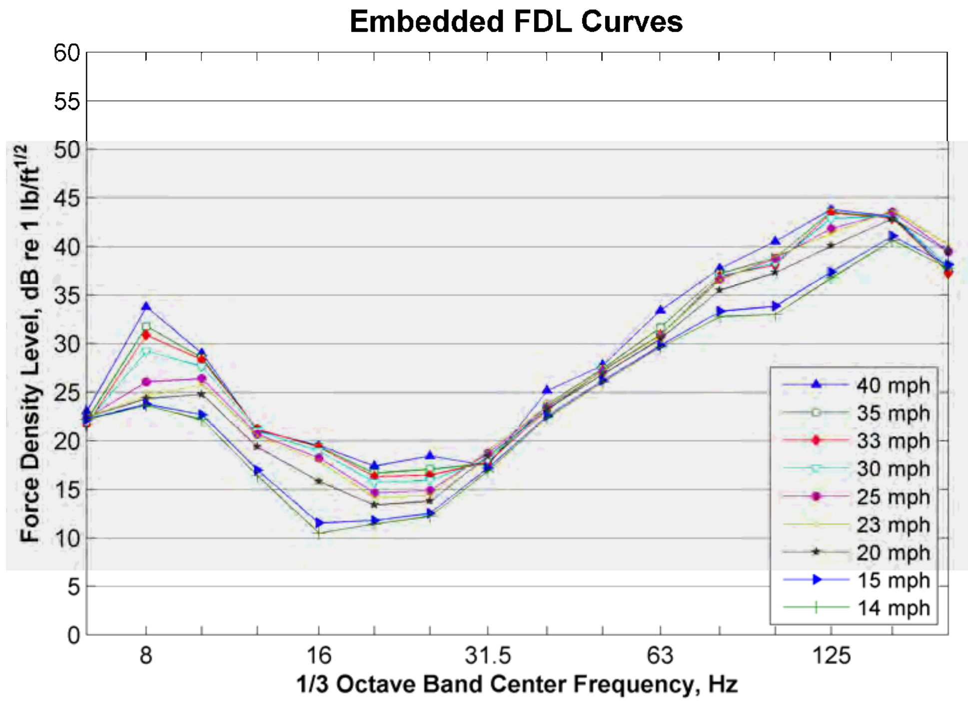


Figure 36: LRV FDL Curves Used for Predictions Lmax, Embedded Track

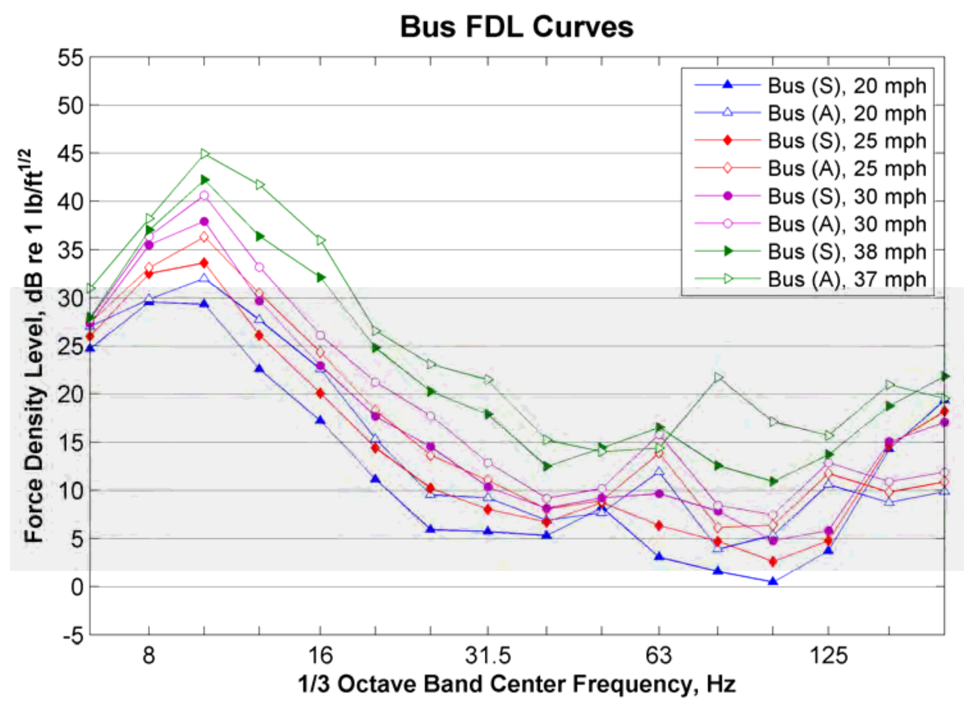


Figure 37: Bus FDL Curves Levels for Predicting Lmax

5.8 Difference between Bus and LRV Vibration

The primary purpose for testing bus vibration was to determine how the vibration from the light rail operations will compare to the existing ambient vibration from buses. The difference between the bus and LRV vibration is shown in Figure 38 and Figure 39. Figure 38 shows the bus and LRV FDL curves at similar speeds. It is clear from Figure 38 that bus vibration is higher than LRV vibration at frequencies lower than 25 to 30 Hz and that LRV vibration is substantially higher than bus vibration at frequencies above 40 Hz.

Figure 39 shows the articulated bus FDL and the LRV FDL with different levels of mitigation for the LRV vibration. The graph in the upper left is with no mitigation, the graph in the upper right is with high-resilience direct fixation track fasteners, and the bottom graph is with a 7 to 8 Hz floating slab. See Section 4 for a discussion of the vibration attenuation assumed with the different types of vibration mitigation. Figure 39 shows that:

- The vibration from LRV operations in the Central Corridor is expected to be lower than the vibration from articulated buses currently operating in the corridor (along Washington Avenue at the U of M and along University Avenue in Minneapolis and in St. Paul) at frequencies below 31.5 Hz.
- With the use of resilient fasteners to reduce vibration at frequencies greater than 20 Hz, the LRV vibration is expected to be lower or essentially equivalent to articulated bus vibration at frequencies of 50 Hz and lower.
- With the use of a 7 to 8 Hz floating slab, the LRV vibration would be lower than articulated bus vibration at frequencies of 63 Hz and lower and would be approximately equivalent to vibration from buses at higher frequencies.

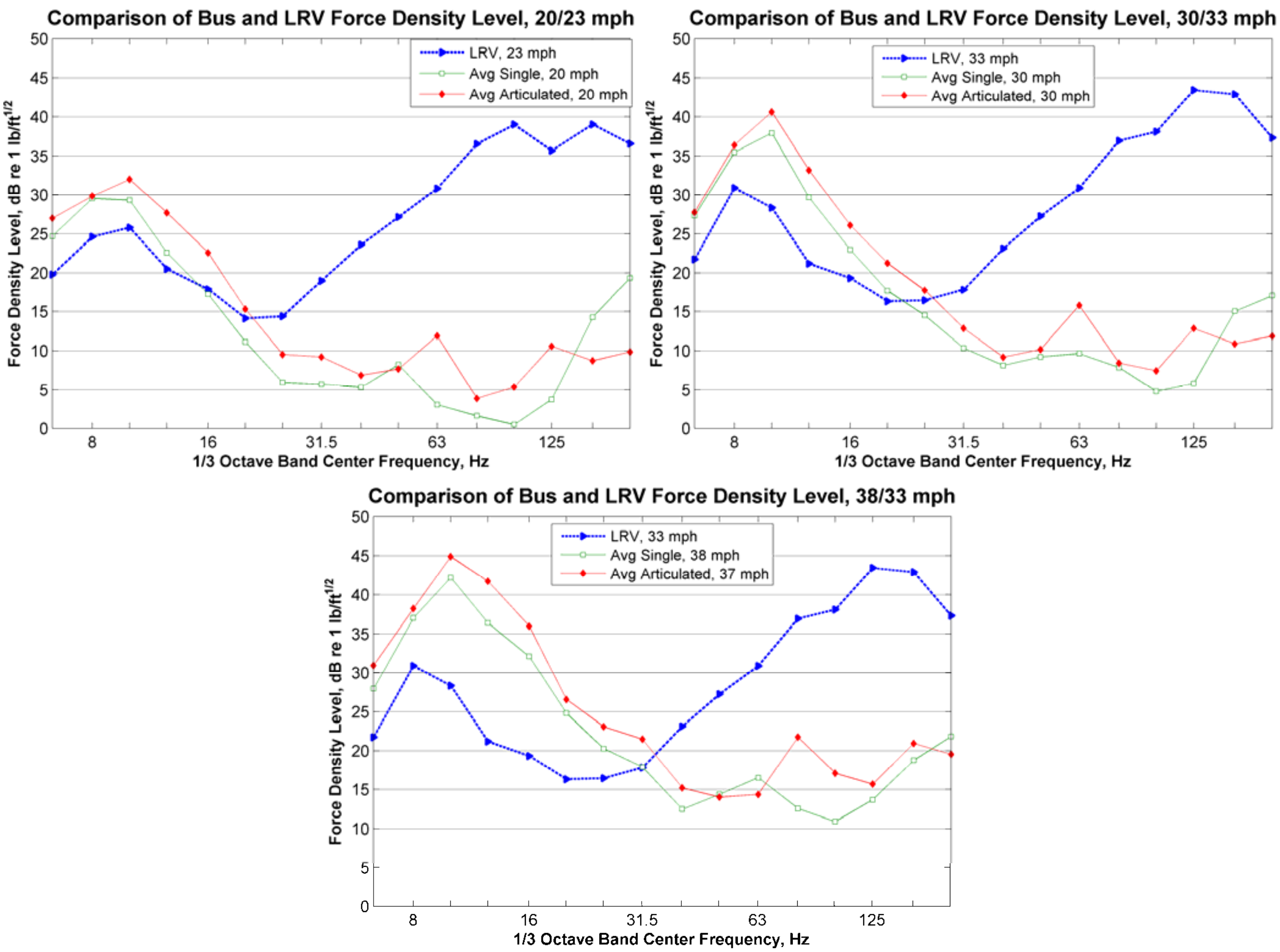


Figure 38: Comparison of Bus and LRV FDL Curves

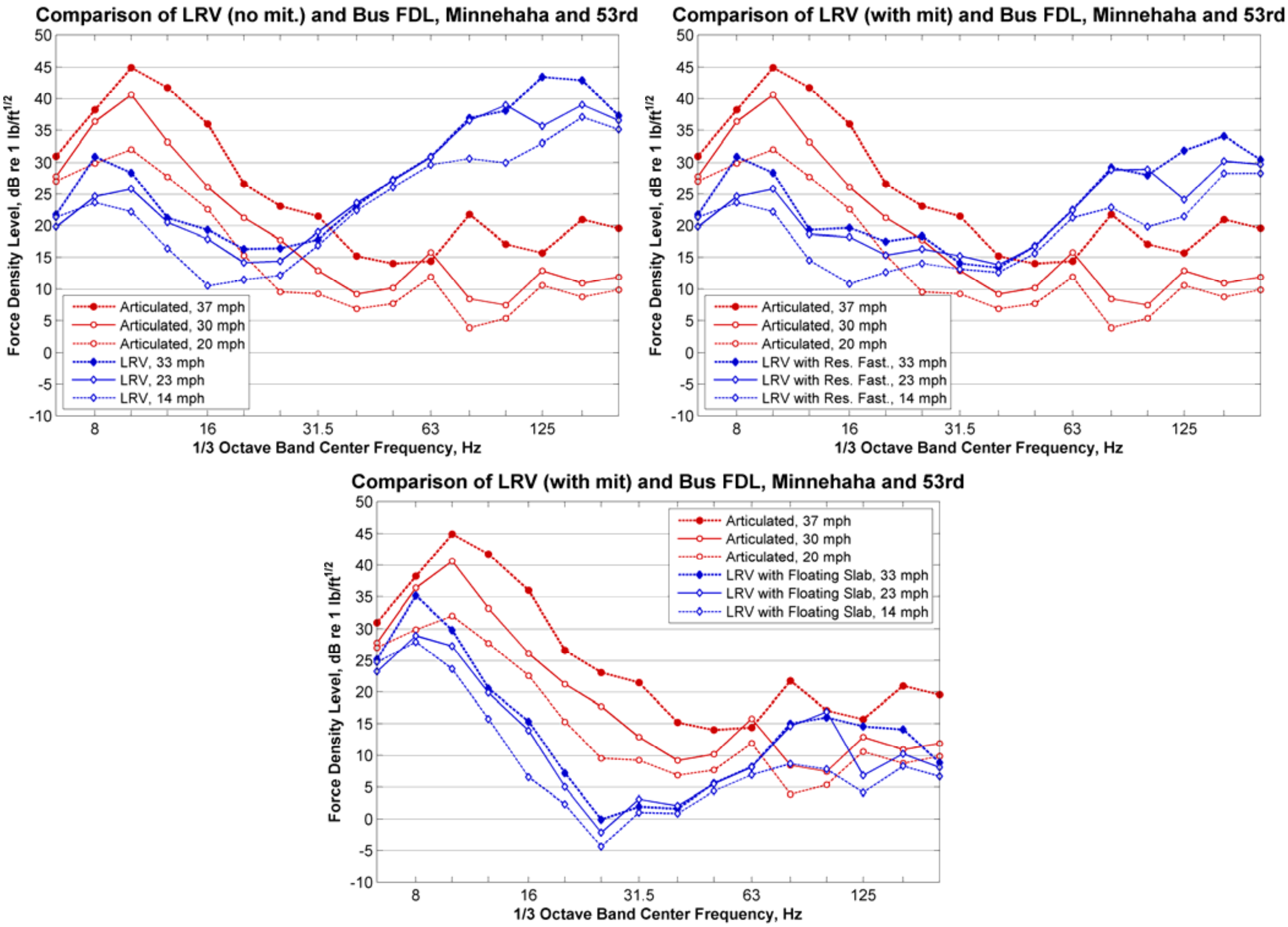


Figure 39: Comparison of Bus and LRV Force Density Curves, Minnehaha and 53rd

5.9 Vibration Difference between Two Car and Three Car Trains

The LRV vibration predictions in this analysis are all based on FDLs derived using a 150 ft long impact line with the impacts at 15 ft intervals. One question was how much vibration levels increase with a three car train compared to a two car train. To investigate this question we developed a simple spreadsheet model assuming a uniform attenuation of vibration level with distance for each individual point source. The two assumptions used to develop the model are:

1. Vibration attenuates from a point vibration source proportional to a constant times $\log_{10}$(distance). The constant was varied between 10 and 40.
2. The ground is completely homogeneous so that vibration attenuation with distance is the same at all of the impact positions.

The expected effect is shown in Figure 40. The horizontal axis is the distance from the tracks and the vertical axis is the increase in vibration expected from a three-car train compared to a two-car train.

Experience indicates that the vibration attenuation from a point vibration source is typically around 20*log(dist), although there can be substantial variation and the attenuation is often more of an S shape rather than a straight line. However, this model shows that the range of differences expected at different distances are:

25 ft:	0.0 to 0.8
50 ft:	0.2 to 1.2
100 ft:	0.8 to 1.5
200 ft:	1.4 to 1.8
400 ft:	1.7 to 1.9
800 ft:	1.9
1000 ft:	1.9

To ensure that the predictions are on the conservative side, the following adjustments can be used to estimate how much higher vibration levels will be during periods when three-car trains are likely to be in operation:

Less than 50 ft:	+0.5 dB
50 ft to 100 ft:	+1.0 dB
100 to 300 ft:	+1.5 dB
Greater than 300 ft:	+2.0 dB

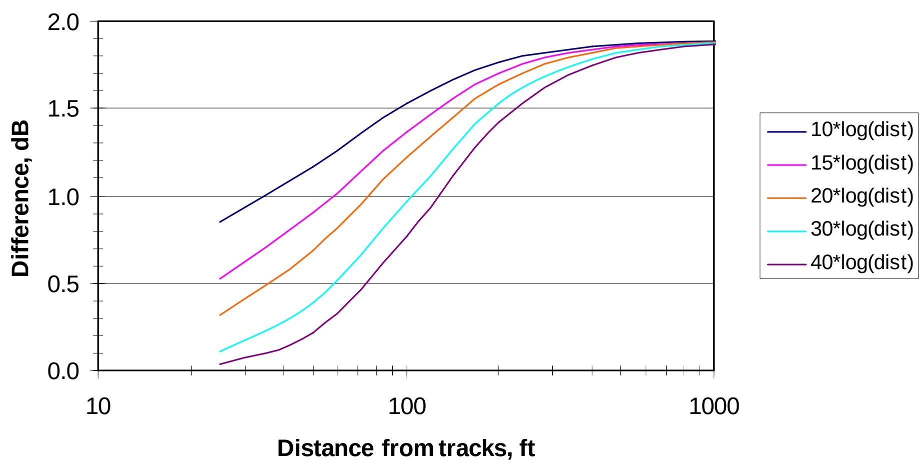


Figure 40: Expected Vibration Difference for a 3-Car Train Compared to a 2-Car Train

6. U OF M RESEARCH FACILITIES

Many of the U of M buildings along Washington Avenue house various types of vibration sensitive research equipment. A number of these facilities were selected for either vibration propagation testing or ambient vibration measurements. The impact lines for most of the vibration propagation tests were on the sidewalk of Washington Avenue at a distance of 2 to 3 feet from the curb. The measurements typically consisted of several accelerometers outside the building plus one or more accelerometers inside the building at the location of the sensitive equipment. Figure 41 shows the various sites on campus where impact testing was performed, and Figure 42 shows the locations of the ambient vibration measurements. Ambient vibration was also measured at all of the vibration propagation test sites. Table 8 provides an overview of all of the measurements performed at the U of M along with showing the overall ambient vibration levels and the predicted vibration levels inside each of the lab spaces. This table is discussed in more detail below.

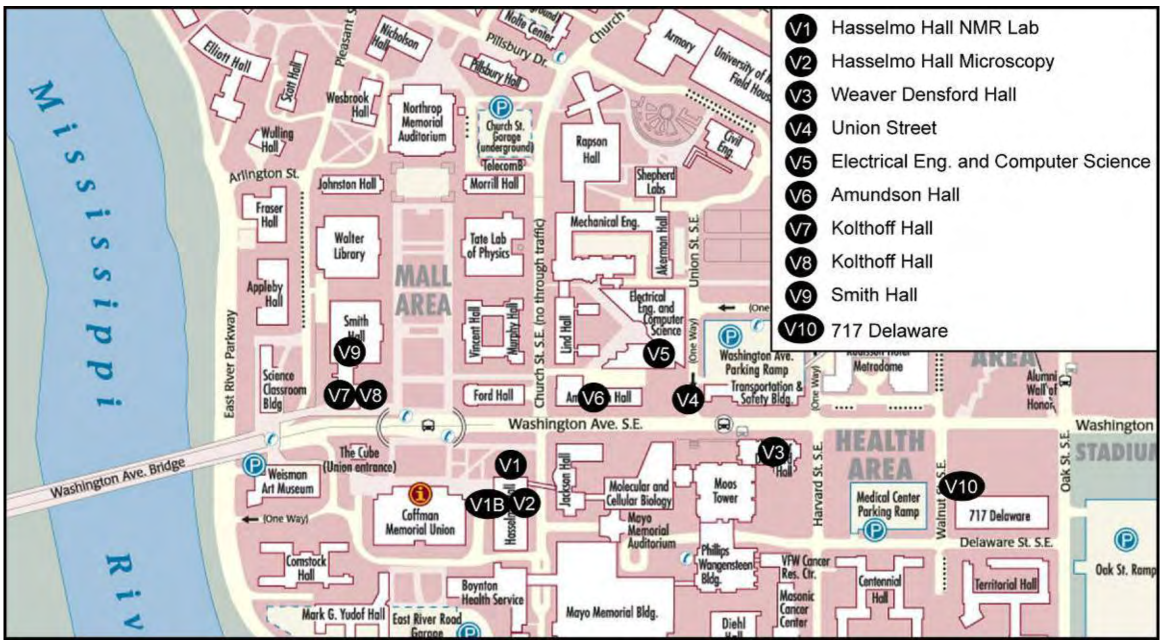


Figure 41: Vibration Propagation Test Sites on U of M Campus

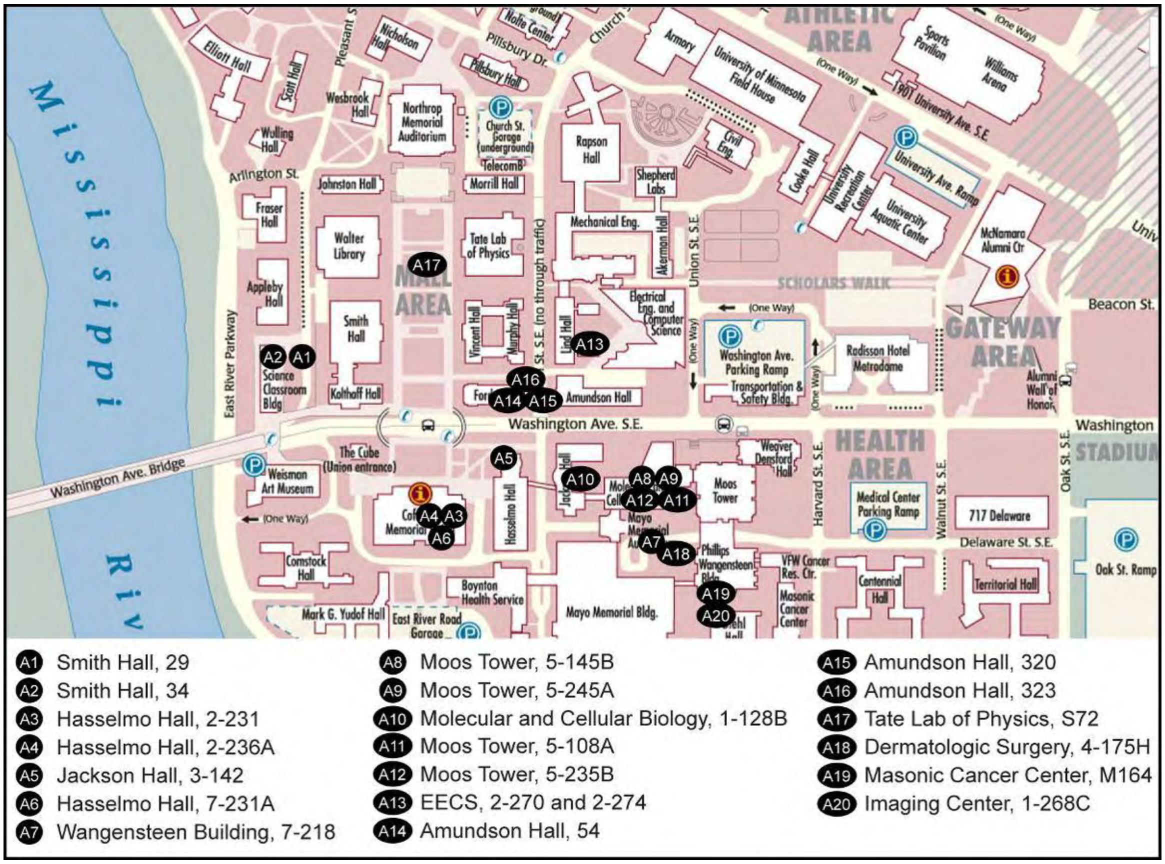


Figure 42: Ambient Vibration Measurement Sites on U of M Campus

Note that ambient vibration was also measured at all of the vibration propagation test sites in Figure 41.

The U of M resources where vibration propagation tests and ambient vibration measurements were performed were selected in consultation with U of M staff who are partnering with the Central Corridor Project Office (CCPO). A comprehensive inventory of vibration sensitive facilities was prepared based on a survey of the U of M staff. The process of identifying the locations where vibration tests would be performed consisted of identifying the most sensitive equipment jointly with CCPO staff, U of M staff, and Wilson, Ihrig and Associates, the vibration consultant engaged by the U of M. Thirteen of the labs that have equipment or experiments that are highly sensitive to vibration were selected for vibration propagation tests. Most of these facilities are located with 200 to 300 ft from Washington Avenue. Ambient vibration measurements were performed in the remainder of the labs. Overnight measurements of ambient vibration were performed in several of the labs to obtain a more comprehensive picture of the diurnal fluctuations of the ambient vibration.

As discussed below, for the labs closest to Washington Avenue the low frequency vibration was largely caused by traffic on Washington Avenue. This vibration would drop during the nighttime hours and increase in the early morning hours. Vibration at the labs farther from Washington Avenue tended to be relatively constant over the measurement period indicating the equipment in the building rather than human activity was responsible for most of the vibration.

At this point we are confident that (1) we have an exhaustive inventory of the vibration sensitive resources near Washington Avenue, (2) the measurements that have been performed to date are sufficient to define the vibration mitigation requirements, and (3) that the proposed vibration mitigation measures will adequately address potential problems with vibration interfering with U of M research.

The results of the LSTM measurements and the projected vibration levels from light rail vehicles are summarized below for each test. A train speed of 25 mph has been assumed for all of the vibration predictions on the U of M campus, consistent with the CCLRT Operations Plan. The predictions are for two-car trains. The difference between the vibration with two-car trains and three-car trains is discussed in Section 5.9. All of the graphs of predicted vibration levels are for two car trains. The discussions for each lab indicate how much higher the vibration would be with three-car trains. The predicted overall vibration levels in Table 8 are for three-car trains.

The approach taken to estimate levels of LRV vibration inside the laboratories where ambient vibration was measured but no vibration propagation tests were performed was to use the closest outdoor measurement plus an adjustment of -10 decibels to account for the reduction as vibration propagates from the ground, through the building structure, and into the laboratory space. The 10 decibel adjustment is based on the outdoor-to-indoor attenuation measured in the vibration propagation tests. Figure 43 shows the differences for four of the LSTM tests. The curves that the data in Figure 43 are derived from and the coherences are given in Appendix B. The left graph in Figure 43 shows all of the data and the right graph shows only the data where the coherence exceeds a threshold. A threshold of 0.3 was used for all except the data from the basement of EECS. Even using a threshold of 0.15 for the EECS basement, there are only two points that exceed the threshold.

The conclusion drawn from Figure 43 is that 10 decibels is a conservative estimate of the outdoor-to-indoor vibration attenuation This is consistent with experience that outdoor-to-indoor attenuation tends to be greater for larger steel frame and concrete frame buildings. Factors that would tend to reduce the attenuation and can even lead to amplification include flexible floors caused by wide unsupported floor spans or undersized floor joists. Flexible floors can result in noticeable vibration as people walk across the floors. Conditions that lead to flexible floors were not observed at any of the U of M test locations.

The only location where the outdoor-to-indoor difference is less than 10 decibels is the Hasselmo NMR Lab. This lower attenuation may be the result of the lab structure being physically separated from the remainder of Hasselmo Hall.

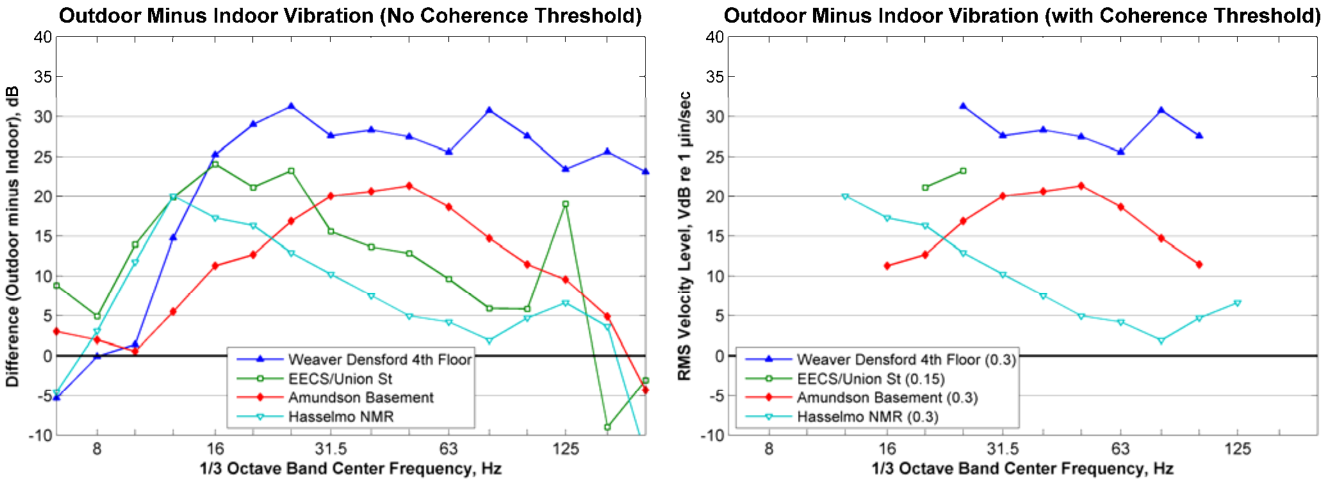


Figure 43: Difference between Outdoor and Indoor Vibration

The graph on the left shows the difference between the outdoor LSTM and the indoor LSTM. The graph on the right shows the same data with the values excluded when the coherence values for both LSTMs did not exceed a threshold. The thresholds used are the in parentheses in the legend.

The most important changes relevant to the U of M since the preliminary of this memorandum was prepared in July 2008 are:

1. Tests of the light rail vehicle force density levels have been performed at two locations on the Hiawatha Corridor. These measurements eliminated the confusion caused by the anomalous results measured at the embedded track section at 5th Street and 5th Avenue. A single force density level is now used for all of the vibration predictions.
2. Tests were performed to compare the vibration from buses and from light rail vehicles. The tests showed that ground vibration from buses is focused at frequencies below 30 Hz and that vibration from light rail vehicles is lower than bus vibration at these frequencies.
3. Additional vibration propagation tests were performed at three locations on the U of M campus and ambient vibration was measured in 20 labs on the campus with vibration sensitive equipment.

The analysis for all of the U of M labs where vibration testing was performed is discussed in the following sections. The analysis is based on the force density levels discussed in Section 5 for both buses and light rail vehicles.

The criteria used to identify lab spaces where LRV vibration could interfere with current research are:

1. No impact is predicted if the predicted LRV vibration is less than the ambient vibration. The ambient vibration level exceeded 1% of the time (L1%) is used for this comparison. L1% represents the typical maximum vibration from intermittent events. Because the vibration from each LRV train would last for only a few seconds, as long as the LRV vibration is less than the L1%, the future vibration environment would be equivalent to the existing vibration environment.
2. Where the predicted LRV vibration exceeds the ambient vibration but is at least 5 decibels below the VC-E curve (see Figure 2, Section 4), no impact was predicted.

3. The vibration levels at frequencies greater than 100 Hz were not considered in the impact assessment. This is because most vibration sensitive equipment is less sensitive at higher frequencies and many criteria for acceptable vibration environments are undefined above 80 Hz or 100 Hz.

Table 8 shows the ambient and predicted vibration levels for each of the U of M labs where vibration measurements were made. Shown in bold are the locations where impact is predicted and mitigation is recommended. The values in the Table 8 include the overall vibration levels and the maximum level in any 1/3 octave band. The VC ratings can be determined from the maximum 1/3 octave band level as follows:

Maximum 1/3 Octave Band Level	VC Rating
< 66	VC-A
< 60	VC-B
< 54	VC-C
< 48	VC-D
< 42	VC-E

A key conclusion of the measurements and analysis is that at frequencies below 30 Hz the vibration from light rail vehicles will be lower than the vibration that is currently generated by buses operating on Washington Avenue. The predictions of LRV vibration indicate that the vibration at frequencies above 30 Hz could adversely affect sensitive equipment in several labs that are close to Washington Avenue. The vibration reductions that can be achieved through the use of appropriate resilient fasteners should be sufficient to keep LRV at frequencies less than 100 Hz below or approximately equal to existing background vibration in most of the labs. The only exceptions are labs with levels of existing ambient vibration that are well below the VC-E curve.

Based on the measurements and the vibration analysis, there is potential that LRV vibration would interfere with existing research at Kolthoff Hall, Nils Hasselmo Hall, Amundson Hall, Jackson Hall, and Weaver Densford Hall. At all of these locations the predicted vibration levels can be reduced to the below the impact criteria discussed above through the use of and embedded track system that is constructed using high-resilience direct fixation rail fasteners. The locations of the predicted vibration impacts and the extent of the recommended mitigation are shown in Figure 44.

The following sections present the measured levels and the predictions of LRV vibration for each of the 30 different lab spaces where ambient vibration or LSTM measurements were performed.

Table 8: Summary of U of M Vibration Measurements and Predictions

Test/Location		Test Date	Test Type(1)	Existing Ambient(1) (VdB)		Predicted LRV(2) (VdB)		Recommend Mitigation?
				L1%	L10%	No Mitig'n	With Mitig'n(3)	
V1	**Nils Hasselmo Hall NMR Lab**	**9/30/2008**	**VP**	**53 (48)**	**50 (47)**	**60 (54)**	**51 (46)**	**Yes**
V1B	Nils Hasselmo Hall Crystallography Lab Rooms 1-269 and 1-272	9/30/2008	VP	58 (54) (4)	56 (53)(4)	43 (40) (4)	37 (32) (4)	No
V2	**Nils Hasselmo Hall Microscopy Equipment (Basement)**	**5/20/2008**	**VP**	**47 (42)**	**45 (41)**	**45 (43)**	**35 (31)**	**Yes(5)**

Test/Location		Test Date	Test Type(1)	Existing Ambient(1) (VdB)		Predicted LRV(2) (VdB)		Recommend Mitigation?
				L1%	L10%	No Mitig'n	With Mitig'n(3)	
V3	**Weaver Densford Hall (8th Flr)**	**5/20/2008**	**VP**	**58 (54)**	**56 (52)**	**48 (43)**	**43 (39)**	**Yes(6)**
V4	Union Street (Shepherd Labs Basement)	5/22/2008	VP/Amb.	53 (50)	51 (49)	26 (24) (7)	27 (25) (7)	No
V5	Electrical Engineering and Computer Science Microscopy Center (Inside Lab)	5/22/2008	VP	35 (30)	32 (26)	35 (33)	25 (20)	No
V6	**Amundson Hall (Room B22)**	**5/22/2008**	**VP**	**54 (49)**	**51 (46)**	**70 (65)**	**61 (57)**	**Yes**
V7	**Kolthoff Hall Labs 194/196)**	**5/22/2008**	**VP**	**56 (52)**	**53 (49)**	**55 (50)**	**47 (41)**	**Yes**
V8A	**Kolthoff Hall, Basement**	**9/30/2008**	**VP**	**59 (57)**	**58 (56)**	**58 (54)**	**50 (45)**	**Yes**
V8B	**Kolthoff Hall, 484 & 485**	**9/30/2008**	**VP**	**62 (59)**	**58 (54)**	**57 (52)**	**50 (45)**	**Yes**
V9	Smith S20 (Floor)	9/30/2008	VP	48 (42)	46 (40)	42 (35)	36 (31)	No
V10	717 Delaware NMR Lab (4th Floor)	10/1/2008	VP	55 (53)	53 (51)	40 (37)	33 (28)	No
A1	Smith 29	10/3/2008	Amb.	59 (56)	58 (55)	45 (40)	38 (32)	No
A2	Smith 34	9/30/2008	Amb.	72 (69)	69 (67)	45 (40)	38 (32)	No
A3	**Nils Hasselmo Hall, Room 2-231**	**9/30/2008**	**Amb.**	**58 (52)**	**56 (51)**	**45 (41)**	**38 (32)**	**Yes(5)**
A4	**Nils Hasselmo Hall, Room 2-236A**	**10/14/2008**	**Amb.**	**53 (49)**	**50 (47)**	**45 (41)**	**38 (32)**	**Yes(5)**
A5	**Jackson Hall, Room 3-142**	**10/14/2008**	**Amb.**	**61 (57)**	**59 (55)**	**49 (44)**	**43 (35)**	**Yes**
A6	Hasselmo Hall, Room 7-231A	10/14/2008	Amb.	62 (59)	60 (57)	45 (41)	38 (32)	No
A7	Philip Wangensteen Building Room 7-218	10/14/2008	Amb.	61 (56)	57 (54)	31 (26)	28 (25)	No
A8	Moos Tower Room 5-145B	10/14/2008	Amb.	62 (58)	58 (56)	44 (39)	38 (32)	No
A9	Moos Tower Room 5-245A	10/15/2008	Amb.	67 (63)	63 (61)	46 (41)	40 (33)	No
A10	Molecular and Cellular Biology Room 1-128B	10/15/2008	Amb.	38 (32)	36 (31)	53 (49)	46 (40)	No
A11	Moos Tower Room 5-108A	10/15/2008	Amb.	66 (61)	59 (54)	42 (38)	37 (31)	No
A12	Moos Tower Room 5-235B	10/15/2008	Amb.	62 (56)	58 (54)	42 (38)	37 (31)	No
A13	EECS Rooms 2-270 and R 2-274	10/15/2008	Amb.	63 (62)	61 (60)	40 (36)	36 (30)	No
A14	**Amundson Hall Room 54**	**10/15/2008**	**Amb.**	**59 (55)**	**54 (50)**	**63 (59)**	**55 (51)**	**Yes**
A15	**Amundson Hall Room 320**	**10/16/2008**	**Amb.**	**59 (55)**	**54 (50)**	**61 (55)**	**53 (47)**	**Yes**
A16	**Amundson Hall Room 323**	**10/16/2008**	**Amb.**	**60 (55)**	**58 (54)**	**58 (53)**	**50 (44)**	**Yes**
A17	Tate Lab of Physics, Room S72	10/16/2008	Amb.	41 (35)	37 (31)	30 (26)	25 (19)	No
A18	Dermatologic Surgery and Laser Center, Room 4-175H	10/16/2008	Amb.	60 (56)	56 (51)	29 (24)	27 (24)	No
A19	Masonic Cancer Center, Room M164	10/16/2008	Amb.	58 (54)	56 (52)	27 (22)	25 (22)	No

Test/Location	Test Date	Test Type[(1)]	Existing Ambient[(1)] (VdB)		Predicted LRV[(2)] (VdB)		Recommend Mitigation?
			L1%	L10%	No Mitig'n	With Mitig'n[(3)]	
A20 Philip Wangensteen Building Imaging Center	10/17/2008	Amb.	55 (50)	52 (48)	29 (24)	27 (24)	No

Notes:

1. Test types: VP = vibration propagation test to measure LSTM
   Amb. = separate measurement of ambient vibration
2. Overall levels are for frequency range of 20 to 100 Hz. Buses will dominate lower frequency vibration and the vibration sensitivity of most equipment is rarely defined above 100 Hz. The numbers in parentheses are the maximum level in any 1/3 octave band between 20 and 100 Hz. The maximum 1/3 octave band levels can be used to determine the VC ratings of the vibration. The predicted vibration levels are for three-car LRV trains.
3. As for the existing conditions, the overall levels are for frequency range of 20 to 100 Hz and the numbers in parentheses are the maximum level in any 1/3 octave band between 20 and 100 Hz.
4. The levels in the 100 Hz 1/3 octave band were excluded because of interference at that frequency from the lab equipment during the measurement.
5. Vibration impact is predicted only for three car LRV trains.
6. Vibration mitigation is recommended for Weaver Densford Hall because the predicted vibration levels at frequencies greater than 50 Hz are substantially higher than the ambient at these frequencies.
7. Predictions are for vibration outside Shepherd Lab and are based on extrapolations of the Union Street vibration propagation tests to 800 ft.

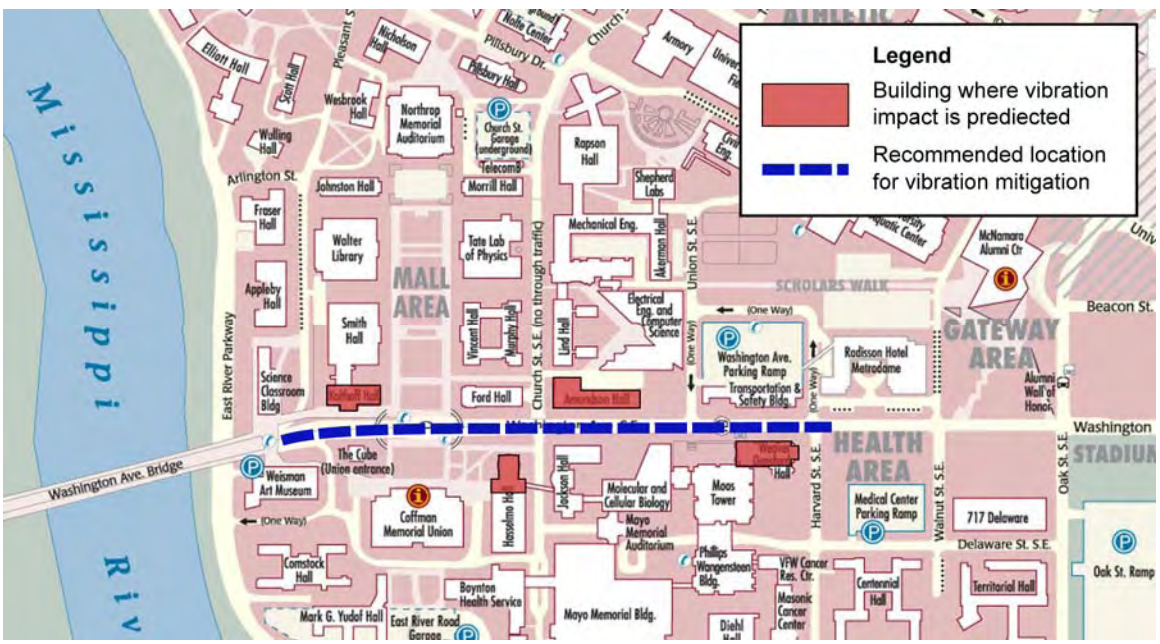


Figure 44: Predicted Vibration Impact on U of M Campus and Location of Vibration Mitigation

6.1 Nils Hasselmo Hall NMR, Test V1

The NMR Lab is located at the north end of the subbasement of Hasselmo Hall. The north wall of the lab is approximately 50 feet from the edge of Washington Avenue. Two vibration propagation test have been performed in the NMR Lab. The first was performed the afternoon of May 20, 2008 with the impact line located at the curb of the south sidewalk. In addition to the accelerometer located in the Lab, there were five accelerometers located at outdoor positions, four in a line perpendicular to Washington Avenue and the fifth located in the grass near the northwest corner of the building.

A second LSTM test was performed on September 30, 2008. The second test was performed at approximately 10:30 PM when background vibration from mechanical equipment and human activity in the building and from vehicular traffic on Washington Avenue was lower than it is during the day. In addition, traffic control was used during the second LSTM test to divert traffic from the eastbound, curb lane of Washington Avenue. This allowed locating the impact line in the roadway instead of on the sidewalk as had been necessary for the first LSTM test. After the LSTM test had been completed, a vibration monitor was installed to measure continuously the ambient vibration in the lab. The ambient vibration measurement started at 11:30 PM and continued until 3 PM the following day.

Measurement Results, Ambient Vibration

Figure 45 shows the overall vibration velocity levels measured in the lab. The top graph shows the overall vibration levels between 6.3 and 200 Hz and the bottom graph shows the levels over the 6.3 to 31.5 Hz frequency range. Figure 46 shows the same data for a single daytime hour (1 to 2 PM) and Figure 47 shows the same data for a nighttime hour (2 to 3 AM). Some observations from these figures are:

- The overall vibration levels typically ranged from 45 to 50 VdB over the entire measurement period. The average daytime levels are only 1 to 2 decibels greater than the average nighttime hours.
- There are intermittent peaks during the nighttime hours and frequent peaks during the daytime hours that appear to be caused by vehicular traffic on Washington Avenue.
- The difference between daytime and nighttime hours is substantially more pronounced when looking at the low-frequency levels. The average low-frequency levels during the nighttime hours are 5 to 8 decibels lower than the average daytime levels. This is an indication that the low-frequency vibration is generated by vehicular traffic on Washington Avenue and that the higher frequency components are caused by lab or building mechanical equipment that is operational at all times.
- Referring to the typical nighttime hour in Figure 46, it appears that four heavy vehicles passed during the hour. Each peak is distinct when looking just at the low frequencies.
- Referring to the typical daytime hour in Figure 47, it appears that between 30 and 40 heavy vehicles passed during the hour. We assume that there were predominantly buses because of the large number of buses that operate on Washington Avenue.
- There was a significant vibration event in the lab between 1 and 2 AM, possibly from a vacuum cleaner being operated close to the accelerometers. This high vibration level did not affect the overall results.
- We were told that some equipment was being moved within the lab on the morning of October 1. This activity does not appear to have had more than a marginal effect on the overall results.

Two accelerometers were located in the NMR Lab for the second set of LSTM tests and the ambient vibration measurements. Figure 48 shows a comparison of the vibration levels exceeded 1% of the time (the left graph) and the average vibration (Leq) for both the nighttime hours and the daytime hours. For this analysis, nighttime is defined at 11:30 PM to 5 AM and daytime is defined at 8:00 AM to 3:00 PM. The period between 5 and 8 AM is when the vibration levels transitioned from the nighttime to the daytime levels. The vibration levels for the two channels at all frequencies are within 1 to 2 decibels. Therefore, the other graphs of ambient vibration in this section only show Channel 1.

The 1/3 octave band spectra of the vibration exceeded different percentages of the time are shown in Figure 49. The vibration levels exceeded 1% of the time represent the typical maximum from intermittent events and the level exceeded 90% of the time represents the background vibration during periods when all intermittent vibration sources are quiescent. In this case, the 90% exceedance level basically represents the vibration when no traffic is passing on Washington Avenue and there is no activity inside the NMR Lab. The graphs in Figure 49 show that:

- Vibration levels at 80 Hz and higher are relatively constant and do not vary from daytime to nighttime.
- There is a peak in the vibration spectra in the 50 and 63 Hz 1/3 octave bands that fluctuates but has the same level during the daytime and nighttime hours. The consistency of this vibration between daytime and nighttime hours suggests that it is caused by mechanical equipment that cycles on and off.
- The vibration levels at frequencies of 40 Hz and lower are substantially lower during the nighttime hours. As discussed above, the primary source of vibration in this frequency range appears to be vehicular traffic on Washington Avenue. The lower nighttime levels reflect the lower traffic volumes during nighttime hours.

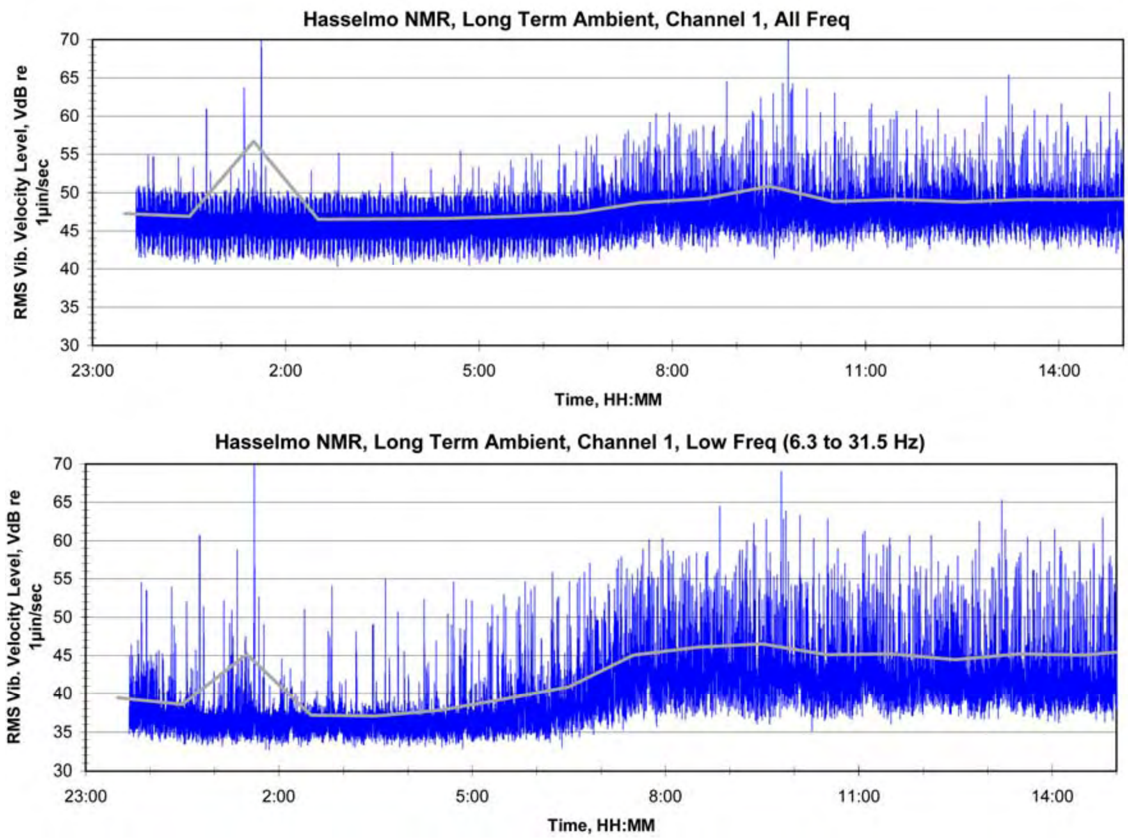
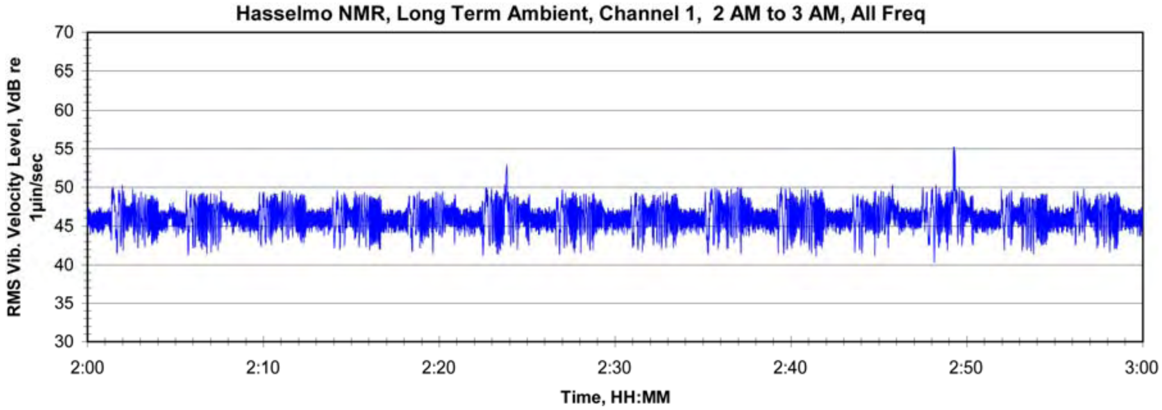


Figure 45: Ambient Vibration in Hasselmo NMR Lab

Measurement was performed from 11:30 PM September 30, 2008 to 3:00 PM October 1, 2008. The upper graph shows the overall vibration velocity level over the 6.3 to 200 Hz frequency range. The bottom graph shows the same data with the levels above the 31.5 Hz 1/3 octave band eliminated. The solid gray lines are the hourly average vibration levels (Leq) and the blue lines are the vibration velocity at 1 second intervals.



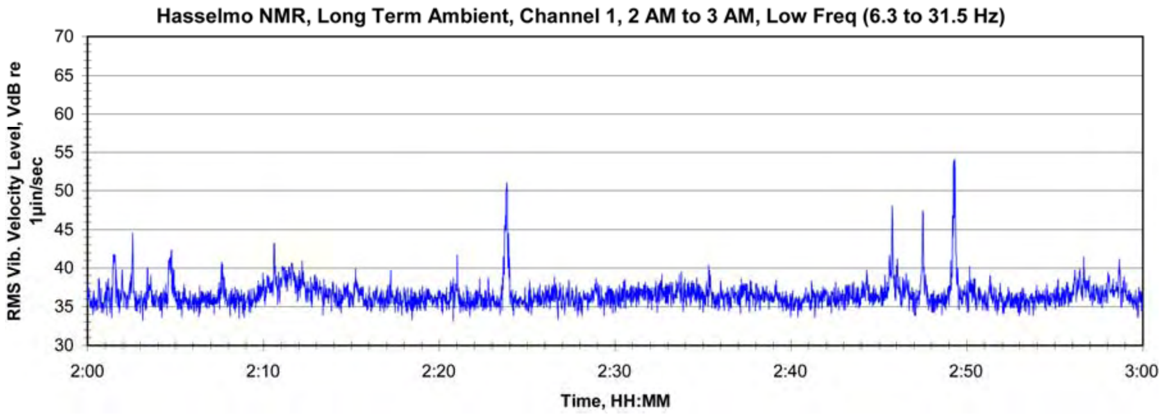


Figure 46: Ambient Vibration in Hasselmo NMR Lab, Typical Nighttime Hour
The upper graph shows the overall vibration velocity level at 1-second intervals. The bottom graph shows the same data with the levels above the 31.5 Hz 1/3 octave band eliminated.

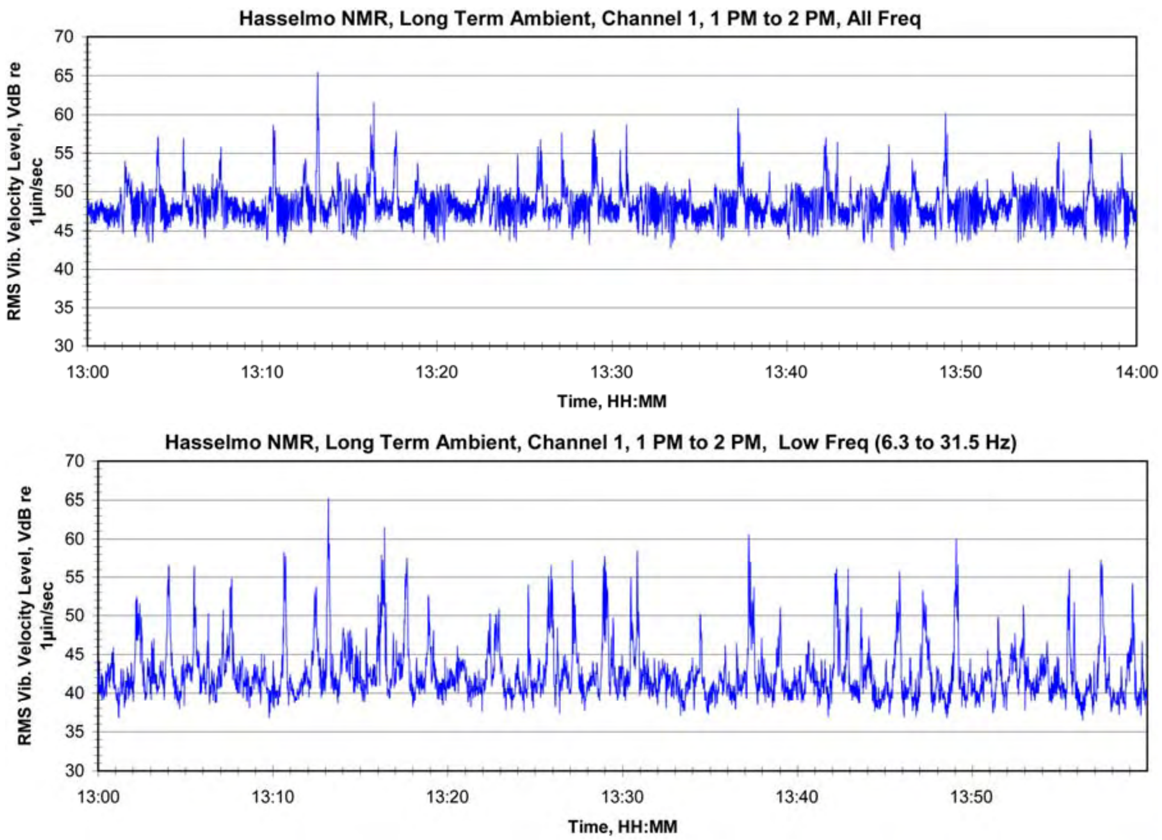


Figure 47: Ambient Vibration in Hasselmo NMR Lab, Typical Daytime Hour
The upper graph shows the overall vibration velocity level at 1-second intervals. The bottom graph shows the same data with the levels above the 31.5 Hz 1/3 octave band eliminated.

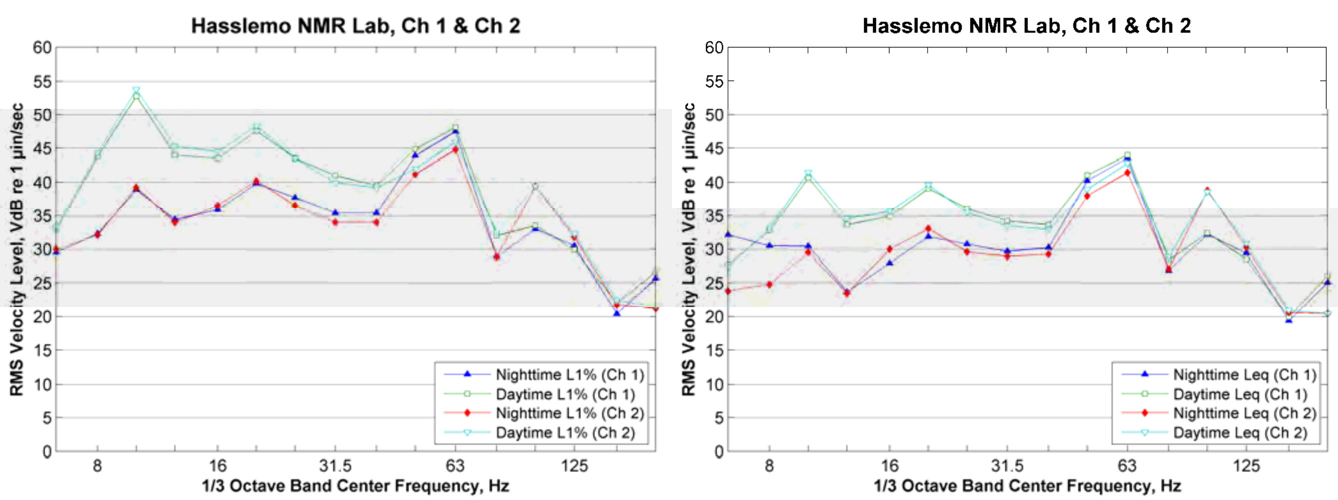


Figure 48: Comparison of Channel 1 and Channel 2 Ambient Vibration, Hasselmo NMR Lab
The left graph shows the spectra of the levels exceeded 1% of the time and the right graph shows the rms average (Leq) over the daytime and nighttime periods.

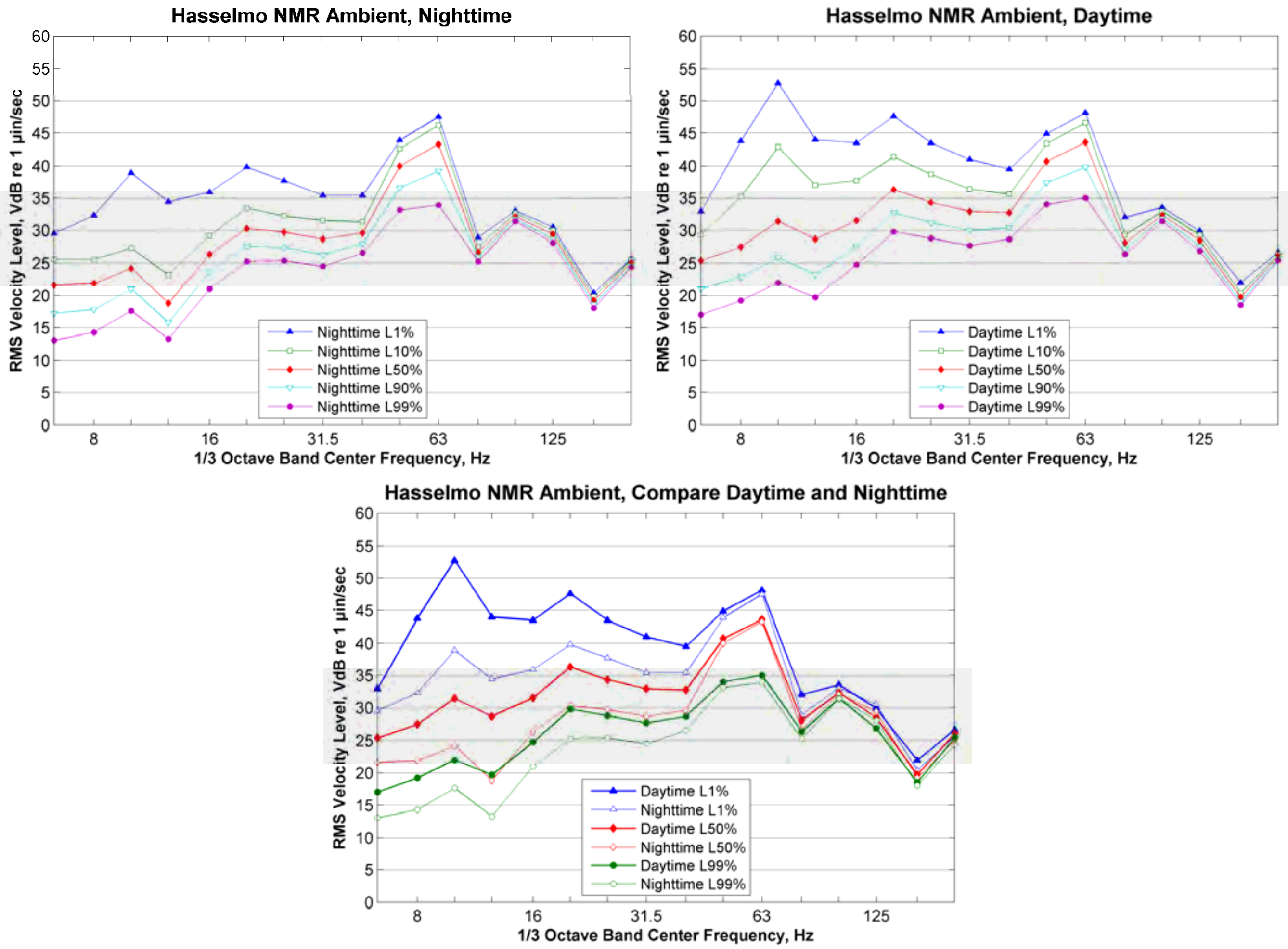


Figure 49: Daytime and Nighttime Exceedance Levels, Ambient Vibration in Hasselmo NMR Lab (Channel 1)

Measured Transfer Mobility and Vibration Predictions

The measured LSTM between the ground surface and the floor of the NMR Lab are shown in Figure 50. The coherence curves indicate that the LSTM results in the lab are valid over the 20 to 125 Hz frequency range. It is interesting that the LSTMs measured with an impact line at the centerline of the curb lane of Washington Avenue are 3 to 5 decibels lower than the LSTM measured with an impact line on sidewalk. This indicates slightly less efficient vibration propagation from the street to the lab than from the sidewalk to the lab.

The predicted vibration levels inside the NMR lab are shown in Figure 51. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 0.5 to 1 decibel higher for a 3-car consist. Figure 51 shows the predicted LRV vibration levels with no mitigation and with high resilience direct fixation fasteners as mitigation. Also shown are the predicted vibration levels for an articulated bus, the VC(E) and VC(D) vibration criteria curves, and the daytime ambient vibration levels exceeded 1% and 10% of the time inside the NMR Lab. Note that the predicted levels are the 1-second Lmax, which means that each train operation would be expected to generate vibration levels this high for a maximum of 1 second each time a train passes on the eastbound track.

The predicted bus vibration is consistent with the ambient vibration, up to 40 Hz. The predicted LRV vibration exceeds the VC(E) curve and the background vibration at 31.5 Hz and the VC(D) curve at 40 Hz. With the mitigation provided by resilient fasteners, the LRV vibration does not exceed the background vibration until the 80 Hz 1/3 octave band.

Mitigation

Specific criteria for acceptable vibration levels were not supplied for this facility, although the vibration limits shown in Figure 3 (page 12) from a Varian NMR installation manual were supplied. The conclusion from the predicted LRV vibration shown in Figure 51 is that the mitigation provided by high resilience direct fixation fasteners will result in vibration levels that are lower than, or consistent with, existing vibration levels. The only exception is at frequencies of 80 Hz and greater.

The predicted LRV vibration with and without vibration mitigation are shown in Figure 52. Also shown in Figure 52 is the NMR vibration limits from the Varian Manual (see Figure 3, page 12). As shown in Figure 52, the predicted LRV vibration with mitigation exceeds the Varian criterion curve and the existing background vibration in the 80 Hz, 100 Hz, 160 Hz and 200 Hz 1/3 octave bands.[*] The amount that the predictions exceed the Varian curve is as much as 10 decibels. Additional mitigation for these frequencies does not appear to be warranted because:

1. Ambient vibration in the 50 Hz and 63 Hz 1/3 octave bands exceeds the Varian criteria curve by approximately the same amount as the predicted LRV vibration does at higher frequencies.
2. The ambient in the 50 and 63 Hz 1/3 octave bands is likely to be caused by vacuum pumps or other equipment associated with the NRM equipment.
3. It is common for equipment sensitivity to vibration to decrease with increasing frequency. For example, the VC curves are not defined for frequencies greater than 80 Hz and the Varian vibration limits are not defined above 100 Hz.

Therefore, unless the NMR equipment has sensitivity to vibration at 80 Hz and higher, there is no reason to consider more extensive vibration mitigation measures, such as a floating slab or tire derived aggregate. Note that if a 7 to 10 Hz floating slab is considered and the buses will share the guideway, the vibration generated by buses in the 5 to 15 Hz range will be amplified. This is the peak frequency range for bus vibration and could result in a 5 to 10 decibel increase in the existing ambient vibration inside the NMR Lab at these frequencies.

[*] The Varian curve is not defined for frequencies greater than 100 Hz. If the Varian curve is extended as a straight line, the predicted LRV levels with mitigation exceed the extended curve at 160 and 200 Hz.

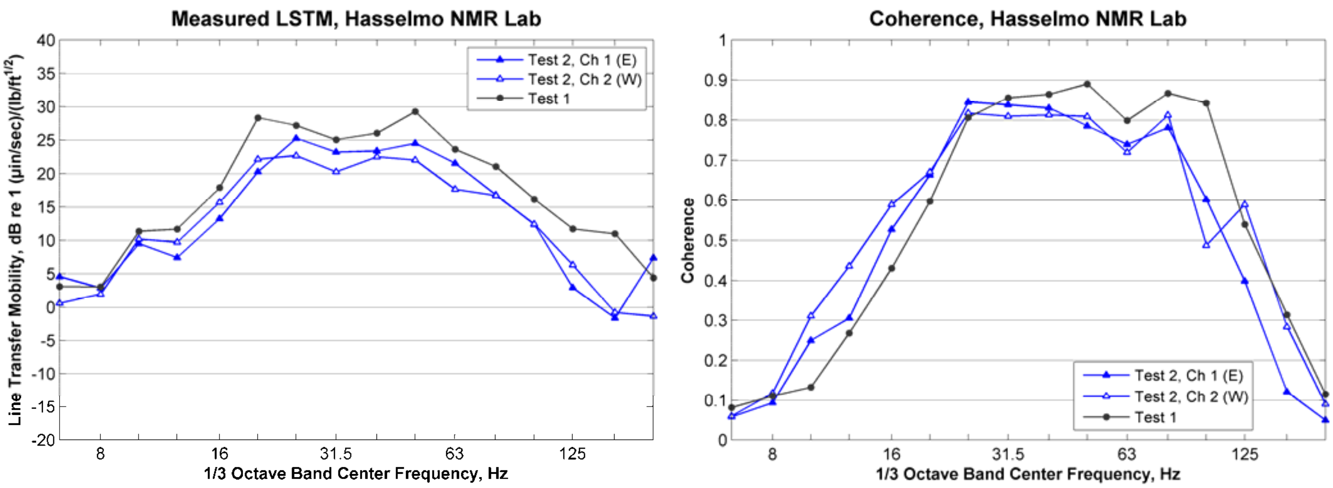


Figure 50: Measured LSTM, Hasselmo Test 1 (NMR Facility)
Test 1 was performed in May 2008 and Test 2 was performed in September 2008. Channel 1 for Test 2 was located on the east side of the lab and Channel 2 was located on the west side.

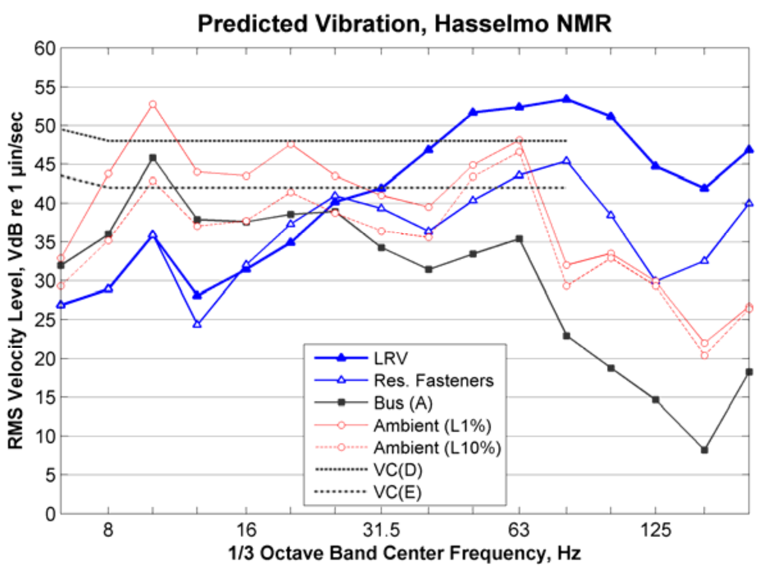


Figure 51: Predicted Train Vibration inside Hasselmo NMR Lab
The predictions use the LSTM from Test 2, Ch 1

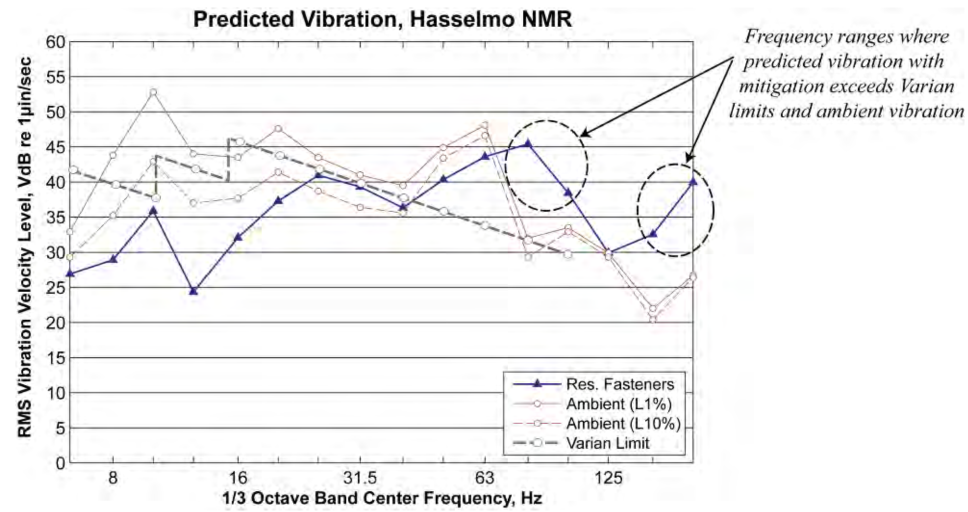


Figure 52: Predicted Train Vibration with Mitigation inside Hasselmo NMR Lab
This figure shows the same data as Figure 51 with the Varian vibration limits (See Section 3).

6.2 Nils Hasselmo Hall X-Ray Crystallography Lab, Rooms 1-269 and 1-272, Test V1B

Measurement Results

The x-ray crystallography lab is located in the basement of Hasselmo approximately 200 ft south of the NMR Lab. Propagation tests to Rooms 1-269 and 1-272 were performed on September 30, 2008 at the same time that the second test at the NMR Lab was performed. The measured LSTMs are shown in Figure 53. The coherence is close to zero for the entire frequency range indicating that the background vibration entirely masked the vibration pulses from the impacts. As a result, the LSTMs shown in Figure 53 represent an upper bound and the actual LSTMs are likely to be substantially lower at all frequencies.

Figure 54 shows the 1/3 octave band spectra of the ambient vibration measured inside rooms 1-269 and 1-272. These measurements were performed between 10:30 and 11:30 PM when there was little traffic on Washington Avenue or other nearby streets and activity within the building was a minimum. Therefore, it is likely that the measured vibration was largely due to mechanical equipment within the labs itself or in other nearby labs. The strong peak at 100 Hz in Room 1-272 is clearly from a piece of equipment operating within the room.

Predicted Vibration

Figure 55 shows the predicted vibration from LRV operations and buses in Rooms 1-269 and 1-272. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1.5 decibel higher for a 3-car consist. As stated above, the measured LSTMs were strongly affected by the ambient vibration and the curves in Figure 55 represent an upper bound for the vibration. In particular, the peak at 100 Hz for Room 1-272 is due to the ambient vibration at this frequency. The predicted bus vibration exceeding the ambient vibration in the 8 and 10 Hz 1/3 octave bands is a further indication that the predictions are an upper bound and that the actual vibration levels will be substantially lower.

The conclusion is that the LRV vibration will be below the existing ambient without any mitigation.

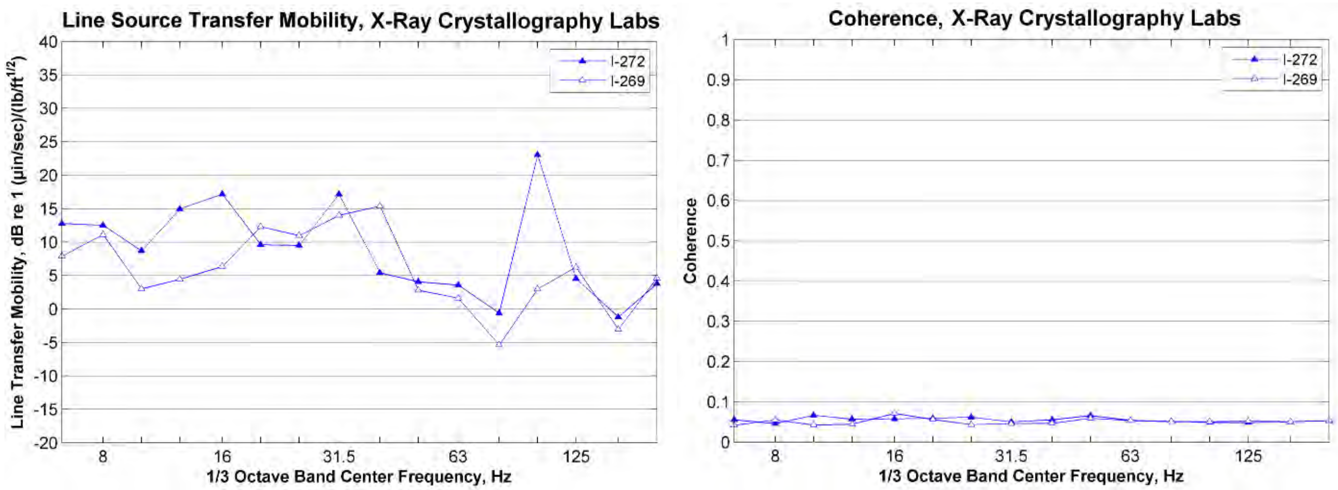


Figure 53: Measured Line Source Transfer Mobility, Hasselmo Rooms 1-272 and 1-269

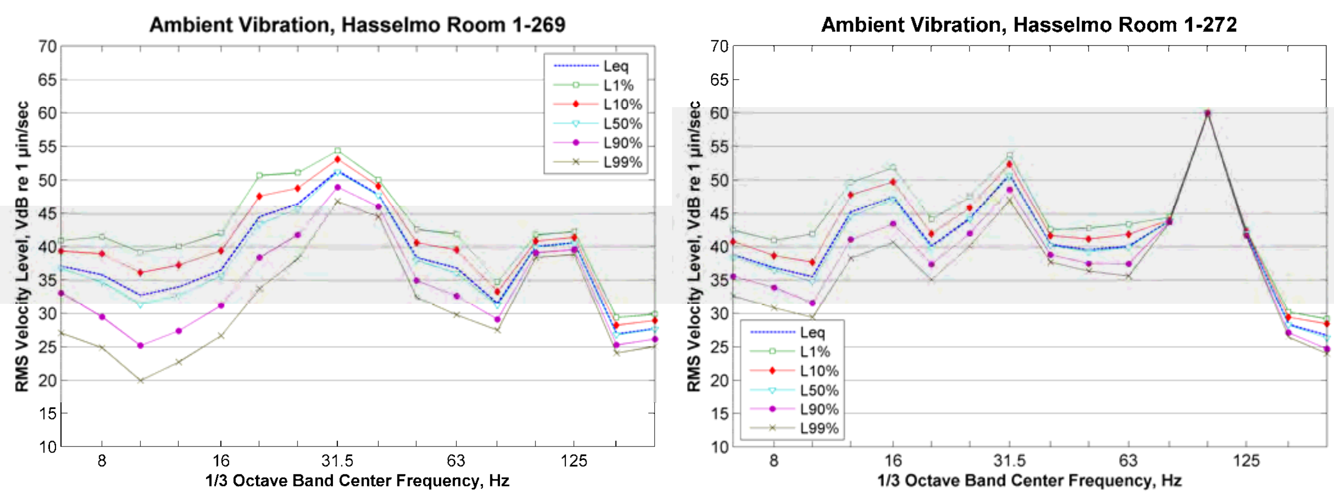


Figure 54: Ambient Vibration inside the X-Ray Crystallography Labs, Hasselmo Rooms 1-296 and 1-272

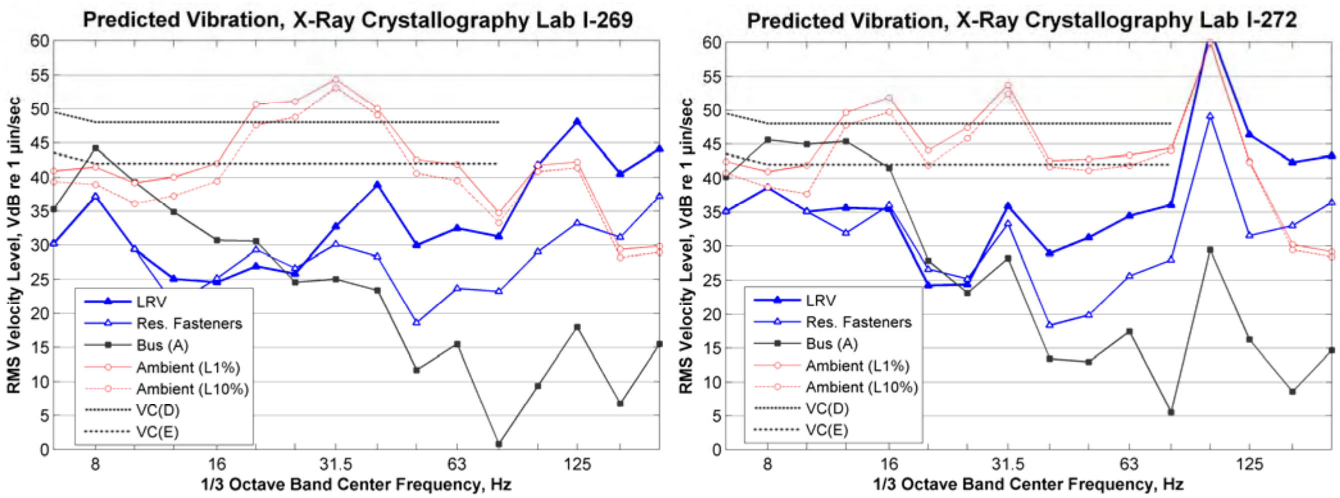


Figure 55: Predicted Vibration inside the X-Ray Crystallography Labs at Hasselmo

6.3 Nils Hasselmo Hall Microscopy Equipment, Test V2

This test location was in the basement of Nils Hasselmo Hall at a distance of approximately 300 feet south of Washington Avenue. The test was performed in May 2008. The vibration sensitive microscopy equipment is located on a concrete slab that is vibration isolated from the rest of the building. The measurements consisted of two accelerometers located at the surface, the third accelerometer was located at the microscopy center off of the isolated slab, and the fourth accelerometer was located on the isolated slab. The results of the LSTM tests are shown in Figure 56. There was very little response from the impacts at the two accelerometers located at the microscopy equipment. At best, there was a small response in the 20 to 30 Hz range; at all other frequencies the average coherence is essentially zero. As a result, the LSTMs for the microscopy center shown in Figure 56 represent an upper bound. Except in the 20 to 30 Hz range, the true LSTMs are likely to be substantially lower than the curves in Figure 56.

The predicted vibration levels and the measured background vibration are shown in Figure 57. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 2 decibels higher for a 3-car consist.

The predictions show that the train vibration will be at or below the ambient at all frequencies below 100 Hz. As noted above, the predictions above 100 Hz represent an upper bound. Vibration sensitivity of microscopy equipment is usually limited to frequencies below 80 Hz, and, as shown in Figure 4 (page 12), microscopy equipment is more sensitive to low frequencies than high frequencies. Therefore, no vibration mitigation is recommended for this equipment.

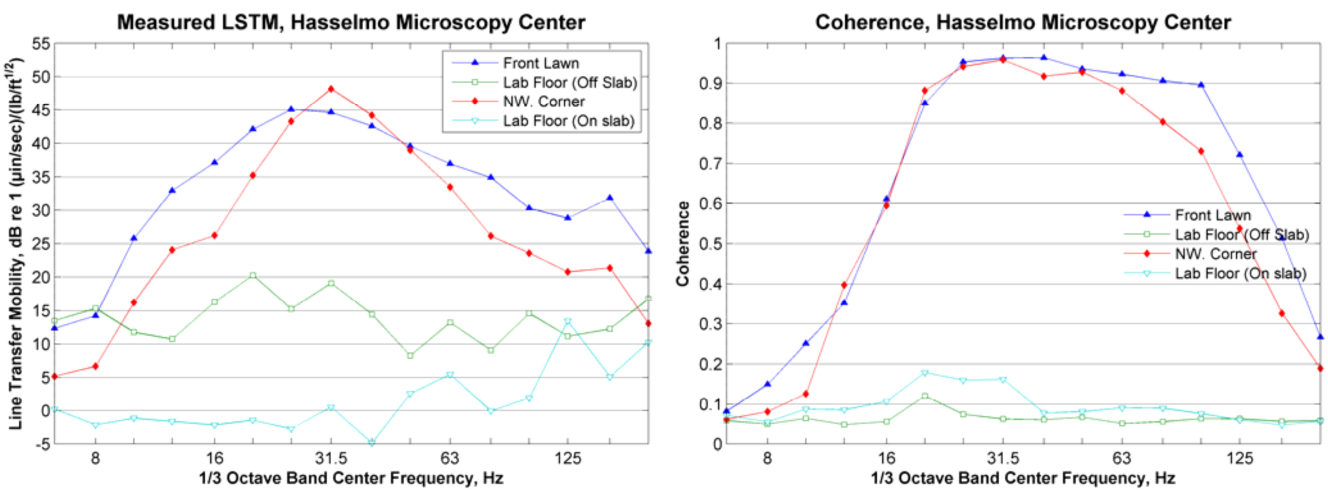


Figure 56: Measured Line Source Transfer Mobility, Hasselmo Microscopy Center

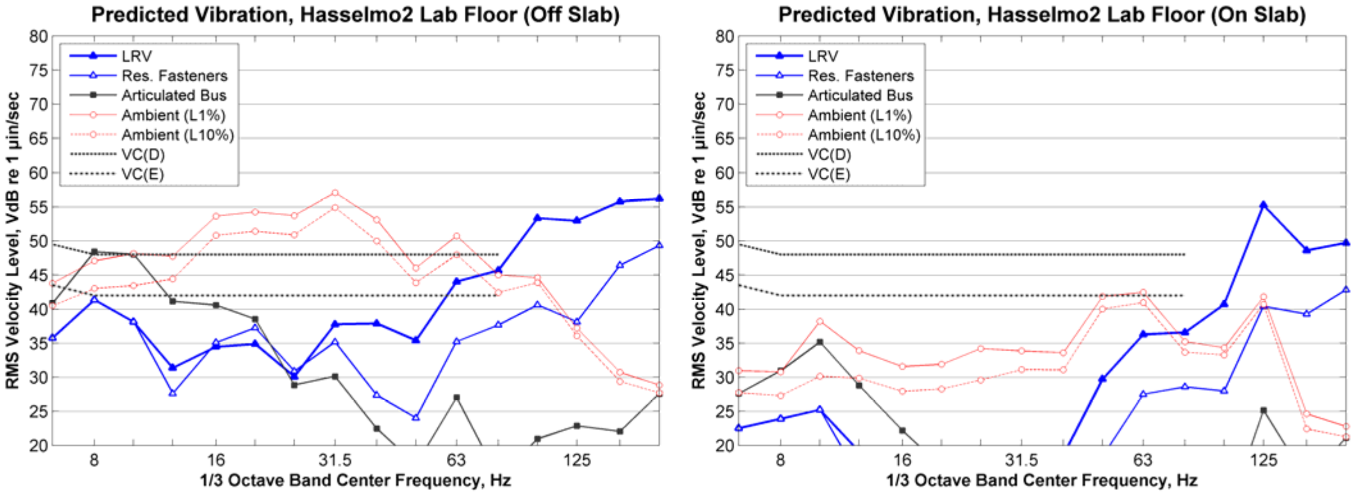


Figure 57: Predicted Train Vibration inside Hasselmo Microscopy Center

6.4 Weaver Densford Hall, Test V3

Measurement Results and Predictions

The measurements at Weaver-Densford were made from the sidewalk into floors 4 through 8 of the building. The fourth floor is about 10 feet higher than the sidewalk of Washington Avenue. The impact line was on the sidewalk on the south side of Washington Avenue. The first vibration channel was located on the sidewalk next to an emergency exit to the building. The LSTM results in Figure 58 show that there is a considerable attenuation of vibration as it transmits from the ground into the building. The largest difference is in the 20 to 40 Hz range where the outdoor LSTM is 30 to 35 decibels lower than the indoor LSTMs. This is an indication that the indoor vibration is largely uncoupled from the outdoor vibration.

The right graph in Figure 58 shows the coherence curves. The coherence indicates that the range of valid data is 30 to 60 Hz for the 4th floor with the valid frequency range decreasing with each floor. By the 8th floor, coherence is around 0.1, which indicates that the vibration pulse generated by the dropped weight was almost completely masked by the ambient vibration. In general the transfer mobilities decrease with each increasing floor, the primary exception is the 8th floor at frequencies below 20 Hz. In this frequency range the transfer mobility is controlled by the background vibration and the measurement results are an upper bound for the true transfer mobility.

Another point to note is that there was a peak in the background vibration in the 125 Hz 1/3 octave band on floors 5, 6 and 8. This shows up in the transfer mobilities for these floors but is not an indication of more efficient vibration transmission at 125 Hz.

The predicted vibration levels for each floor are shown in Figure 58. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 0.5 decibel higher for a 3-car consist. Except at very low frequencies, particularly the 10 Hz 1/3 octave band, and very high frequencies, the vibration levels are equivalent to or lower than the background vibration. The sensitive equipment of concern is located on the 8th floor. At this location the predicted vibration levels are above an extended VC-E curve at frequencies above 80 Hz.

Mitigation

To ensure that LRT-generated vibration at frequencies greater than 60 Hz does not interfere with vibration sensitive equipment located in Weaver Densford Hall, the use of high-resilience direct fixation rail fasteners is recommended. The predicted vibration levels are shown in Figure 59.

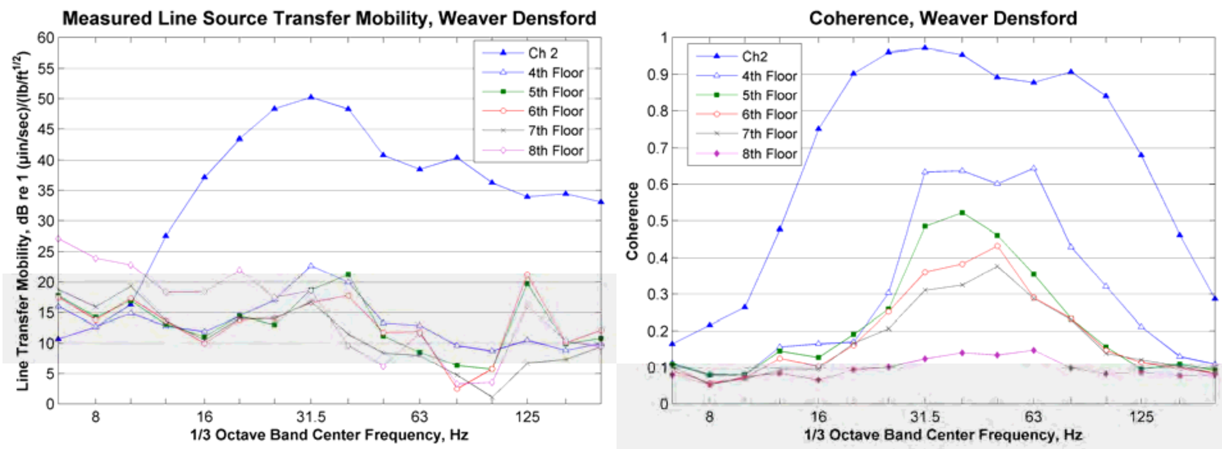


Figure 58: Measured Line Source Transfer Mobility, Weaver Densford Hall

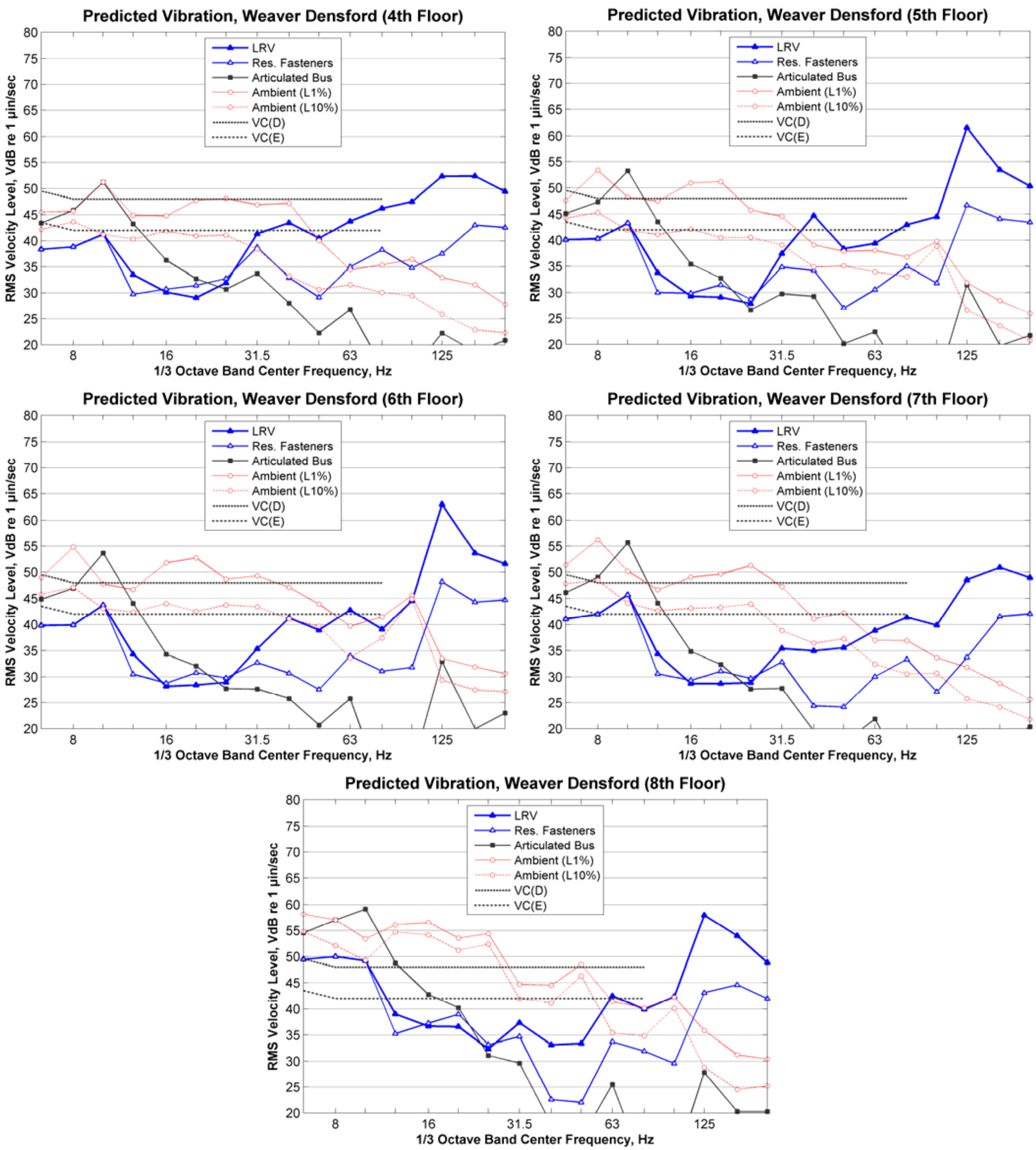


Figure 59: Predicted Train Vibration inside Weaver Densford Hall

6.5 Union Street (Shepherd Labs), Test V4

Measurement Results

Shepherd Labs contains transmission electron microscopes and scanning electron microscopes in the basement of the building that is very sensitive to vibration. The equipment is located on an isolated slab that was designed to minimize ambient vibration. The testing for Shepherd Labs included vibration propagation tests along Union Street perpendicular to Washington Avenue and ambient vibration measurements inside and just outside the lab that houses the most sensitive microscopy equipment.

The existing ambient was measured for 20 minutes on May 22, 2008 starting at 7:20 PM. The results of the ambient vibration measurements are shown in Figure 60. The Lxx% levels shown in Figure 60 are the values which the measured vibration levels exceeded for the specified percentage of the measurement period. For example, in a 1-hour period (3600 seconds), the L1% is the value that the measured vibration level exceeded for 36 seconds of the hour and L99% is the value that the measured vibration level exceeded for 3564 seconds. The right graph shows the results on the isolated slab and the left graph shows the results just outside the microscopy lab off of the isolated slab. Based on the measurements results, the isolated slab is reducing vibration levels over the 8 to 30 Hz frequency range by 10 to 15 decibels.

Because the Shepherd Lab building is approximately 800 ft from Union Street, it was not possible to directly measure the LSTM between Union Street and the Shepherd Labs microscopy center. In place of direct measurements, the LSTM was measured at distances of 25 to 300 ft from Washington Avenue and the best-fit curves of LSTM versus distance were used to extrapolate and estimate the LSTM at 800 ft. The measured LSTMs and the extrapolated LSTM at 800 ft are shown in Figure 61. The graph on the left shows the measured LSTMs and the extrapolated LSTM and the average coherence for the measurements are shown on the right. The coherence at 300 ft is close to zero except for frequencies between 16 and 50 Hz. At lower and higher frequencies the measured LSTM represents an upper bound of the actual LSTM. Similarly for the LSTM extrapolated to 800 ft, the values at low and high frequencies represent an upper bound estimate of the actual LSTM.

The predicted outdoor vibration at 300 ft and 800 ft along with the ambient vibration measured at 300 ft and in Shepherd Labs (off the isolated slab) are shown in Figure 62. The predictions are for a two-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 2 decibels higher for a three-car consist. The ambient vibration levels are the levels exceeded for 10 percent of the measurement period (L10%), which is the vibration level exceeded for 6 minutes out of an hour. The LRT vibration will occur for a maximum of a few seconds in any hour. Therefore, if LRT vibration will be lower than the existing L10, it is reasonable to conclude that the LRT vibration will not degrade the vibration environment.

The predictions represent the outdoor vibration levels. The other measurements performed into laboratory spaces at U of M buildings show that vibration levels attenuate at least 10 decibels as the vibration is transmitted from the ground into the building. The curves shown in Figure 62 show that:

- Over the frequency range of 16 to 100 Hz, the LRT vibration should be substantially lower than the existing ambient vibration.
- At frequencies lower than 31.5 Hz, vibration from buses and other vehicular traffic will exceed the vibration from LRV operations.
- At frequencies higher than 100 Hz, the predictions indicate that LRT vibration could exceed the ambient vibration by a small amount. The measured and extrapolated LSTMs are an upper

bound in this range and the actual vibration is expected to be substantially lower than the predictions..

Mitigation

The predictions being an upper bound along with the attenuation that will occur as the vibration propagates from the ground into the building structure are sufficient to conclude that LRT vibration inside Shepherd Labs will be lower than the existing ambient vibration. No vibration mitigation is required for Shepherd Labs.

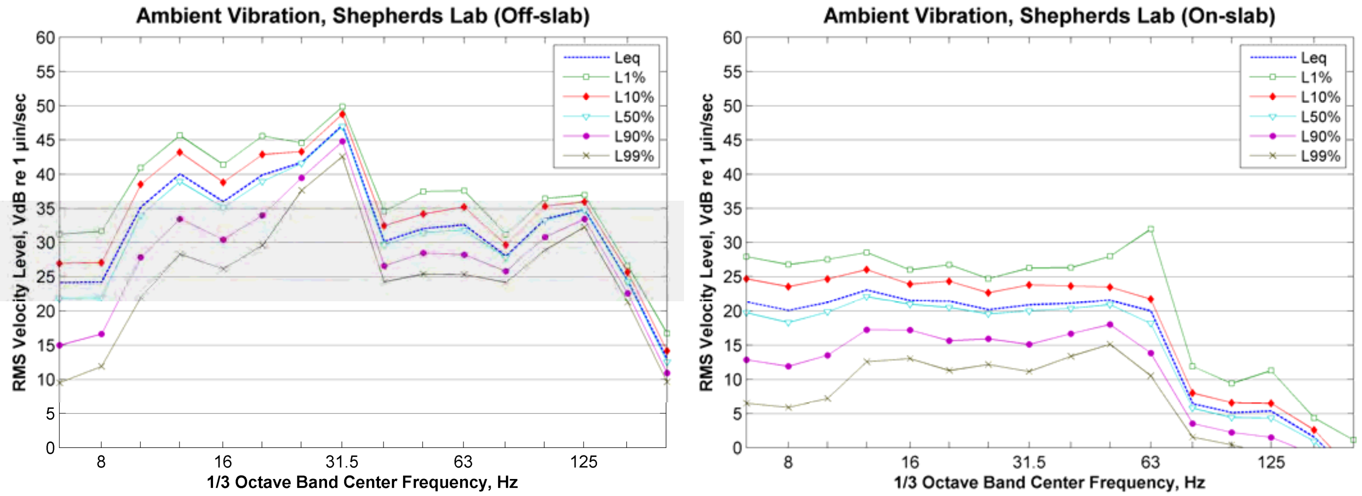


Figure 60: Ambient Vibration in Shepherd Labs Microscopy Center

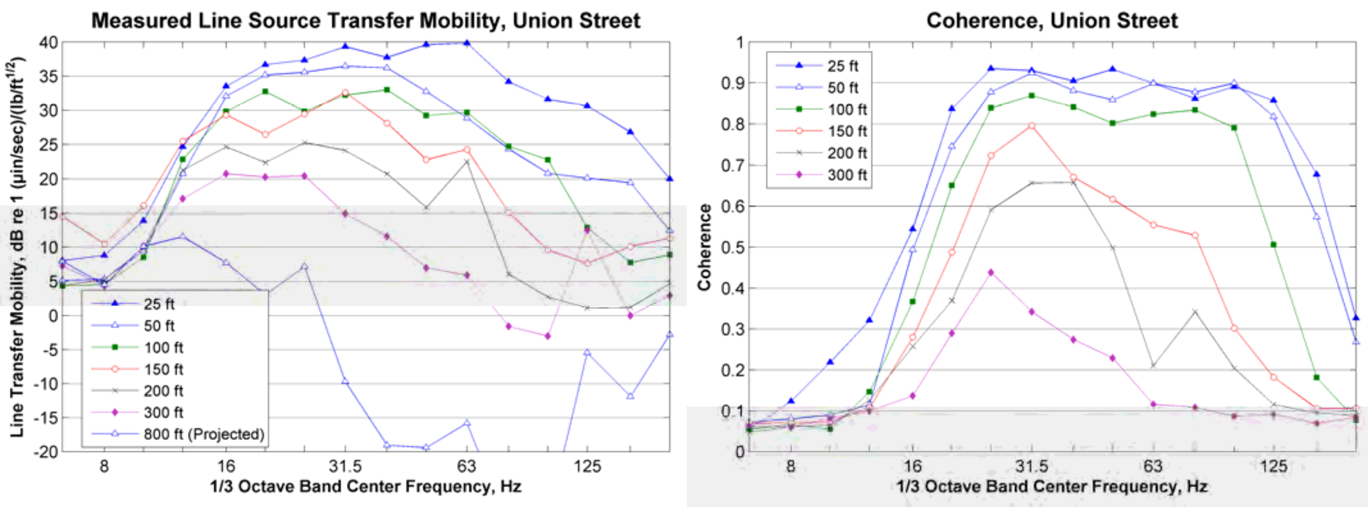


Figure 61: Measured Line Source Transfer Mobility, Union Street
The 800 ft LSTM has been extrapolated using the best-fit curves of the 25 to 300 ft data

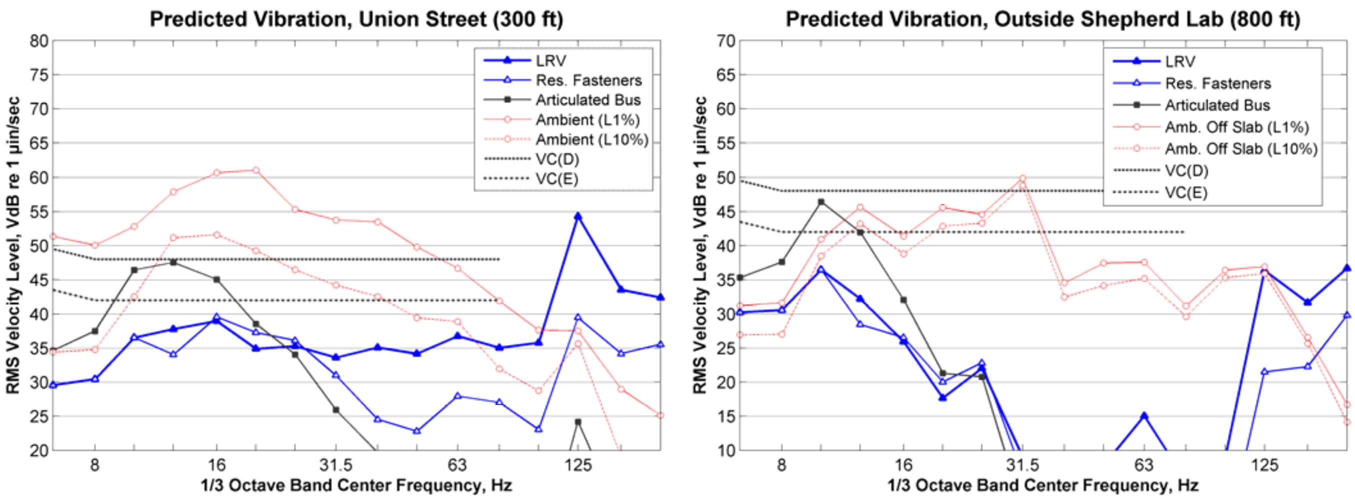


Figure 62: Predicted Vibration on Union Street and Outside Shepherd Labs

Notes for Figure 62:

a. The predicted vibration levels for Shepherd Lab are outside the building

b. The ambient at Shepherd Lab is the vibration measured off of the vibration isolation slab.

c. “300 ft” is predicted vibration at measurement position 300 ft from Union Street.

6.6 Electrical Engineering and Computer Science (EECS), Test V5

Measurement Results

The test in the EECS building was designed to predict vibration levels at the microscopy center in the basement of the building. The sensitive equipment included a Raith electron beam lithography system, an optical pattern generator and an atomic force microscope that are mounted on a separate slab that was designed to be vibration isolated from the remainder of the building. The impacts were performed along the north side of Washington Avenue approximately 3 feet from the curb. Two accelerometers were located inside EECS, one was placed off the isolated slab and the second was placed on the isolated slab. In addition, two accelerometers were located outside, one on the sidewalk 25-feet from the impact line and the second in the courtyard approximately 100-feet from the impact line.

The measured transfer mobility functions are shown in Figure 63. As can be seen, the transfer function from the street to the lab spaces is very low. Referring to the coherence plot on the right, it appears that the only valid transfer mobility data is in the 16 to 40 Hz range, and the coherence is marginal for this frequency range. This means that the measured transfer mobility functions are an upper bound of the true transfer mobility. The jump in the transfer mobility above 125 Hz was caused by background vibration and is not an indication of more efficient vibration propagation at these frequencies.

The predicted levels of train and bus vibration and the average background vibration are shown in Figure 64 for the measurements on and off of the isolated slab. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 2 decibels higher for a 3-car consist. The only frequency range where the predicted vibration levels exceed the average background vibration is at 100 Hz and above. The predicted bus vibration exceeds the measured ambient, which is further confirmation that the predicted levels are an upper bound.

Mitigation

Because the predicted vibration levels are well below the VC-E curve, no vibration mitigation is required. However, the use of resilient fasteners to control vibration at buildings closer to Washington Avenue will ensure the vibration from LRV operation is below the ambient at all frequencies.

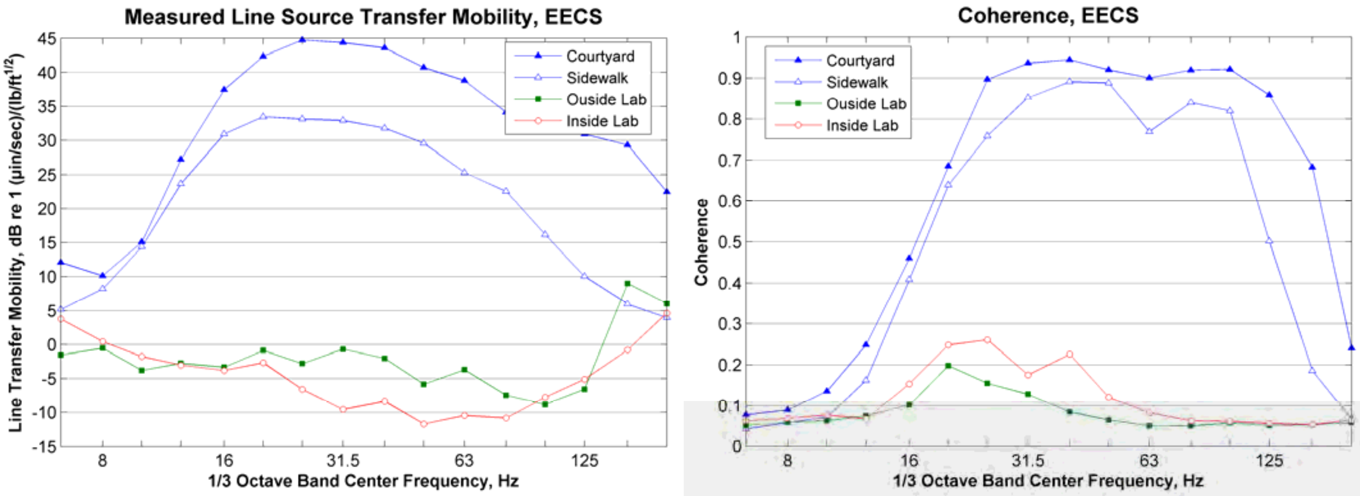


Figure 63: Measured Line Source Transfer Mobility, EECS

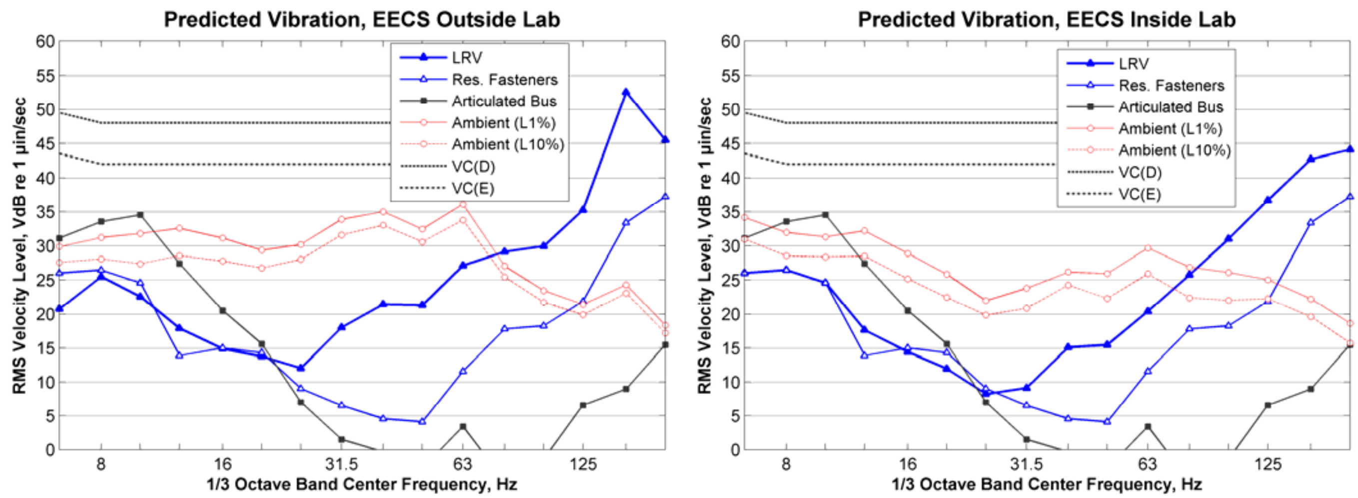


Figure 64: Predicted Train Vibration, EECS Microscopy Lab

6.7 Amundson Hall, Test V6

Measurement Results

The measurements in Amundson Hall were made in Room B22, which is in the basement of the building, and in the hallway just inside the door opening onto Washington Avenue. The concern in Room B22 was an atomic force microscope. The impact line was centered on Room B22 and was approximately 3-feet from the curb. In addition to the two accelerometers located inside the building, accelerometers were mounted on the north edge of the sidewalk and in the lawn 5-feet from the building foundation.

The measured LSTM curves are shown in Figure 65. The measurement inside the lab shows relatively efficient transmission into the lab space in the 30 to 50 Hz range. The average coherence curves indicate that the indoor LSTM curves are valid over the 20 to 100 Hz range. At higher and lower frequencies, the measured levels represent an upper bound for the transfer mobility. The measured transfer mobility curves are relatively high because the two indoor measurement positions are only 30 to 40 feet from the edge of Washington Avenue.

Figure 66 shows the predicted vibration levels based on the measurement in the hallway and Figure 67 shows the predictions inside Room B22. Except above 125 Hz, the predicted vibration levels in Room B22 are higher than the predicted levels at the hallway measurement position. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be less than 1 decibel higher for a 3-car consist. The predicted train vibration levels in the hallway are between the VC-D and VC-E curves except at higher frequencies. The maximum spectrum levels of the predicted train vibration in Room B22 are between the VC-B and VC-C curves. According to the descriptions given in Table 4, VC-B conditions are suitable for "… high-power optical microscopes (1000X), inspection and lithography equipment to 3 micron line widths," and VC-C conditions are adequate for "…most lithography and inspection equipment to 1 micron detail size."

Mitigation

The predictions with resilient fasteners shown in Figure 66 and Figure 67 indicate that most labs in the basement of the building would have a vibration environment between VC-D and VC-E. Vibration isolation tables could then be used for equipment that requires lower ambient vibration levels. The predicted levels of bus vibration are close to the ambient vibration level exceeded 1% of the time. These vibration levels are expected to be unchanged by the CCLRT operations.

The current environment is not suitable for highly sensitive microscopy and NMR tools that require vibration levels lower than the VC-E curve unless the equipment can be mounted on vibration isolation tables.

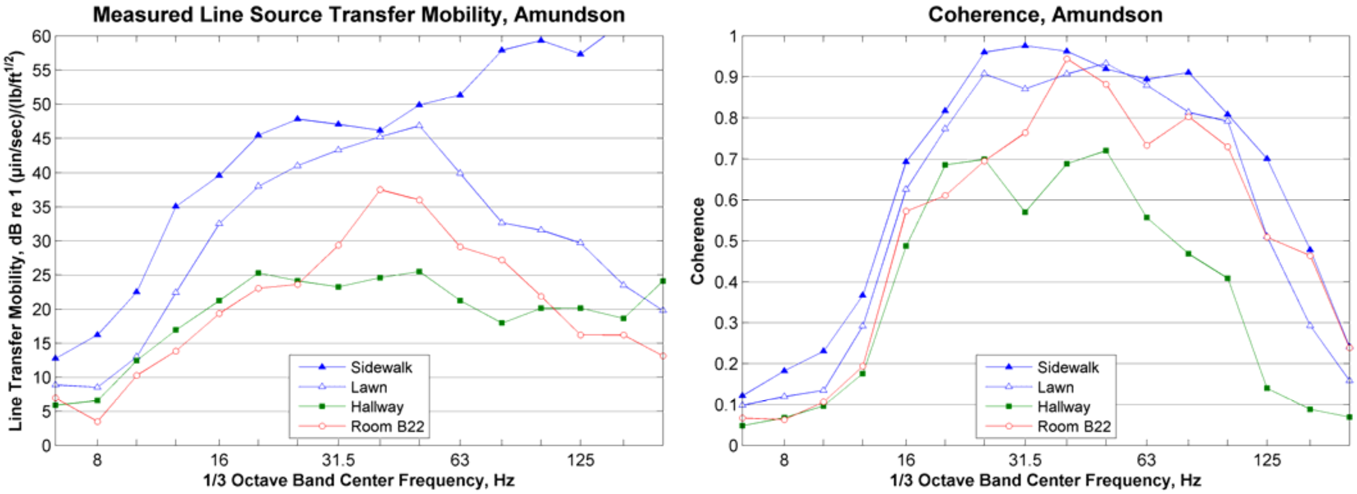


Figure 65: Measured Line Source Transfer Mobility, Amundson Hall

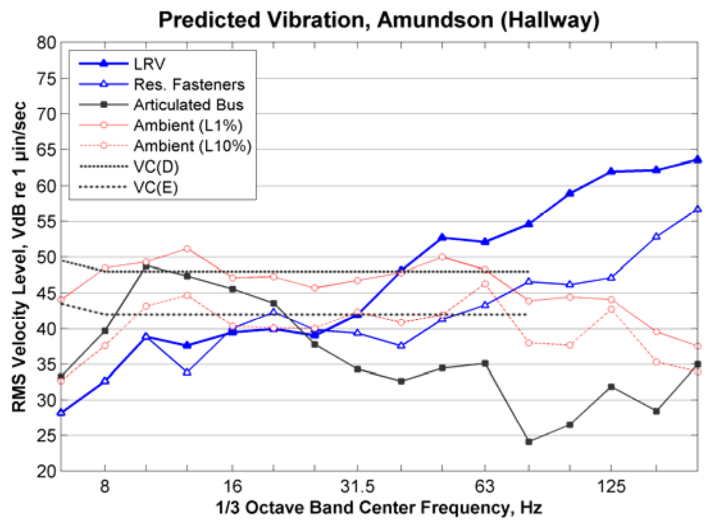


Figure 66: Predicted Train Vibration inside Amundson Hall (Hallway)

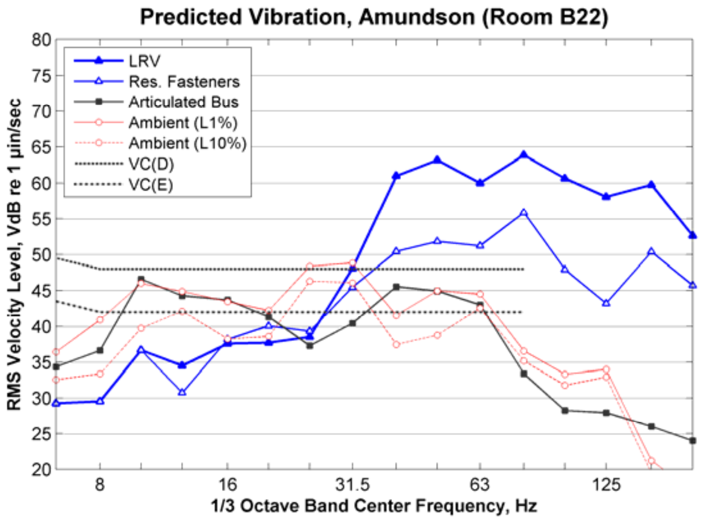


Figure 67: Predicted Train Vibration inside Amundson Hall (Room B22)

6.8 Kolthoff Hall Rooms 194/196, Test V7

Measurement Results

This test at Kolthoff hall was performed because of an NMR facility with six superconducting NMR spectrometers located in Rooms 194/196. The impact line for the Kolthoff Hall measurement was along the north side of Washington Avenue under the pedestrian bridge. Two accelerometers were located outside, one on the sidewalk and one 4 feet from the building foundation. The two indoor accelerometers were located in the hallway outside Rooms 194/196 and inside Rooms 194/196. The measured LSTM curves are shown in Figure 68 and the predicted train vibration is shown in Figure 69 for the measurement position in the hallway and for the measurement position in the laboratory space.

The background vibration peaks at 10 Hz outside the lab and at 16 Hz inside the lab. It is likely that this vibration is caused by buses on Washington Avenue. Referring to the coherence plots in the right graph in Figure 68, the measured LSTM is valid over the frequency range of 25 to 100 Hz. At lower and higher frequencies, the measured LSTMs represent an upper bound for the vibration; the actual LSTMs will be lower.

The vibration predictions in Figure 69 show that below 40 Hz, the background vibration will be higher than or equivalent to the train vibration inside Rooms 194/196. Above 40 Hz, the train vibration will probably exceed the ambient vibration. The predicted LRV vibration above 50 Hz exceeds the VC-E curve and the predicted vibration above 80 Hz exceeds the extended VC-D curve. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1 decibel higher for a 3-car consist.

Mitigation

Figure 69 shows the predicted levels of train vibration assuming use of high-resilience direct fixation rail fasteners to reduce the vibration levels at higher frequencies. The predictions show that use of the high-resilience fasteners will be sufficient to keep the train vibration levels at or equivalent to the ambient vibration inside the laboratory up to 60 Hz and below the VC-E curve above 60 Hz.

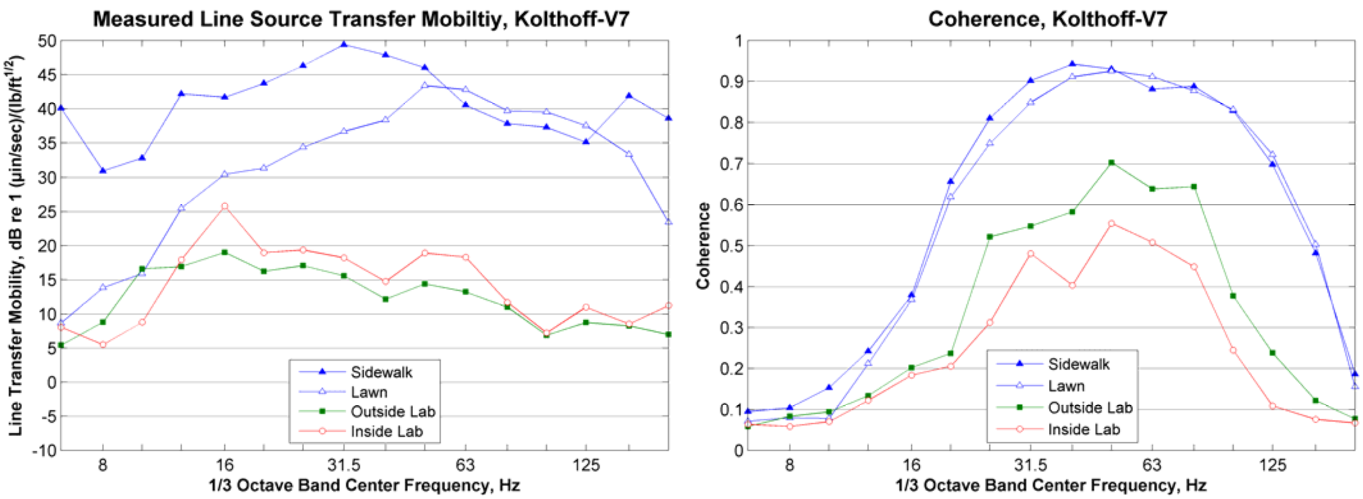


Figure 68: Measured Line Source Transfer Mobility, Kolthoff Hall Rooms 194/196

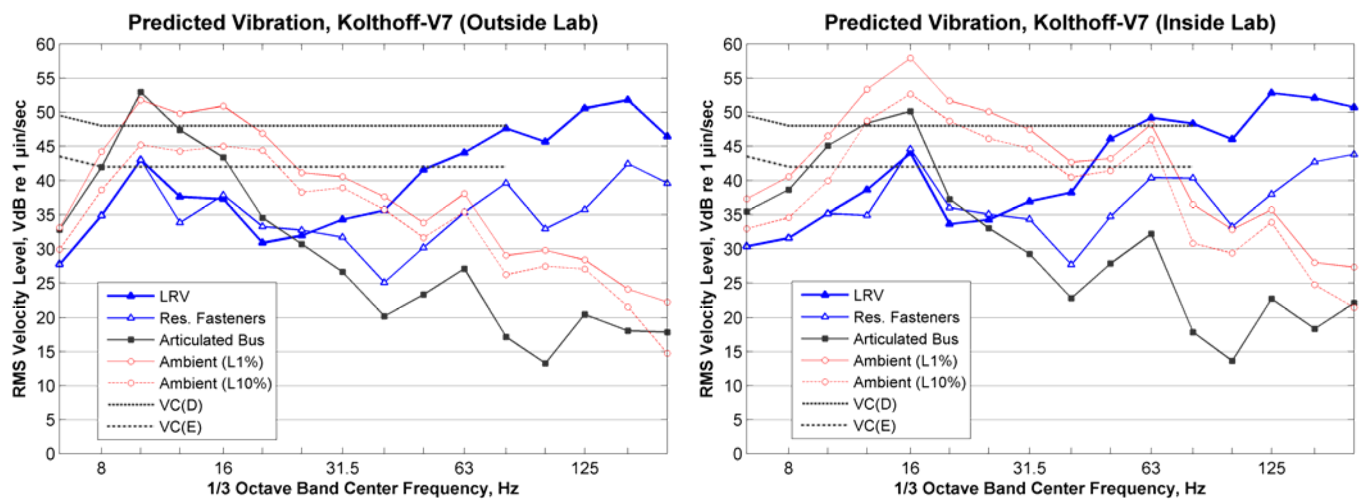


Figure 69: Predicted Train Vibration inside Kolthoff Hall Rooms 194/196

6.9 Kolthoff Hall, Professor Blank's Lab (in basement), Test V8A

The measurement in the basement lab of Kolthoff Hall was performed on September 30, 2008. Measurements were made at two positions in the lab, one on south side closest to the impact line and the second on the north side of the lab. The impact line was along the north curb of Washington Avenue under the pedestrian overpass. Figure 70 shows the ambient vibration and Figure 71 shows the measured LSTM curves. The ambient vibration at the two positions was almost identical. As seen in the time history of the vibration at the south side of the lab, the vibration fluctuated over a 5 decibel range for the entire 1-hour period with no strong peaks. The bottom two plots in Figure 70 show the spectrum plots of the ambient vibration. From these plots it is evident that a peak at 80 Hz dominated the vibration level. This peak was probably caused by mechanical equipment in the lab or in nearby labs. The vibration at frequencies below 40 Hz was probably caused by buses on Washington Avenue.

The coherence for the LSTM measurement is relatively low at frequencies below 31.5 Hz and above 100 Hz.

Figure 72 shows the predicted bus and LRV vibration. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1 decibel higher for a 3-car consist. The predicted bus vibration is close to the L1% ambient at low frequencies confirming that buses are the most probable cause of the low frequency vibration. Without mitigation, the predicted LRV vibration is equivalent to or lower than the ambient at frequencies below 80 Hz. Although most research equipment is relatively insensitive to vibration at frequencies of 80 Hz and higher, vibration mitigation in the form of high-resilience fasteners is recommended to ensure that the environment in this laboratory remains suitable for research projects.

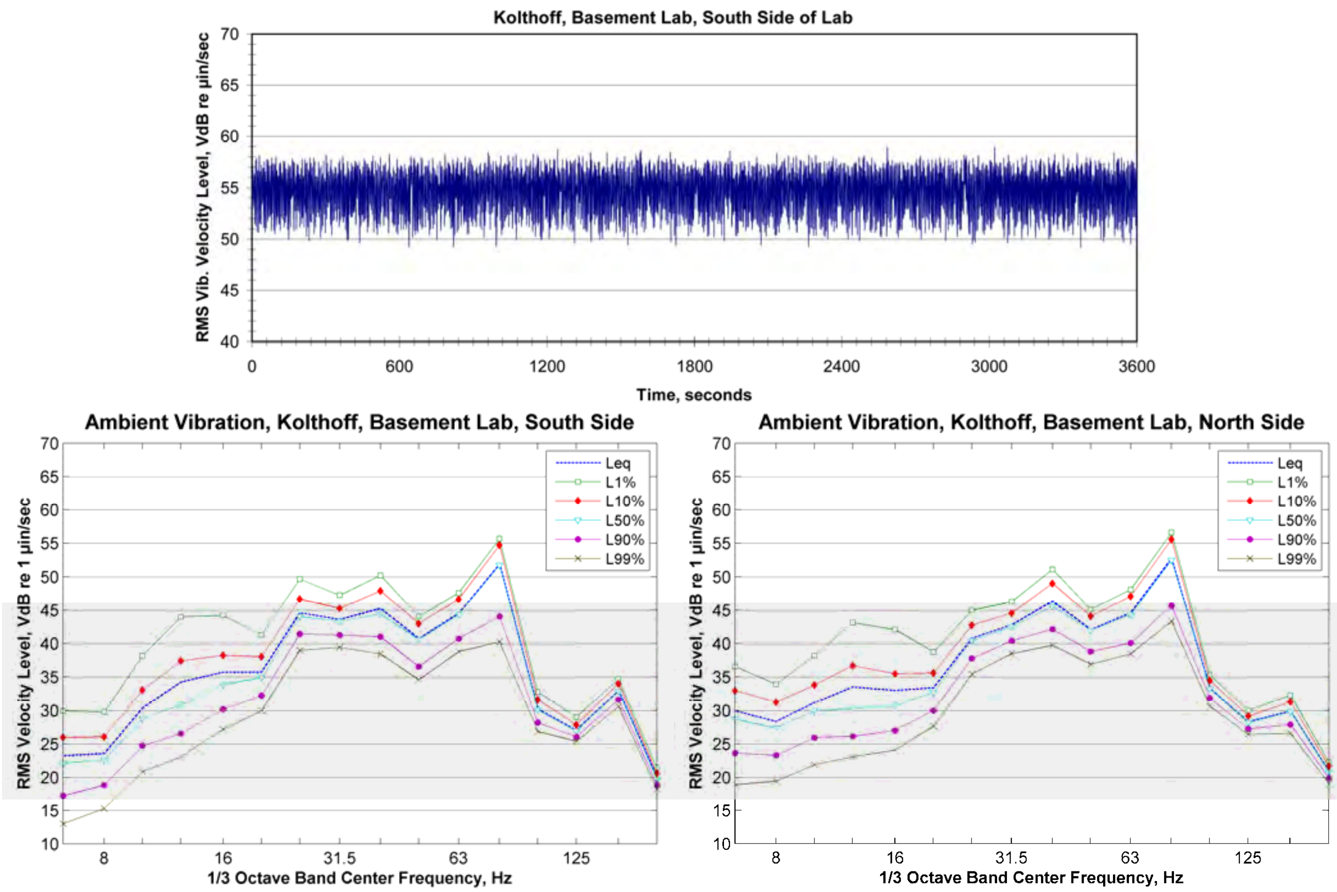


Figure 70: Ambient Vibration Measured in Kolthoff Basement Lab

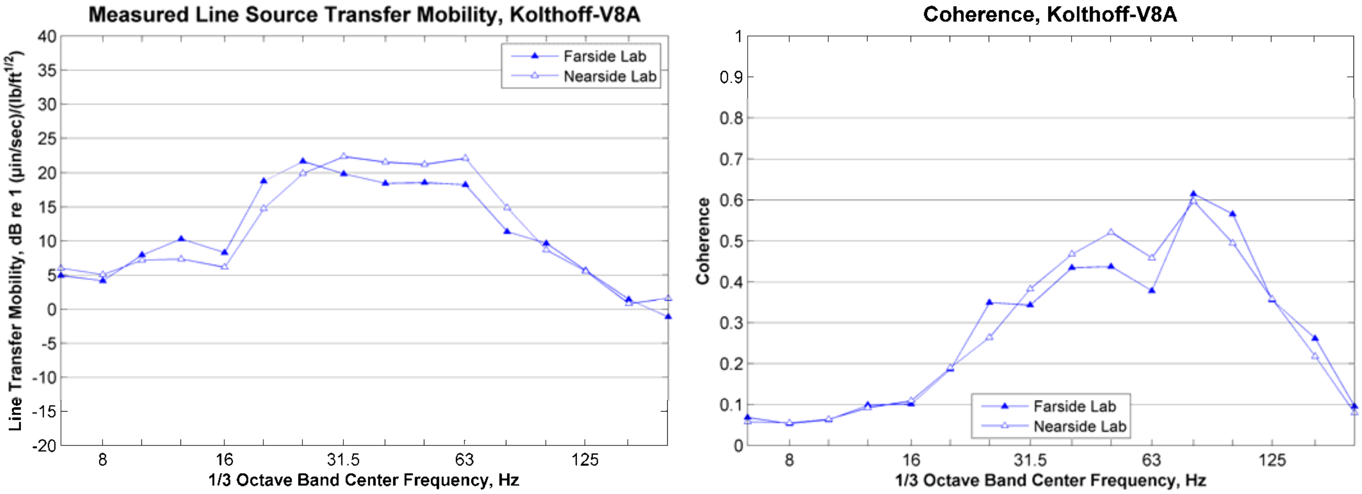


Figure 71: Measured Line Source Transfer Mobility in the Basement of Kolthoff Hall

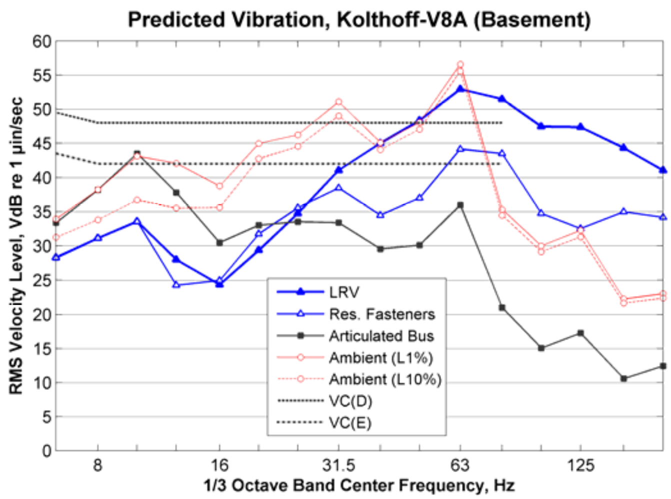


Figure 72: Predicted Vibration and Mitigation for Prof. Blank's Lab inside Kolthoff Hall

6.10 Kolthoff Hall, Professor Kass' Lab (4th Floor), Test V8B

This measurement in a 4th floor lab of Kolthoff Hall was performed at the same time as the measurement in the basement (test V8A). The impact line was along the curb of Washington Avenue. The ambient vibration in the lab is shown in Figure 73. The existing vibration levels are relatively high and exceed the VC-D curve by a substantial amount at low frequencies. The time history of the vibration fluctuates over a 15 decibel range. This fluctuation was probably caused by traffic on Washington Avenue. The highest vibration levels are at frequencies of 12 to 20 Hz and appear to have been caused by buses on Washington Avenue. The vibration at higher frequencies was probably caused by mechanical equipment within Kolthoff.

Figure 74 shows the LSTM measured at the indoor accelerometer and the LSTMs measured at two outdoor positions. The coherence for the indoor measurement is close to zero below 16 Hz and moderately good at higher frequencies. Figure 75 shows the predicted bus and LRV vibration inside the

4th floor lab. Without mitigation, the predicted LRV vibration is lower than the ambient at frequencies below 80 Hz. This result is quite similar to the basement lab in Kolthoff (Test V8A). As for the basement lab, vibration mitigation in the form of high-resilience fasteners is recommended to ensure that the vibration environment is suitable for future research projects. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1 decibel higher for a 3-car consist.

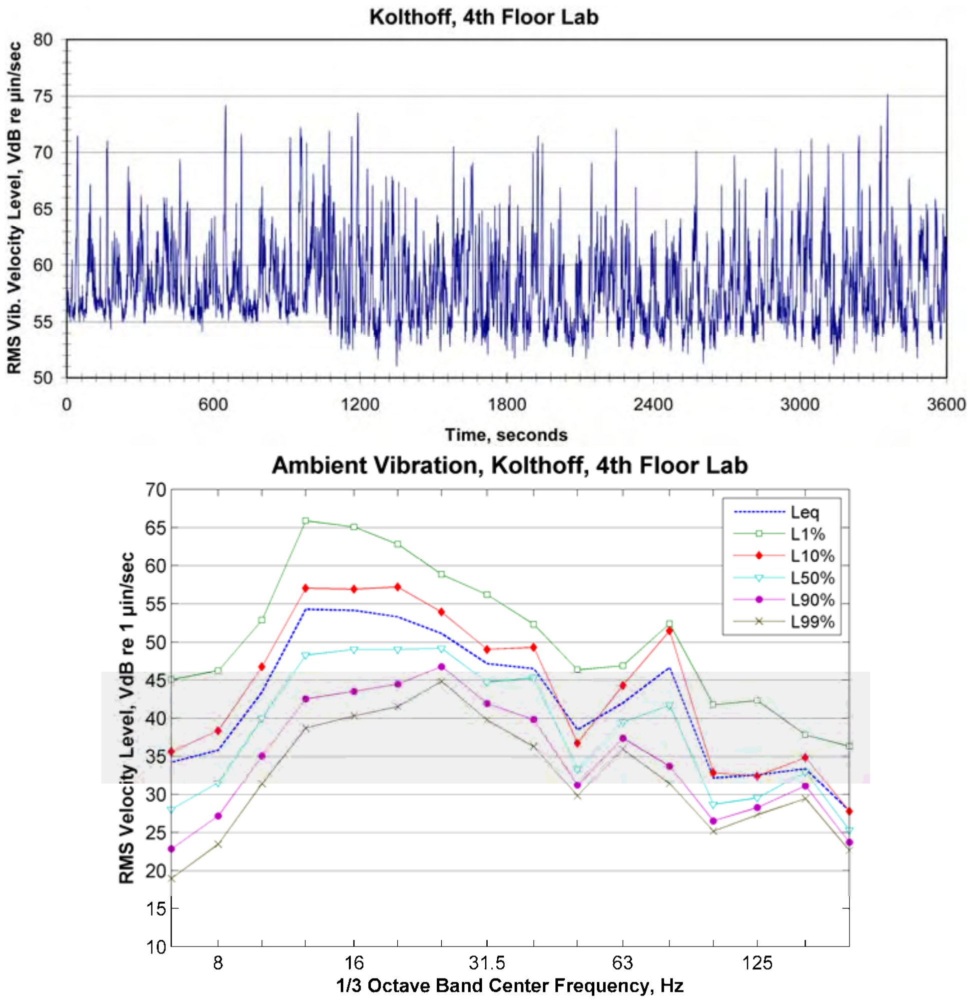


Figure 73: Ambient Vibration, Kolthoff Hall, 4th Floor Lab

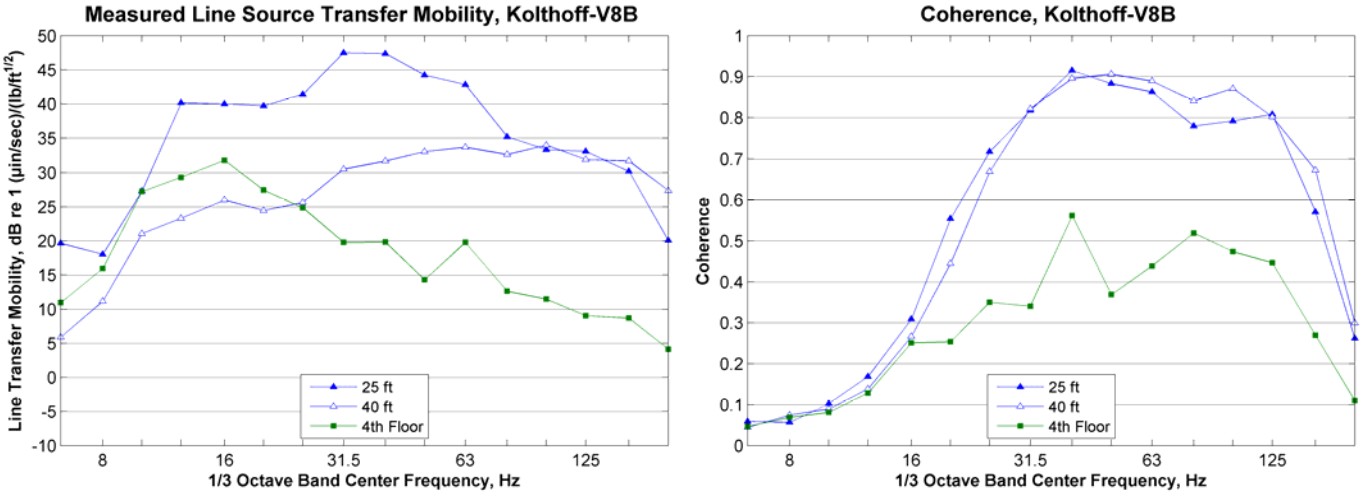


Figure 74: Measured Line Source Transfer Mobility inside Kolthoff Hall 4th Floor

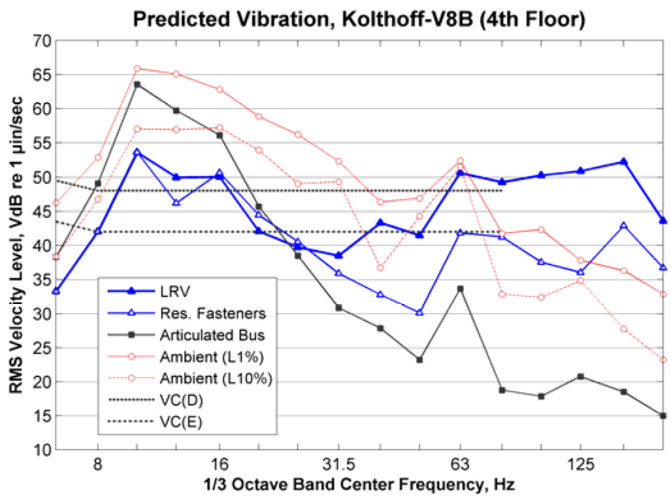


Figure 75: Predicted Vibration and Mitigation inside 4th Floor Lab, Kolthoff Hall

6.11 Smith S20, Test V9

The measurements in Smith S20 included ambient vibration and LSTM on the floor and on a table that used for optics equipment. Figure 76 shows the time history of the ambient vibration. The time history plots include the overall vibration (the top graph) and the low-frequency vibration. This analysis was performed to help determine whether traffic on Washington was causing vibration peaks in the lab. There is greater fluctuation in the vibration levels when the frequencies above 31.5 Hz are excluded; however, the peaks are of short duration and may not be caused by Washington Avenue traffic.

Figure 77 shows the spectrum of the ambient vibration. Although there is low-frequency energy, it is not clear whether the traffic on Washington Avenue is the source of the low-frequency vibration. Note that the ambient vibration measurement was temporarily stopped in the middle of the measurement to adjust the monitor settings. The right graph in Figure 77 provides a comparison of the two average levels (Leq) for the two tests. The correspondence between the results for both of the measurement positions shows that adjusting the settings had no effect on the measurement results.

Figure 78 shows the measured LSTM at this site. The same impact line was used as for Test V8A and V8B. Because of time constraints, it was not possible to do a complete set of 11 impact positions for this test. The alternative procedure used to derive a line-source transfer mobility from the three point-source transfer mobilities was to calculate the transfer mobility for a 30 ft line source using the three impact positions and then to adjust to a 150 ft line source using an adjustment of 10log(150/30), which equals 7 dB. This approach was tested using the data from Test V8A and found to give a reasonable estimate of LSTM for a 150 ft source. The coherence for the LSTM tests is relatively low over the entire frequency range indicating that the measured LSTM is an upper bound on the actual LSTM.

Figure 79 shows the predicted bus and LRV vibration levels inside Room S20. The prediction of bus vibration corresponds to the low-frequency of the ambient vibration. This indicates that vibration from bus traffic on Washington Avenue is contributing to the ambient in the lab; however, low coherence means that the LSTM is an upper bound and that the predicted bus vibration is higher than the actual bus vibration.

The predicted LRV vibration is lower than the measured ambient vibration at all frequencies below 100 Hz. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 2 decibels higher for a 3-car consist. The conclusion from this data is that no vibration mitigation is required to achieve existing ambient vibration conditions in the future with LRT operations on Washington Avenue..

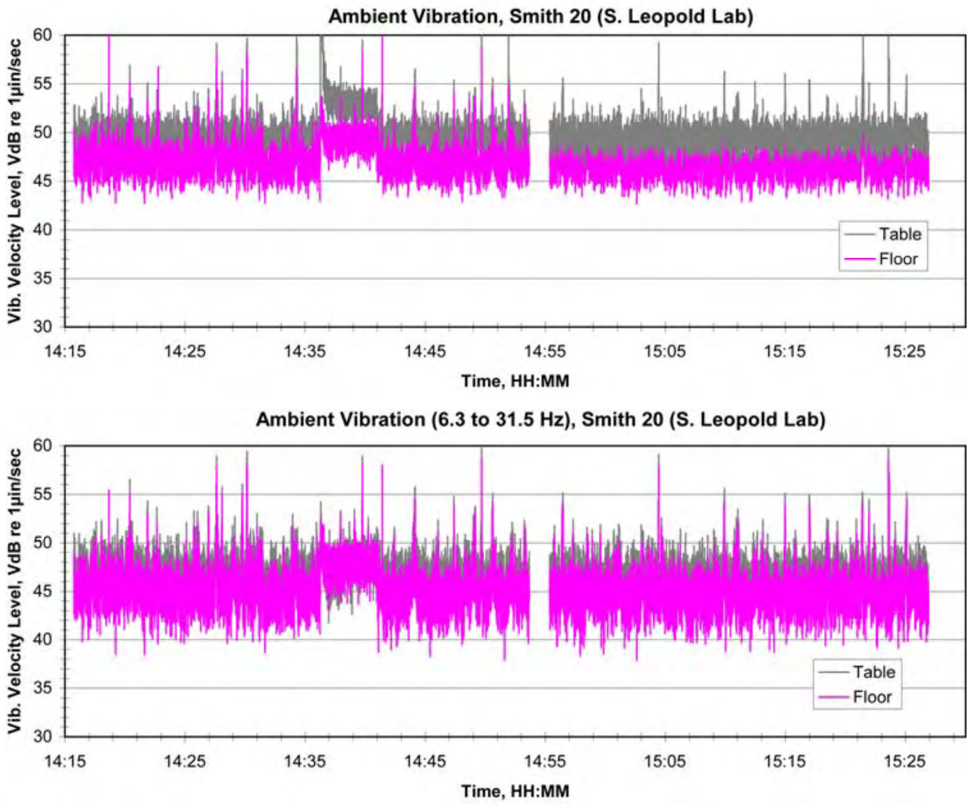


Figure 76: Time History of Ambient Vibration, Room Smith S20
The top graph shows the overall vibration velocity level (6.3 to 200 Hz). The bottom graph shows the vibration velocity level over the low-frequency range (6.3 to 31.5 Hz). A motor was turned on between 14:36 and 14:42. This period was not included in the analysis.

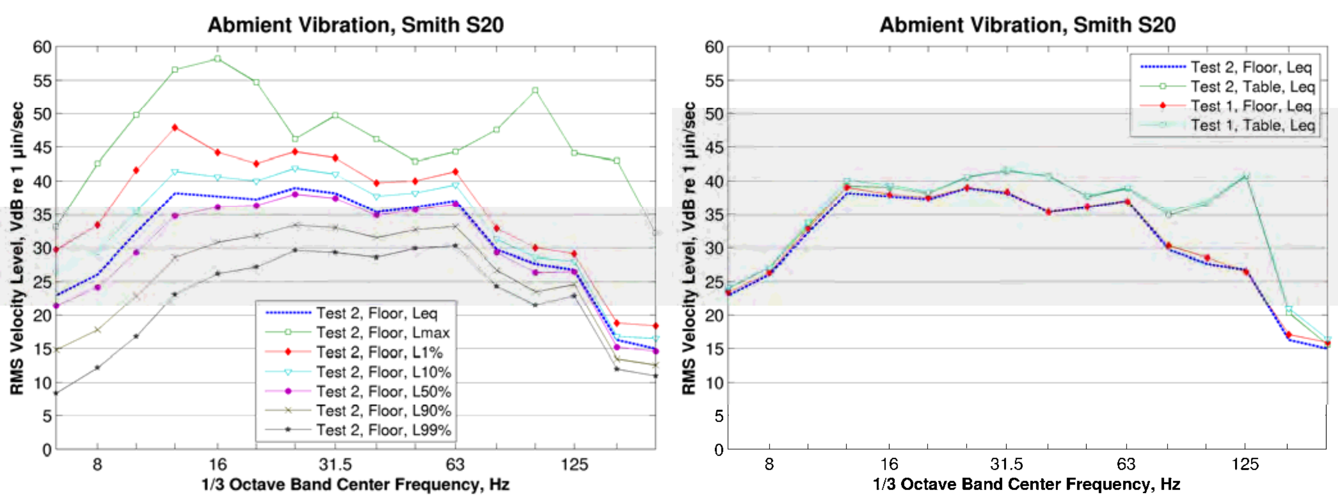


Figure 77: Vibration Spectra of Ambient Vibration, Room Smith S20
The left graph shows average level over the second test (Leq) the maximum vibration (Lmax) and the vibration levels exceeded 1%, 10%, 50%, 90% and 99% of the measurement period. The right graph shows the average vibration levels for the two measurements at both measurement positions.

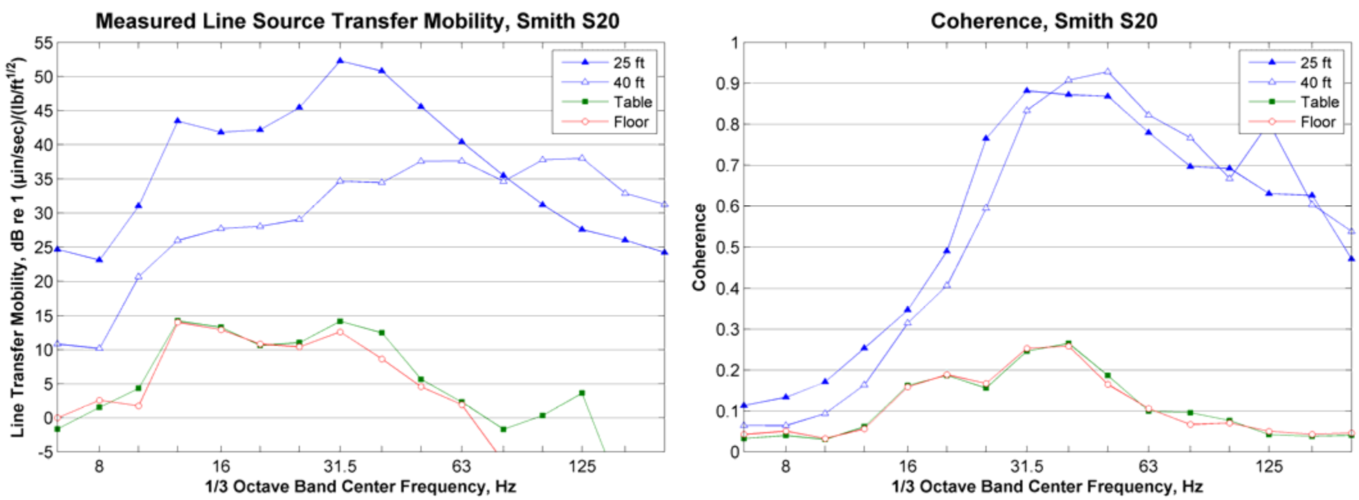


Figure 78: Measured Line Source Transfer Mobility, Smith S20

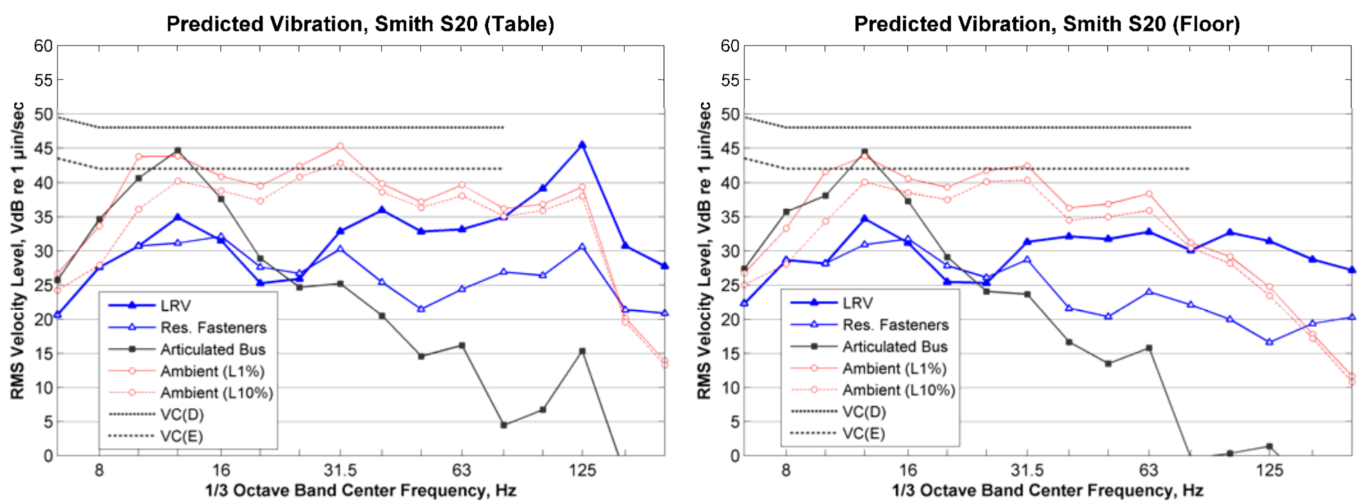


Figure 79: Predicted Vibration and Mitigation inside Smith S20

6.12 717 Delaware NMR Lab (4th Floor), Test V10

The final LSTM measurement was performed for an NMR facility in the 717 Delaware building. The impact line was along the south curb of Washington Avenue and the accelerometer line was along the east side of Walnut Street. Because of the distances involved, it was not feasible to run a cable into the NMR lab for the LSTM test. Therefore, the outdoor vibration at the distance from the building to from Washington Avenue was used to estimate the future vibration levels at the NMR facility. As explained above (see page 52), for the laboratories where only ambient vibration was measured, an outdoor-to-indoor vibration attenuation of 10 decibels has been assumed to develop the predictions.

The time history and the vibration spectra of the ambient vibration are shown in Figure 80. The vibration was relatively constant at 55 VdB ±2 decibels. The maximum levels were around 16 Hz. This is about the frequency in which bus vibration would be expected. However, the fact that the vibration was so constant indicates that the dominant vibration source was probably equipment within the building rather than an external source.

Figure 81 shows the measured LSTM curves. The measurements were made along Walnut Street at distances of 40 to 250 ft from the curb of Washington Avenue. The coherence at 250 ft was reasonably good between 16 and 80 Hz. The predicted vibration levels inside the NMR lab are shown in Figure 82. As discussed above, the predictions use the 250 ft LSTM and assume a 10 decibel outdoor-to-indoor vibration reduction. The predicted levels are below the ambient vibration at all frequencies indicating that no mitigation is required to maintain the existing ambient vibration environment at the 717 Delaware NMR lab. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 2 decibels higher for a 3-car consist.

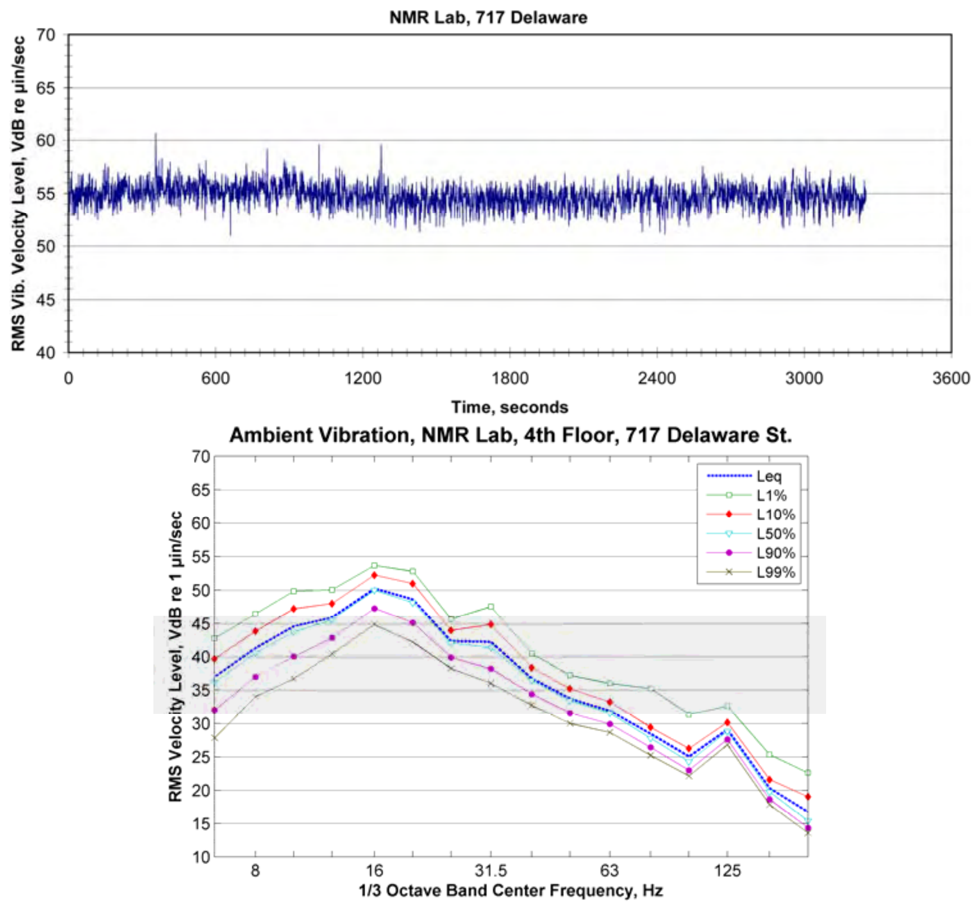


Figure 80: Ambient Vibration, 717 Delaware Street, NRM Lab on 4th Floor

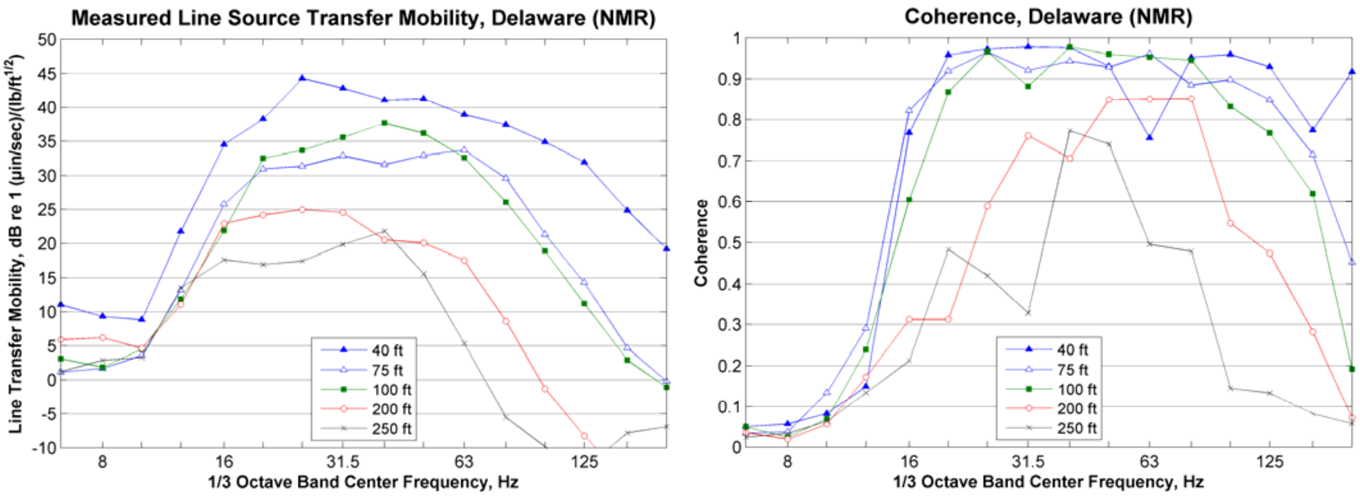


Figure 81: Measured Line Source Transfer Mobility, Delaware (Outdoors)

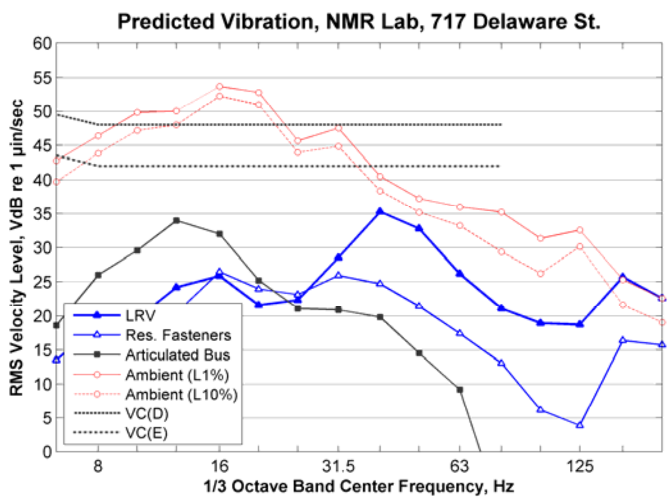
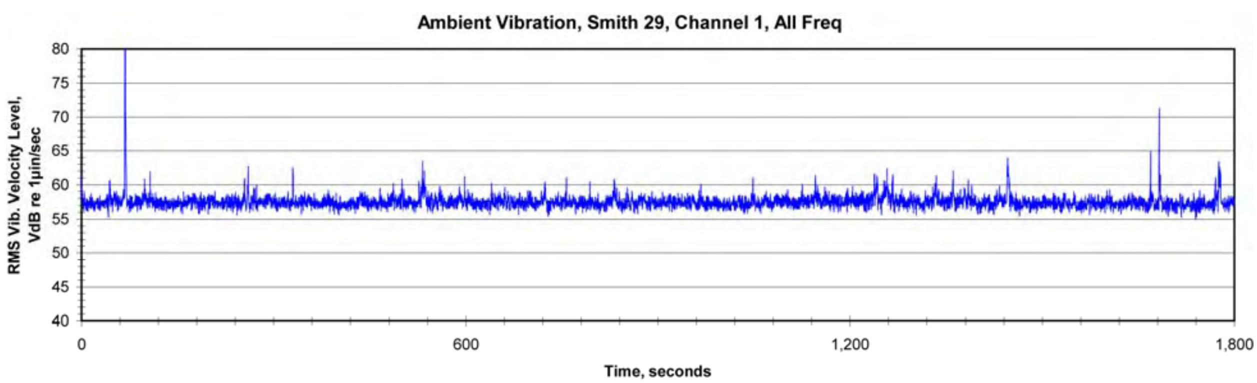


Figure 82: Predicted Vibration in NMR Lab, 717 Delaware Street

6.13 Smith S29, Test A1

A 30 minute ambient vibration measurement was performed on October 3, 2008 in Room 29 of Smith Hall. The concern was pulsed nozzles Fourier transform microwave spectrometer. This room is approximately 200 feet from Washington Avenue. The time history and the vibration spectra of the ambient vibration are shown in Figure 83. The vibration levels were relatively constant at 57 VdB ±2 decibels with the maximum levels at around 25 Hz. The vibration was so constant indicates that major vibration sources were likely equipment within the building rather than external sources. The room is near an elevator shaft that could cause substantial vibration when the elevator is operating. There were no apparent operations of the elevator during the measurement.

Figure 84 shows the predicted vibration levels. The predictions use the 200 ft LSTM from the Delaware NMR propagation test and assumes a 10 decibel outdoor-to-indoor vibration reduction. The predicted LRV vibration is equivalent to or lower than the ambient at all frequencies with the exception of 50 Hz. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1.5 decibels higher for a 3-car consist. The predicted levels are low enough that no vibration mitigation is required.



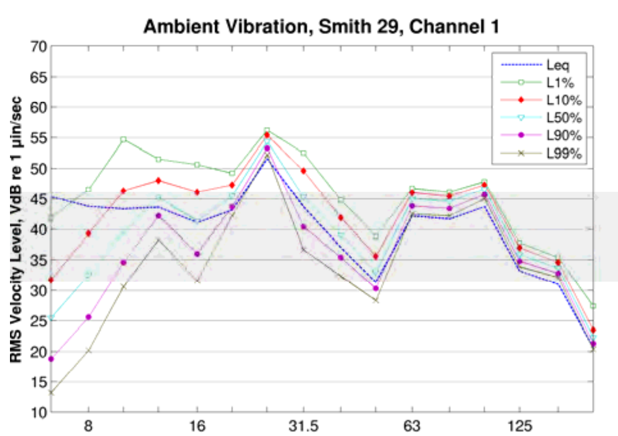


Figure 83: Ambient Vibration inside Room S29 at Smith Hall

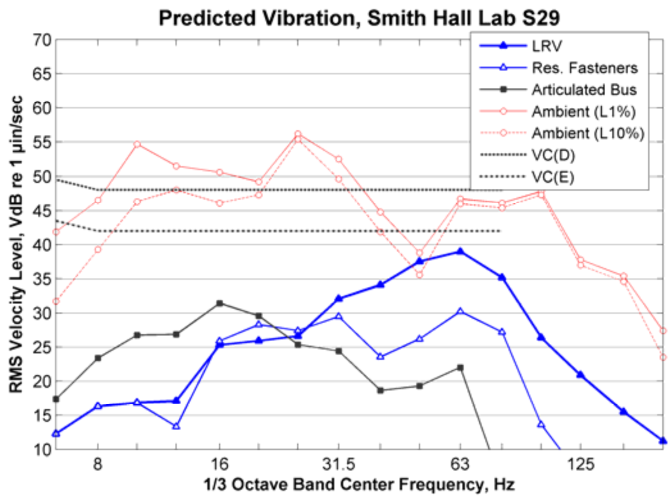


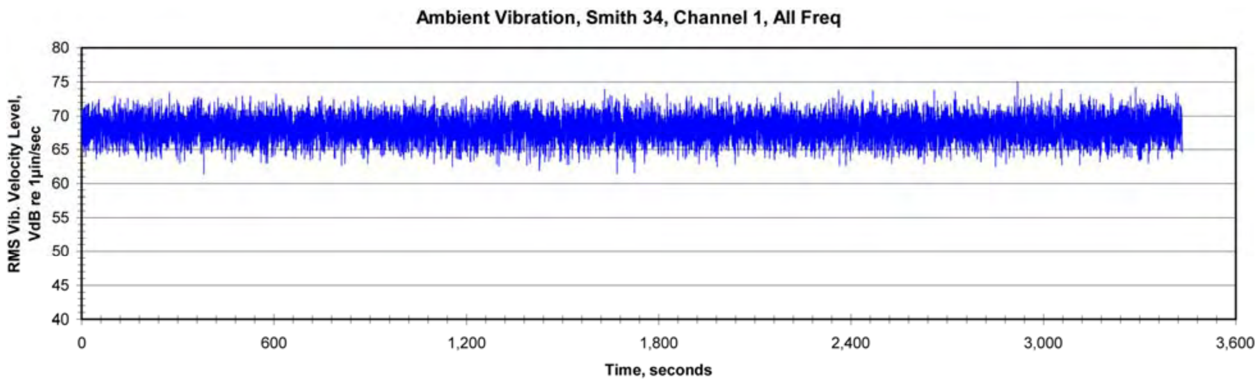
Figure 84: Predicted Vibration inside Room S29 at Smith Hall

6.14 Smith 34, Test A2

A one hour ambient vibration measurement was performed on September 30, 2008 in Room 34 of Smith Hall to address the concern for an ultrafast Laser system. This room is approximately 200 feet from Washington Avenue. Figure 85 shows both the time history and vibration spectra for the ambient vibration measurement. A relatively high vibration level of 68±4 VdB was observed throughout the measurement. The maximum levels were at 16 Hz and 31.5 Hz. The peak at 31.5 Hz together with the consistency of the vibration levels indicates that the vibration source was mechanical noise from equipment in the lab.

The predicted vibration levels inside Room 2-231 are shown in Figure 86. The predictions use the 200 ft LSTM from the Delaware NMR propagation test and assumes a 10 decibel outdoor-to-indoor vibration reduction. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1.5 decibels higher for a 3-car consist.

The predicted LRV vibration is well below the ambient at all frequencies indicating that no vibration mitigation is required.



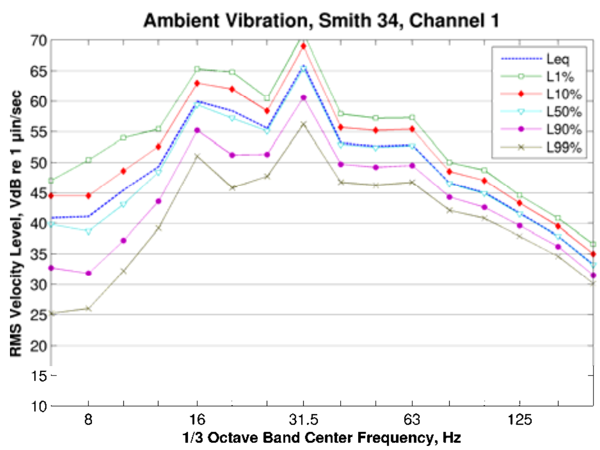


Figure 85: Ambient Vibration inside Room S34 at Smith Hall

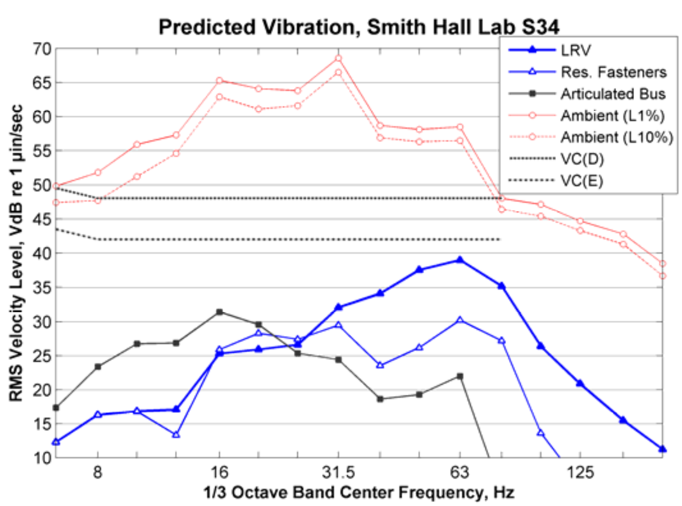


Figure 86: Predicted Vibration inside Room S34 at Smith Hall

6.15 Nils Hasselmo Hall, Room 2-231, Test A3

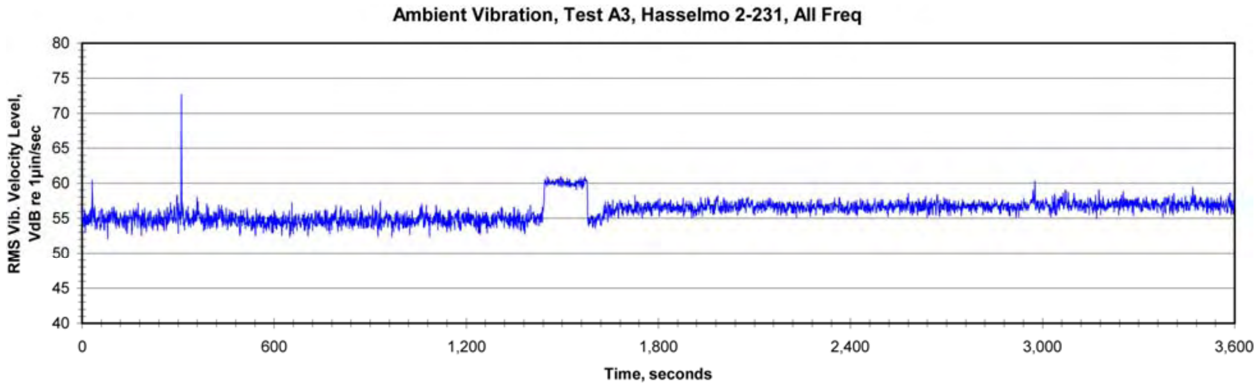
A one hour ambient vibration measurement was performed on October 14, 2008 in Room 2-231 in Nils Hasselmo Hall (see Figure 87) to address the concern for an unbiased stereology microscopy set-up in Professor Nick's darkroom located on the second floor of the building. The room is approximately 200 feet from Washington Avenue. Figure 88 shows the time history and the vibration spectra of the ambient measurement.

The measured vibration was constant at 55±3 VdB during the entire measurement period, except during four short periods. The frequency spectrum was consistent except for a spike at 10 Hz during the second half of the test. Because of the distance between Washington Avenue and the relatively constant vibration levels, it may be inferred that the vibration source was likely to be equipment within the building rather from external sources.

Figure 89 shows the predicted vibration levels inside Room 2-231. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1.5 decibels higher for a 3-car consist. The prediction uses the best fit LSTM for 200 ft from the Delaware propagation test and assumes a 10 decibel outdoor-to-indoor vibration reduction.

With the adjustment for a 3-car consist, the predicted levels just exceed the impact threshold that is being used for the U of M vibration sensitive facilities. With the addition of high-resilience direct fixation track fasteners, the predicted ground-borne vibration levels are well below the ambient vibration at all frequencies.

Figure 87: A view of Vibration Measurement inside Room 2-231 at Nils Hasselmo Hall



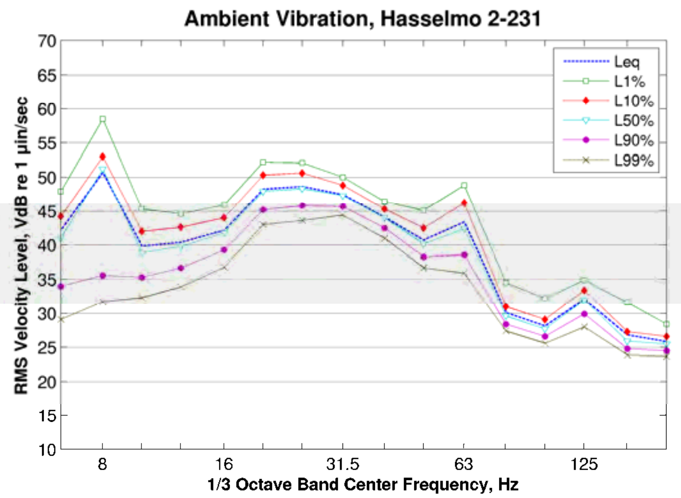


Figure 88: Ambient Vibration inside Room 2-231 at Nils Hasselmo

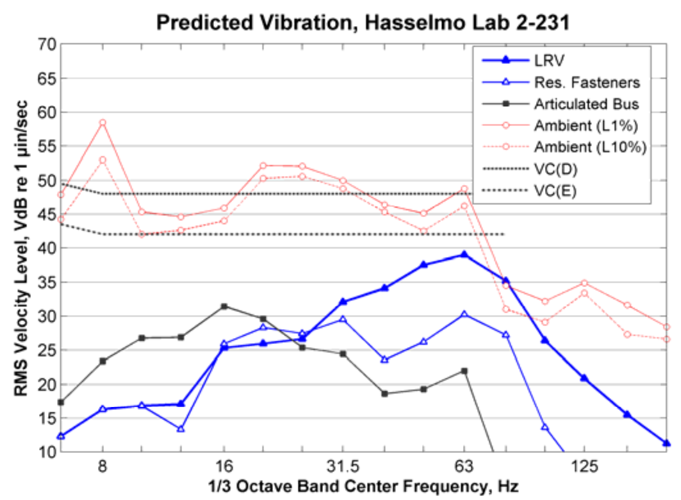


Figure 89: Predicted Vibration inside Room 2-231 at Nils Hasselmo

6.16 Nils Hasselmo Hall, Room 2-236A, Test A4

Room 2-236A is located on the second floor of Nils Hasselmo Hall. The concern is for an acute in-vivo intracellular recording set-up and a Brian slice whole cell patch recording set. A one hour ambient vibration measurement was performed on October 14, 2008. The lab is approximately 200 feet from Washington Avenue.

The time history and the spectra of the ambient vibration are shown in Figure 91. The vibration was relatively constant at 49±2 VdB decibels with the frequency spectrum staying consistent throughout the measurement. It is likely that all of the peaks within the time history graph were caused by pedestrian traffic and that in general, measured vibration levels were caused by equipment within or adjacent to room 2-236A rather than from external sources.

The predicted vibration levels inside Room 2-231 are shown in Figure 89. The predictions use the 200 ft LSTM from the Delaware NMR propagation test and assumes a 10 decibel outdoor-to-indoor vibration reduction. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1.5 decibels higher for a 3-car consist.

With the adjustment for a 3-car consist, the predicted levels just exceed the impact threshold that is being used for the U of M vibration sensitive facilities. With the addition of high-resilience direct fixation track fasteners, the predicted ground-borne vibration levels are well below the ambient vibration at all frequencies.

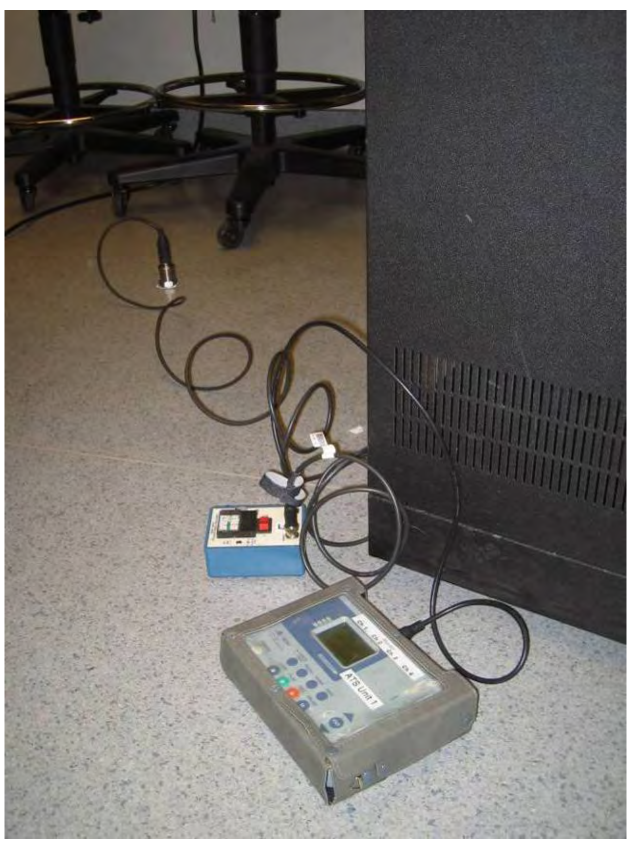
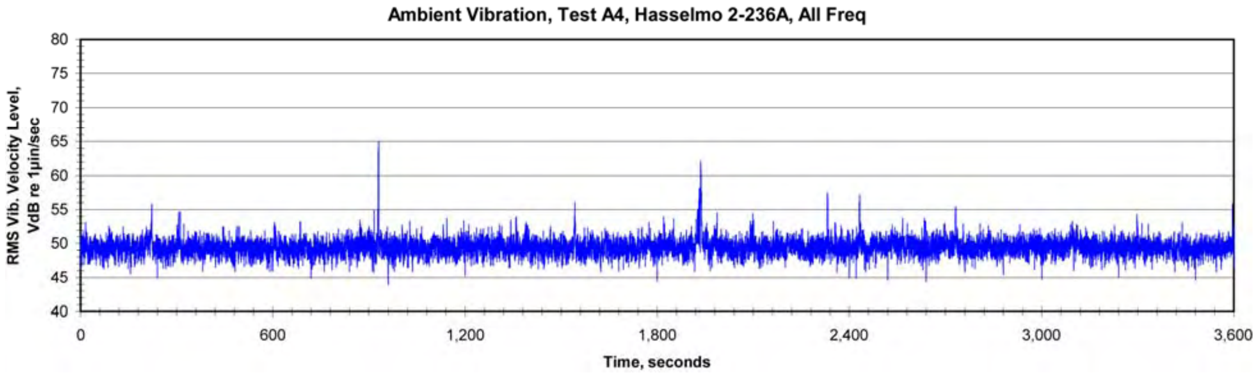


Figure 90: Accelerometer inside Room 2-236 A of Nils Hasselmo



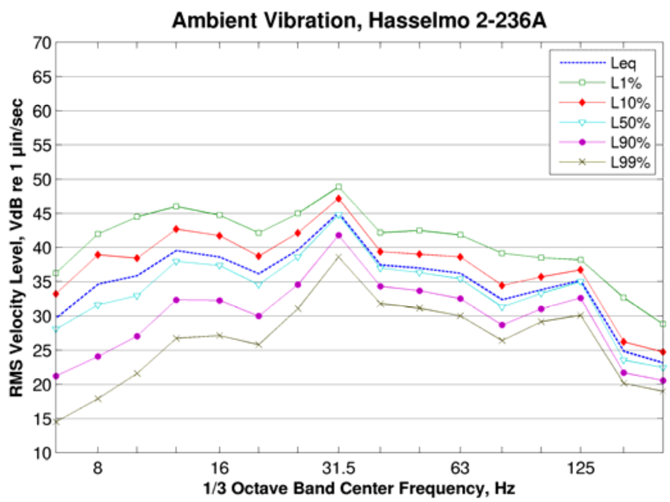


Figure 91: Ambient Vibration Inside Room 2-236 at Nils Hasselmo

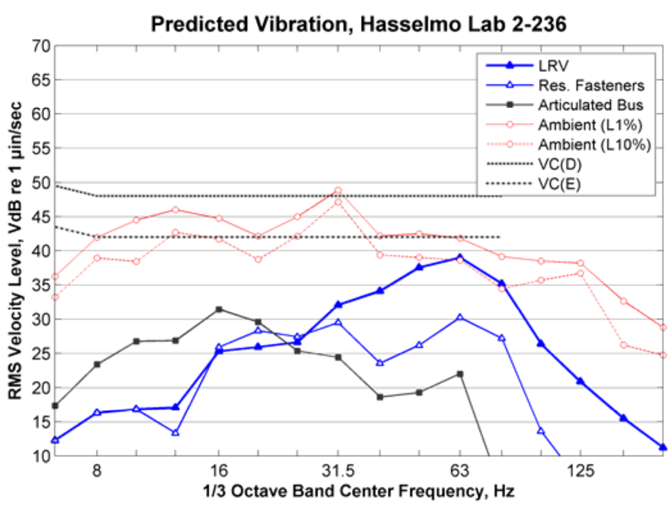


Figure 92: Predicted Vibration inside Room 2-236 at Nils Hasselmo

6.17 Jackson Hall, Room 3-142, Test A5

An ambient vibration measurement was taken over 11 hours on the third floor of Jackson Hall on October 14 and October 15, 2008. Room 3-142 houses sensitive equipment to measure active and passive responses of muscles. Figure 93 shows where the accelerometer was placed on the floor beneath an isolation table where the equipment was located. The lab is approximately 160 feet from Washington Avenue.

One-hour and 11-hour time history plots as well as vibration spectra of the ambient vibration are shown in Figure 94. The vibration was relatively constant at 62±3 VdB with the frequency spectrum staying consistent throughout the measurement. Because of the lack of variation in the measured vibration levels, it is likely that the ambient vibration was caused by equipment within the building rather than from external sources.

The predicted vibration levels inside Room 2-231 are shown in Figure 95. The prediction is based on the best fit curves for 160 feet LSTM from the Delaware NMR propagation test and assumes a 10 decibel outdoor-to-indoor vibration reduction. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1.5 decibels higher for a 3-car consist.

The predicted LRV vibration is equivalent or lower than the ambient vibration below 50 Hz. Vibration at higher frequencies exceeds the impact criteria being used for the U of M facilities. The relatively high vibration levels at lower frequencies indicate that the equipment currently in the room with the vibration attenuation provide by the vibration isolation table, is relatively insensitive to vibration. In any case, vibration mitigation in the form of high-resilience fasteners will ensure that the environment in this room remains suitable for the research project.

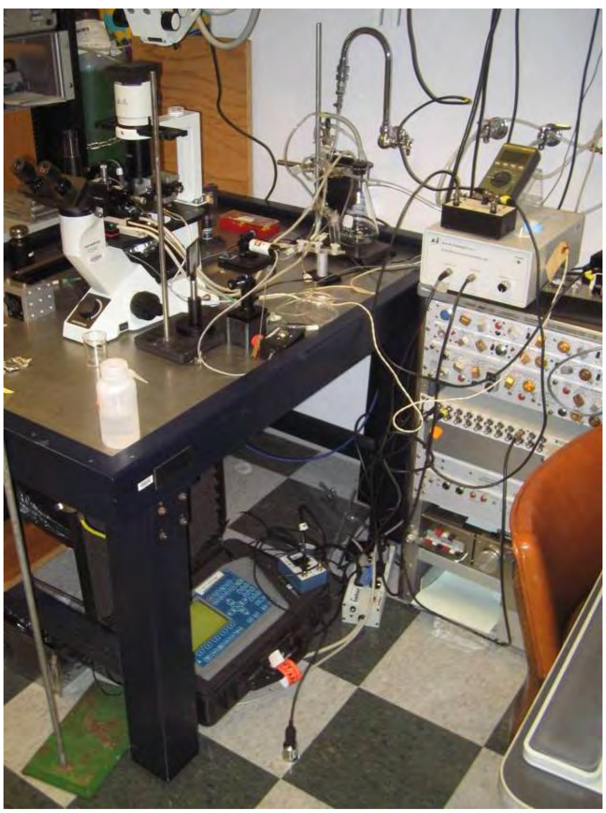
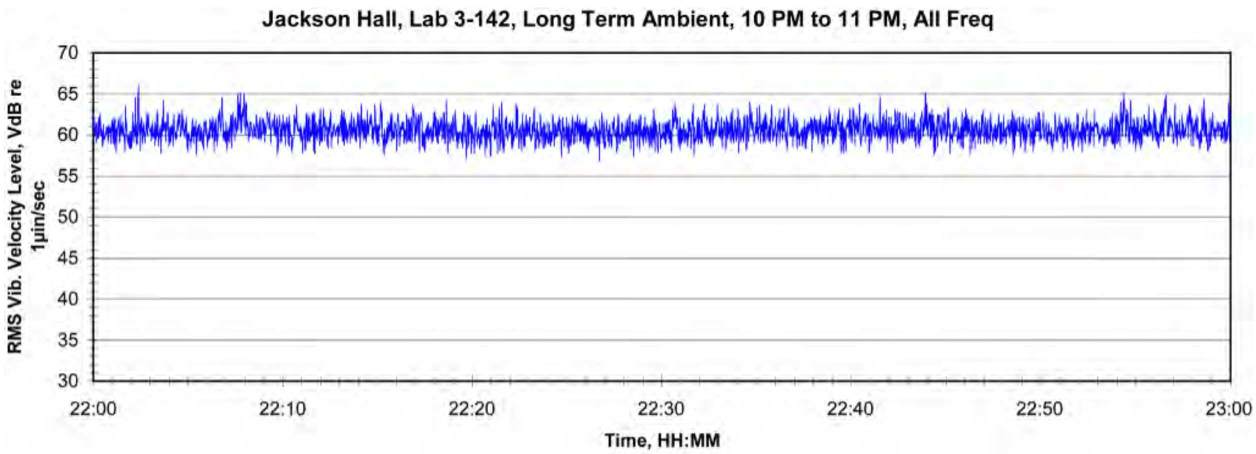
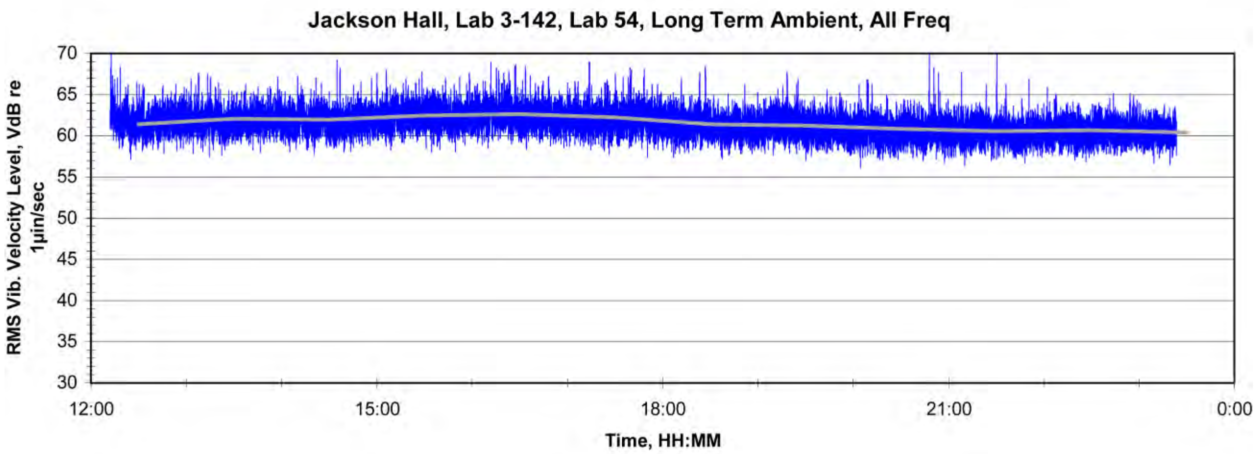


Figure 93: Accelerometers on the Floor inside Jackson Hall





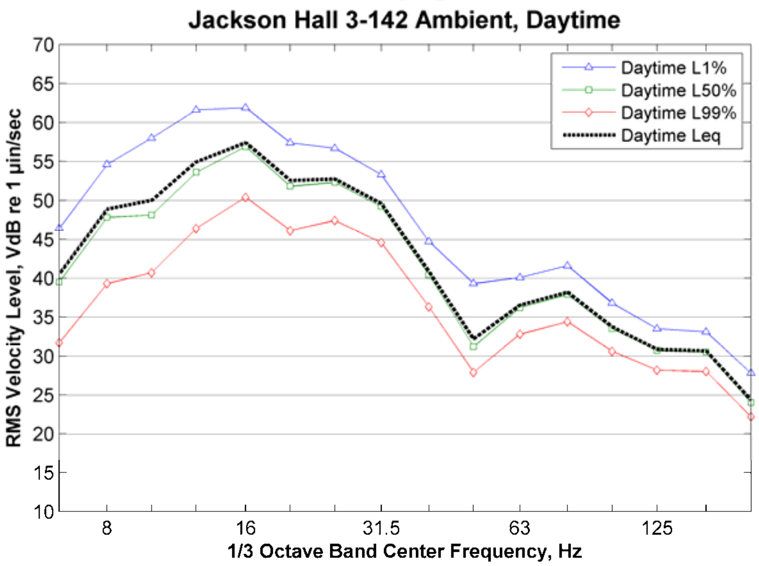


Figure 94: Ambient Vibration inside Room 3-142 at Jackson Hall

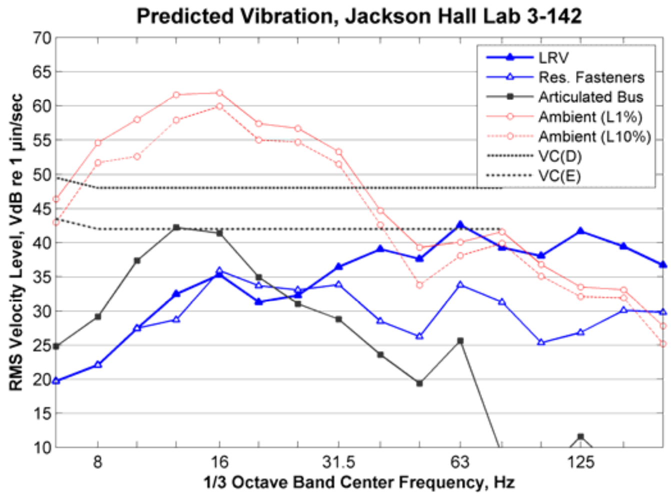


Figure 95: Predicted Vibration inside Room 3-142 at Jackson Hall

6.18 Nils Hasselmo Hall, Room 7-231A, Test A6

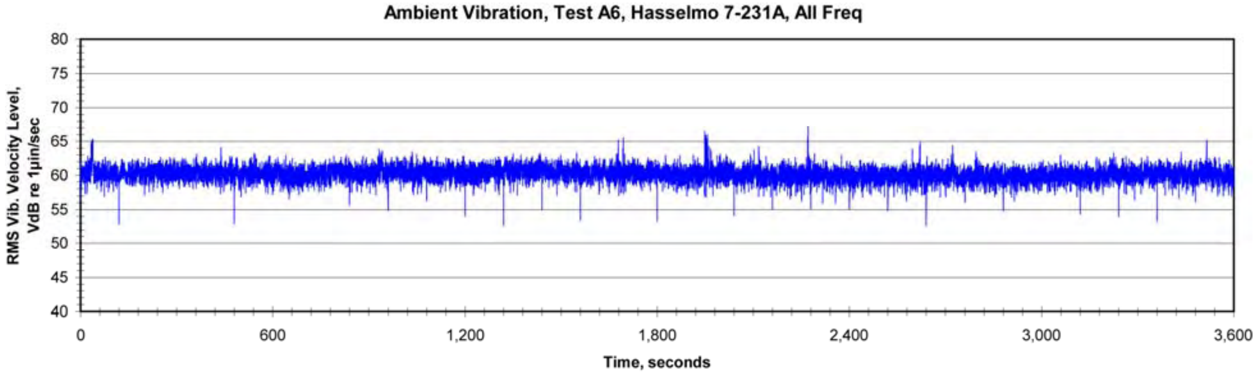
A one hour ambient vibration measurement was performed in room 7-231A on the seventh floor of Nils Hasselmo Hall on October 14, 2008. The lab houses microscopes used for electrophysiological recordings from brain cells and is located on an isolated slab. The lab is approximately 200 feet from Washington Avenue.

The time history and the vibration spectra of the ambient vibration are shown in Figure 97. The vibration was relatively constant at 60±3 VdB. Peaks in the one third octave band spectra occurred at 8 Hz and 31.5 Hz. Given the consistency of the vibration levels and the distance from Washington Avenue, it is likely that the ambient vibration was caused by equipment within the building rather than from external sources.

The predicted vibration levels inside Room 2-231 are shown in Figure 98. The predictions are based on the LSTM from the Delaware NMR propagation test and assume a 10 decibel outdoor-to-indoor vibration reduction. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1.5 decibels higher for a 3-car consist.

The predicted levels are well below the ambient vibration at all frequencies, indicating that no mitigation is required to maintain the existing ambient vibration environment.

Figure 96: Ambient Vibration Measurement Location inside Room 7-231A at Nils Hasselmo Hall



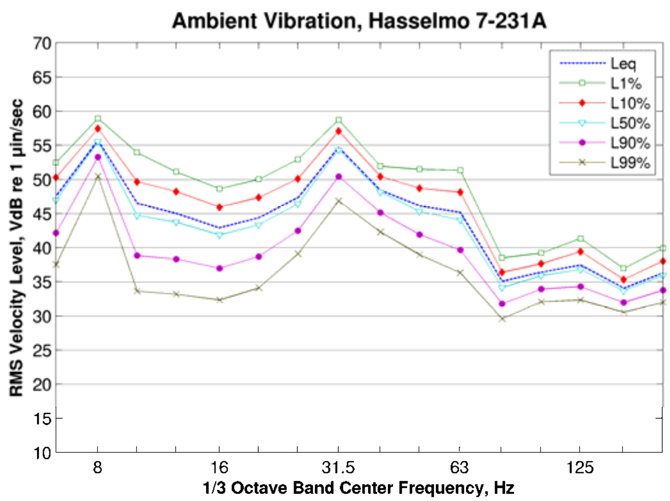


Figure 97: Ambient Vibration inside Room 7-231A at Nils Hasselmo Hall

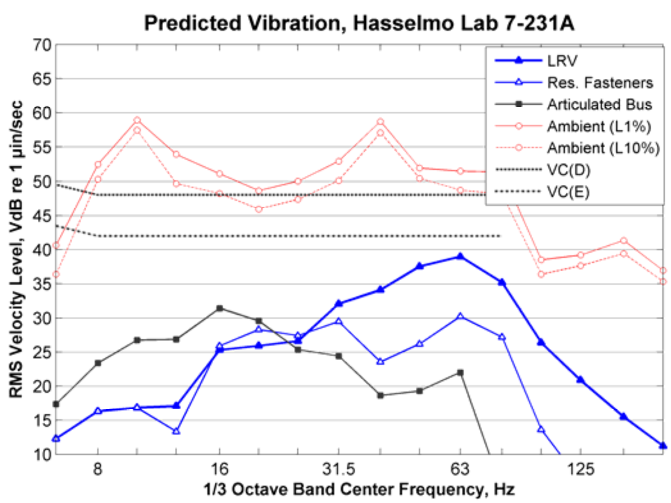


Figure 98: Predicted Vibration inside Room 7-231A at Nils Hasselmo Hall

6.19 Philip Wangensteen Building Room 7-218, Test A7

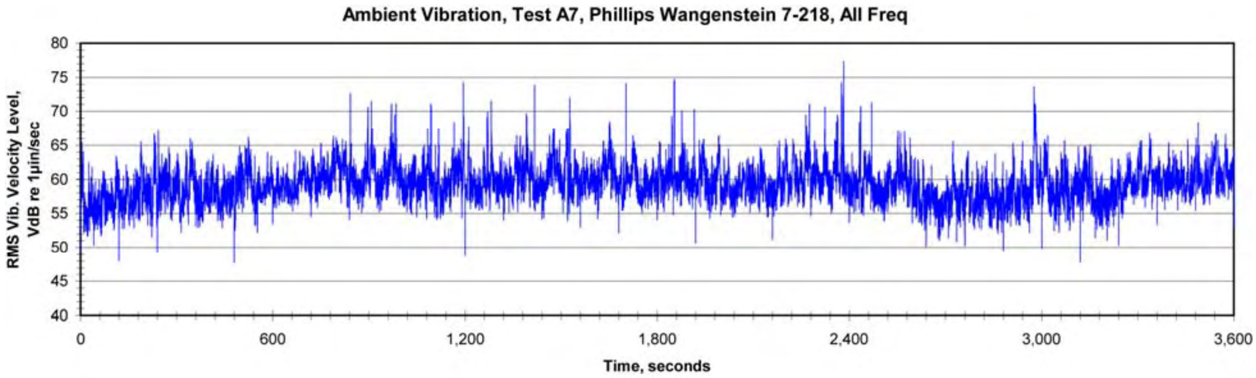
Room 7-218 is located on the seventh floor of the Philip Wangensteen Building. The concern is for a 600 MHz superconducting Varian NMR spectroscopy equipment. A one hour ambient vibration measurement was performed adjacent to the lab on October 14, 2008. The lab is approximately 400 feet from Washington Avenue.

The time history and the vibration spectra of the ambient vibration are shown in Figure 100. The vibration levels were measured at 60±5 VdB. The main vibration source and wide variance in levels was pedestrian traffic in the vicinity of the measurement location. The maximum levels were below 16 Hz as well as a peak at 63 Hz.

The predicted vibration levels inside Room 7-218 are shown in Figure 101. The predictions use the 200 ft LSTM from the Delaware NMR propagation test and assumes a 10 decibel outdoor-to-indoor vibration reduction. This is a very conservative assumption because the building is considerably farther from Washington Avenue. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 2 decibels higher for a 3-car consist.

The predicted levels are below the ambient vibration at all frequencies indicating that no mitigation is required to maintain the existing ambient vibration environment.

Figure 99: Vibration Measurement outside Room 7-218 at Philip Wangensteen Building



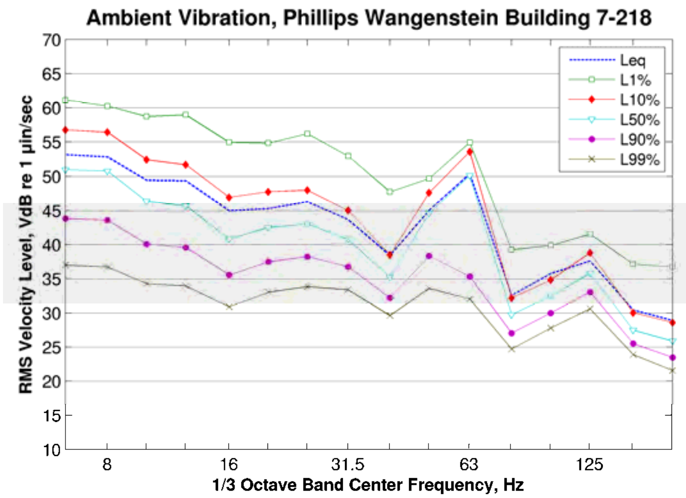


Figure 100: Ambient Vibration inside Room 7-218 at the Philip Wangensteen Building

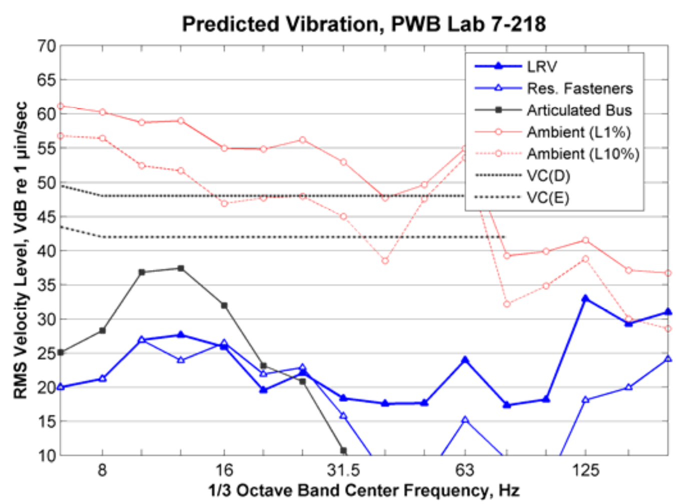


Figure 101: Predicted Vibration inside Room 7-218 at the Philip Wangensteen Building

6.20 Moos Tower Room 5-145B, Test A8

Room 5-145B is located on the fifth floor of Moos Tower. The concern is for microscopy equipment. A one hour ambient vibration measurement was performed on October 15, 2008. The lab is approximately 215 feet from Washington Avenue.

The time history and the vibration spectra of the ambient vibration are shown in Figure 103. The vibration levels were 57±5 VdB and had peaks that reached a maximum of 71 VdB. The source of the peaks was pedestrian traffic in the vicinity of the measurement location. The maximum levels were caused by a peak at 63 Hz.

The predicted vibration levels inside Room 5-145B are shown in Figure 104. The predictions use the 215 ft LSTM from the Union Street propagation test and assumes a 10 decibel outdoor-to-indoor vibration reduction. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1.5 decibels higher for a 3-car consist.

Without mitigation, the predicted LRV vibration is lower than the ambient at frequencies below 125 Hz. The predicted levels do not exceed the impact criteria and vibration mitigation is not required.

Figure 102: Accelerometer on the floor of Moos Tower Room 5-145B

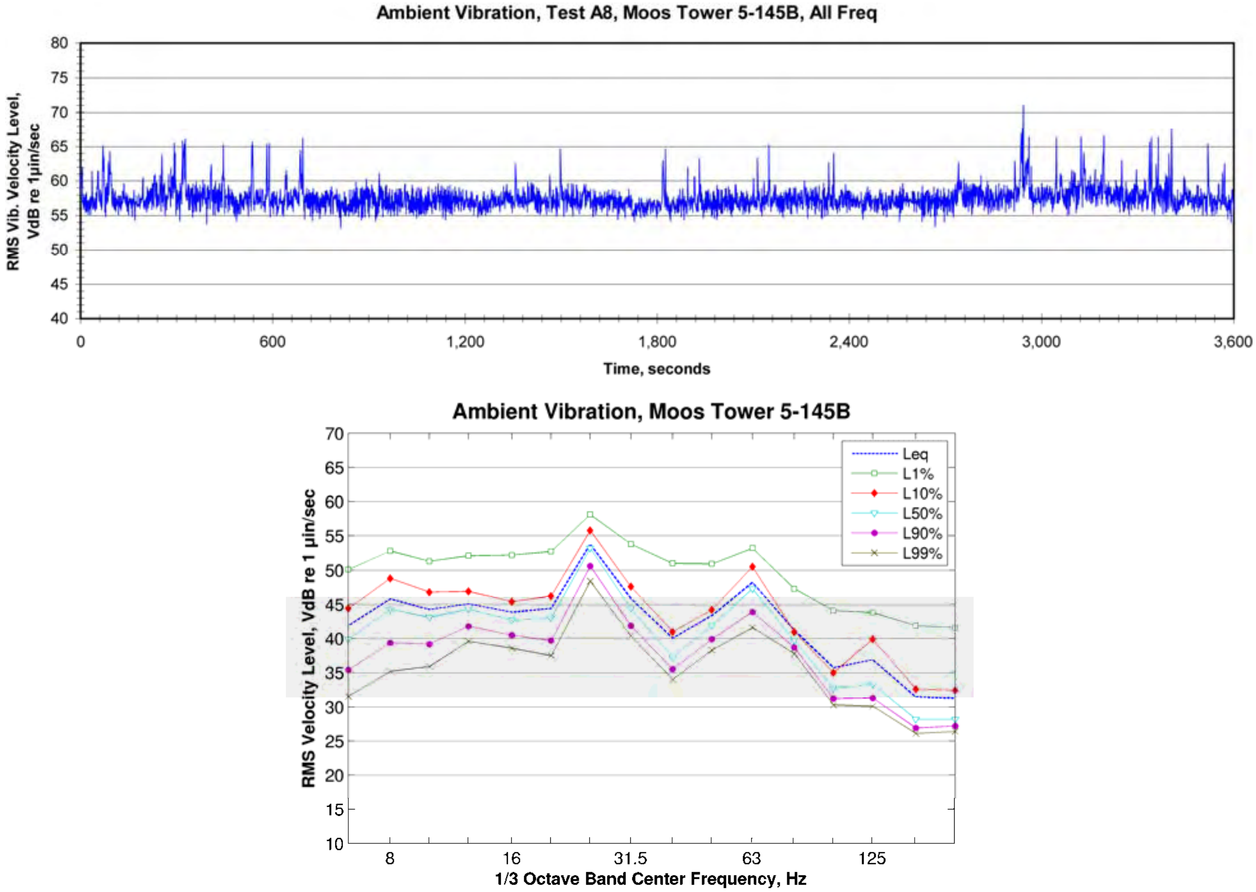


Figure 103: Ambient Vibration inside Room 5-145B at Moos Tower

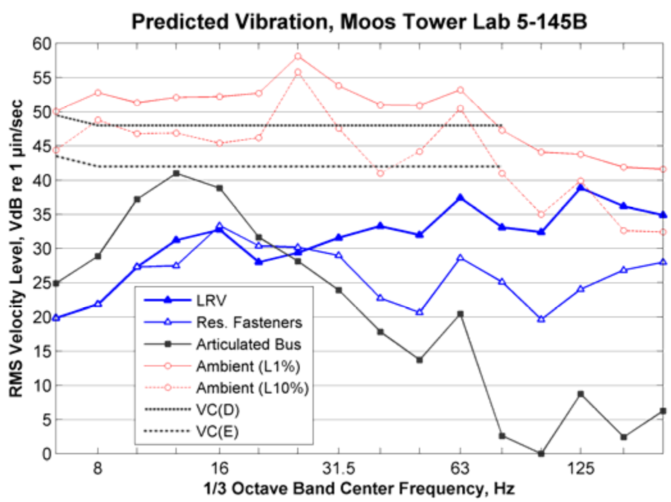


Figure 104: Predicted Vibration inside Room 5-145B at Moos Tower

6.21 Moos Tower Room 5-245A, Test A9

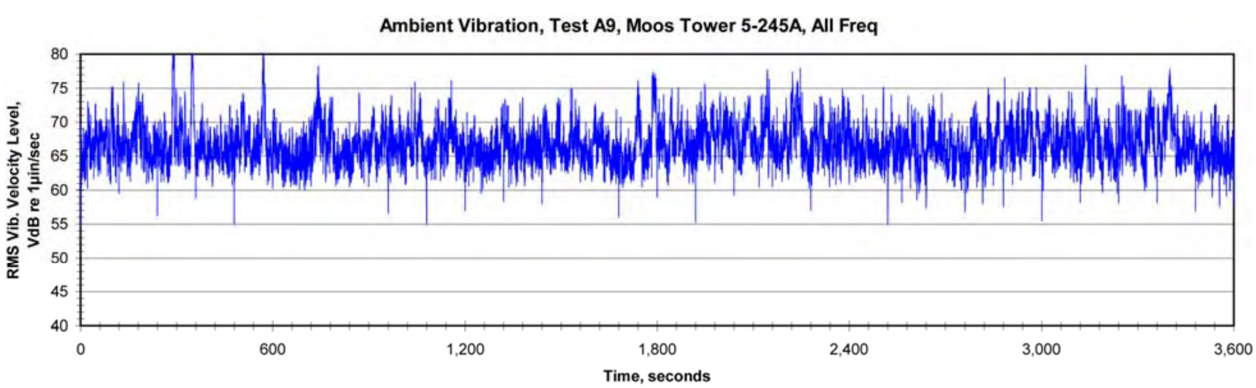
A one hour ambient vibration measurement was performed on October 15, 2008 in Room 5-245A in Moos Tower. The concern was for sensitive microscopy equipment located on the fifth floor of the building. The lab is approximately 190 feet from Washington Avenue.

The time history and the vibration spectra of the ambient vibration are shown in Figure 106. The vibration levels were 67±10 VdB. The main vibration source was human activity within the room at the time of the measurement. The maximum levels were below 16 Hz and a peak at 25 Hz.

The predicted vibration levels inside Room 5-245A are shown in Figure 107. The predictions are based on the LSTM from the Union Street propagation test and assume a 10 decibel outdoor-to-indoor vibration reduction. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1.5 decibels higher for a 3-car consist.

Without mitigation, the predicted LRV vibration is equivalent to or lower than the ambient at frequencies below 125 Hz. No vibration mitigation is required for this space.

Figure 105: Vibration Measurement on the Floor of Moos Tower 5-245A



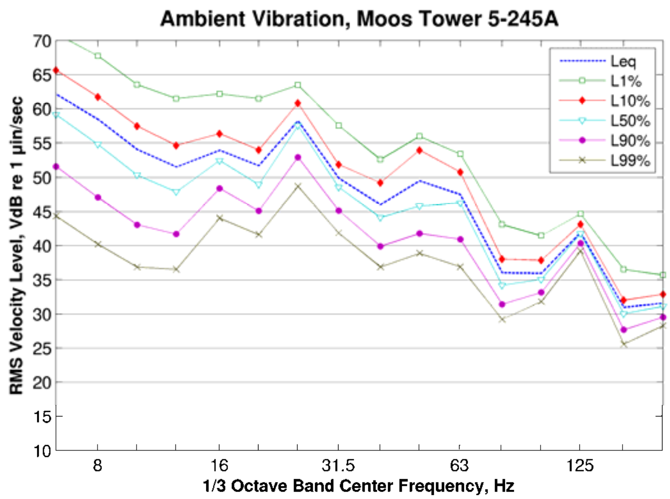


Figure 106: Ambient Vibration inside Room 5-245A at Moos Tower

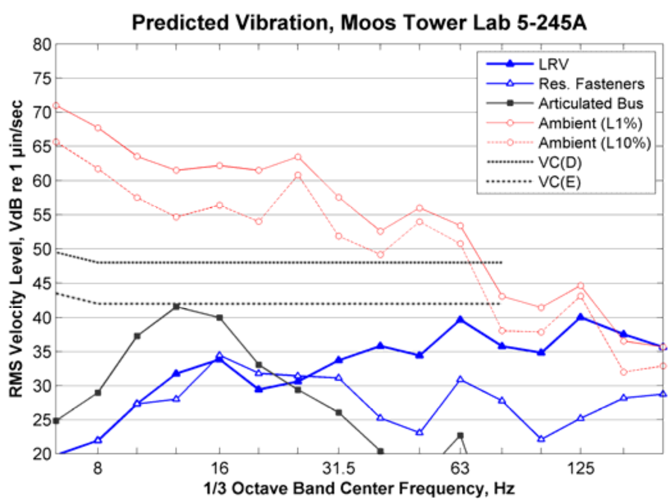


Figure 107: Predicted Vibration inside Room 5-245A at Moos Tower

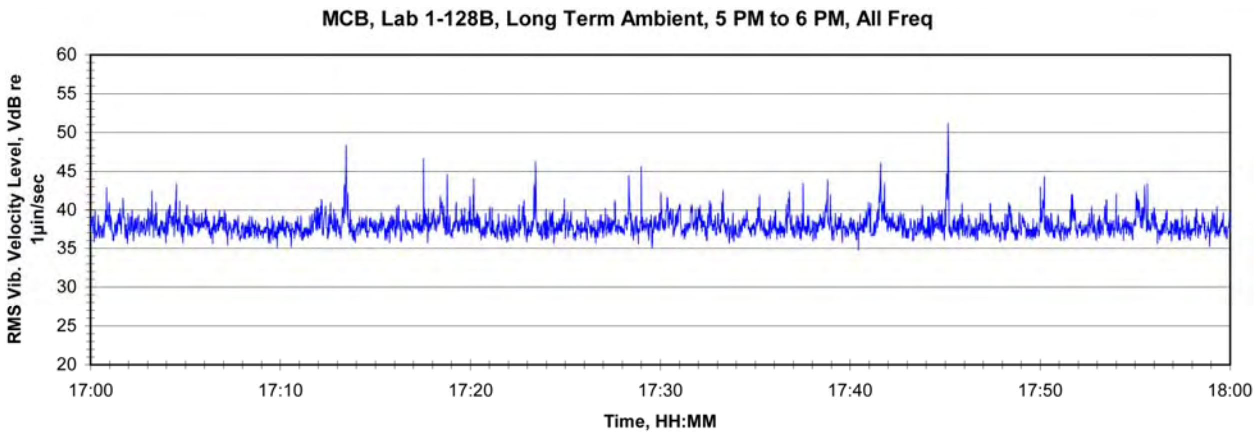
6.22 Molecular and Cellular Biology Room 1-128B, Test A10

An ambient vibration measurement was taken over 18 hours in the Basement of the Molecular and Cellular Biology Building on October 15 and October 16, 2008. Room 1-128B is part of the Animal Research Department and houses mice. Professor Gammill's concern is that any change to the lab's existing ambient environment could detrimentally affect the breeding habits of the mice. The lab is approximately 120 feet from Washington Avenue.

The time history of typical daytime and nighttime ambient vibration is shown in Figure 109 and Figure 110 respectively. The daytime vibration levels were typically 38±2 VdB with occasional peaks up to 45 to 50 VdB. These are some of the lowest vibration levels recorded at any of the U of M research spaces that are not on isolated slabs specifically designed to provide a low vibration environment. Nighttime levels were slightly lower daytime levels with fewer peaks. The peaks appear to have been caused by human activity in the room during the daytime The vibration spectra of the ambient vibration are shown in Figure 111. The background vibration has a peak at 10 Hz that could be caused by buses traffic on Washington Avenue.

The predicted vibration levels inside Room 1-128B are shown in Figure 112. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1.5 decibels higher for a 3-car consist. The predicted LRV levels with and without mitigation exceed the ambient levels. However, the vibration level without mitigation is well below the VC-E curve which is considered suitable for highly sensitive imaging equipment and is well below the threshold of perception of for mammals. As an example, Ref. 8 indicates that lab animals, including breeding mice, are not affected by vibration up to at least 73 VdB (4,500 µin/sec.), which is approximately 25 decibels higher than the predicted vibration levels from LRV operations. The conclusion is that the LRV vibration is very unlikely to affect the lab animals.

Figure 108: Vibration Measurement on the Floor of MCB Room 1-128B



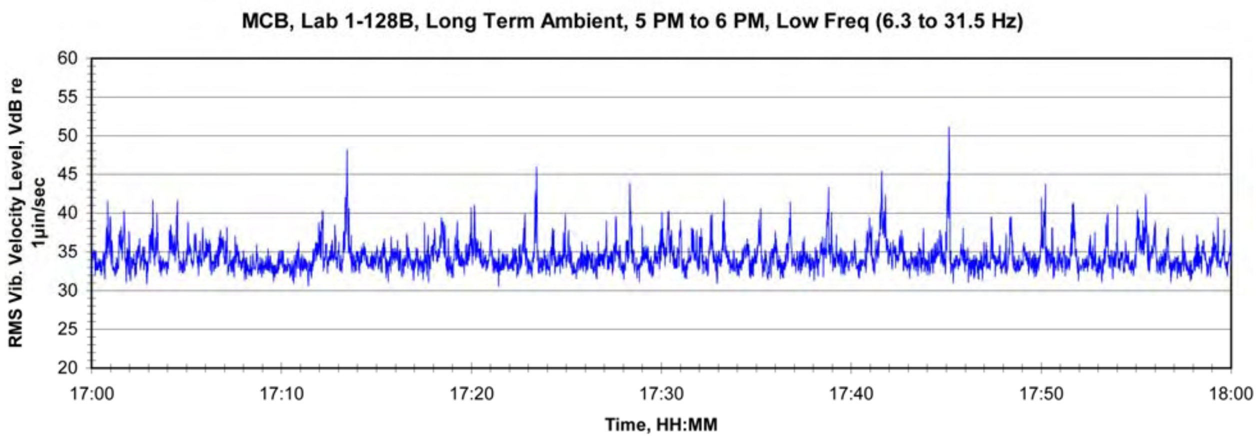


Figure 109: Time History of Vibration inside Room 1-128B at MCB, Typical Day Time

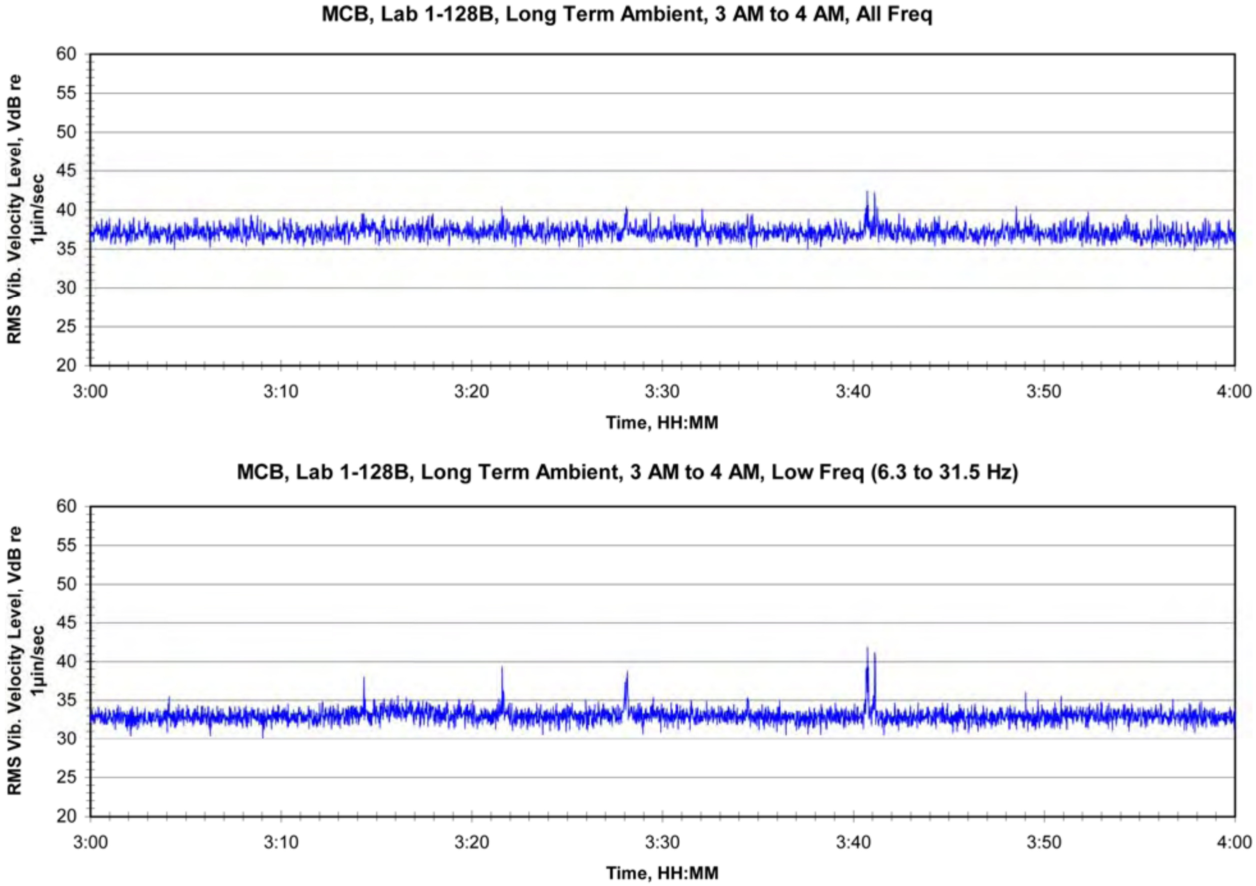


Figure 110: Time History of Vibration inside Room 1-128B at MCB, Typical Night Time

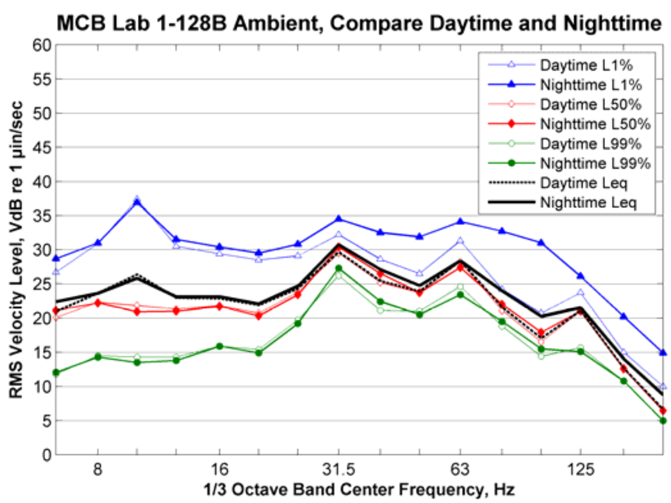


Figure 111: Ambient Vibration Spectrum inside Room 1-128B at MCB

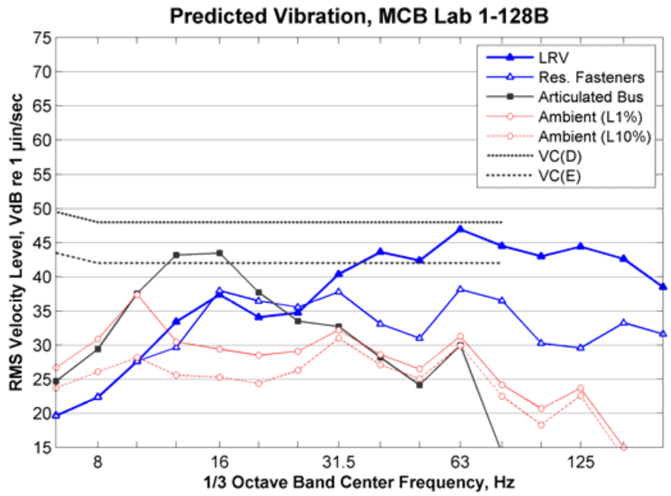


Figure 112: Predicted Vibration inside Room 1-128B at the Molecular and Cellular Biology Building

6.23 Moos Tower Room 5-108A, Test A11

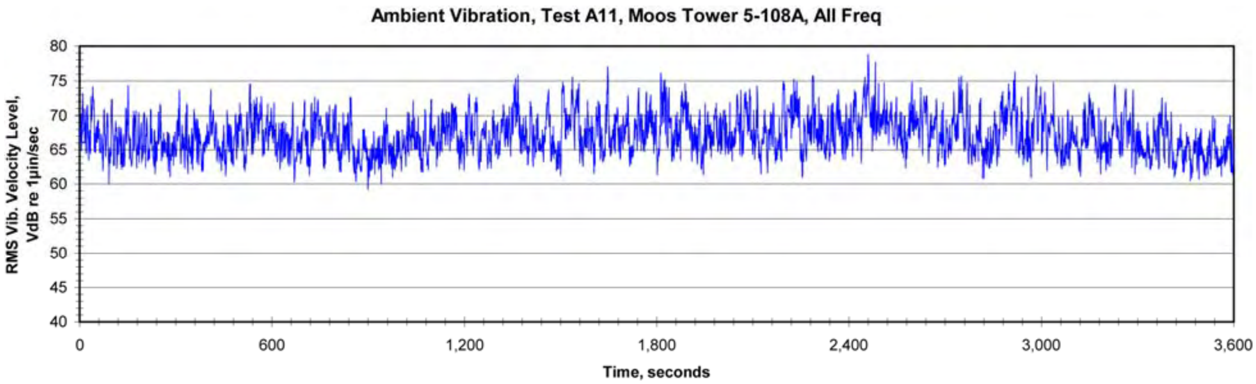
A one hour ambient vibration measurement was performed on October 16, 2008 in Room 5-108A in Moos Tower. The concern was for sensitive microscopes located on the fifth floor of the building. The lab is approximately 230 feet from Washington Avenue.

The time history and the vibration spectra of the ambient vibration are shown in Figure 114. The main vibration source was pedestrian traffic in the vicinity of the measurement location. The maximum levels below 31.5 Hz were probably due to transients caused by pedestrians. The peak at 125 Hz was probably caused by mechanical equipment.

The predicted vibration levels inside Room 5-108A are shown in Figure 115. The predictions use the 230 ft LSTM from the Union Street propagation test and assumes a 10 decibel outdoor-to-indoor vibration reduction. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1.5 decibels higher for a 3-car consist.

Without mitigation, the predicted LRV vibration is equivalent to or lower than the ambient at frequencies. No mitigation is needed to maintain the vibration environment in this space.

Figure 113: Vibration Measurement on the Floor of Room 5-108A at Moos Tower



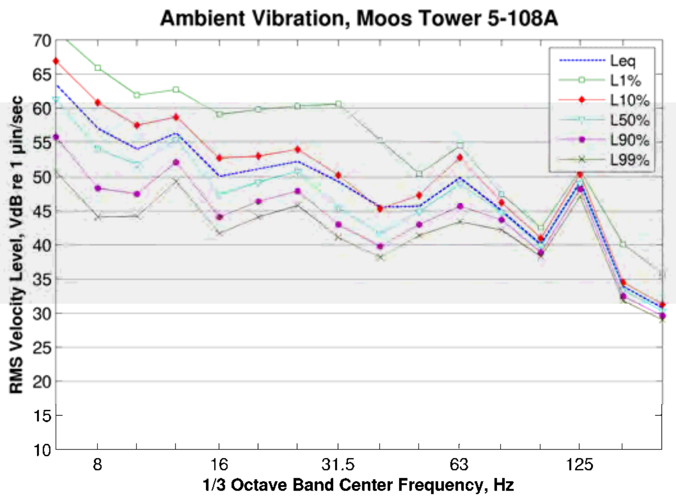


Figure 114: Ambient Vibration inside Room 5-108A at Moos Tower

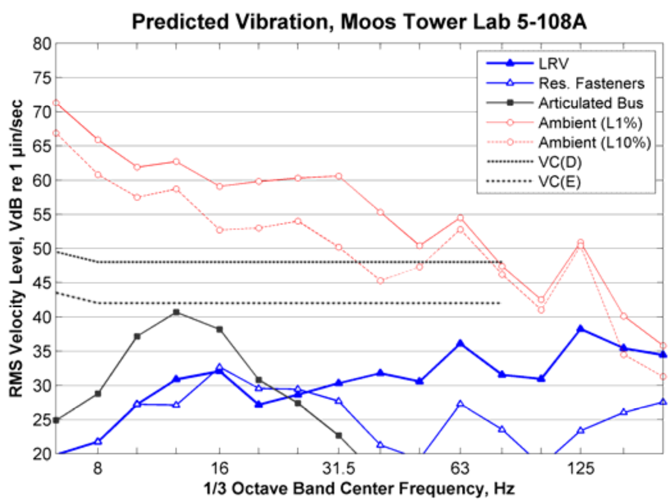


Figure 115: Predicted Vibration inside Room 5-108A at Moos Tower

6.24 Moos Tower Room 5-235D, Test A12

Room 5-235D is located on the fifth floor of Moos Tower. Microscopy equipment is located within the lab on an isolation table. A one hour ambient vibration measurement was performed on October 16, 2008. The lab is approximately 230 feet from Washington Avenue.

The time history and vibration spectra are shown in Figure 117. Vibration levels were consistently between 53 and 60 VdB with intermittent peaks over the entire measurement. There was human activity near the measurement location that is the most likely source of the peaks. At the halfway point of the measurement, there was drop in overall levels for frequencies above 30 Hz followed by a return to their original levels towards the end of the measurement. This would indicate that some equipment or machinery was being used in the vicinity of the measurement location that was cycled off and back on. A refrigerator was operating in the adjacent room could have been responsible for this. The background vibration spectra are relatively flat with a minor peak at 63 Hz.

The predicted vibration levels inside Room 5-235D are shown in Figure 118. The predictions are based on the LSTM from the Delaware NMR propagation test and assume a 10 decibel outdoor-to-indoor vibration reduction. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1.5 decibels higher for a 3-car consist.

Without mitigation, the predicted LRV vibration is equivalent to or lower than the ambient at frequencies below 125 Hz. The conclusion is that no mitigation is required to maintain the vibration environment in this space.

Figure 116: Measurement Location on the Floor of Moos Tower Room 5-235D

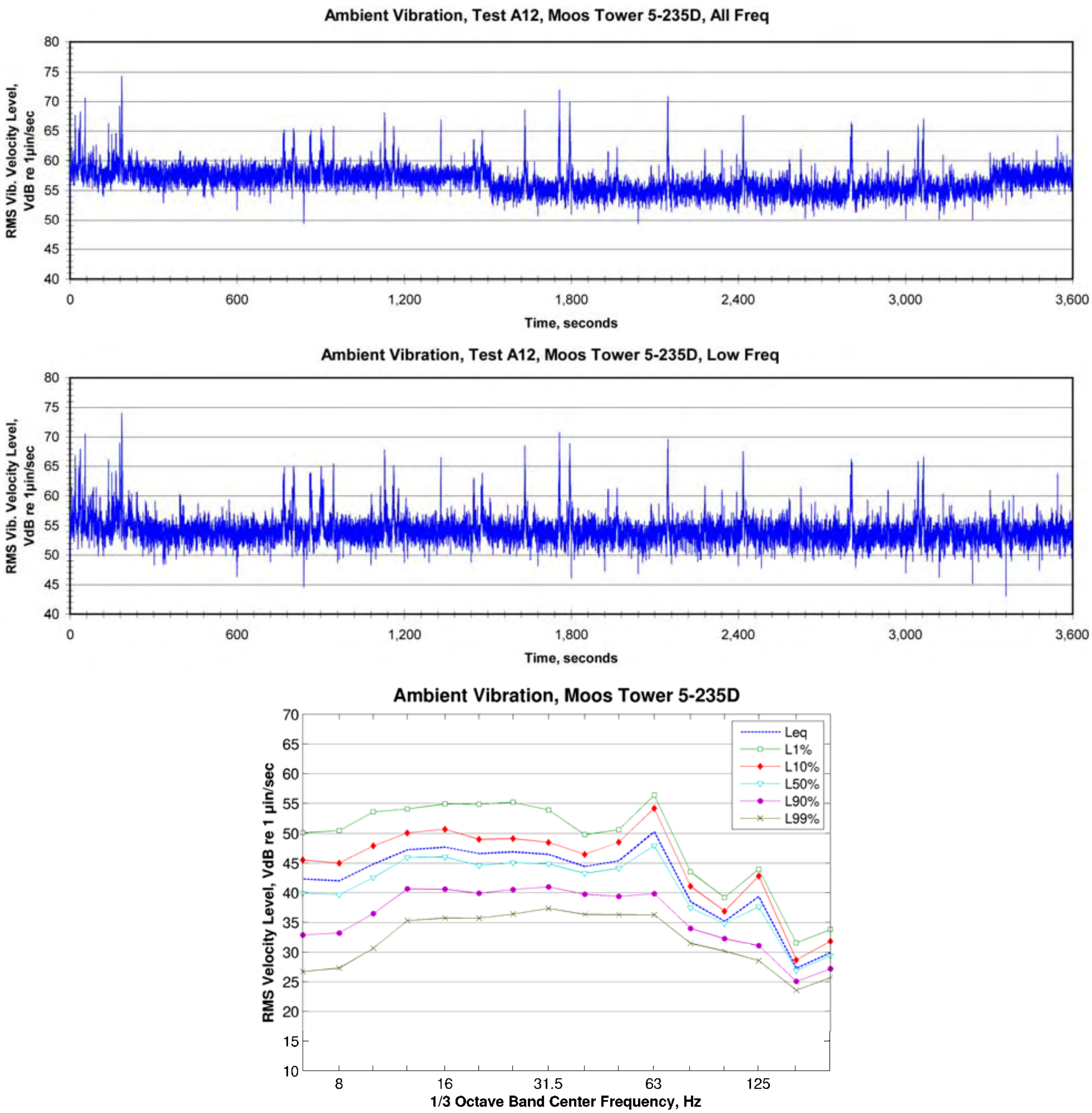


Figure 117: Ambient Vibration inside Moos Tower Room 5-235D

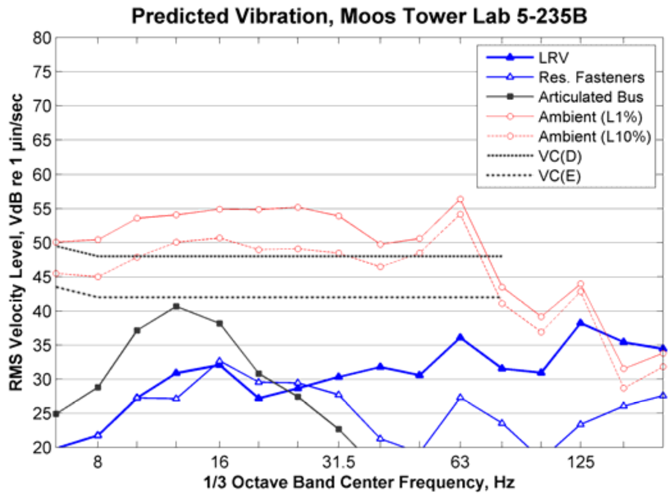


Figure 118: Predicted Vibration inside Room 5-235D at Moos Tower

6.25 Electrical Engineering and Computer Science Rooms 2-270 and 2-274, Test A13

Rooms 2-270 and 2-274 are adjoining labs located on the second floor of the Electrical Engineering and Computer Science Building. The lab is approximately 250 feet from Washington Avenue. The concern is for the atomic force microscope and optical tweezers located on isolation tables. A one hour ambient vibration measurement was performed on October 15, 2008. Two accelerometers were used, one located next to each of the vibration isolation table with the sensitive equipment.

The time history and the vibration spectra for Room 2-270 and 2-274 are shown in Figure 121 and Figure 122. The vibration levels at both locations are nearly identical with vibration levels of approximately 53 VdB ±6 decibels. There was mechanical equipment cycling on and off throughout the measurement that had generated vibration in the 63 Hz 1/3 octave band. Referring to the graphs showing the vibration at all frequencies and just at the low frequencies (6.3 to 31.5 Hz), it is evident that there was substantial fluctuation in the low frequency vibration. The low-frequency vibration peaks at 16 Hz, which is consistent with the vibration being caused by bus traffic on Washington Avenue.

The predicted vibration levels inside Room 7-218 are shown in Figure 101. The predictions use the LSTM from the Union Street propagation test and assume a 10 decibel outdoor-to-indoor vibration reduction. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 1.5 decibels higher for a 3-car consist.

Without mitigation, the predicted LRV vibration is substantially lower than the ambient vibration level at frequencies below 125 Hz. The conclusion is that vibration mitigation is not required.

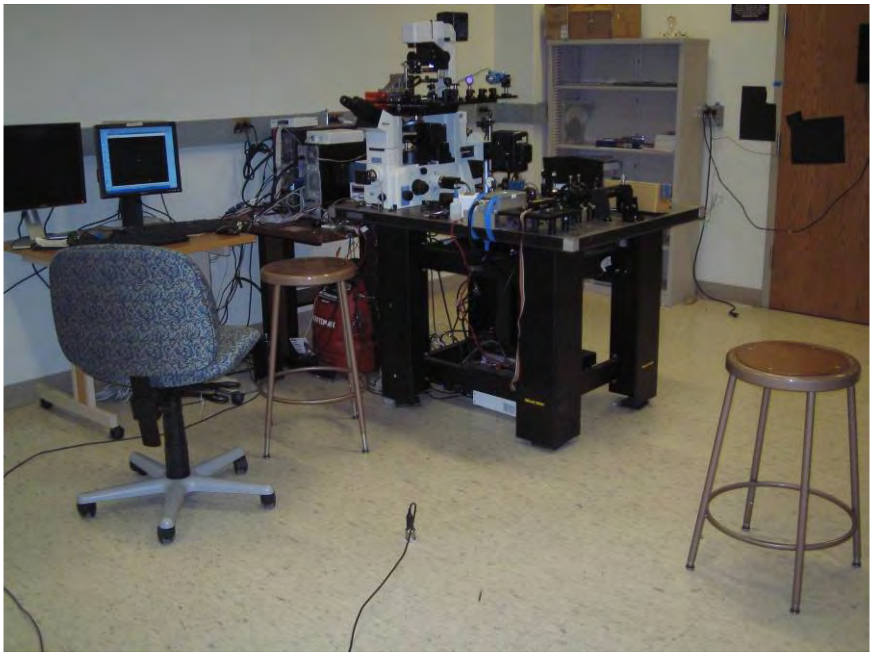


Figure 119: Measurement on the Floor of EECS 2-270

Figure 120: Measurement on the Floor of EECS 2-274

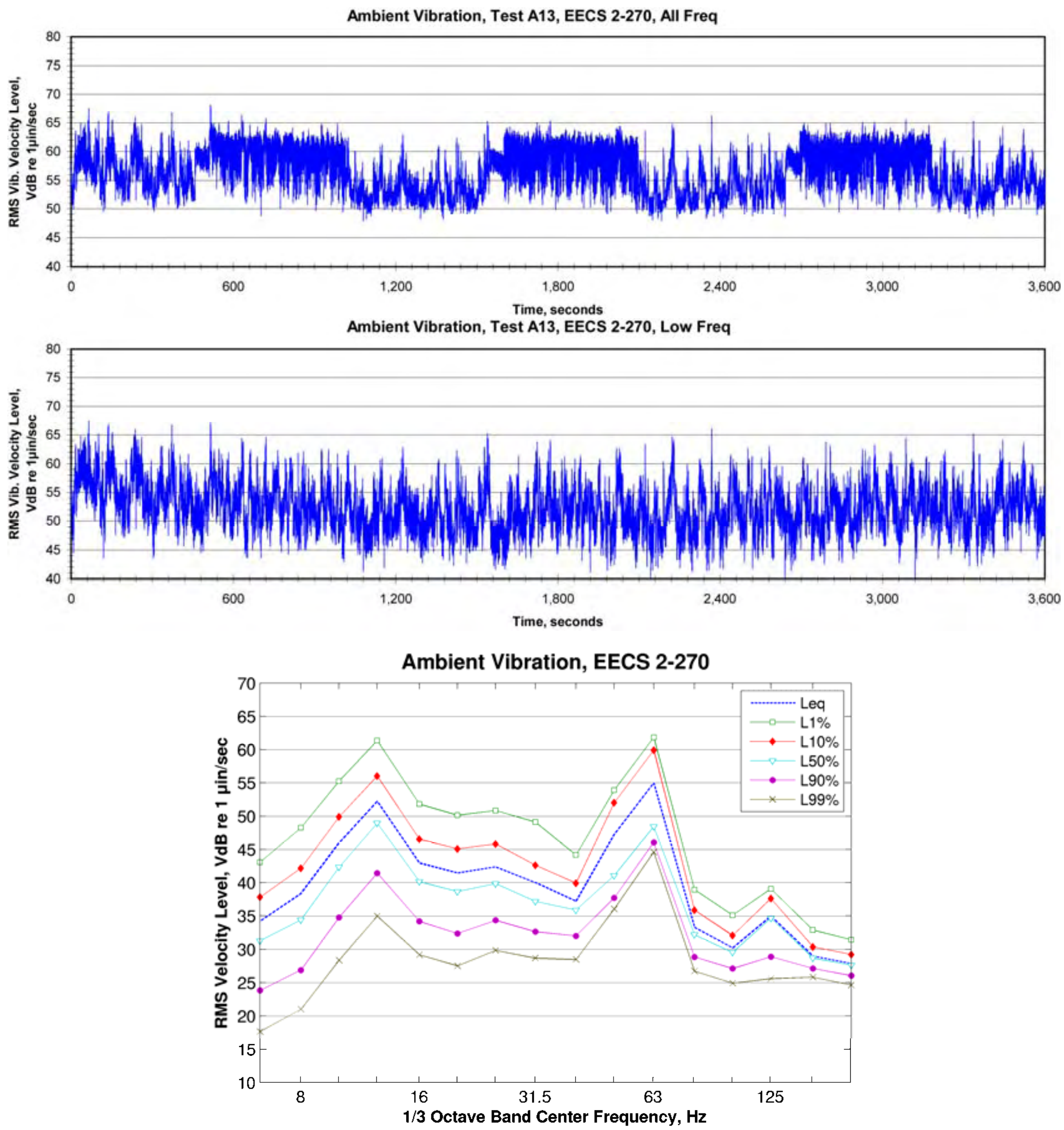


Figure 121: Ambient Vibration at EECS 2-270

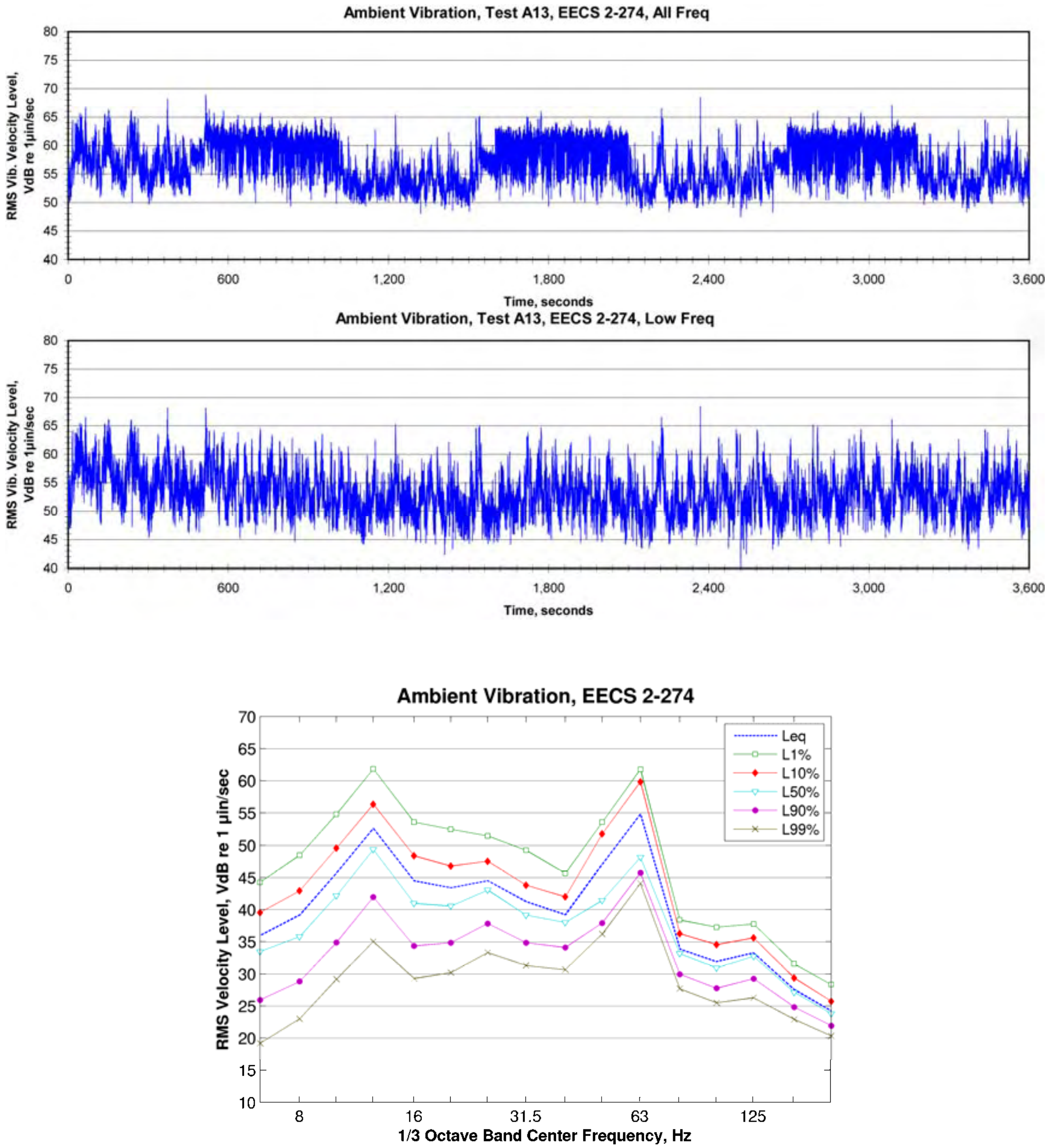


Figure 122: Ambient Vibration at EECS Room 2-274

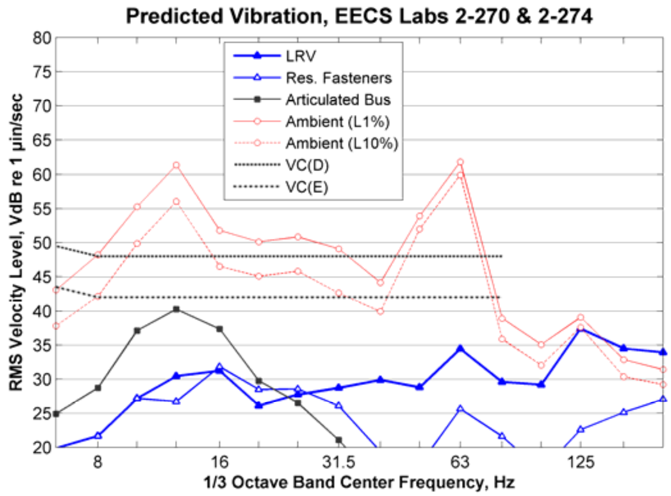


Figure 123: Predicted Vibration inside Rooms 2-270 and 2-274 at the Electrical Engineering and Computer Science Building

6.26 Amundson Hall Room 54, Test A14

A long term (19 hour) ambient vibration measurement was taken on the first floor of Amundson Hall on October 16 and October 17, 2008. The equipment of concern is a Superconducting Quantum Interference Device (SQUID) which measures subtle changes in electromagnetic fields, and a cryostat used to measure electronic properties of materials. A Scanning Probe Microscope is also scheduled for future installation in this room. The laboratory is approximately 35 feet from Washington Avenue.

The vibration level time history for the entire measurement is shown in Figure 125. The time history for a typical nighttime hour is shown in Figure 126 and for a typical daytime hour is shown in Figure 127. The peaks are probably due to traffic on Washington Avenue. The ambient vibration spectra for L1% shown in Figure 128 peaks at 12.5 Hz and is approximately 10 decibels higher than the Leq, which is further indication that the peaks are due to buses and other traffic on Washington Avenue. Referring to Figure 128, the nighttime levels are very similar to the daytime levels at 40 Hz and above. The largest difference between the daytime and nighttime levels is in the L1% at frequencies below 40 Hz, which also suggests that traffic on Washington Avenue is the dominant source of low-frequency vibration.

The predicted vibration levels inside Room 54 are shown in Figure 129. The predictions are based on the Union Street propagation test and assume a 10 decibel reduction as the vibration passes into the building structure. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 0.5 decibel higher for a 3-car consist.

Without mitigation, the predicted LRV vibration level is equivalent to or lower than the ambient vibration level at frequencies below 40 Hz. At frequencies of 40 Hz and greater, the predicted LRV vibration exceeds the existing ambient. Vibration mitigation in the form of high resilience fasteners would reduce the predicted LRV vibration levels to be equivalent to the existing ambient vibration level.

Figure 124: Measurement on the Floor of Amundson Hall Room 54

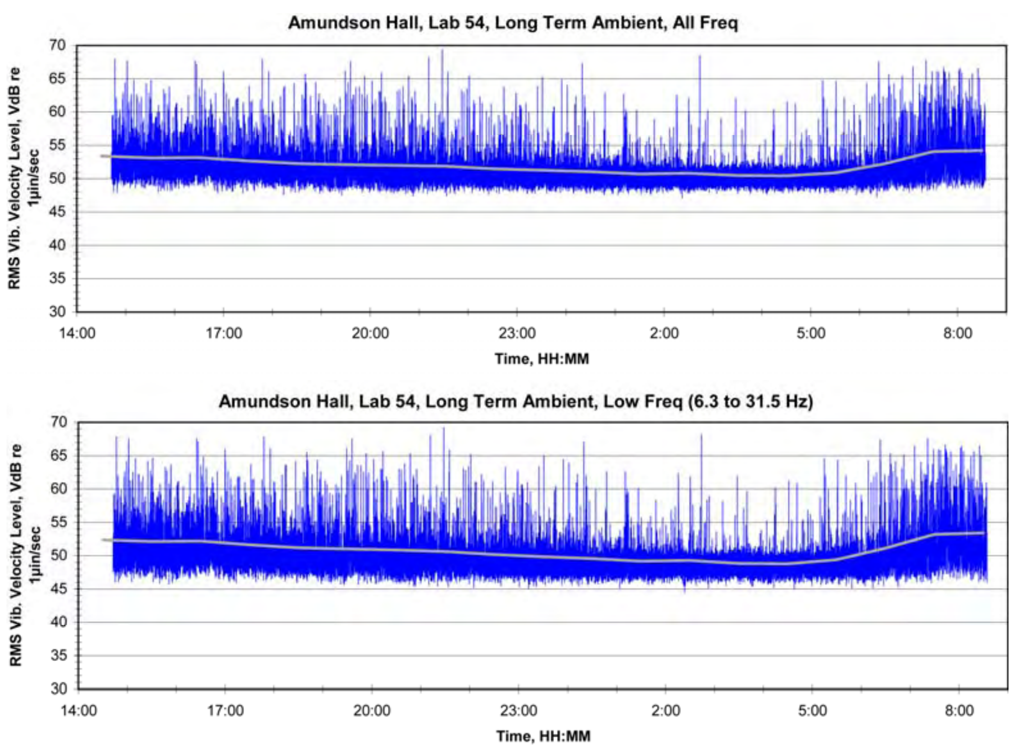
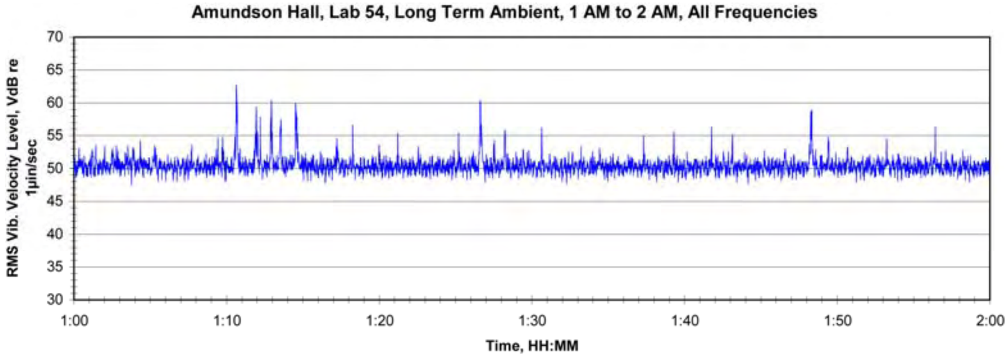


Figure 125: Time History of Ambient Measurement inside Room 54 at Amundson Hall



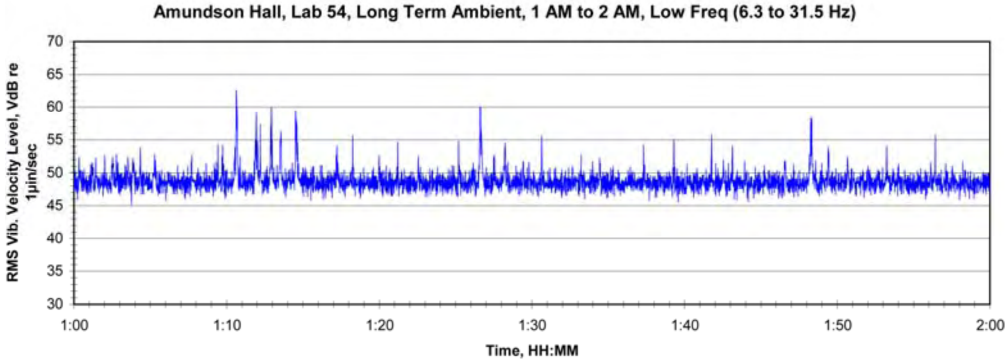
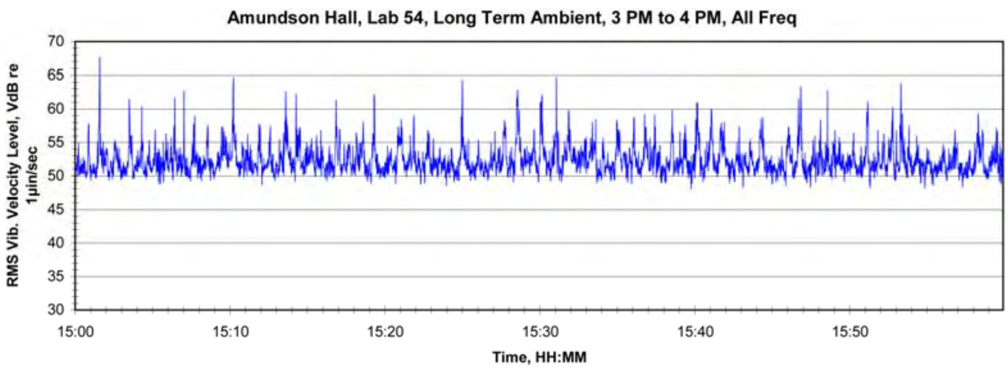


Figure 126: Ambient Vibration in Amundson Room 54, 1 AM to 2 AM



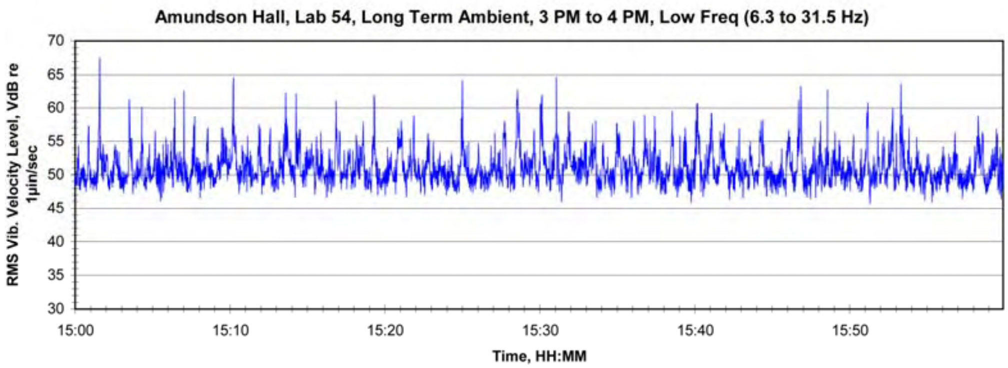


Figure 127: Ambient Vibration in Amundson Room 54, 3 PM to 4 PM

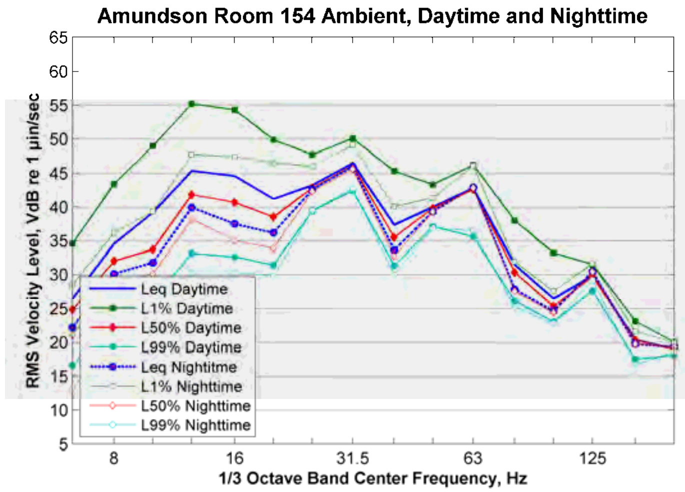


Figure 128: Ambient Vibration Spectrum inside Room 54 at Amundson Hall

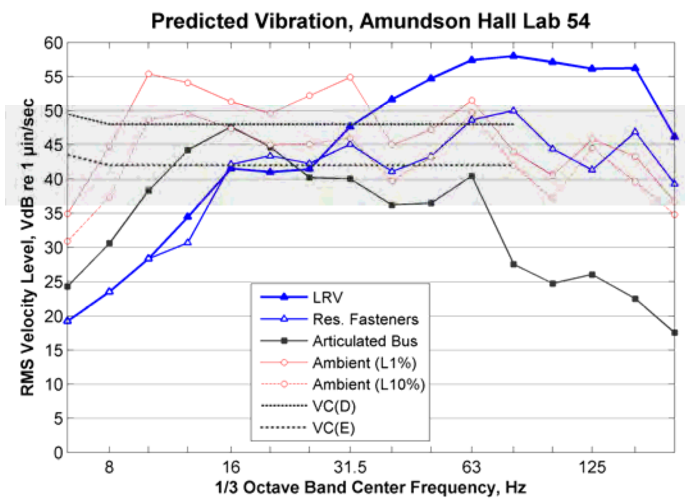


Figure 129: Predicted Vibration inside Room 54 at Amundson Hall

6.27 Amundson Hall Room 320, Test A15

Room 320 is located on the third floor of Amundson Hall. The concern is for the vibration sensitive Coulter LS 230 Particle Size Analyzer housed in this laboratory. A one hour ambient vibration measurement was performed on October 16, 2008. The lab is approximately 60 feet from Washington Avenue.

The time history and the vibration spectra of the ambient vibration are shown in Figure 131. The Vibration levels were measured at 54 VdB ±3 decibels with peaks reaching 64 VdB during the measurement. Lower frequencies between 6.3 Hz and 31.5 Hz tended to be around 3 VdB lower with the peaks at the same levels as for all frequencies. The spectra of the ambient vibration is shown in Figure 128. The background vibration between 8 Hz and 16 Hz is likely to have been caused by buses and other traffic on Washington Avenue. The vibration at higher frequencies is likely to have been caused by equipment inside the building.

The predicted vibration levels inside Room 320 are shown in Figure 132. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be less than 1 decibel higher for a 3-car consist. Without mitigation the predictions exceed the ambient and the VC-D curve at frequencies of 40 Hz and greater.

With the mitigation from resilient fasteners the predicted vibration levels are lower than or equivalent to the existing vibration at all frequencies.

Figure 130: Measurement on the Floor of Room 320 at Amundson Hall

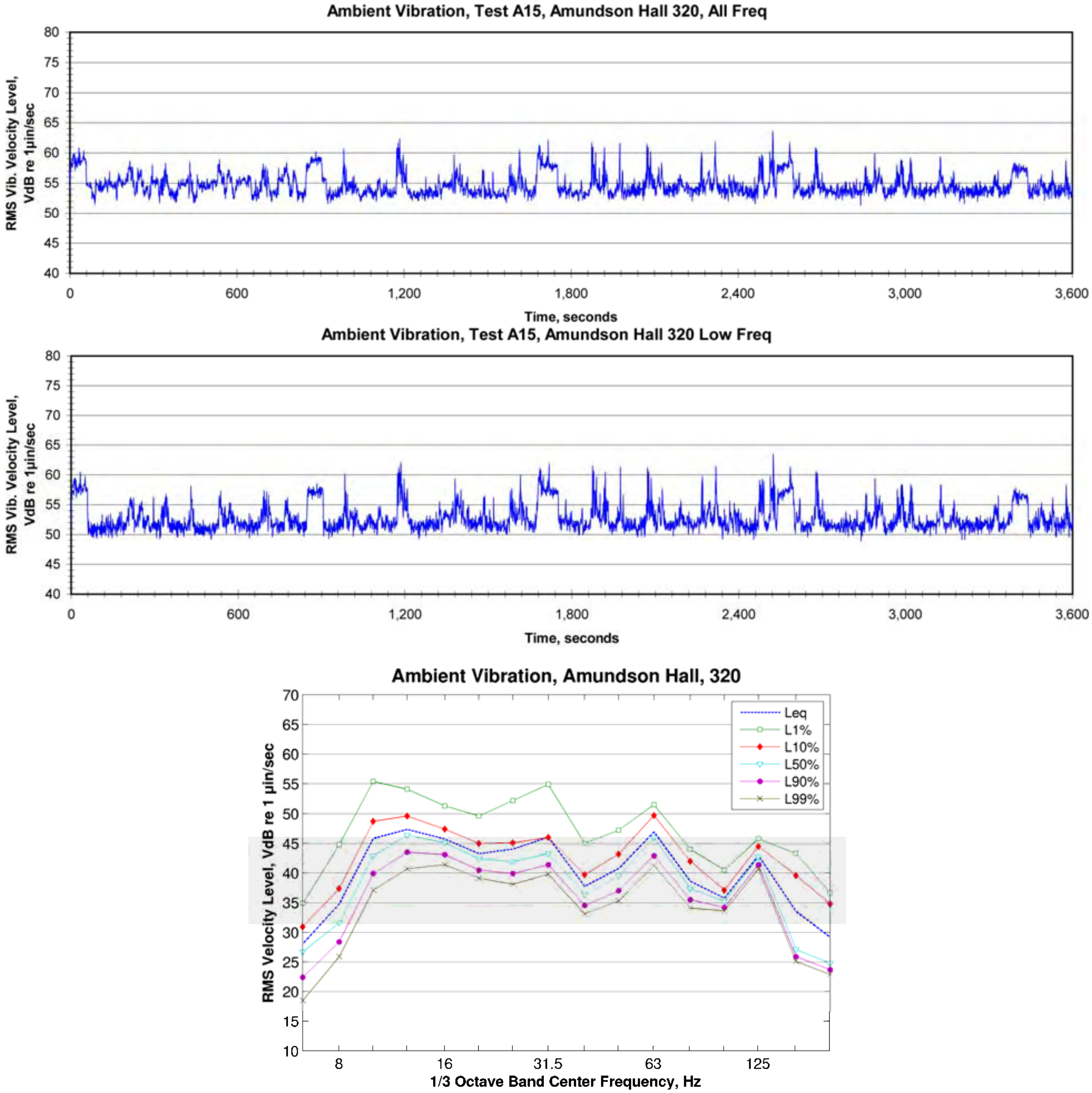


Figure 131: Ambient Vibration Spectrum inside Room 320 at Amundson Hall

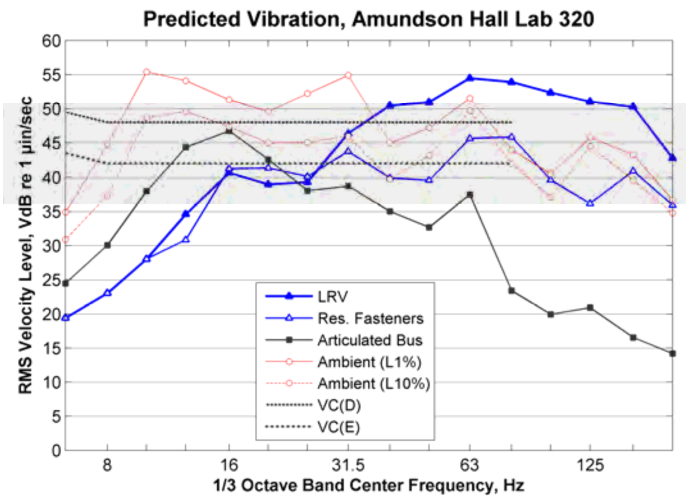


Figure 132: Predicted Vibration inside Room 320 at Amundson Hall

6.28 Amundson Hall Room 323, Test A16

A one hour ambient vibration measurement was performed in Room 323 on the third floor of Amundson Hall on October 16, 2008. The concern is for sensitive Rheometers housed in the laboratory. The laboratory is approximately 80 feet from Washington Avenue.

The time history and the vibration spectra of the ambient vibration are shown in Figure 134. The ambient vibration level was 58 VdB ±2 decibels with intermittent peaks up to 65 VdB. Figure 135 shows the spectrum of the ambient vibration. There is a strong peak at 40 Hz that was probably caused by a piece of equipment that operated for the entire measurement period. The wide fluctuation in the vibration at lower frequencies is consistent with the vibration at these frequencies being caused by buses and other traffic on Washington Avenue.

The predicted vibration levels inside Room 7-218 are shown in Figure 136. The predictions are based on the Union Street propagation test and assume a 10 decibel outdoor-to-indoor vibration reduction. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be approximately 1 decibel higher for a 3-car consist.

Without mitigation, the predicted LRV vibration is equivalent to or lower than the ambient at frequencies below 63 Hz, but exceeds the ambient and the VC-D curve at frequencies of 63 Hz and greater. Vibration mitigation in the form of high-resilience fasteners would reduce the predicted LRV vibration levels below the existing ambient vibration level and ensure that the environment in this room remains suitable the current research projects.

Figure 133: Accelerometer on the Floor of Room 323 at Amundson Hall

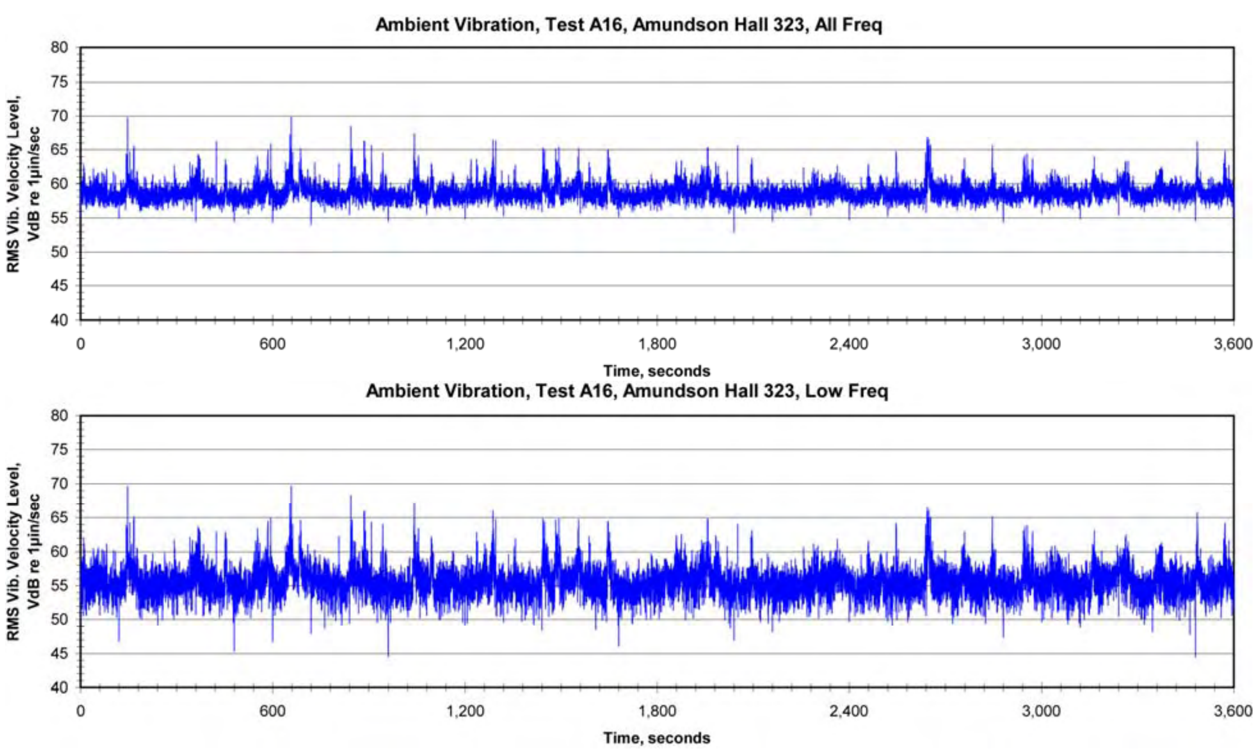


Figure 134: Time History of Ambient Measurement inside Room 323 at Amundson Hall

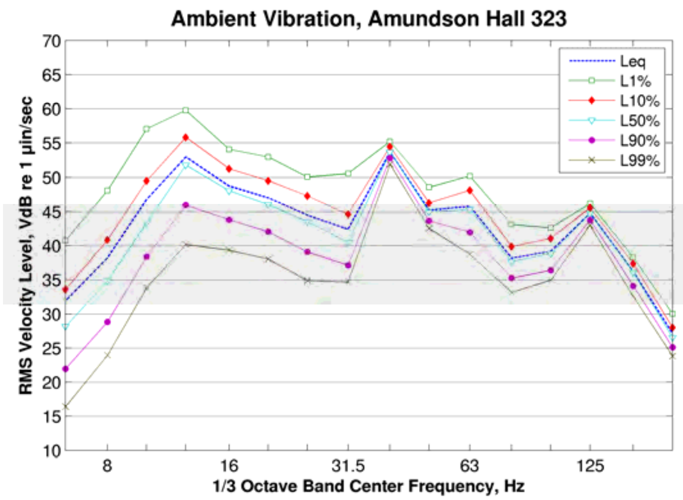


Figure 135: Ambient Vibration Spectrum inside Room 323 at Amundson Hall

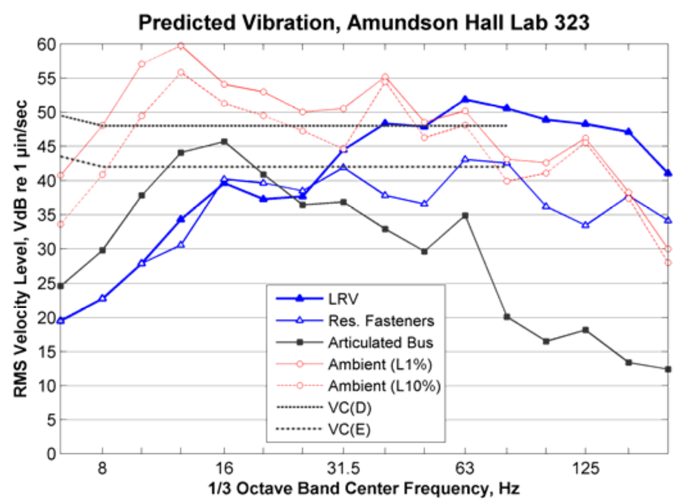


Figure 136: Predicted Vibration inside Room 323 at Amundson Hall

6.29 Tate Lab of Physics, Room S72, test A17

A one hour ambient vibration measurement was performed on October 16, 2008 in Room S72 in the Tate Lab of Physics. The concern was for sensitive equipment located in the sub-basement of the building. The lab is approximately 550 feet from Washington Avenue.

The time history and the vibration spectra of the ambient vibration are shown in Figure 138. The ambient levels were about 40 VdB decibels and no significant vibration events were noticed during the measurement. There was some pedestrian traffic that did not cause vibration levels to exceed 45 VdB. The vibration spectra were relatively flat below 63 Hz.

The predicted vibration levels inside Room S72 are shown in Figure 139. The predictions use 717 Delaware LSTM test extrapolated to a distance of 550 ft. A 10 decibel outdoor-to-indoor vibration reduction is assumed. . The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 2 decibels higher for a 3-car consist.

The predicted levels are below the ambient vibration at all frequencies indicating that no mitigation is required to maintain the existing ambient vibration environment

Figure 137: Measurement on the Floor of Room S72 at the Tate Lab of Physics

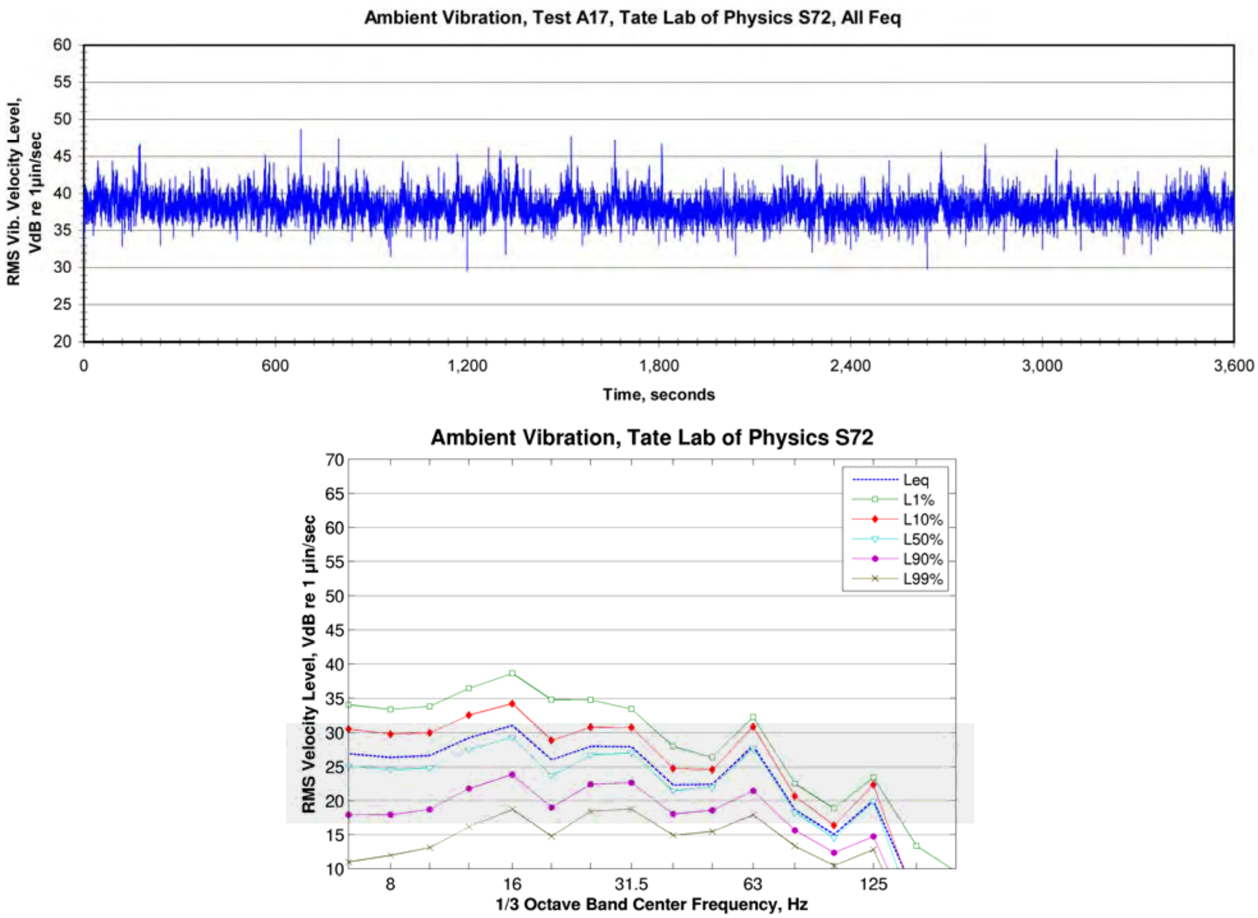


Figure 138: Ambient Vibration Spectrum inside the Tate Lab of Physics

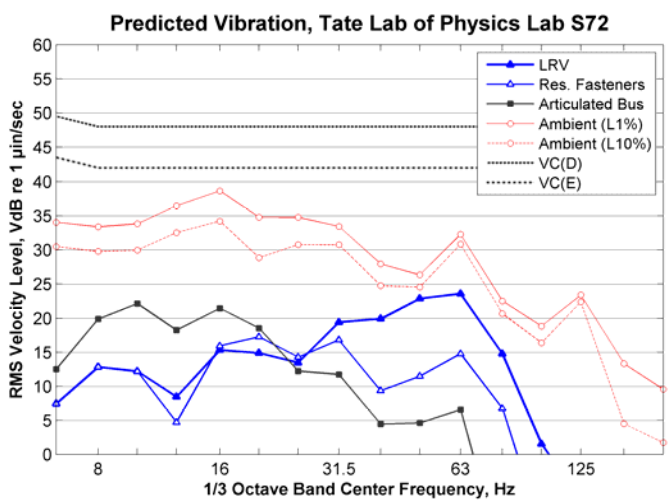


Figure 139: Predicted Vibration inside Room S72 at the Tate Lab of Physics

6.30 Dermatologic Surgery and Laser Center, Room 4-175H, Test A18

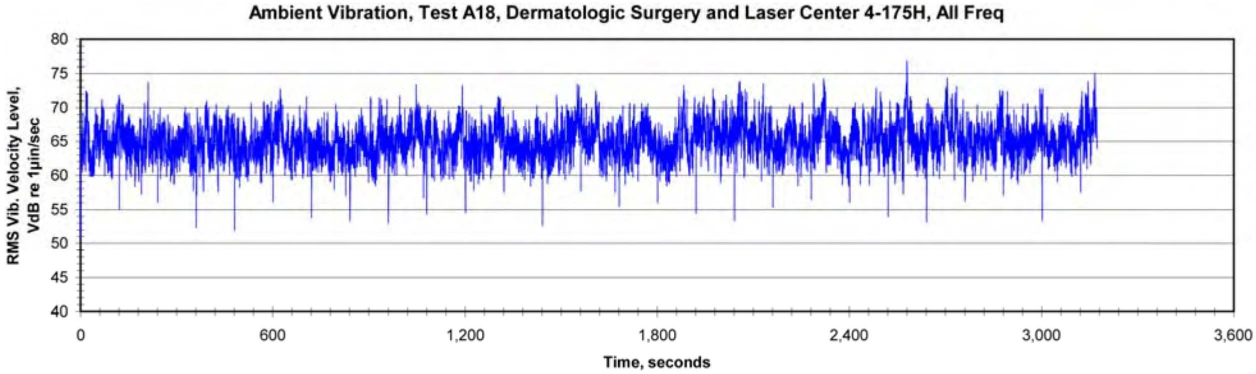
The Dermatologic Surgery and Laser Center is located on the fourth floor of the Phillips Wangensteen Building. The concern is for sensitive surgical and measurement equipment used in the center. A one hour ambient vibration measurement was performed on October 16, 2008. The lab where the accelerometer was placed is located approximately 430 feet from Washington Avenue.

The time history and the vibration spectra of the ambient vibration are shown in Figure 141. The average vibration level was approximately 65 VdB with levels fluctuating about ±5 decibels. The adjacent rooms and hallways were in use by both patients and staff. The maximum vibration levels were below 12.5 Hz and it is unclear as to the major source of the vibration.

The predicted vibration levels inside Room 4-175H are shown in Figure 142. The predictions use the extrapolated LSTM from the Union Street propagation test for a distance of 430 feet and assume a 10 decibel vibration reduction as the effect of passing into the building structure. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 2 decibels higher for a 3-car consist.

The predicted LRV vibration levels are below the ambient vibration at all frequencies indicating that no mitigation is required to maintain the existing ambient vibration environment.

Figure 140: Measurement on the Floor of Room 4-175H



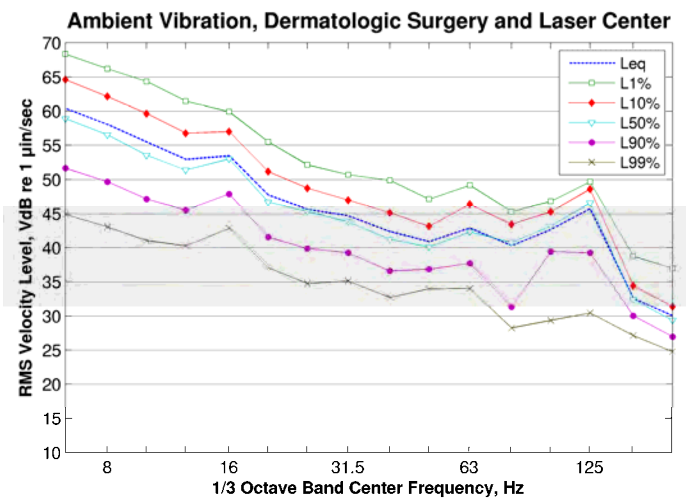


Figure 141: Ambient Vibration Spectrum inside the Dermatology Surgery and Laser Center

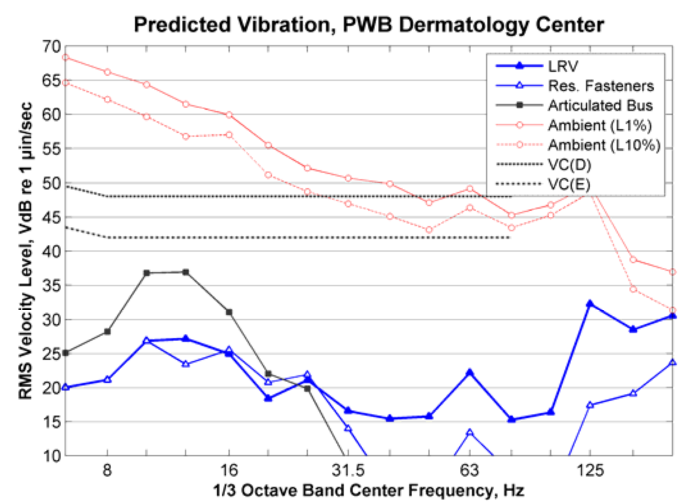


Figure 142: Predicted Vibration inside Room 4-175H at the Dermatology Surgery and Laser Center

6.31 Masonic Cancer Center Room M164, Test A19

A one hour ambient vibration measurement was performed in Room M164 on the ground floor of the Masonic Cancer Center on October 17, 2008. There are several labs within the center that house sensitive equipment. The laboratory where the accelerometer was placed is located approximately 480 feet from the light rail corridor on Washington Avenue.

The time history and one-third octave band vibration spectra of the ambient vibration are shown in Figure 144. The ambient vibration levels were averaged 55 VdB. There is a pattern with a period of approximately 6 seconds in the vibration time history that could be caused by some type of mechanical equipment within the Cancer Center. Given the consistency of the vibration, it is likely that the major vibration source was equipment within the building rather than external sources such as buses and trucks on nearby roads. The maximum vibration levels were between 16 Hz and 31.5 Hz.

The predicted LRV vibration levels inside Room M164 are shown in Figure 145. The predictions use the extrapolated LSTM from the Union Street propagation test at a distance of 480 feet and assume a 10 decibel outdoor-to-indoor vibration reduction. The predictions are for a 2-car light rail vehicle consist operating on embedded track at a speed of 25 mph. The predicted vibration levels would be 2 decibels higher for a 3-car consist.

Without mitigation, the predicted LRV vibration is lower than the ambient at frequencies below 200 Hz. The conclusion is that vibration mitigation is not required for this space.

Figure 143: Ambient Vibration Measurement on the Floor of Room M 164 at the Cancer Center

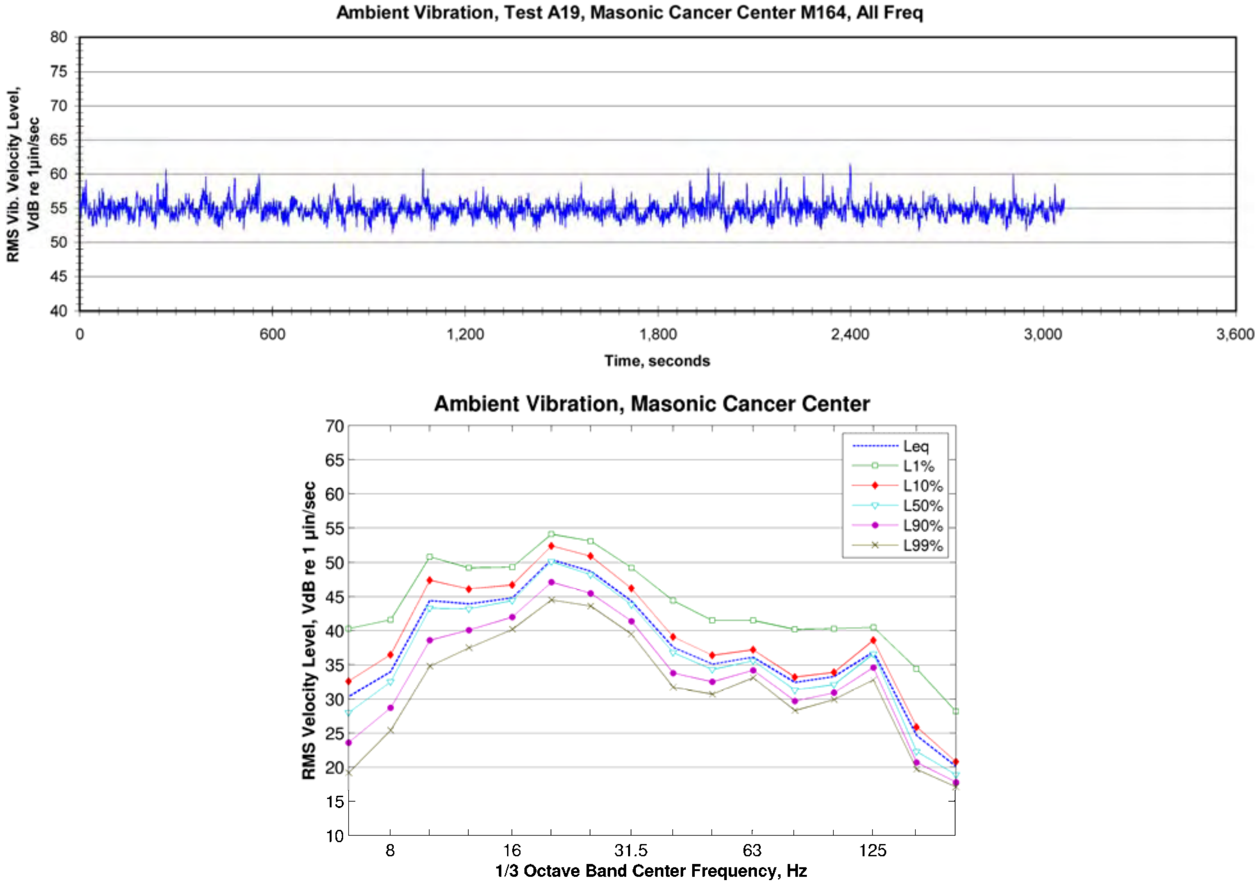


Figure 144: Ambient Vibration inside the Masonic Cancer Center

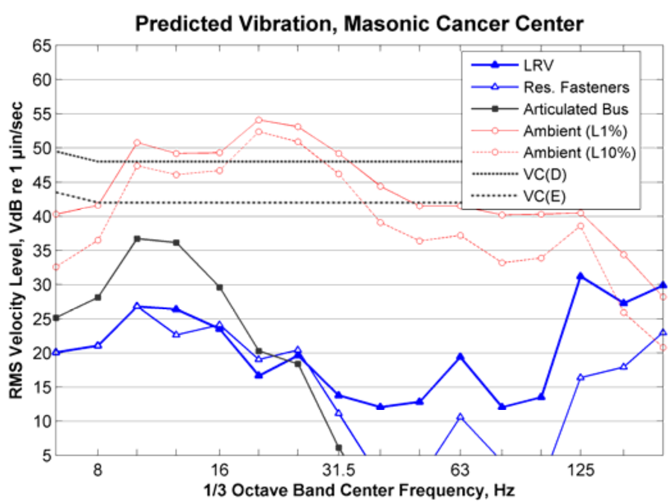


Figure 145: Predicted Vibration inside Room M164 at the Masonic Cancer Center

6.32 Imaging Center Room 1-268C, Test A20

The Imaging Center is located on the first floor of the Phillips Wangensteen Building. The concern is for MRI scanning equipment housed in the center. A one-hour ambient vibration measurement was performed next to an MRI scanner on October 17, 2008. The Lab is approximately 430 feet from Washington Avenue.

The time history and the vibration spectra of the ambient vibration are shown in Figure 147. For the first 45 minutes of the measurement, vibration levels were measured averaged 65 VdB with a fluctuation of approximately ±5 decibels. The MRI equipment was in use for the last 15-minutes of the measurement as can be seen in the time history. The main vibration source was activity from patients and nurses within the room as well as the MRI equipment. The maximum levels were at 63 Hz and below.

The predicted vibration levels inside Room 1-268C are shown in Figure 148. The predictions use the 430 ft LSTM from the Union Street propagation test and assumes a 10 decibel outdoor-to-indoor vibration reduction. Without mitigation, the predicted LRV vibration is equivalent to or lower than the ambient at frequencies below 125 Hz. No mitigation is required to maintain the vibration environment in this space.

Figure 146: Measurement on the Floor of the Imaging Center

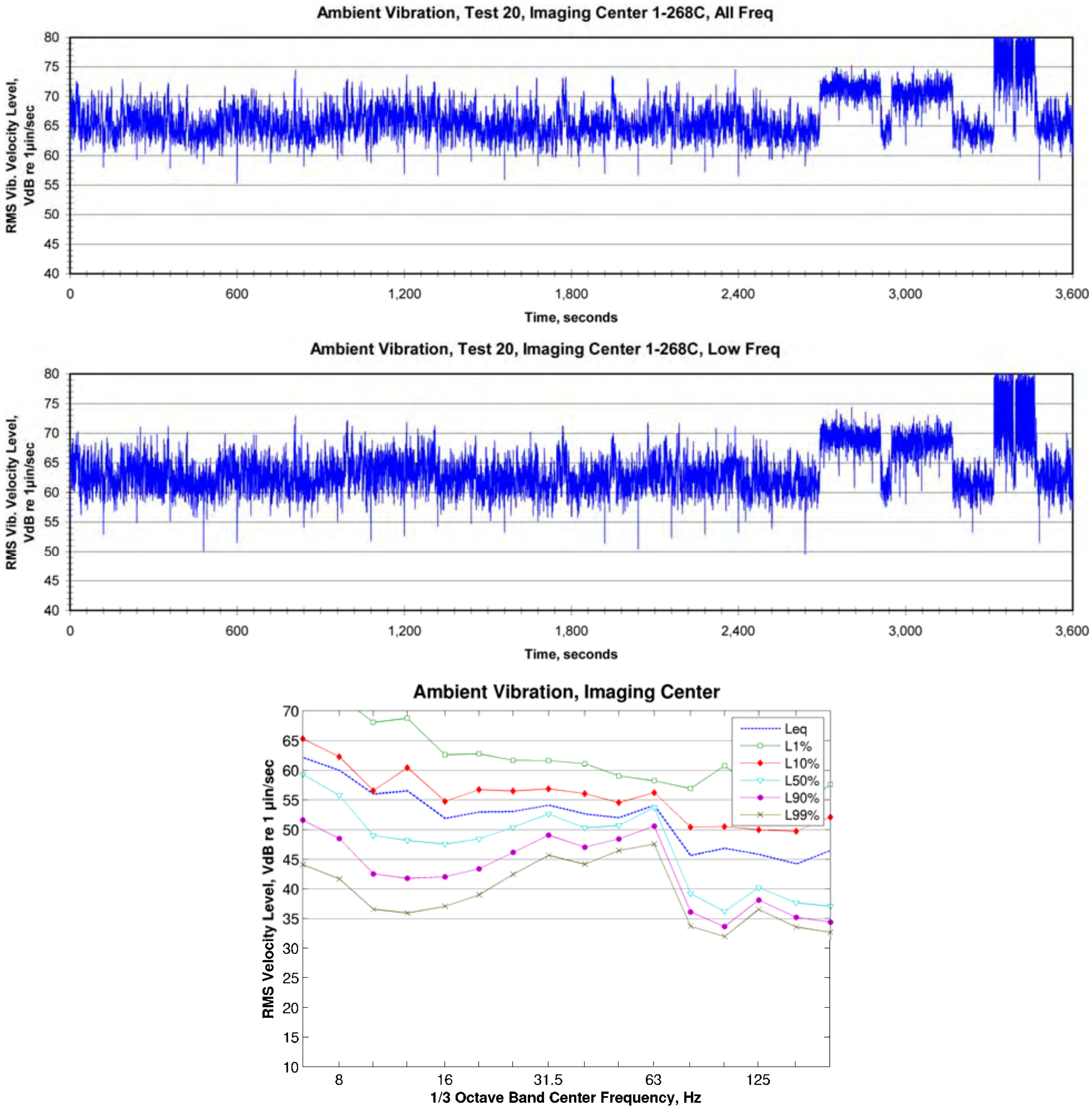


Figure 147: Ambient Vibration Spectrum inside the Imaging Center at the Philip Wangensteen Building

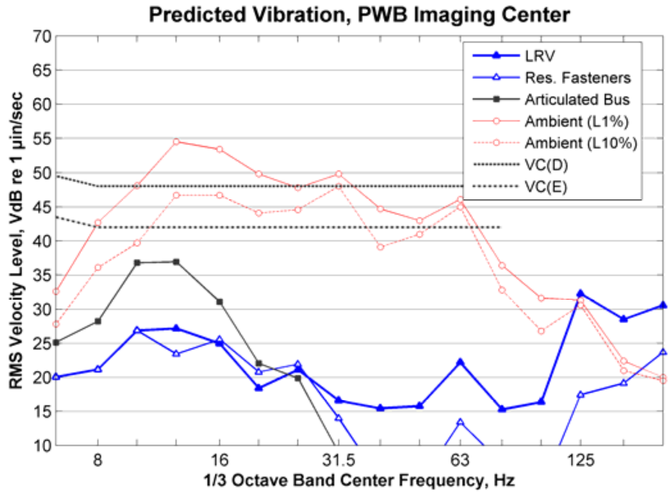


Figure 148: Predicted Vibration inside the Imaging Center at the Philip Wangensteen Building

7. MINNESOTA DEPARTMENT OF HEALTH (MDH)/MINNESOTA DEPARTMENT OF AGRICULTURE (MDA) LAB BUILDING, 601 ROBERT STREET N

The MDH/MDA Lab Building has several pieces of vibration sensitive research equipment in the labs on the third floor. The impact line for the testing was on the sidewalk of Robert Street. One transducer was located outdoors near the building foundation and one was located in the stairwell just inside the door. The other three accelerometers were located on the third floor on the balcony, inside the northeast laboratory and in the hallway outside the second laboratory to the west.

The LSTM results are shown in Figure 149. As would be expected, the average coherence is close to 1 between 20 and 125 Hz for the sidewalk and stairwell positions and is much lower for the measurements on the third floor. The coherence for the measurement outside the second laboratory to the west is particularly low. The conclusion is that the measured LSTM curves for the third floor measurements represent upper bounds and the actual LSTM is lower. The is particularly true at frequencies of 100 Hz and greater where the coherence is very close to zero for all of the third floor measurement positions.

Figure 150 shows the predicted LRV vibration at all three of the third floor measurement positions. Except at frequencies greater than 100 Hz, the predicted vibration levels are below the ambient vibration. Therefore it is unlikely that vibration from LRT operations would affect the vibration sensitive laboratory equipment and mitigation is not required.

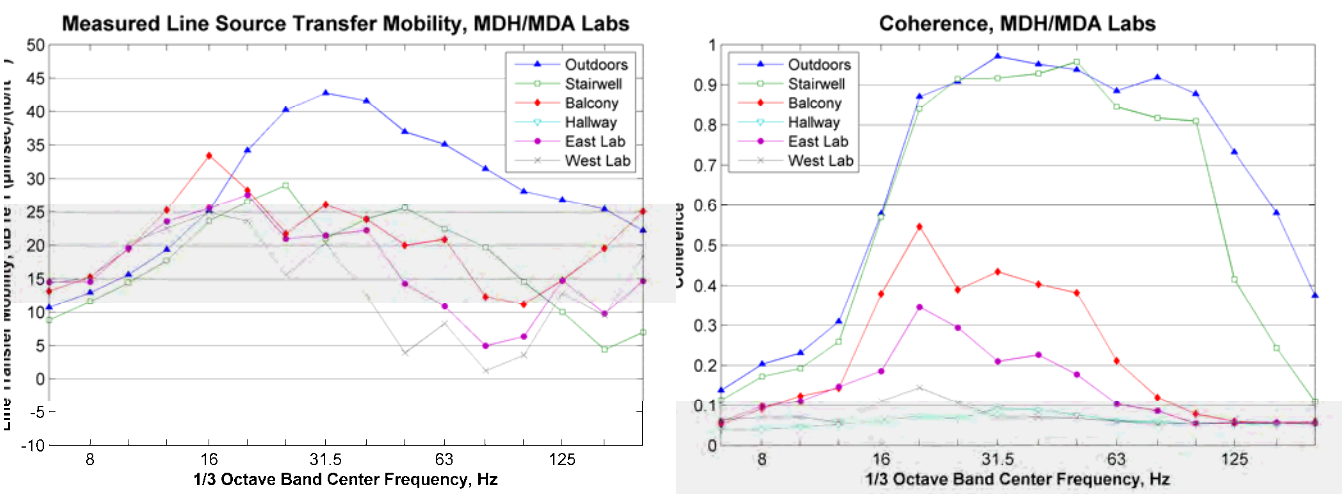


Figure 149: Measured Line Source Transfer Mobility, MDH/MDA Lab Building

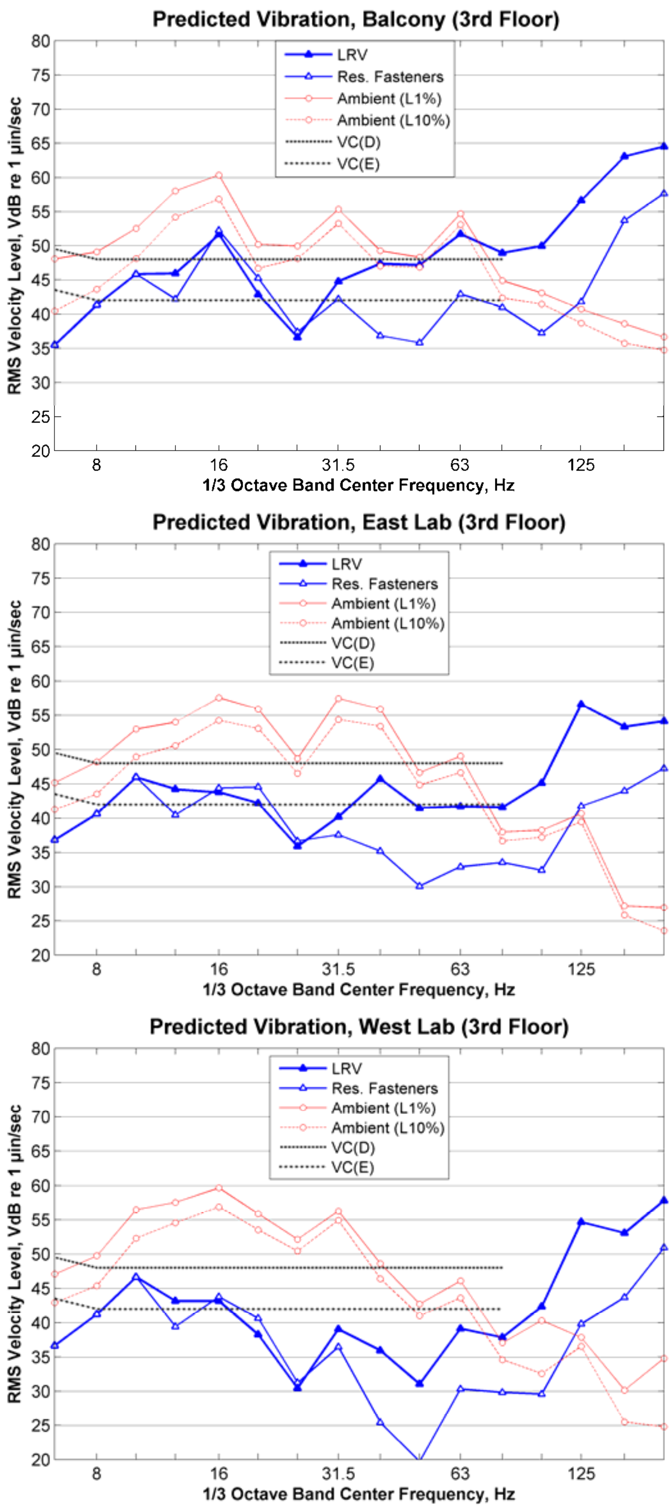


Figure 150: Predicted Vibration inside MDH/MDA Lab Building, 3rd Floor

KSTP TELEVISION STUDIO

Measurement Results

The KSTP Television Studio is located at 3415 University Avenue W. The sensitive spaces in the building that will be closest to the CCLRT tracks are the small broadcast/recording studios on the south side of the building. The main broadcast studios are approximately 100 to 150 ft farther from University Avenue. The impact line for these tests was along the sidewalk of University Avenue approximately 8-feet from the edge of University Avenue. The accelerometers were placed in a line perpendicular to University Avenue. The fifth accelerometer was placed approximately 5-feet from the building foundation. The spaces facing University Avenue are offices and there are small recording studios located across the hallway from the offices. The sixth accelerometer was located inside one of the studios (see Figure 151). Figure 152 is a photograph of the accelerometer line taken from University Avenue. Measurements were not taken inside the larger broadcast studios because they are farther back from University Avenue.

As can be seen from the measured LSTM curves shown in Figure 153, the vibration attenuates at a relatively constant rate with increasing distance. The attenuation from outside the building to inside the studio ranges from 5 to 8 decibels except at the frequencies below 16 Hz. The low coherence at these frequencies indicates that the measured LSTM is an upper bound estimate and that the real LSTM may be substantially lower than indicated in Figure 153.

Figure 154 shows the predicted levels of train vibration. The FTA impact thresholds for television studios are 65 VdB for ground-borne vibration and 25 dBA for ground-borne noise. The overall levels calculated from the curves shown in Figure 154 are:

	Without Mitigation	With High-Resilient Fasteners
Ground-borne vibration:	62 VdB	61 VdB
Ground-borne noise:	37 dBA	25 dBA

The conclusion is that predicted vibration levels are below the FTA impact threshold and that the predicted ground-borne noise exceeds the impact threshold.

Mitigation

Use of high-resilience track fasteners reduces the predicted ground-borne noise to 25 dBA, which does not exceed impact threshold. However, it is questionable whether mitigation is warranted in this case because, as seen in Figure 154, the predicted ground-borne vibration exceeds the ambient in the studio only in the 125 and 160 Hz 1/3 octave bands. Additional testing should be performed during the design stages of the CCLRT project to verify that vibration mitigation would be beneficial. The additional tests would include measurements of ambient sound inside the studios and could include an additional vibration propagation test that is focused on estimating the vibration at frequencies of 63 Hz and higher. Because the predicted ground-borne vibration levels exceed the ambient vibration only in at frequencies of 80 Hz and higher and the amount that the predictions exceed the background is a maximum of 8 decibels, additional measurement may show that LRV vibration would not exceed the ambient vibration.

Note that the levels of ground-borne noise are predicted to be sufficiently lower in the main broadcast studios because they are farther from University Avenue and because the part of the building that they are contained in appears to have a more substantial foundation than the smaller studios where impact is predicted.

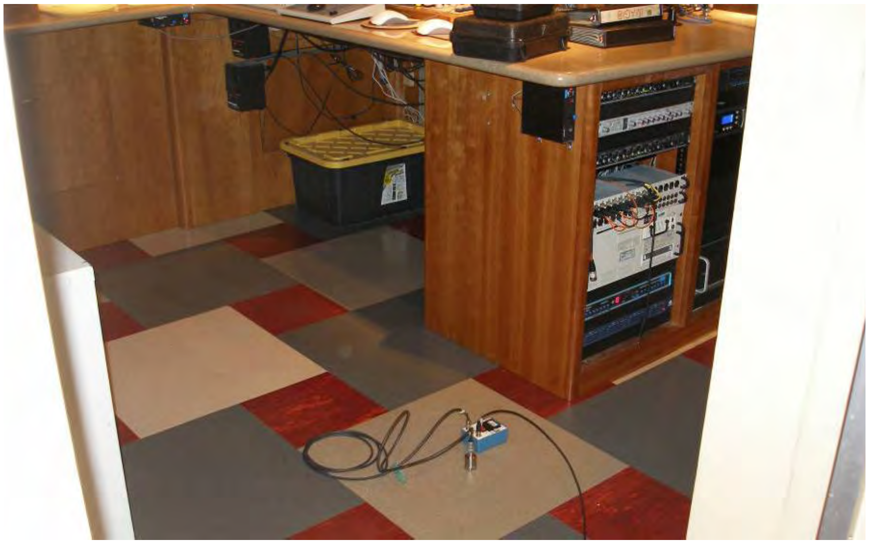


Figure 151: Indoor Accelerometer at KSTP Television Studio

Figure 152: View of Accelerometer Line at KSTP Television Studio

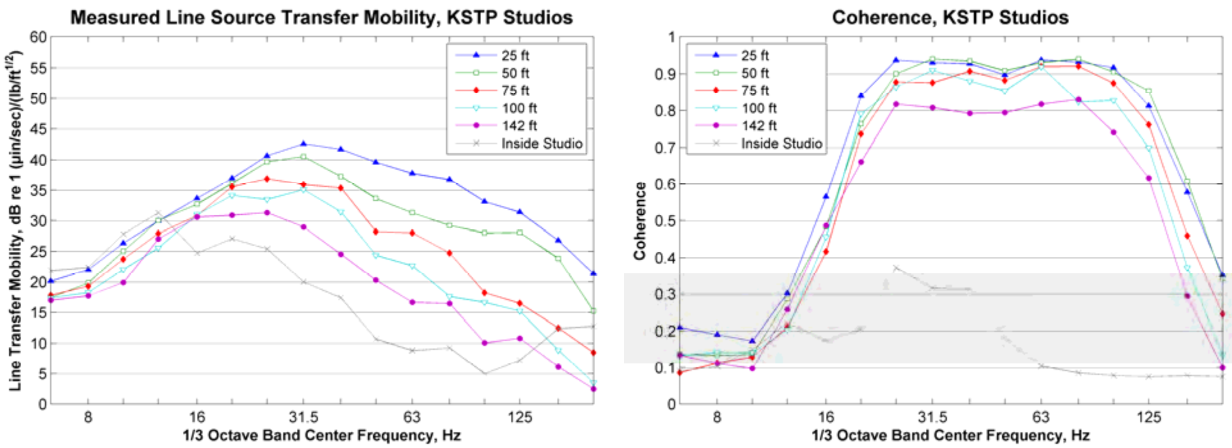


Figure 153: Measured Line Source Transfer Mobility, KTSP Studio

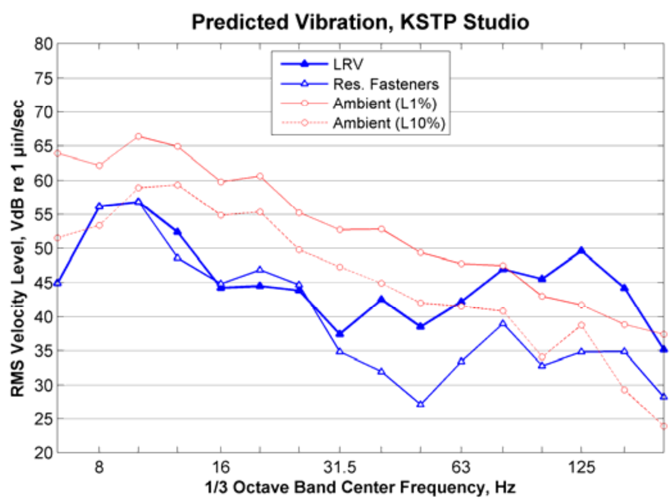


Figure 154: Predicted Train Vibration inside KSTP Studio

8. 1951 UNIVERSITY AVENUE

Measurement Results

1951 University Avenue is a commercial building with various business uses. The space of concern is a recording studio that is located in the basement that extends south of the building and is directly under the sidewalk. Four accelerometers were located at the surface at distances of 25 to 100 ft from the impact line and two were located inside the studio, one attached to the floor and one attached to the ceiling. The lane closest to the sidewalk on the north side of University Avenue was blocked off for the measurements so that the impacts could be performed close to where the light rail tracks will be located (see Figure 155).

Figure 157 shows the predicted levels of train vibration for the floor and the ceiling. The FTA impact thresholds for recording studios are 65 VdB for ground-borne vibration and 25 dBA for ground-borne noise. The overall levels calculated from the curves shown in Figure 157 are summarized in Table 9. The noise levels are based on the predicted levels for the ceiling and the vibration levels are based on the predicted levels for the floor. The conclusion is that predicted vibration levels are below the FTA impact threshold for vibration impact and that the predicted ground-borne noise is above the impact threshold. Mitigation ranging from 15 to 28 decibels at frequencies greater than 63 Hz would be required to reduce the predicted ground-borne noise level to below the FTA impact threshold of 25 dBA for recording studios.

Mitigation

Also shown in Table 9 are the predicted vibration and noise levels with mitigation. Use of high-resilience track fasteners would reduce the ground-borne noise level to 41 dBA (based on the ceiling vibration), which is still 16 decibels greater than the impact threshold. Going to a floating slab would reduce the noise level to 23 dBA. Installation of a floating slab is a very costly solution typically used to address highly sensitive structures and uses. In this instance, because the recording studio is a relatively small, private facility located in a structure that would not otherwise require vibration mitigation, more cost-effective solutions may be to assist the studio to relocate or to vibration isolate the studio itself.

The basic approach to vibration isolating the studio would be to build a "room within a room" in the studio. The design would include a floated floor with walls and ceiling disconnected from the existing room structure. Vibration isolators would be used for any structural connection between the surfaces of the isolated room and the existing structure. The primary disadvantage of this approach is that it would reduce the volume of the existing space by a minimum of 6 inches on all surfaces.

Table 9: Predicted Levels inside Studio at 1951 University Avenue

Type	FTA Impact Threshold	Floor	Ceiling
Without Mitigation			
Ground-borne vibration:	65 VdB	61 VdB	68 VdB
Ground-borne noise:	25 dBA	36 dBA	**50 dBA(1)**
With Resilient Fasteners			
Ground-borne vibration:	65 VdB	57 VdB	62 VdB
Ground-borne noise:	25 dBA	27 dBA	**41 dBA(1)**
With Floating Slab or Equiv.			
Ground-borne vibration:	65 VdB	56 VdB	58 VdB
Ground-borne noise:	25 dBA	12 dBA	23 dBA(1)

Note:
1. The vibration of the ceiling would be the dominate source of ground-borne noise.

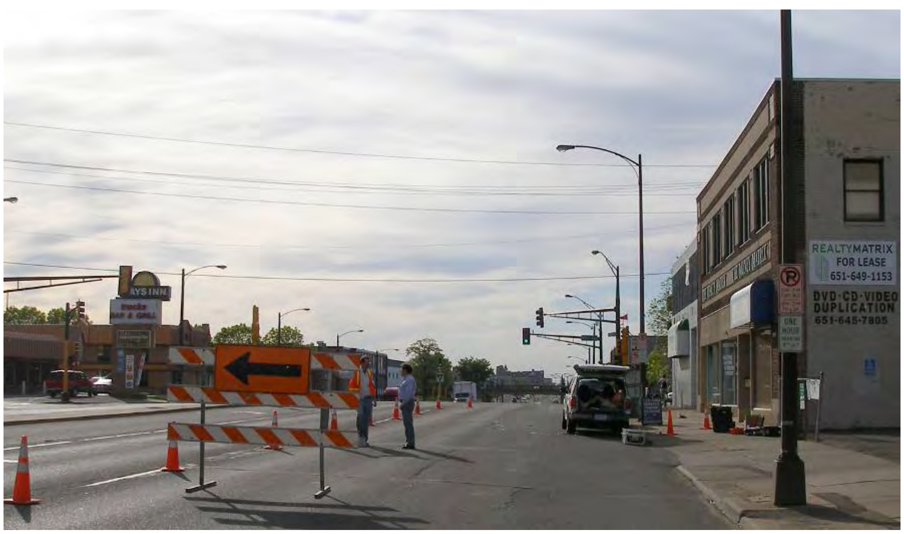


Figure 155: Location of Impact Line for Recording Studio at 1951 University

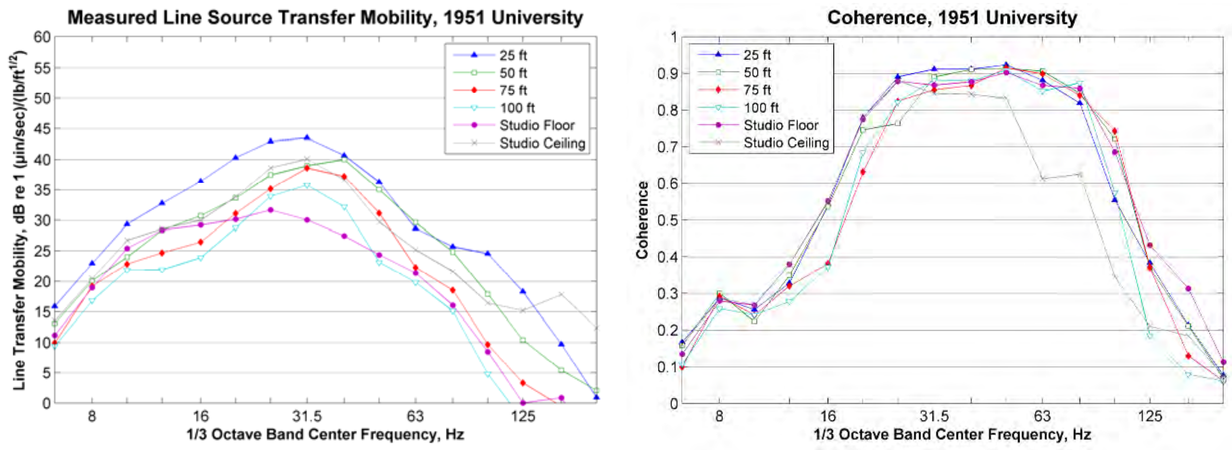


Figure 156: Measured Line Source Transfer Mobility, 1951 University

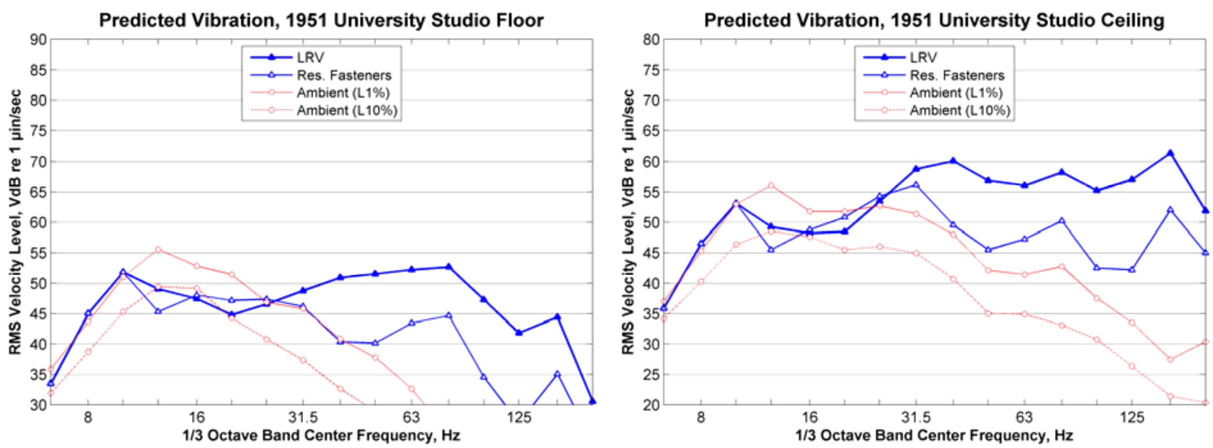


Figure 157: Predicted Train Vibration inside Studio, 1951 University

9. CHURCH OF ST. LOUIS KING OF FRANCE AND CENTRAL PRESBYTERIAN CHURCH

The two churches on Cedar Street are being evaluated as a special case because of the bedrock being so close to the surface, the potential effects on fragile stained glass windows, and potential issues with the foundations of the churches. Another issue that has been investigated is whether the vibration from LRV operations could have any adverse effect on the pipe organs in the churches. The measurements that have been performed consist of transfer mobility from the east lane of Cedar Street into different areas of the churches and ambient vibration at the same measurement positions used for the transfer mobility tests. At the request of the Church of Saint Louis, a supplementary set of vibration measurements was performed to investigate the sensitivity of church's organ to vibration.

Ambient Vibration

The measurement positions used for the ambient vibration are listed in Table 10. The primary question that the second set of measurements at the St. Louis Church was intended to answer is whether there is any potential for vibration from the trains to cause damage to the organ. As discussed below, it is evident that vibration from the organ itself will be higher than the vibration from Central Corridor Light Rail Transit operations.

The 1/3 octave band spectra of the ambient vibration measurements performed at the same time as the LSTM tests are shown in Figure 158 for Central Presbyterian Church and Figure 159 for St. Louis Catholic Church. There was relatively little activity within the churches at time of the measurements and the primary sources of vibration were traffic on Cedar Street, mechanical equipment within the church and footfalls from people walking within the church. Although there are variations between the measurement positions and between the two churches, the ambient vibration was always well below the threshold of human perception and was low enough that radiation of the vibration off of room surfaces would not generate audible noise.

The second test at the St. Louis Catholic Church was performed with and without the organ playing. The accelerometers were located in the organ cabinet, the basement under the sanctuary, on a balcony near the organ, and on the ledge under the north stained-glass window. The results from this measurement are shown in Figure 160. The top graph shows the time history of the vibration levels. The first 20 minutes of the measurement was without any organ music (from 10:30 to 10:50), and the last four minutes (from 10:51 to 10:55) was with the organ being played. As is evident in this graph, the vibration levels were substantially higher when the organ was being played. The lower four graphs show the frequency spectra of the vibration with and without the organ playing. These graphs include the L1%, L10% and L90% of the ambient vibration and the L10% and Leq with the organ playing.

Referring to Figure 160, the additional vibration from the organ in the basement and at the north window exceeded the ambient vibration only at frequencies of 63 Hz and greater. In contrast, the vibration on the balcony and in the organ cabinet exceeded the ambient vibration over the entire frequency range. The vibration with the organ playing was below the threshold of human perception in the basement and at the north window, and exceeded or approached the threshold of human perception on the balcony and in the organ cabinet.

Table 10. Measurement Positions at Central Presbyterian Church and St. Louis Catholic Church

Channel	Central Presbyterian Church	St. Louis Catholic Church
LSTM Tests, May 2008		
2	Ground outside of church	Planter area north of front stairs
3	Top of front stairs	Top of front stairs
4	Basement near west foundation	Ledge under stained-glass window, south façade
5	Ledge under stained-glass window, south façade	Under pews
6	Ledge under stained-glass window, west façade	Ledge under stained-glass window, north façade
7	Under pews	Basement near west foundation
Supplementary Ambient Vibration, October 2008		
1		Ledge under stained-glass window, north façade
2		Basement under sanctuary
3		Balcony near organ
4		Inside organ

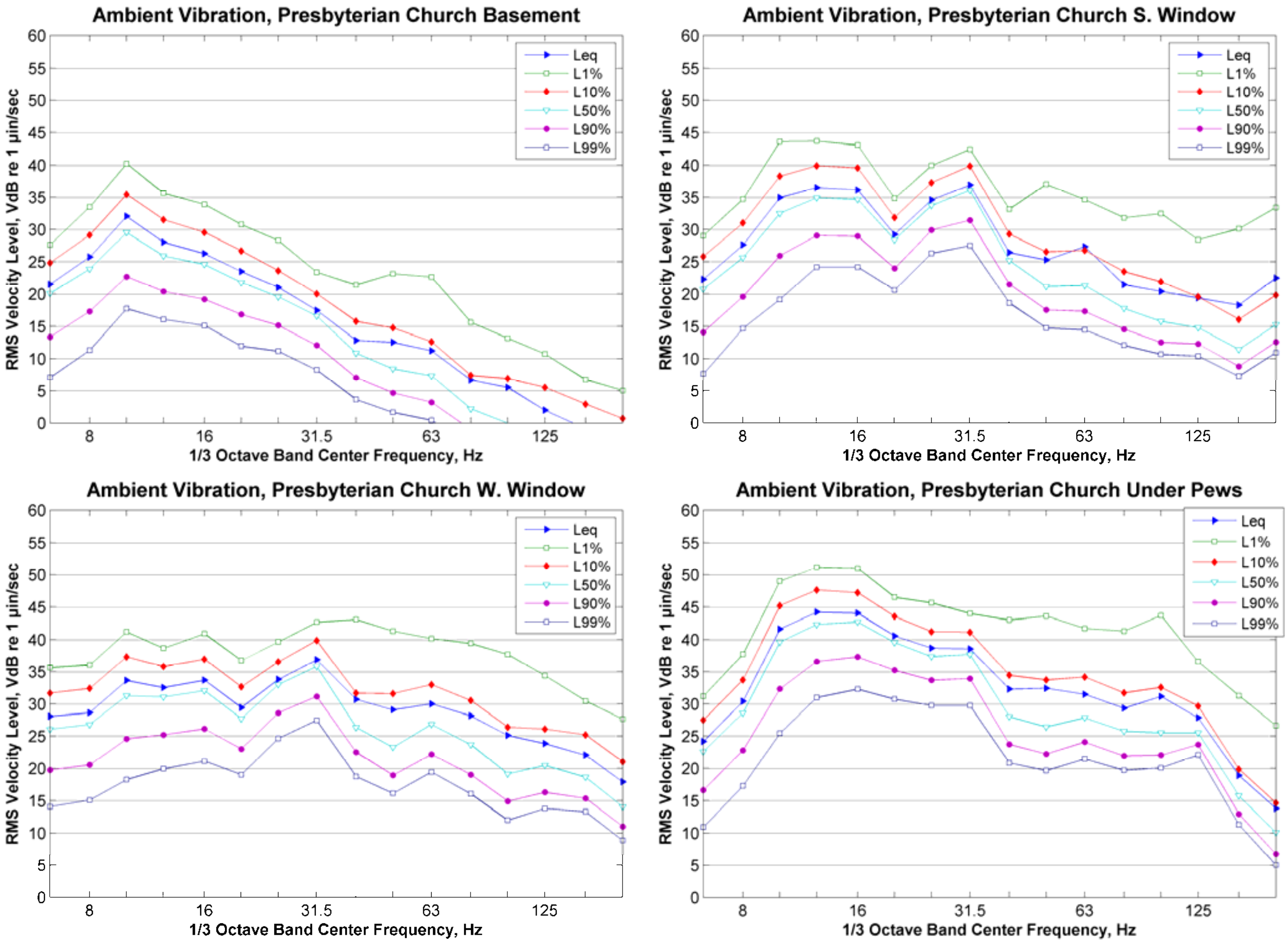


Figure 158: Ambient Vibration at Indoor LSTM Measurement Positions, Central Presbyterian Church

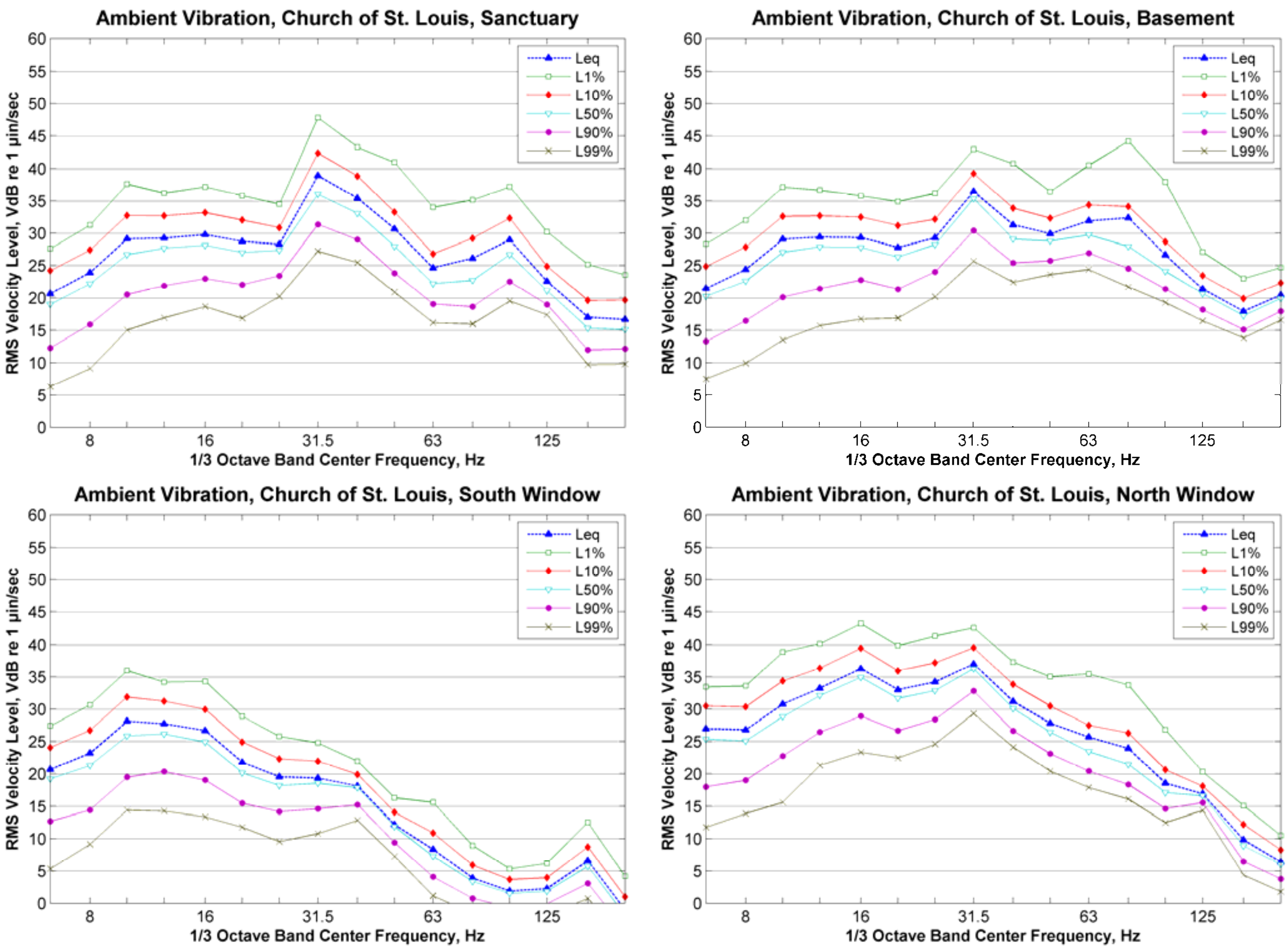
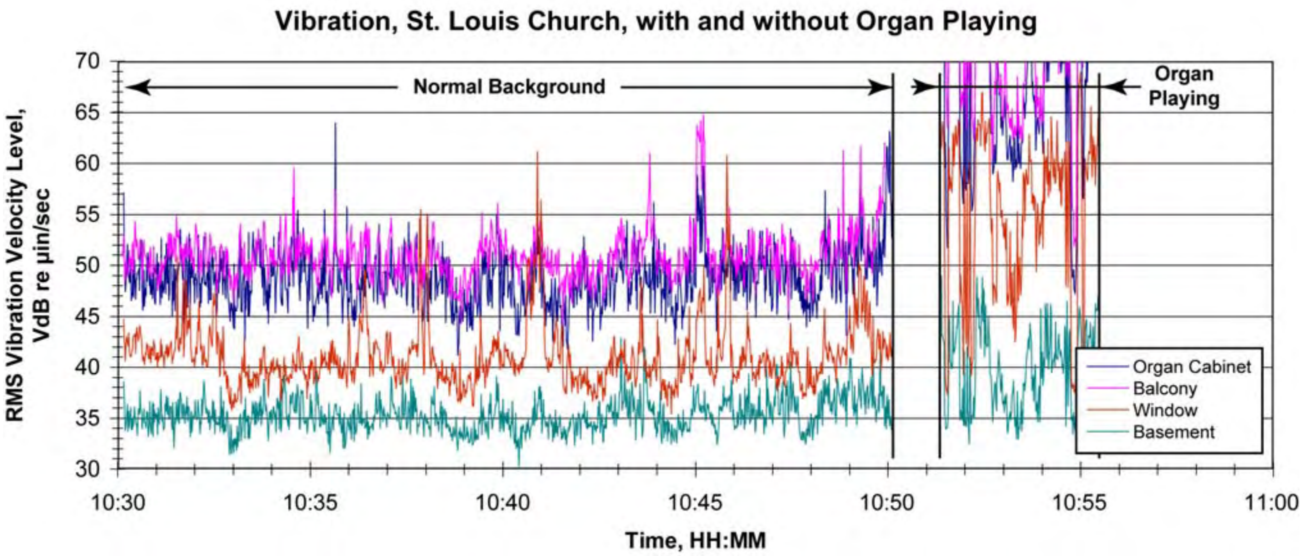
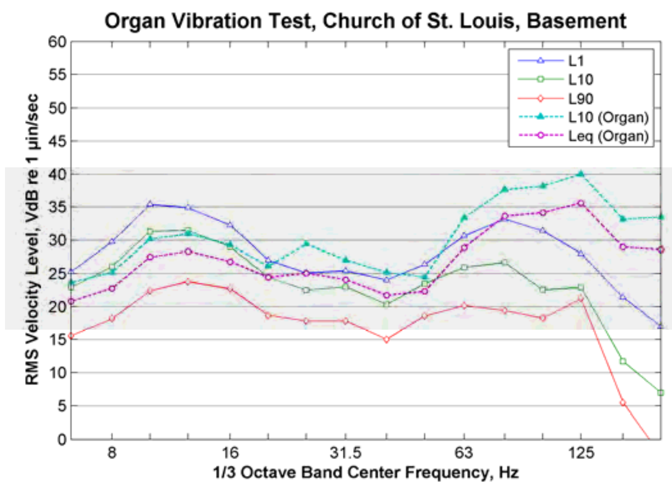
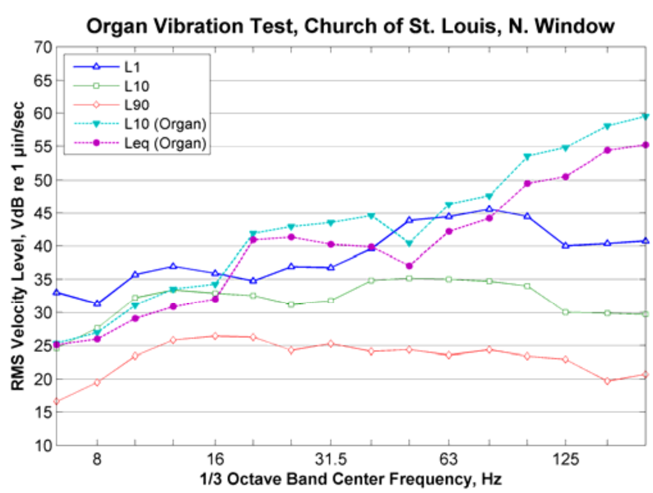


Figure 159: Ambient Vibration at Indoor LSTM Measurement Positions, Church of St. Louis


Vibration, St. Louis Church, with and without Organ Playing
Normal Background
Organ Playing
RMS Vibration Velocity Level, VdB re µin/sec
Organ Cabinet
Balcony
Window
Basement
Time, HH:MM
10:30
10:35
10:40
10:45
10:50
10:55
11:00


Organ Vibration Test, Church of St. Louis, Basement
L1
L10
L90
L10 (Organ)
Leq (Organ)
RMS Velocity Level, VdB re 1 µin/sec
1/3 Octave Band Center Frequency, Hz
8
16
31.5
63
125


Organ Vibration Test, Church of St. Louis, N. Window
L1
L10
L90
L10 (Organ)
Leq (Organ)
RMS Velocity Level, VdB re 1 µin/sec
1/3 Octave Band Center Frequency, Hz
8
16
31.5
63
125

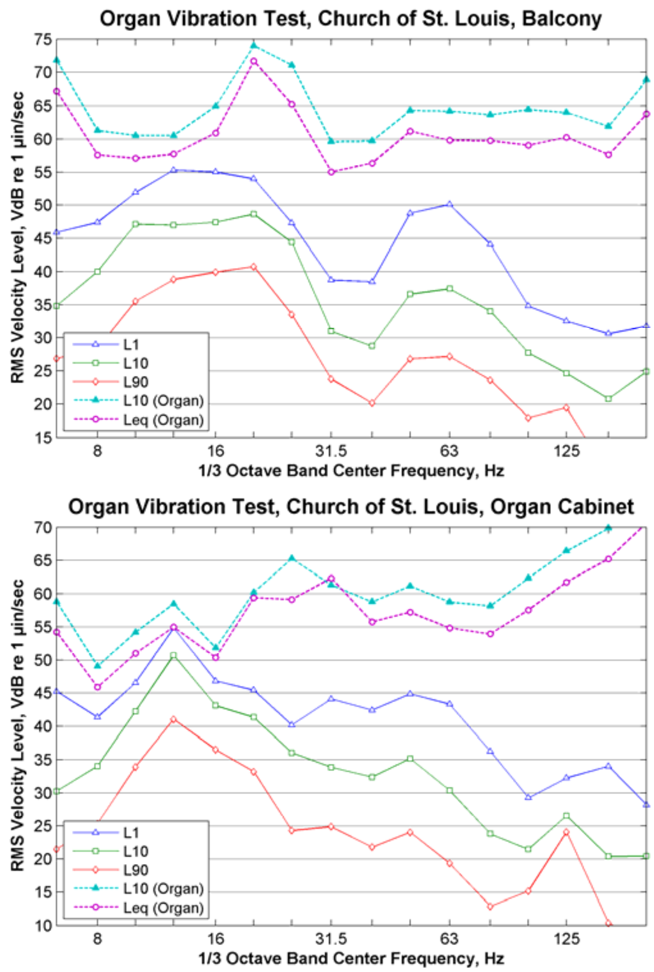


Figure 160: Ambient Vibration with and without Organ Music, Church of St. Louis
(The overall levels shown in the top graph are over the frequency range of 16 to 200 Hz.)

Measured LSTM and Predicted Vibration

The measured LSTMs are shown in Figure 161 and Figure 162. The test results show relatively efficient transmission of vibration from Cedar Street into the churches, particularly at frequencies greater than 40 Hz. The predicted vibration levels and ground-borne noise levels are summarized in Table 11 and are shown in terms of the vibration spectra in Figure 163 for the Central Presbyterian Church and Figure 164 for the St. Louis Catholic Church. The procedure used to predict the ground-borne noise levels from the predicted ground-borne vibration levels is described in Appendix C. LSTM was measured in four locations inside each church, three in the main sanctuary where services and musical performances are held and one in the basement. The far right column of Table 11 shows the predicted vibration level on the floor under the pews and the ground-borne noise combining all three of the measurement positions. The three ground-borne noise predictions were combined into a single estimate by taking the decibel average, which is equivalent to an RMS average.

The predicted levels in Table 11 and in the figures show that:

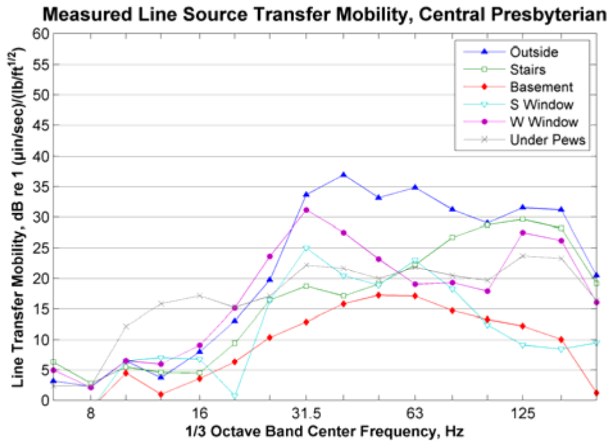
- The ground-borne vibration generated by LRT operations should be well below the damage screening threshold of 90 VdB (equivalent to 0.12 in/sec peak particle velocity). This is a very restrictive threshold that is used to protect fragile historic buildings.
- The ground-borne vibration levels at the pews will be well below the FTA impact threshold of 75 VdB.
- Without mitigation, the audible noise generated by vibrating room surfaces is likely to exceed the FTA impact threshold of 40 dBA for institutional land uses such as churches.
- With resilient direct fixation fasteners as mitigation the predicted ground-borne noise levels inside the Central Presbyterian Church exceed the FTA impact threshold for institutional land uses such as churches by 5 decibels. The predicted ground-borne vibration level in the St. Louis Catholic Church is right at the 40 dBA impact threshold for institutional land uses.
- With a floating slab or equivalent vibration mitigation measure, the predicted ground-borne noise levels in both churches are below the more restrictive thresholds for theaters (35 dBA) and for auditoriums (30 dBA). The churches are used for organ recitals and other musical performances, which means that the conservative approach would be apply the more restrictive impact thresholds for ground-borne noise.

Table 11: Predicted Ground-borne Vibration and Noise, Cedar Street Churches

Central Presbyterian Church		Measurement Location				
		Basement	**S. Window**	**W. Window**	**Under Pews**	**Combined, Sanctuary**
Without Mitigation	Vib, VdB	60	61	73	70	70
	Noise(2), dBA	**43**	**43**	**58**	**55**	**55**
With Resilient Fasteners	Vib, VdB	49	52	62	60	60
	Noise(2), dBA	33	34	**48**	**46**	**45**
With Floating Slab or Equivalent	Vib, VdB	38	40	46	46	46
	Noise(2), dBA	16	17	30	27	27
St. Louis Catholic Church		**Basement**	**S. Window**	**N. Window**	**Under Pews**	**Combined, Sanctuary**
Without Mitigation	Vib, VdB	69	58	61	65	65
	Noise(2), dBA	**56**	**44**	**47**	**52**	**48**
With Resilient Fasteners	Vib, VdB	60	50	52	57	57
	Noise(2), dBA	**48**	**37**	**38**	**44**	**40**
With Floating Slab or Equivalent	Vib, VdB	42	36	40	41	41
	Noise(2), dBA	28	16	19	24	20

Notes:

1. Applicable Impact Thresholds:
   - Screening for cosmetic damage: 90 VdB
   - Annoyance from vibration: 75 VdB
   - Ground-borne noise (depending on how space is categorized)
     - 40 dBA (church)
     - 35 dBA (theater)
     - 30 dBA (auditorium)
2. Noise levels inside the church would be a combination of the noise radiated off the different room surfaces.



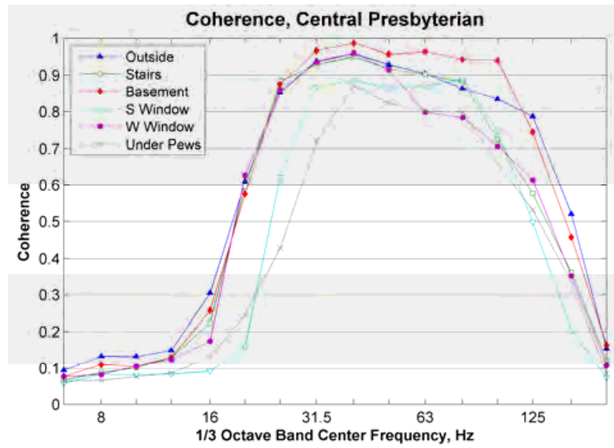
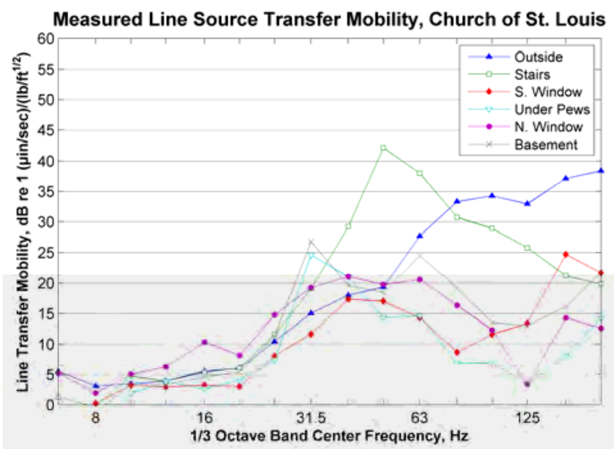


Figure 161: Measured Line Source Transfer Mobility, Central Presbyterian Church



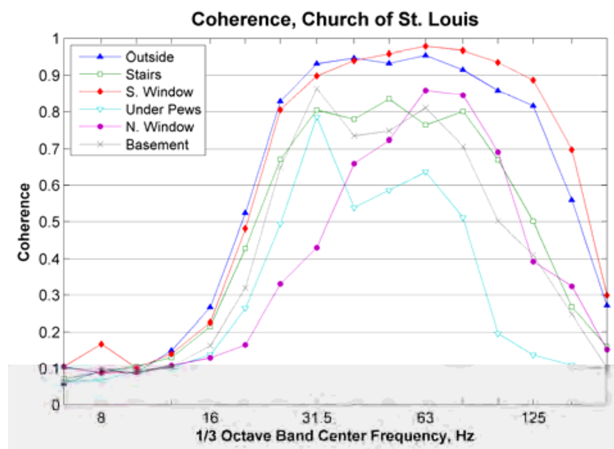


Figure 162: Measured Line Source Transfer Mobility, Church of St. Louis

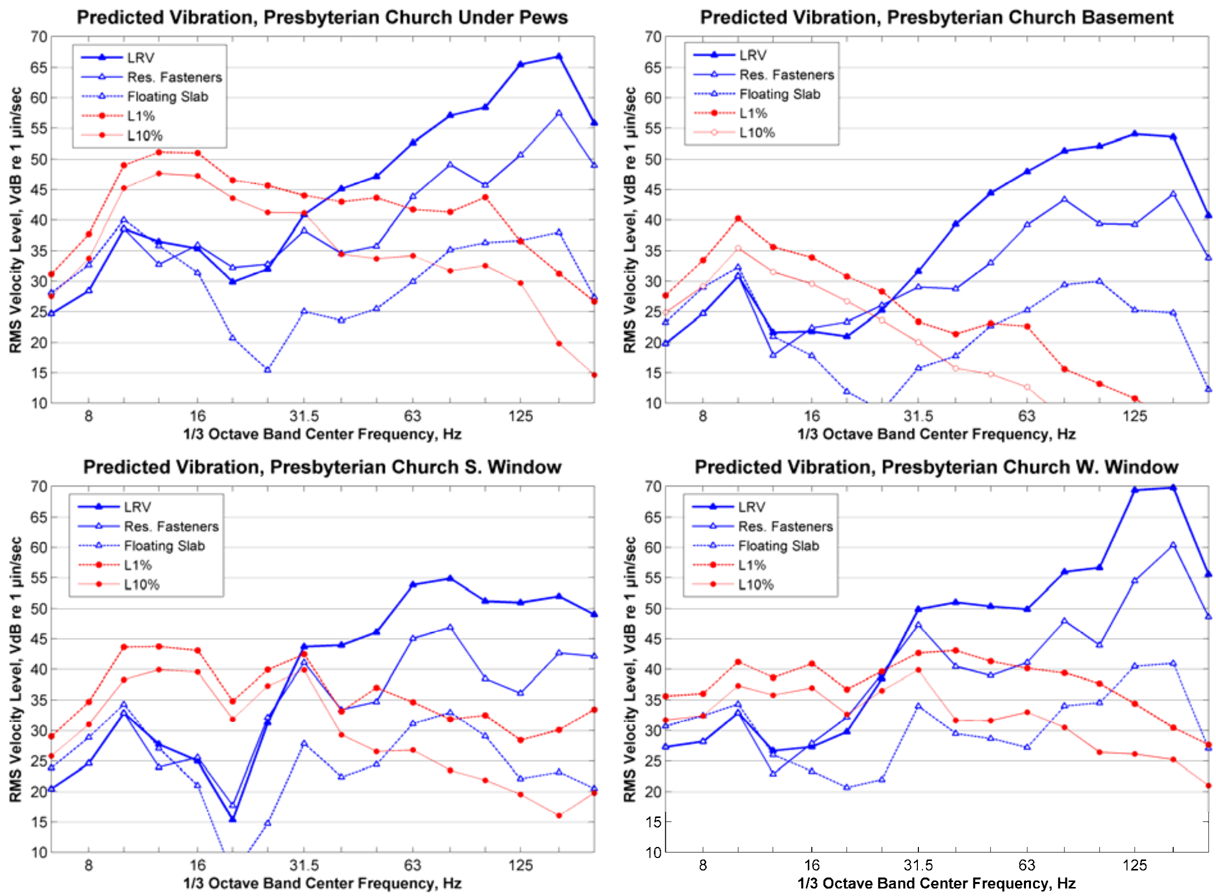


Figure 163: Predicted LRT Vibration, Central Presbyterian Church

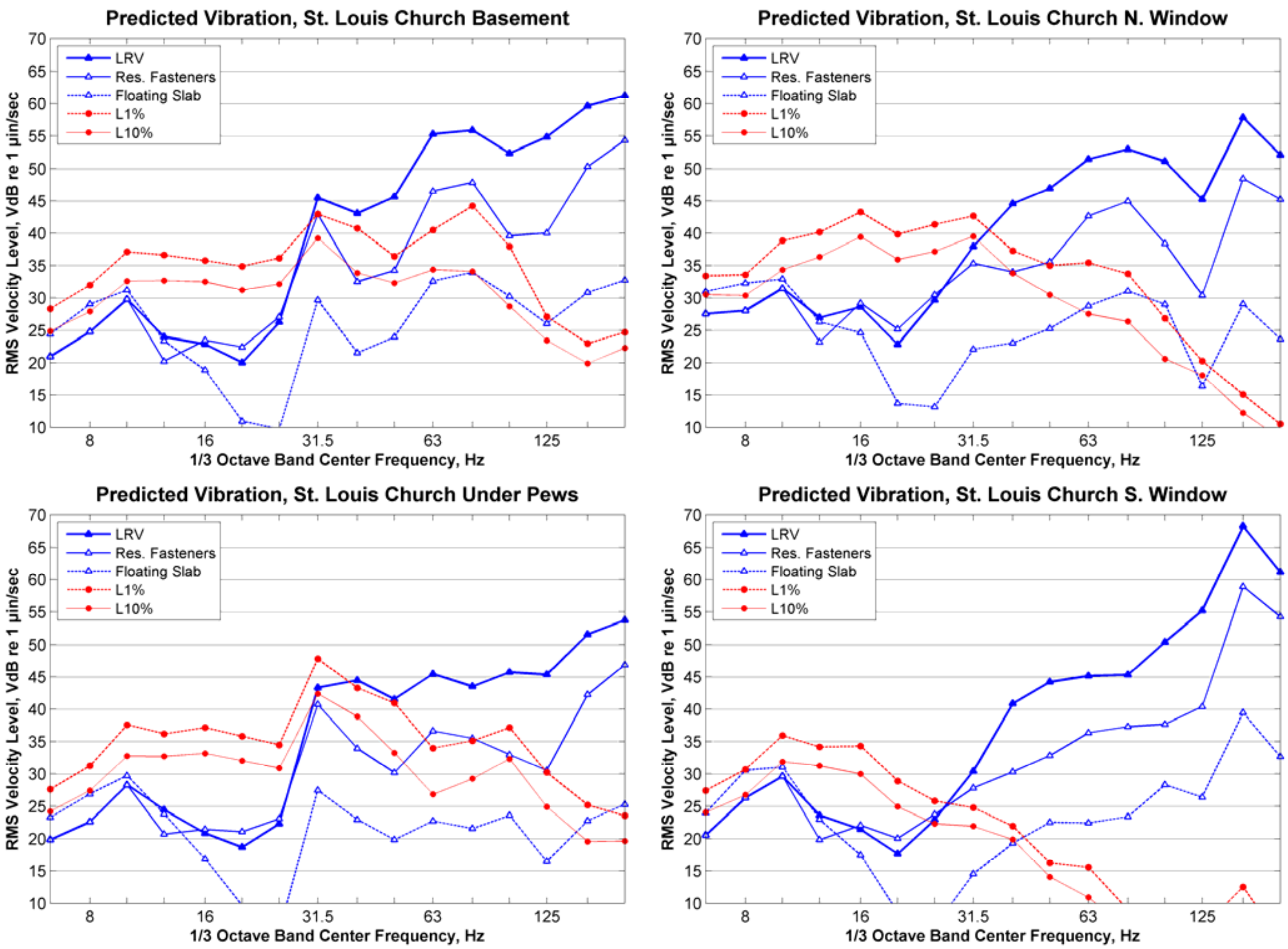


Figure 164: Predicted LRT Vibration, Church of Saint Louis

10. MCNALLY SMITH PERFORMANCE CENTER

McNally Smith College of Music located at 19 Exchange Street East, Saint Paul is between Wabasha Street and Cedar Street. There are several recording studios at the college that college staff said were the spaces that would be most sensitive ground-borne noise. There are also practice and recital facilities at the Saint Paul Conservatory, but we understand that these facilities are not designed for recording and are therefore not as sensitive.

For the LSTM tests one accelerometer was located inside the performing area of an unused studio and three accelerometers were located along the sidewalk of Exchange Street at distances of 30, 60 and 100 ft from Cedar Street. There was some interference from music coming from an adjacent studio.

The line source transfer mobility (LSTM) result for the test inside the McNally Smith studio is shown in Figure 165 and the predicted vibration levels are shown in Figure 166. The LSTM is shown on the left side of Figure 165 and the average coherence function is shown on the right. Coherence is a measure of the data quality and the results indicate valid data between 20 and 63 Hz. The primary reasons for low coherence are a weak transmission path between the impact locations and the receiver position and background vibration that masks the vibration pulse generated by the dropped weight. An important point is that when background vibration masks the vibration pulse generated by the dropped weight (as indicated by a low coherence), the resulting LSTM will be an overestimate of the real LSTM, which will in turn lead to overestimating the levels of LRT vibration.

The overall levels calculated from the curves shown in Figure 166 are given in Table 12. The FTA impact thresholds for recording studios are 65 VdB for ground-borne vibration and 25 dBA for ground-borne noise. The predictions indicate that:

- The vibration levels without mitigation are below the FTA impact threshold and approximately equal to the L1% ambient vibration during the measurements.
- The predicted ground-borne noise level is 7 decibels greater than the ambient ground-borne noise (L1%) with no mitigation and is 14 decibels greater than the FTA impact threshold for ground-borne noise.
- With mitigation in the form of high-resilience direct fixation fasteners, the predicted ground-borne noise level is equal to the ambient vibration (L1). The predicted ground-borne noise exceeds the measured ambient only in the 160 and 200 Hz 1/3 octave band.

Although the resilient fasteners are not sufficient to bring the predicted ground-borne noise levels below the FTA impact threshold for recording studios, additional vibration mitigation is not recommended for the following reasons:

1. The predicted ground-borne noise level is equal to the ambient ground-borne noise predicted from the measured ambient vibration levels.
2. The predicted ground-borne noise levels are an upper-bound estimate because the estimate of ground-borne noise from the predicted ground-borne vibration is conservative (see Appendix C) and because the LSTM used for the predictions is conservative in the frequency range where the predicted levels exceed the ambient.

The conclusion is that a worst case is that with the mitigation provided by high-resilience fasteners, the levels of ground-borne noise will be approximately equal to the existing levels of ground-borne noise.

Table 12: Predicted Ground-Borne Noise and Vibration Levels, McNally Smith Recording Studio

	FTA Impact Threshold	Without Mitigation	With High-Resilience Fasteners	Ambient (L1)	Ambient (L10)
Ground-borne vibration	65 VdB	53 VdB	44 VdB	52 VdB	47 VdB
Ground-borne noise[1]	25 dBA	39 dBA	32 dBA	32 dBA	28 dBA

Notes:
1. The procedures for estimating ground-borne noise is presented in Appendix C.

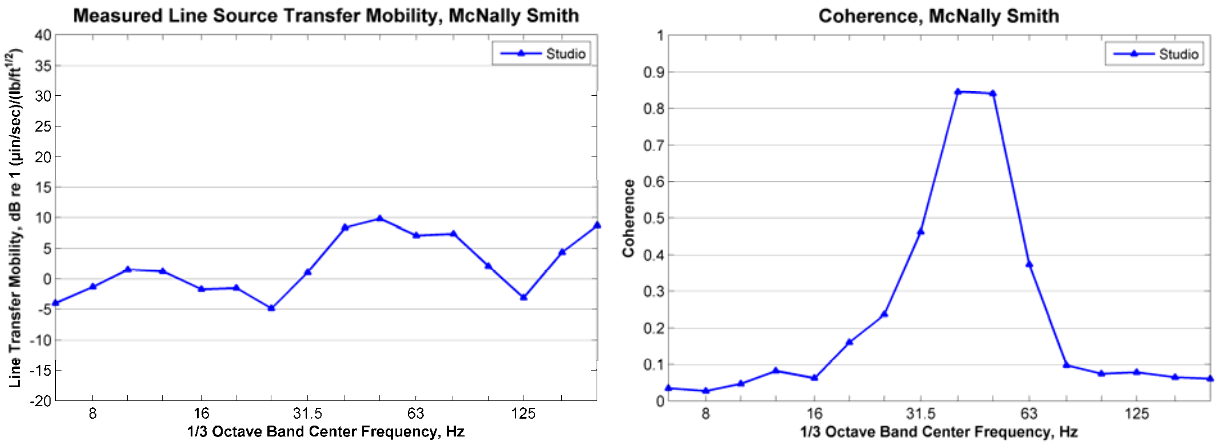


Figure 165: Measured LSTM & Coherence at McNally Smith Performance Center

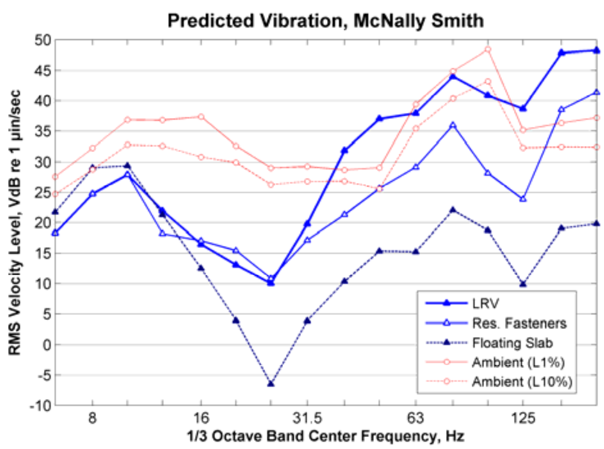


Figure 166: Predicted Vibration at McNally Smith Performance Center

11. MINNESOTA PUBLIC RADIO (MPR)

11.1 Overview

The MPR facility at 480 Cedar Street in Saint Paul has a number of studios used to record and broadcast radio programs. The MPR facility consists of two buildings joined at the lobby area. The original building is to the south of the entrance and the new facility is to the north. We understand that the new facility was constructed to have stiffer floors than normal so that the floor vibration would be lower. The floors in the original building are flexible floors that are more prone to be excited into resonant vibration from exterior vibration sources such as buses and the proposed light rail system. The primary concern relative to the MPR facility is that vibration from LRT operations has the potential to cause ground-borne noise that could interfere with use of the studios. Detailed vibration testing was performed inside seven of the MPR studios so that accurate predictions of ground vibration can be developed specifically for these studios.

The potential for light rail vehicle (LRV) operations on Cedar Street to cause intrusive ground-borne noise inside the Fitzgerald Theater is also a concern. The Fitzgerald Theater is located at the 10 East Exchange Street, one block east of Cedar Street. A specific analysis has not been performed for the Fitzgerald Theater because it is considerably farther from the planned tracks than the sensitive buildings along Cedar Street and the vibration mitigation required for the buildings on Cedar Street will also reduce vibration levels at the Theater. In addition, the testing and analysis performed for the McNally Smith recording studios showed that high-resilience track fasteners would be sufficient to maintain the existing vibration environment in the recording studios center (see Section 10). The recording studios are between Wasbasha Street and Cedar Street and are closer to Cedar Street than the Fitzgerald Theater.

The initial testing at MPR was performed in May 2008. Those tests consisted of vibration propagation tests from Cedar Street into seven of the MPR studios using a dropped weight as the vibration source. The impact line for the testing at MPR was along Cedar Street parallel to the front of the MPR building. Traffic controls placed by the St. Paul Department of Public Works diverted traffic from the east lane of Cedar Street so that the impact line could be at the approximate location that the light rail tracks closest to MPR would be. Figure 167 shows one of the accelerometers being installed in a studio with carpet on the floor. As seen in Figure 167, a metal plate with spikes was used in rooms with carpet to ensure firm contact with the floor under the carpet. In addition, short measurements of background vibration were performed in the each of the studios.

There have been several modifications to the analysis since the previous draft of this memorandum. The primary changes relative to the MPR facilities are:

- Supplementary measurements of background vibration have been performed inside two of the MPR studios,
- A revised light rail vehicle (LRV) force density function that incorporates two supplementary force density tests was used for the predictions, and
- The vibration predictions now include predictions of vibration from existing bus traffic on Cedar Street.

Details on the force density level (FDL) measurements for LRVs and buses are given in Section 5.

Following is a summary of the vibration propagation tests that were performed at MPR on May 23, 2008:

Test MPR1 – Three Studios in Old Building

Channel 1: Impact Force

Channel 2: Just outside entrance to building
Channel 5: Studio on 3rd floor
Channel 6: Large recording studio on 4th floor (Studio M)
Channel 7: Smaller recording studio on 4th floor (Studio P)

9 impact positions at 20 ft intervals starting at a point approximately 20 ft north of dividing line of the old and new buildings and extending south to 9th Street.

Test MPR2 – Three Studios in New Building

Channel 1: Impact Force
Channel 2: Just outside entrance to building
Channel 5: Edit suite 318
Channel 6: Studio 335
Channel 7: Studio 4B

9 impact positions at 20 ft intervals starting just to the north of the northwest corner of the new building and extending to a point approximately 60 ft south of the dividing line between the old and new buildings.

Test MPR3 – Studio 4G in Old Building

Channel 1: Impact Force
Channel 2: Just outside entrance to building
Channel 5: Studio on 4th floor

7 impact positions at 20 ft intervals starting at a point approximately 20 ft south of dividing line of old and new buildings and extending south to 9th Street.

A 21-minute recording of ambient vibration was made after this test had been completed. The ambient vibration measurement was continued until a bus traveling south on Cedar Street had a green light at 9th Street so that it passed the MPR building without stopping or slowing.

Short measurements of ambient vibration inside the studios were made at the same time as the vibration propagation testing.

Supplementary measurements of ambient vibration were made in October 2008 to develop a better picture of ambient vibration inside two of the studios. The supplementary measurements included overnight measurements using unattended monitors in studio P and studio 334. Studio P is located in the original MPR building and studio 334 is located in the new building. In addition, noise and vibration were recorded inside studio P for 90 minutes while bus and truck traffic on Cedar Street was logged. The purpose of this test was to characterize the vibration in the studios that is generated by the existing bus traffic on Cedar Street.

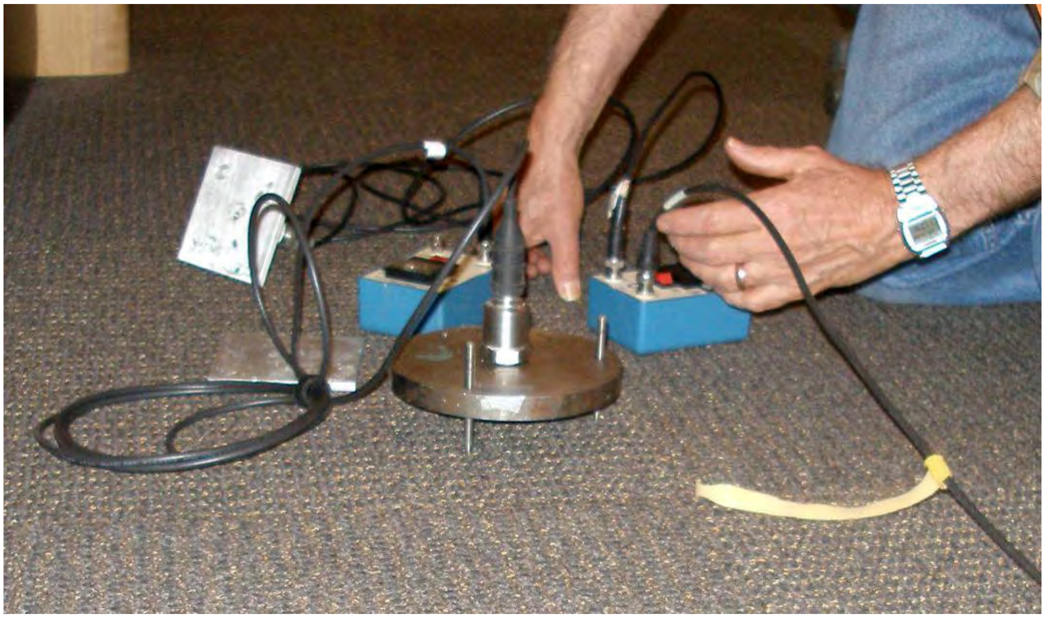


Figure 167: Installation of Accelerometer on Carpeted Floor

11.2 Transfer Mobility Results

The line source transfer mobility (LSTM) results for the three tests are shown in Figure 168. The LSTMs are shown on the left side and the average coherence functions are shown on the right. The coherence is a measure of the data quality. A coherence close to 1 indicates a strong relationship between the impact of the dropped weight and the response at the accelerometer. Coherence drops as the relationship between the impact and the vibration at the receiver position becomes weaker. A coherence of 0.1 or less indicates that there is little or no relationship between the input force and the vibration at the receiver position and indicates that the background vibration was higher than the vibration generated by the dropped weight.

As can be seen in the figures, the coherence for many of the tests indicates valid data over a limited frequency range. The primary reasons for low coherence are a weak transmission path between the impact and the receiver position and background vibration that masks the vibration pulse generated by the dropped weight. An important point is that a low coherence tends to increase the LSTM values, which will in turn lead to overestimating the levels of LRT vibration.

The LSTM curves for the MPR studio measurements grouped by building are shown in Figure 169. The measured LSTM for Studios P and M are relatively high at low frequencies. This was caused by the background vibration in the studios and is not an indication of efficient vibration propagation at these frequencies. The lowest coherence is for studio 4G, which on the far side of the original building.

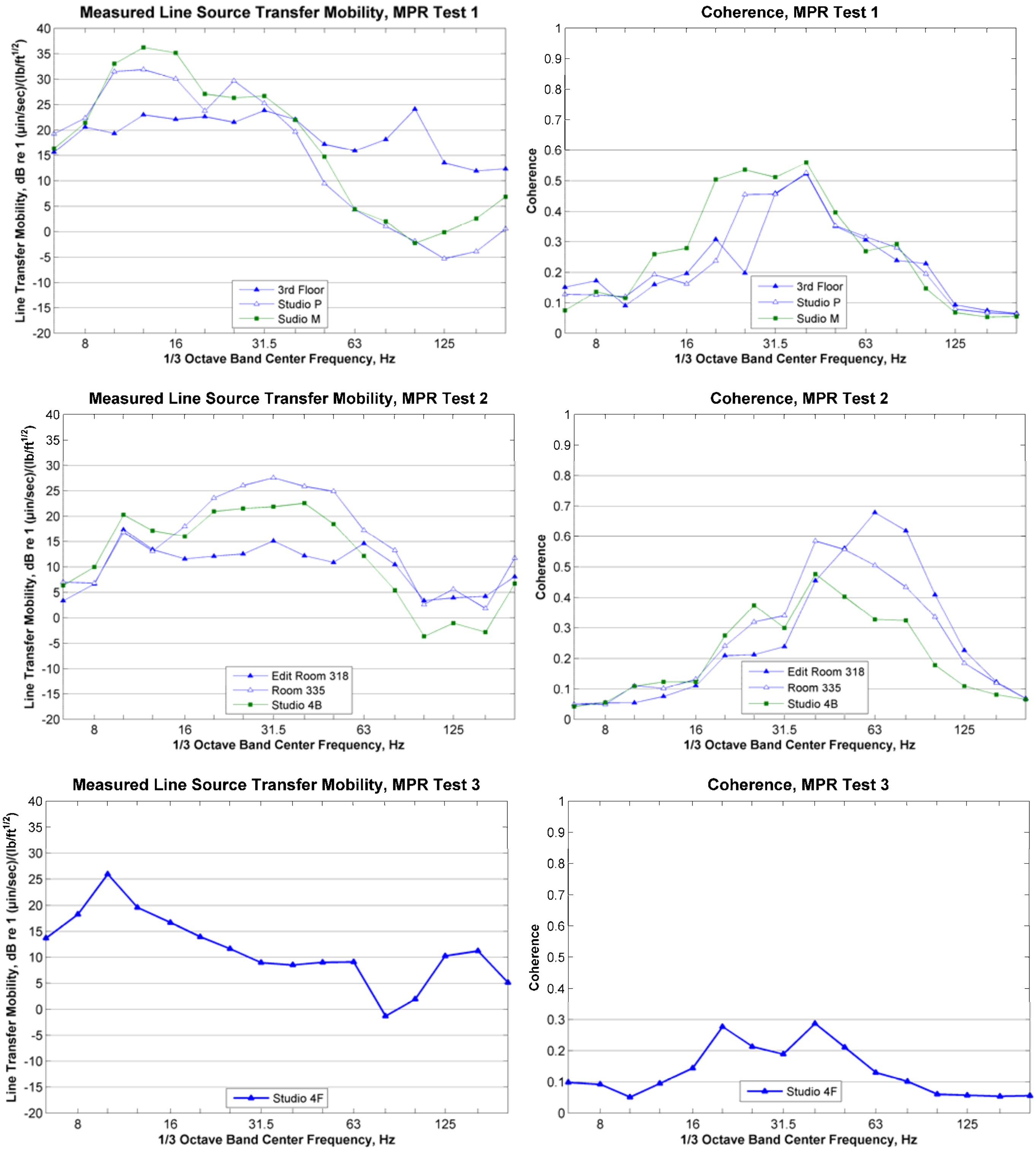


Figure 168: Measured Line Source Transfer Mobility, Tests MPR1, MPR2 and MPR3

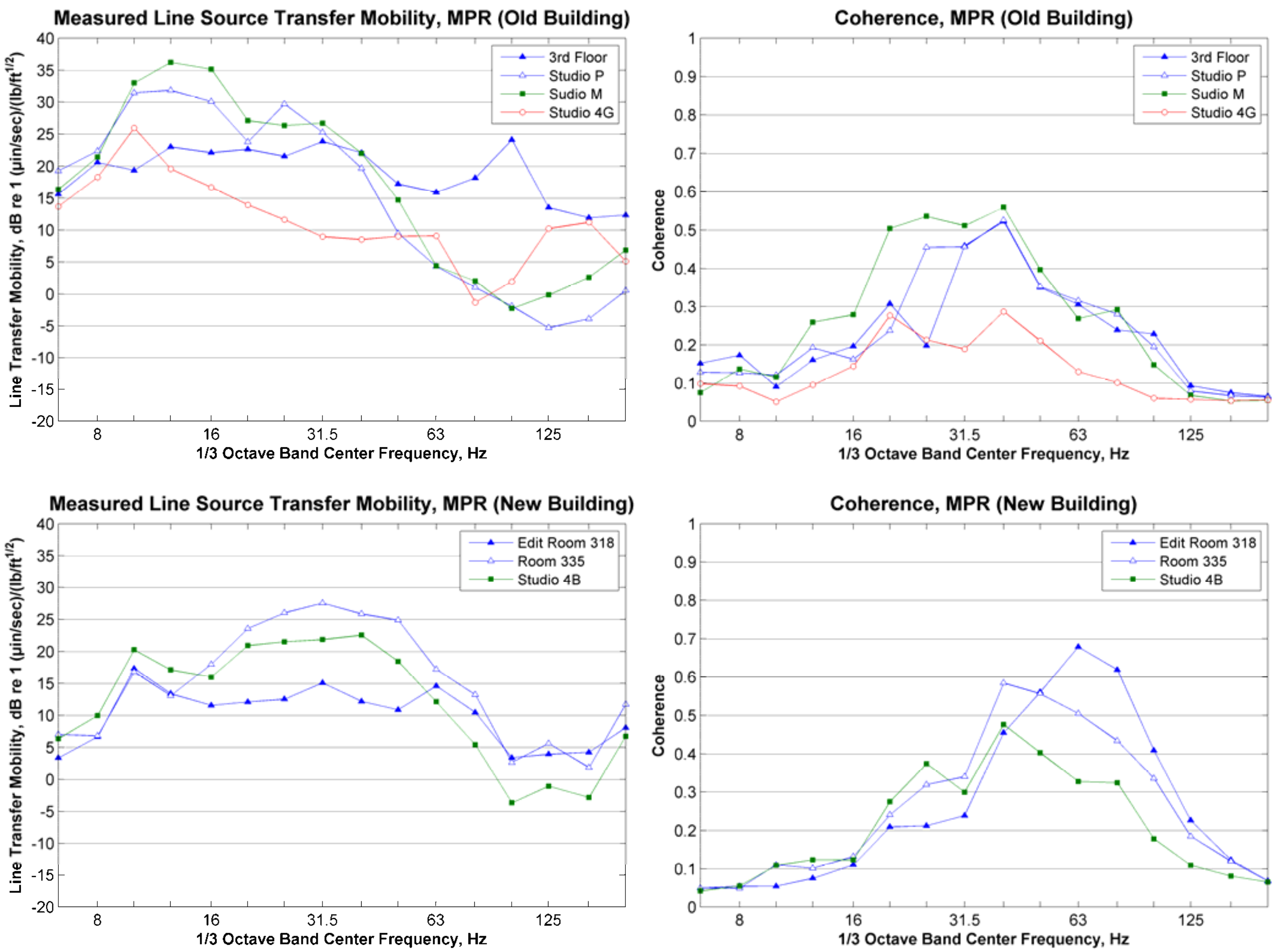


Figure 169: Comparison of LSTM Curves Measured Studios in Original and New MPR Buildings

11.3 MPR Ambient Vibration Measurement

Limited measurements of ambient vibration were made inside the studios at the same time as the LSTM tests in May 2008. For the first two tests, the ambient vibration was derived from the recordings of the impacts by deleting the sections of the recordings with the impacts. Ambient vibration was recorded for 21 minutes in Studio 4G following the third test. More comprehensive measurements of ambient vibration in studio P in the original building and studio 334 in the new building were performed in October 2008.

Figure 170 and Figure 171 show the statistics of the ambient vibration measured inside studios of the original and new MPR buildings respectively. These figures include the overnight measurements inside studios P and 334 that were made in October 2008. The statistics of the 90 minute measurement of noise and vibration in Studio 334 are shown in Figure 172. The overnight measurements are shown in a 3D format in Figure 173 and the simultaneous noise and vibration measurements in studio 334 are shown in 3D and spectrogram formats in Figure 174.

Some observations are:

- Studios M and P have higher levels of vibration in the 8 to 16 Hz range than the other three studios in the original building where measurements were performed. Bus traffic on Cedar Street is one of the sources of vibration at these frequencies. The higher levels are probably the result of a floor resonance close to 16 Hz and the studios being closer to Cedar Street.
- The ambient vibration inside studios P and M are similar. This is to be expected because the studios are located next to each other.
- The overnight vibration for studio P shows substantially less variation that the short-term measurement made during the LSTM tests (see the two middle graphs in Figure 170). This is probably an indication that there was activity in or near studio P when the short-term measurement was performed. The ambient vibration levels from the overnight measurement have been used for the analysis.
- The ambient vibration in the studios in the new MPR building tends to have substantially less low frequency energy than in the new building. At higher frequencies, the vibration levels are roughly comparable between the two buildings.
- There was a strong peak at 31.5 Hz in studio 334. It is not clear what caused this peak, but it is likely to have been caused by some type of mechanical equipment that was operating near the studio.
- The peak in the 25 and 31.5 1/3 octave bands in studio P appears to have been caused by air handling equipment. There was an approximately 2 minute period at 13:25 during the simultaneous noise and vibration measurement when this equipment was turned off. The reduced noise and vibration levels in the 25 and 31.5 Hz 1/3 octave bands are evident in the spectrograms of Figure 174. It is also evident in the spectral plots of in Figure 172. Referring to Figure 172, there is a 7 to 10 decibel difference between the L90% and the L99% at 25 and 31.5 Hz for both the sound and the vibration. The L90% and L99% are within 2 to 3 decibels of each other at all other frequencies. This difference indicates a substantial drop in the noise and vibration levels for a short period of time during the measurement.
- Referring to the 3D plots in Figure 173 of overnight vibration in studios P and 334, the difference in the character of the vibration in the two rooms is evident. There is much more low frequency vibration in studio P and studio 334 has a strong, consistent peak at 31.5 Hz that is similar to the peak seen in the earlier measurements in studio 334. The graphs on the left in Figure 173 show the vibration at 30-second intervals and the graphs on the right show the vibration at 5-minute intervals. The intermittent peaks at 12.5 Hz in studio 334 were probably caused by buses or trucks passing the MPR building on Cedar Street. The higher levels near the end of both measurements were probably caused by activity inside the studio or in adjacent spaces as the workday started.
- Also referring to Figure 173, the vibration in studio P between 18:00 and 08:00 (6 PM to 8 AM) is quite consistent except in the 10 to 16 Hz range. This is the peak frequency range for bus vibration and the fluctuation is likely to have been caused by bus traffic on Cedar Street.
- The spectrograms of the 90 minute sound and vibration measurements in studio P (the bottom two graphs in Figure 174) show time on the horizontal axis, frequency on the vertical axis, and use color to indicate the vibration and sound amplitudes. The white x’s at the top of the spectrograms are the time that buses or trucks passed the MPR building. Referring to the figures there is some indication of a correlation between the vibration peaks and higher vibration levels in the 10 to 16 Hz range. There is no evident correlation with sound.

- Some other observations from comparing the vibration and sound graphs in Figure 174 are:
  - The sound graphs use the same frequency range as the vibration graphs. The bottom end of the range of human hearing is 16 to 20 Hz. The sound data below 16 Hz should be disregarded.
  - The sound and vibration levels in the 25 and 31.5 Hz 1/3 octave bands are similar with the sound being a few decibels higher. Because the vibration and sound levels appear to be independent in this frequency range, it is unlikely that the sound at these frequencies is being caused by the vibration. A more likely scenario is that the sound and vibration are caused by the same source.
  - There are intermittent peaks in the 80 Hz band for sound that are not reflected in the vibration. Again, this is an indication that the sound is not being caused by the vibration.

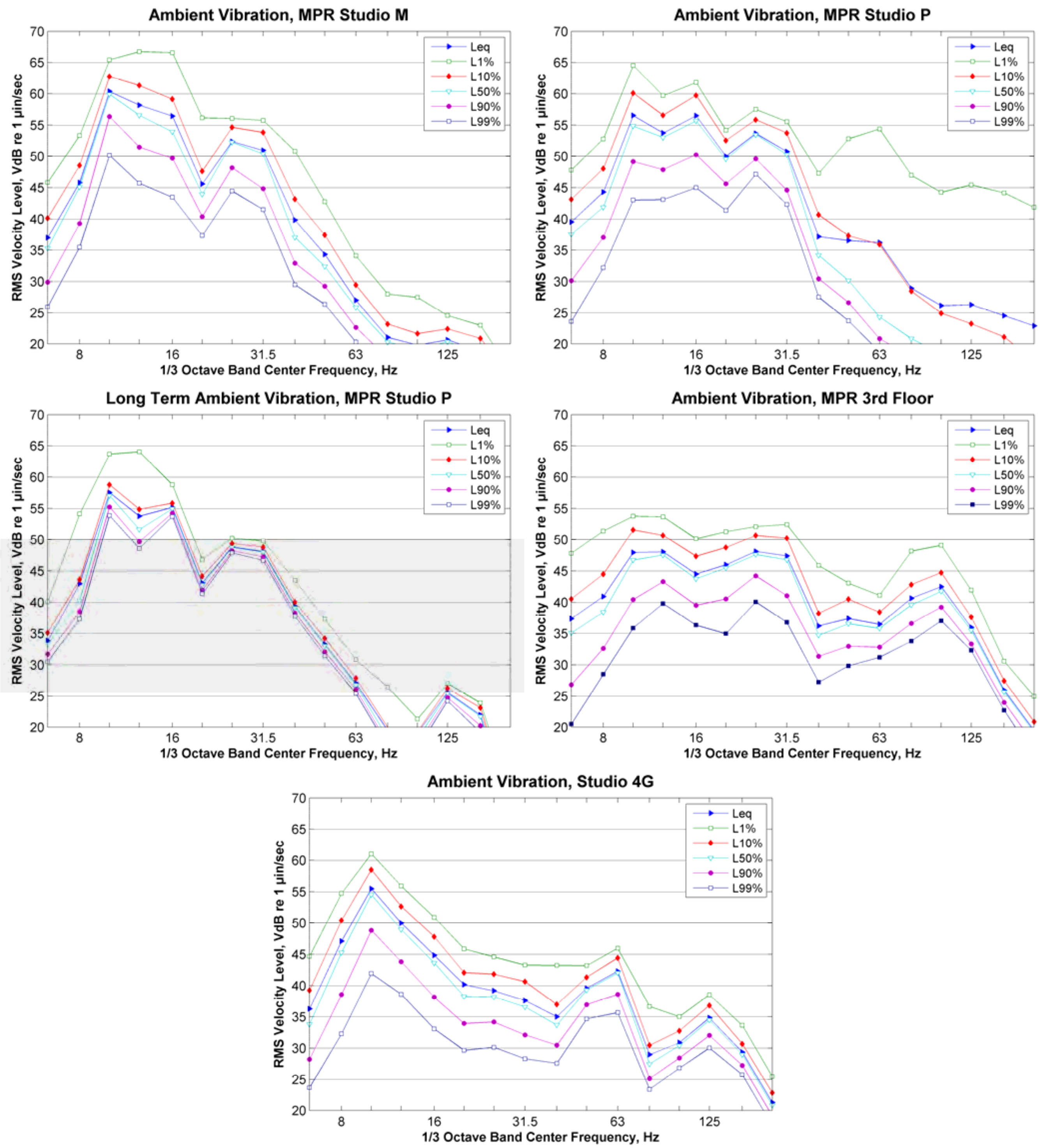


Figure 170: Ambient Vibration Measurements in Original MPR Building

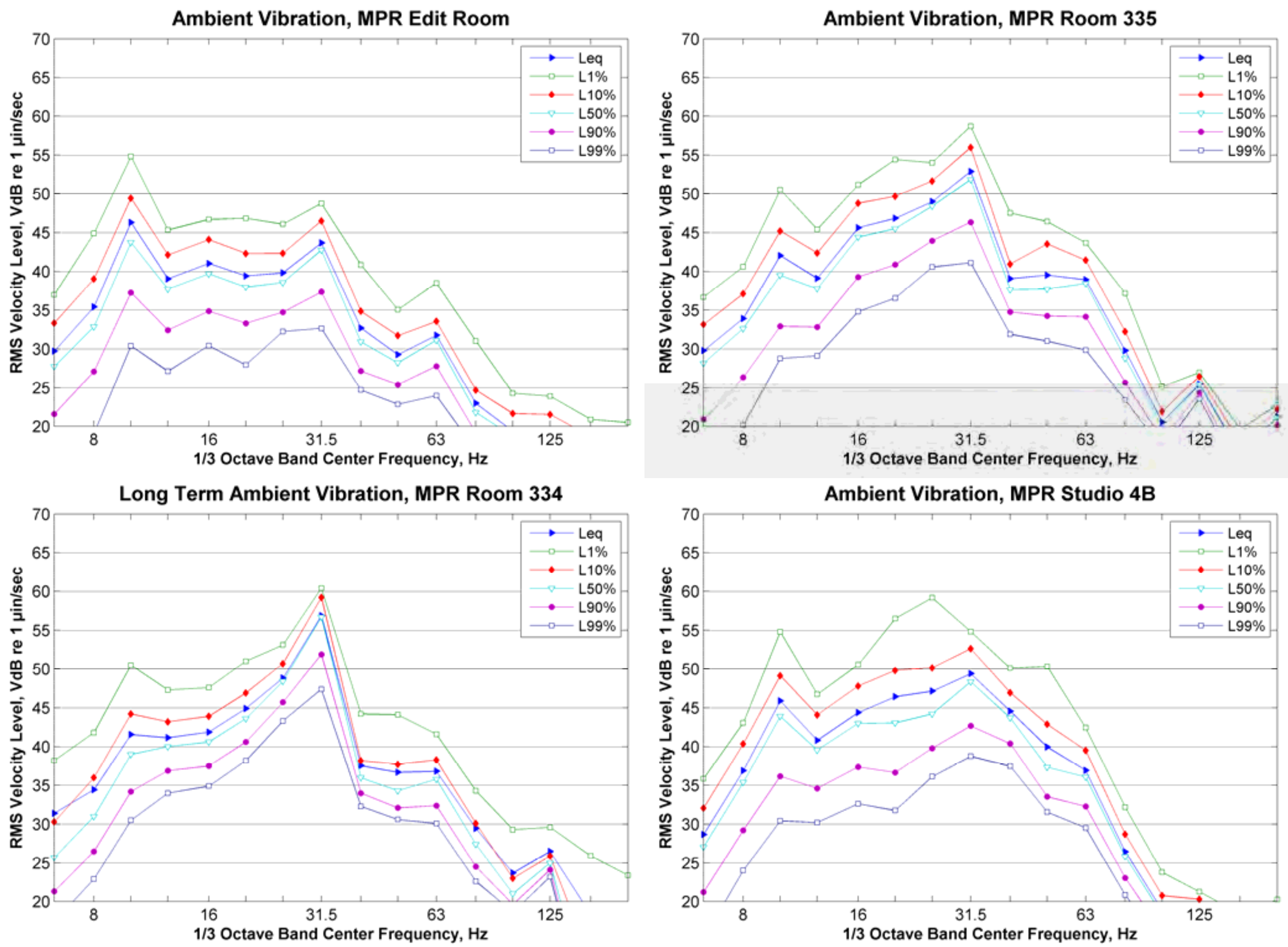


Figure 171: Ambient Vibration Measurements in New MPR Building

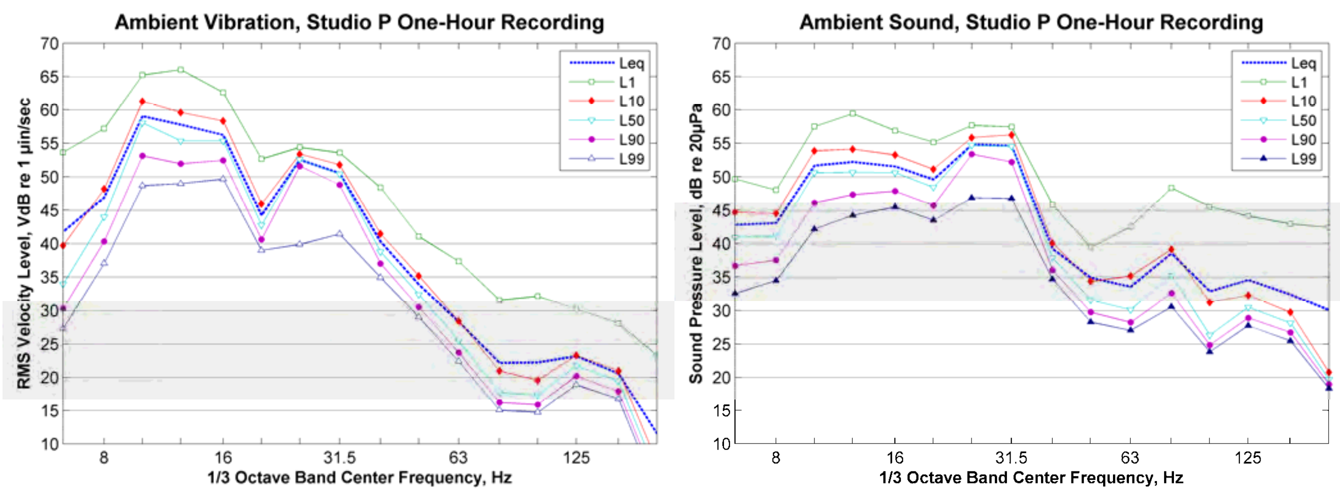
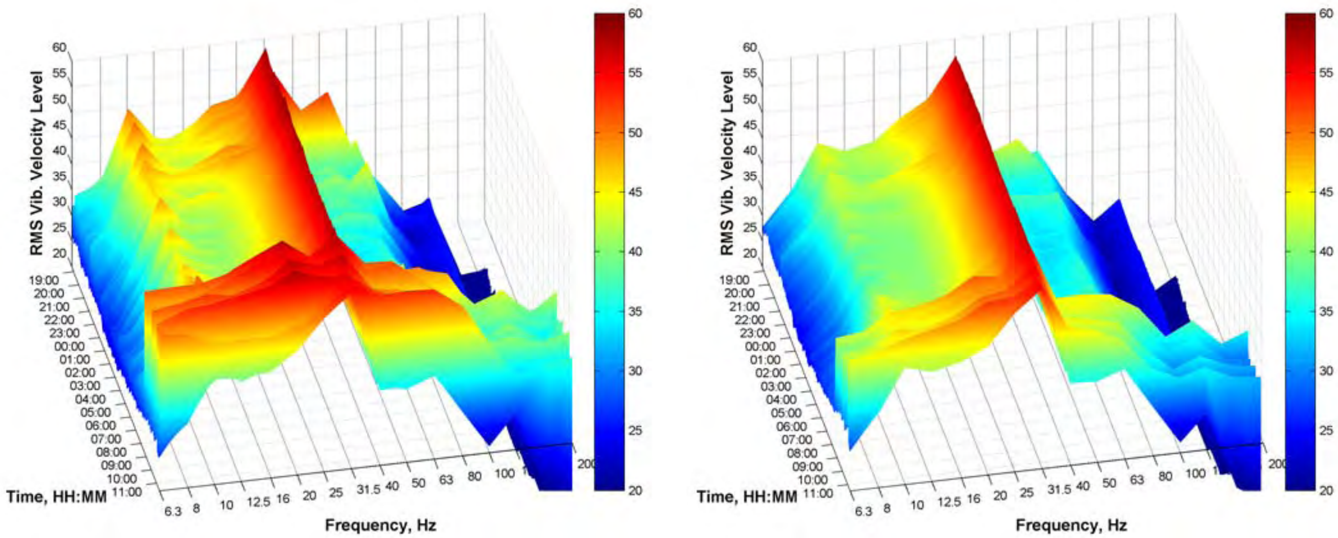
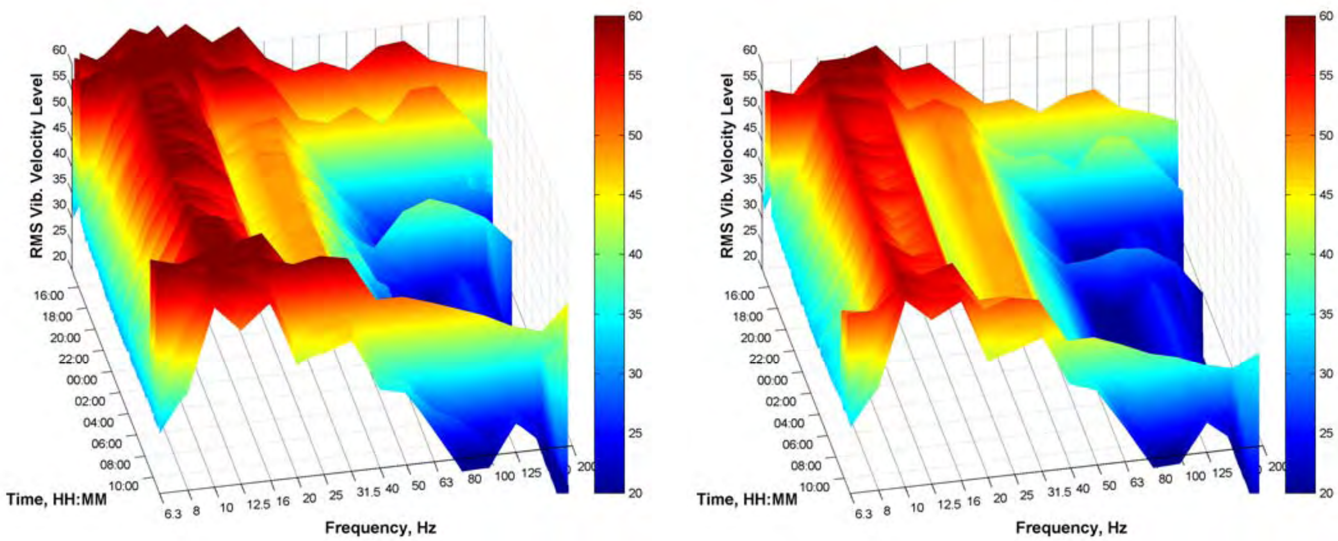


Figure 172: Statistics of Simultaneous Vibration and Sound Measurements inside Studio P



Overnight Measurement, Studio 334



Overnight Measurement, Studio P

Figure 173: 3D Plots of Overnight Vibration Measurements, Studios 334 and Studio P

Graphs on left are average vibration levels at 30-second intervals. The graphs on the right are vibration levels averaged over 5 minute intervals.

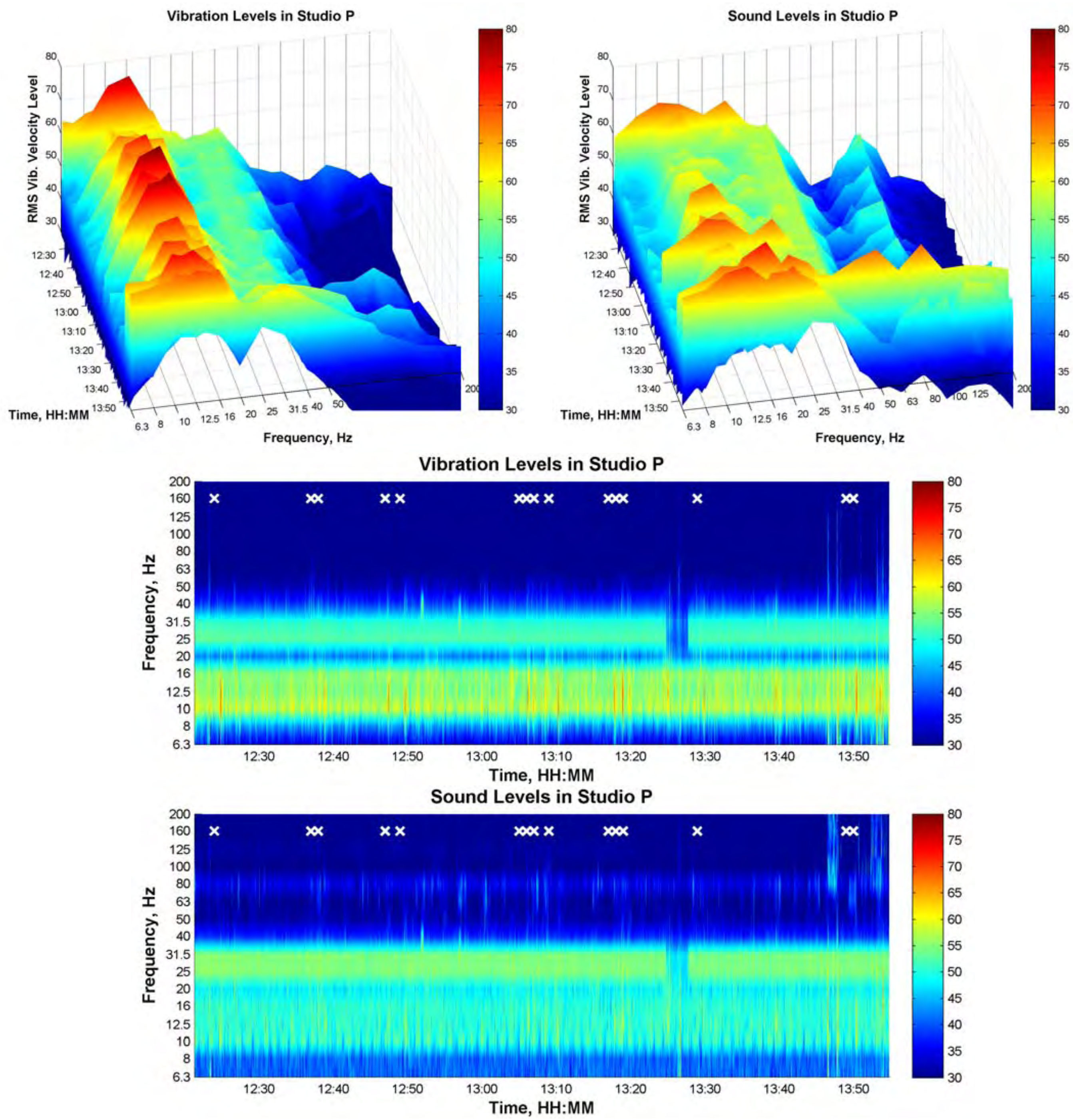


Figure 174: Detailed Results of Simultaneous Noise and Vibration Measurements in Studio P

The top graphs show the vibration levels on the left and the sound levels on the right in a 3D format. The lower two graphs show the same data in a spectrogram format. The horizontal axis is time, the vertical axis is frequency, and the vibration and sound levels in decibels are indicated by the color scale. The white x's at the top of the spectrograms indicate when buses or trucks passed the MPR building on Cedar Street. Although the sound is shown on the same frequency scale as the vibration, 16 Hz is considered the minimum frequency that is audible to most humans.

11.4 Predicted Vibration and Noise Levels inside MPR Studios

Figure 175 shows the predicted LRV and bus vibration for the MPR studios in the original building and Figure 176 show predictions for the studios in the new building. The overall levels in terms of both vibration and A-weighted sound level are summarized in Table 13. Appendix C is a discussion of the procedure used to predict sound pressure level from the predicted vibration levels. Note that an adjustment of -5 decibels was used in predicting the vibration from buses on Cedar Street. This was to account for the LSTM measurements being made on the east side of Cedar Street while the buses typically operate toward the west side of Cedar Street. The predicted bus vibration levels are close to the measured L1 level in the 10 Hz 1/3 octave band for all of the studios. L1 is the level exceeded 1% of the and is representative of typical maximum vibration levels. The correspondence is a confirmation of the procedure used to predict vibration levels inside the MPR studios.

The predictions show the following:

- The highest vibration levels will occur in the low frequency range and are predicted to be created by the existing bus traffic. The predicted ground-borne vibration levels for all of the studios tested are below the FTA impact threshold.
- The predicted ground-borne noise levels exceed the FTA impact threshold of 25 dBA in all of the studios.
- The predicted ground-borne noise level with mitigation in the form of high-resilience direct fixation fasteners are 8 to 10 decibels lower than for the no mitigation case. However, the predicted noise levels still exceed the FTA impact threshold in all of the studios except studio P. This is a bit deceptive because the exceedance of the criteria is caused by higher frequencies where the predictions are conservative. For all of the studios in the original building, the predicted vibration levels with resilient fasteners exceed the ambient vibration only in the 160 and 200 Hz 1/3 octave bands.
- The predicted ground-borne vibration and noise levels inside all of the studios are below the measured L1% ambient vibration in all of the studios assuming the use of a vibration mitigation measure that provides attenuation equivalent to that of a that of a floating slab. One concept for a mitigation measure that could provide sufficient vibration attenuation is shown in Figure 5 (Section 4, page 4).

11.5 MPR Mitigation

The vibration analysis shows that vibration mitigation is needed to ensure that the vibration from LRV vibration does not interfere with the use of the MPR studios. Section 4 discussed several vibration mitigation measures that would be effective for the MPR studios. The final decision about which vibration mitigation measure to apply and the trackbed design to implement the mitigation measure will occur during the final design. One step that should be taken before the final decision is made on the vibration mitigation design is to check the ambient sound levels the studios to confirm that the predicted levels of ground-borne noise exceed the ambient sound levels.

Table 13: Summary of Predicted Vibration and Noise Levels Inside MPR Studios
(FTA impact thresholds for recording studios are 65 VdB for vibration and 25 dBA for noise.)

Test	Location	Predicted Ground-borne Vibration and Noise Levels[1]					
		No Mitigation		With Resilient Fasteners		With Floating Slab or Equivalent	
		Vib, VdB	Noise, dBA	Vib, VdB	Noise, dBA	Vib, VdB	Noise, dBA
MPR1 Original Building	Studio M	65	**48**	56	**38**	54	23
	Studio P	60	**32**	60	24	61	5
	Third Floor	63	**38**	62	**30**	63	10
MPR2 New Building	Edit 318	55	**39**	48	**31**	46	12
	Room 335	59	**42**	52	**34**	47	14
	Studio 4B	54	**36**	50	**29**	49	9
MPR3 Original Building	Studio 4G	59	**43**	54	**33**	55	14

Notes:
1. Numbers in **bold** exceed the FTA impact threshold.
2. High-resilience direct fixation fasteners are the assumed mitigation measure.

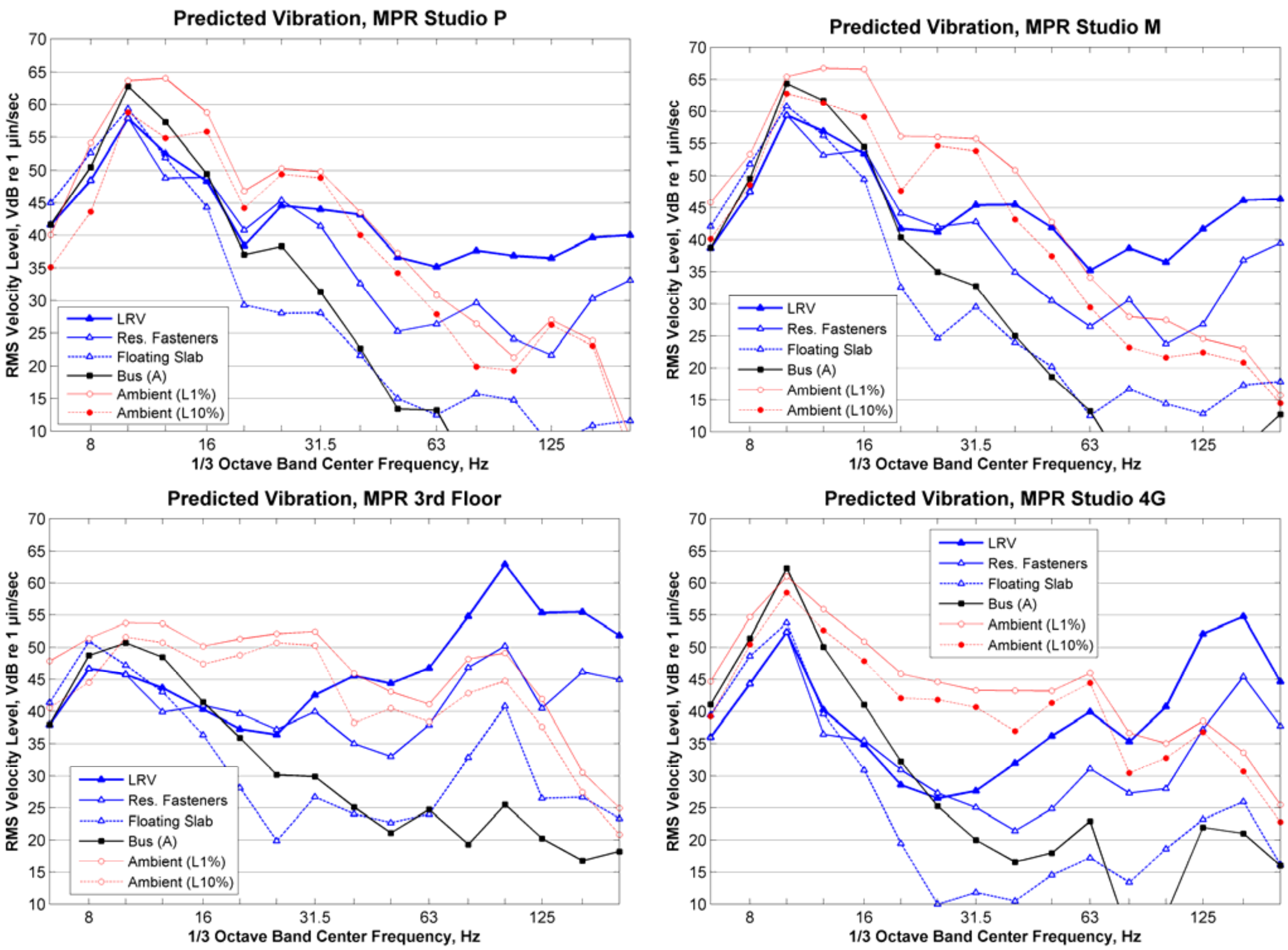


Figure 175: Predicted Vibration in Studios in Original Building

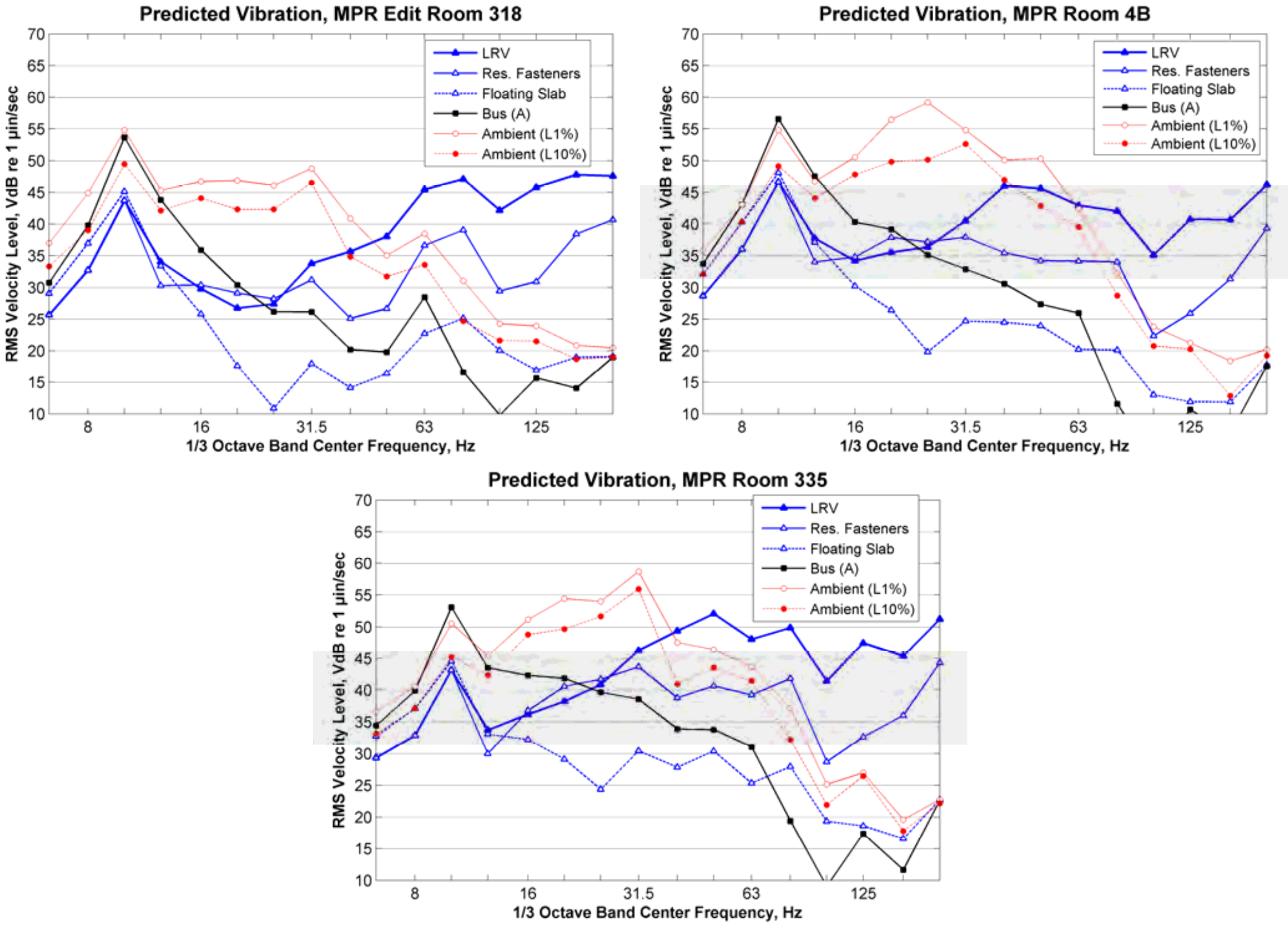


Figure 176: Predicted Vibration in Studios in New Building

12. CONSTRUCTION VIBRATION

12.1 Limits for Construction Vibration

Most limits on construction vibration are based on minimizing the potential for damage to nearby structures. The construction procedure that is most commonly associated with building damage is blasting, either for mining operations or for excavating through rock layers. Blasting would not be required for construction of the CCLRT, which substantially reduces the potential for structural damage. Other construction procedures that generate relatively high vibration levels include pile driving, use of hoe rams and jackhammers for demolition, vibratory compaction, and tracked vehicles such as bulldozers.

Limits for construction vibration are almost always expressed in terms of the peak particle velocity (PPV). The most common vibration limit is a PPV of 2 in/sec, which is largely based on studies performed by the U.S. Bureau of Mines. A study reported on in USBM Bulletin 656 (1971) investigated the effect of blasting vibration on roadways, bridges, concrete structures, and residential structures. The results indicated that minor damage such as cracks in masonry, drywall, and plaster in old residential structures can occur at a vibration level above 5.4 in/sec. The "threshold of damage" limit recommended by the USBM was 4.0 in/sec, which was considered sufficient to avoid structural or cosmetic damage to residences. A recommendation of the US Office of Surface Mining is to use a limit of 0.75 in/sec to protect against growth of hairline cracks in weak residential structures including hairline cracks that may be too small to be seen without magnification.

In addition, there are several European standards that specify substantially lower limits to protect against damage to fragile historic structures. One example is Swiss Standard SN640312a (April 1992) from the Association of Swiss Highway Professionals, Committee VSS 272. The values from the Swiss Standard are shown in Table 7. Based on the definitions in the Swiss Standard, residences in the project area would be categorized as "Average Sensitivity" and any historic buildings in the corridor (e.g., Central Presbyterian Church and the Church of Saint Louis on Cedar Street in St. Paul) would be classified as "Particularly High Sensitivity." The rate of occurrence would be considered "Frequent." The Swiss Standard indicates that a vibration limit between 0.12 and 0.24 in/sec (PPV) for vibration below 30 Hz is appropriate for the sensitive historic structures. This is substantially lower than the vibration limits in most other standards.

The ratio of PPV to root mean square (rms) is referred to as the crest factor. The crest factor for construction vibration is typically in the range of 4 to 6, which means that the PPV vibration can be expressed in terms of rms vibration velocity decibels using the following relationship:

$$L_V \approx 20 \times \log\left(\frac{PPV}{CF \times 10^{-6}}\right)$$

where CF is the crest factor and L_V is the vibration velocity level in VdB. Using a CF of 4 will give a conservative estimate of L_V. The FTA Guidance Manual uses this relationship and the limits in the Swiss Standard to recommend 90 VdB as a conservative threshold to avoid damage to fragile historic structures. Based on the Swiss Standard, the equivalent threshold is 96 VdB for vibration at frequencies greater than 60 Hz.

Table 14: Guideline Values for Construction Vibration (Swiss Standard SN640312a)

Sensitivity Category	Rate of Occurrence	Guideline Value (in/sec)		
1. Very Low Sensitivity		Up to 3 times the values for Sensitivity Category 3		
2. Low Sensitivity		Up to 2 times the values for Sensitivity Category 3		
3. Average Sensitivity		< 30 Hz	30 to 60 Hz	> 60 Hz
	Occasional	0.59	0.79	1.18
	Frequent	0.24	0.31	0.47
	Permanent	0.12	0.16	0.24
4. Particularly High Sensitivity		Between 0.5 and 1 times the values for Sensitivity Category 3		

The approach recommended by the FTA Guidance Manual is to use thresholds of 90 to 102 VdB to identify buildings where there is potential for damage and use the vibration criteria applied to operational vibration to identify locations where there is potential for vibration to be annoying to building occupants. The 90 VdB threshold applies to buildings that are extremely susceptible to vibration damage and the 102 VdB threshold applies to "reinforced-concrete, steel or timber (no plaster)" buildings that are much less prone to be damaged by vibration.

Based on the guidance on construction vibration provided in the FTA Guidance Manual, the thresholds in Table 15 have been used to determine potential impact from construction vibration. These thresholds are sufficient to avoid damage to buildings, interference to most research and recording activities, and will minimize annoyance of building occupants. When construction is necessary in close proximity to facilities such as the U of M research laboratories and the recording studios at MPR, it may not be feasible to achieve the thresholds shown in Table 15. As discussed later, in these cases coordinating the construction schedule to minimize interference with the use of the studios and research facilities would be necessary.

Table 15: Impact Thresholds Used to Evaluate Construction Vibration

Land Use	Threshold		Comments
	PPV (in/sec)	**RMS[1] (VdB)**	
Fragile historic buildings	0.12	90	Avoiding vibration that exceeds this threshold should be sufficient to protect the most fragile buildings.
Normal single family residences, office buildings and commercial buildings	0.5	102	This limit is considered sufficient to avoid even minor cosmetic damage to typical construction.
Annoyance, residential land uses, daytime	0.022	75	This limit is applicable to construction vibration that would last for an extended period of time.
Annoyance, residential land uses, nighttime	0.016	72	This limit is applicable to construction vibration that would last for an extended period of time.
Annoyance, institutional land uses	0.022	75	This limit is applicable to construction vibration that would last for an extended period of time.

Recording studios and theaters while in use	0.007	65	
Interference with vibration sensitive equipment	0.0005	42	It may not be feasible to achieve this limit with many of the construction processes that will be used.
Notes: 1. A crest factor of 4 has been used to estimate equivalent RMS vibration.			

12.2 Construction Vibration Impacts

The construction processes for the CCLRT project that are expected to generate the highest vibration levels include pile driving, demolition using jackhammers and hoe rams, and operation of heavy tracked equipment such as bulldozers and backhoes. Following is a summary of the procedure used to estimate vibration levels during construction:

1. The typical vibration levels given in Table 16 for different classes of construction equipment at a reference distance of 25 ft were used as the starting point. The typical PPV for impact pile driving in Table 16 (0.644 in/sec) was used as the basis for assessing the potential for vibration to exceed the damage threshold in locations where pile driving might be required. For other locations, the PPV for hoe rams and large tracked vehicles was used (0.089 in/sec).
2. The vibration amplitudes as a function of distance were estimated using the following relationship:

$$PPV_{equip} = PPV_{ref} \times \left(\frac{25}{D}\right)^{1.5}$$

where: PPV_{equip} = peak particle velocity of the equipment adjusted for distance,
PPV_{ref} = peak particle velocity in in/sec at 25 feet from Table 16, and
D = distance from the equipment to the receiver.

Figure 177 shows the vibration levels versus distance for a range of construction processes.

3. The curves of vibration amplitude as a function of distance and the impact thresholds in Table 15 were used to estimate the impact distances.

Table 16: Vibration Source Levels for Construction Equipment

Equipment		PPV at 25 ft (in/sec)
Pile Driver (impact)	upper range	1.518
	typical	0.644
Pile Driver (sonic)	upper range	0.734
	typical	0.170
Clam shovel drop (slurry wall)		0.202
Hydromill (slurry wall)	in soil	0.008
	in rock	0.017
Vibratory Roller		0.210
Hoe Ram		0.089
Large bulldozer		0.089
Caisson drilling		0.089
Loaded trucks		0.076
Jackhammer		0.035
Small bulldozer		0.003
Source: FTA Guidance Manuals (FTA 2006)		

As discussed above, the impact thresholds for damage are a PPV of 0.5 in/sec for normal buildings and 0.12 in/sec for fragile historic buildings. The threshold of annoyance during daytime at residences and institutional land use is 0.022 in/sec. The threshold of annoyance during nighttime at residences is 0.016 in/sec. The impact threshold for U of M research facilities housing sensitive equipment is 0.0005 in/sec and for the recording studios is 0.007 in/sec. The impact distances for various sensitive receivers from construction vibration are given in Table 17. One factor to note is that the predicted impact distances for recording studios and research facilities range from 500 to 5000 ft. Although the accuracy of the predictions decreases with distance, this is an indication that the use of high-vibration construction equipment at distances of less than about 1/2 mile from research labs may interfere with use of vibration sensitive equipment. Similarly, use of high-vibration construction equipment at distances of less than about 1000 ft from recording studios may interfere with use of the studios.

Table 17: Impact Distances for Construction Vibration

Construction Activity	Land Use and Type of Impact	Impact Threshold, PPV (in/sec)	Estimated Impact Distance (ft)
Impact Pile Driving, Upper Range	Damage to normal buildings	0.5	55
	Damage to fragile historic buildings	0.12	135
	Residential annoyance, daytime	0.022	420
	Residential annoyance, nighttime	0.16	520
	Recording studios	0.007	900
	U of M research facilities	0.0005[2]	5000
Impact Pile Driving, Lower Range	Damage to normal buildings	0.5	30
	Damage to fragile historic buildings	0.12	80
	Residential annoyance, daytime	0.022	240
	Residential annoyance, nighttime	0.16	290
	Recording studios	0.007	500
	U of M research facilities	0.0005[2]	3000
Tracked vehicles, demolition with hoe rams	Damage to normal buildings	0.5	<10
	Damage to fragile historic buildings	0.12	<10
	Residential annoyance, daytime	0.022	65
	Residential annoyance, nighttime	0.16	80
	Recording studios	0.007	135
	U of M research facilities	0.0005[2]	800

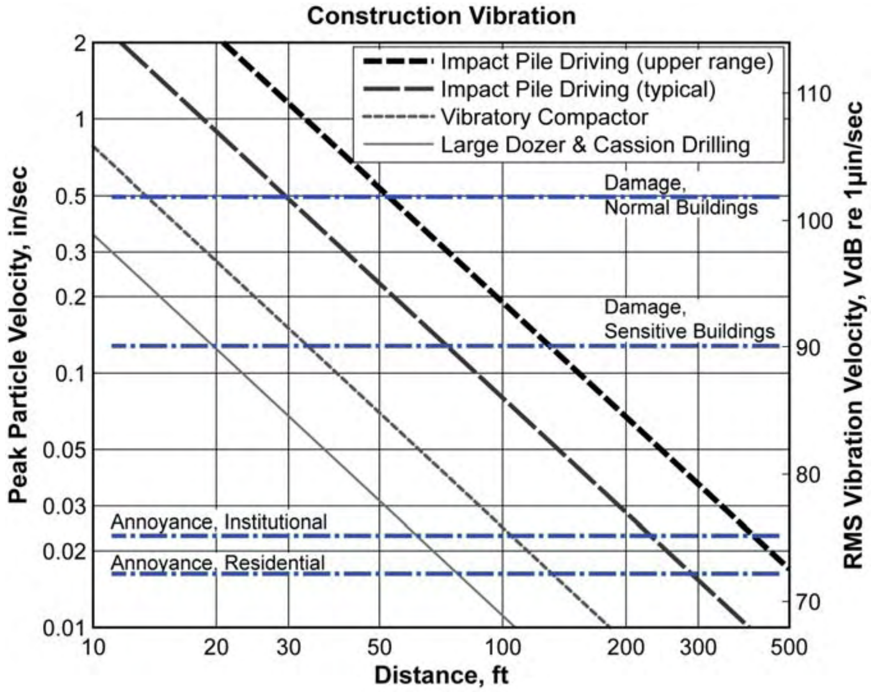


Figure 177: Typical Vibration Levels from Construction Equipment
(The right hand axis is the approximate RMS vibration velocity in decibels assuming a crest factor of 4.)

12.3 Vibration Mitigation During Construction

The best approach for minimizing the impact from construction vibration is to limit the use of high-vibration procedures such as impact pile driving and to include vibration limits in the construction specifications that the contractor is not allowed to exceed.

An approach that has been used successfully on previous projects is to have separate damage and annoyance limits included in the construction specifications. If a process has potential to approach the damage limit at any building, the contractor should be required to arrange for vibration monitoring and, if the vibration exceeds the limit, the offending action must be modified or terminated immediately. More latitude is allowed for exceeding the annoyance limit. To ensure that the vibration monitoring is completely objective with no potential conflicts of interest, the vibration monitoring is sometimes performed under a contract with the construction authority rather than as a subcontract to the contractor.

If complaints are received and monitoring shows that the annoyance limit is being exceeded, then the contractor must come up with an alternative approach that reduces the vibration. It would then be the resident engineer's decision whether to stop construction until modifications are made that reduce the vibration levels.

The recommended vibration mitigation measures during construction are:

1. Pre-Construction Survey: A standard pre-construction survey should be performed to document the existing condition of all structures in the vicinity of sites where major construction will be performed.

2. Vibration Limits: Three sets of vibration limits are recommended. The first is intended to minimize the potential for damage to buildings, particularly of historic structures and churches. The second is to reduce potential for intrusive vibration at sensitive receptors such as residences, schools and theatres. Of particular importance for the second limit is to minimize intrusion during the nighttime hours when people are trying to sleep. The final set of vibration limits is to limit potential intrusion to research activities at the U of M facilities, use of the MPR studios, and performances at the Fitzgerald Theater.

   The recommended limits in terms of PPV are:

   - Damage to normal buildings: 0.5 in/sec
   - Damage to historic buildings including churches:

     0.12 in/sec
   - Annoyance, residential buildings
     - Daytime: 0.022 in/sec
     - Nighttime: 0.016 in/sec
   - Annoyance at office space, schools, churches, and other institutional land:

     0.022 in/sec

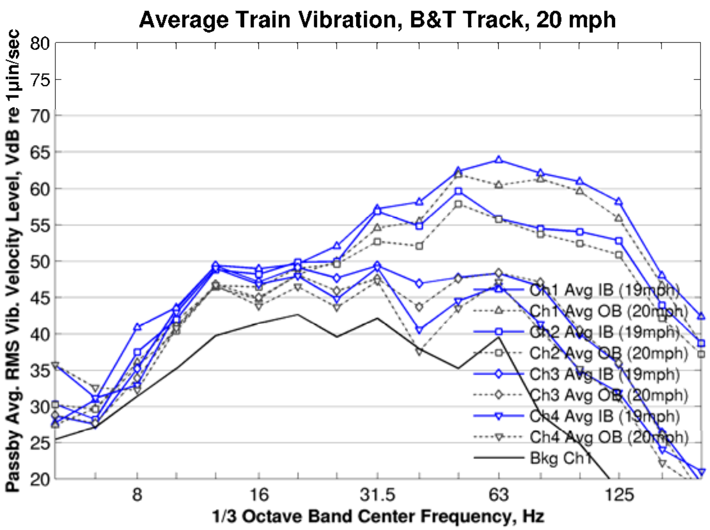
3. Vibration Monitoring: When processes such as pile driving that create high vibration levels will be used near residences, schools or other vibration sensitive receptors, vibration monitoring should be performed to verify that no construction activities exceed the vibration limits. Either the contractor can be required to perform the vibration monitoring or the construction authority can independently arrange for the monitoring to ensure the there are no conflicts of interest. The primary goal of the monitoring is to minimize the potential for damage to structures. Vibration monitoring is a crucial requirement when construction will be within 150 ft of historic buildings. For example, if driven piles are needed near the historic buildings, several test hits should be monitored prior to starting the pile driving to ensure that the levels are below the limits. If vibration from the test hits approaches or exceeds the limits, the force of the pile driver should be reduced until the vibration amplitudes at all sensitive buildings are below the applicable limit. Only then would the actual pile driving commence.

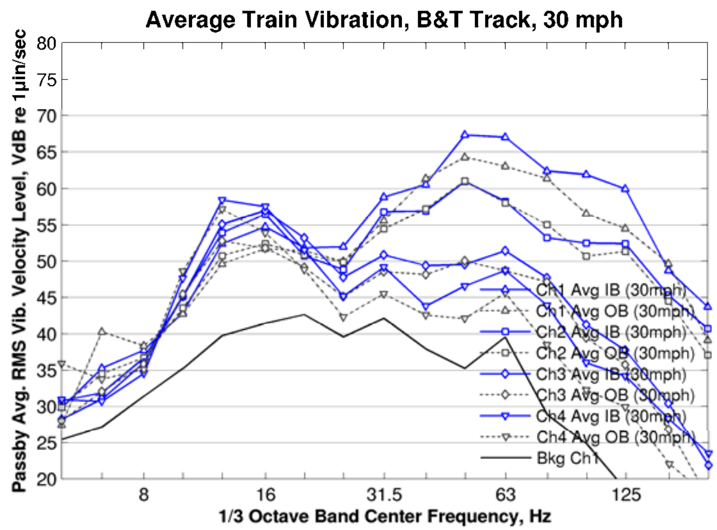
4. Coordinating Construction Schedule: The impact thresholds for the U of M research facilities, MPR recording studios and the Fitzgerald Theater are very low and it may not be feasible to achieve these limits during construction. As a result, it may not be feasible to have vibration producing construction activities concurrently with research using vibration-sensitive equipment, with audio recording, or with theater performances. Therefore, whenever construction would be performed near U of M research facilities, the MPR studios, or the Fitzgerald Theater, the stakeholders should be consulted and notified of the schedule in advance. Construction activities can then be coordinated to ensure the least potential for any disruption or annoyance.

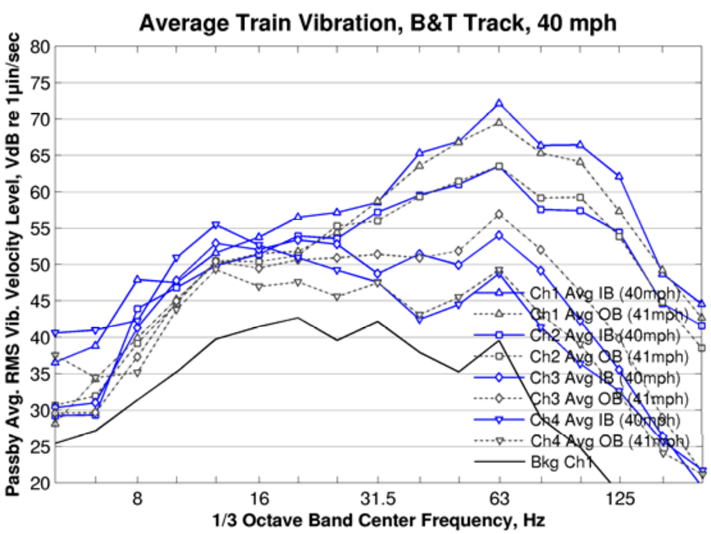
5. Alternative Construction Procedures: Where feasible and cost effective, low vibration construction procedures should be required. For example, in some cases it is feasible to use hydraulic pile drivers in place of impact pile drivers. If hydraulic pile driving is either impractical or cost prohibitive, the adverse vibration effects can be minimized by placing piles in pre-drilled holes and limiting use of impact pile driving to setting the piles.

APPENDIX A. DETAILED RESULTS OF TRAIN VIBRATION MEASUREMENTS

A.1 Train Vibration, 24th Street (Ballast and Tie Track)







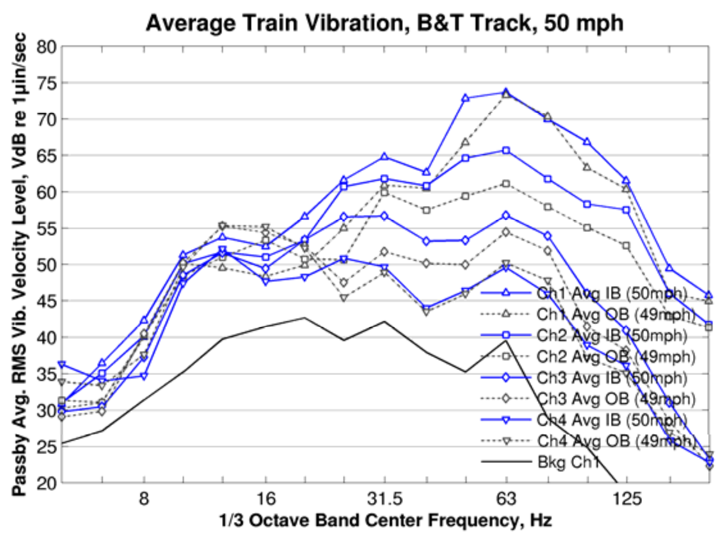
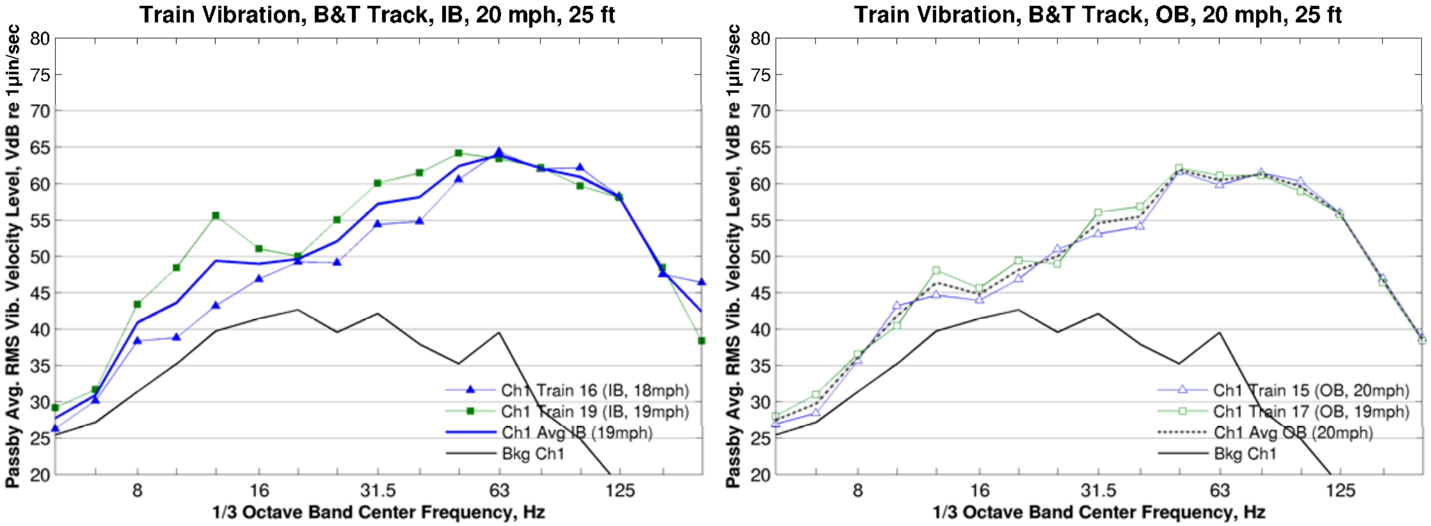


Figure 178: Average Vibration Spectra, Ballast & Tie Track



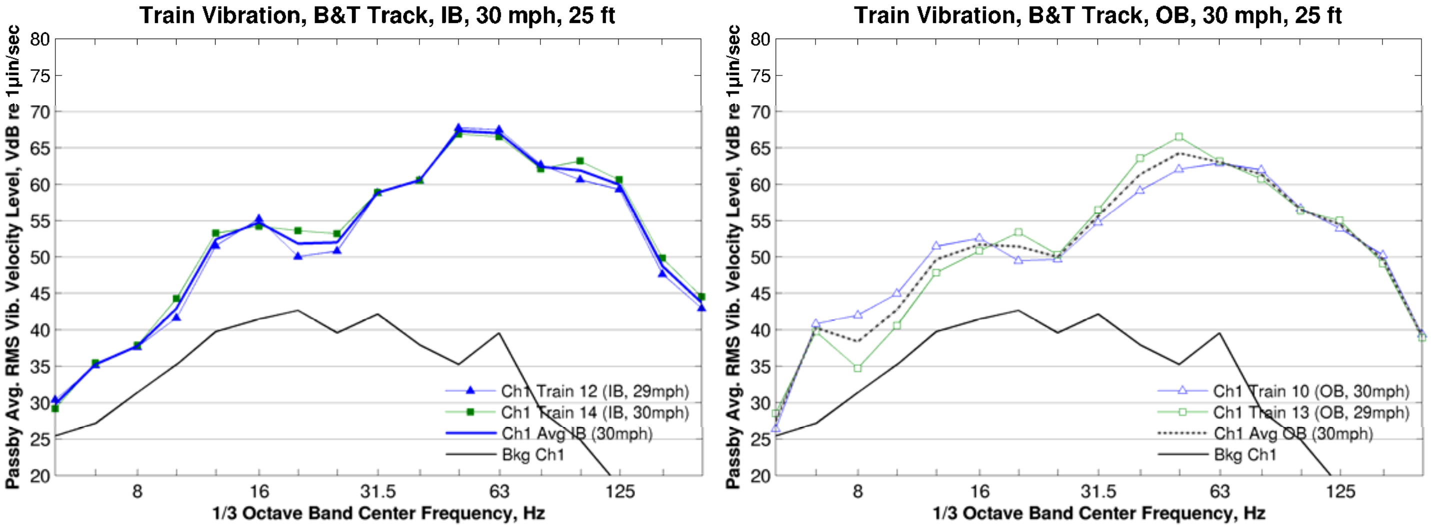


Figure 179: Vibration Spectra, Ballast & Tie Track, 25 ft, 20 and 30 mph

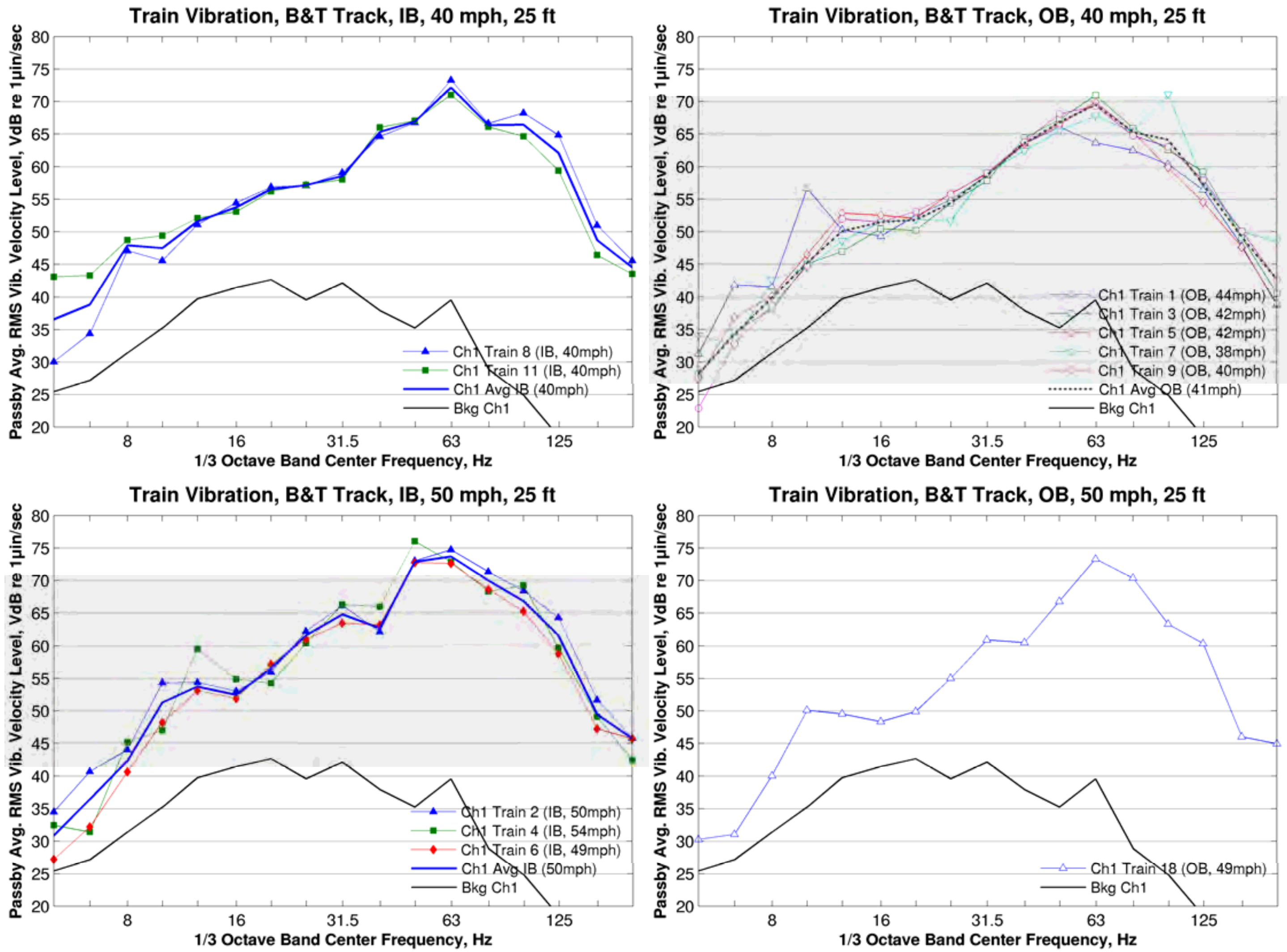


Figure 180: Vibration Spectra, Ballast & Tie Track, 25 ft, 40 and 50 mph

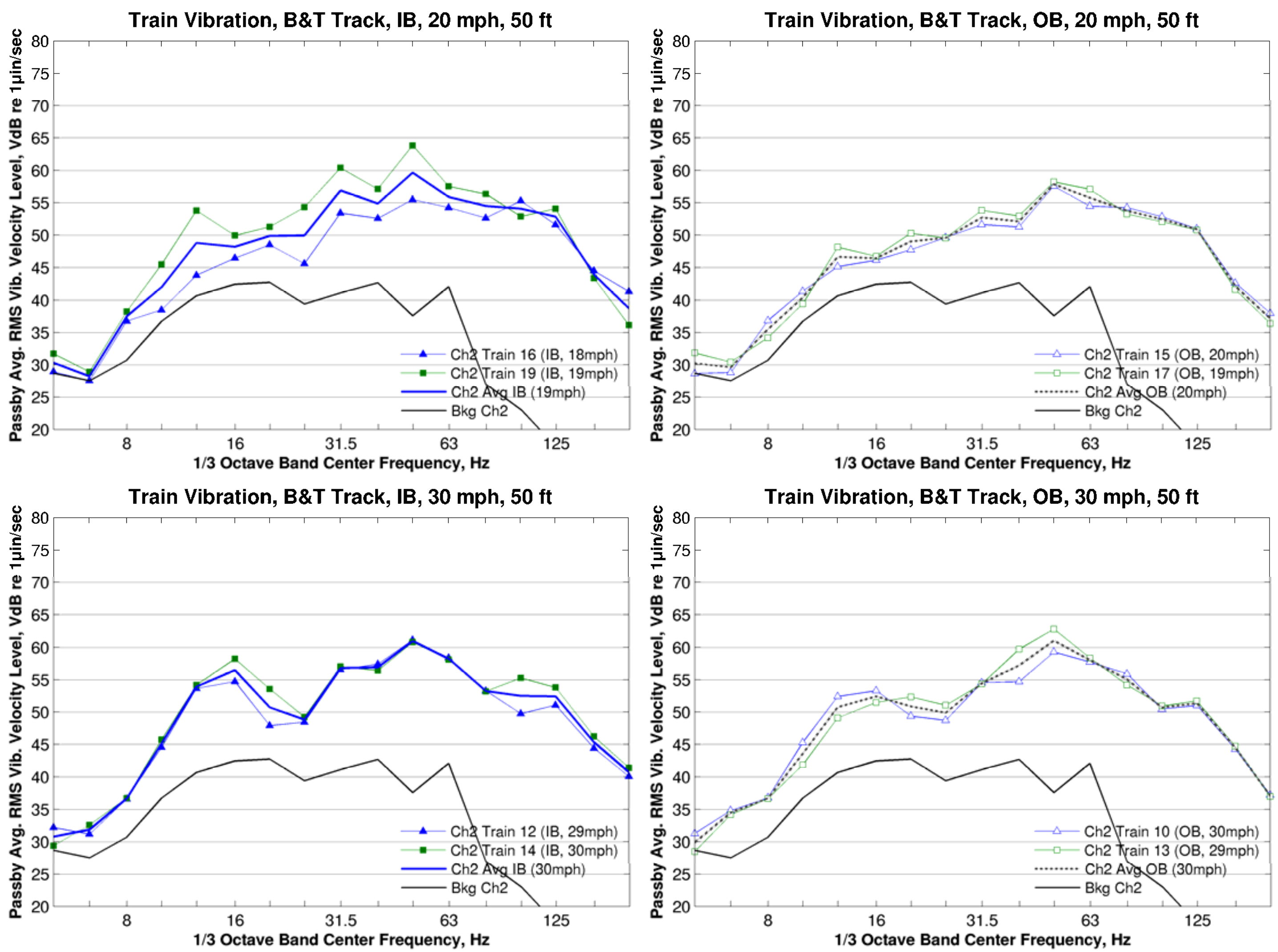


Figure 181: Vibration Spectra, Ballast & Tie Track, 50 ft, 20 and 30 mph

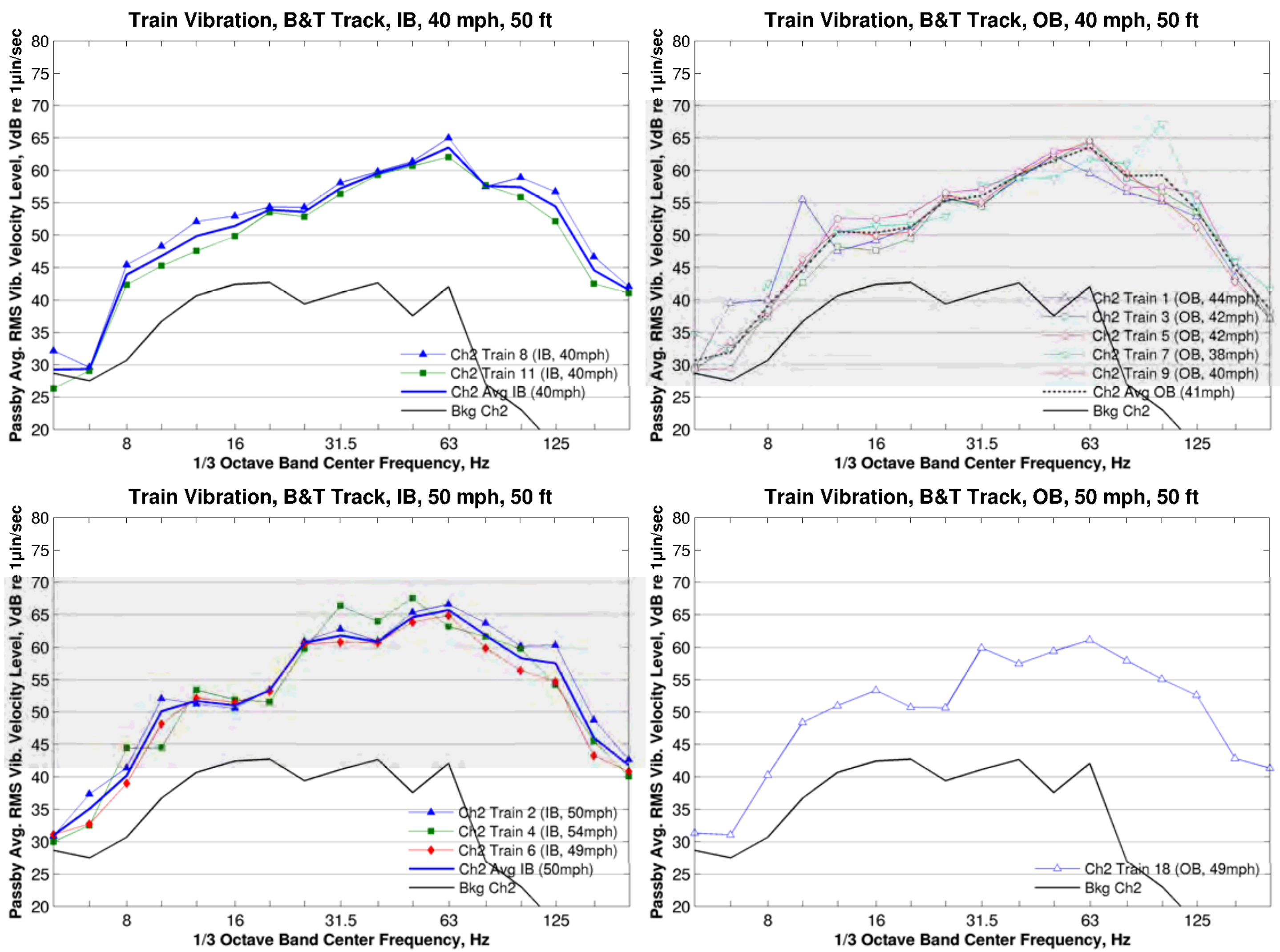


Figure 182: Vibration Spectra, Ballast & Tie Track, 50 ft, 40 and 50 mph

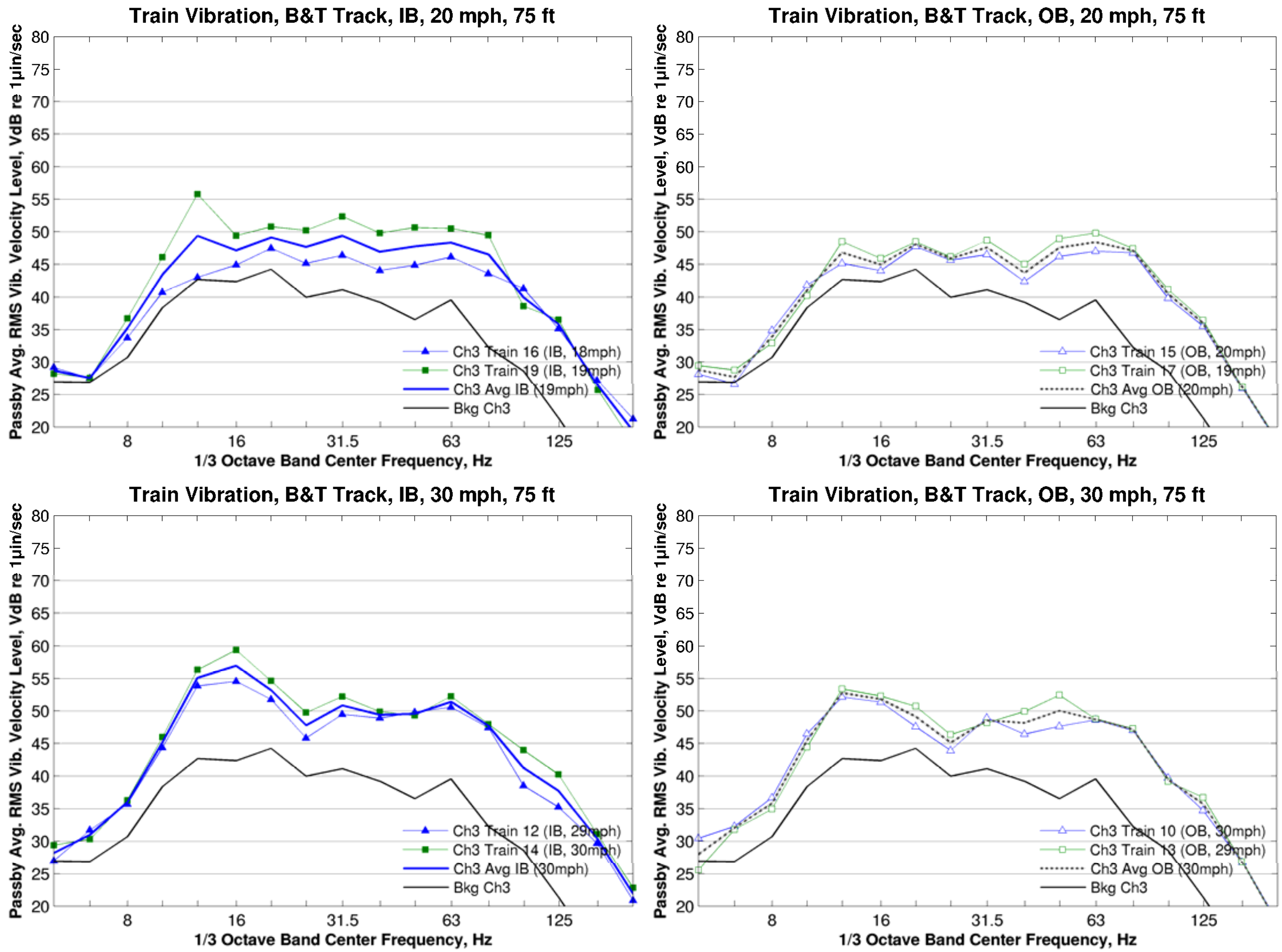


Figure 183: Vibration Spectra, Ballast & Tie Track, 75 ft, 20 and 30 mph

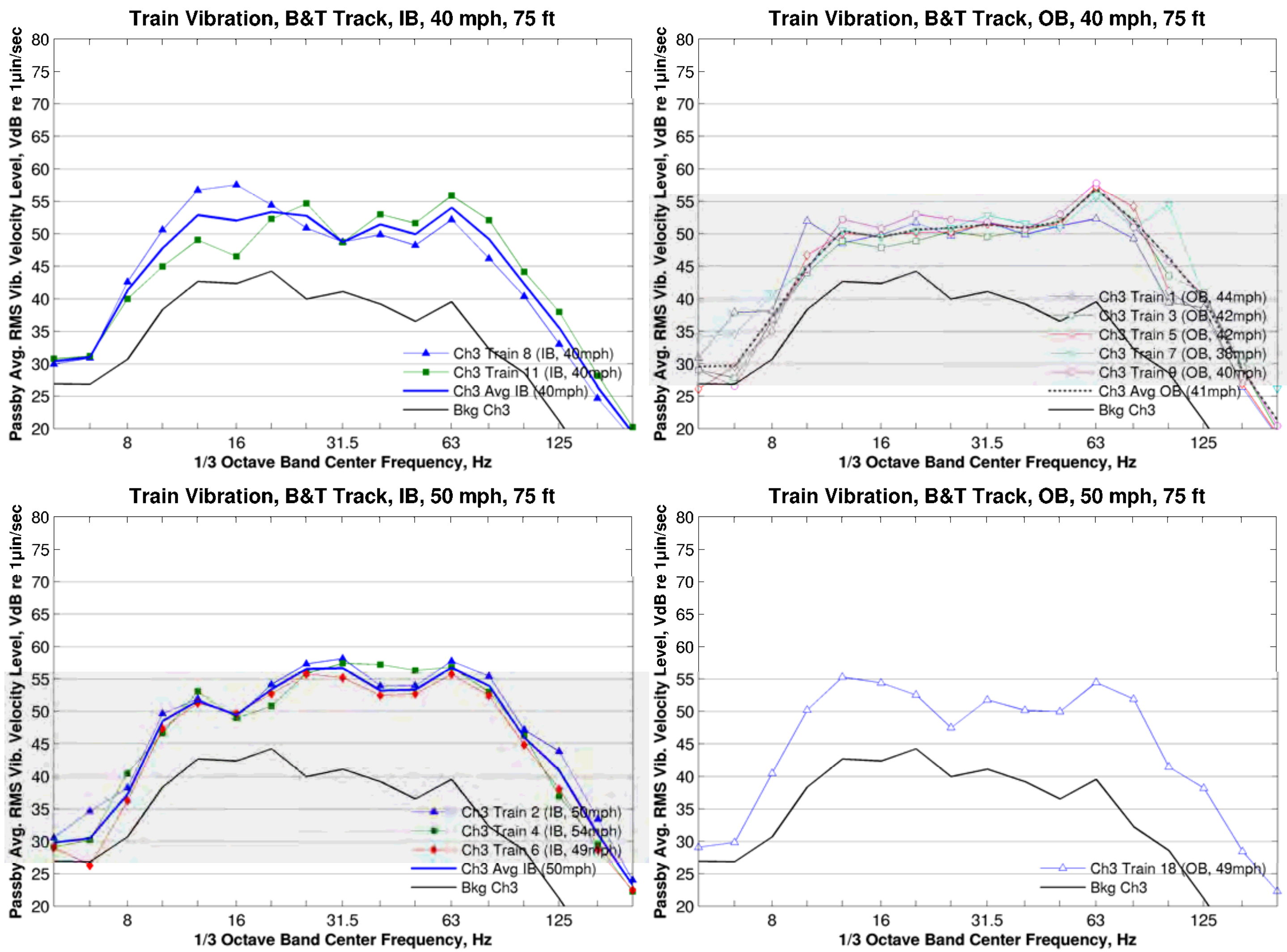


Figure 184: Vibration Spectra, Ballast & Tie Track, 75 ft, 40 and 50 mph

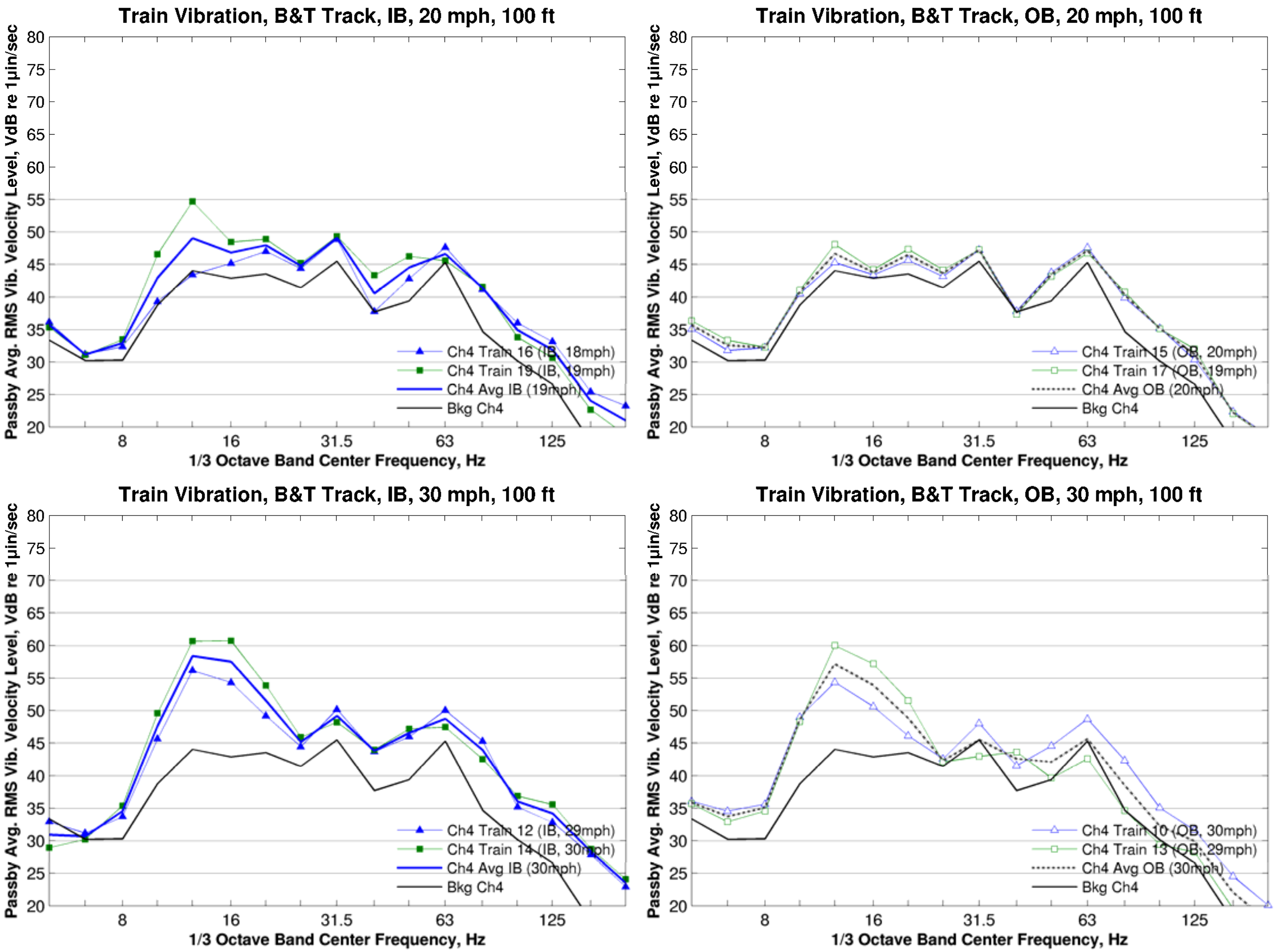


Figure 185: Vibration Spectra, Ballast & Tie Track, 100 ft, 20 and 30 mph

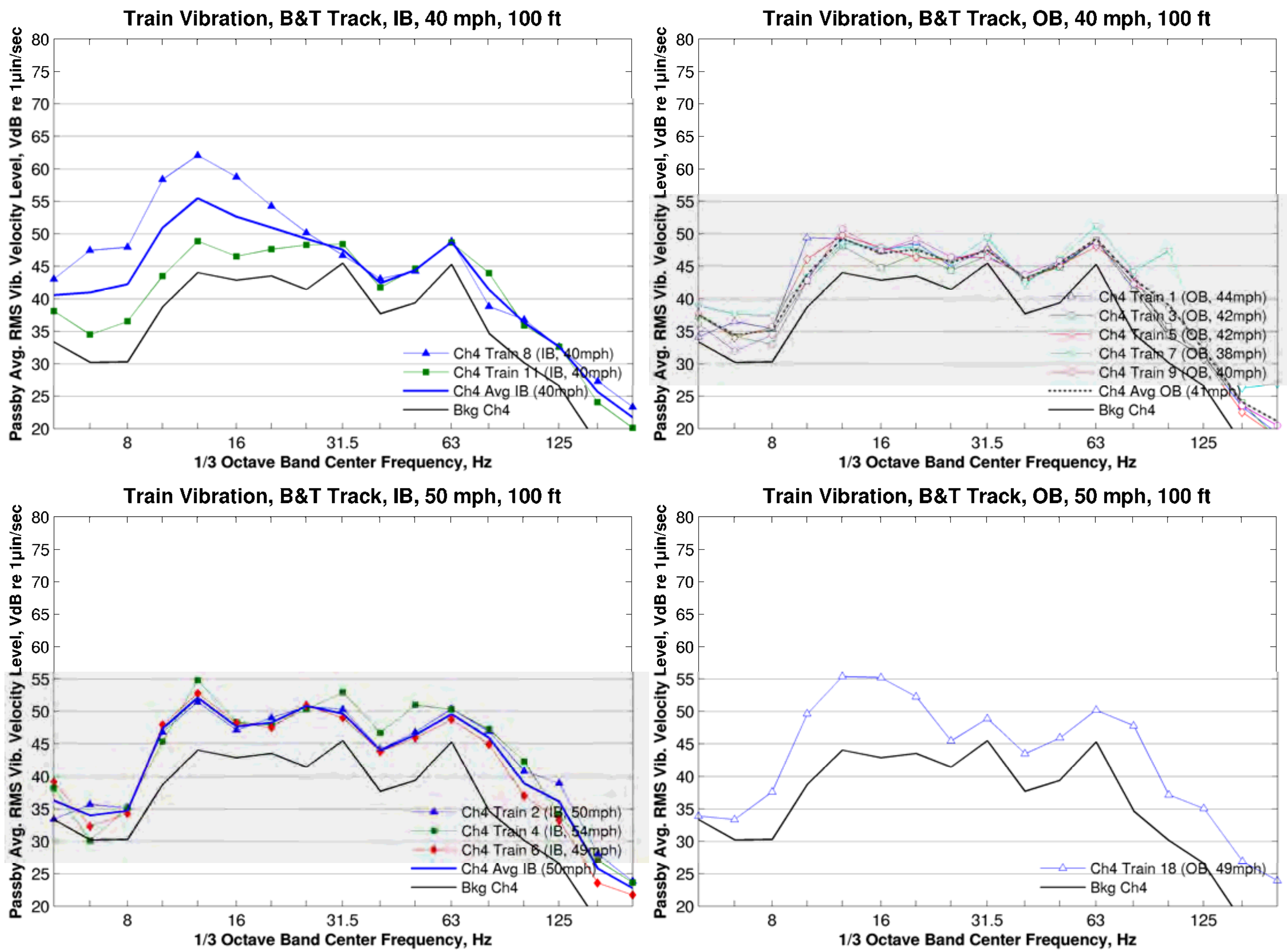


Figure 186: Vibration Spectra, Ballast & Tie Track, 100 ft, 40 and 50 mph

A.2 Train Vibration, 5th Street and 5th Avenue (Embedded Track)

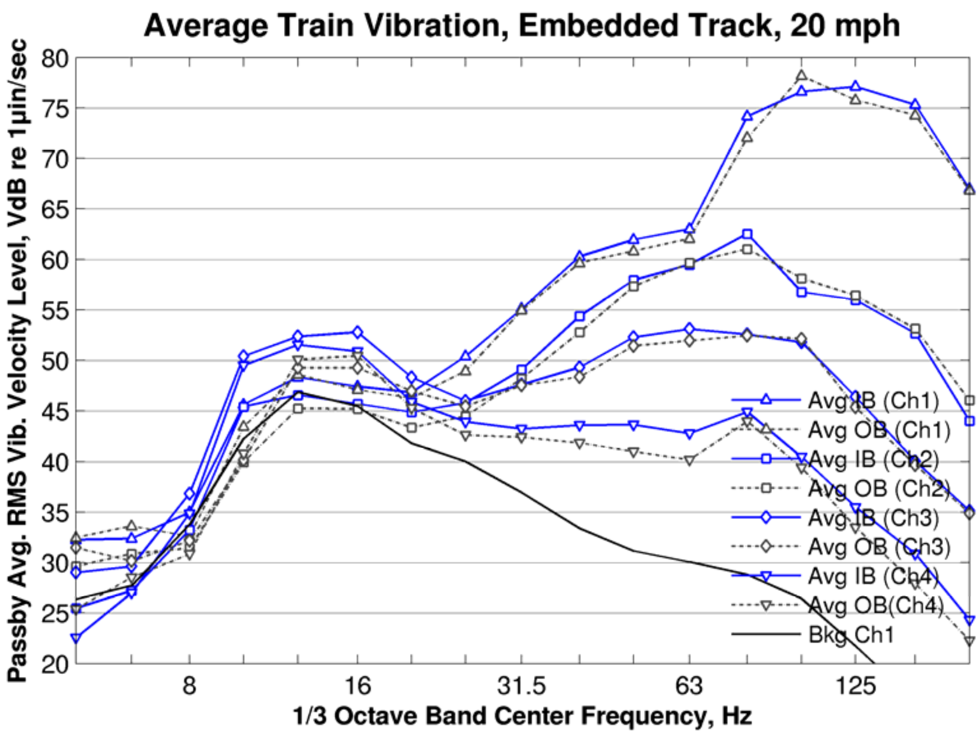


Figure 187: Average Vibration Spectra, 5th Street and 5th Avenue Embedded Track

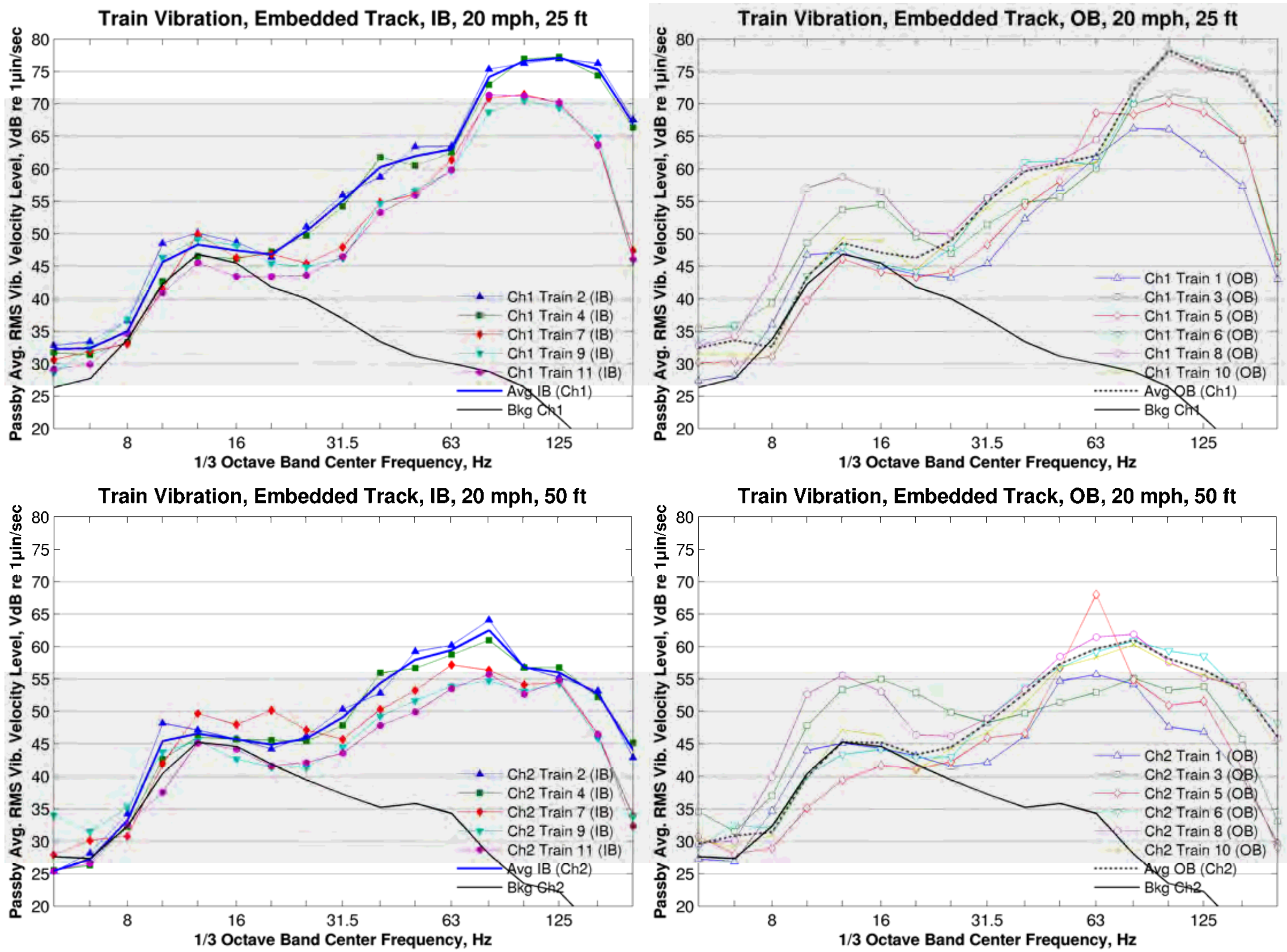


Figure 188: Vibration Spectra, 5th Street and 5th Avenue Embedded Track, 25 and 50 ft, 20 mph

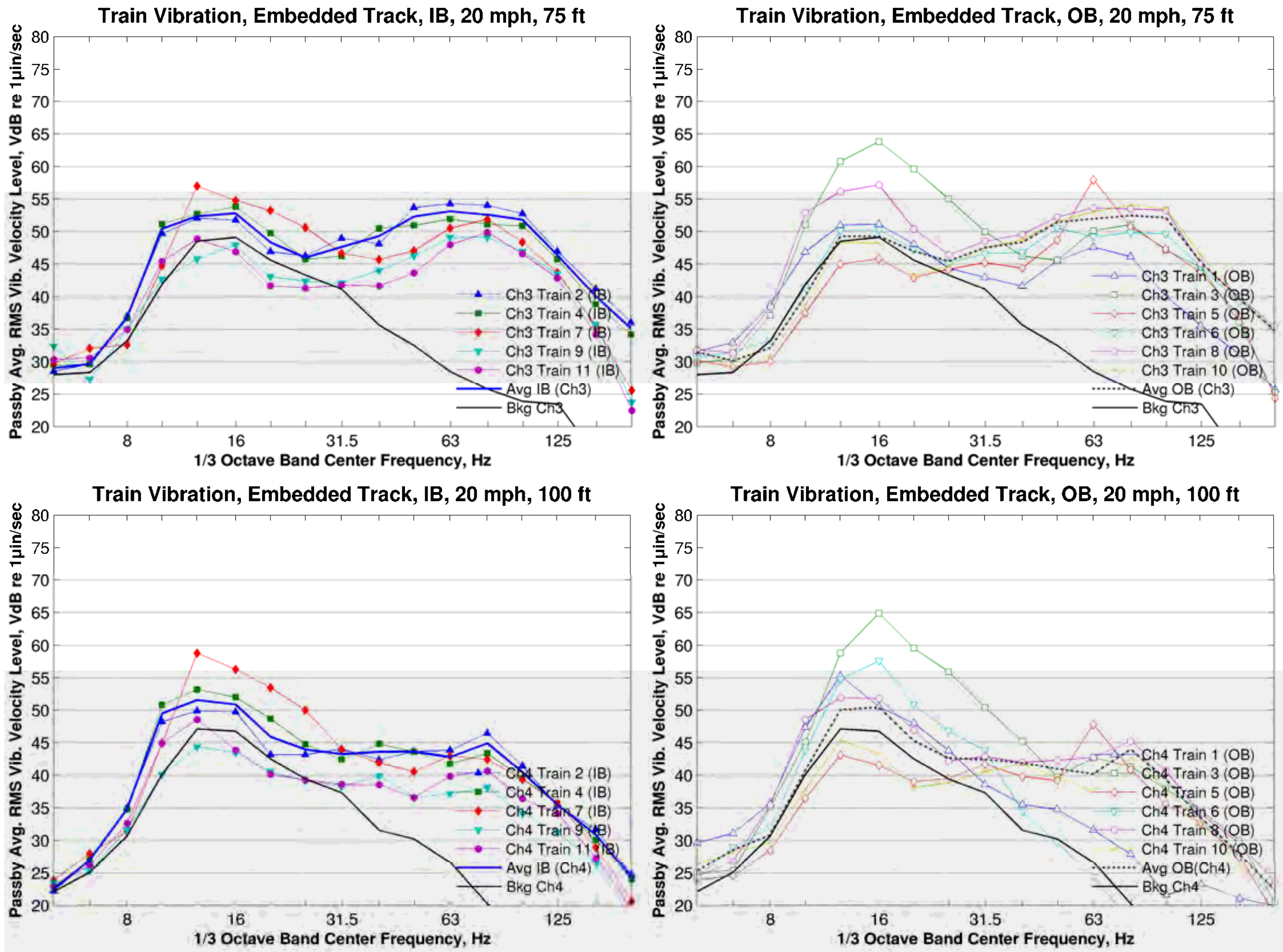


Figure 189: Vibration Spectra, 5th Street and 5th Avenue Embedded Track, 75 and 100 ft, 20 mph

A.3 Train Vibration, 5th Street and Portland Avenue (Embedded Track)

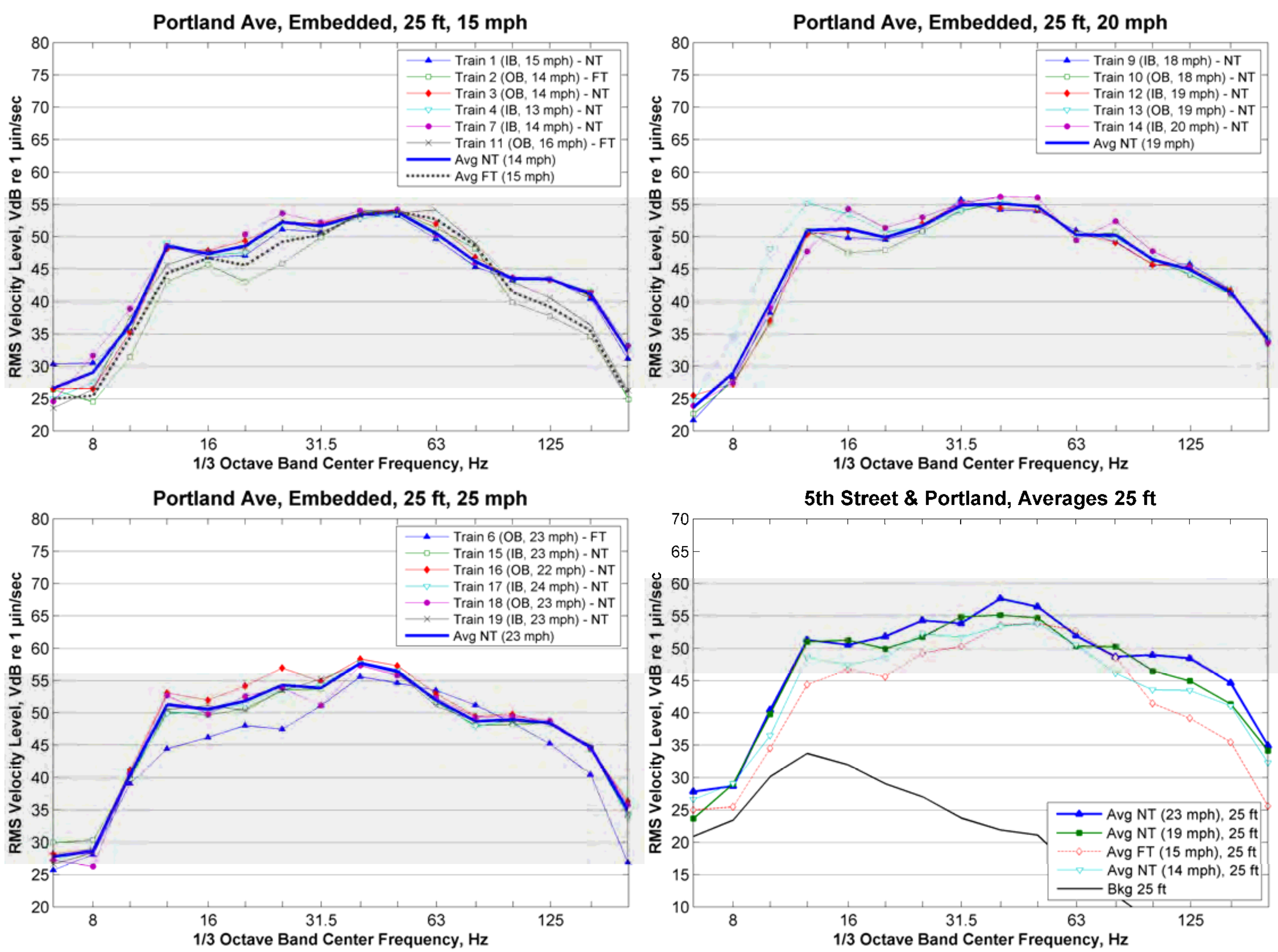


Figure 190: Vibration Spectra, 5th Street and Portland Avenue, 25 ft

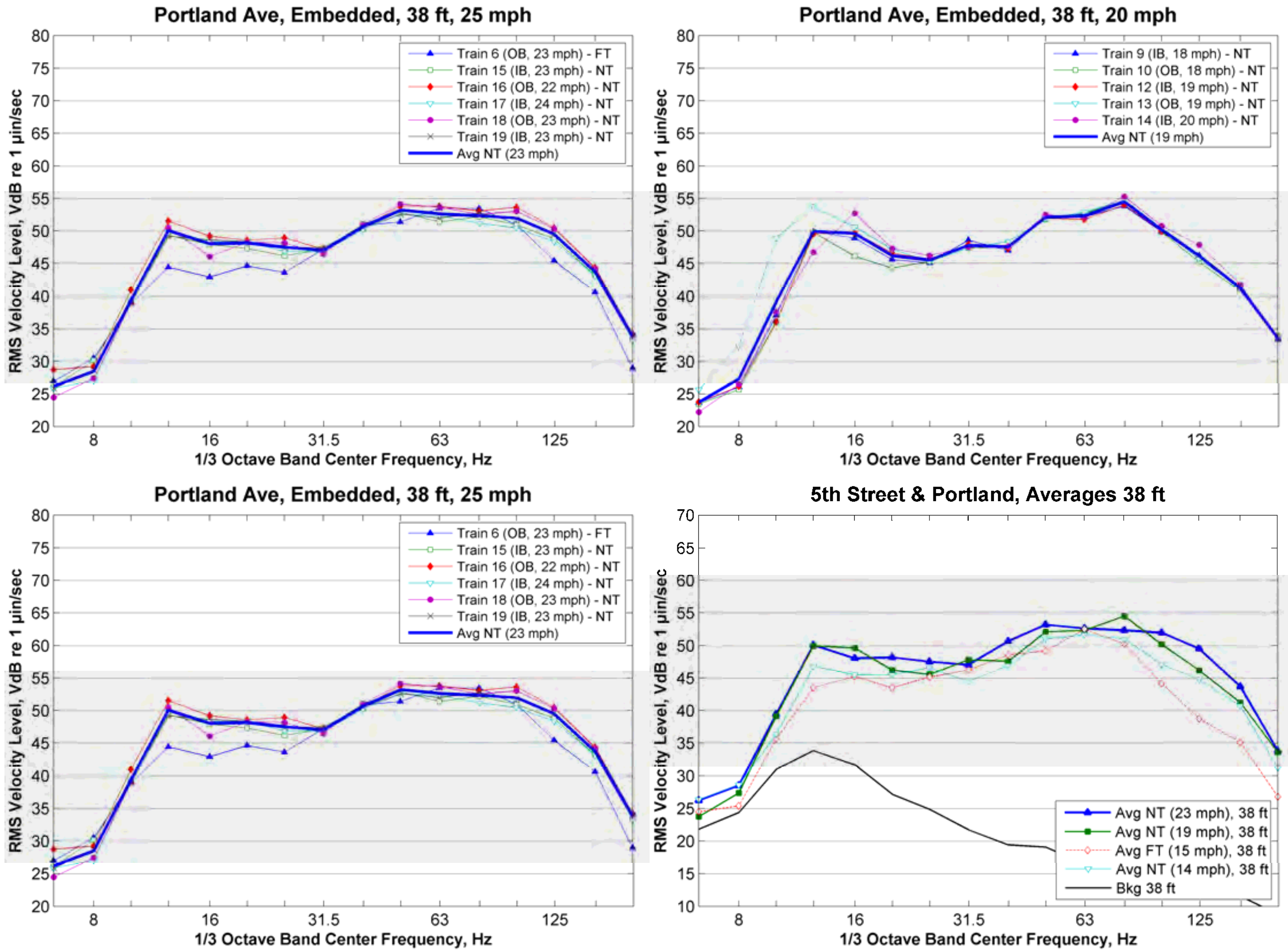


Figure 191: Vibration Spectra, 5th Street and Portland Avenue, 38 ft

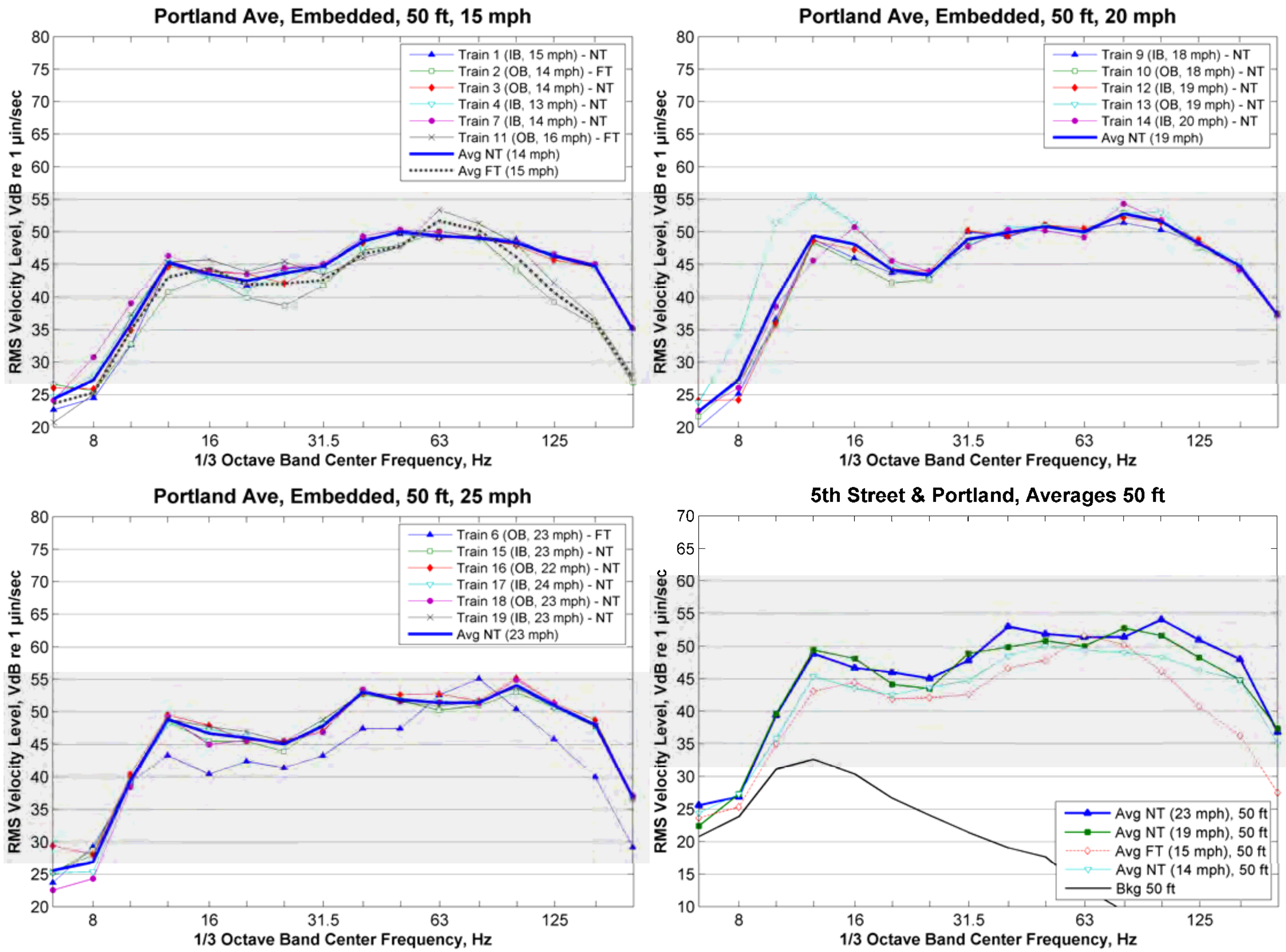


Figure 192: Vibration Spectra, 5th Street and Portland Avenue, 50 ft

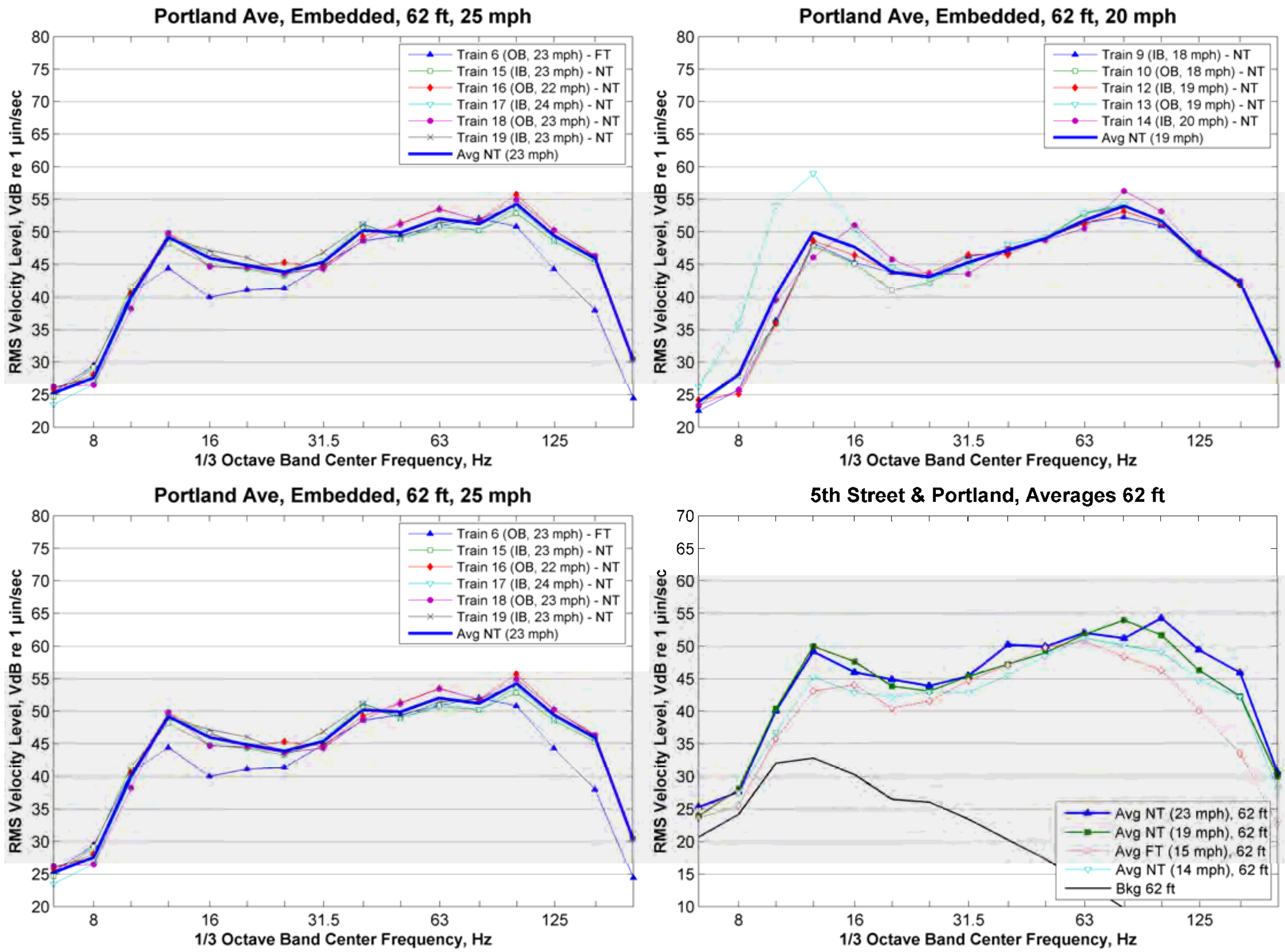


Figure 193: Vibration Spectra, 5th Street and Portland Avenue, 62 ft

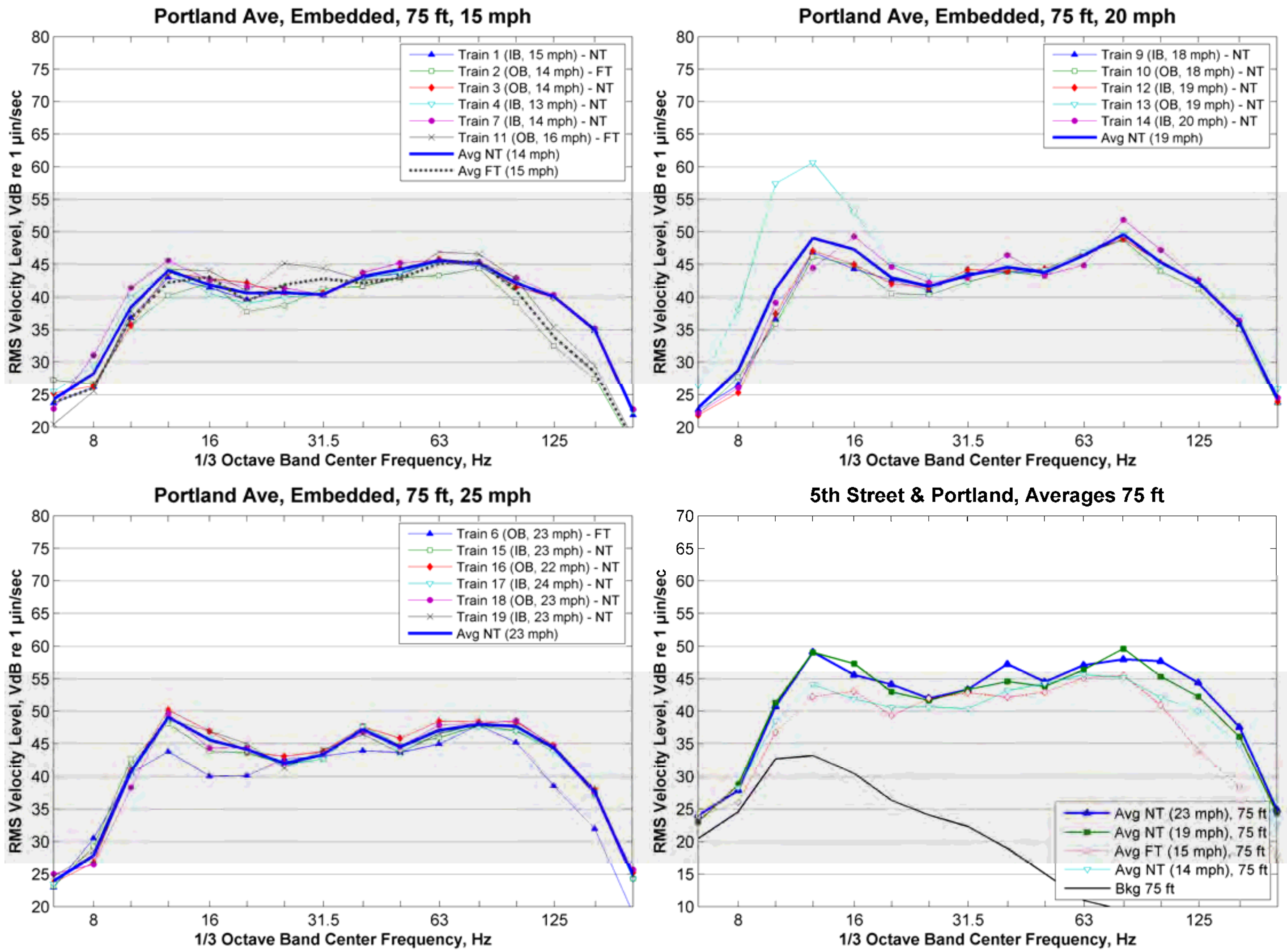


Figure 194: Vibration Spectra, 5th Street and Portland Avenue, 75 ft

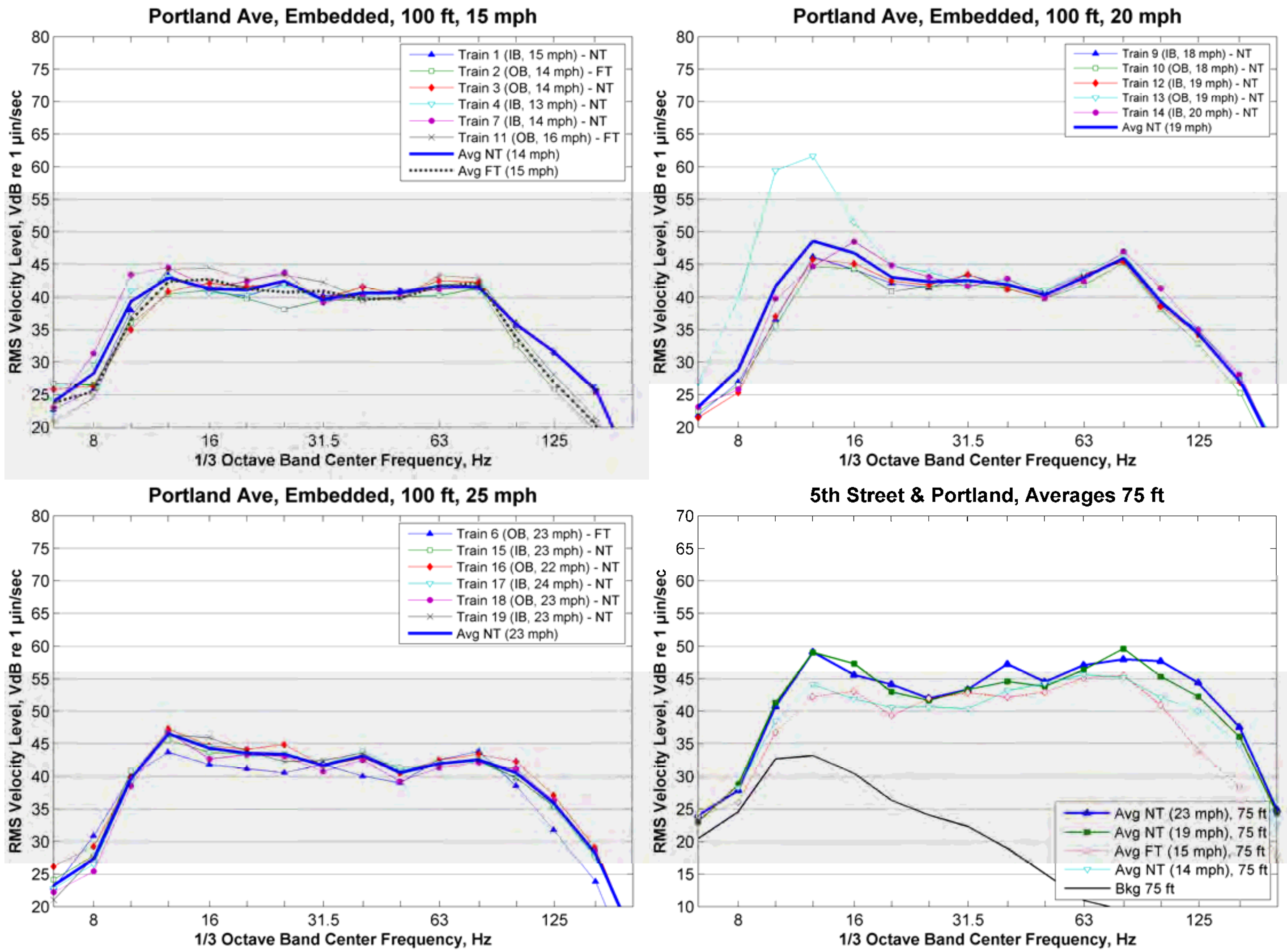


Figure 195: Vibration Spectra, 5th Street and Portland Avenue, 100 ft

A.4 Train Vibration, Minnehaha and 53rd Street (Embedded Track)

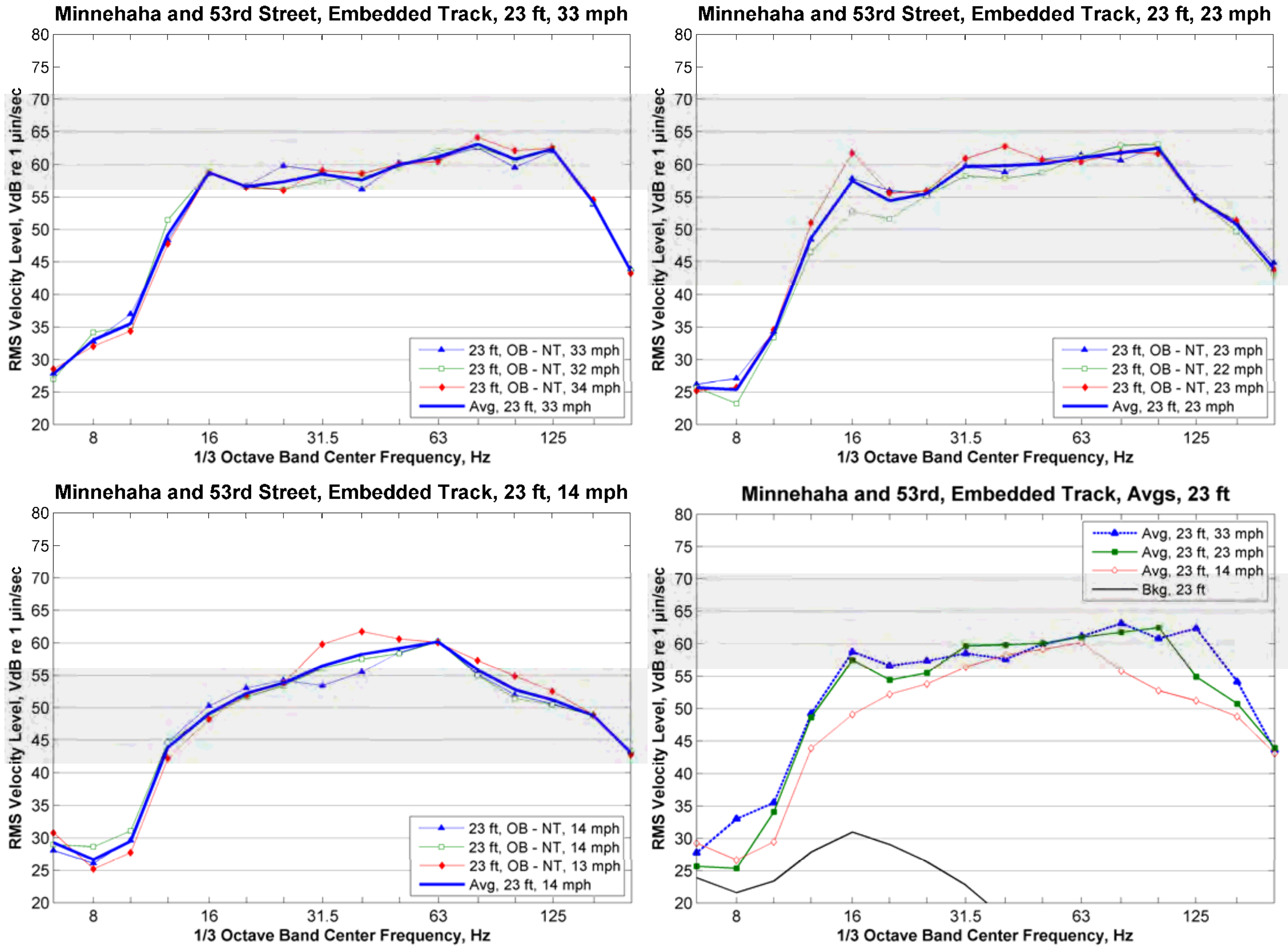


Figure 196: Train Vibration, Minnehaha and 53rd Street, 23 ft from Track Centerline

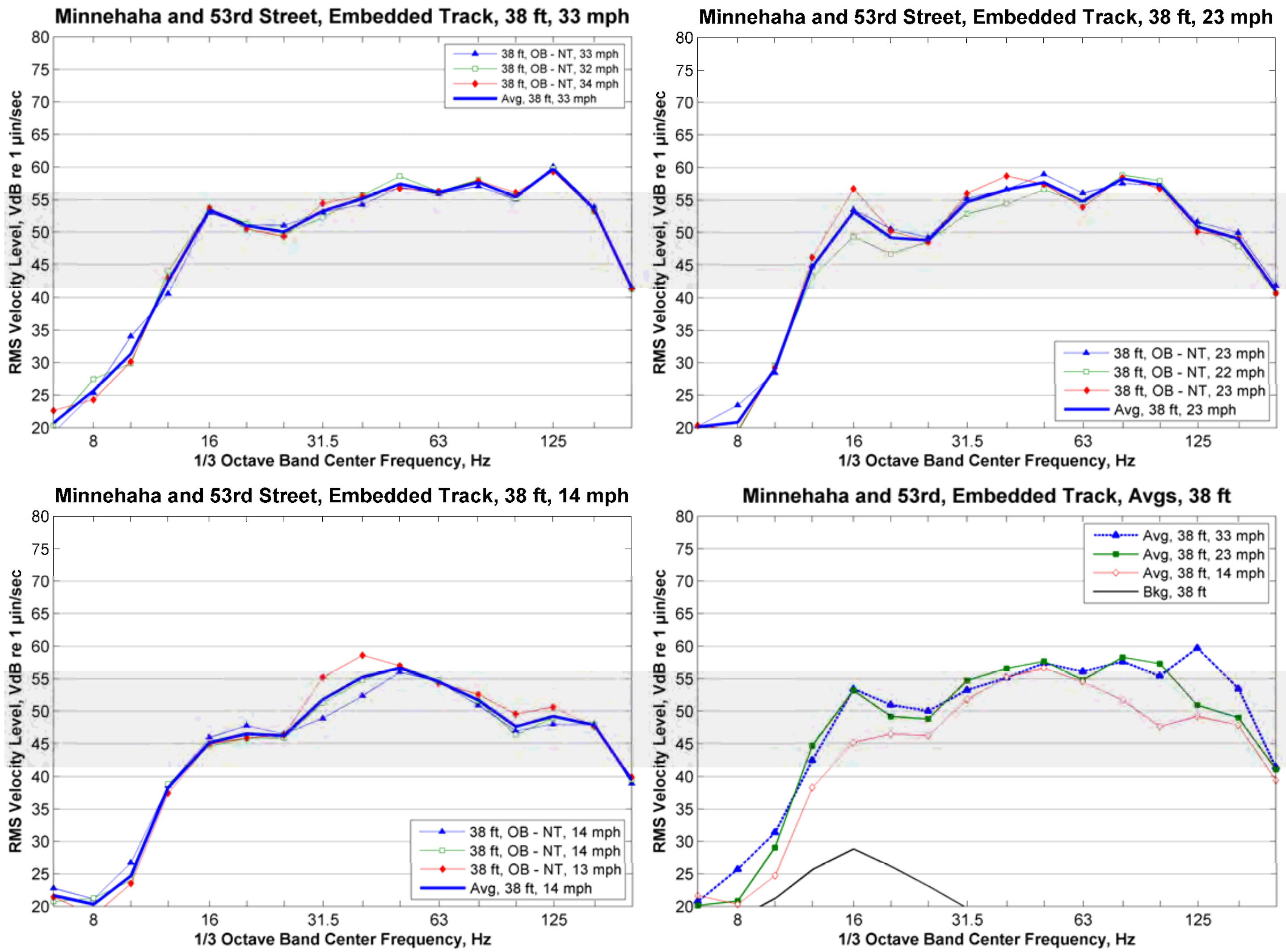


Figure 197: Train Vibration, Minnehaha and 53rd Street, 38 ft from Track Centerline

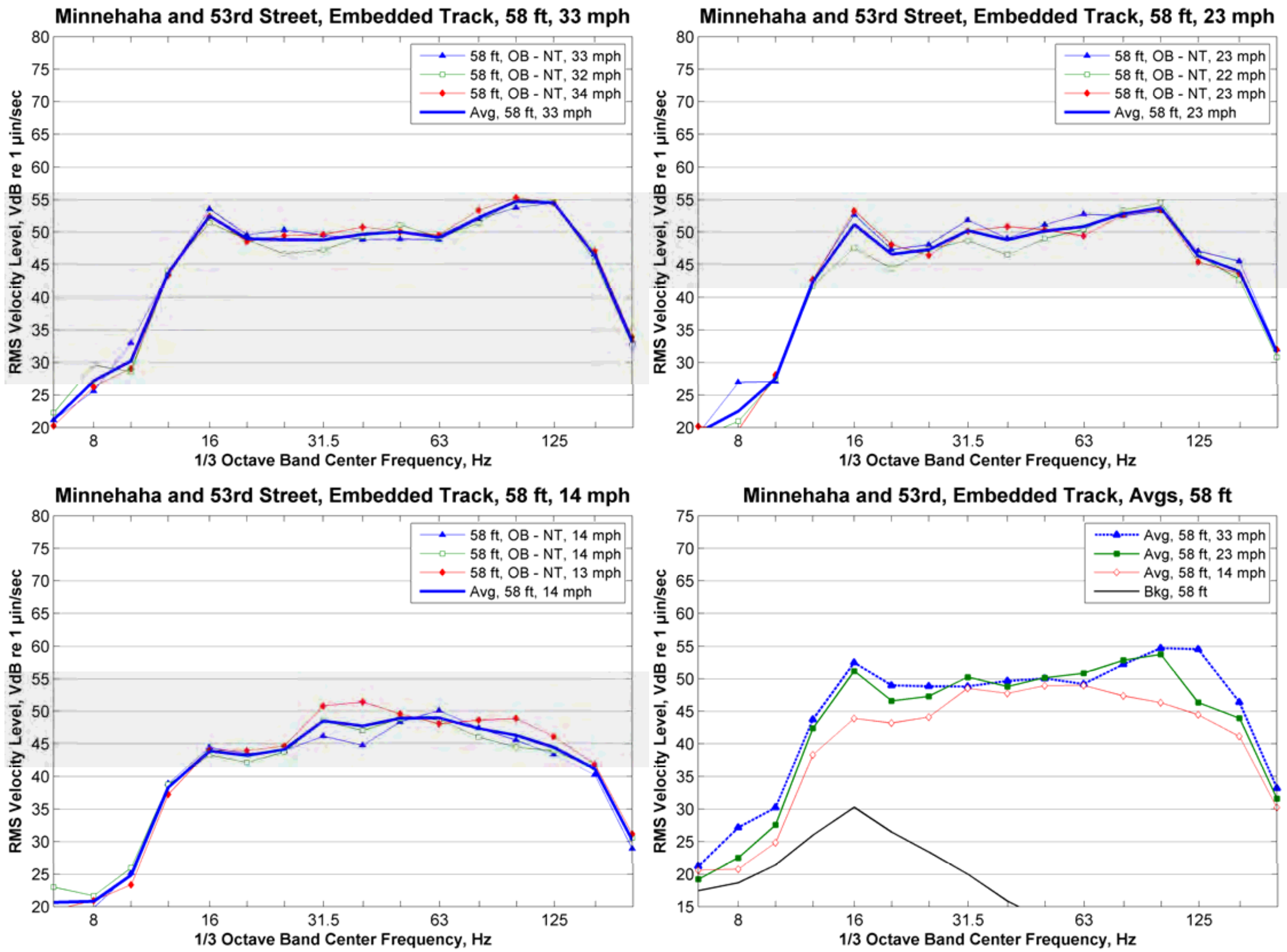


Figure 198: Train Vibration, Minnehaha and 53rd Street, 58 ft from Track Centerline

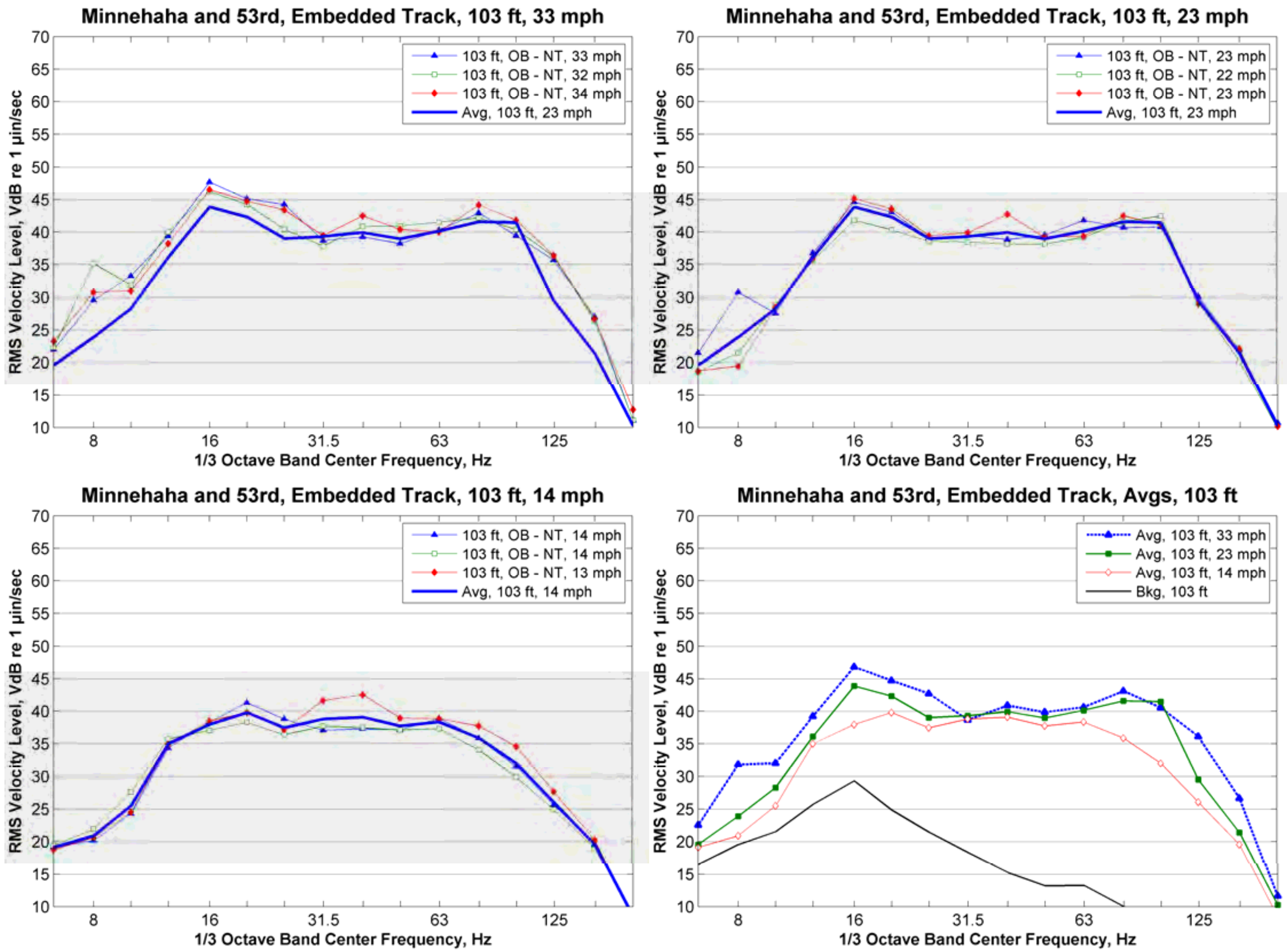


Figure 199: Train Vibration, Minnehaha and 53rd Street, 103 ft from Track Centerline

A.4 Bus Vibration, Minnehaha and 53rd Street

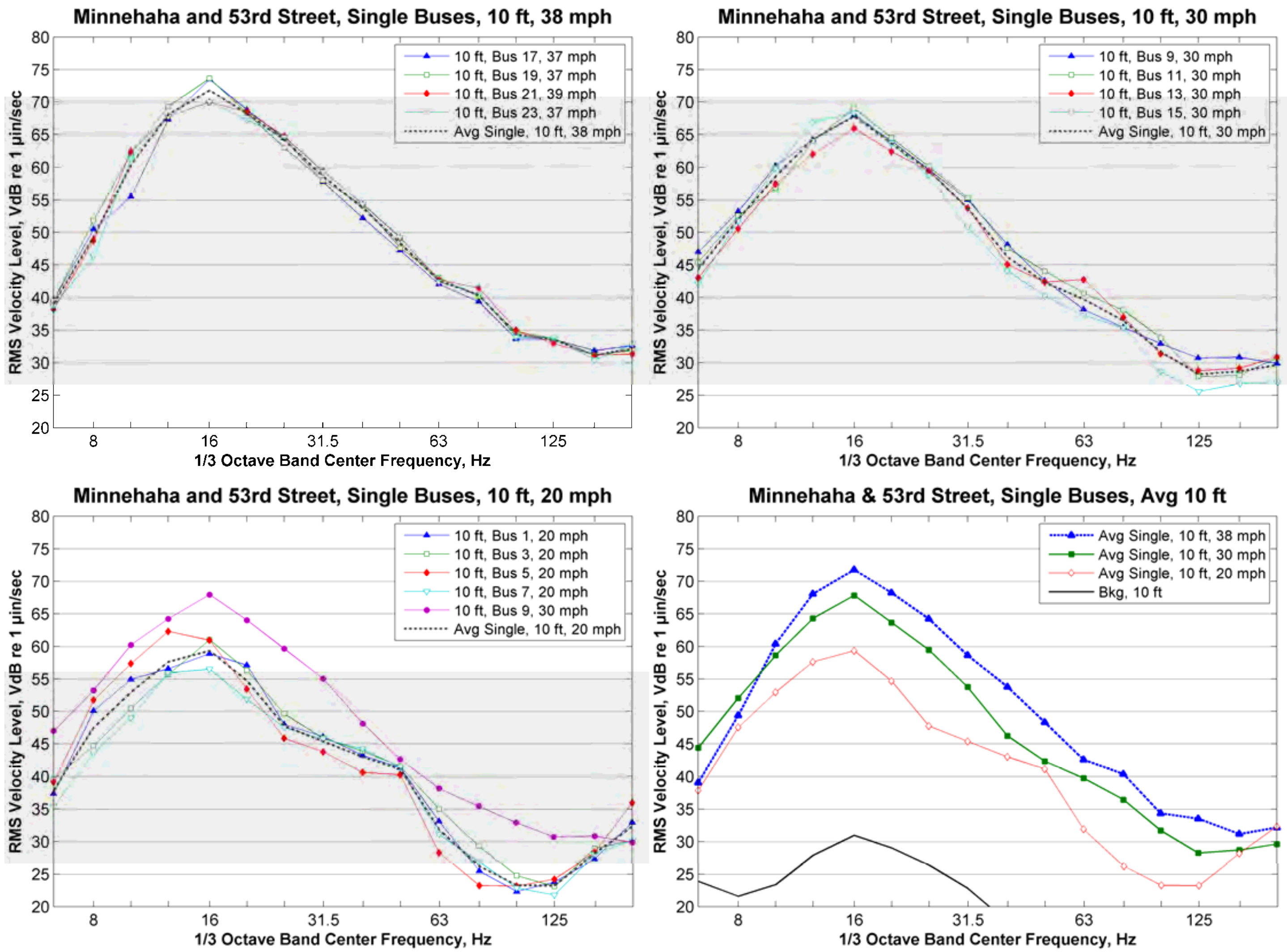


Figure 200: Single Bus Vibration, Minnehaha and 53rd Street, 10 ft from Roadway Centerline

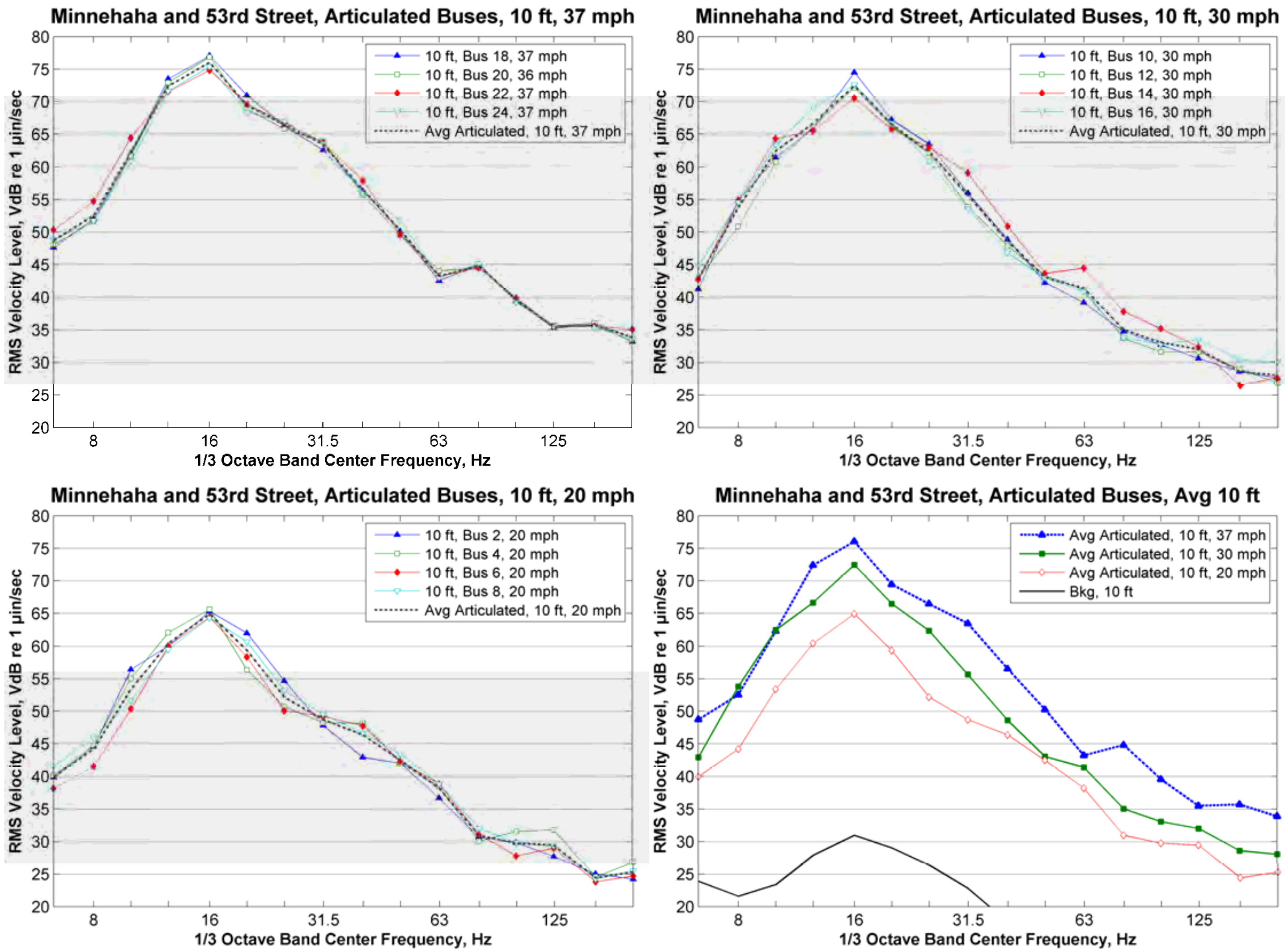


Figure 201: Articulated Bus Vibration, Minnehaha and 53rd Street, 10 ft from Roadway Centerline

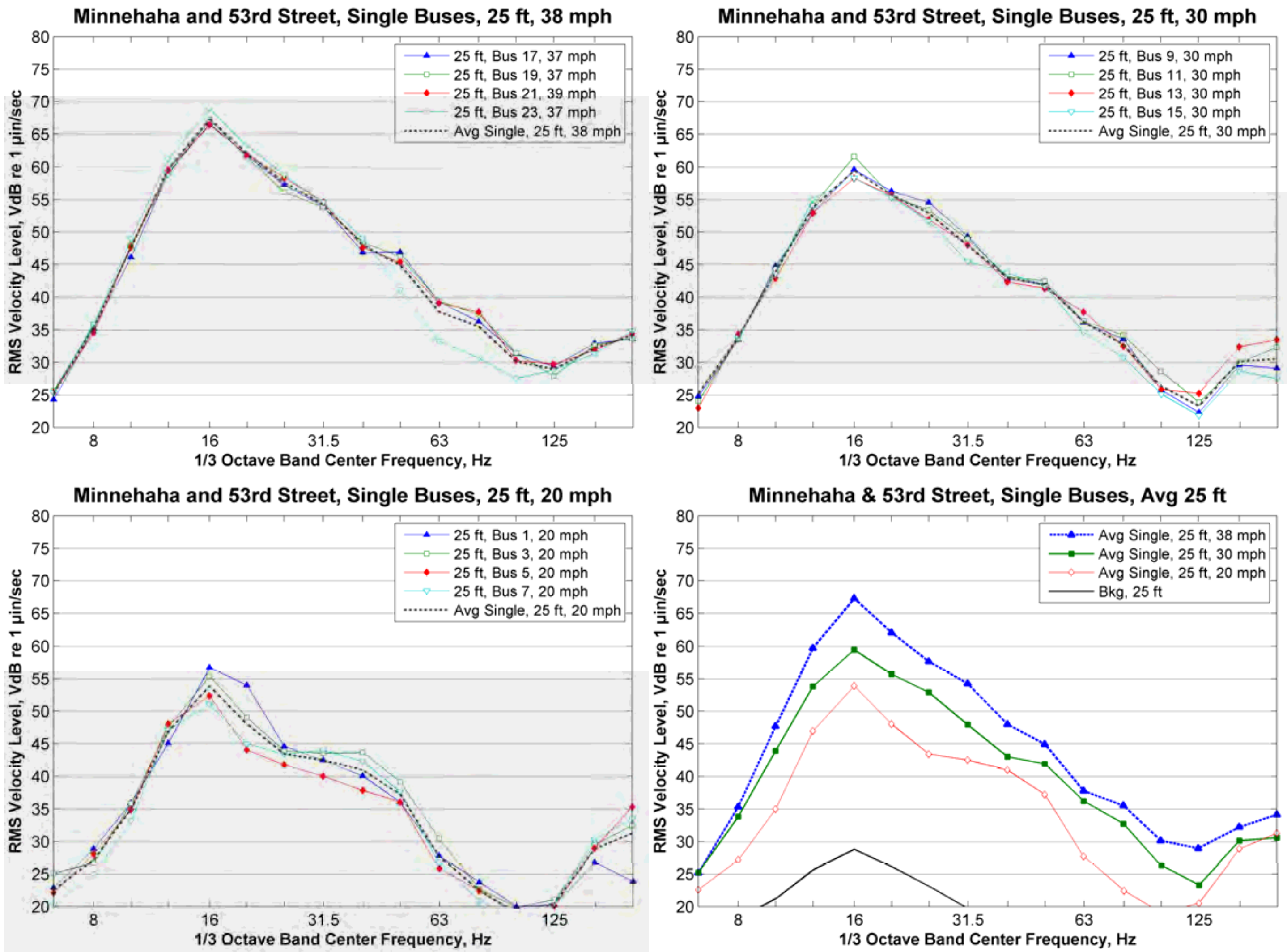


Figure 202: Single Bus Vibration, Minnehaha and 53rd Street, 25 ft from Roadway Centerline

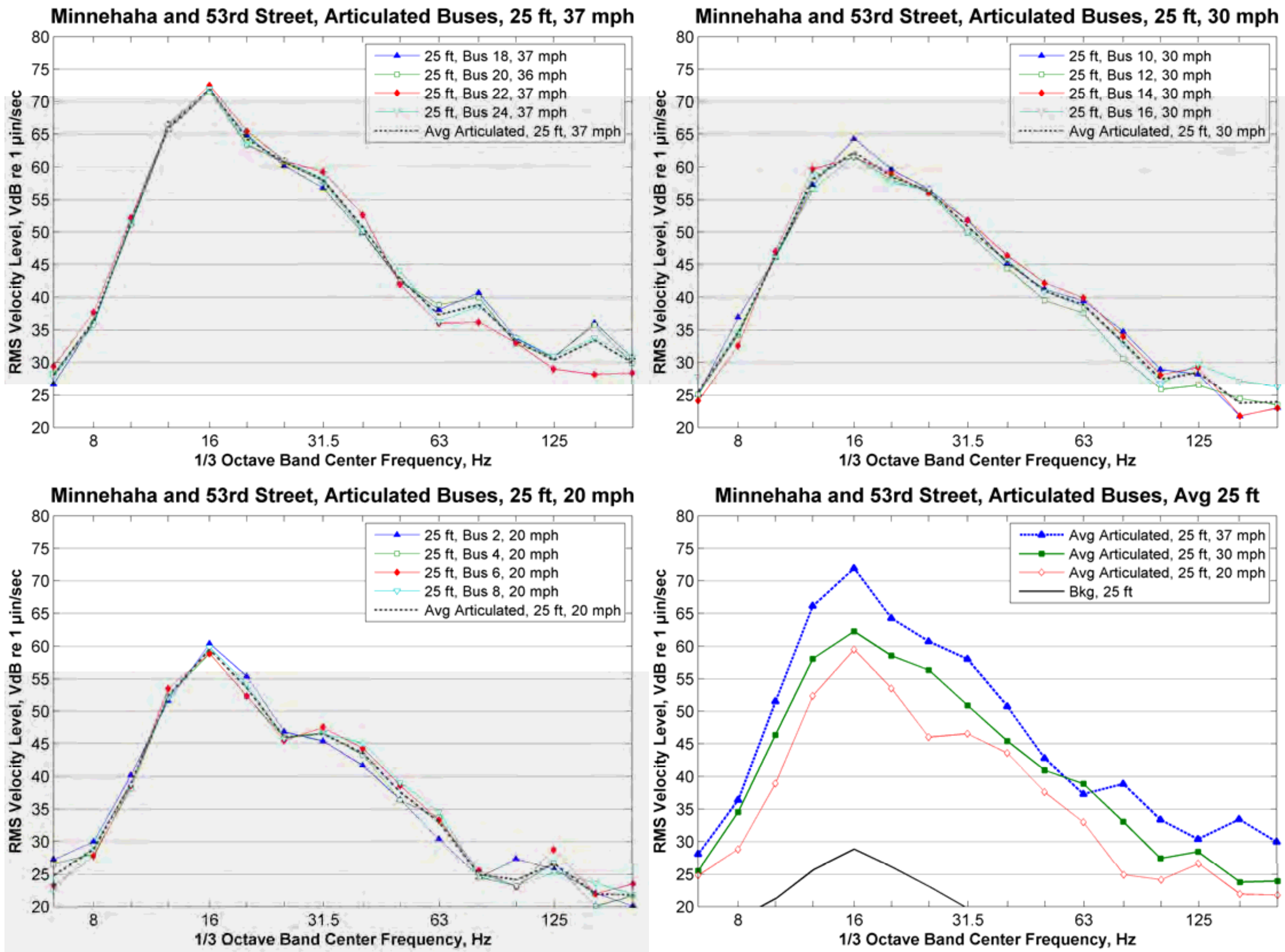


Figure 203: Articulated Bus Vibration, Minnehaha and 53rd Street, 25 ft from Roadway Centerline

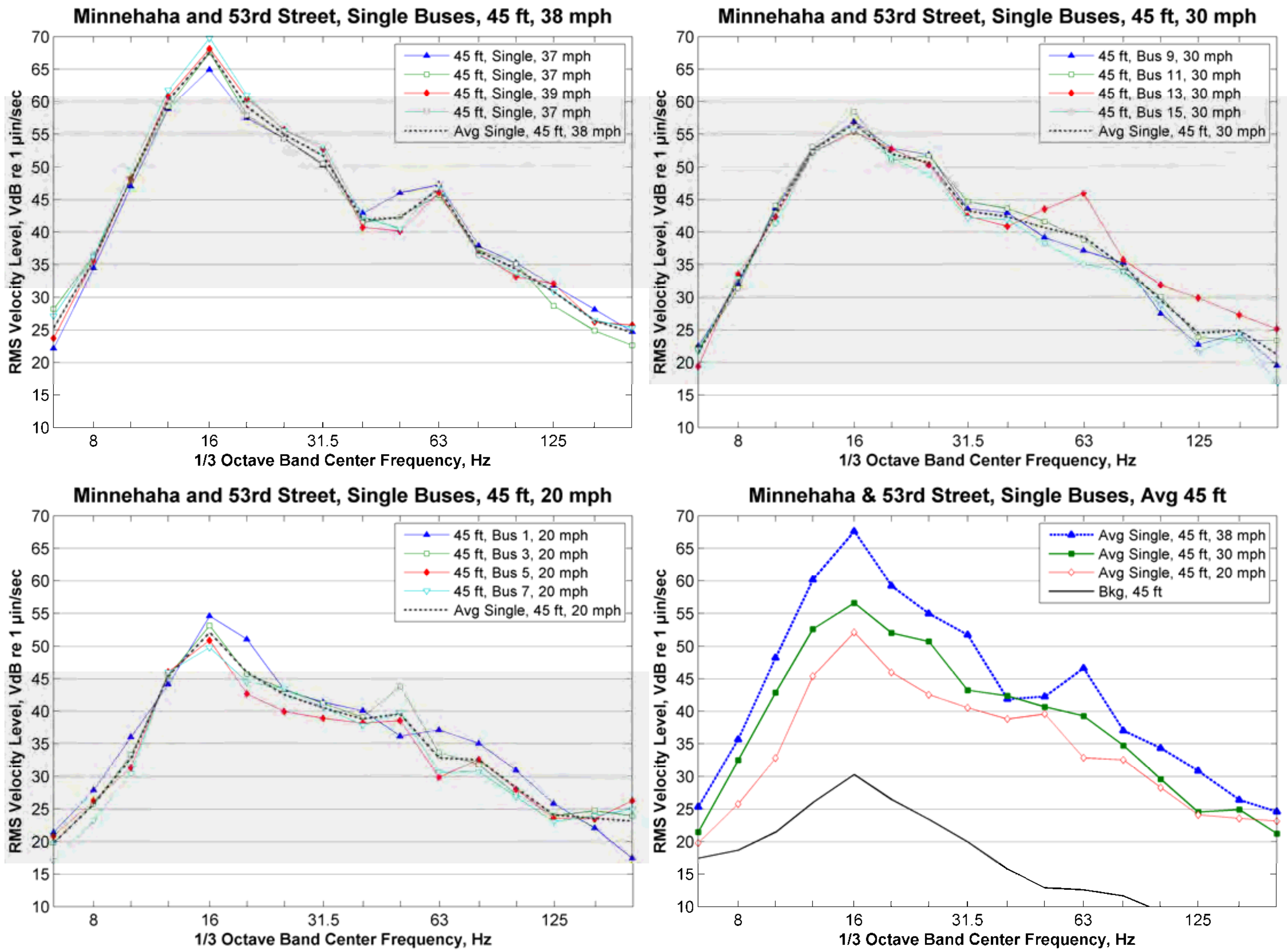


Figure 204: Single Bus Vibration, Minnehaha and 53rd Street, 45 ft from Roadway Centerline

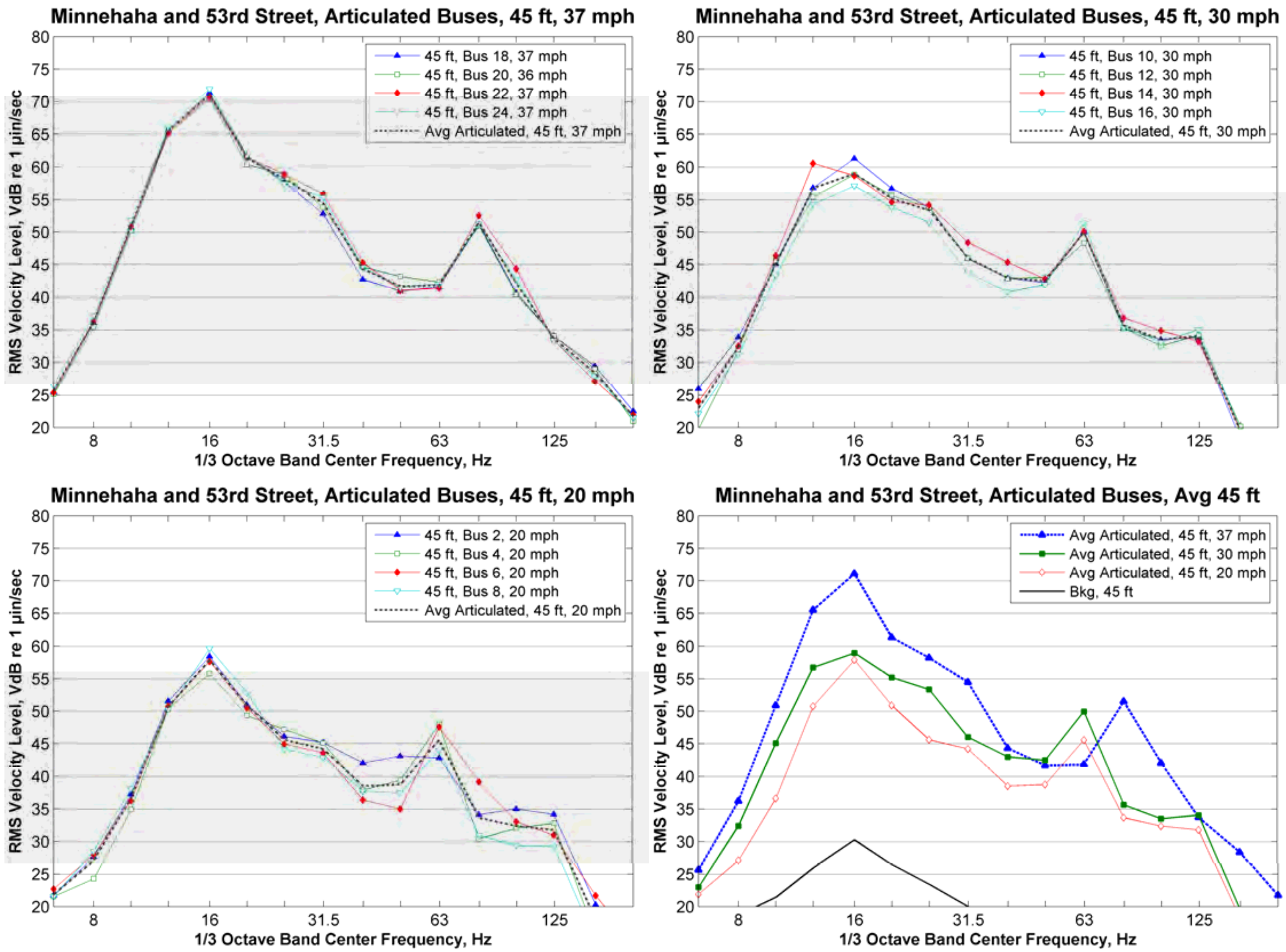


Figure 205: Articulated Bus Vibration, Minnehaha and 53rd Street, 45 ft from Roadway Centerline

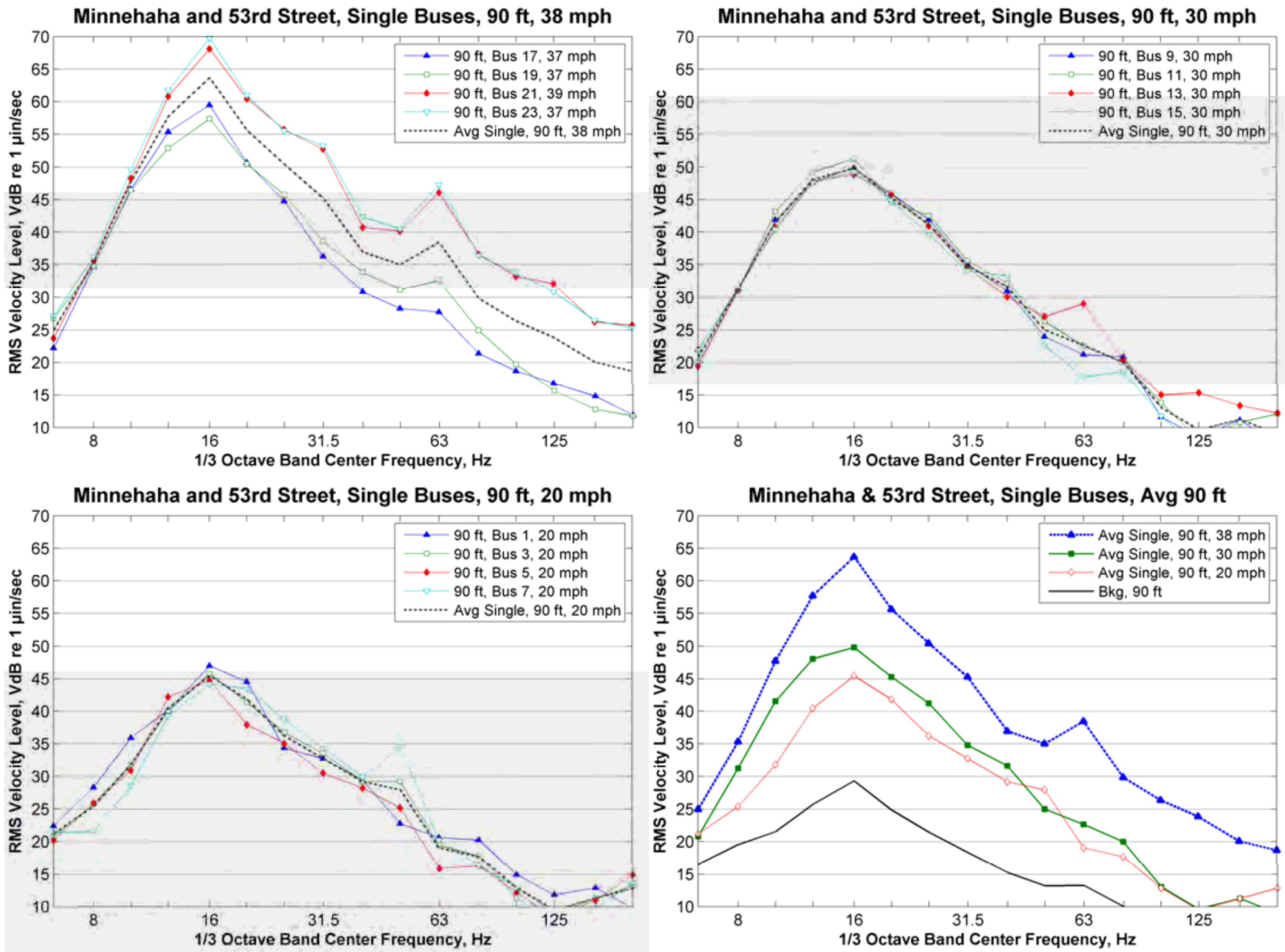


Figure 206: Single Bus Vibration, Minnehaha and 53rd Street, 90 ft from Roadway Centerline

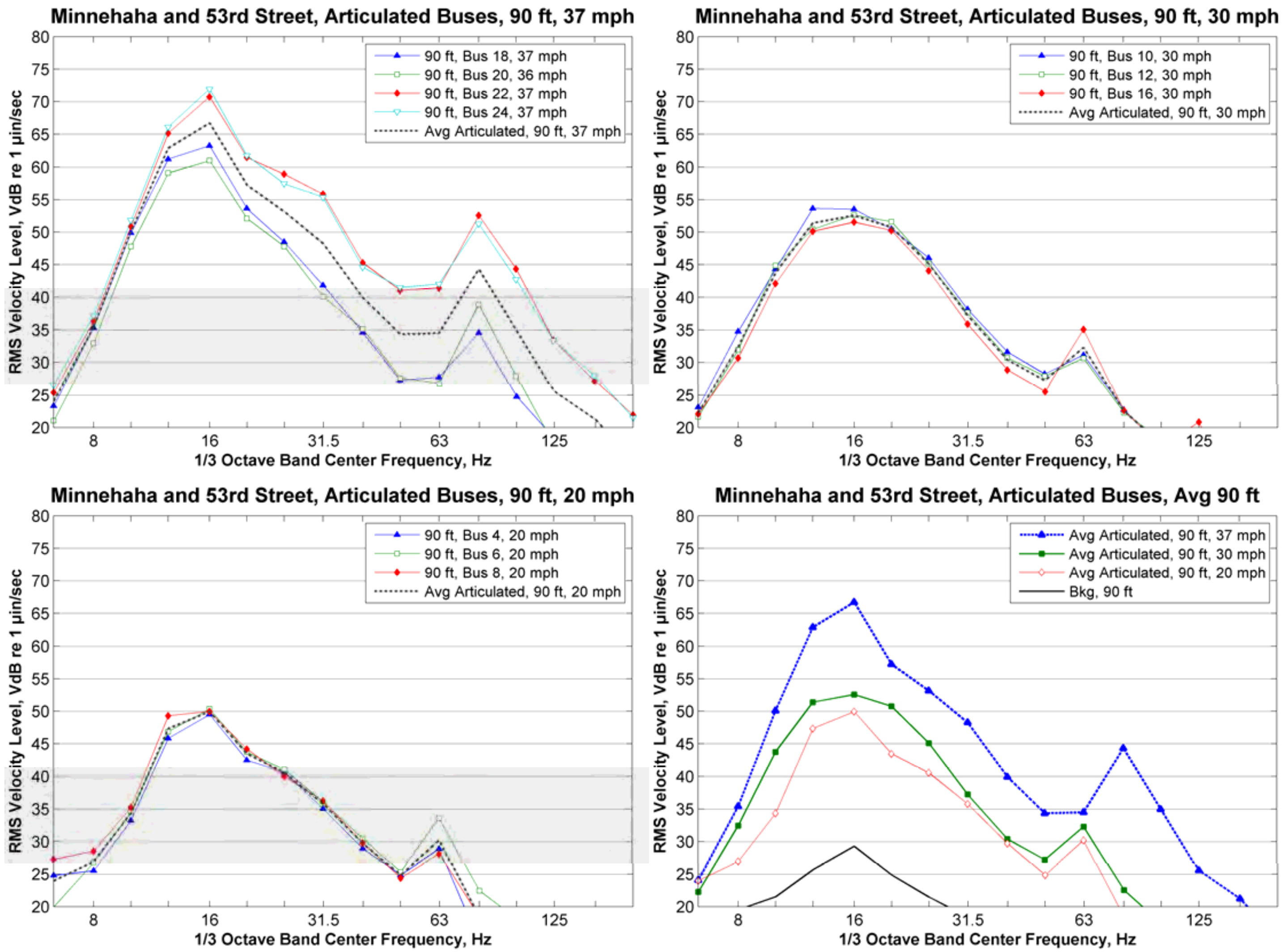
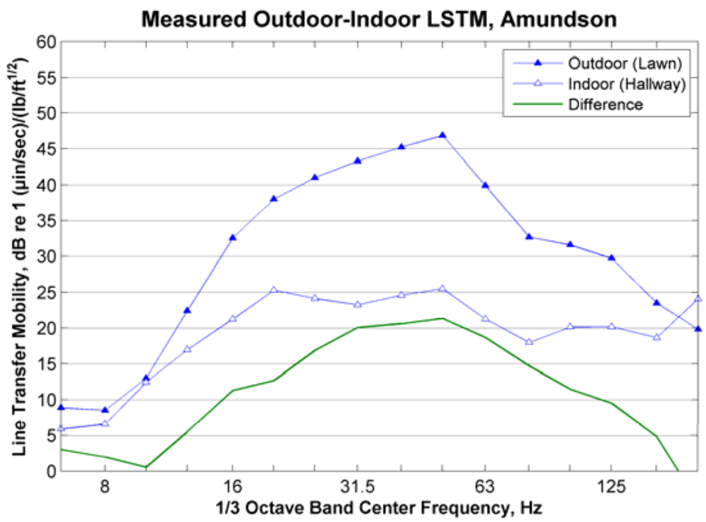
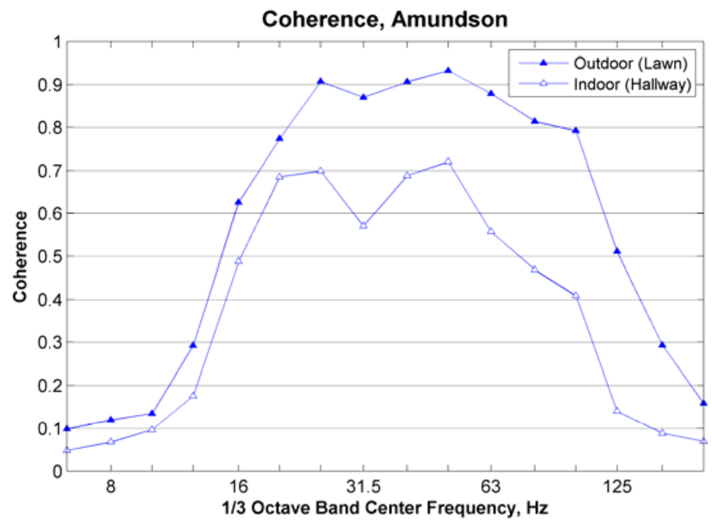


Figure 207: Articulated Bus Vibration, Minnehaha and 53rd Street, 90 ft from Roadway Centerline

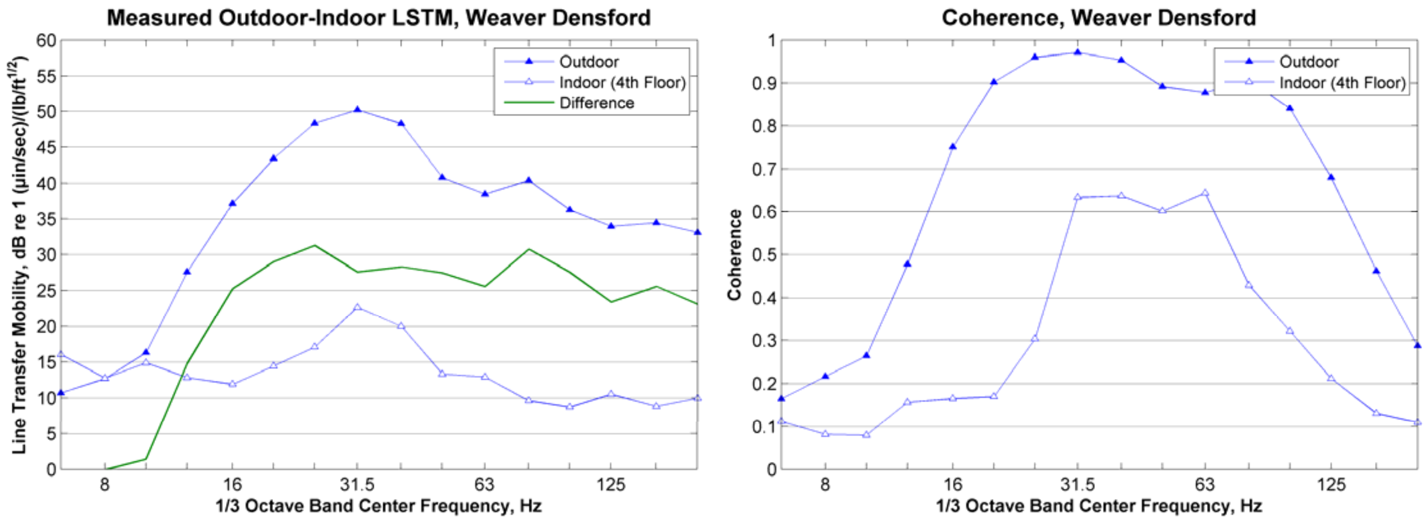
APPENDIX B. OUTDOOR-INDOOR VIBRATION DIFFERENCES

The following figures show the line-source transfer mobilities measured inside and outside of various University of Minnesota research laboratories. The difference in the frequency ranges that the coherences are above 0.3 provide an estimate of the attenuation as ground-borne vibration is transmitted from the ground into building foundations and then to the laboratory spaces.

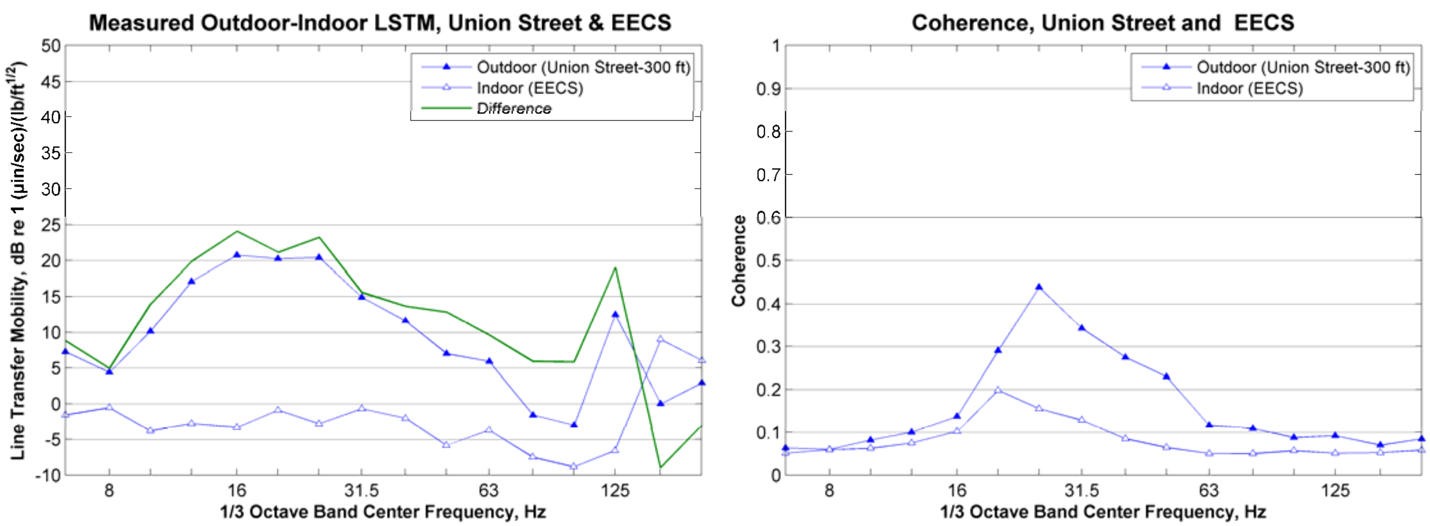




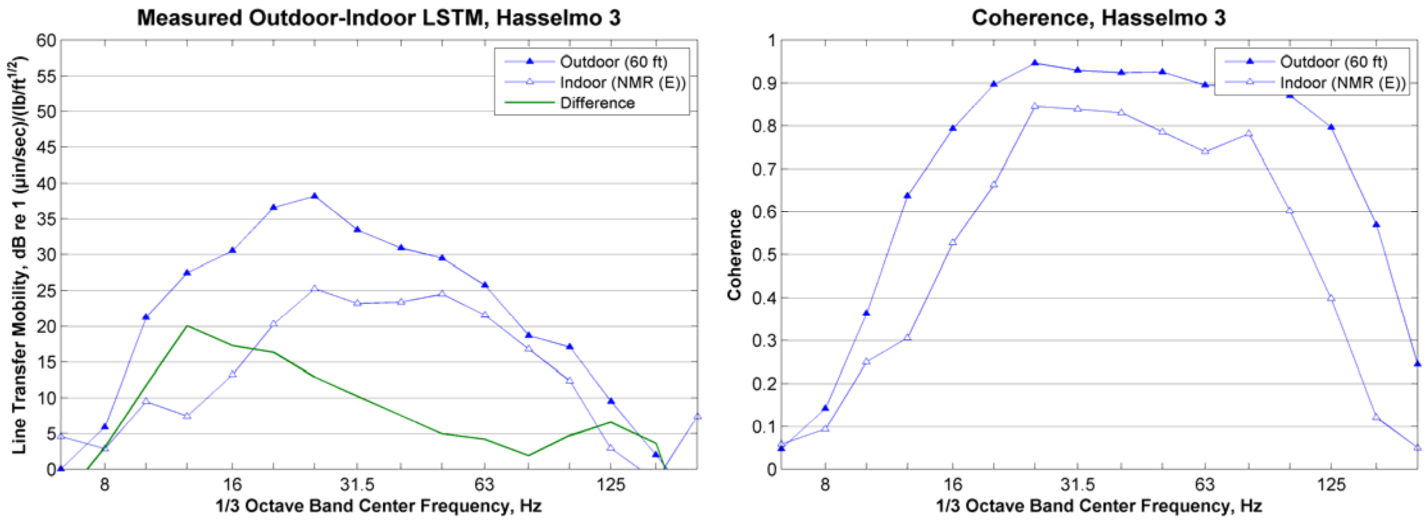
Amundson Hall, Basement Hallway



Weaver Densford Hall, 4th Floor (Street Level relative to Washington Avenue)



Electrical Engineering and Computer Sciences Building Microscopy Center



NMR Center, Basement of Hasselmo Hall

APPENDIX C. ESTIMATING SOUND LEVEL FROM VIBRATION LEVEL

The approach recommended in the FTA Guidance Manual for predicting ground-borne noise is to assume that:

$$\text{Lp (dB re 20µin/sec)} = \text{Lv (VdB re 1µin/sec)}$$

This is largely based on one room surface vibrating and radiating sound as a plane wave. At the boundary of a vibrating surface, the relationship of the surface vibration and the air pressure is:

$$p = \rho c v$$

ρ = density of air
c = speed of sound in air
v = vibration velocity

Ignoring any reverberant sound and any sound radiated off of other room surfaces, the relationship using decibel references of 10^{-6} in/sec for vibration velocity and 20×10^{-6} Pa for sound pressure is:

$$Lp = Lv - 5.7$$

For this study the basic format assumed when predicting the levels of ground-borne noise is:

$$Lp = Lv + K$$

The value of *K* is dependent on the amount of acoustical absorption in the room. For a typical room including recording studios, *K* has been assumed to be zero. That is, the approach recommended by the FTA manual is applied. Experience is that this approach will tend to over predict the levels of ground-borne noise for most spaces.

For spaces that are highly reverberant such sanctuaries of the two churches on Cedar Street, *K* has been assumed to be +3 dB. This accounts for reflections causing sound levels to be slightly more than 8 decibels greater than the directly radiated sound.

For a typical room with some sound-absorbing materials such as carpets, books, and upholstered furniture, the relationship between the vibration of room surfaces and the radiated sound has been found to be:

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