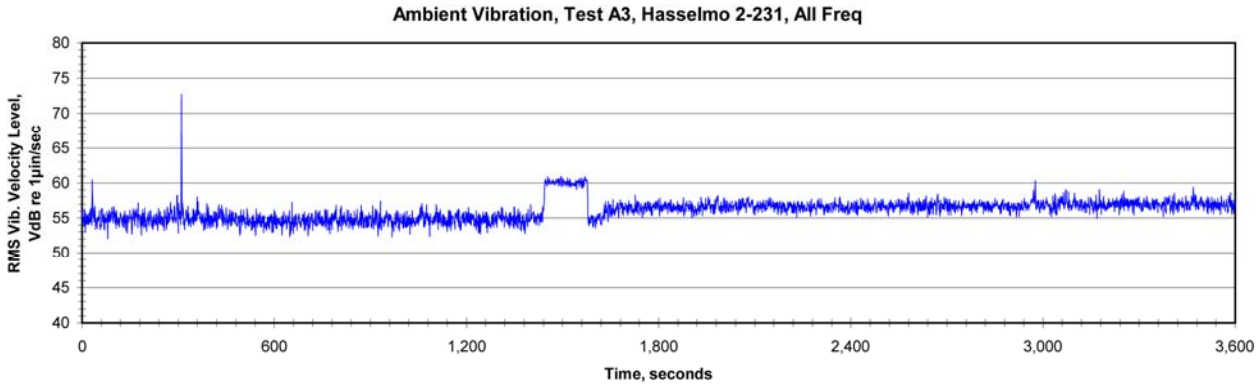


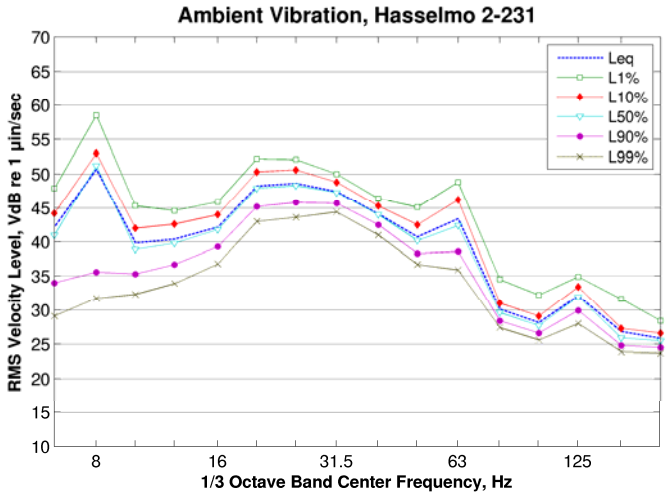


Figure 88: Ambient Vibration inside Room 2-231 at Nils Hasselmo

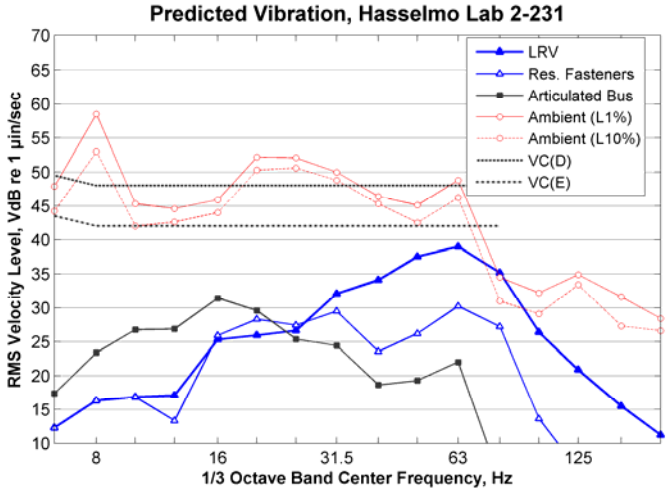


Figure 89: Predicted Vibration inside Room 2-231 at Nils Hasselmo

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.

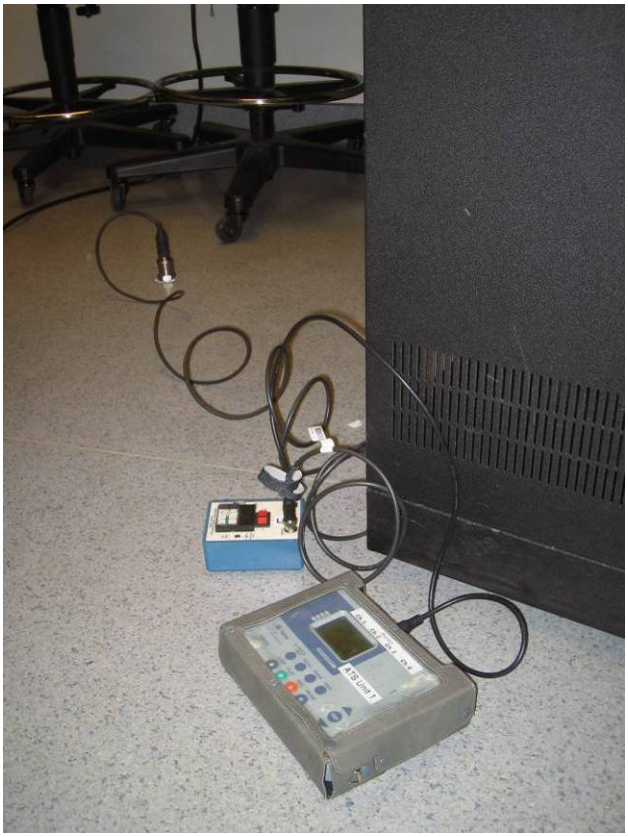
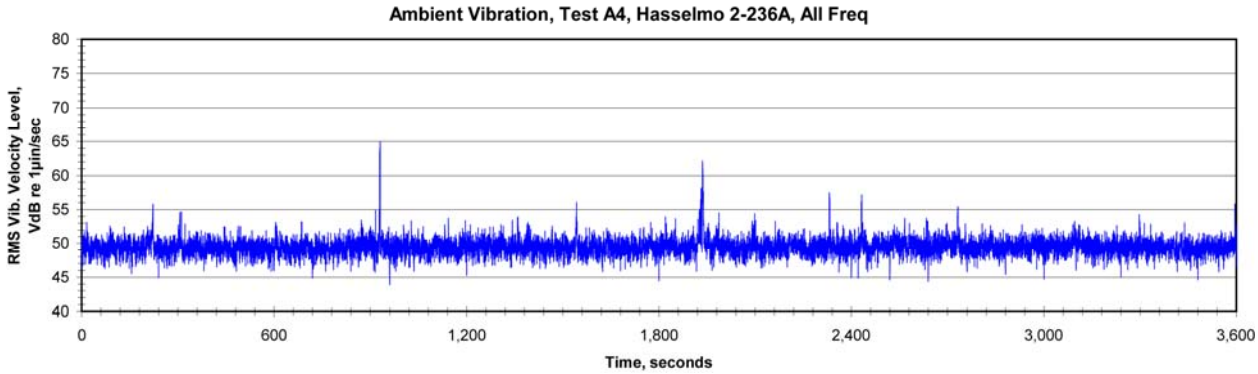


Figure 90: Accelerometer inside Room 2-236 A of Nils Hasselmo



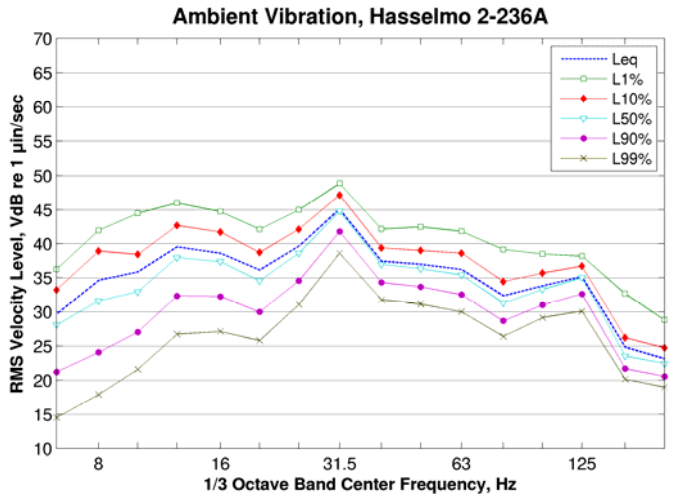


Figure 91: Ambient Vibration Inside Room 2-236 at Nils Hasselmo

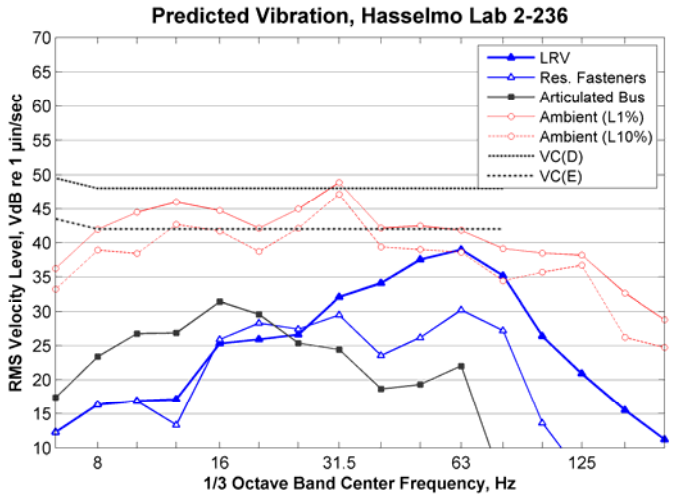


Figure 92: Predicted Vibration inside Room 2-236 at Nils Hasselmo

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.

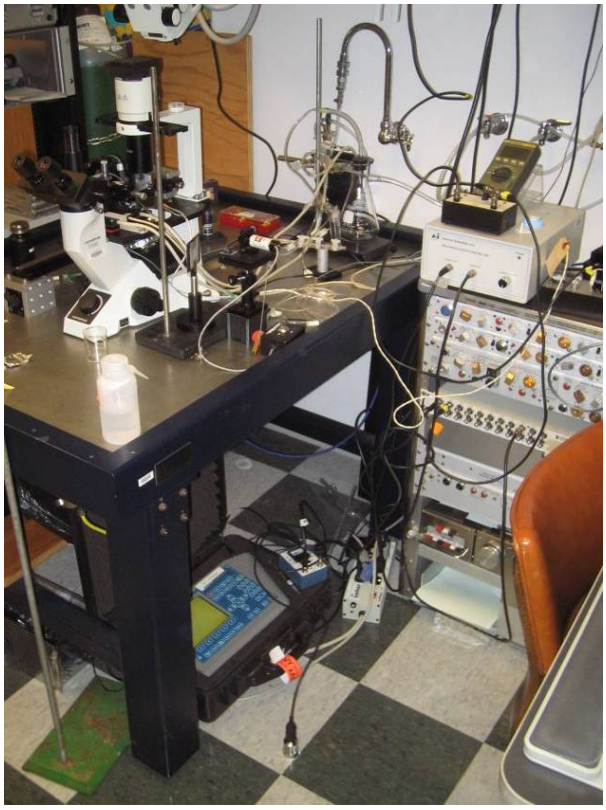
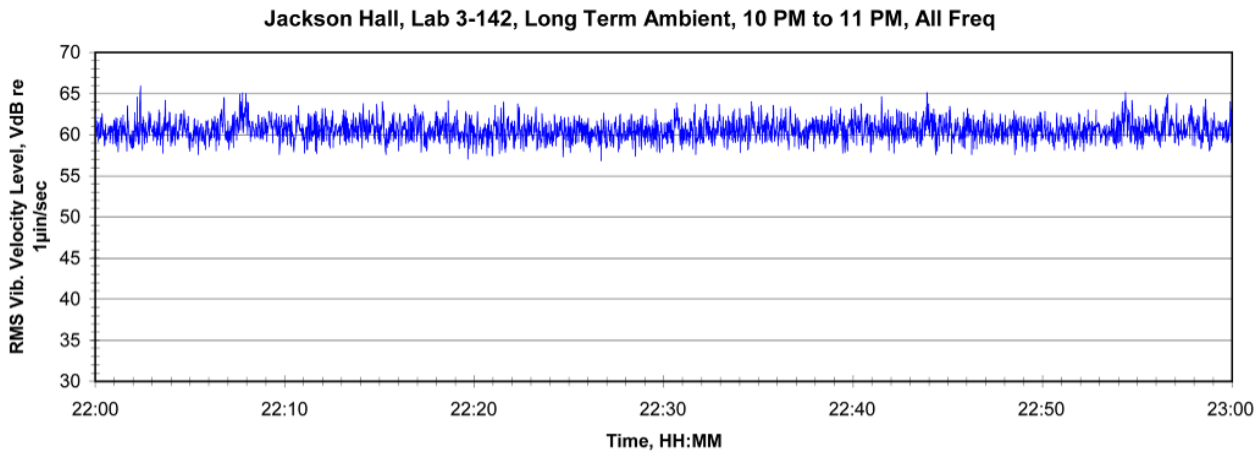
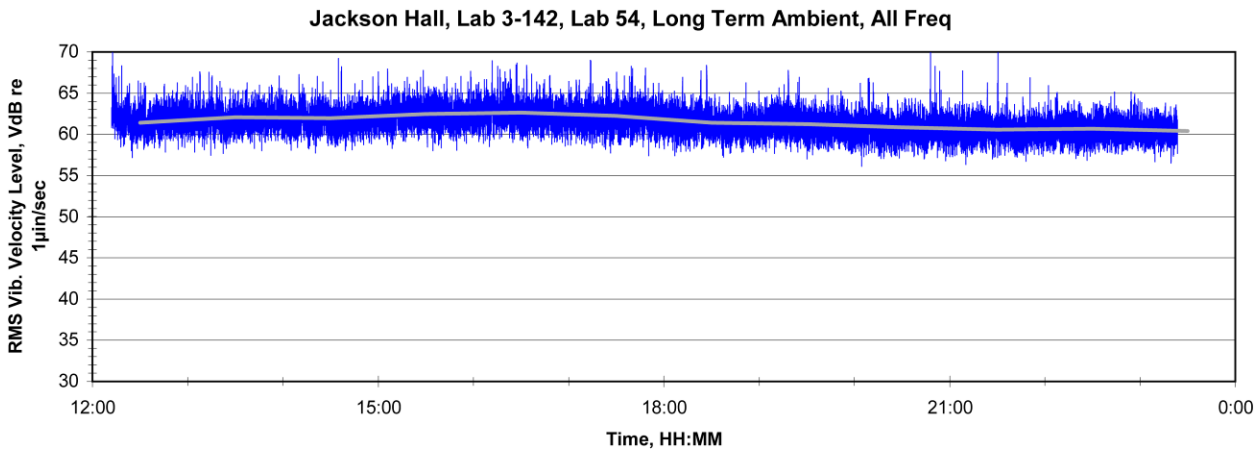


Figure 93: Accelerometers on the Floor inside Jackson Hall





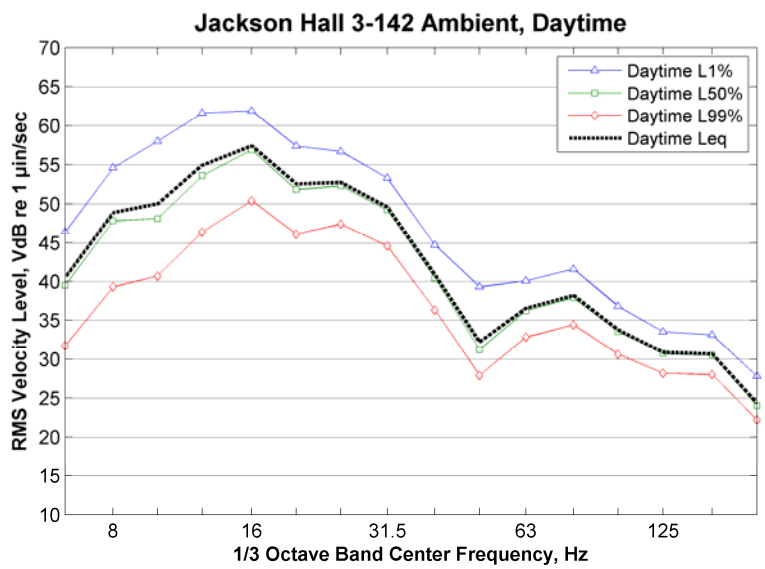


Figure 94: Ambient Vibration inside Room 3-142 at Jackson Hall

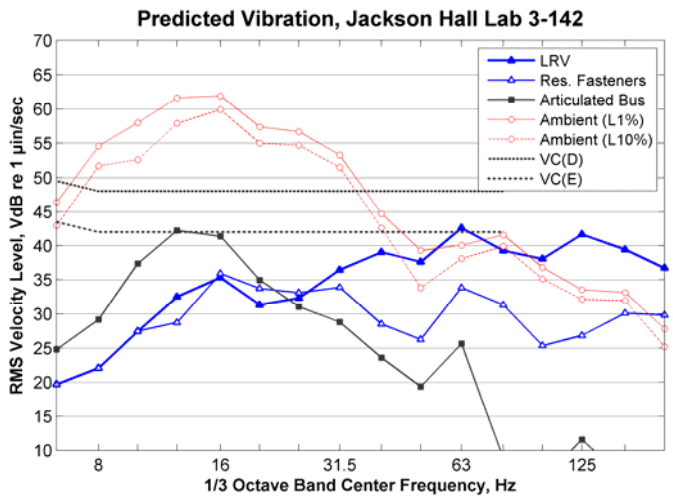


Figure 95: Predicted Vibration inside Room 3-142 at Jackson Hall

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

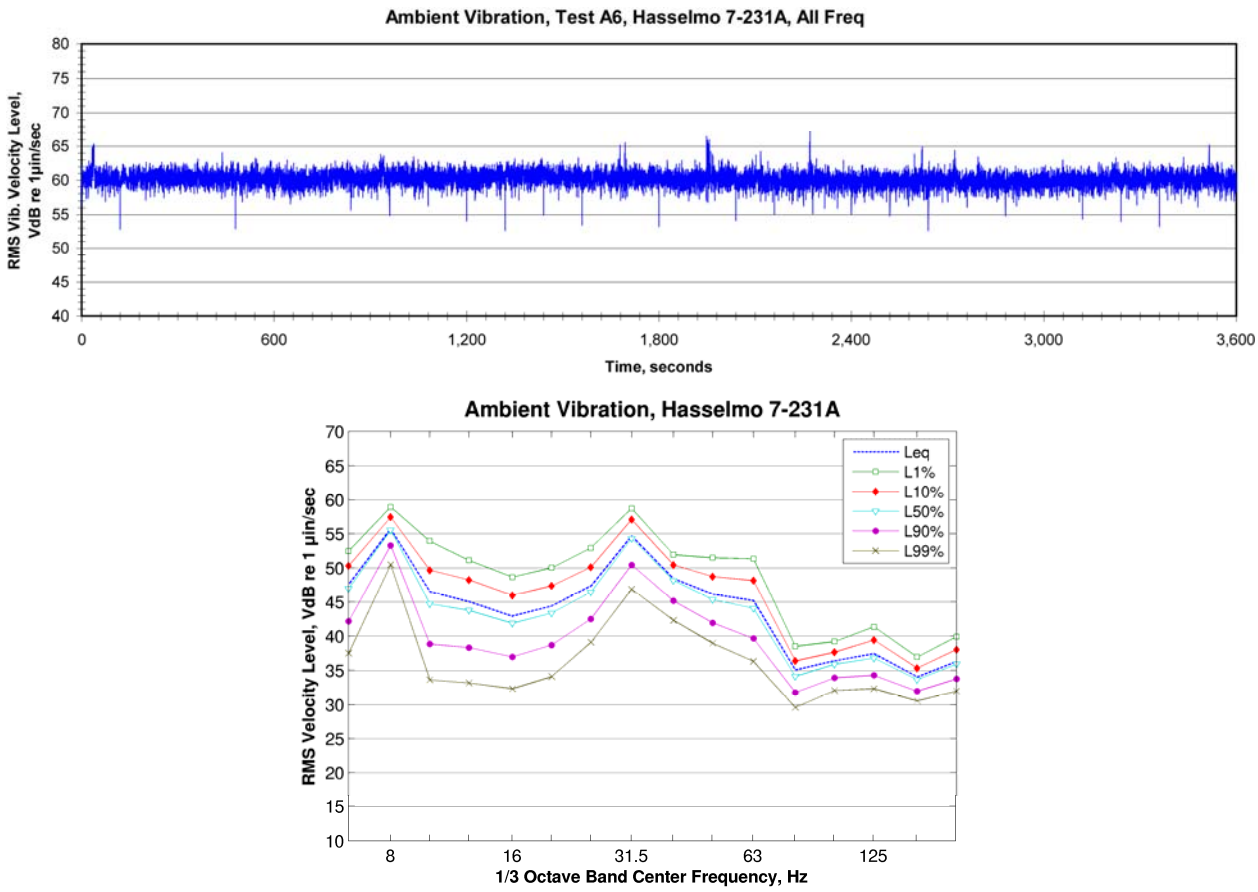


Figure 97: Ambient Vibration inside Room 7-231A at Nils Hasselmo Hall

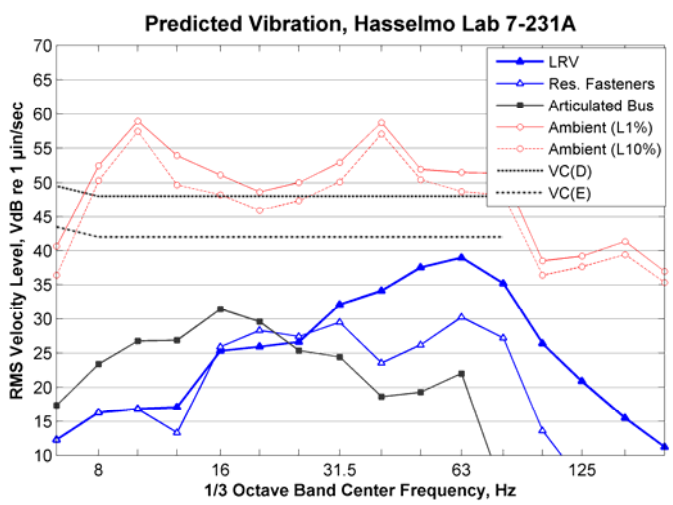


Figure 98: Predicted Vibration inside Room 7-231A at Nils Hasselmo Hall

6.19 Philip Wangensteen Building Room 7-218, Test A7

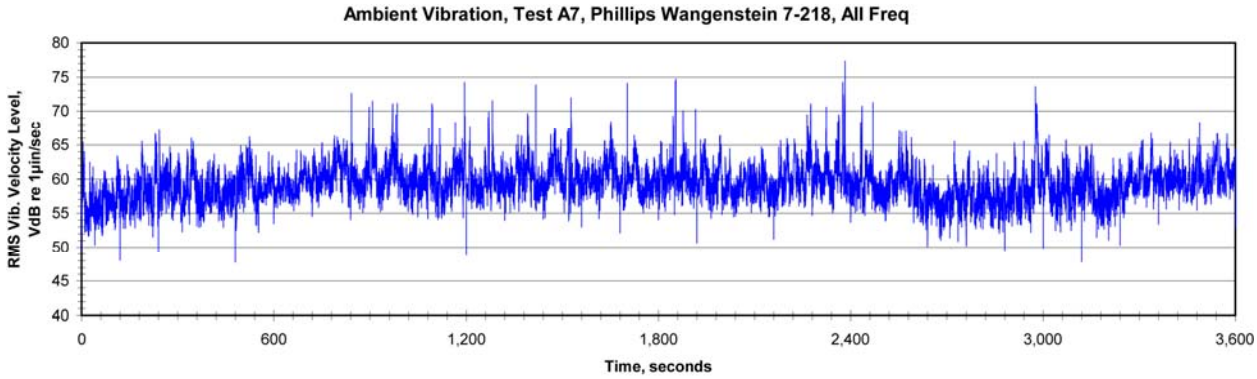
Room 7-218 is located on the seventh floor of the Philip Wangensteen Building. The concern is for a 600 MHz superconducting Varian NMR spectroscopy equipment. A one hour ambient vibration measurement was performed adjacent to the lab on October 14, 2008. The lab is approximately 400 feet from Washington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



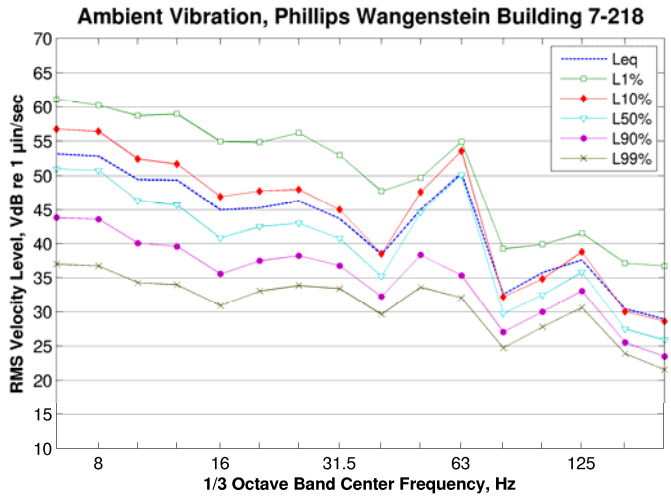


Figure 100: Ambient Vibration inside Room 7-218 at the Philip Wangensteen Building

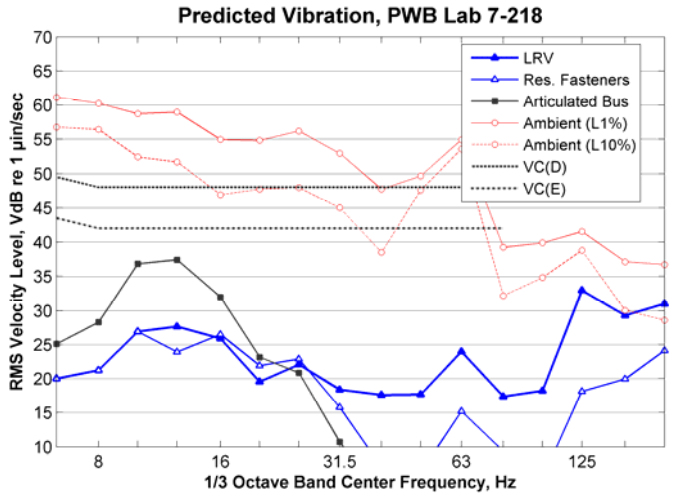


Figure 101: Predicted Vibration inside Room 7-218 at the Philip Wangensteen Building

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

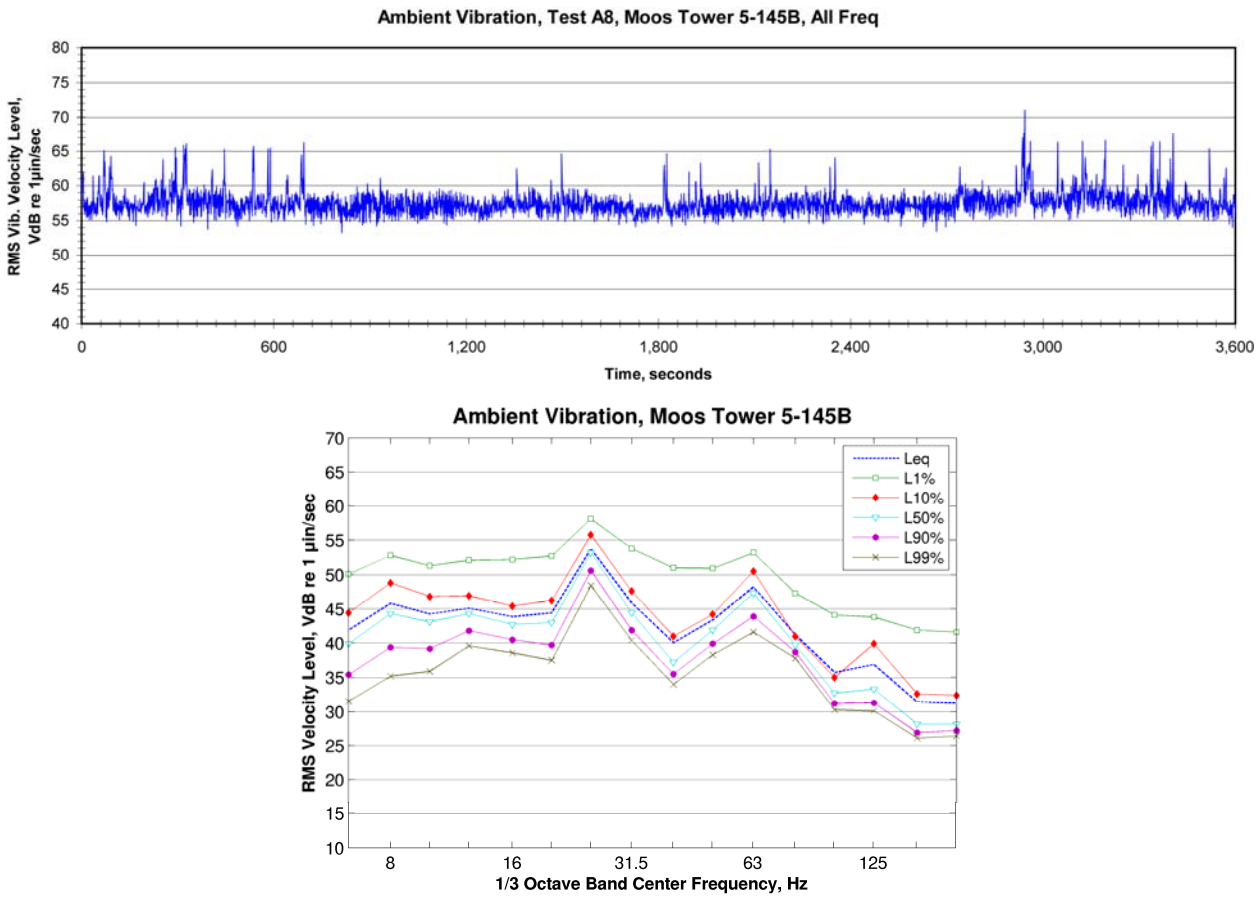


Figure 103: Ambient Vibration inside Room 5-145B at Moos Tower

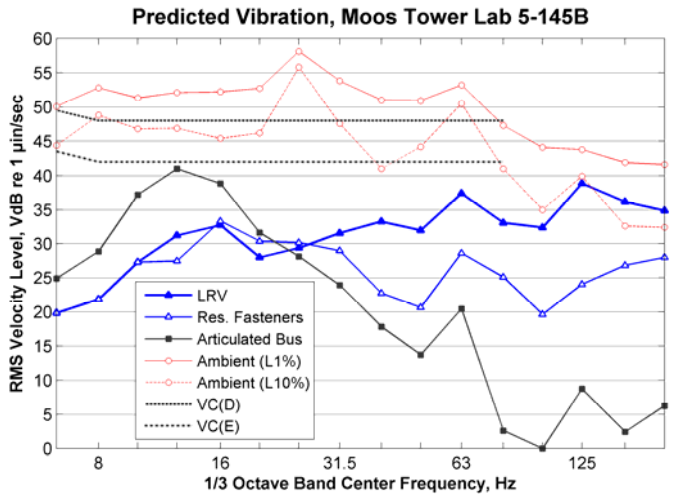


Figure 104: Predicted Vibration inside Room 5-145B at Moos Tower

6.21 Moos Tower Room 5-245A, Test A9

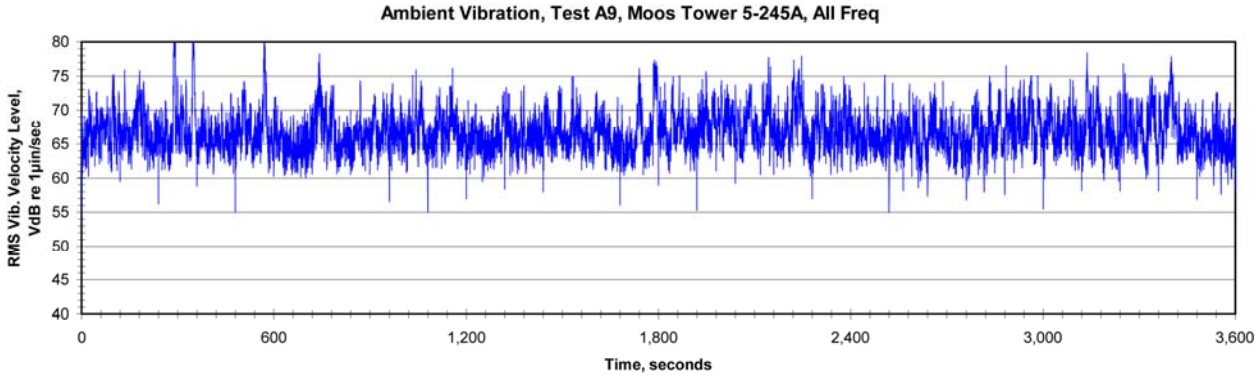
A one hour ambient vibration measurement was performed on October 15, 2008 in Room 5-245A in Moos Tower. The concern was for sensitive microscopy equipment located on the fifth floor of the building. The lab is approximately 190 feet from Washington Avenue.

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



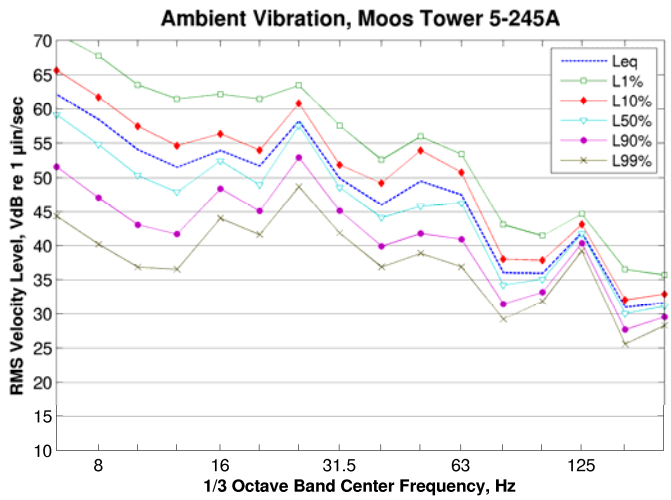


Figure 106: Ambient Vibration inside Room 5-245A at Moos Tower

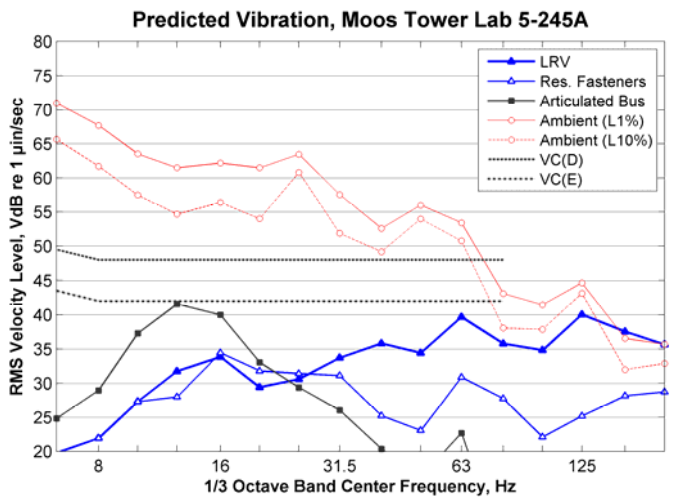


Figure 107: Predicted Vibration inside Room 5-245A at Moos Tower

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

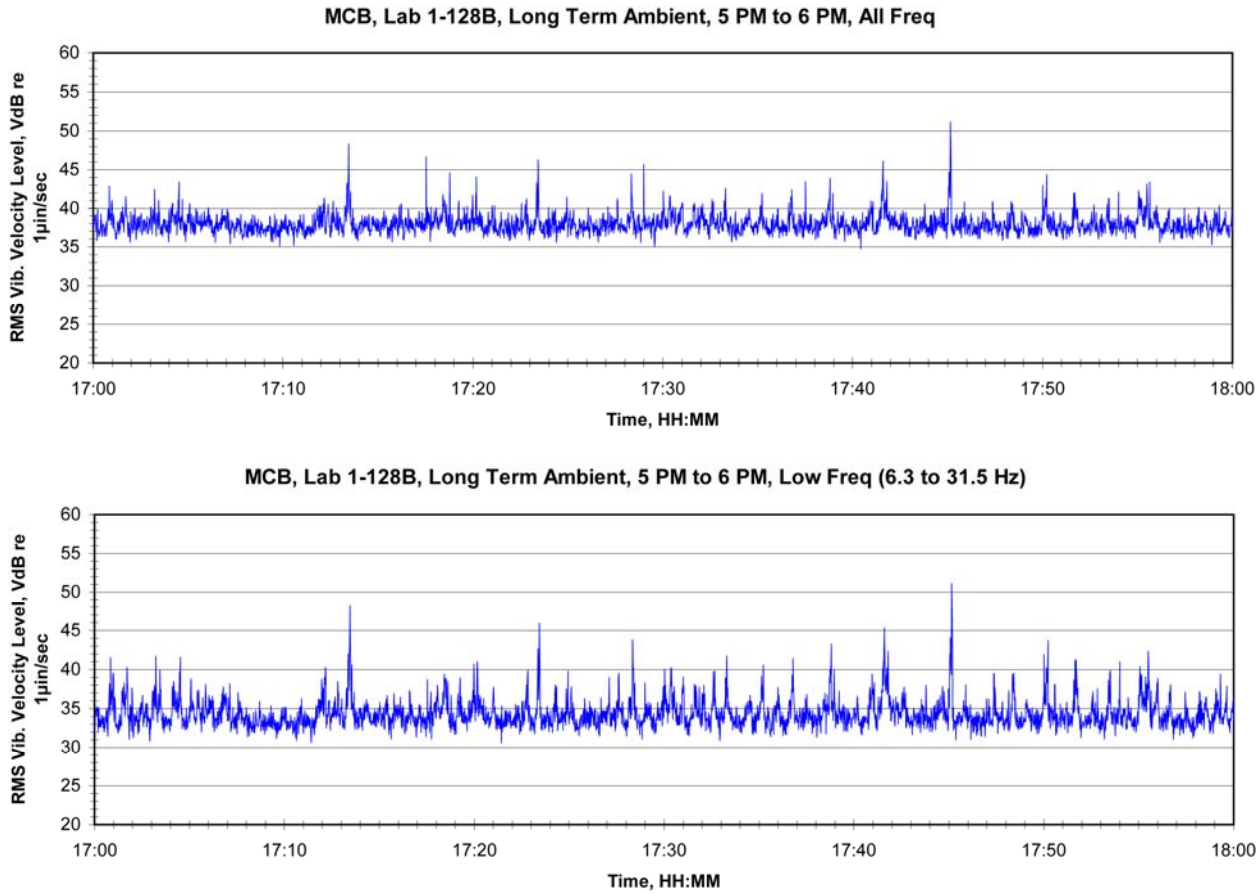


Figure 109: Time History of Vibration inside Room 1-128B at MCB, Typical Day Time

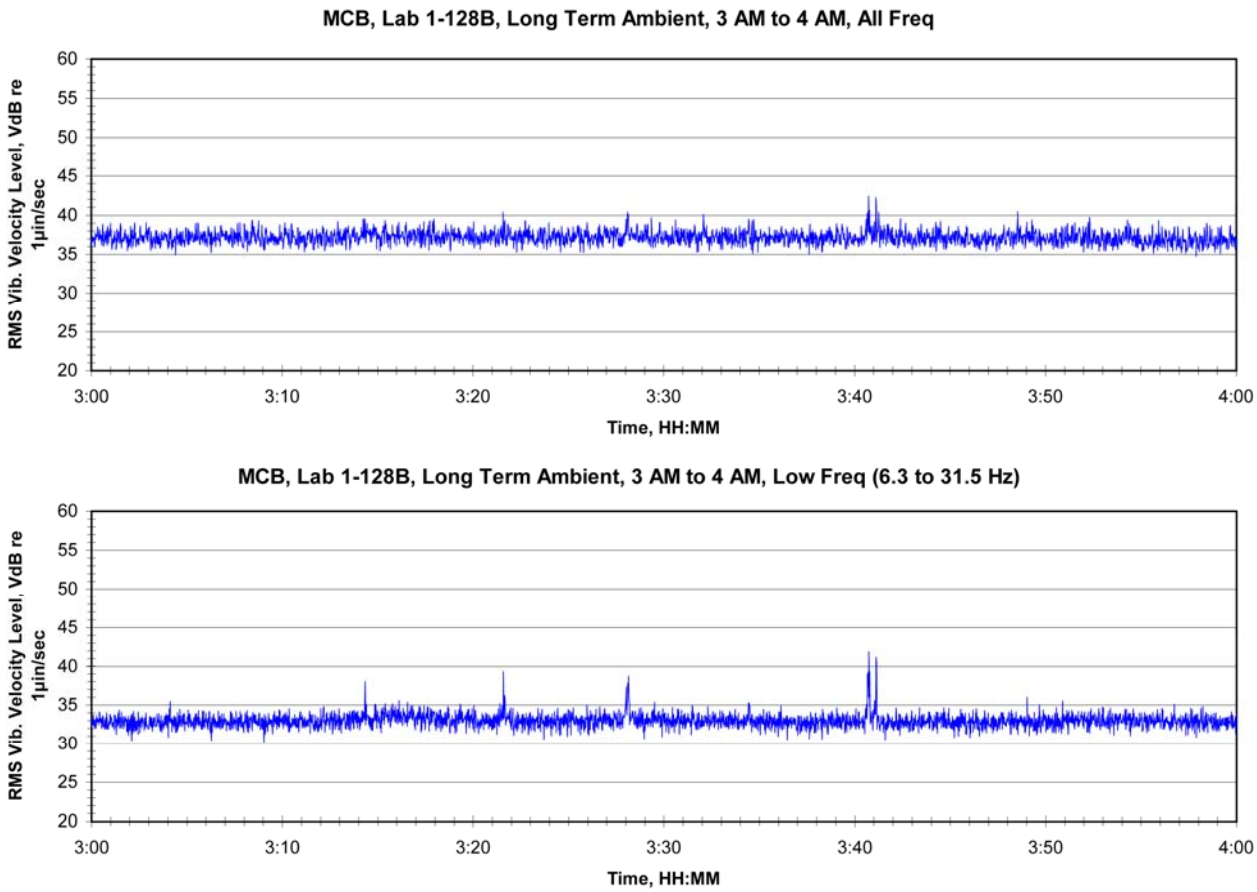


Figure 110: Time History of Vibration inside Room 1-128B at MCB, Typical Night Time

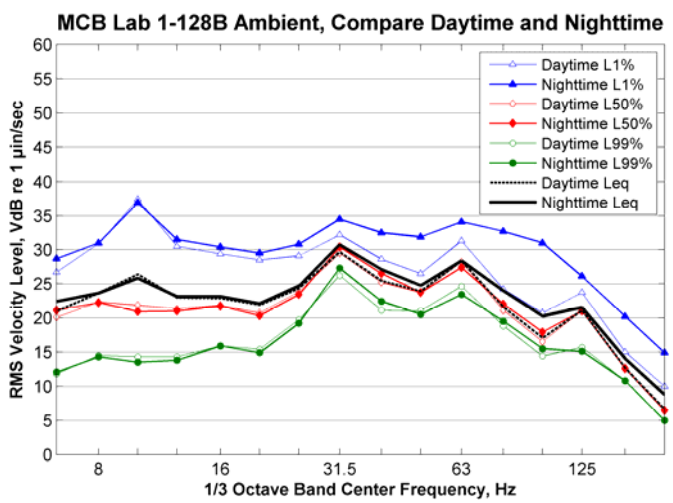


Figure 111: Ambient Vibration Spectrum inside Room 1-128B at MCB

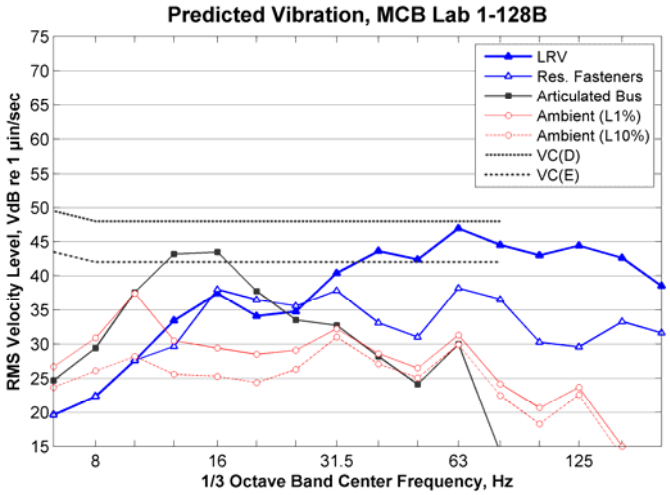


Figure 112: Predicted Vibration inside Room 1-128B at the Molecular and Cellular Biology Building

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

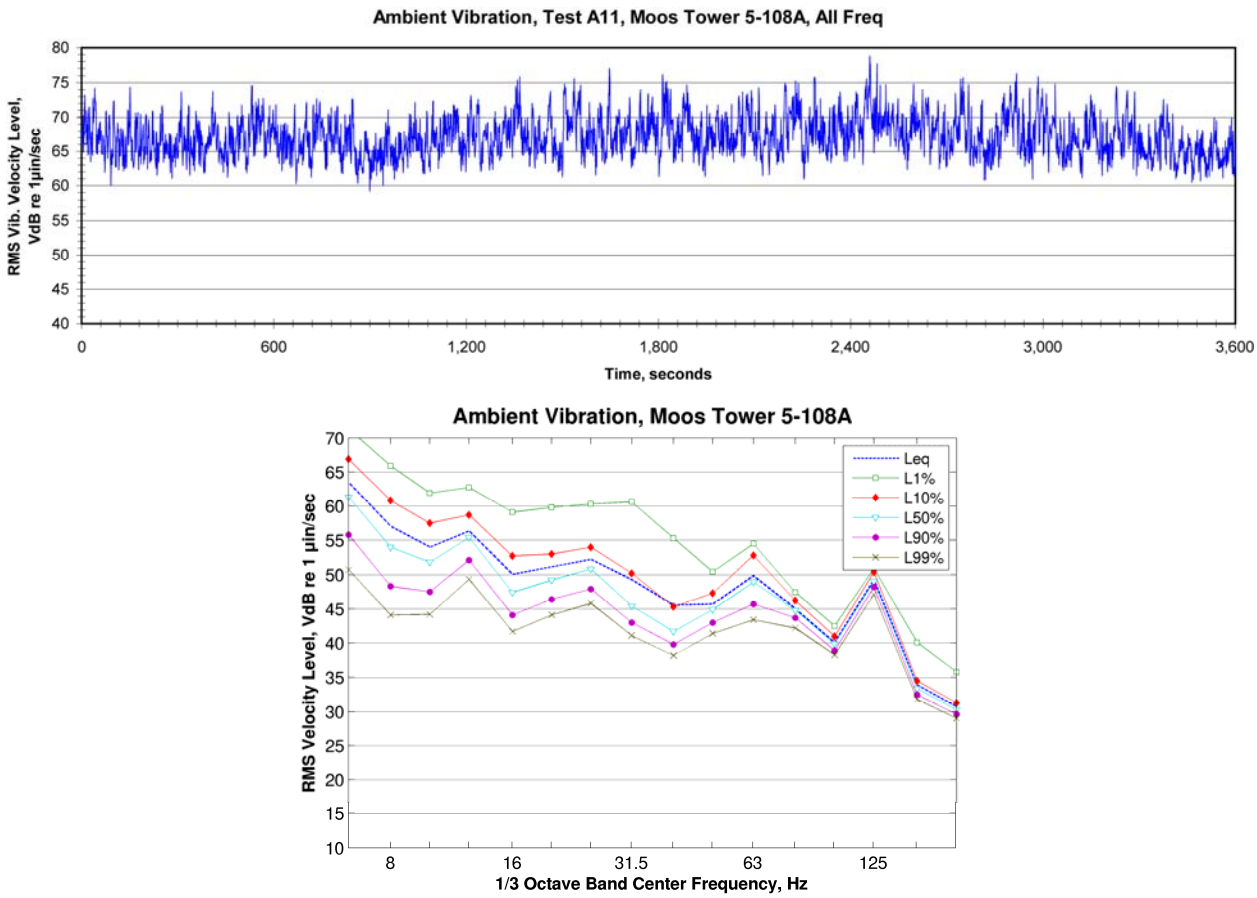


Figure 114: Ambient Vibration inside Room 5-108A at Moos Tower

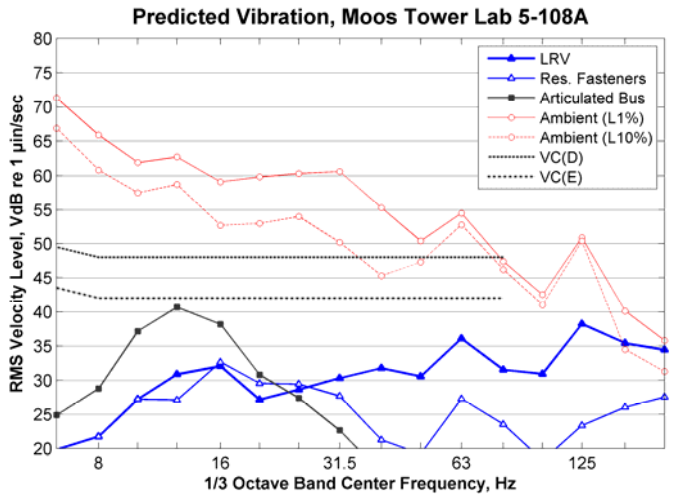


Figure 115: Predicted Vibration inside Room 5-108A at Moos Tower

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

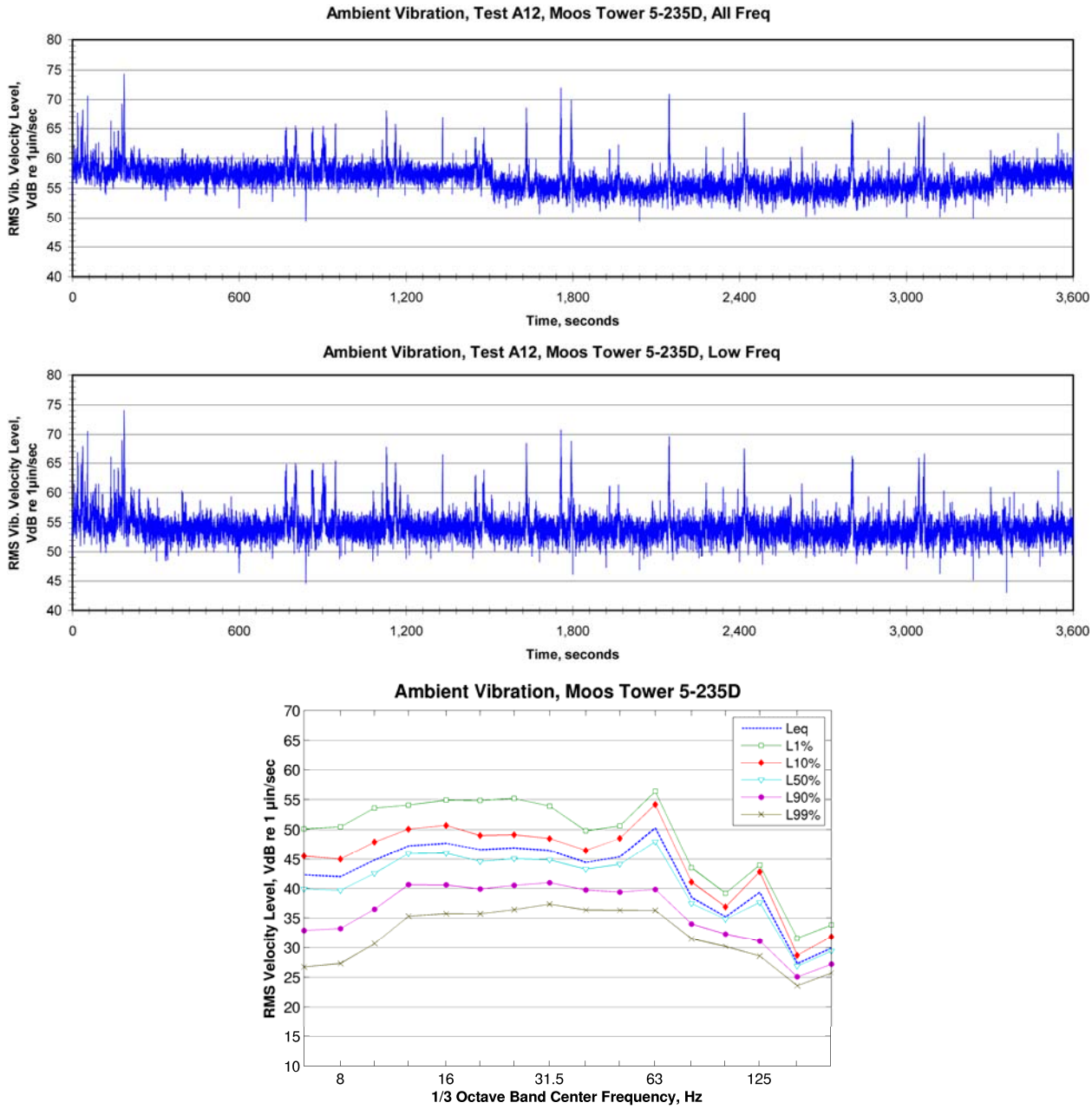


Figure 117: Ambient Vibration inside Moos Tower Room 5-235D

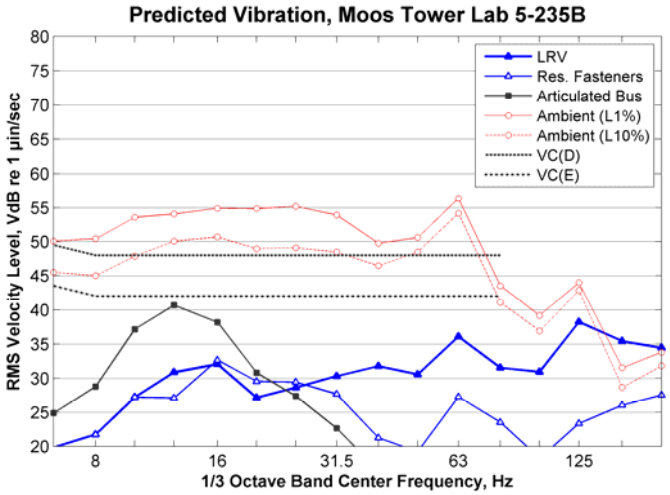


Figure 118: Predicted Vibration inside Room 5-235D at Moos Tower

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.

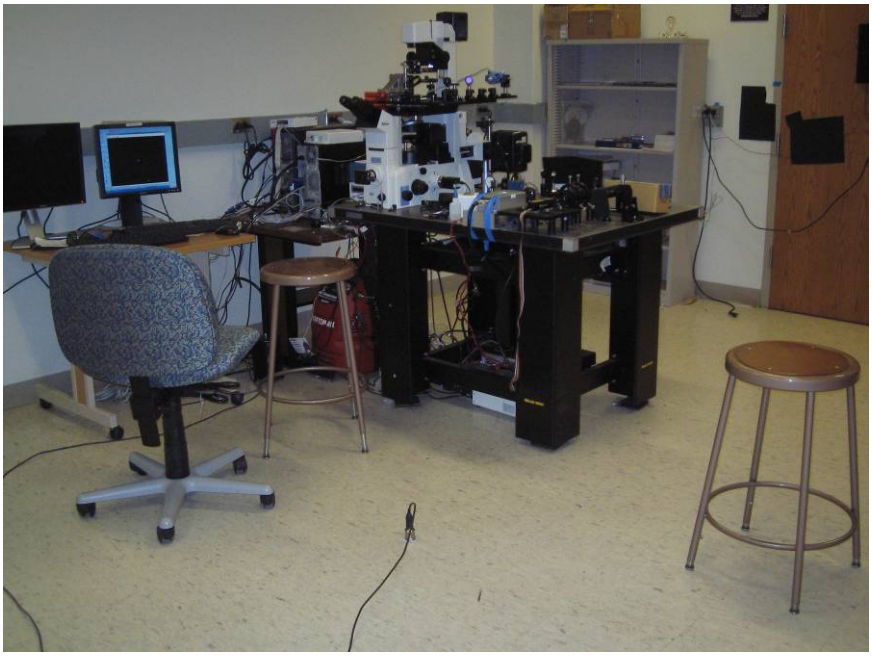


Figure 119: Measurement on the Floor of EECS 2-270

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

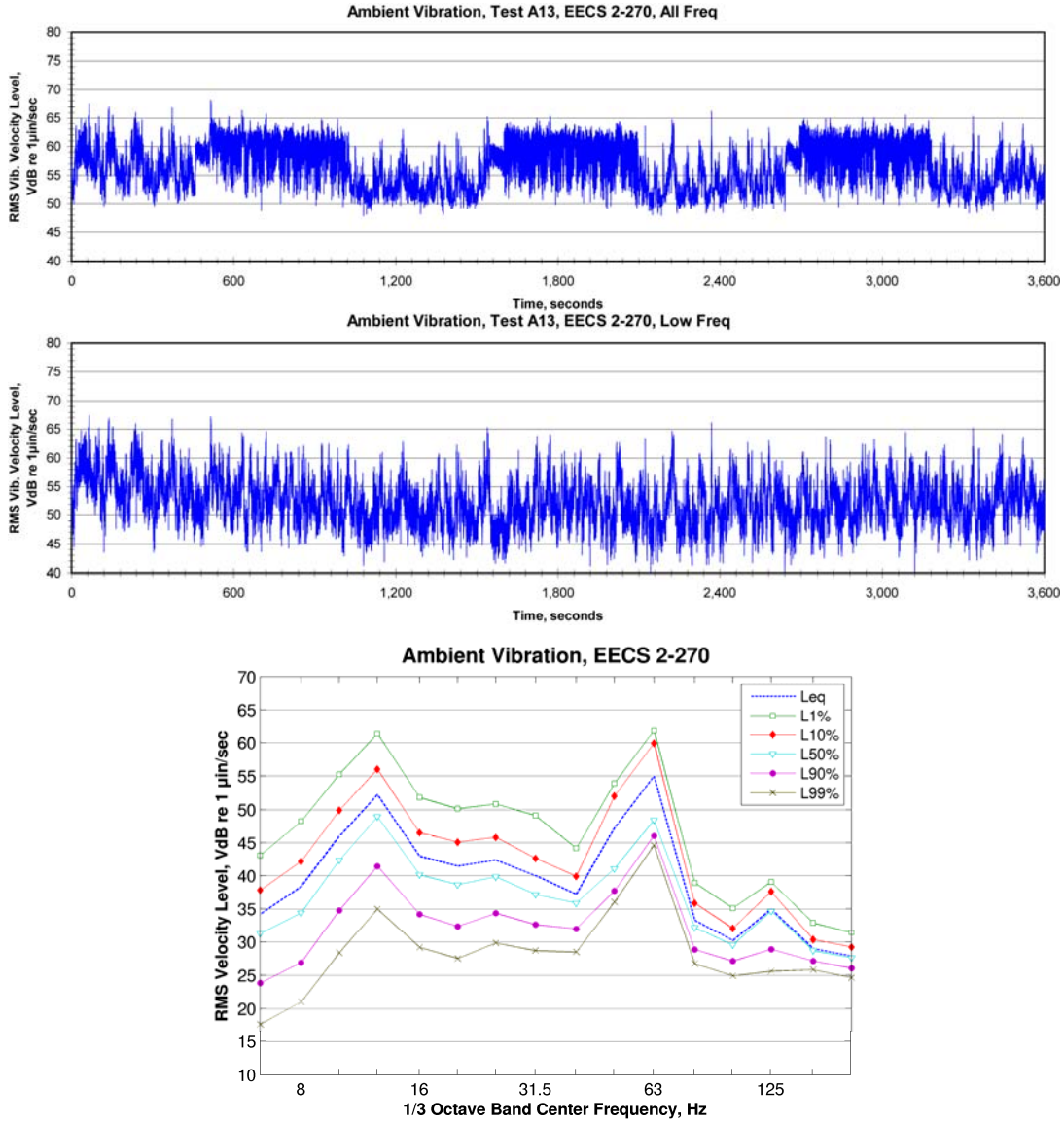
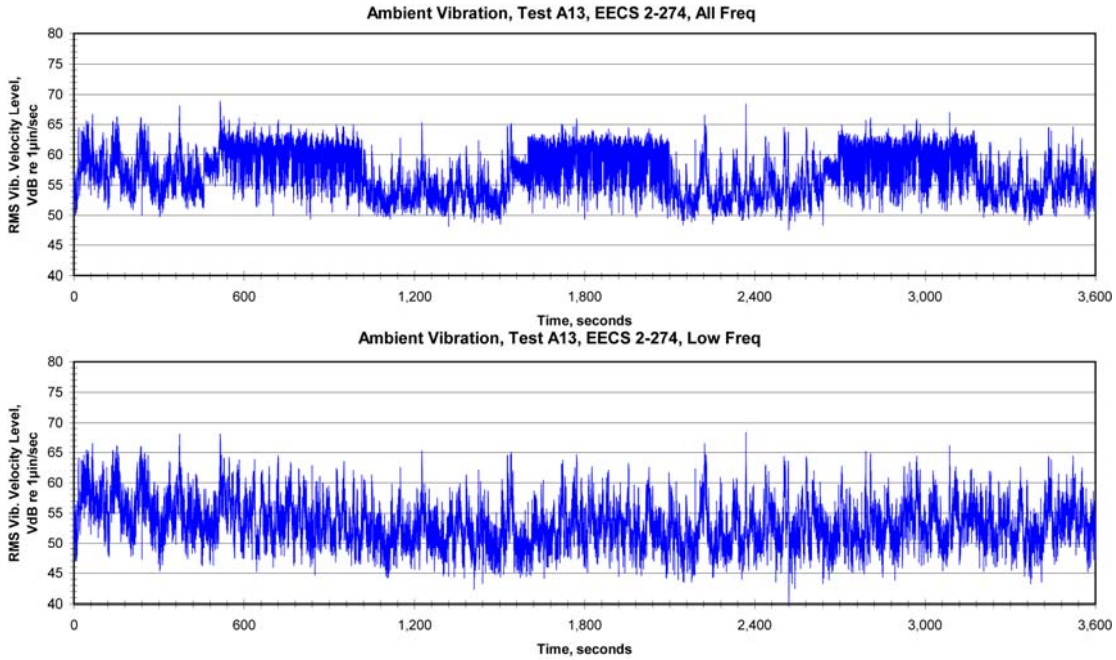


Figure 121: Ambient Vibration at EECS 2-270



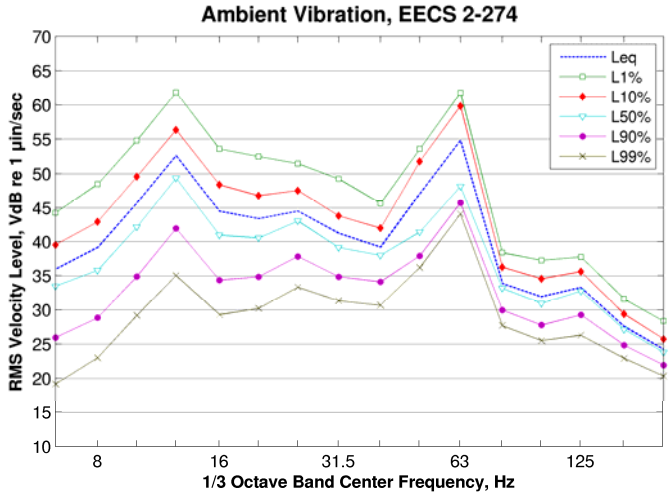


Figure 122: Ambient Vibration at EECS Room 2-274

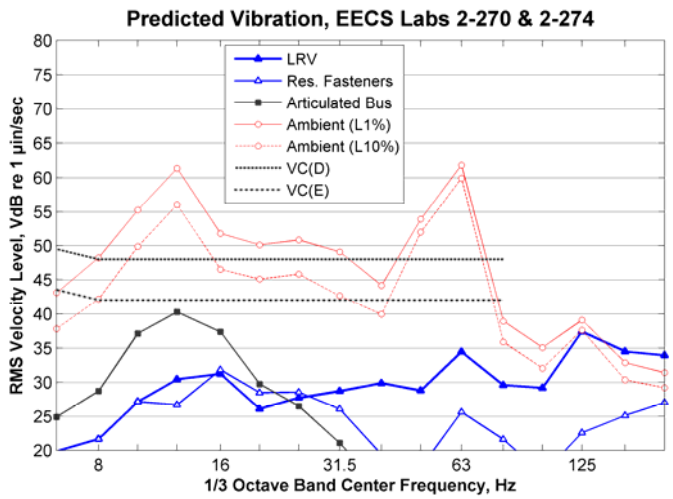


Figure 123: Predicted Vibration inside Rooms 2-270 and 2-274 at the Electrical Engineering and Computer Science Building

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

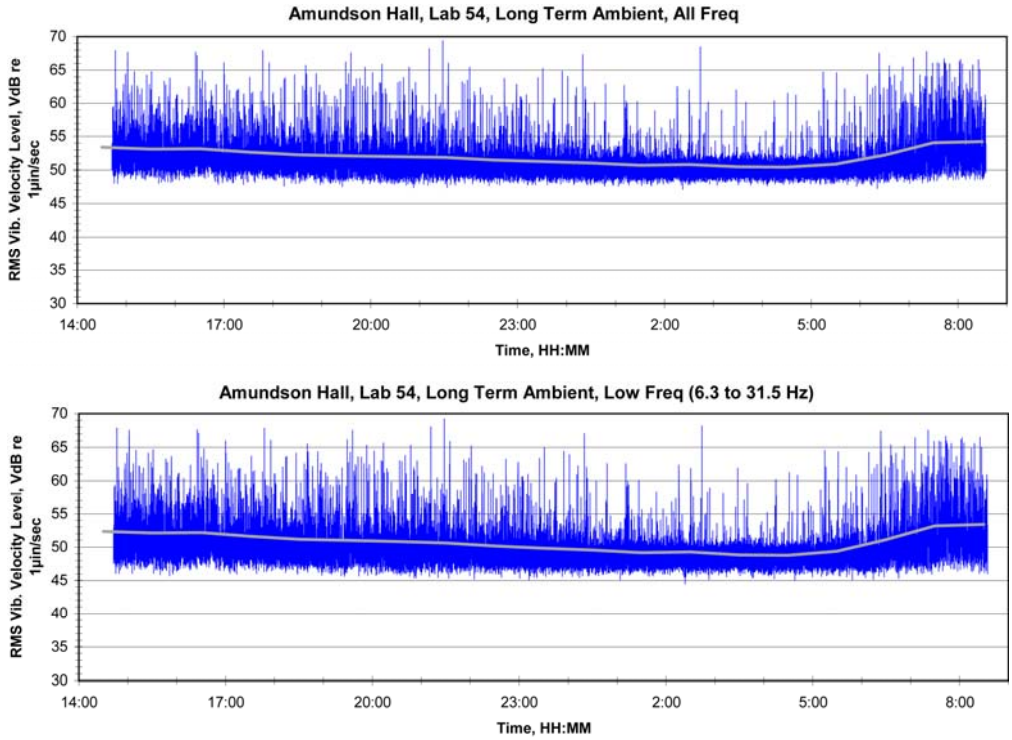


Figure 125: Time History of Ambient Measurement inside Room 54 at Amundson Hall

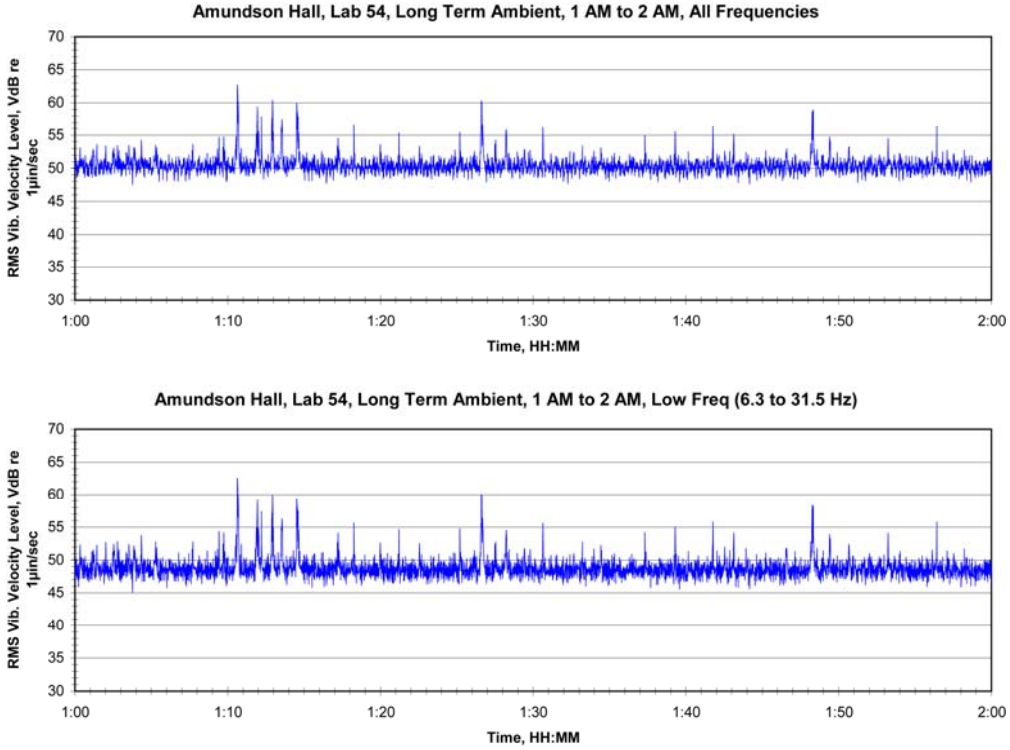


Figure 126: Ambient Vibration in Amundson Room 54, 1 AM to 2 AM

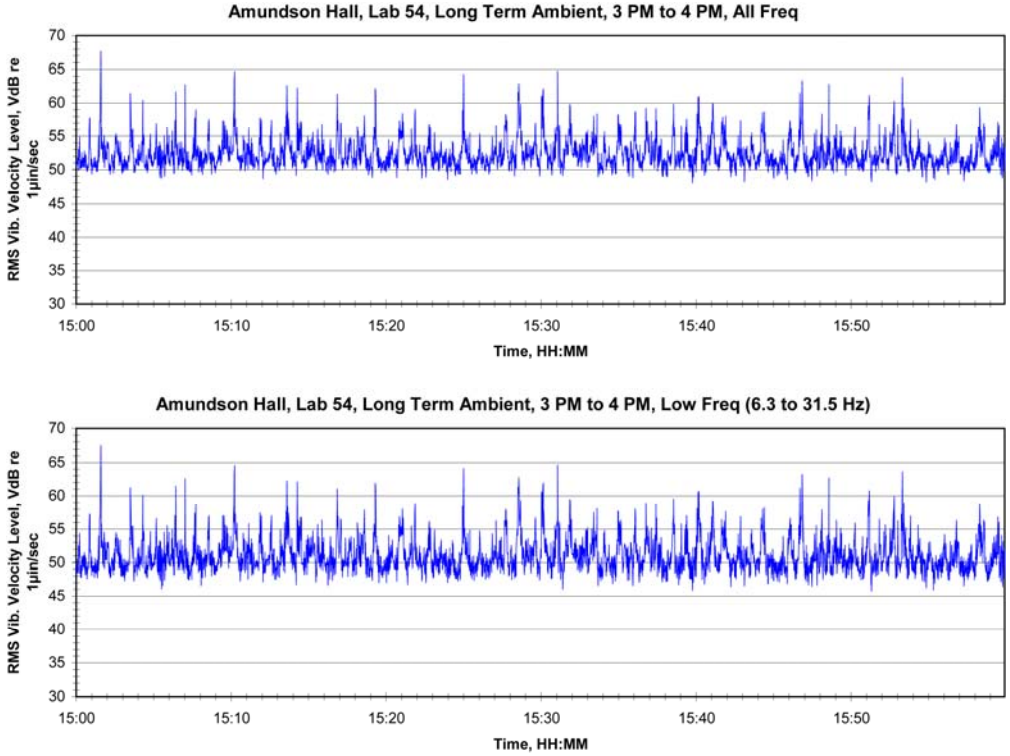


Figure 127: Ambient Vibration in Amundson Room 54, 3 PM to 4 PM

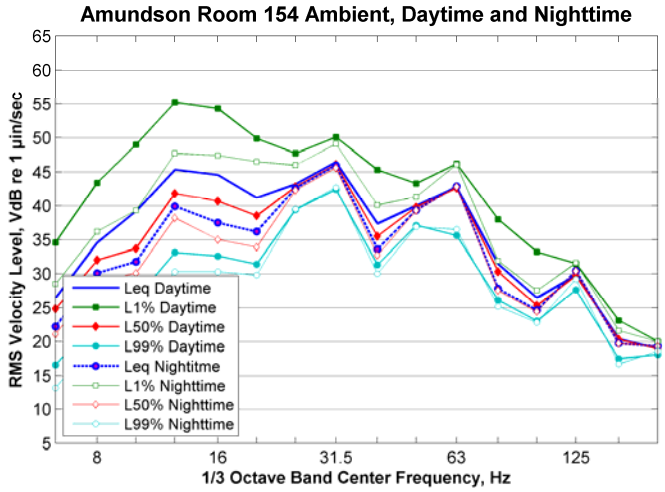


Figure 128: Ambient Vibration Spectrum inside Room 54 at Amundson Hall

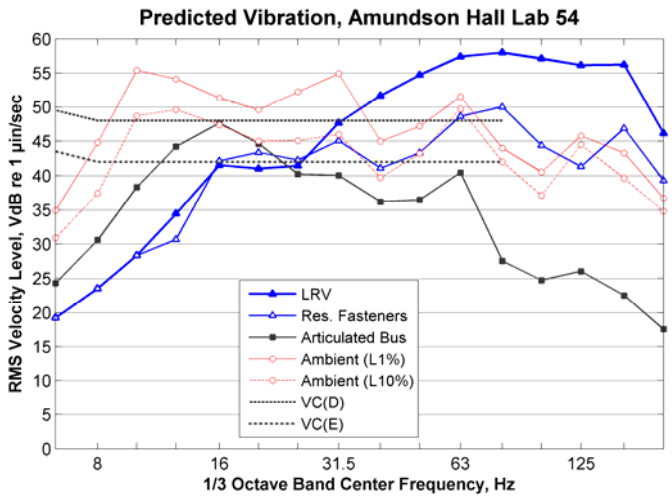


Figure 129: Predicted Vibration inside Room 54 at Amundson Hall

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

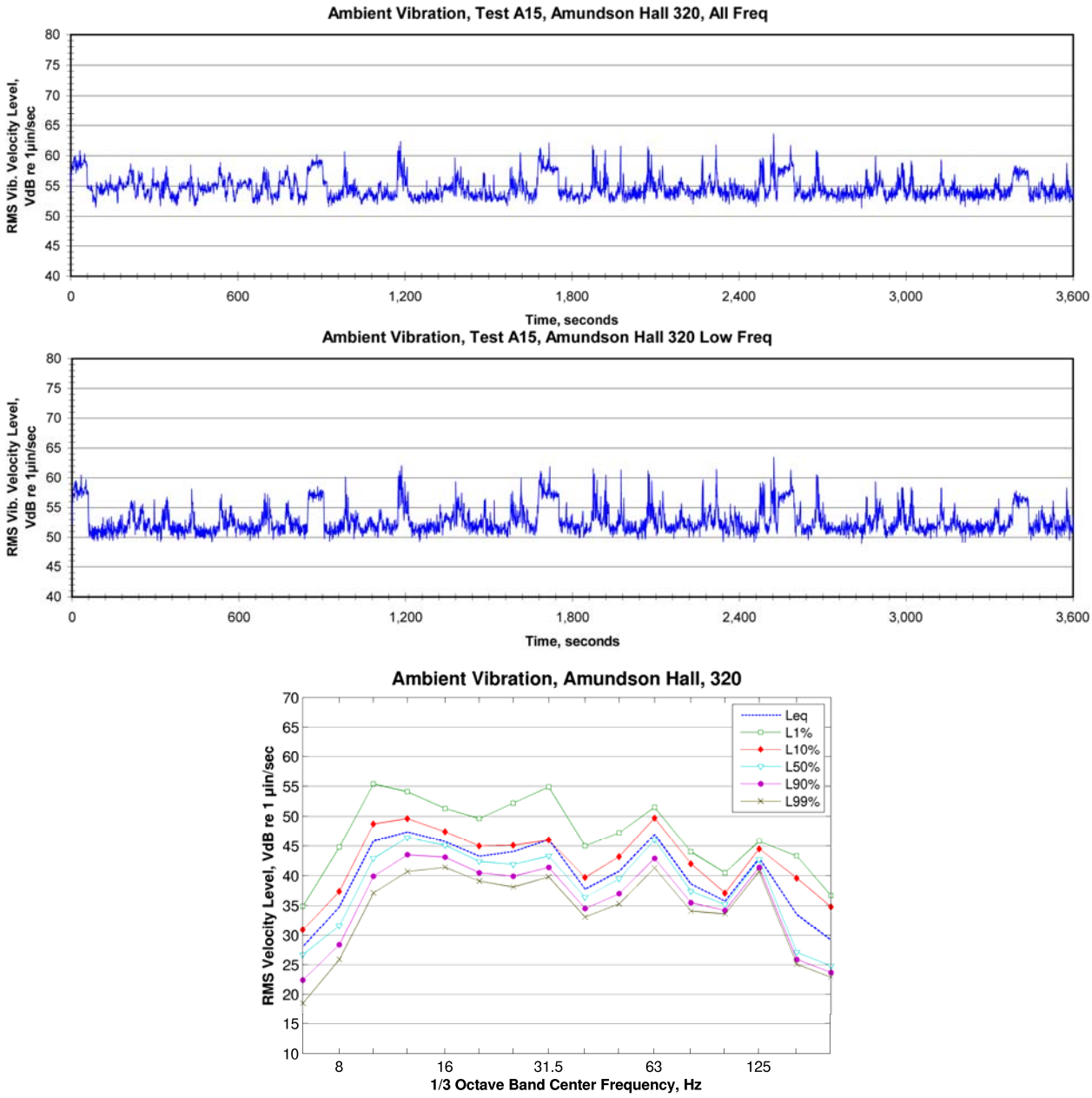


Figure 131: Ambient Vibration Spectrum inside Room 320 at Amundson Hall

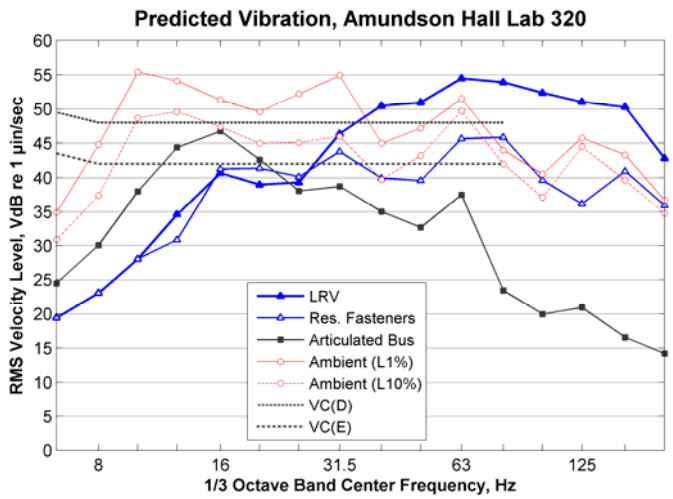


Figure 132: Predicted Vibration inside Room 320 at Amundson Hall

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

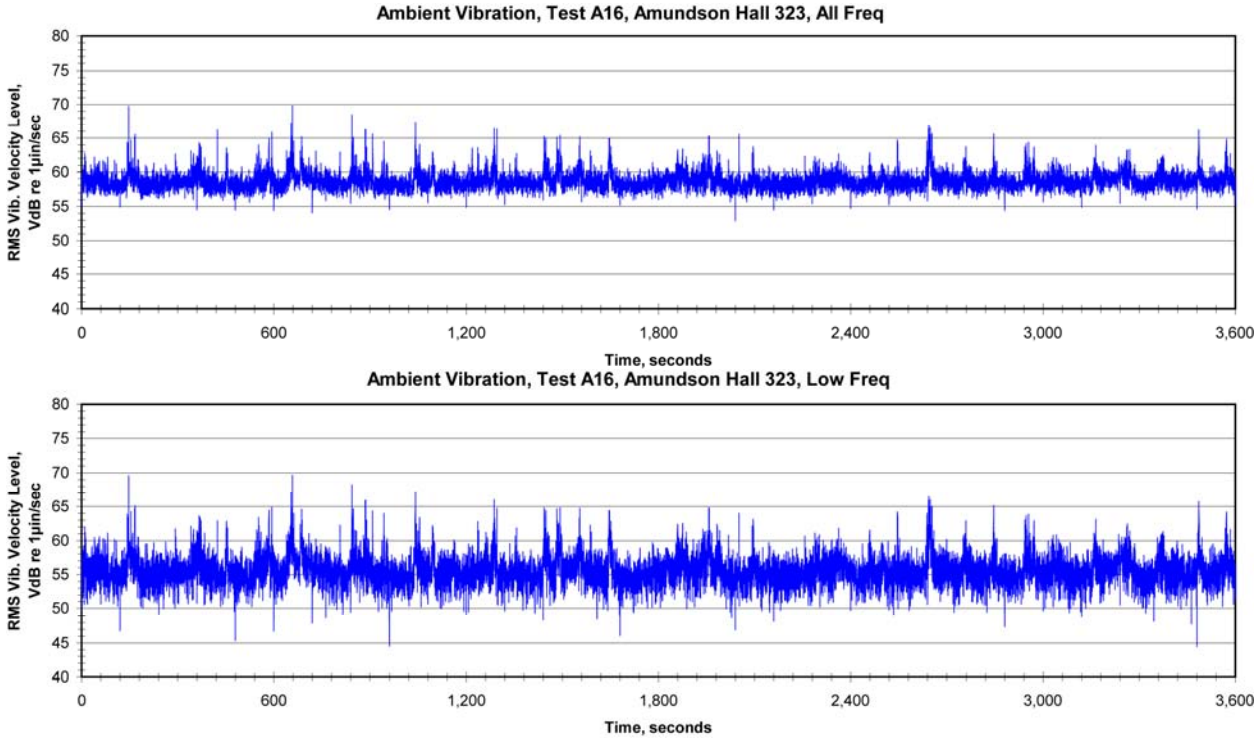


Figure 134: Time History of Ambient Measurement inside Room 323 at Amundson Hall

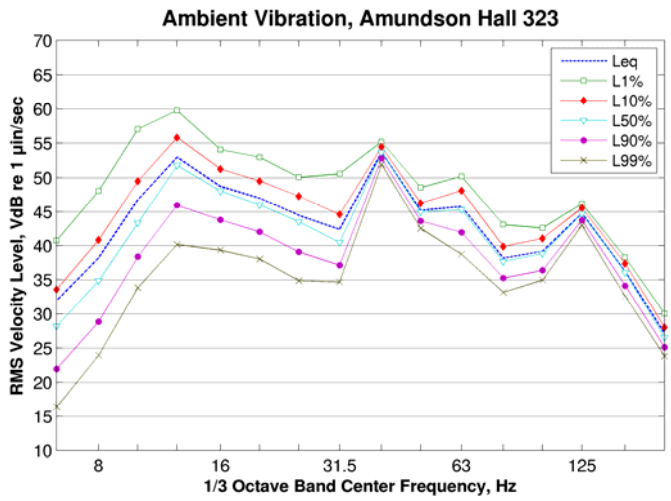


Figure 135: Ambient Vibration Spectrum inside Room 323 at Amundson Hall

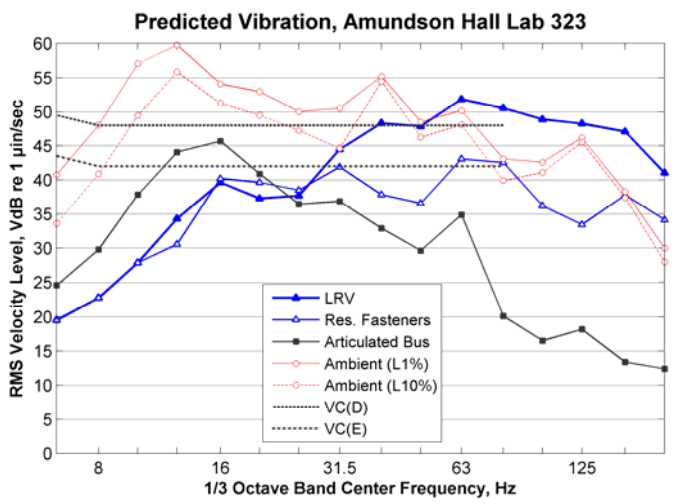


Figure 136: Predicted Vibration inside Room 323 at Amundson Hall

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

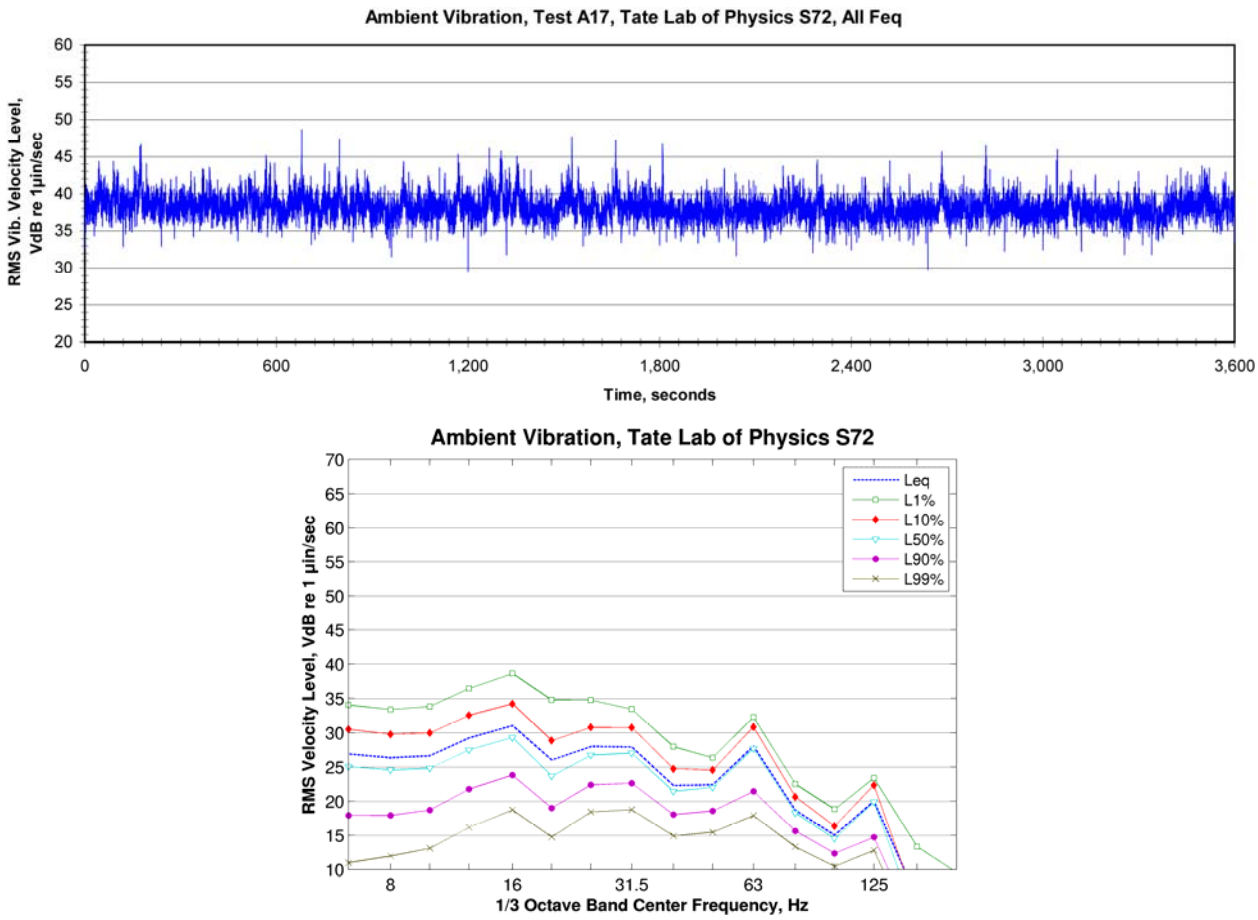


Figure 138: Ambient Vibration Spectrum inside the Tate Lab of Physics

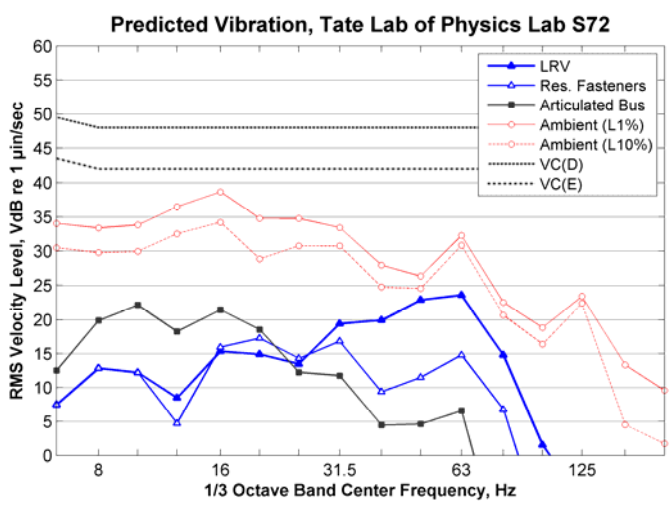


Figure 139: Predicted Vibration inside Room S72 at the Tate Lab of Physics

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

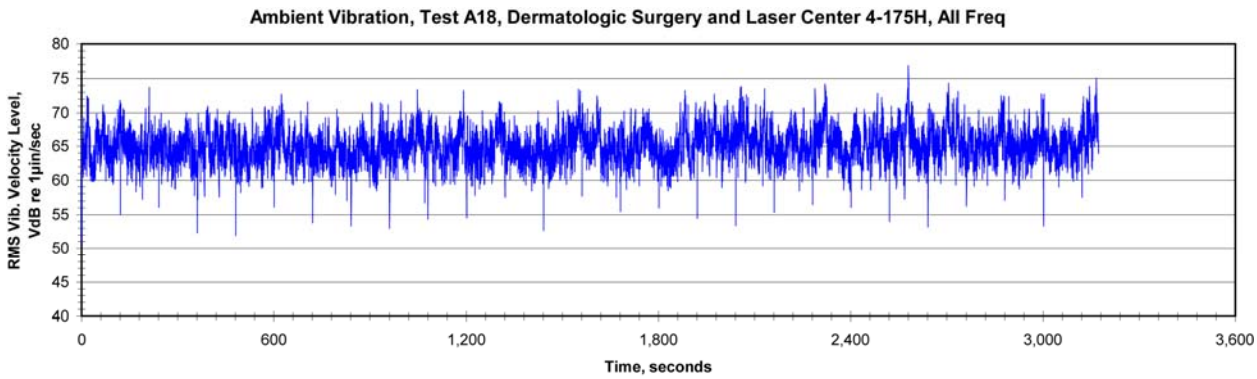
The Dermatologic Surgery and Laser Center is located on the fourth floor of the Phillips Wangensteen Building. The concern is for sensitive surgical and measurement equipment used in the center. A one hour ambient vibration measurement was performed on October 16, 2008. The lab where the accelerometer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



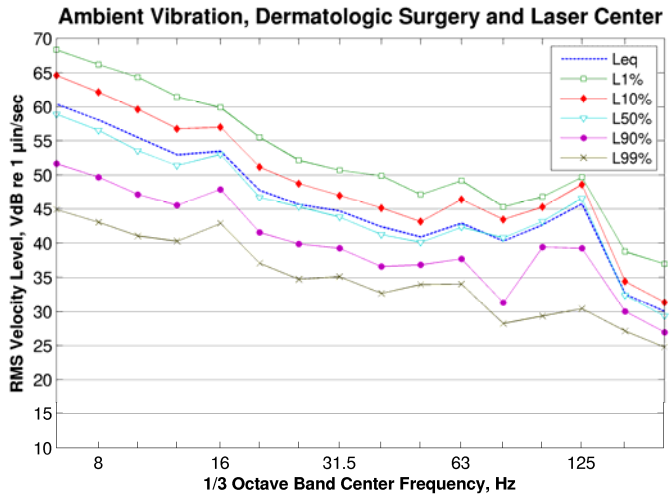


Figure 141: Ambient Vibration Spectrum inside the Dermatology Surgery and Laser Center

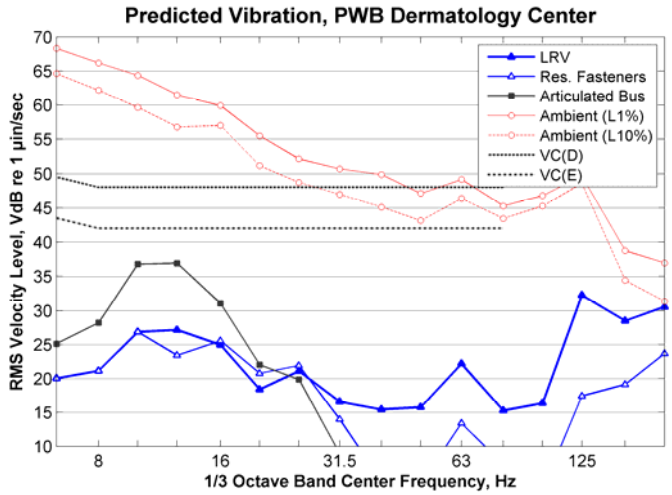


Figure 142: Predicted Vibration inside Room 4-175H at the Dermatology Surgery and Laser Center

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

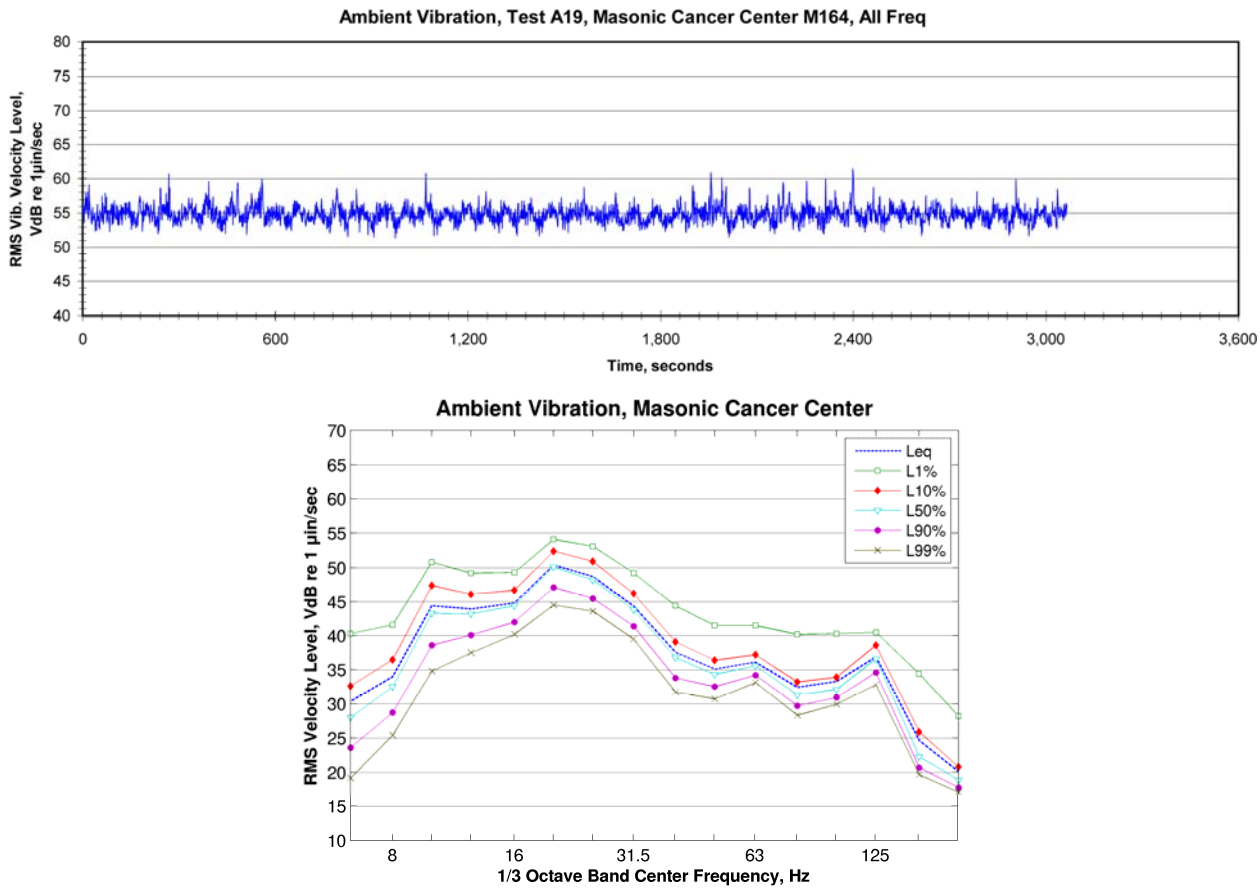


Figure 144: Ambient Vibration inside the Masonic Cancer Center

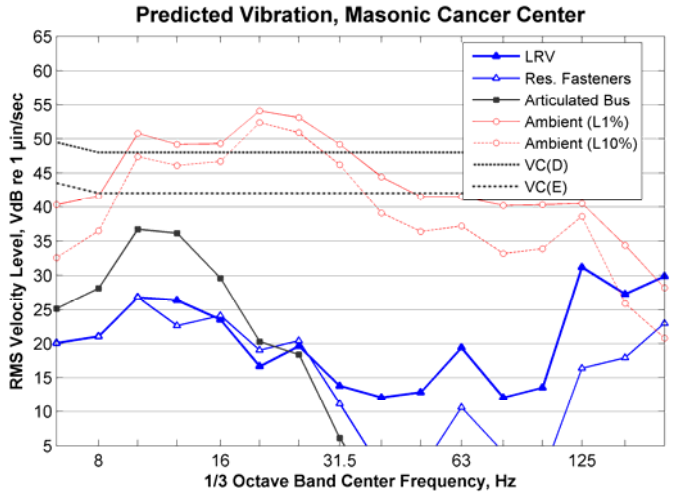


Figure 145: Predicted Vibration inside Room M164 at the Masonic Cancer Center

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

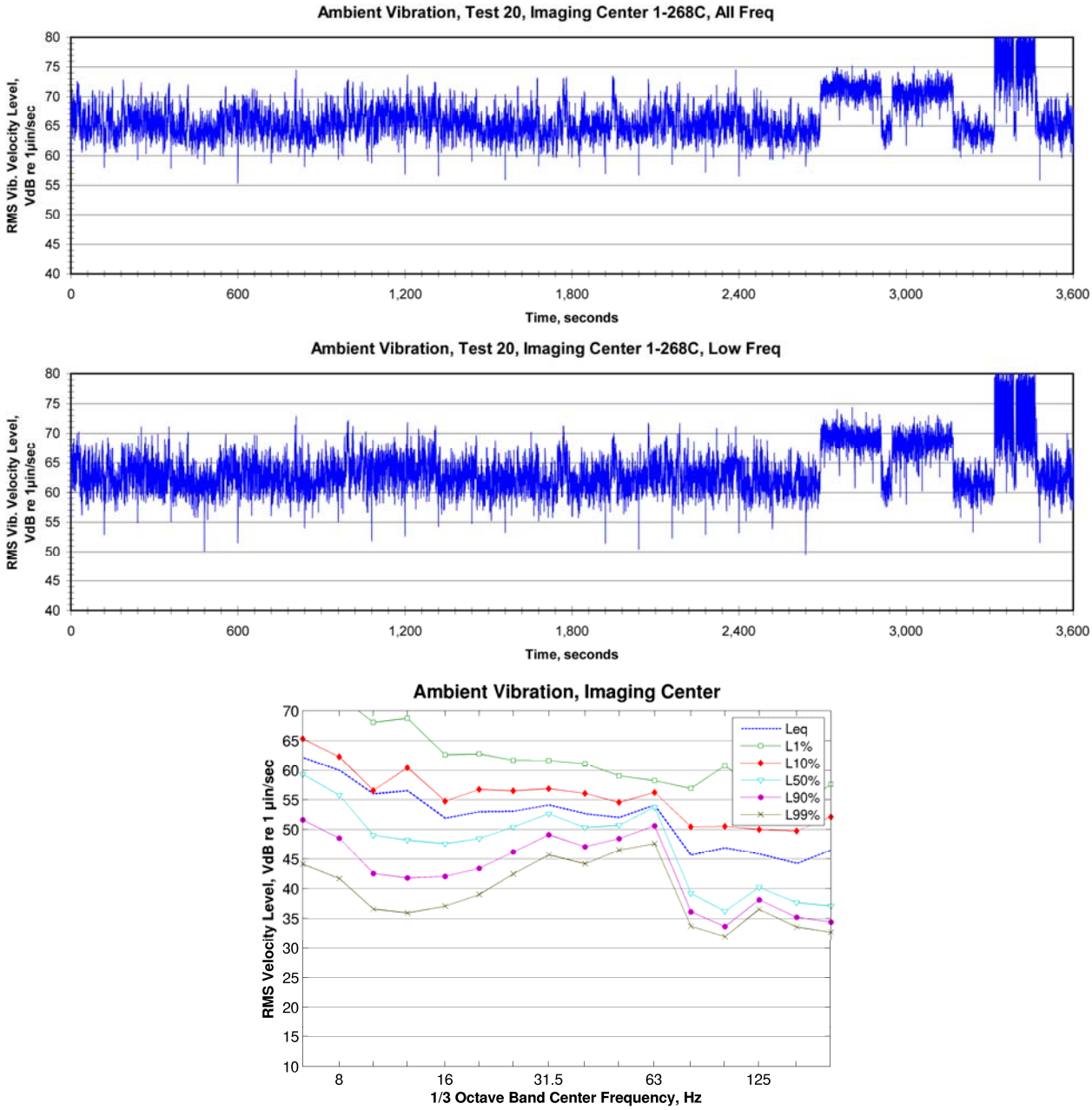


Figure 147: Ambient Vibration Spectrum inside the Imaging Center at the Philip Wangensteen Building

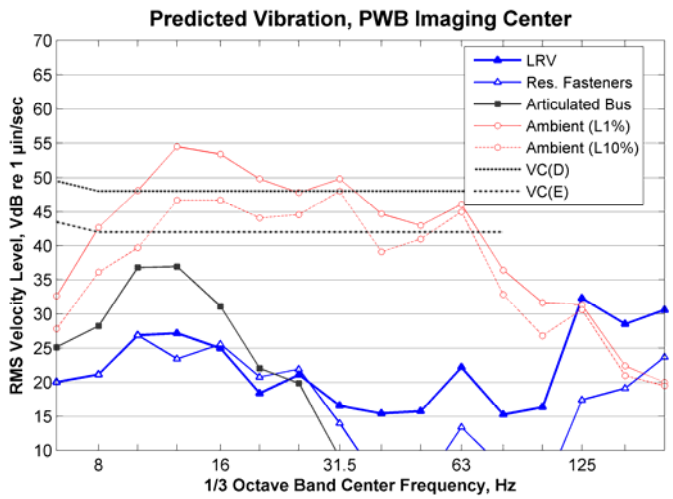


Figure 148: Predicted Vibration inside the Imaging Center at the Philip Wangensteen Building

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.

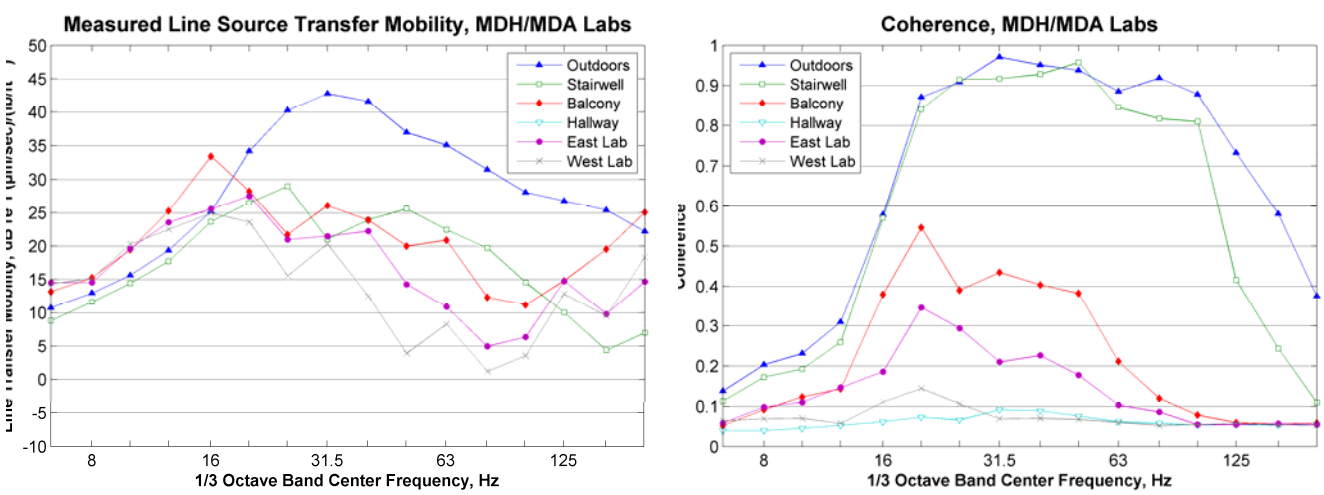


Figure 149: Measured Line Source Transfer Mobility, MDH/MDA Lab Building

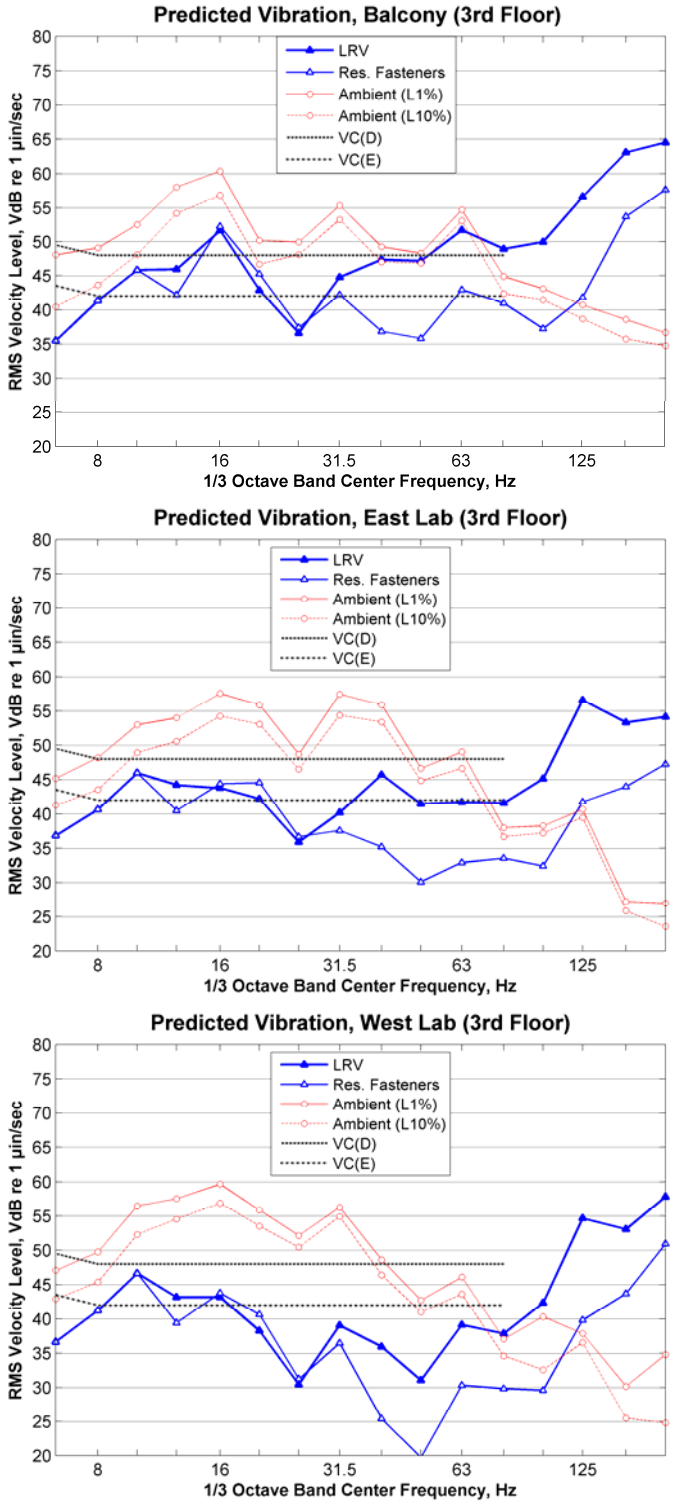


Figure 150: Predicted Vibration inside MDH/MDA Lab Building, 3rd Floor

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

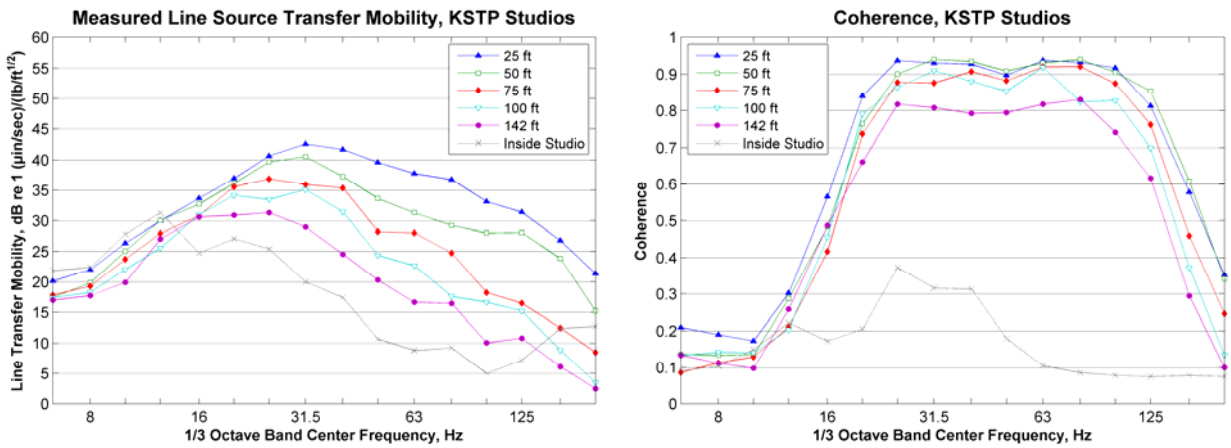


Figure 153: Measured Line Source Transfer Mobility, KTSP Studio

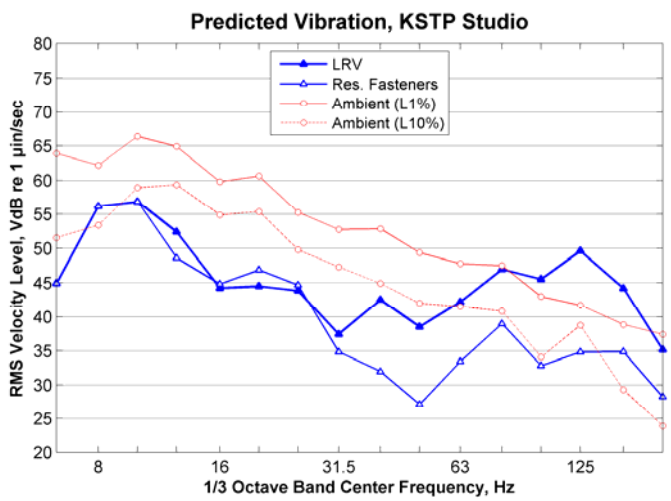


Figure 154: Predicted Train Vibration inside KSTP Studio

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

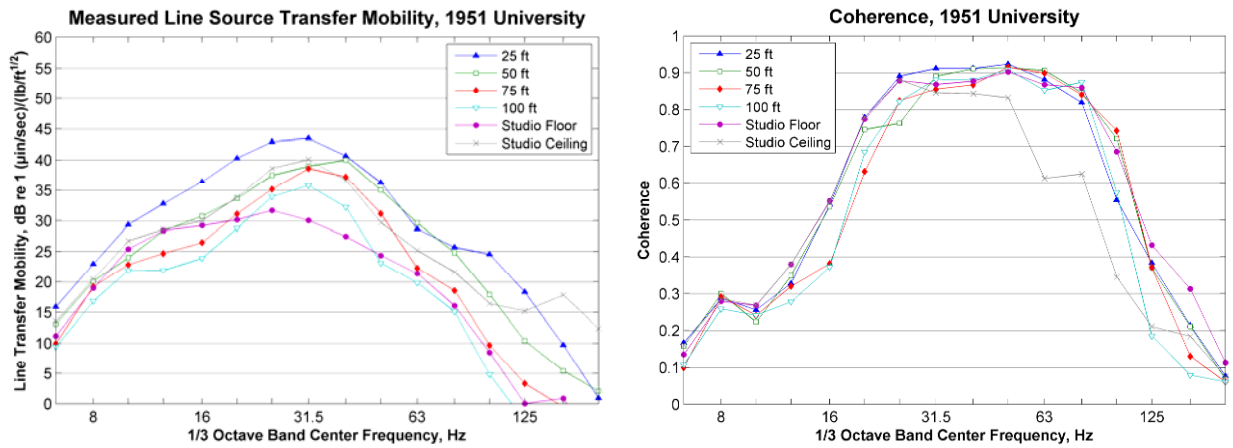


Figure 156: Measured Line Source Transfer Mobility, 1951 University

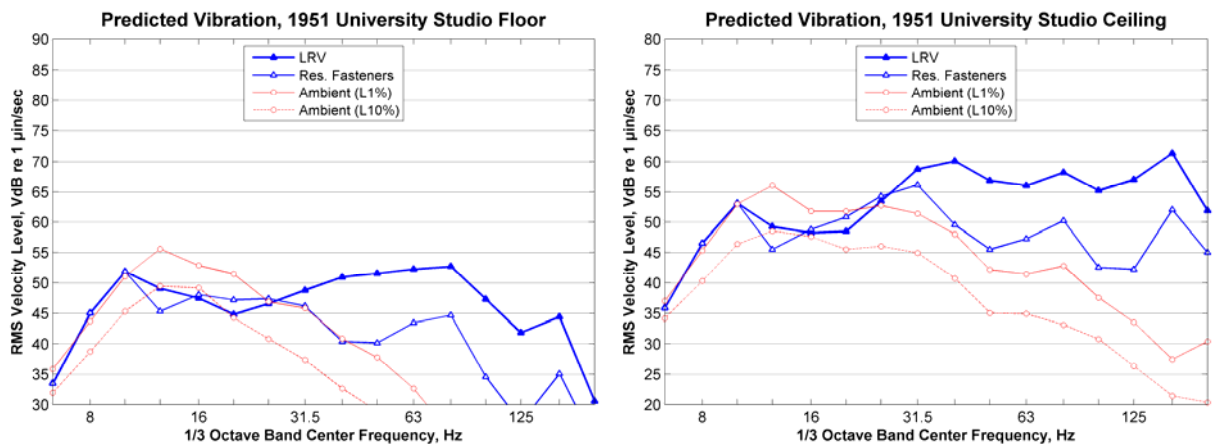


Figure 157: Predicted Train Vibration inside Studio, 1951 University

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

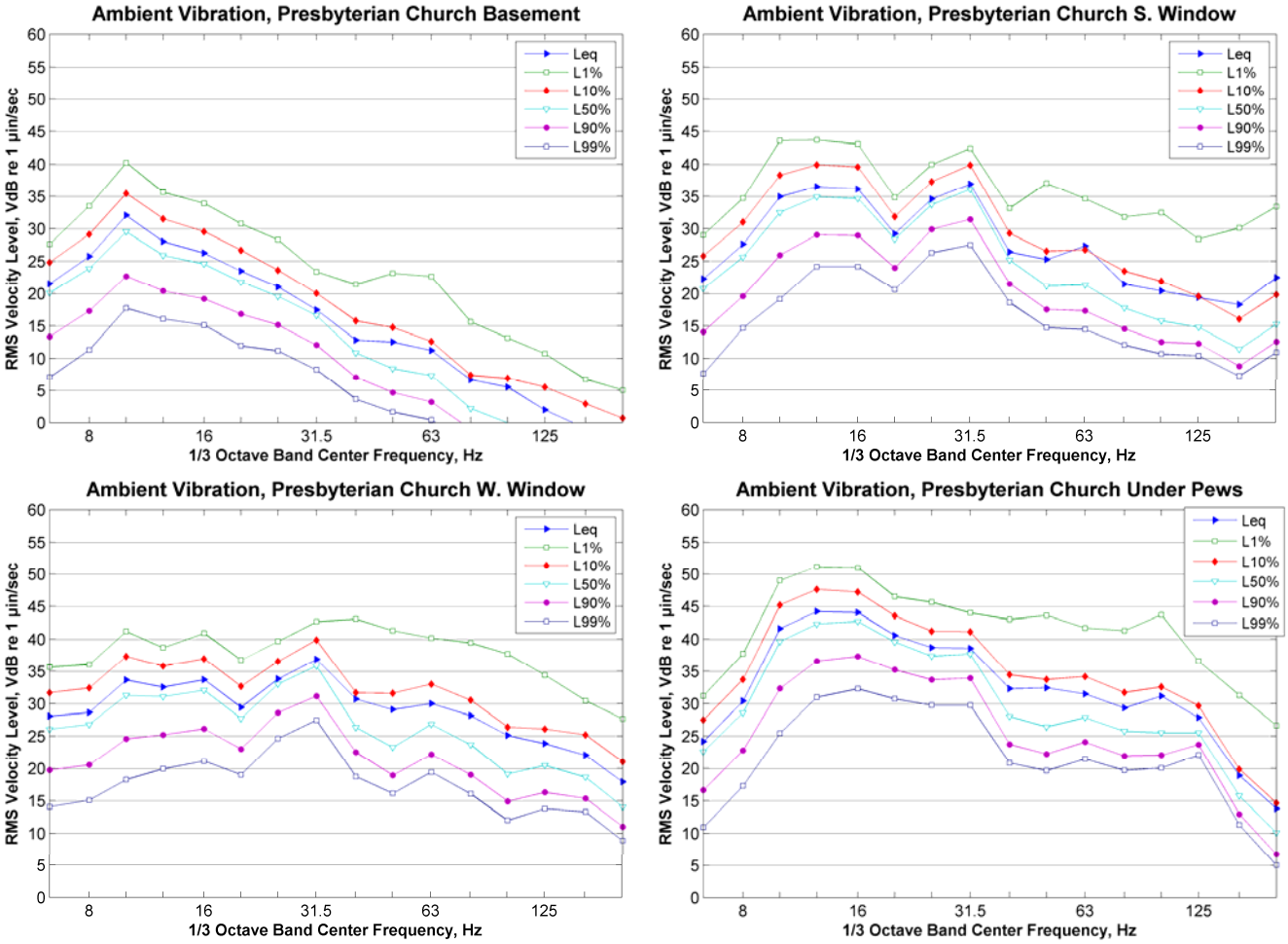


Figure 158: Ambient Vibration at Indoor LSTM Measurement Positions, Central Presbyterian Church

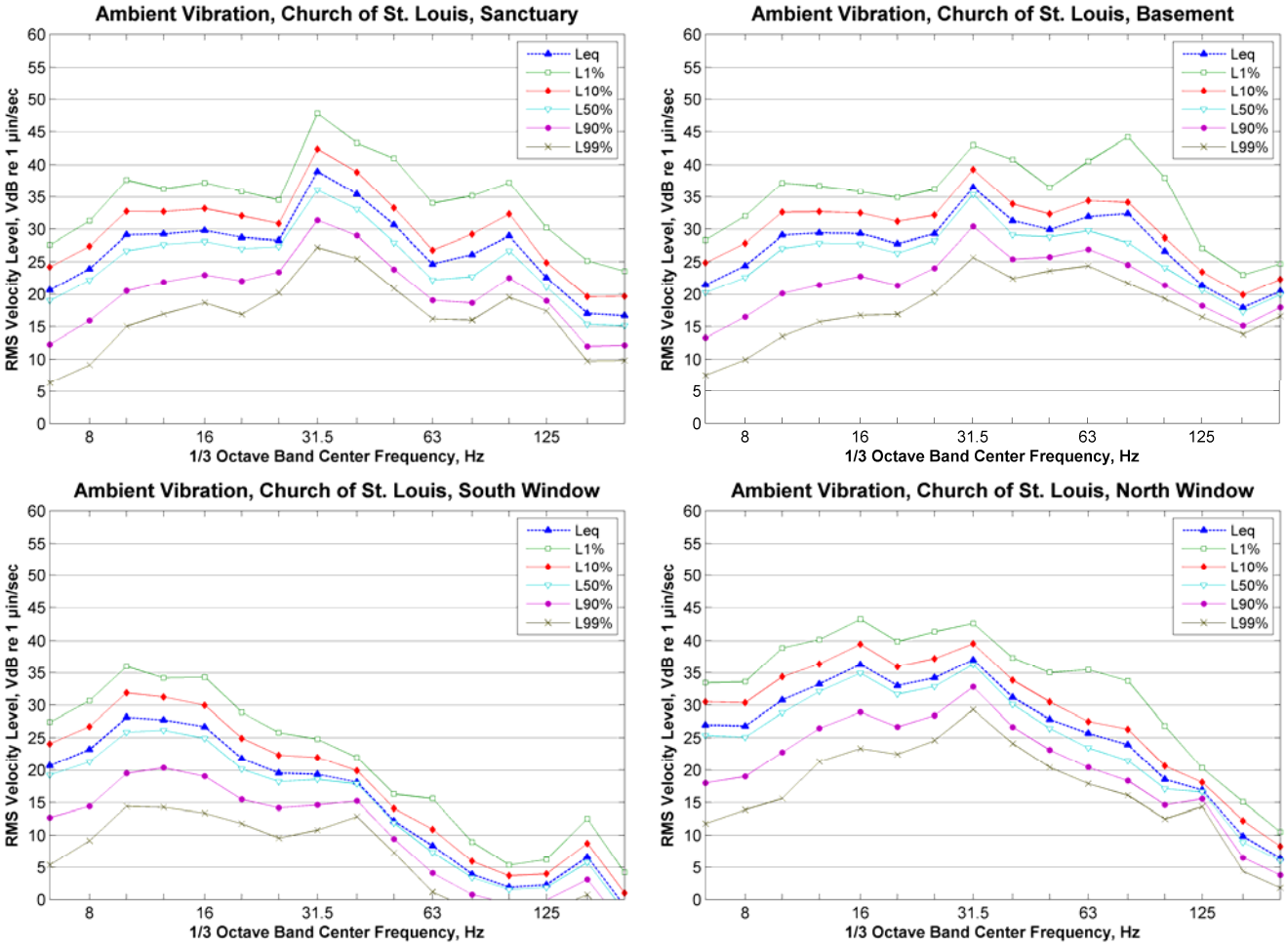
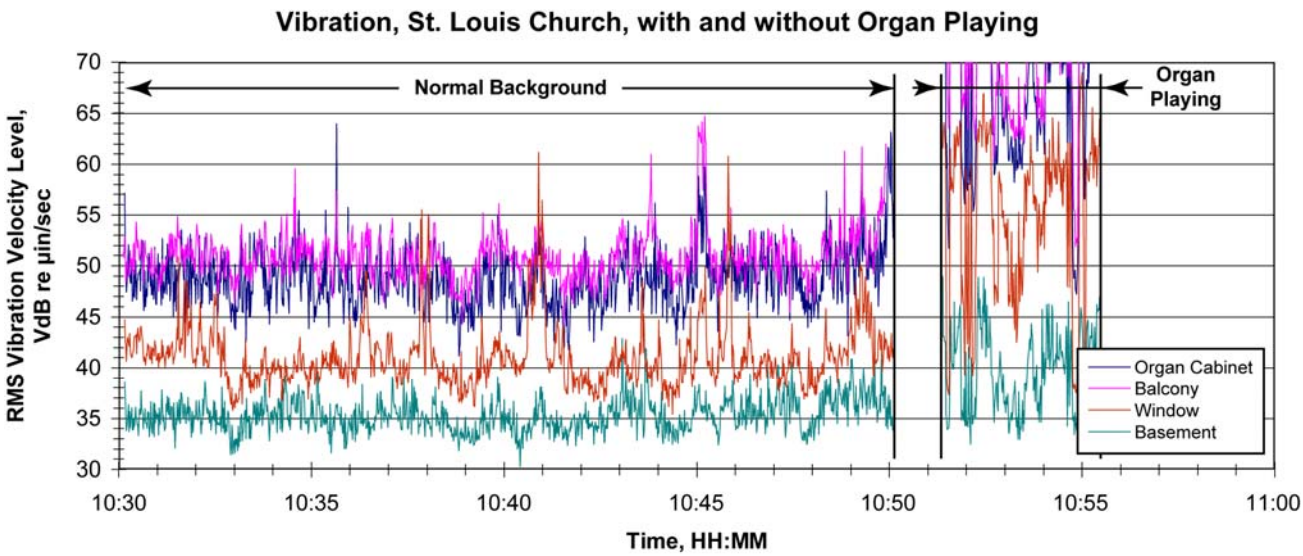
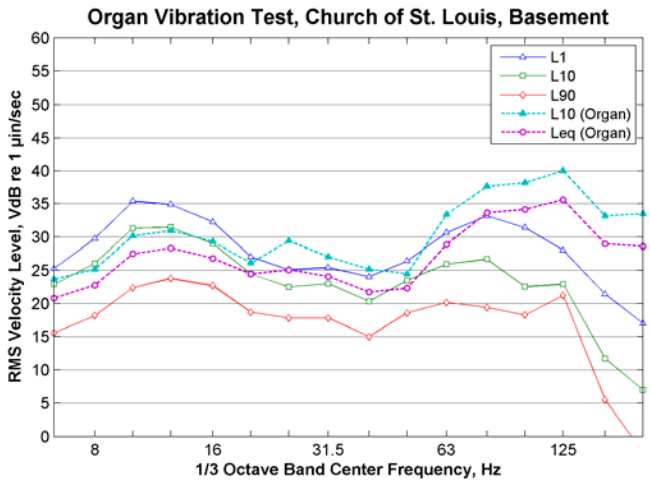
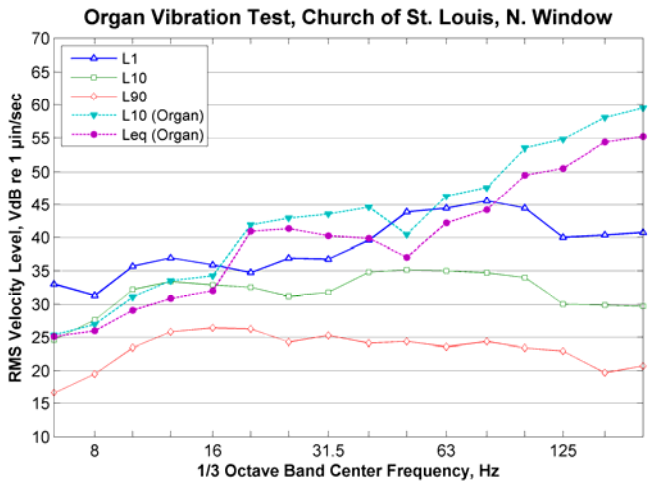


Figure 159: Ambient Vibration at Indoor LSTM Measurement Positions, Church of St. Louis


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


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


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

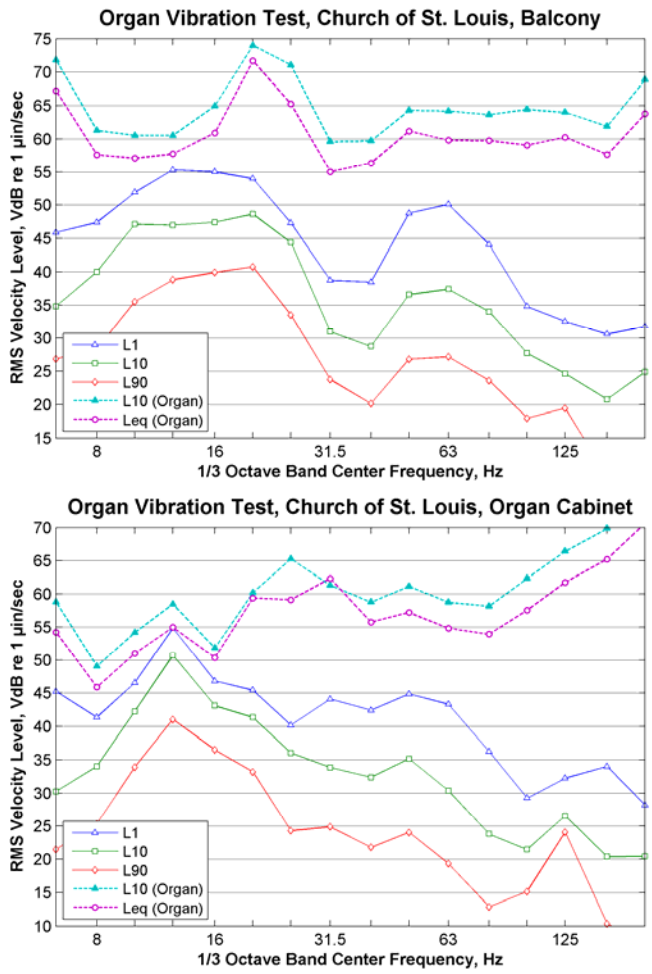


Figure 160: Ambient Vibration with and without Organ Music, Church of St. Louis
(The overall levels shown in the top graph are over the frequency range of 16 to 200 Hz.)

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.

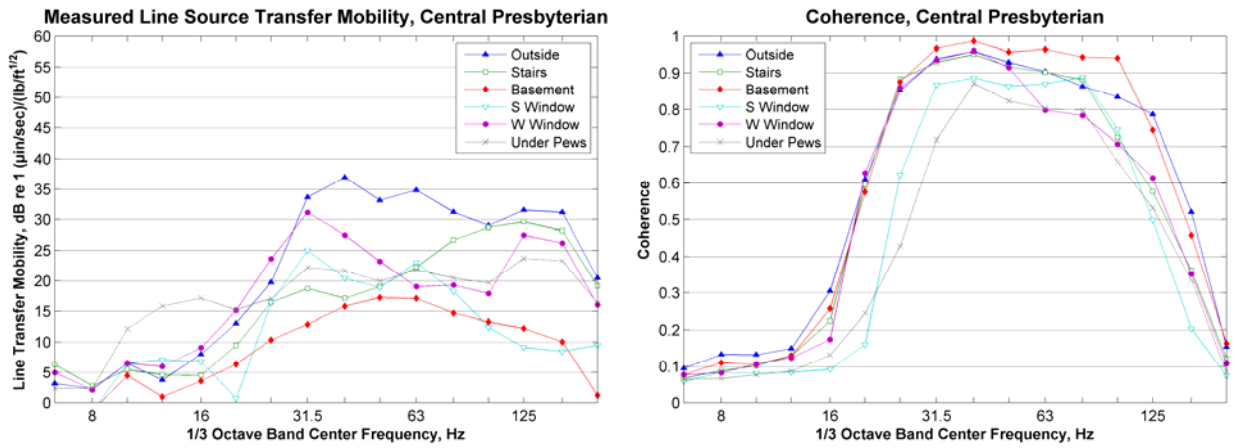


Figure 161: Measured Line Source Transfer Mobility, Central Presbyterian Church

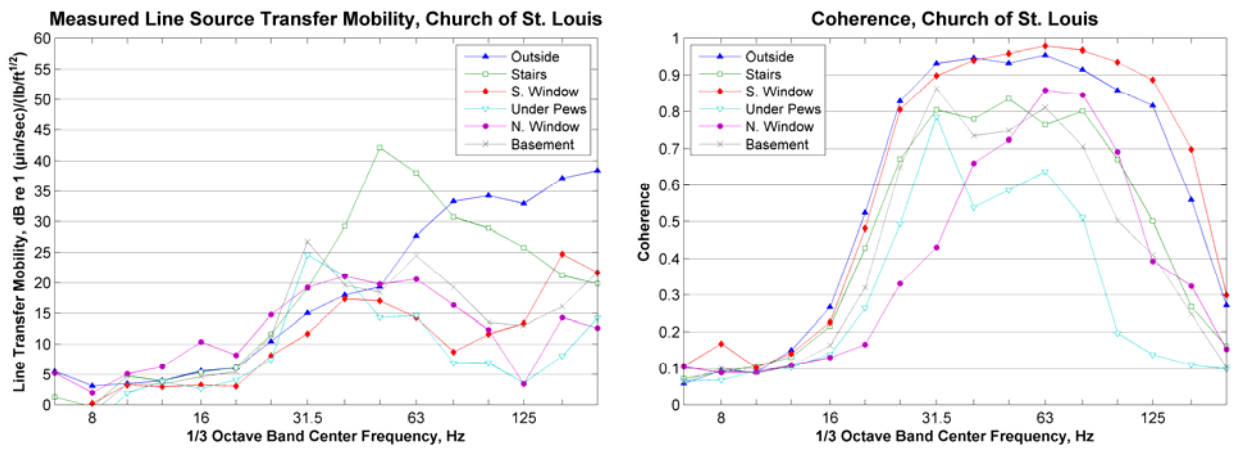


Figure 162: Measured Line Source Transfer Mobility, Church of St. Louis

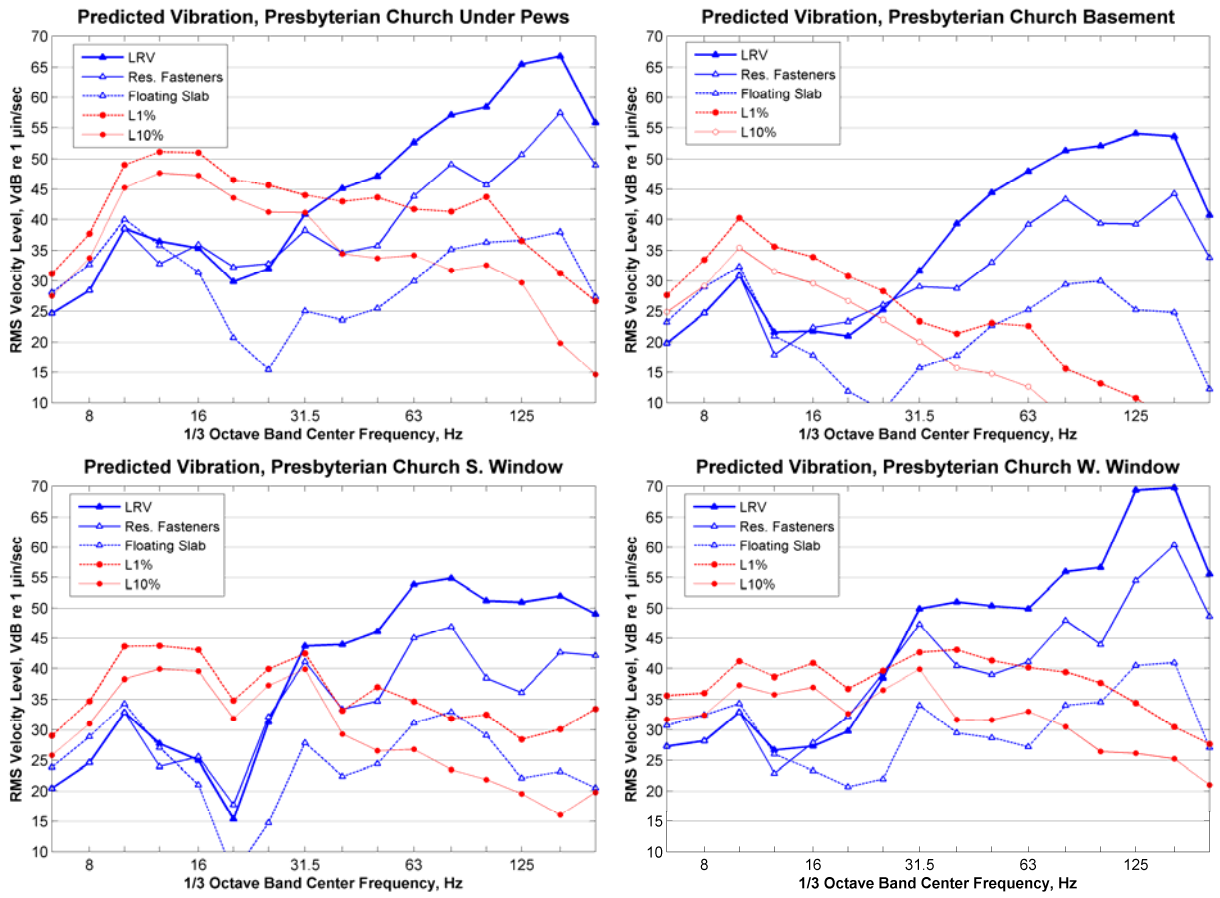


Figure 163: Predicted LRT Vibration, Central Presbyterian Church

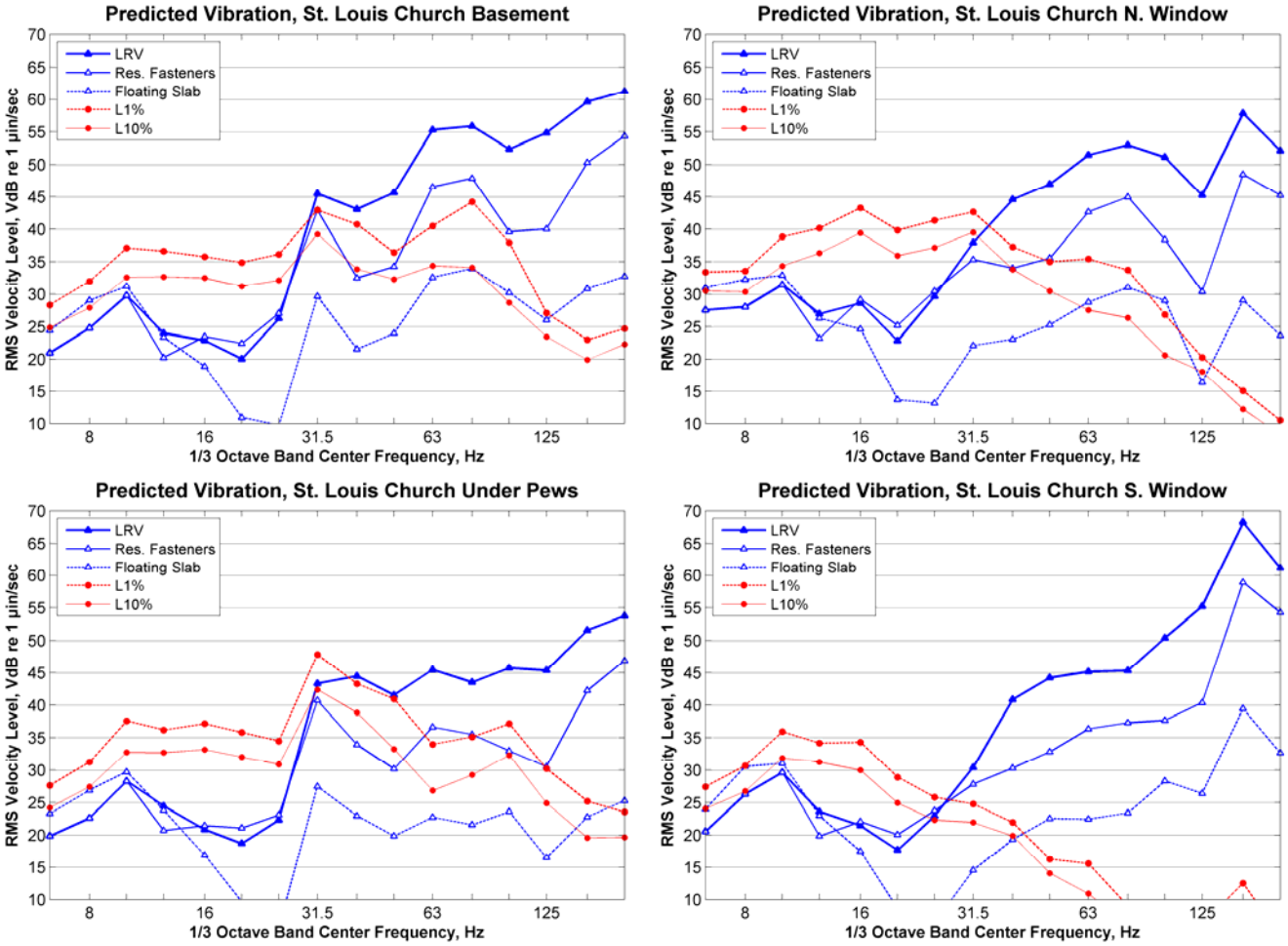


Figure 164: Predicted LRT Vibration, Church of Saint Louis

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.

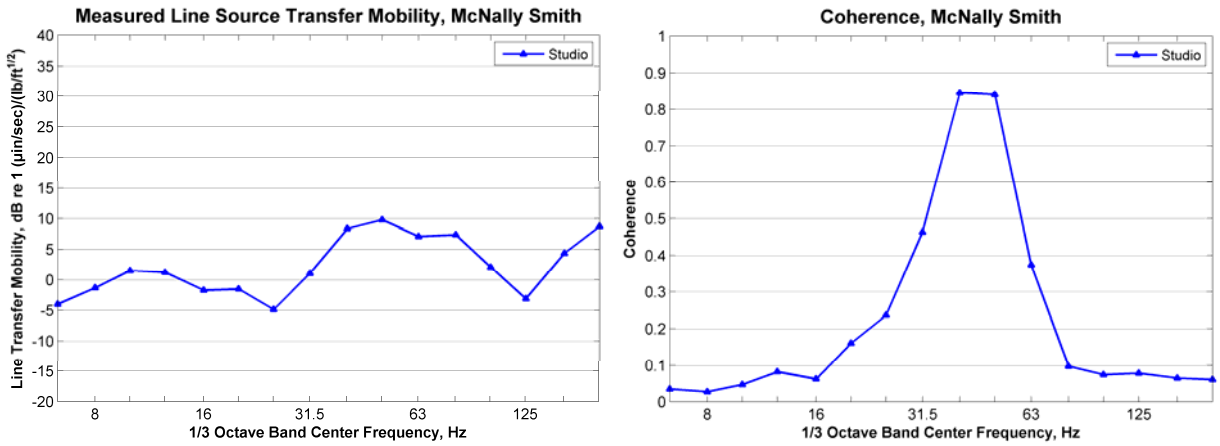


Figure 165: Measured LSTM & Coherence at McNally Smith Performance Center

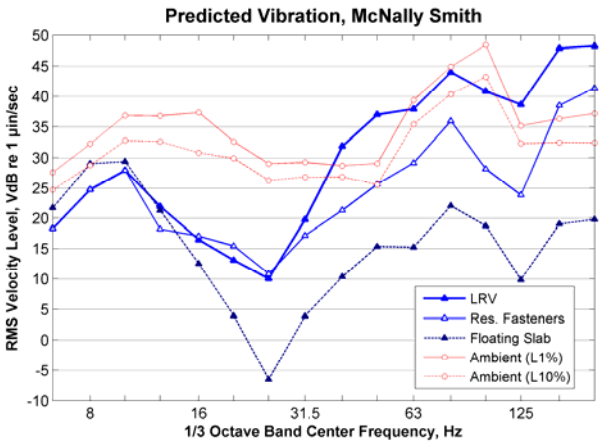


Figure 166: Predicted Vibration at McNally Smith Performance Center

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.

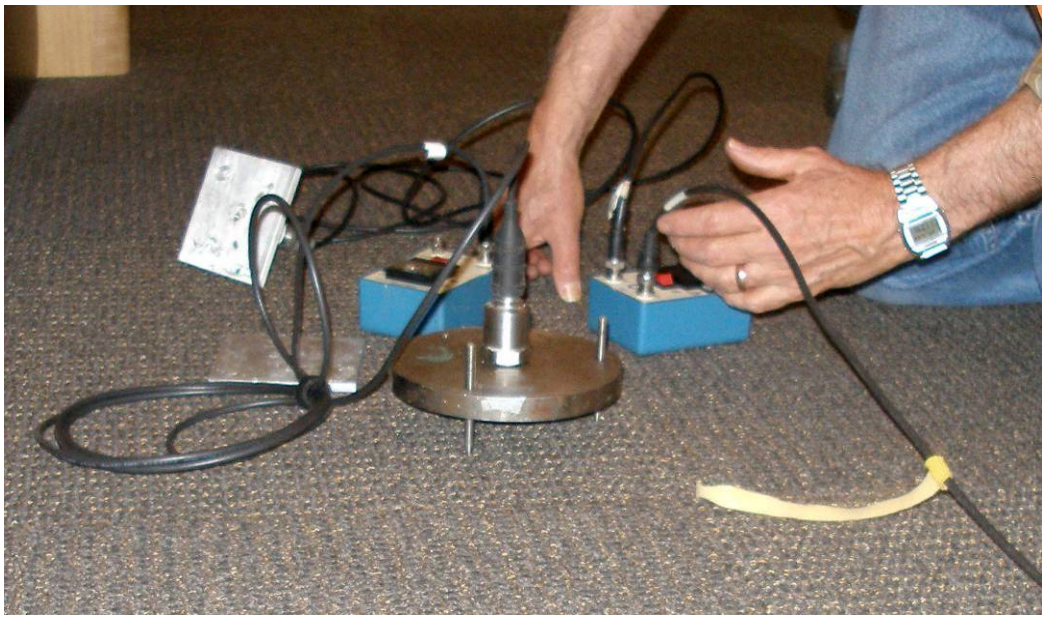


Figure 167: Installation of Accelerometer on Carpeted Floor

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.

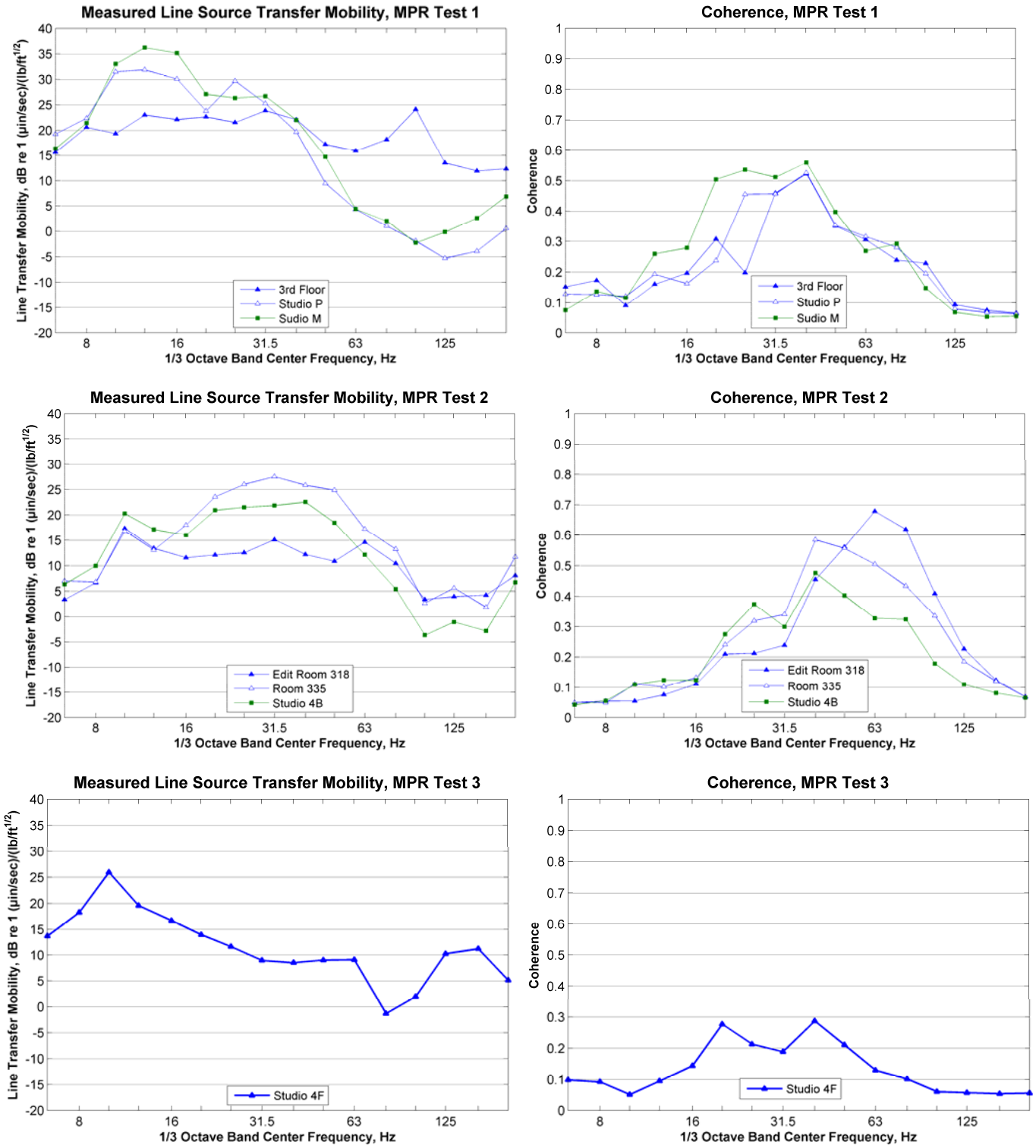


Figure 168: Measured Line Source Transfer Mobility, Tests MPR1, MPR2 and MPR3

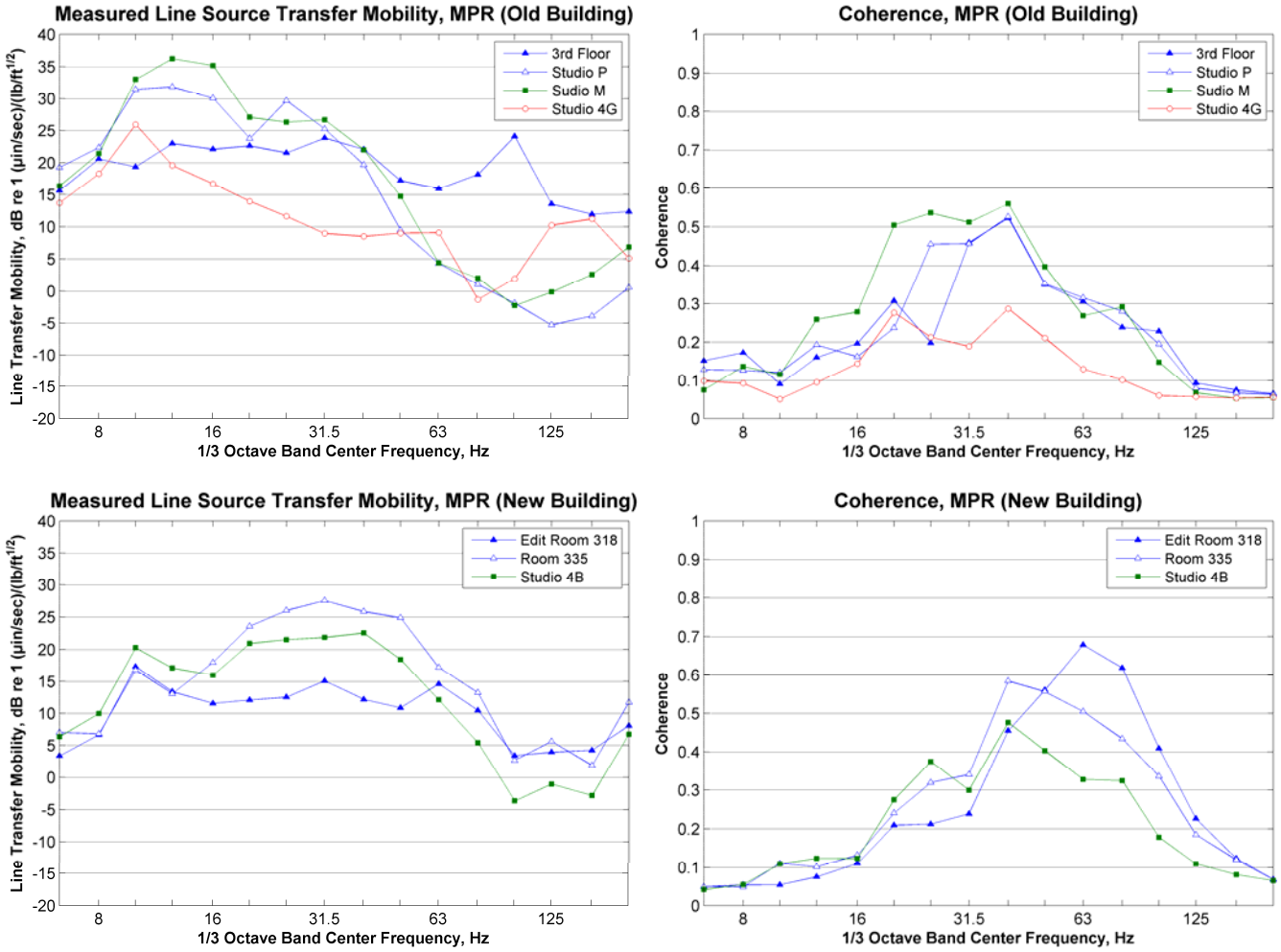


Figure 169: Comparison of LSTM Curves Measured Studios in Original and New MPR Buildings

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.

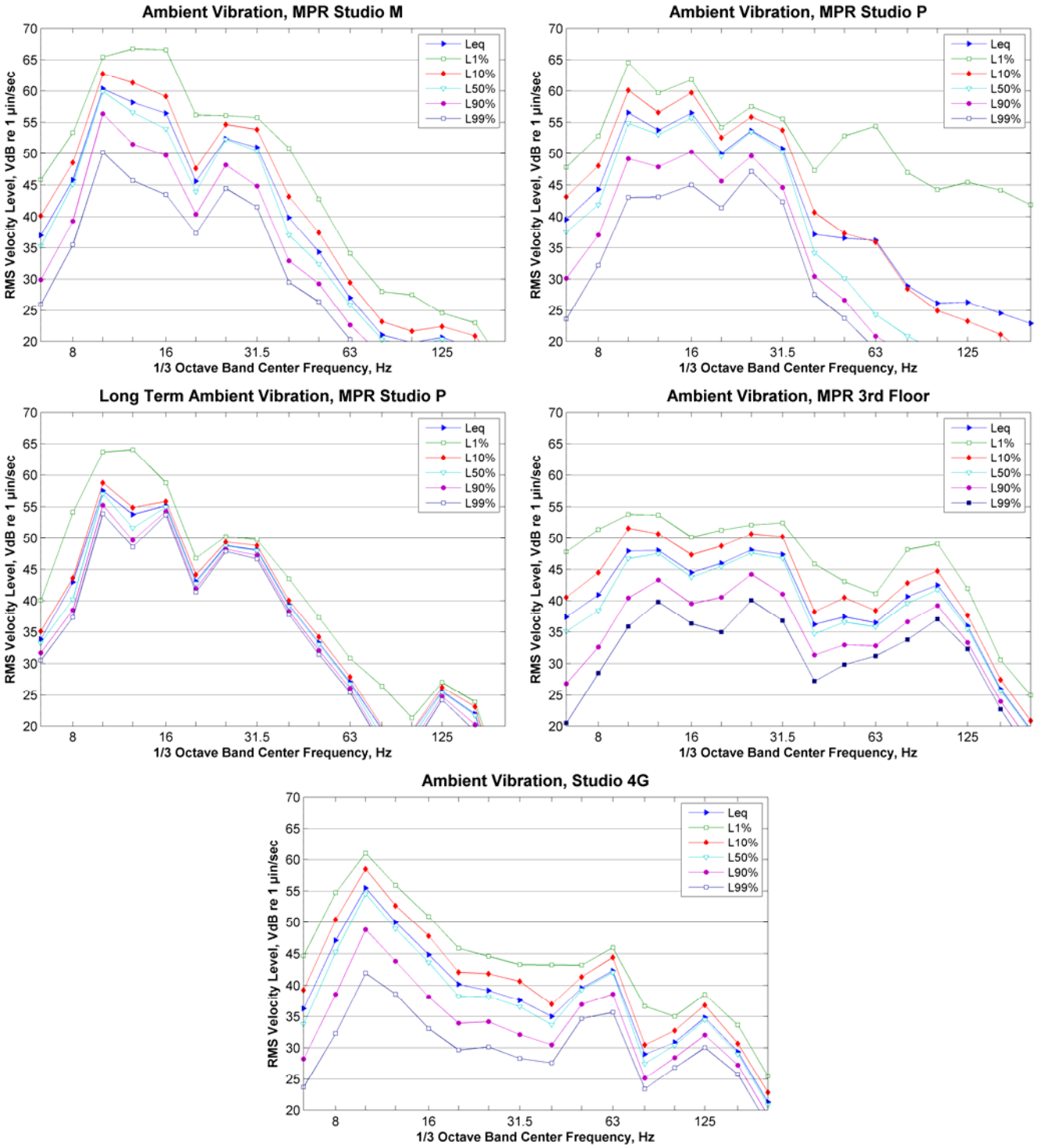


Figure 170: Ambient Vibration Measurements in Original MPR Building

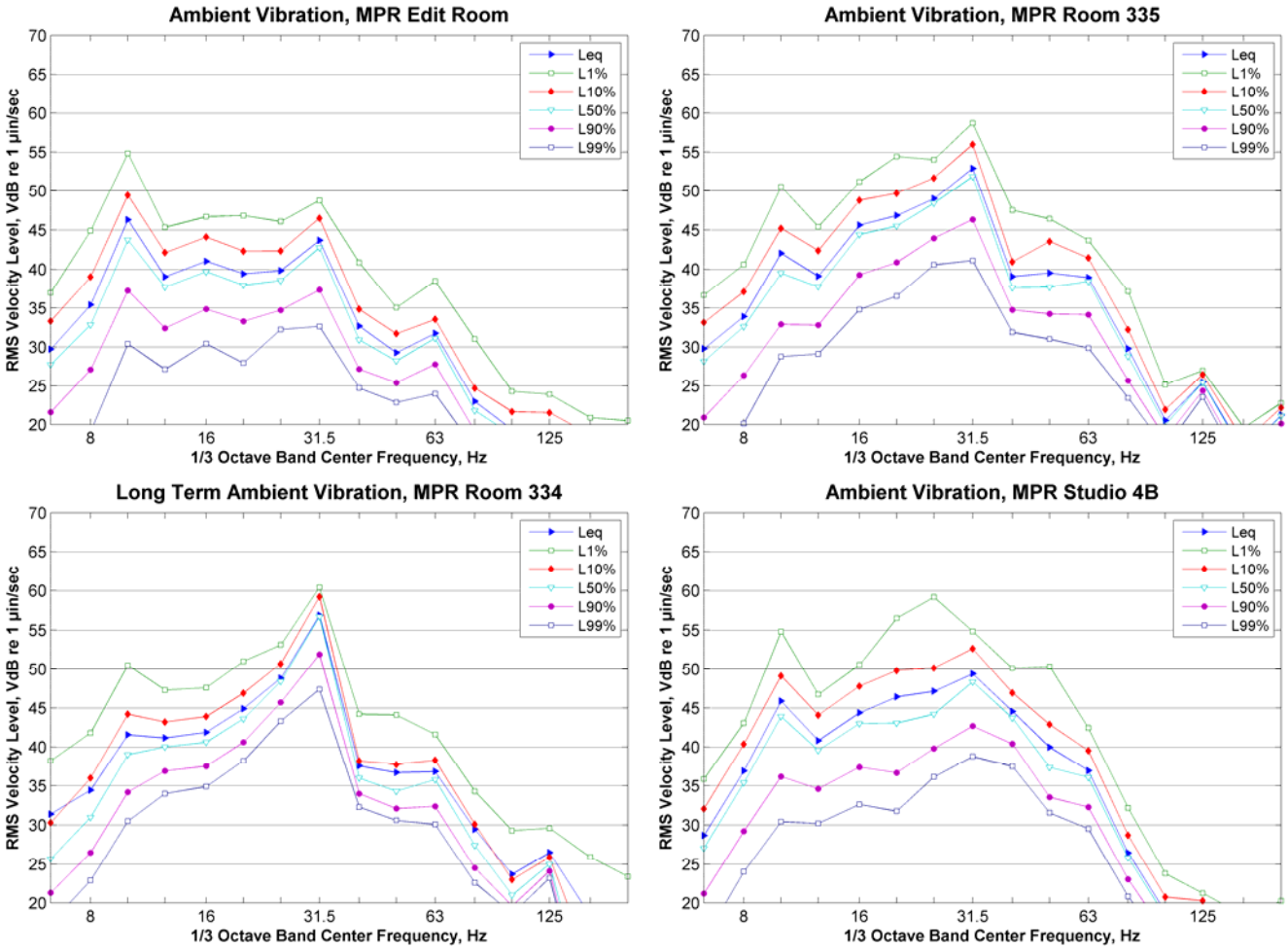


Figure 171: Ambient Vibration Measurements in New MPR Building

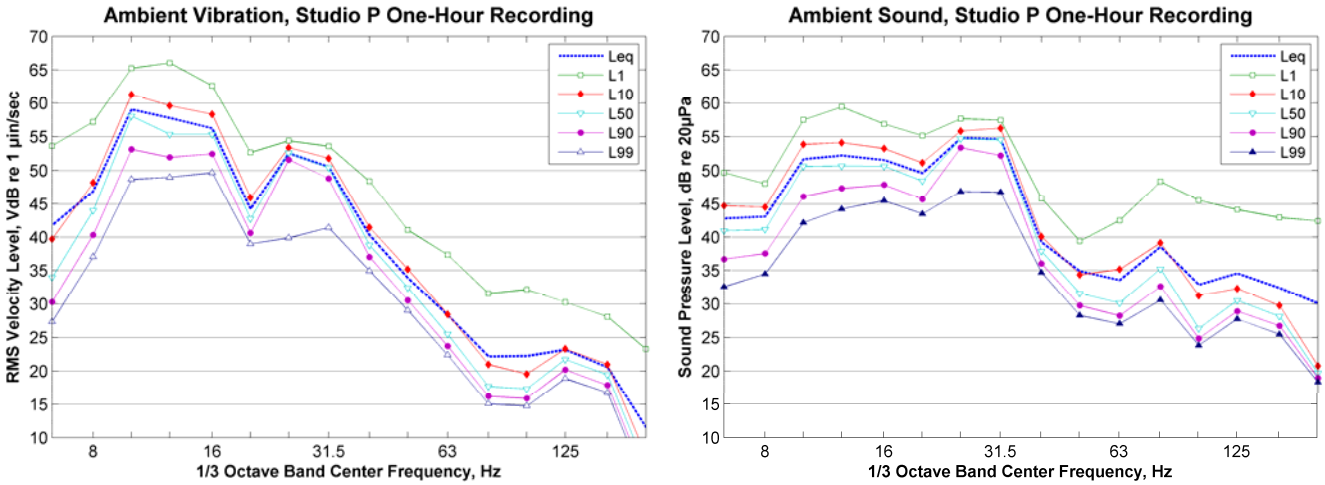
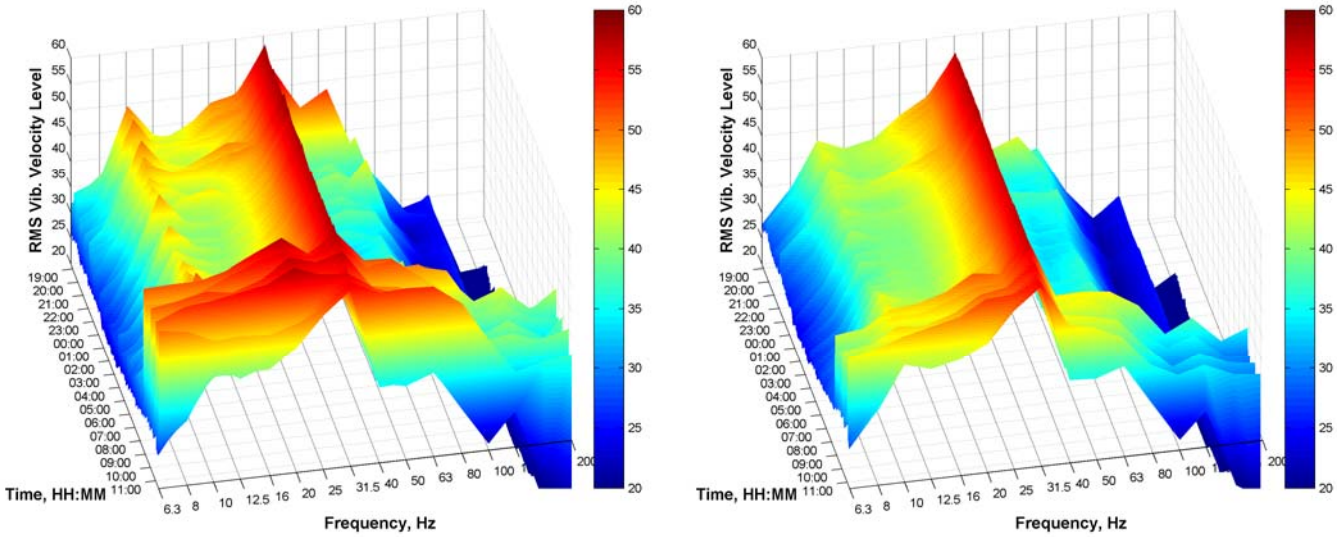
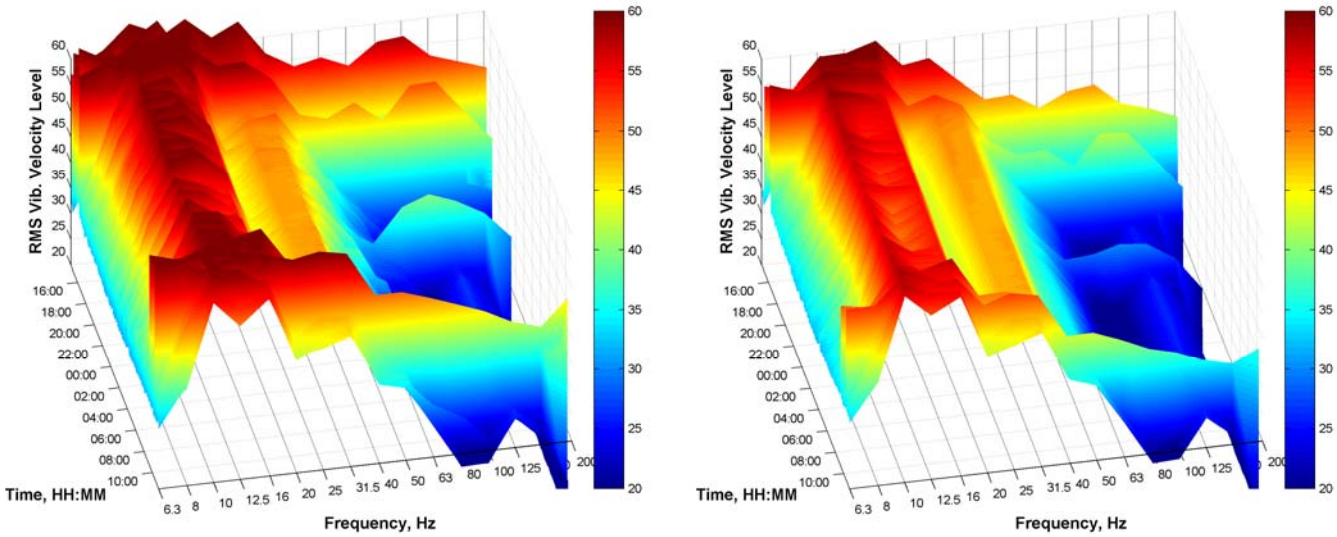


Figure 172: Statistics of Simultaneous Vibration and Sound Measurements inside Studio P



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.

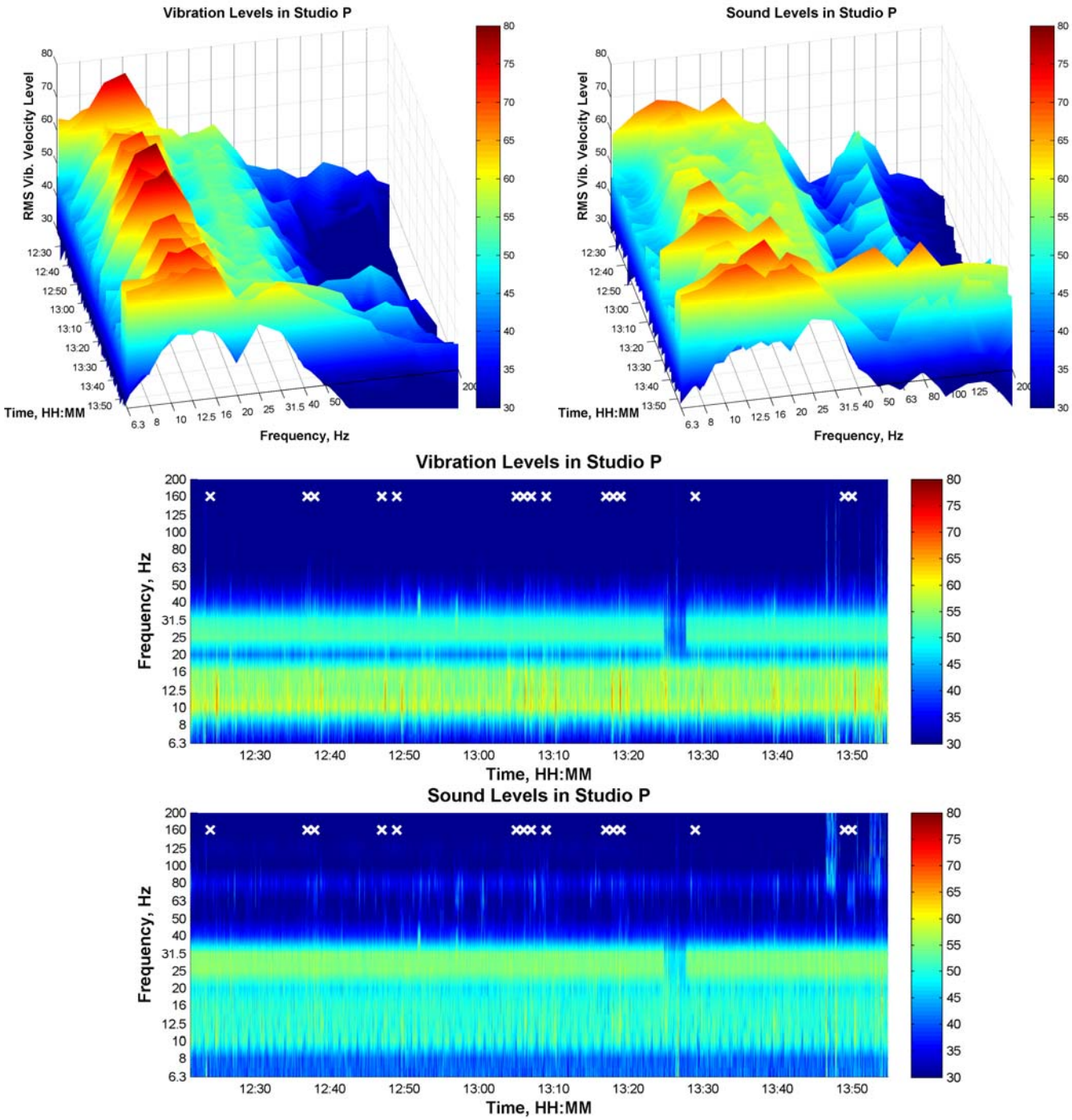


Figure 174: Detailed Results of Simultaneous Noise and Vibration Measurements in Studio P
The top graphs show the vibration levels on the left and the sound levels on the right in a 3D format. The lower two graphs show the same data in a spectrogram format. The horizontal axis is time, the vertical axis 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.

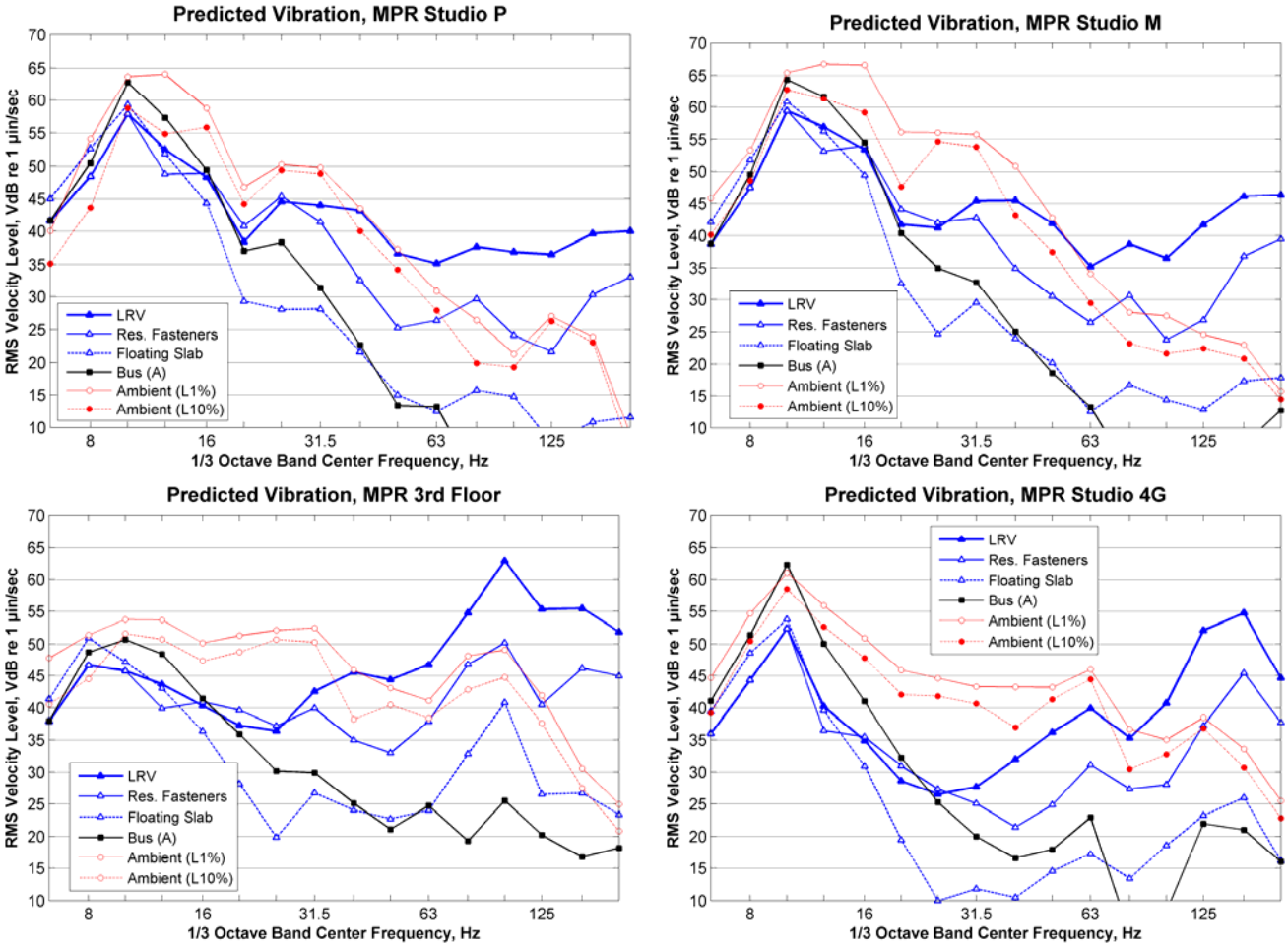


Figure 175: Predicted Vibration in Studios in Original Building

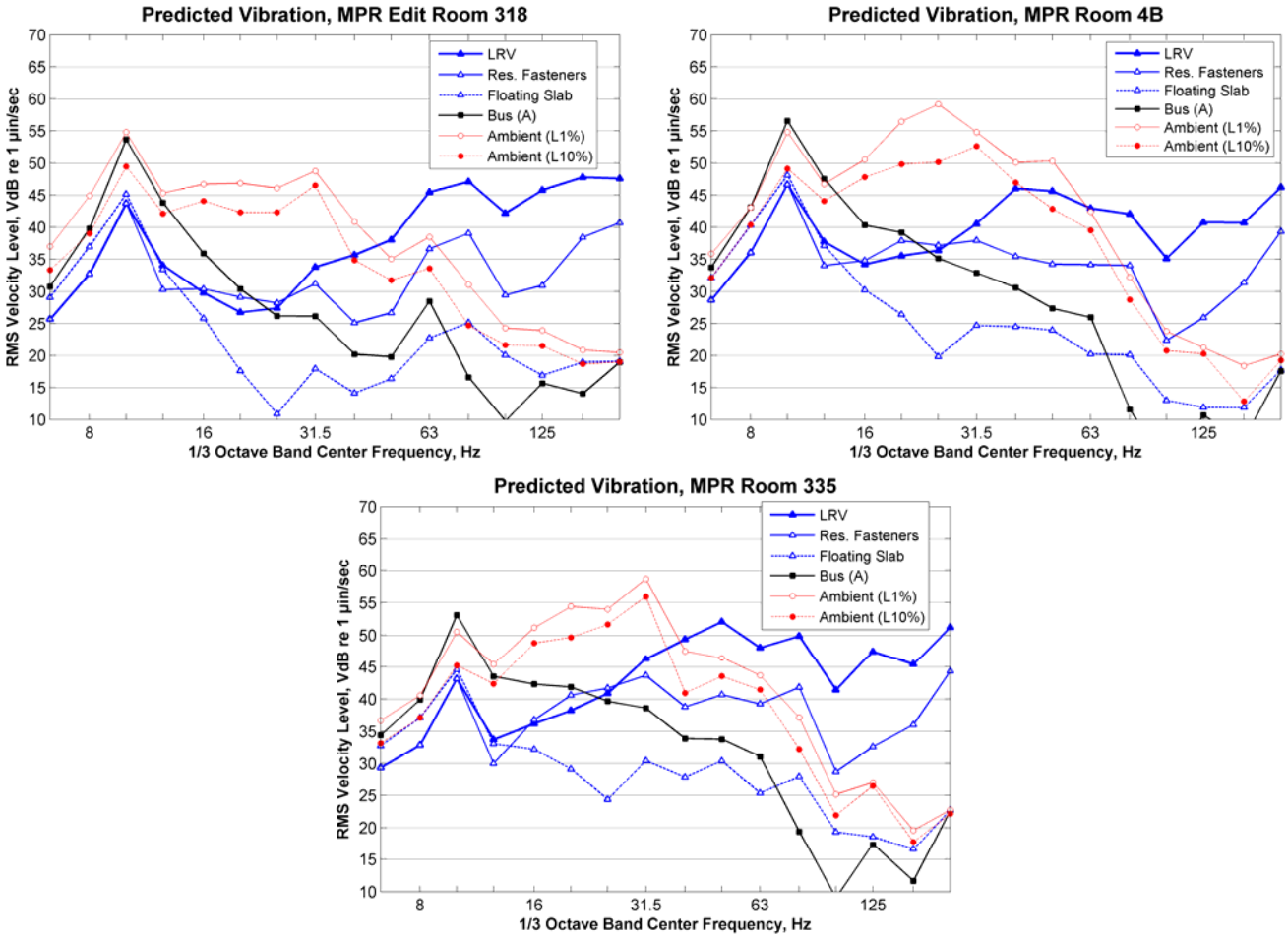


Figure 176: Predicted Vibration in Studios in New Building

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

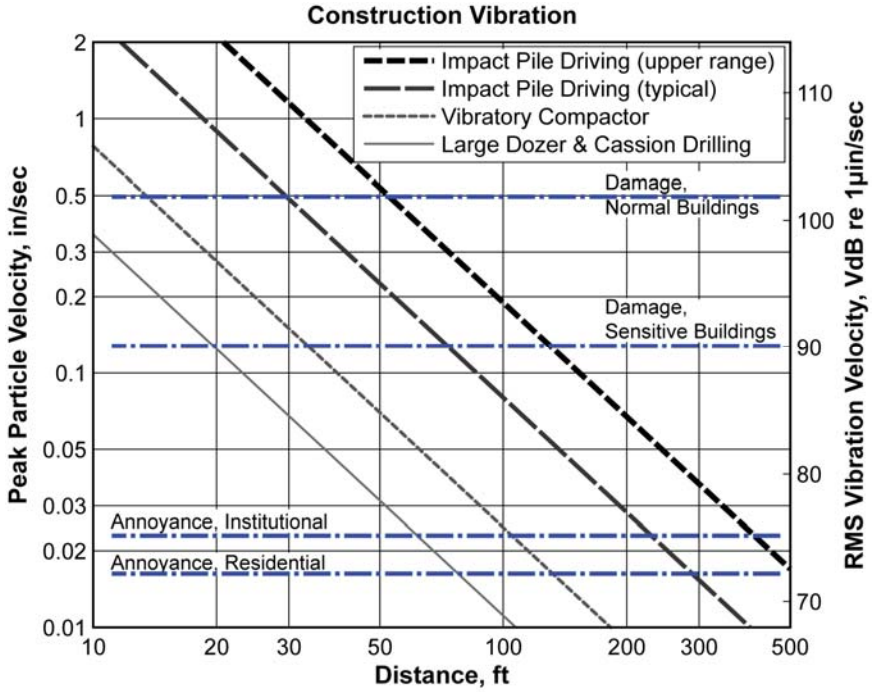


Figure 177: Typical Vibration Levels from Construction Equipment
(The right hand axis is the approximate RMS vibration velocity in decibels assuming a crest factor of 4.)

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)

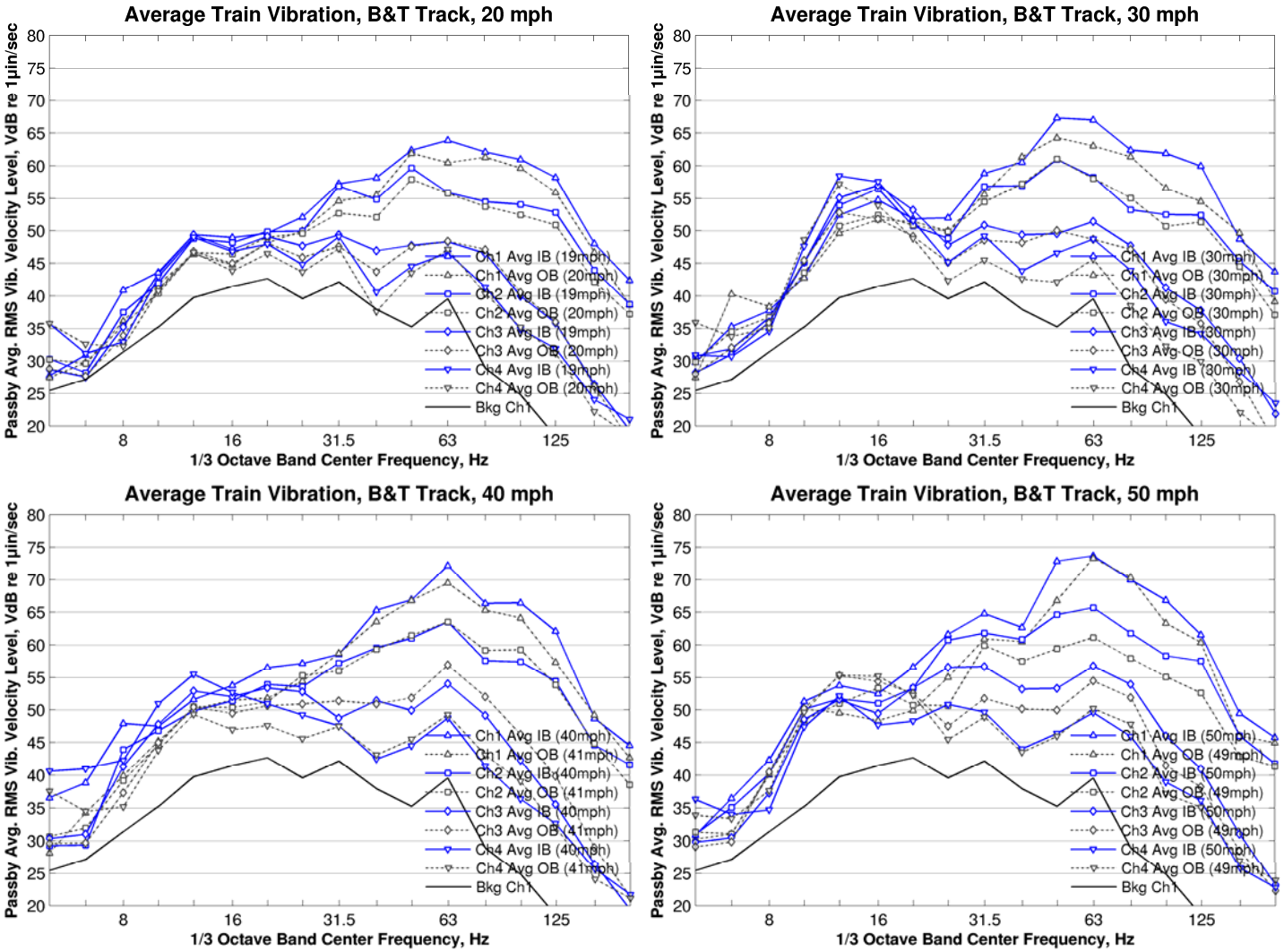


Figure 178: Average Vibration Spectra, Ballast & Tie Track

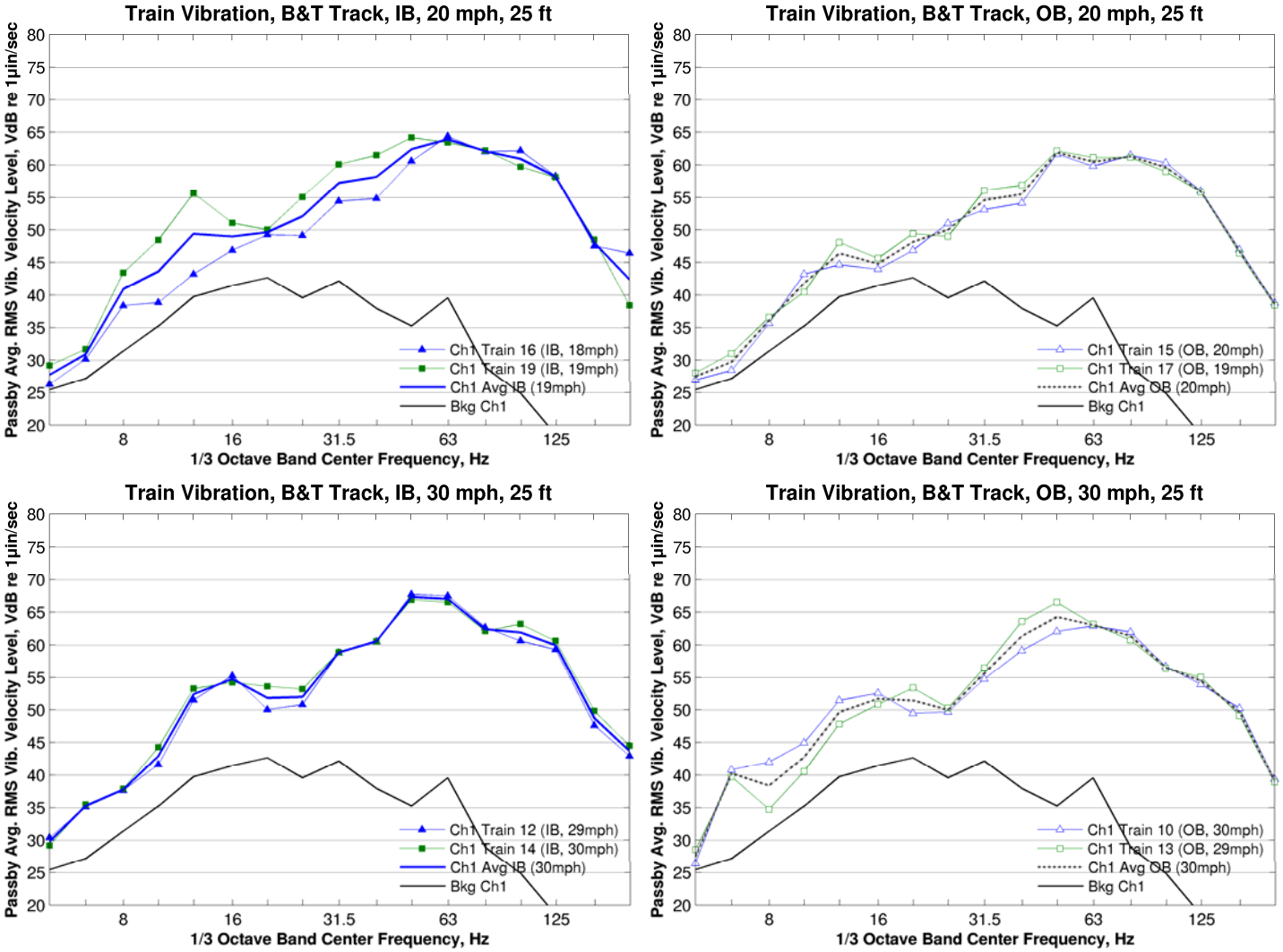


Figure 179: Vibration Spectra, Ballast & Tie Track, 25 ft, 20 and 30 mph

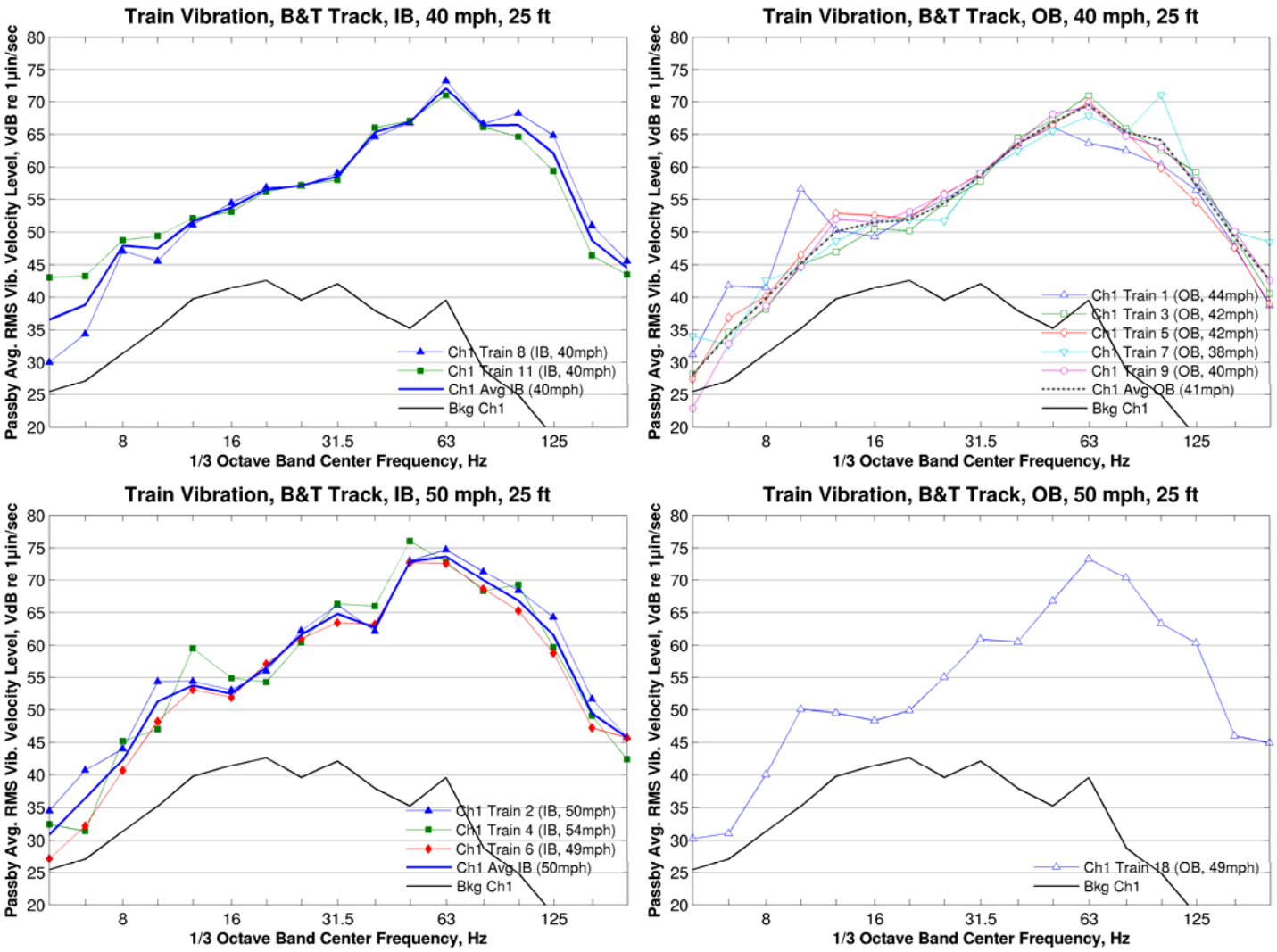


Figure 180: Vibration Spectra, Ballast & Tie Track, 25 ft, 40 and 50 mph

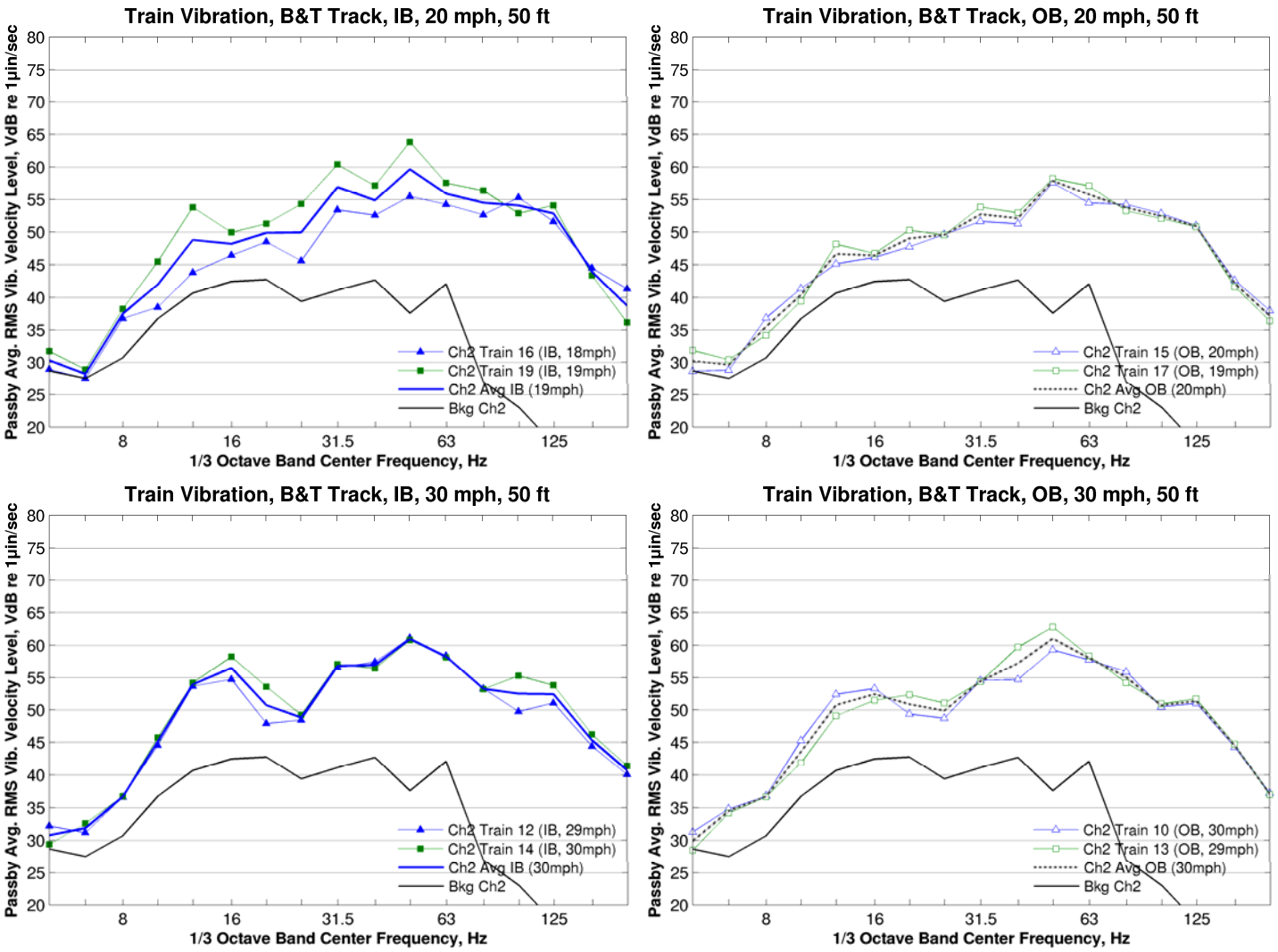


Figure 181: Vibration Spectra, Ballast & Tie Track, 50 ft, 20 and 30 mph

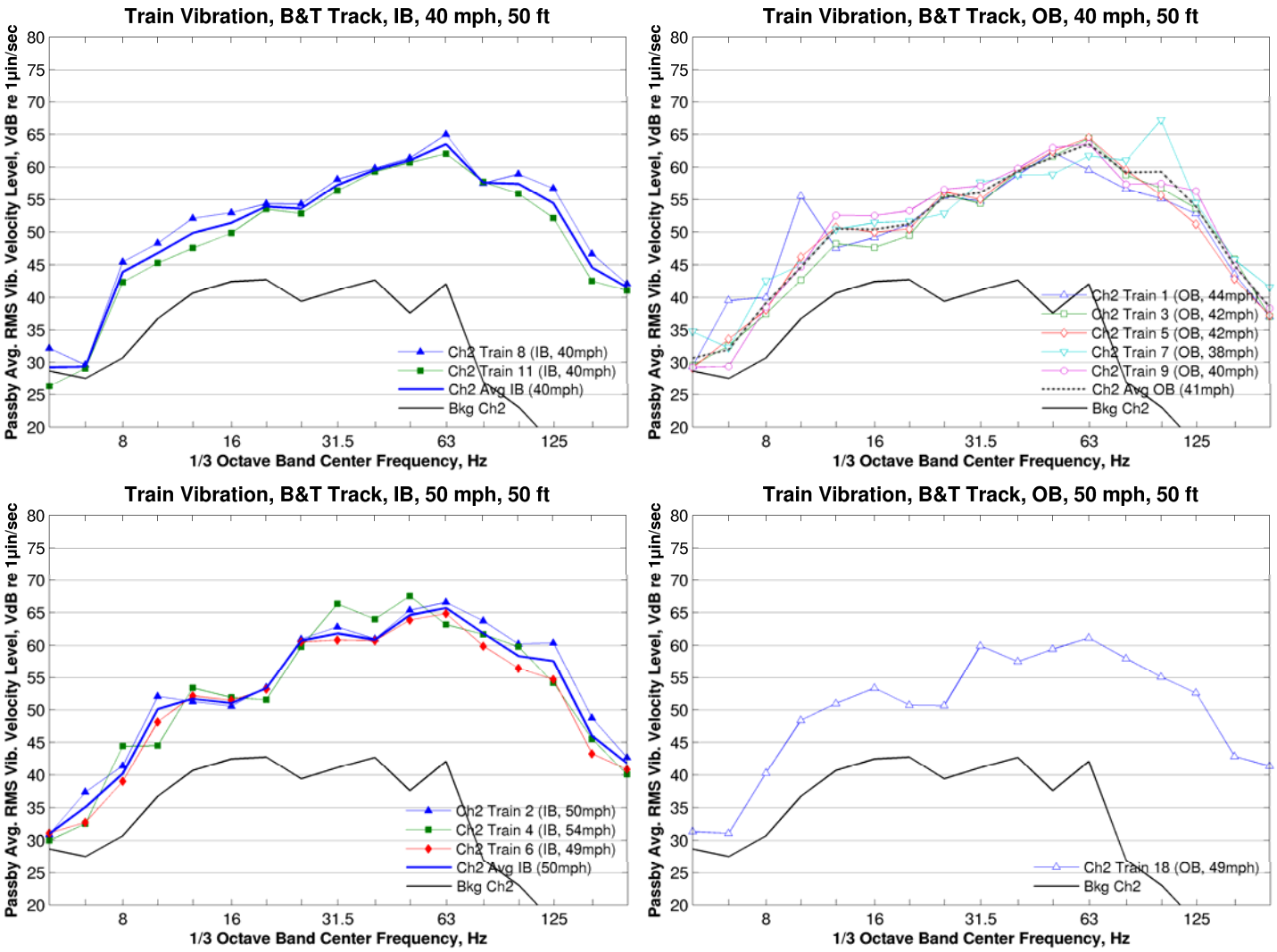


Figure 182: Vibration Spectra, Ballast & Tie Track, 50 ft, 40 and 50 mph

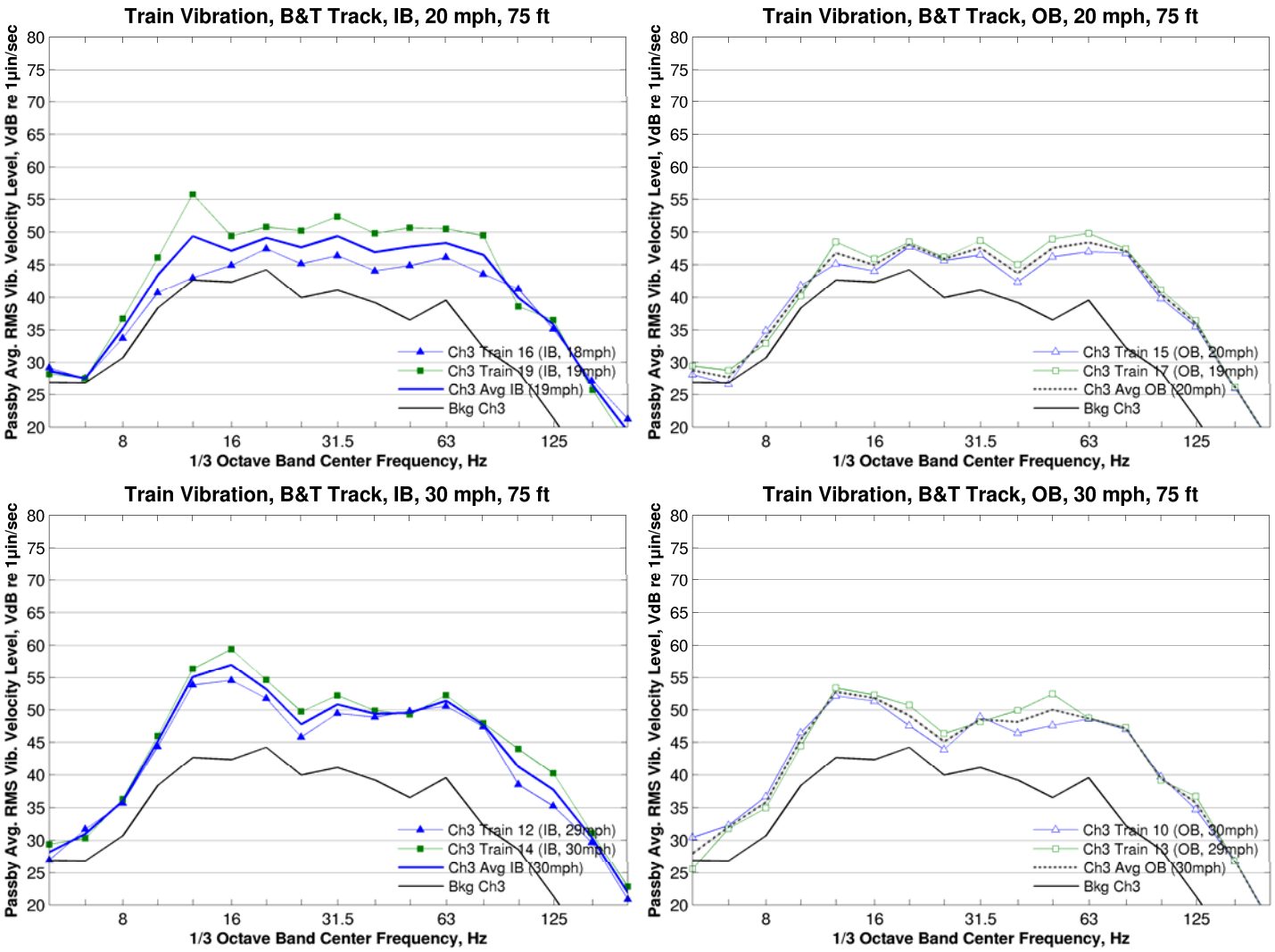


Figure 183: Vibration Spectra, Ballast & Tie Track, 75 ft, 20 and 30 mph

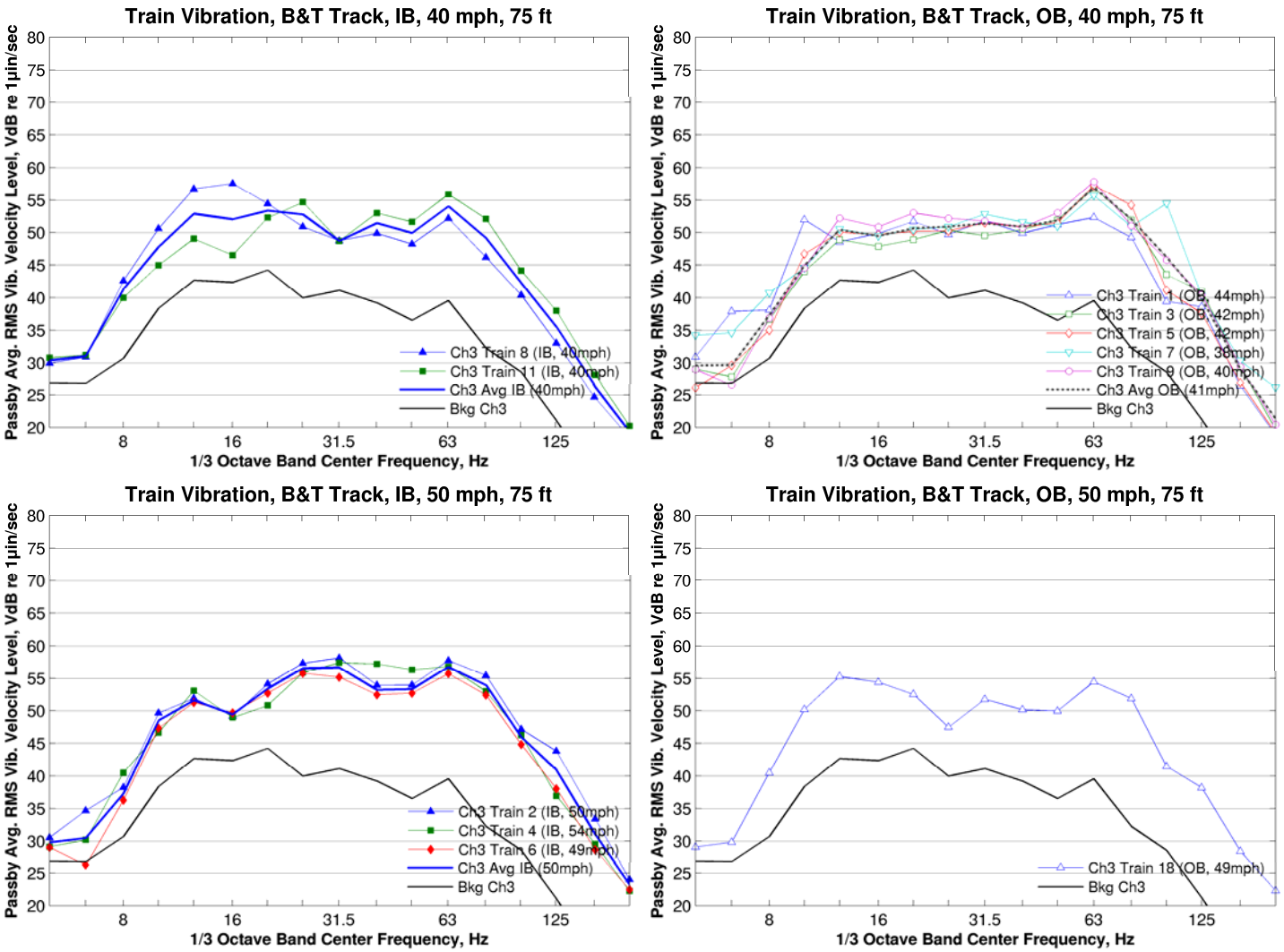


Figure 184: Vibration Spectra, Ballast & Tie Track, 75 ft, 40 and 50 mph

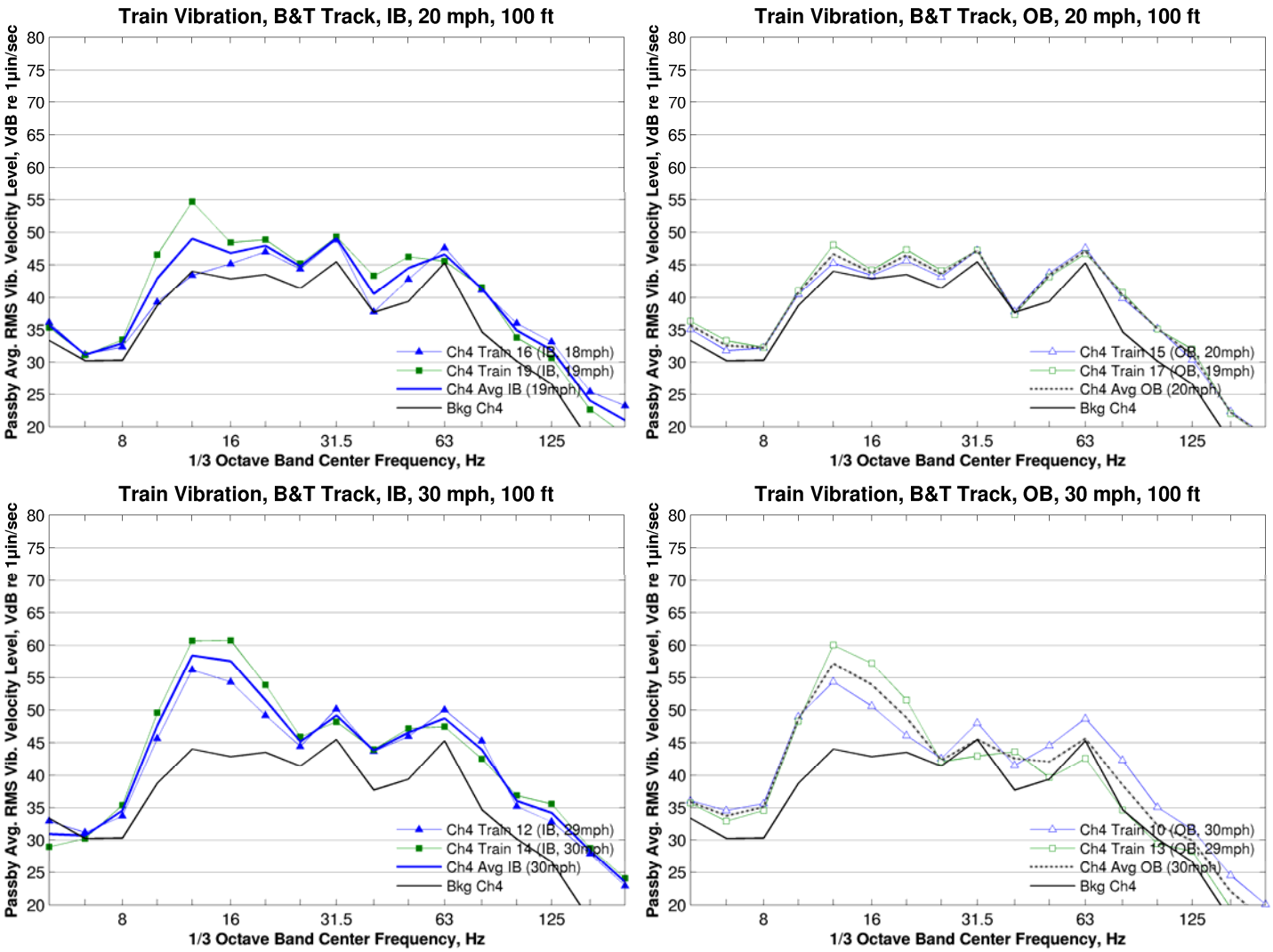


Figure 185: Vibration Spectra, Ballast & Tie Track, 100 ft, 20 and 30 mph

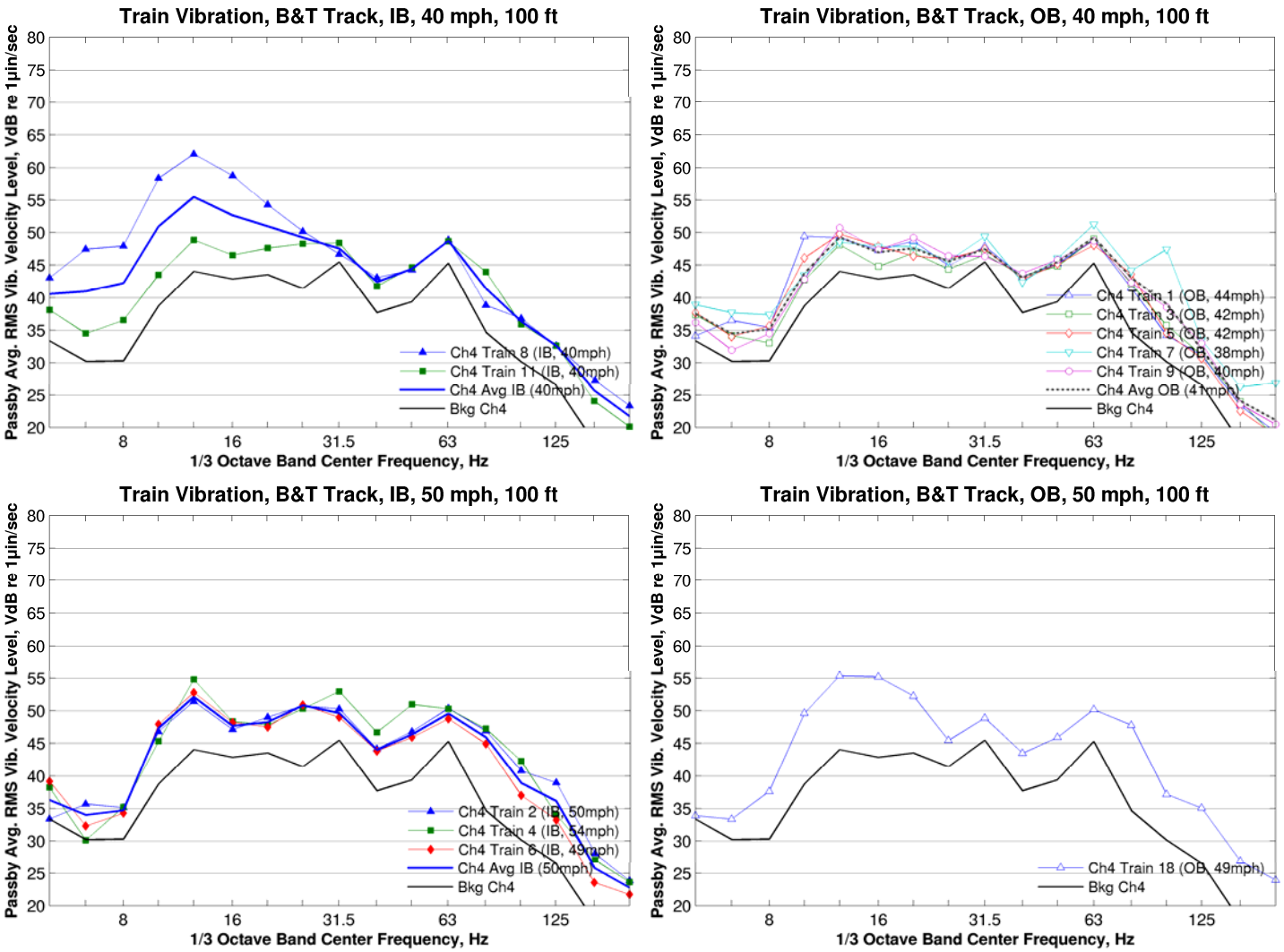


Figure 186: Vibration Spectra, Ballast & Tie Track, 100 ft, 40 and 50 mph

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

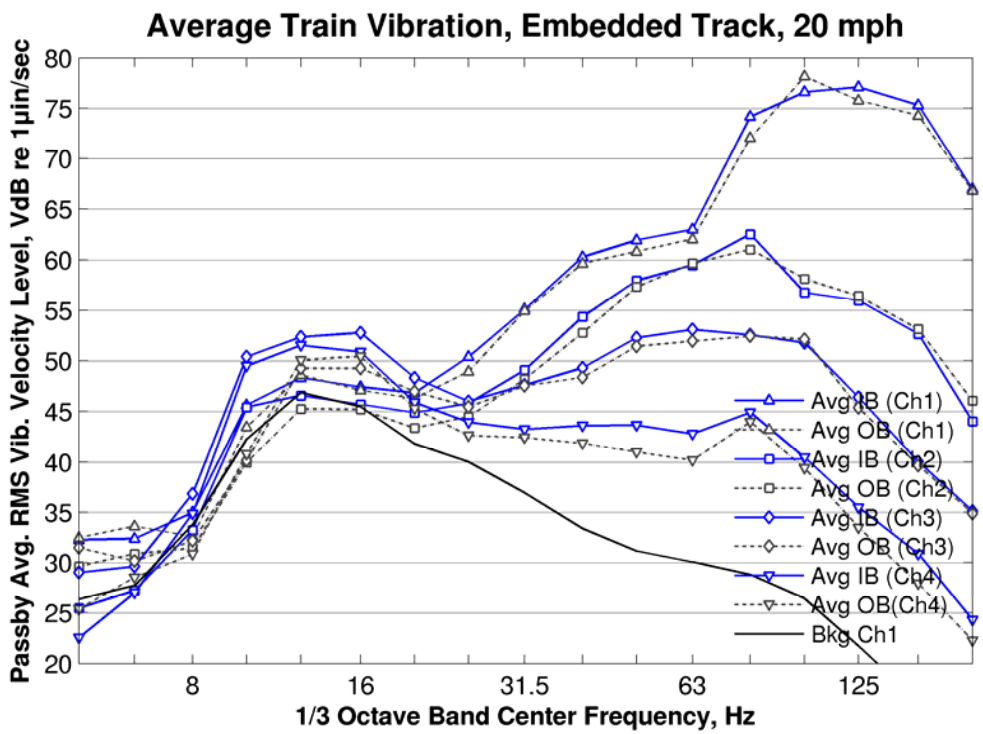


Figure 187: Average Vibration Spectra, 5th Street and 5th Avenue Embedded Track

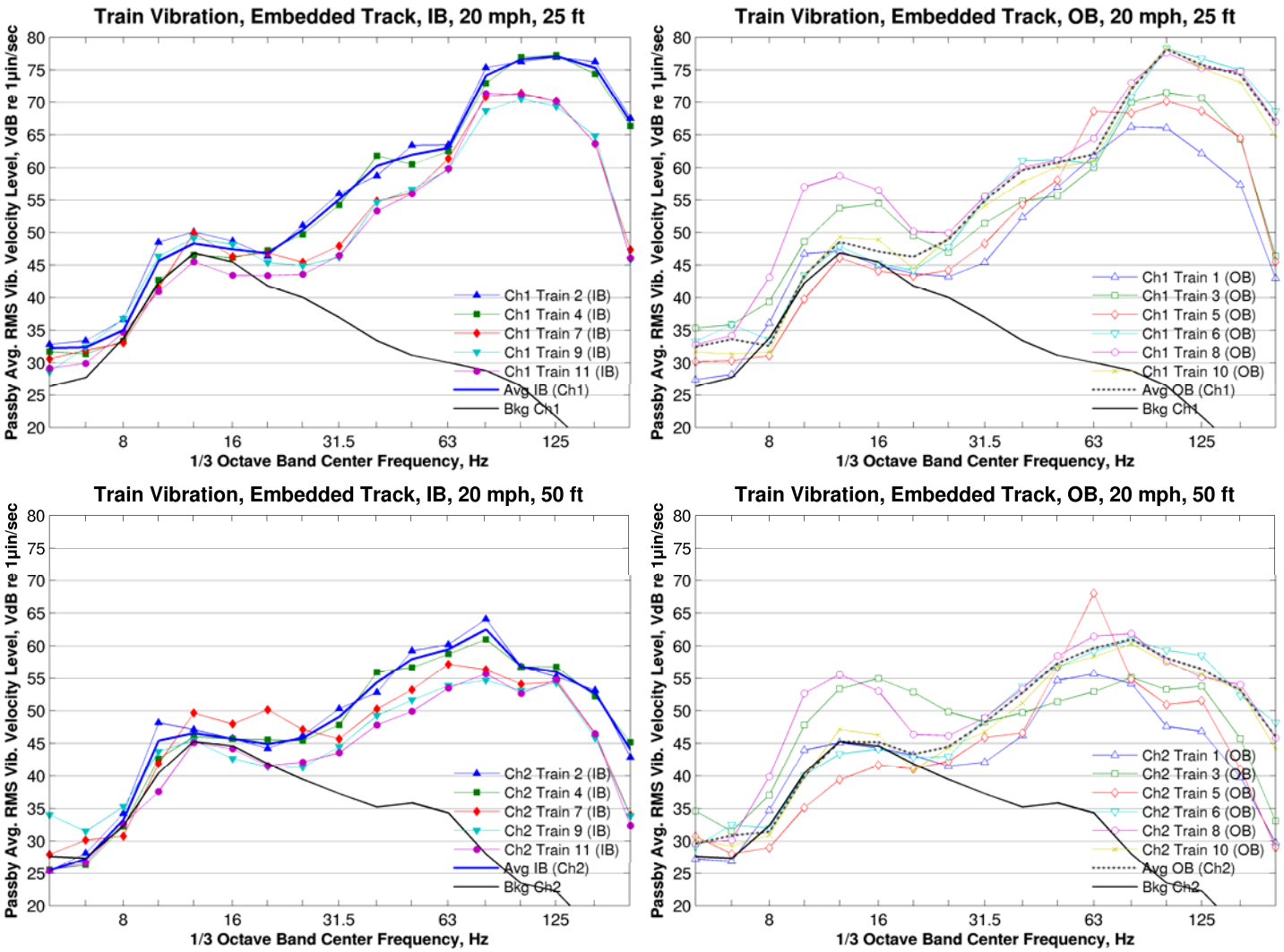


Figure 188: Vibration Spectra, 5th Street and 5th Avenue Embedded Track, 25 and 50 ft, 20 mph

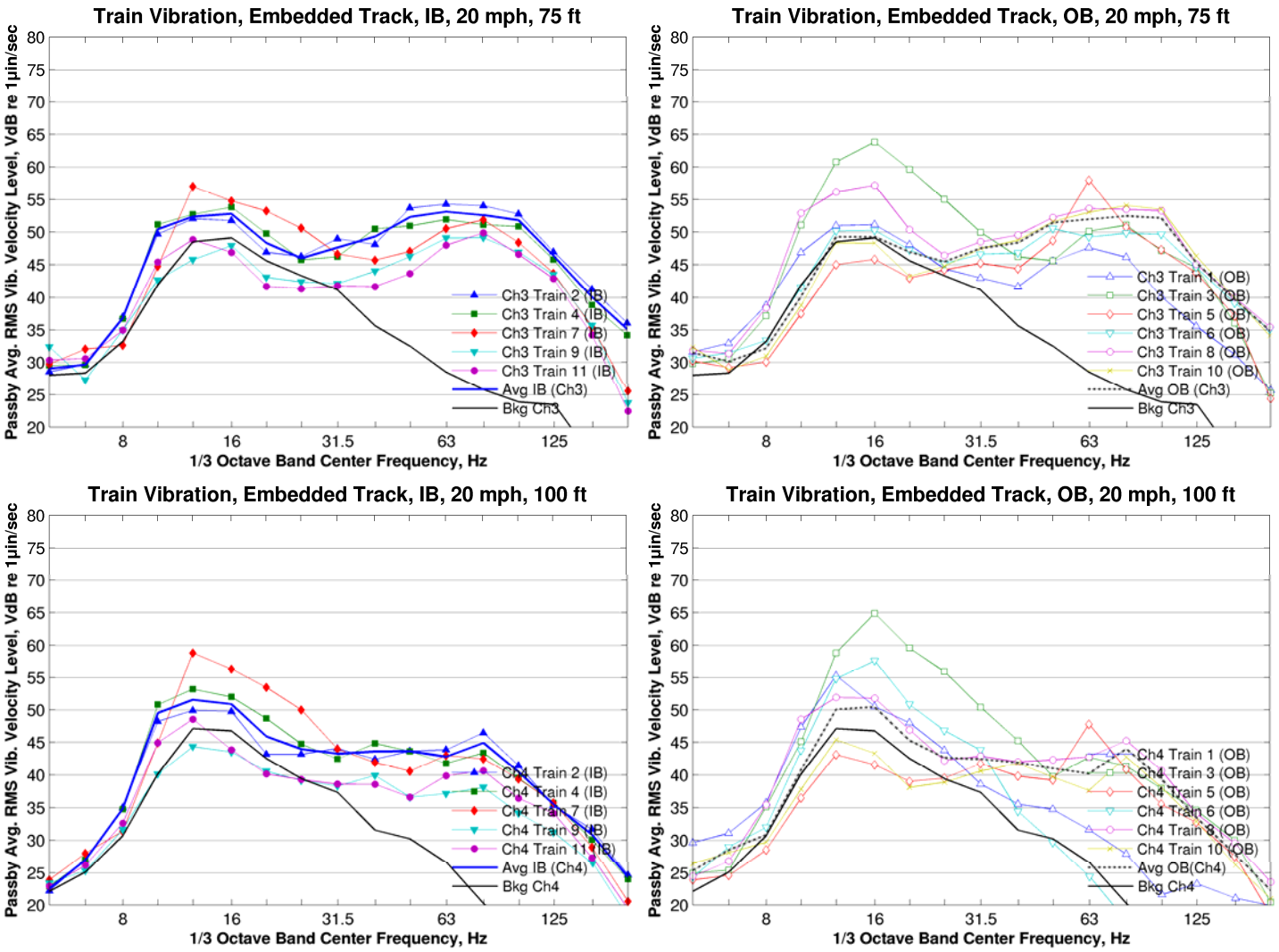


Figure 189: Vibration Spectra, 5th Street and 5th Avenue Embedded Track, 75 and 100 ft, 20 mph

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

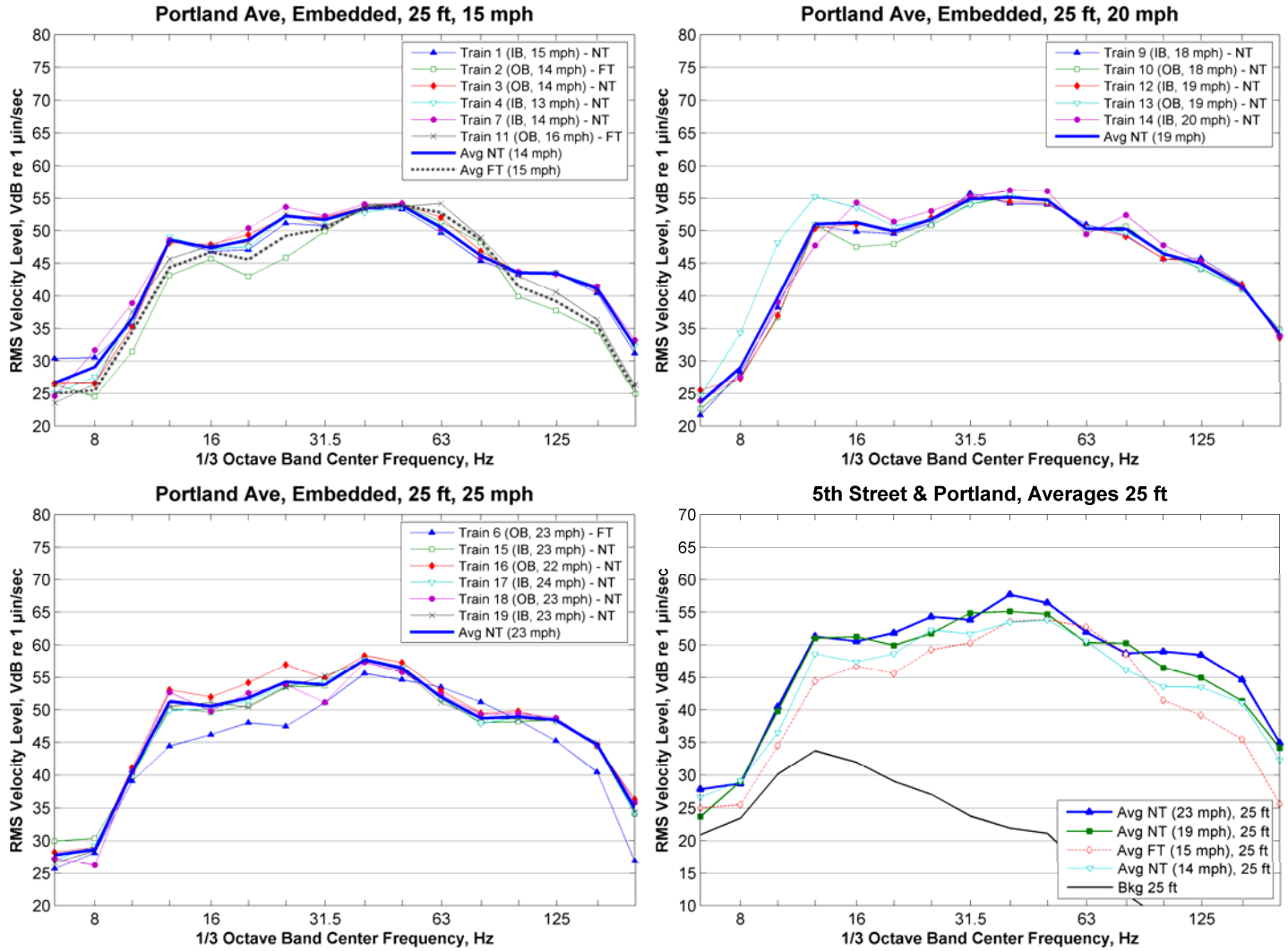


Figure 190: Vibration Spectra, 5th Street and Portland Avenue, 25 ft

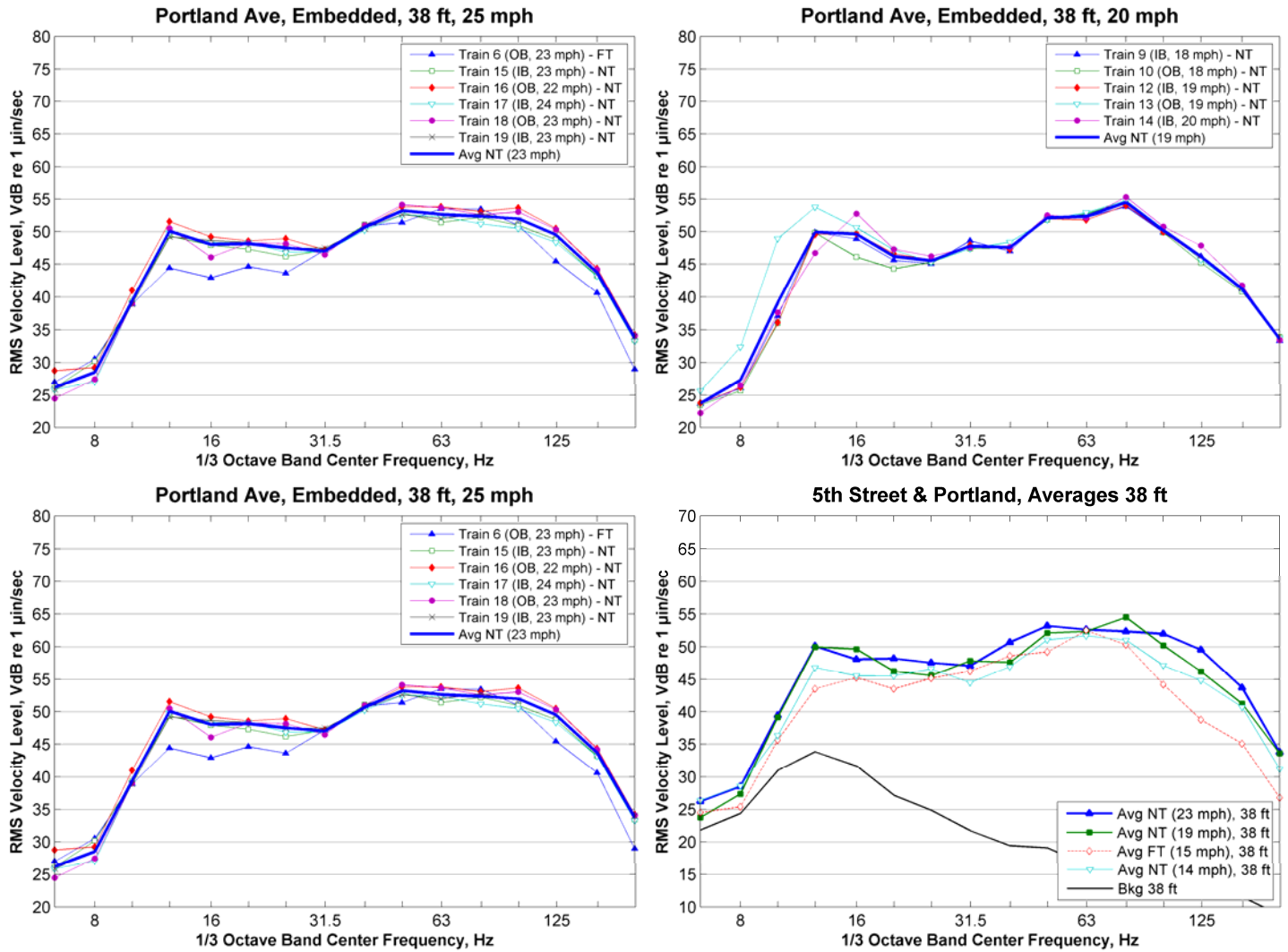


Figure 191: Vibration Spectra, 5th Street and Portland Avenue, 38 ft

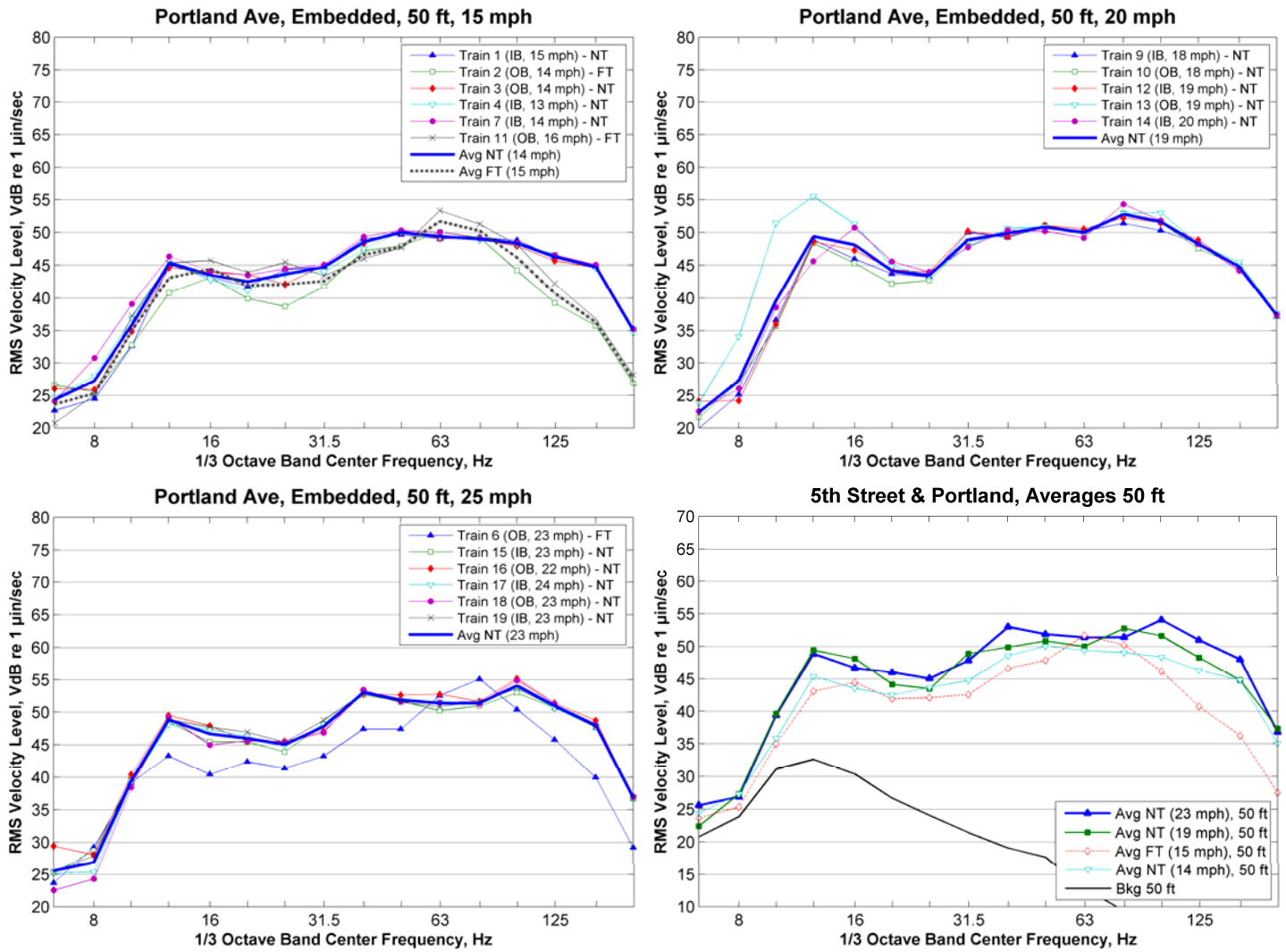


Figure 192: Vibration Spectra, 5th Street and Portland Avenue, 50 ft

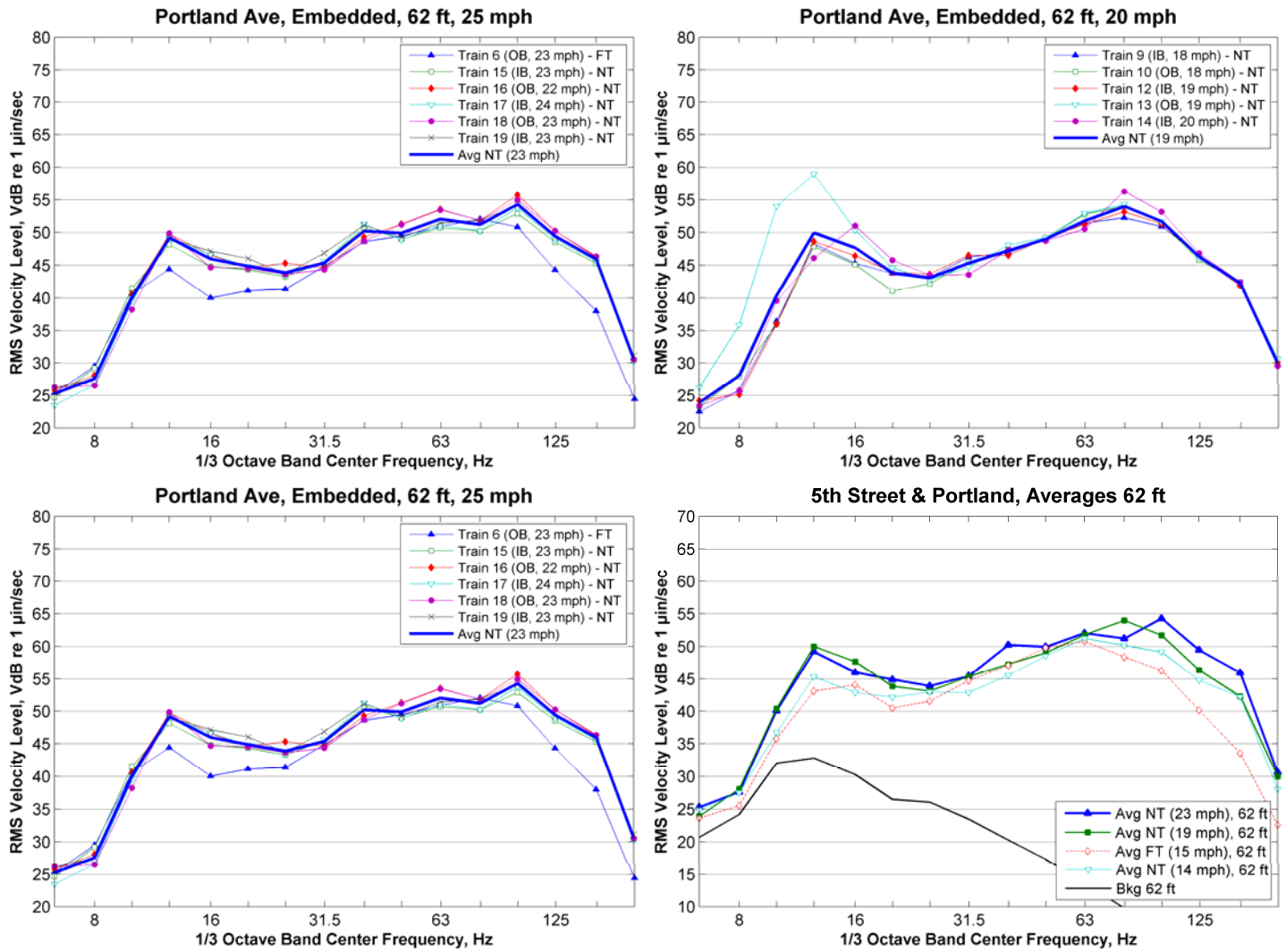


Figure 193: Vibration Spectra, 5th Street and Portland Avenue, 62 ft

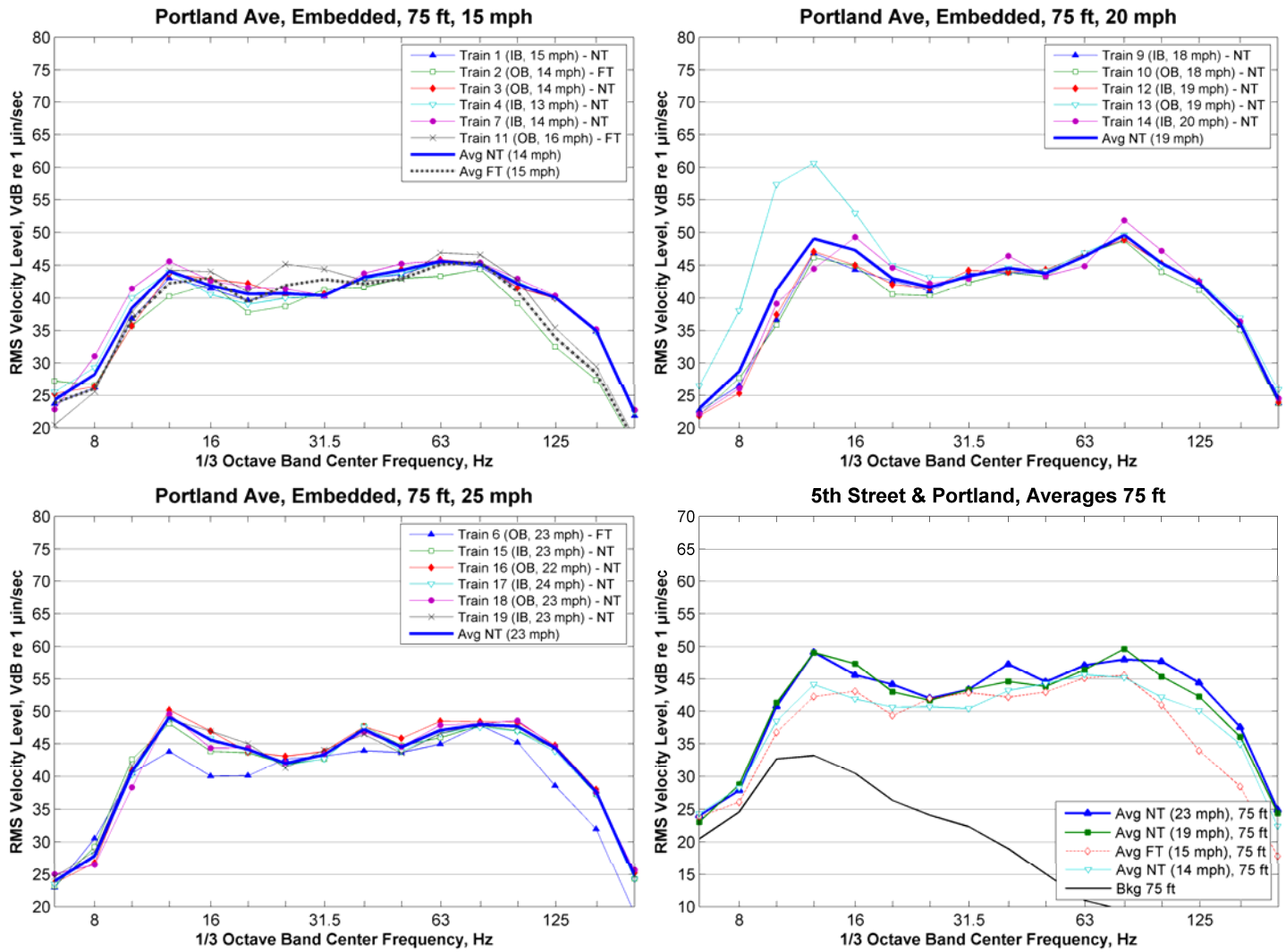


Figure 194: Vibration Spectra, 5th Street and Portland Avenue, 75 ft

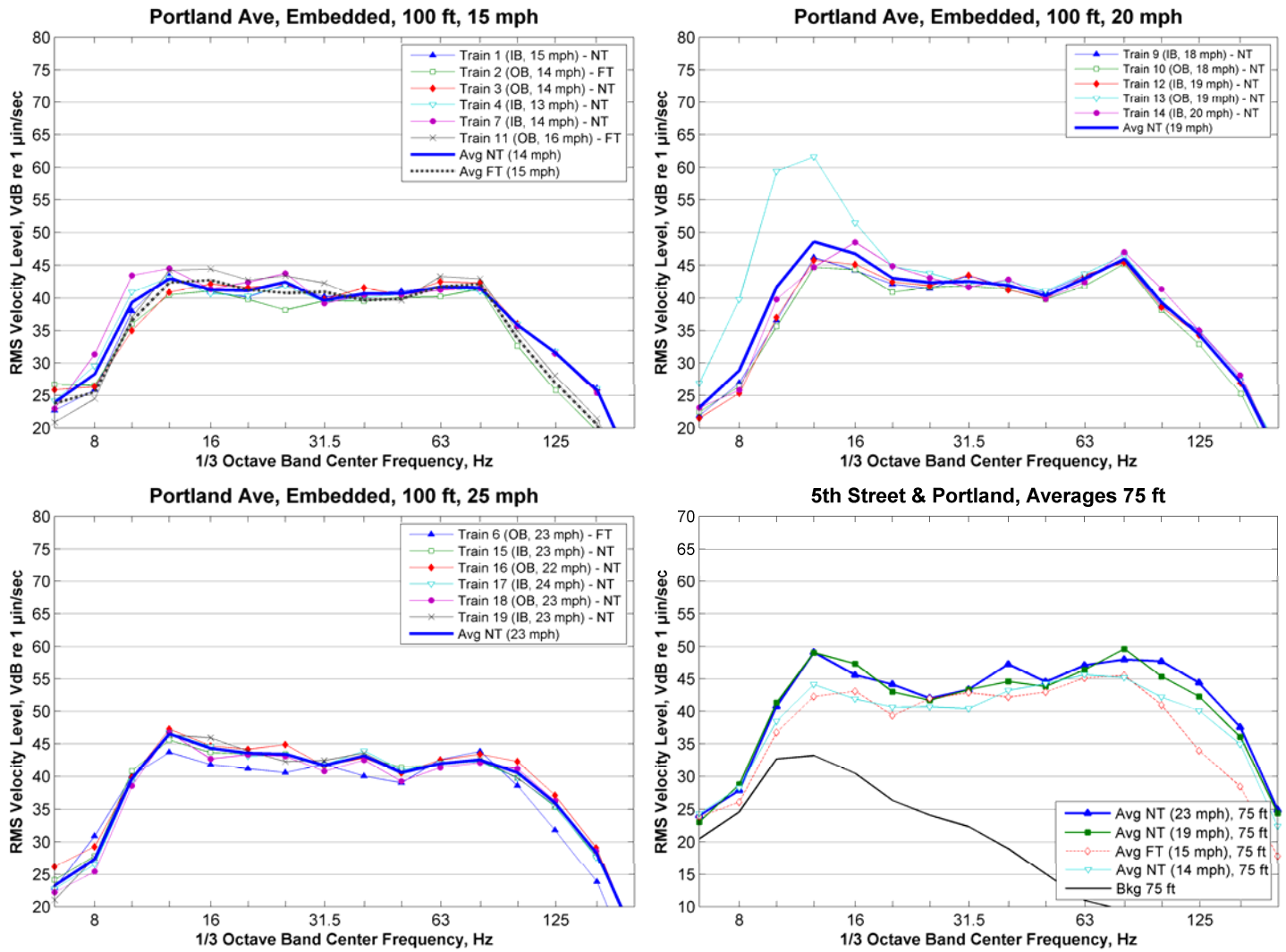


Figure 195: Vibration Spectra, 5th Street and Portland Avenue, 100 ft

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

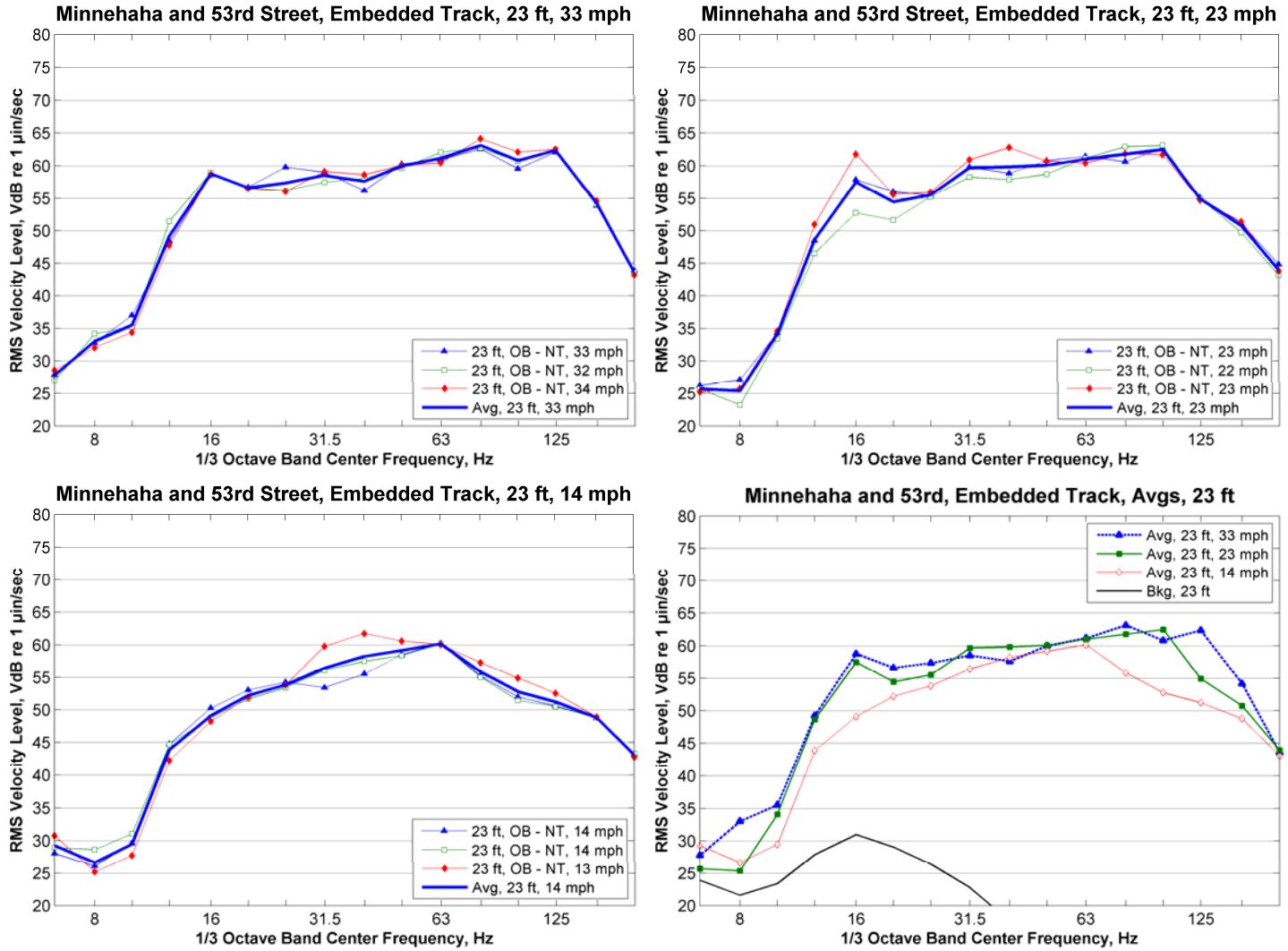


Figure 196: Train Vibration, Minnehaha and 53rd Street, 23 ft from Track Centerline

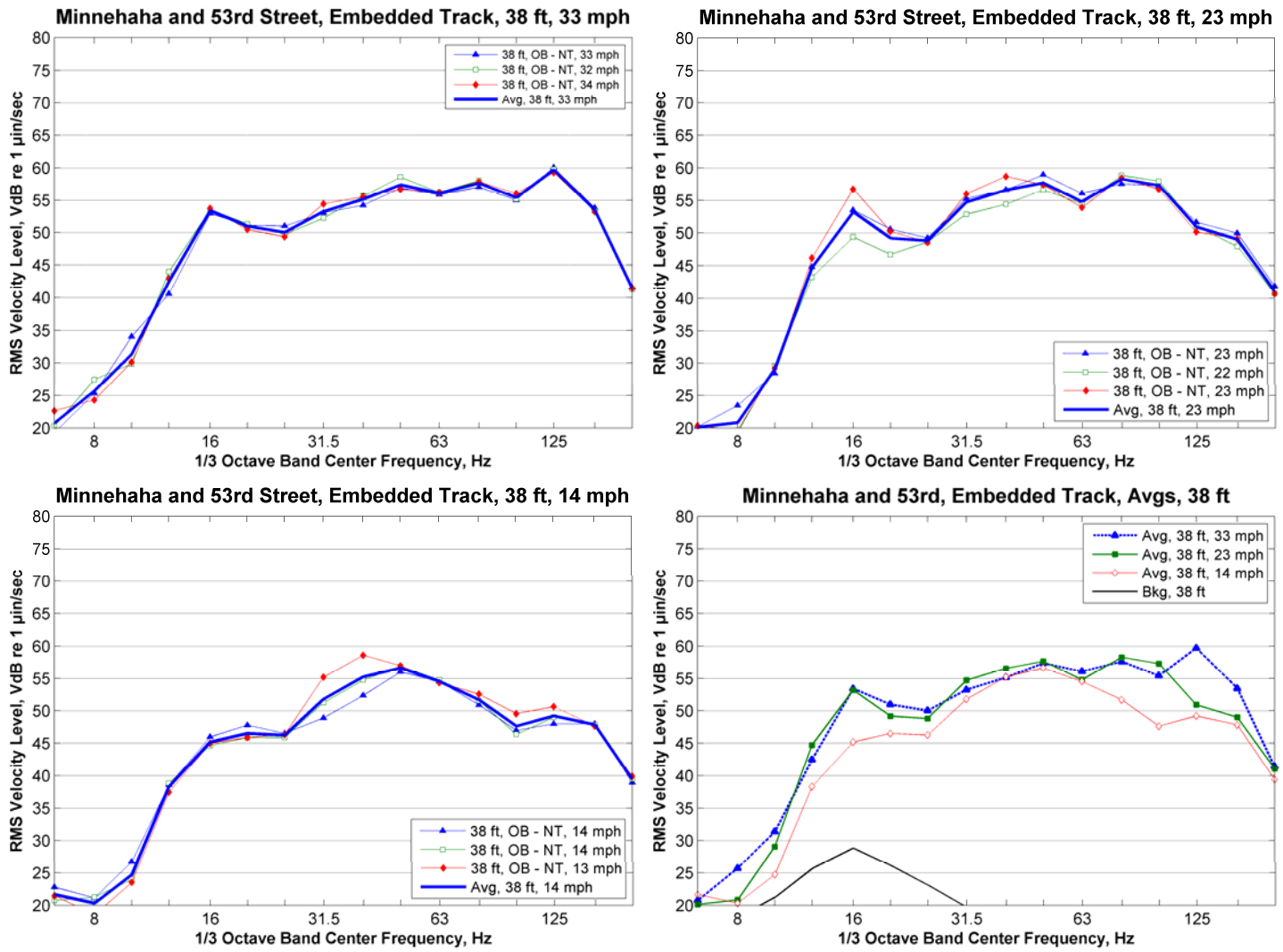


Figure 197: Train Vibration, Minnehaha and 53rd Street, 38 ft from Track Centerline

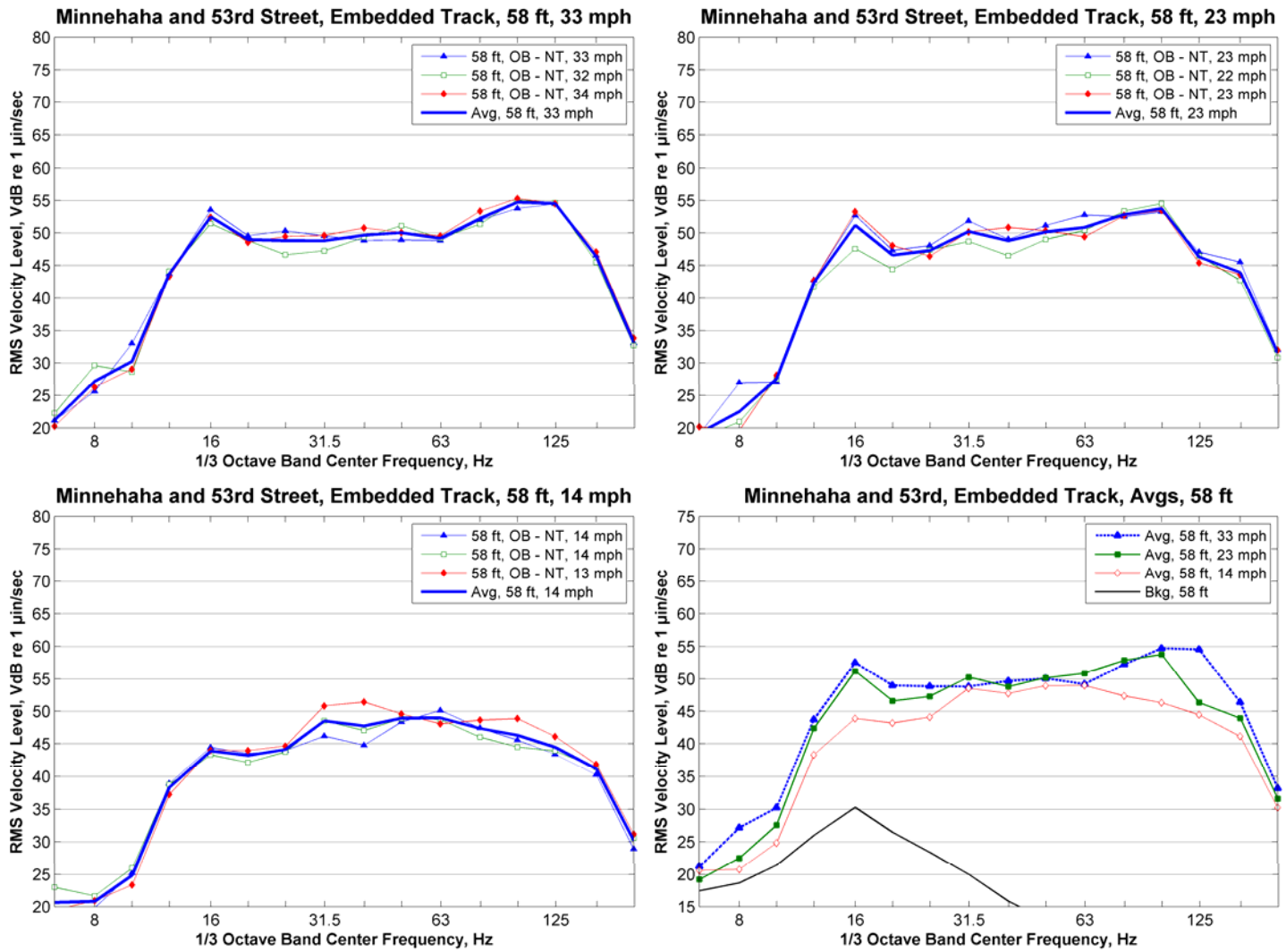


Figure 198: Train Vibration, Minnehaha and 53rd Street, 58 ft from Track Centerline

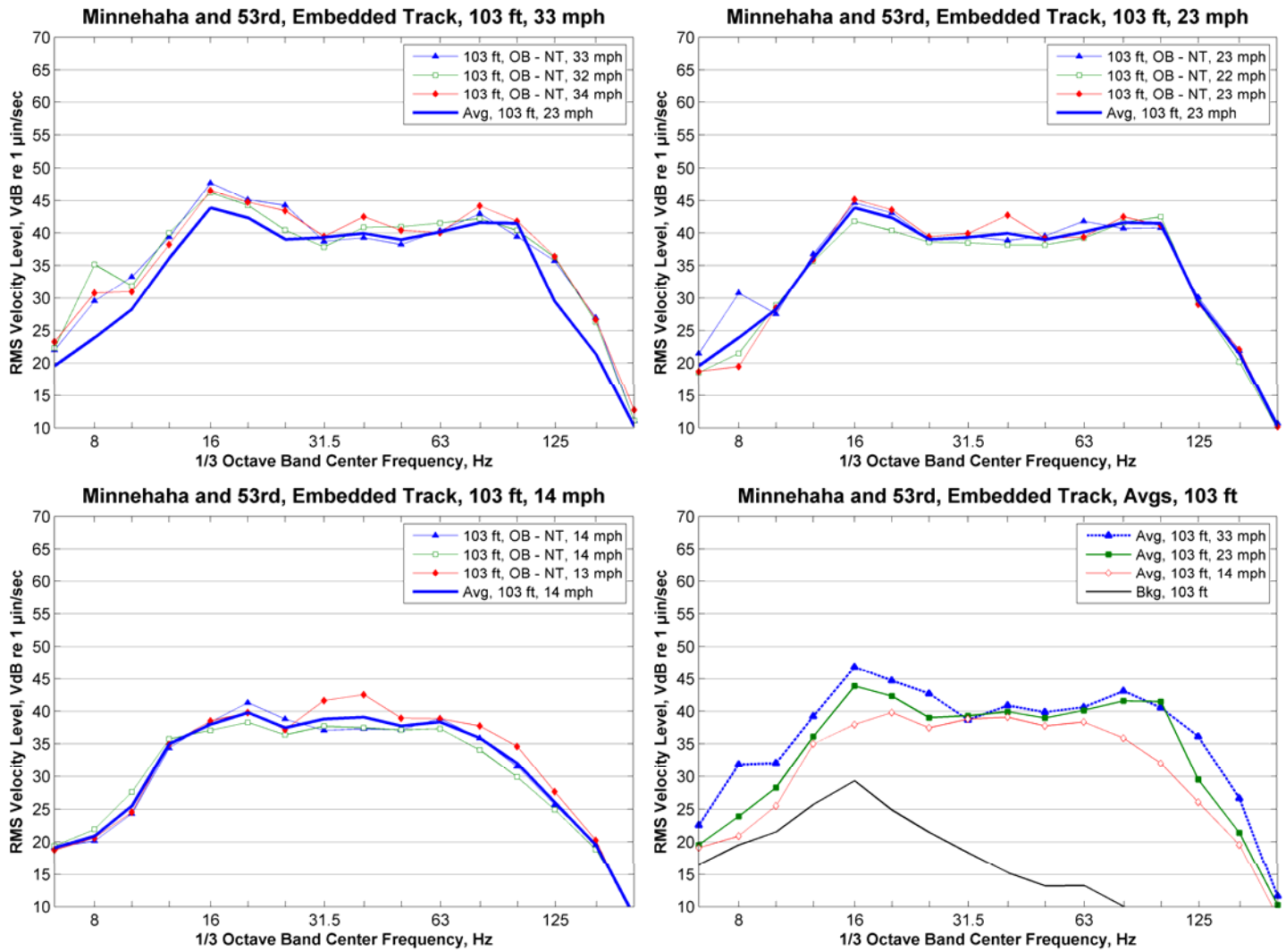


Figure 199: Train Vibration, Minnehaha and 53rd Street, 103 ft from Track Centerline

A.4 Bus Vibration, Minnehaha and 53rd Street

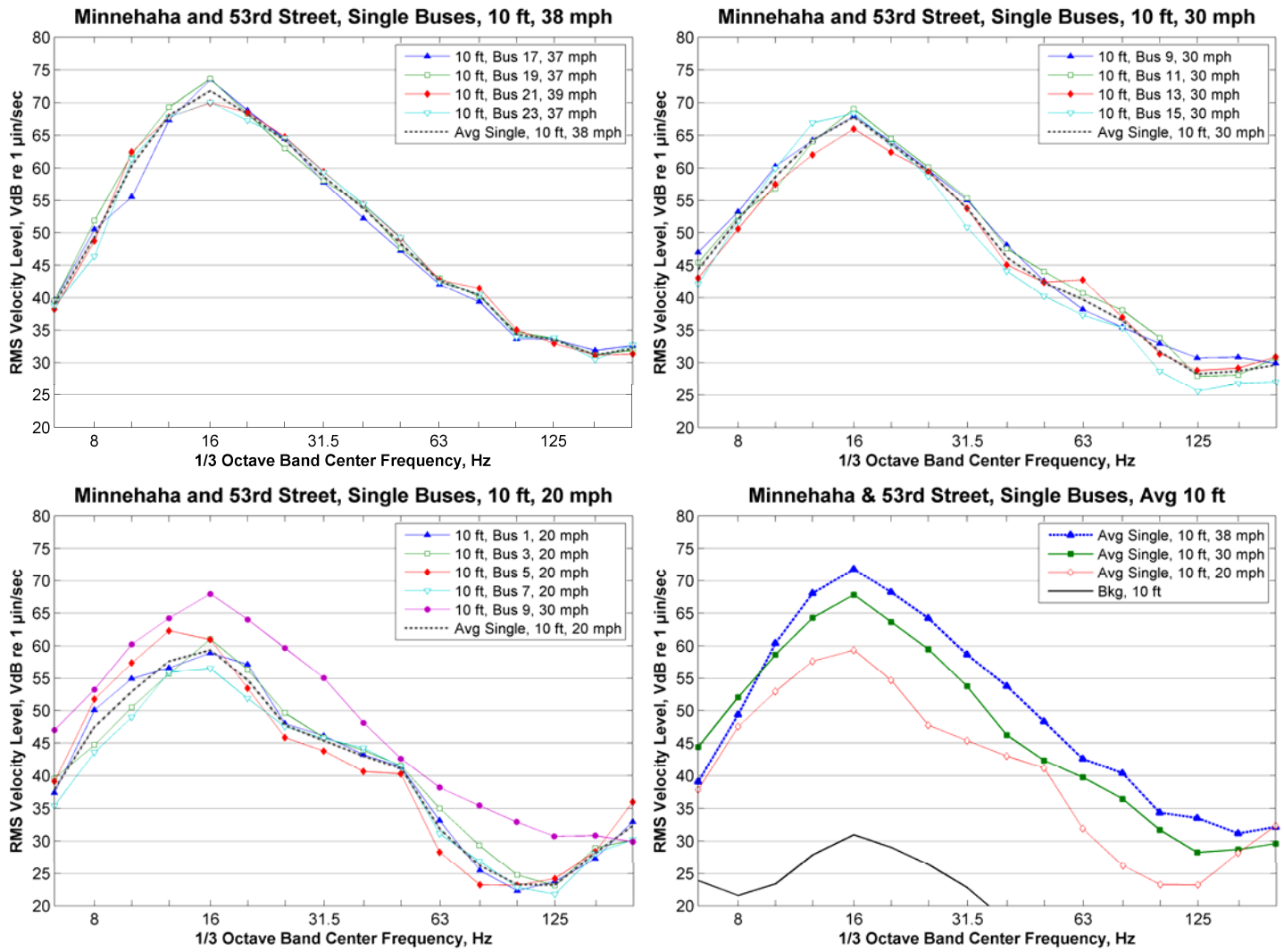


Figure 200: Single Bus Vibration, Minnehaha and 53rd Street, 10 ft from Roadway Centerline

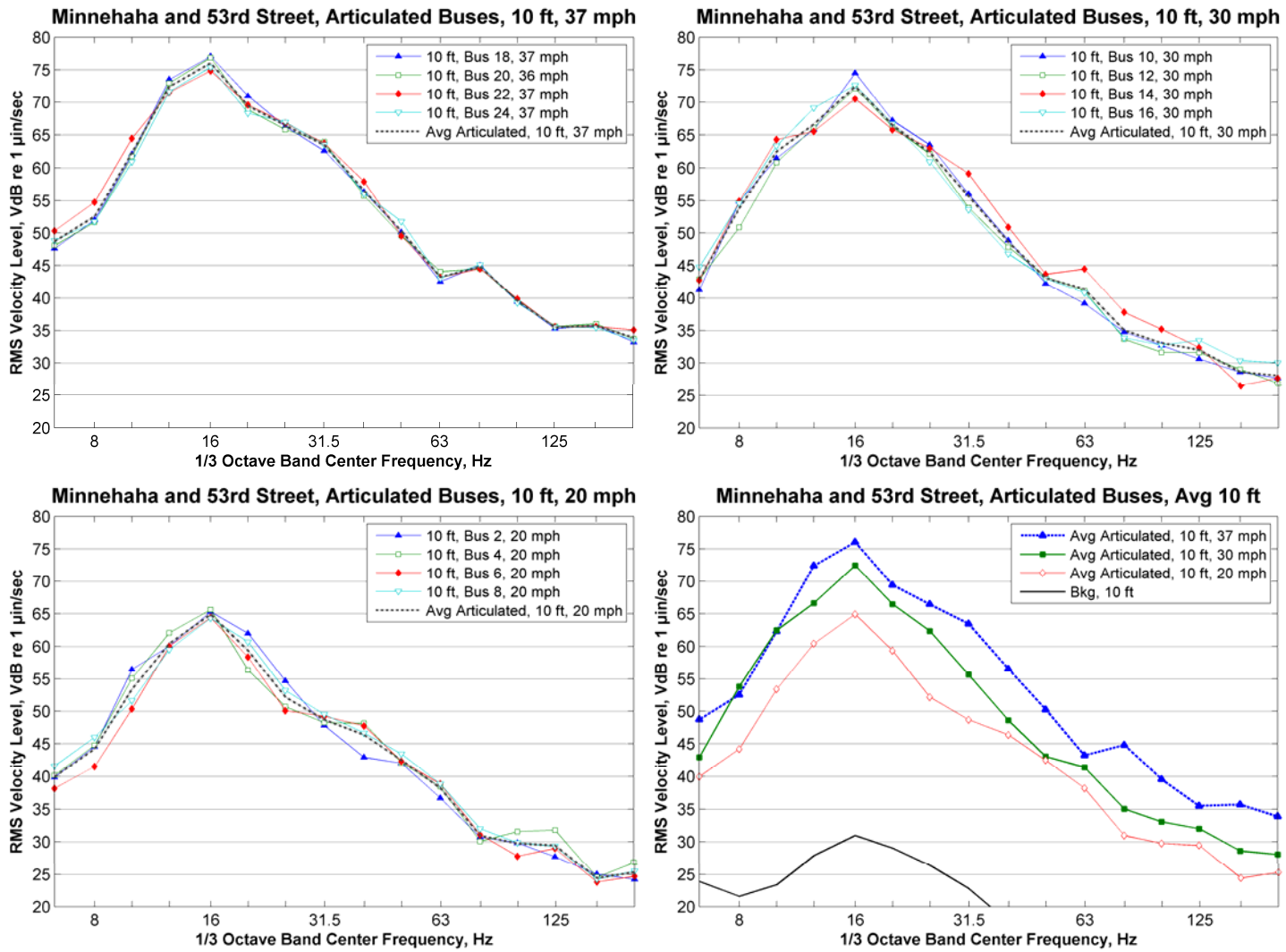


Figure 201: Articulated Bus Vibration, Minnehaha and 53rd Street, 10 ft from Roadway Centerline

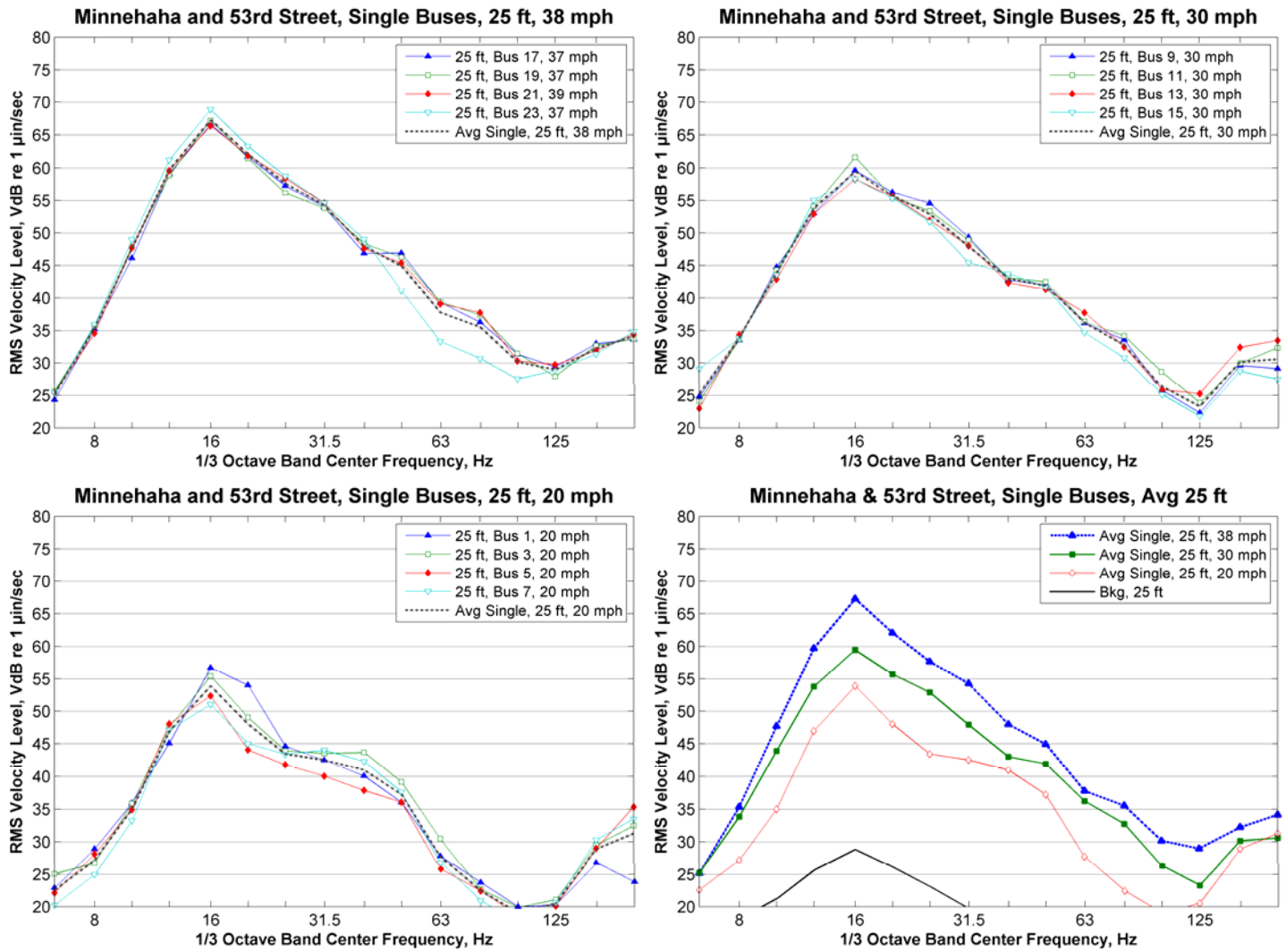


Figure 202: Single Bus Vibration, Minnehaha and 53rd Street, 25 ft from Roadway Centerline

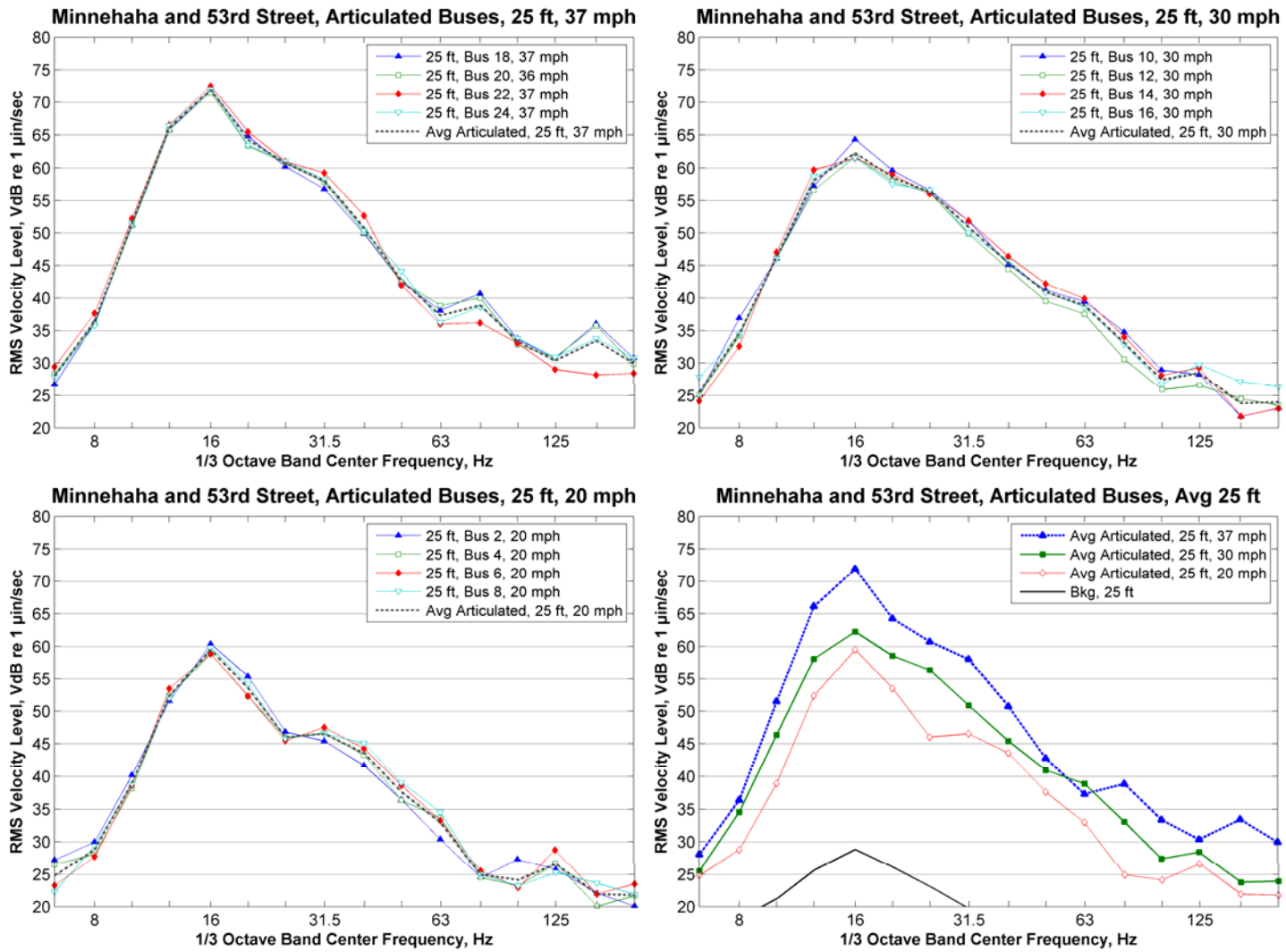


Figure 203: Articulated Bus Vibration, Minnehaha and 53rd Street, 25 ft from Roadway Centerline

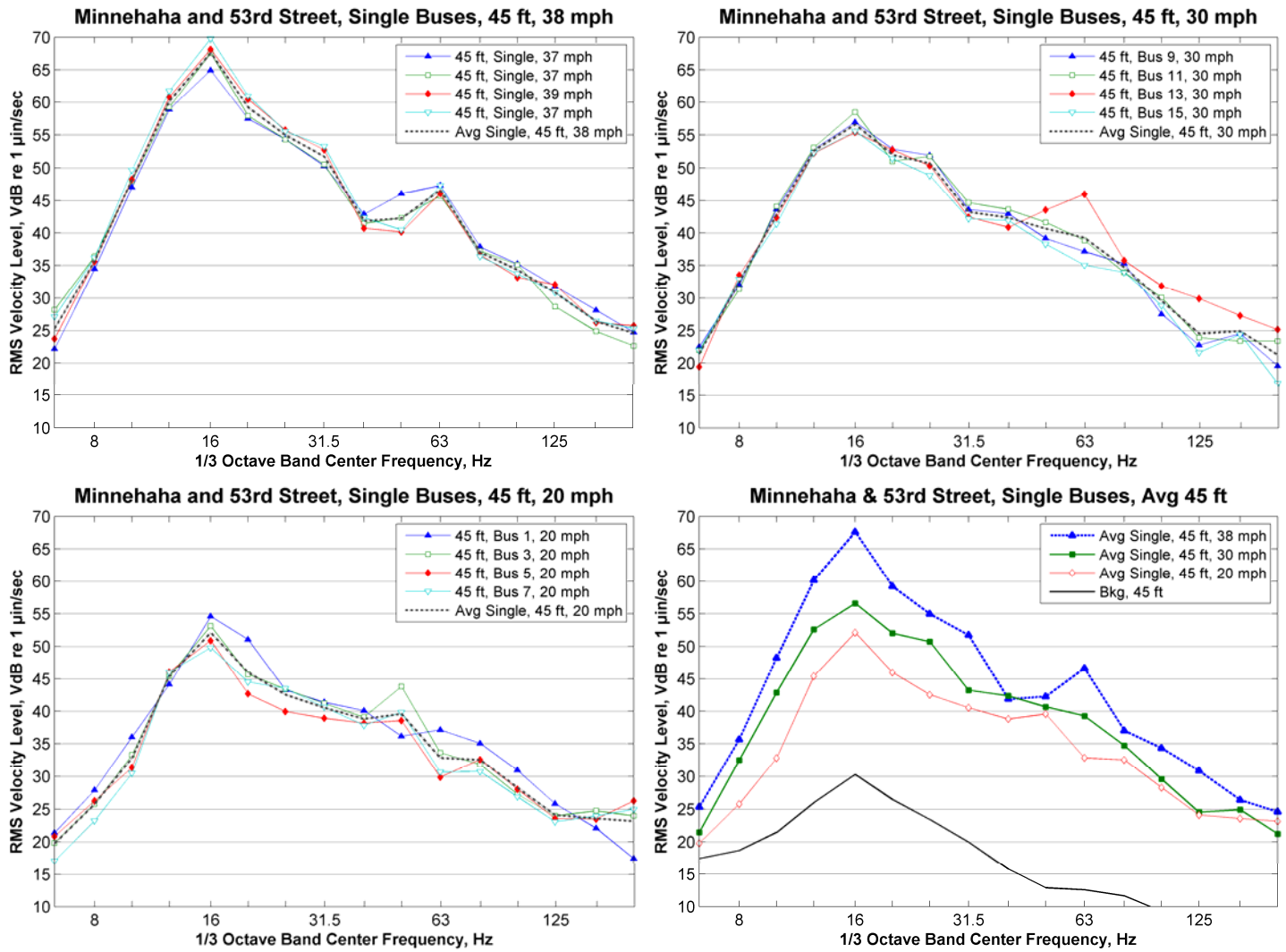


Figure 204: Single Bus Vibration, Minnehaha and 53rd Street, 45 ft from Roadway Centerline

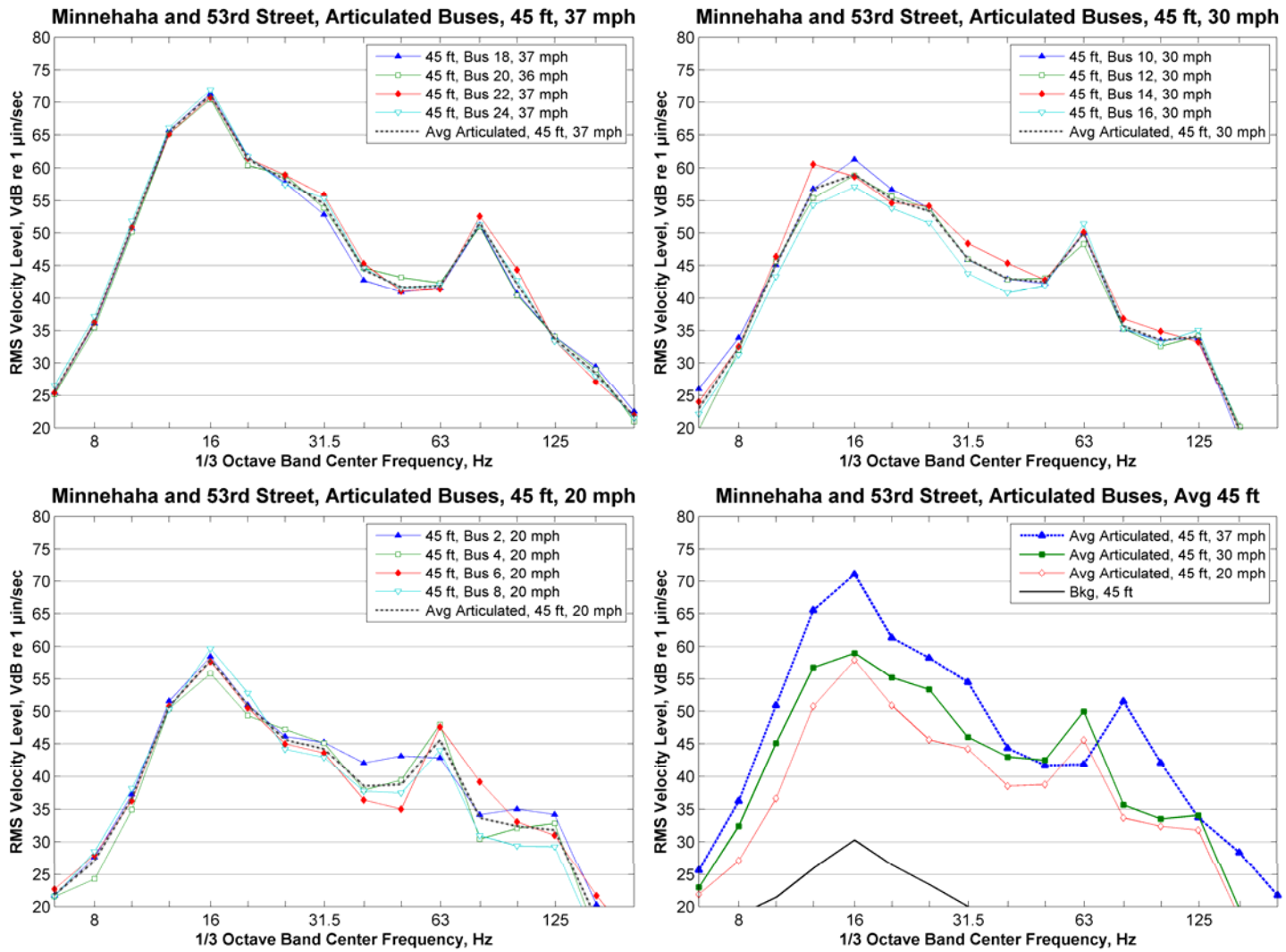


Figure 205: Articulated Bus Vibration, Minnehaha and 53rd Street, 45 ft from Roadway Centerline

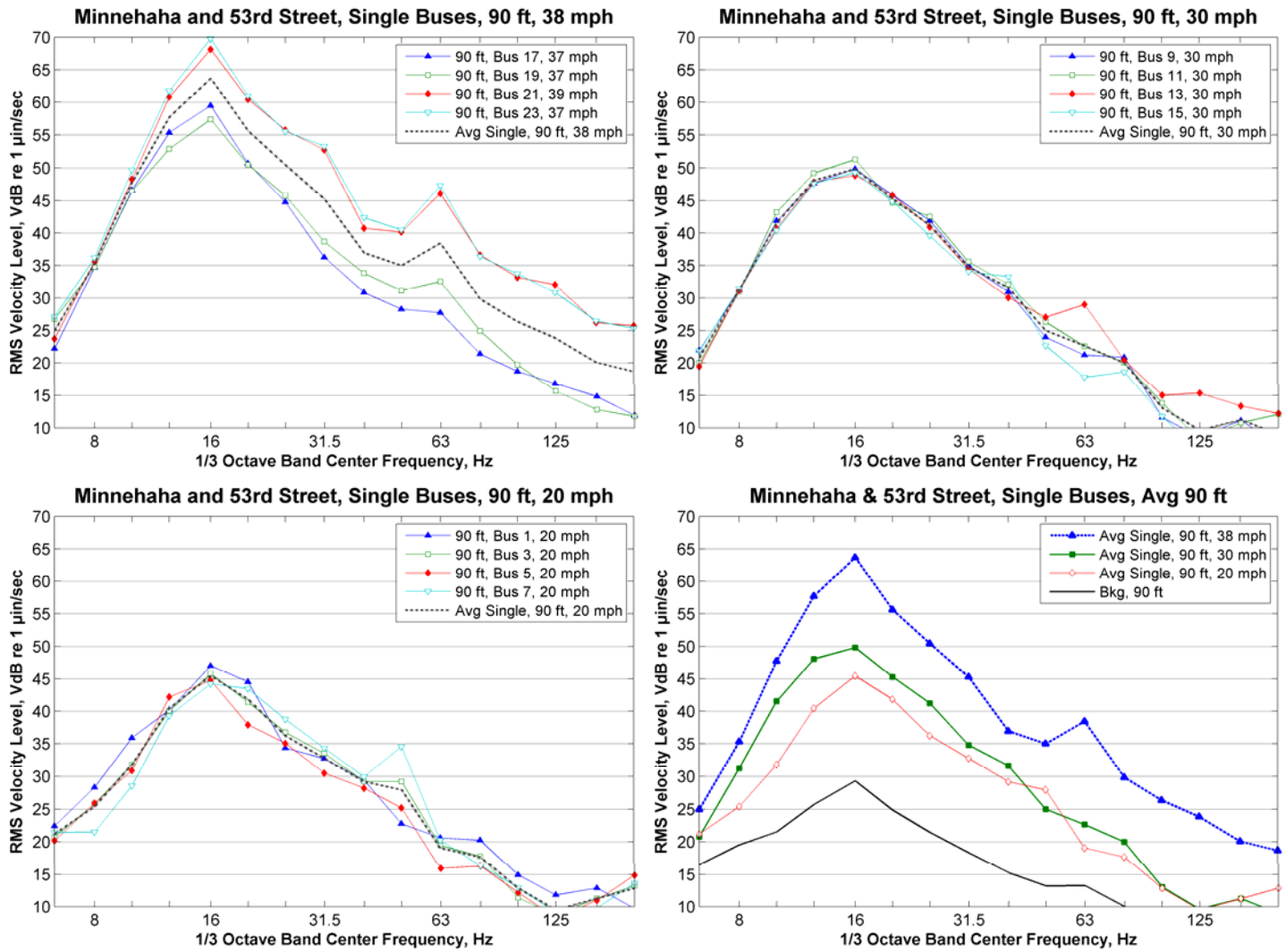


Figure 206: Single Bus Vibration, Minnehaha and 53rd Street, 90 ft from Roadway Centerline

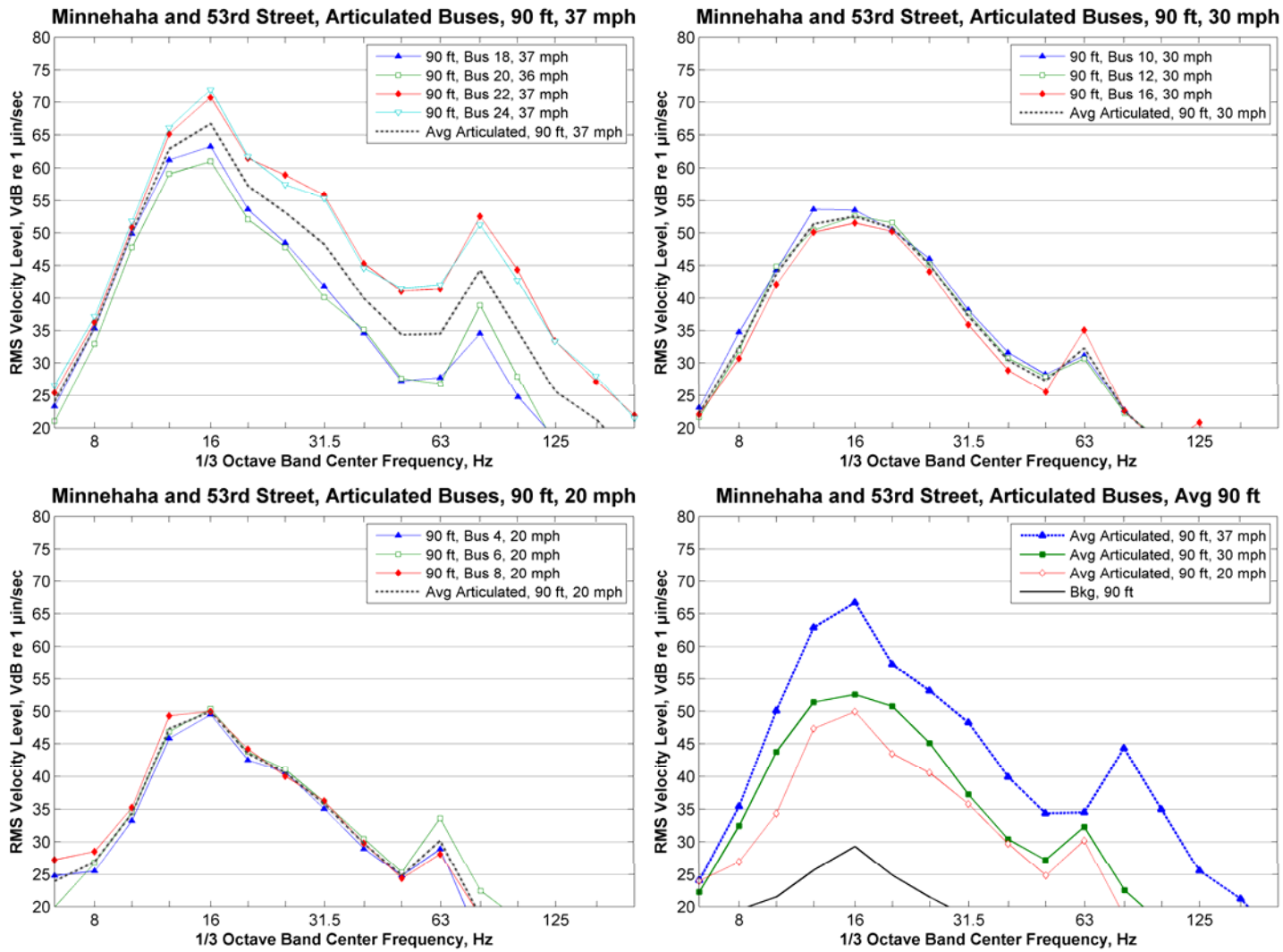
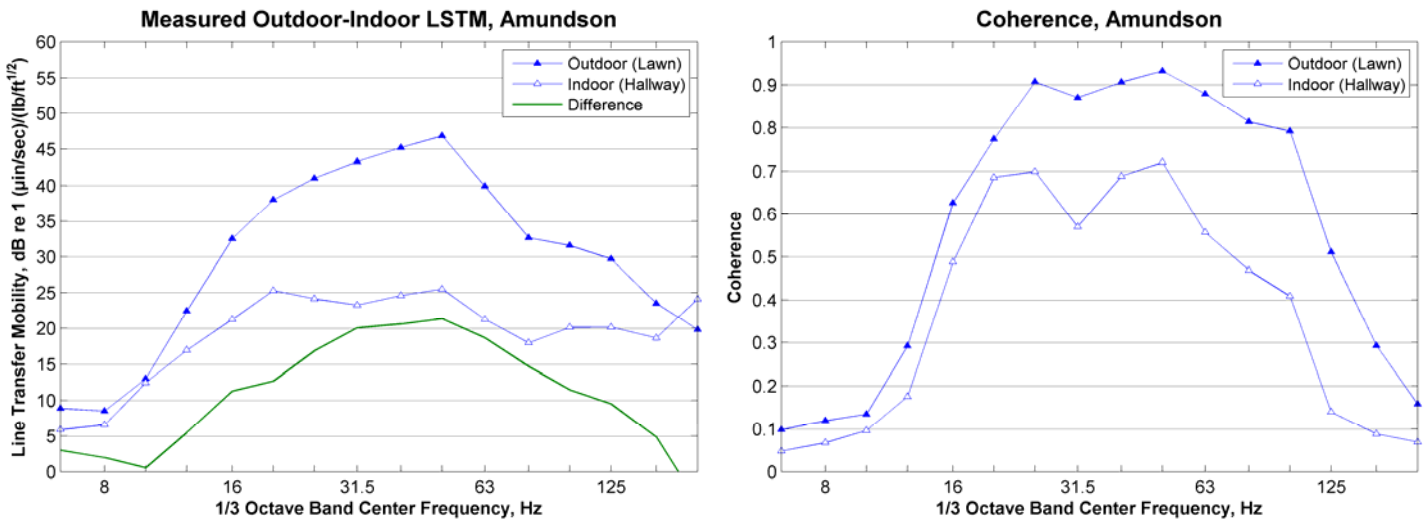


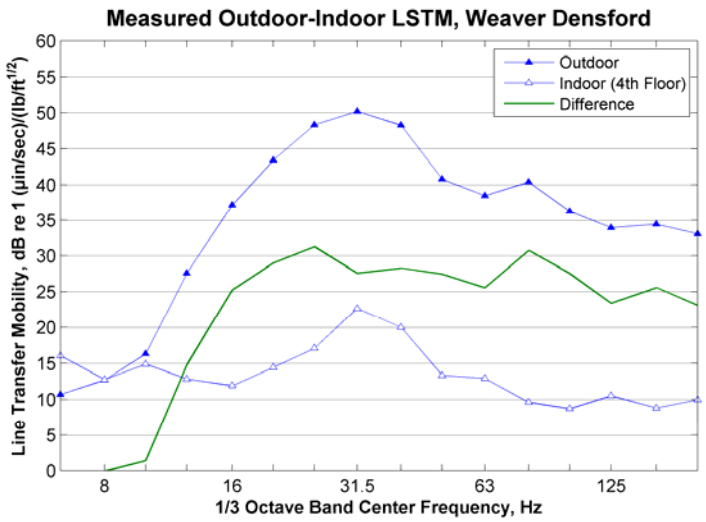
Figure 207: Articulated Bus Vibration, Minnehaha and 53rd Street, 90 ft from Roadway Centerline

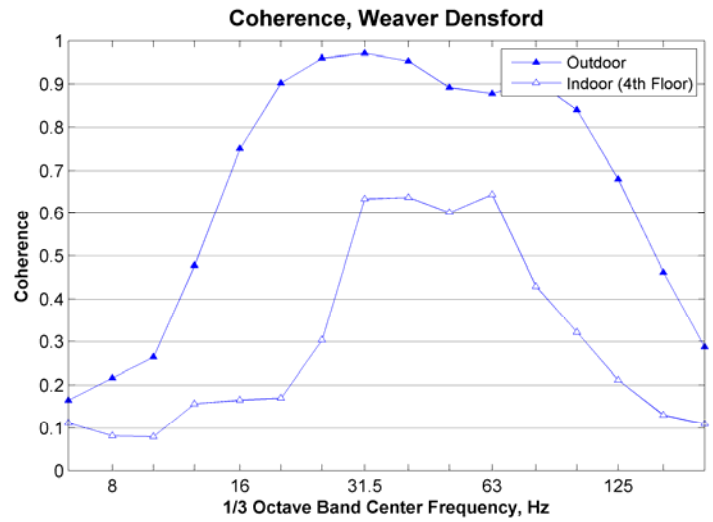
APPENDIX B. OUTDOOR-INDOOR VIBRATION DIFFERENCES

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.

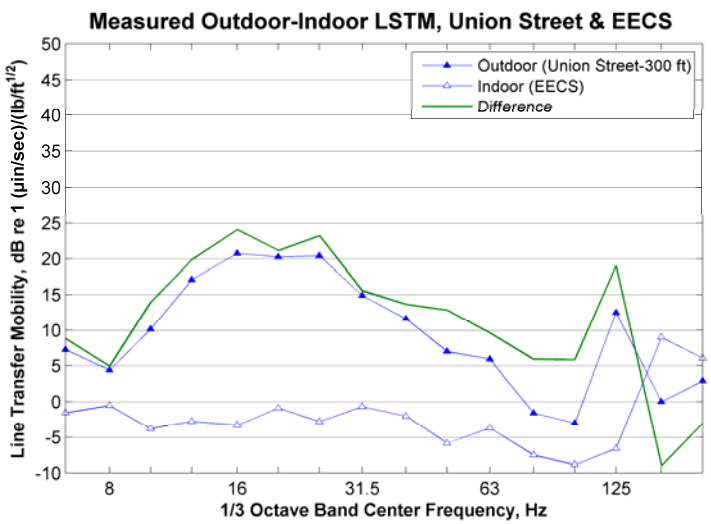


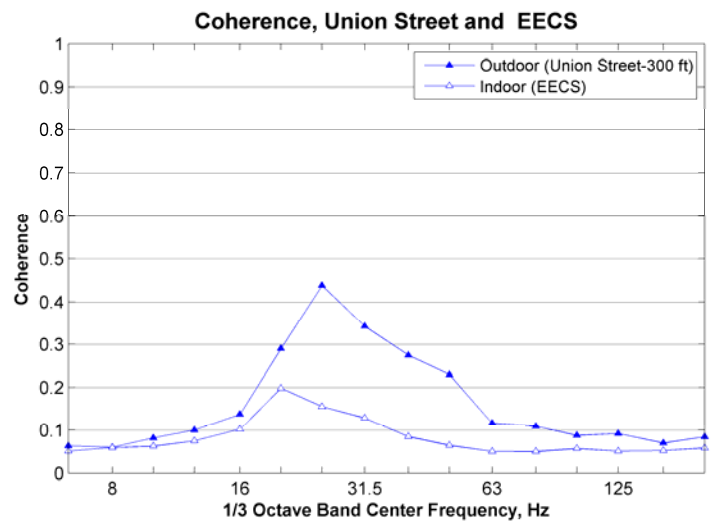
Amundson Hall, Basement Hallway



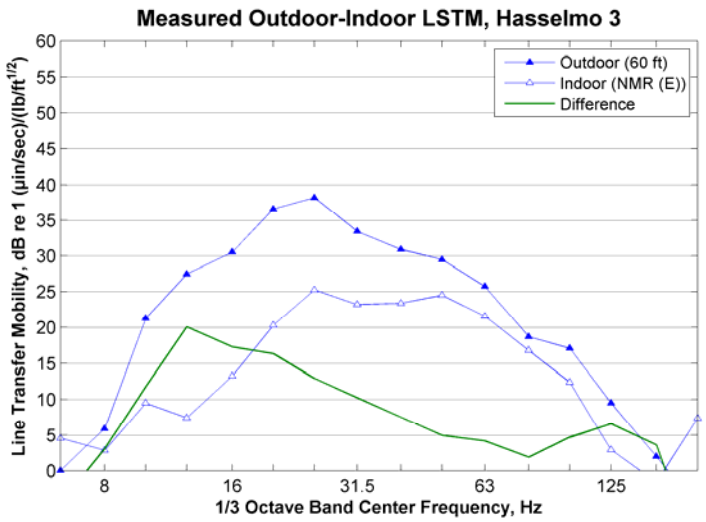


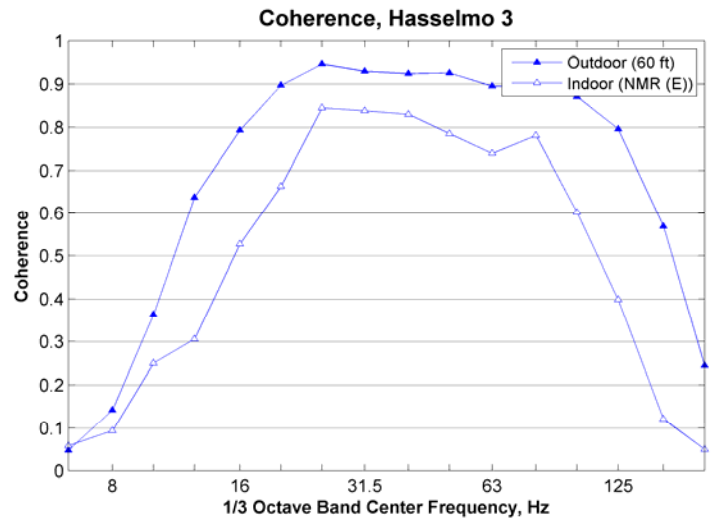
Weaver Densford Hall, 4th Floor (Street Level relative to Washington Avenue)





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:

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

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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2. Acoustical Society of America, "Guide to Evaluation of Human Exposure to Vibration in Buildings," American National Standard: ANSI S3.29-1983 (ASA 48-1983).
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4. Hugh Saurenman, ATS Consulting, "Final Report: Develop Noise and Vibration Mitigation Strategies for the Silicon Valley Rapid Transit Project," prepared for Santa Clara Valley Transportation Authority, January 2006.
5. Thomas Jaquet, Rüdiger Garburg, Deutsche Bahn AG, "Measurements and Investigations at the Floating-Track-Bed System in the North-South Tunnel in Berlin," 9th International Workshop on Railway Noise, Munich, Germany, October 2007.
6. Jeffrey Zapfe, Acentech Incorporated , "Vibration Mitigation Using Pandrol Panguard Resilient Rail Fasteners," presentation at APTA Rail Transit Conference, Miami, FL, June 2004.
7. Steven Wolfe, Wilson, Ihrig & Associates, "Vibration Attenuation Performance of Tire Shred Underlayment for Light Rail Transit Ballast and Tie Track, Results of Field Tests," prepared for Santa Clara Valley Transportation Authority, April 2001.
8. T. J. Sobotka, PhD, S. Harper, DVM, J. Hanig, PhD, M. Robl, DVM, PhD, "Strategy for Controlling Noise and Vibration During Renovation of an Animal Facility," Lab Animal, Vol 32, No. 7, July/August 2003.