

**Analysis and Assessment of
Vibration Issues with Recommendations
for the New MPR Expansion and Existing Building
St Paul, Minnesota**

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ESI Project 1328

Prepared for

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Executive Summary – Revised

Analysis and Assessment of Vibration Issues with Recommendations for the MPR New Expansion and Existing Building - St Paul, Minnesota

ESI ENGINEERING, INC.

This revised report discusses the impact of floor vibration in the new MPR expansion and the existing building. Analyses were done to determine the vibration levels inside the building(s) from the expected LRT line and surrounding vehicular traffic. The results were compared to floor vibration criteria for sensitive broadcasting equipment for an NC-25 noise criteria and an ISO office environment. Vibration impact from the LRT on the 50-ft long span floors of the new expansion is expected to be very high and footfall effects will be noticeable. Vibration impact on the existing floors will only occur in broadcasting areas. Without the LRT, vehicular and bus traffic will have a minimal effect on the new expansion.

LRT Vibration Impact

An assessment of floor vibration from the future LRT line followed procedures outlined by the Federal Transit Administration (FTA). The process consisted of 1) preliminary screening based on distance, 2) generalized assessment based on physical conditions and 3) detailed assessment based on calculations.

Preliminary Screening – This procedure shows that sensitive equipment should be more than 100 feet away from the LRT alignment to minimize the vibration impact.

Generalized Assessment - The general assessment procedure shows that floor vibration in the building at startup of the LRT line will have a significant effect on all areas in the building. Furthermore, the train condition could cause vibration impact to worsen if wheels become worn and flats occur over time.

Vibration effects on the broadcasting studios may be problematic depending on location in the building and individual equipment sensitivity, thus local sound isolation will be required. The generalized assessment indicates the existing Maud Moon Weyerhaeuser studio facing Cedar will very likely be subjected to higher vibration from the LRT line than under present conditions.

Detailed Assessment - The detailed vibration assessment of the building(s) used computer simulations based on finite element methods to predict the impact of the LRT. The soil characteristics and building frame (and floors) were modeled to numerically quantify the vibration through the ground from the LRT to the floors at various locations.

This procedure indicates the floor vibration levels for all broadcast studio areas of the new expansion will be below the criteria. Long span floors supporting open offices greatly exceed the ISO office criteria. A stiffer floor slab or ballast mats under the tracks will be needed for the long span open office areas to satisfy the criteria. The editing suites will be impacted by the LRT because of the longer span floors.

Vibration Mitigation and Isolation

The simplest solution to mitigating vibration from the LRT would be to get an agreement from the Central Corridor Planners (Ramsey County) to declare the MPR building a vibration sensitive site and have ballast mats installed under the tracks. Another solution is to increase the depth of the 50-ft long spans. This would raise the natural frequency above the resonant condition with the LRT speed. Other solutions discussed in the report were less effective.

Another possible mitigation concept that may work well at site is vibration isolation with a trench barrier which causes reflection, scattering, and diffraction of the soil particle waves against the building foundation wall. For the MPR expansion, it may be rather easy to construct an isolation barrier with an air space or with a friable material to form a vibration control mat along the foundation wall.

All HVAC and mechanical equipment in the building should be installed on steel spring or neoprene vibration isolators. Isolators will be sized for the equipment based on weight, horsepower, speed and supporting structure.

Analysis and Assessment of Vibration Issues with Recommendations for the New MPR Expansion and Existing Building - St Paul, Minnesota

ESI ENGINEERING, INC.

1.0 ASSESSMENT SUMMARY

Vibration analyses of the building framing system were completed for the Minnesota Public Radio (MPR) existing building and the new expansion along Cedar Street in St. Paul, Minnesota. These were done to estimate the nature and magnitude of vibration levels from the future light rail transit system expected to pass directly by the building. The results were compared to vibration criteria for noise-sensitive broadcasting equipment.

The MPR building is in downtown St. Paul, currently bounded by Ninth Street on the north, Seventh street on the south and Cedar Street on the west. There are condominiums and parking lots on the east side. The new building expansion will be to the north of the existing MPR building along Cedar and will involve permanent closure of Ninth Street. There are some existing buildings on the site that will be demolished on the north side of Ninth Street.

This report includes analyses completed to assist HGA with an independent evaluation of the potential impacts and costs related to vibration. The work was based upon a review of the existing and new building drawings, information from previous studies on noise and vibration impacts associated with light rail activity and meetings with the planners. The work covers analysis of vibration issues related to the expected light-rail transit line effects.

Broadcasting areas on levels three and four were assessed for vibration impact because of their low vibration requirements. Special attention was given to the west side of the building along Cedar since it is very close to the proposed LRT line. Potential impacts from vibration as well as mitigation concepts are addressed.

Assessment of LRT vibration of the building followed procedures outlined in the manual from the Federal Transit Administration (FTA) entitled: ***Transit Noise and Vibration Impact Assessment Final Report April 1995*** (Reference 1). The process consisted of preliminary screening, generalized assessment and detailed assessment with on-site vibration measurements in addition to data available from previous studies.

1.1 Vibration Impact on MPR

The projected vibration impact from the LRT line is expected to be high based on the General Assessment procedure as shown in Table 1-1. The estimated vibration impact at startup of the LRT line will be very noticeable in some parts of the building even with new equipment. Over time the LRT condition may cause the vibration impact to worsen if train wheels become worn and flats occur.

Detailed vibration analyses of the building frame were completed using finite element analysis (FEA) and other computational methods to predict the impact of the LRT and mechanical equipment. The structure and soil characteristics were modeled with FEA as beam, plate and boundary elements to determine the natural frequencies and mode shapes of the soil-structure interaction. Ground vibration of the LRT was superimposed to determine the amplitudes of building vibration.

Table 1-1 Summary of Vibration Impact Assessment for New & Existing MPR Building

Building Area	FTA Category	FTA Criteria	Vibration Impact At Startup with New Trainset			Vibration Impact After Startup With Worn Wheels or Flats			Mitigation Possibilities
			Buffer Zone (feet)	Estimated Vibration VdB	Level of Impact in Zone	Buffer Zone (feet)	Estimated Vibration VdB	Level of Impact in Zone	
New Open Office Floors with 50 ft Span	Cat 3	75	50	87	High	50	97	Very High	Stiffer Girders
New Private Offices Along Cedar Street	Cat 3	75	22	90	Very High	22	100	Very High	Isolation Barrier
New Broadcast Studio Floors	Special	65	50	87	Very High	50	97	Very High	Floating Floor
Existing Open Office Floors	Cat 3	75	50	87	High	50	97	Very High	None
Existing Private Offices Along Cedar Street	Cat 3	75	50	87	High	50	97	Very High	None
Existing Broadcast Studio Floors	Special	65	60	85	Very High	60	95	Very High	None

The projected ground-borne vibration is much more than 5 decibels greater than the impact threshold. Very high vibration impact is probable and some type of vibration control should be planned for the final design of the project. The effects of all other vehicular traffic are expected to be minimal.

1.2 Vibration Control and Isolation Solutions

The simplest solution to mitigating vibration from the LRT would be to get an agreement from the Central Corridor Planners (Ramsey County) to declare the MPR building a vibration sensitive site and have ballast mats installed under the tracks. Another solution is to increase the depth of the 50-ft long spans. This would raise the natural frequency above the resonant condition with the LRT speed. Two other less effective concepts were studied as follows:

- Increasing the concrete strength of the floor system to increase the stiffness
- Widening the long span beams of the floor system to increase the stiffness

Another possible mitigation concept that may work well at site is vibration isolation with a trench barrier which causes reflection, scattering, and diffraction of the soil particle waves against the building foundation wall. Barriers may consist of solid, fluid, or void zones in the ground. No soil particle waves are transmitted with an open trench; thus it is an effective vibration barrier but the most difficult to construct and maintain.

For the MPR expansion, it may be rather easy to construct an isolation barrier with an air space or with a friable material to form a vibration control mat along the foundation wall with the building structure founded in bedrock. However, a barrier will protect the lower floors nearest Cedar Street.

All HVAC and mechanical equipment in the building should be installed on steel spring or neoprene vibration isolators. Isolators will be sized for the equipment based on weight, horsepower, speed and supporting structure.

2.0 VIBRATION IMPACT CRITERIA

The impact of vibration from any source has the potential to be noticeable and intrusive to people in buildings. There has been research of how people respond to vibration from light-rail but with greater densification of land use more knowledge is being gained on how communities react to various levels of building vibration (Reference 1). This research along with the available national and international standards for vibration criteria present a foundation for predicting the impact from vibration caused by all the various sources in this building.

2.1 Ground-Borne Vibration and Noise Impact Criteria For Light-Rail Transit

The impact criteria for people in buildings subjected to ground-borne vibration and noise from light-rail transit is shown in Table 2-1 is based on the FTA Manual (Reference 1).

Table 2-1 Ground-borne Vibration and Noise Impact Criteria

Land Use Category	Ground-Borne Vibration Impact Levels (VdB re 1 micro inch/sec)		Ground-Borne Noise Impact Levels (dB re 20 micro Pascals)	
	Frequent Events ⁽¹⁾	Infrequent Events ⁽²⁾	Frequent Events	Infrequent Events
Category 1: Buildings where vibration would interfere with interior operations.	65 VdB ⁽³⁾	65 VdB	N/A ⁽⁴⁾	N/A ⁽⁴⁾
Category 2: Residences and buildings where people normally sleep.	72 VdB	80 VdB	35 dBA	43 dBA
Category 3: Institutional land uses with primarily daytime use.	75 VdB	83 VdB	40 dBA	48 dBA
Notes: 1. Frequent Events are defined as more than 70 vibration events per day. 2. Infrequent Events are defined as fewer than 70 vibration events per day. 3. This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. Vibration-sensitive manufacturing or research will require detailed evaluation to define the acceptable vibration levels. Ensuring lower vibration levels in a building often requires special design of the HVAC systems and stiffened floors. 4. Vibration-sensitive equipment is not sensitive to ground-borne noise.				

Some buildings (such as concert halls, TV and recording studios, and theaters) can be very sensitive to vibration and noise but do not fit into any of the three categories above. Because of the sensitivity of these buildings, they usually warrant special attention during the environmental assessment of a transit project. Table 2-2 gives criteria for acceptable levels of ground-borne vibration and noise for various types of special buildings.

Table 2-2 Ground-borne Vibration and Noise Impact Criteria for Special Buildings

Type of Building or Room	Ground-Borne Vibration Impact Levels (VdB re 1 micro inch/sec)		Ground-Borne Noise Impact Levels (dB re 20 micro Pascals)	
	Frequent Events ⁽¹⁾	Infrequent Events ⁽²⁾	Frequent Events	Infrequent Events
Concert Halls	65 VdB	65 VdB	25 dBA	25 dBA
TV Studios	65 VdB	65 VdB	25 dBA	25 dBA
Recording Studios	65 VdB	65 VdB	25 dBA	25 dBA
Auditoriums	72 VdB	80 VdB	30 dBA	38 dBA
Theaters	72 VdB	80 VdB	30 dBA	43 dBA
Notes: 1. <i>Frequent Events</i> are defined as more than 70 vibration events per day. Most transit projects fall into this category. 2. <i>Infrequent Events</i> are defined as fewer than 70 vibration events per day. This category includes most commuter rail 3. If the building will rarely be occupied when the trains are operating, there is no need to consider impact. As an example consider locating a commuter rail line next to a concert hall. If no commuter trains will operate after 7 pm, it should be rare that the trains interfere with the use of the hall.				

2.2 Environmental Vibration Criteria For People and Equipment In Buildings

Research organizations have established various comfort criteria for people subjected to vibration. Results of work on an international level led to development of a set of standards published by the International Organization for Standardization. The standards *ISO 2631/1*, *2631/3* (References 2 and 3) and *ISO 6897* (Reference 4) give an evaluation of human exposure to whole-body vibration. The American Standards Institute (ANSI) in conjunction with the Acoustical Society of America have developed and published a similar set of standards, *ANSI S3.29-1983* (Reference 5). The recommendations from these ISO standards for various occupancies are shown in Figure 2.2-1.

Floors supporting sensitive equipment need a vibration environment acceptable for the equipment. The criteria usually specify vibration at the supports, i.e., the floor under the equipment. If the criteria for the equipment is not known, one needs to use the more limiting generic criteria as shown in Figure 2.2-1. These criterion also apply to footfall-induced vibrations.

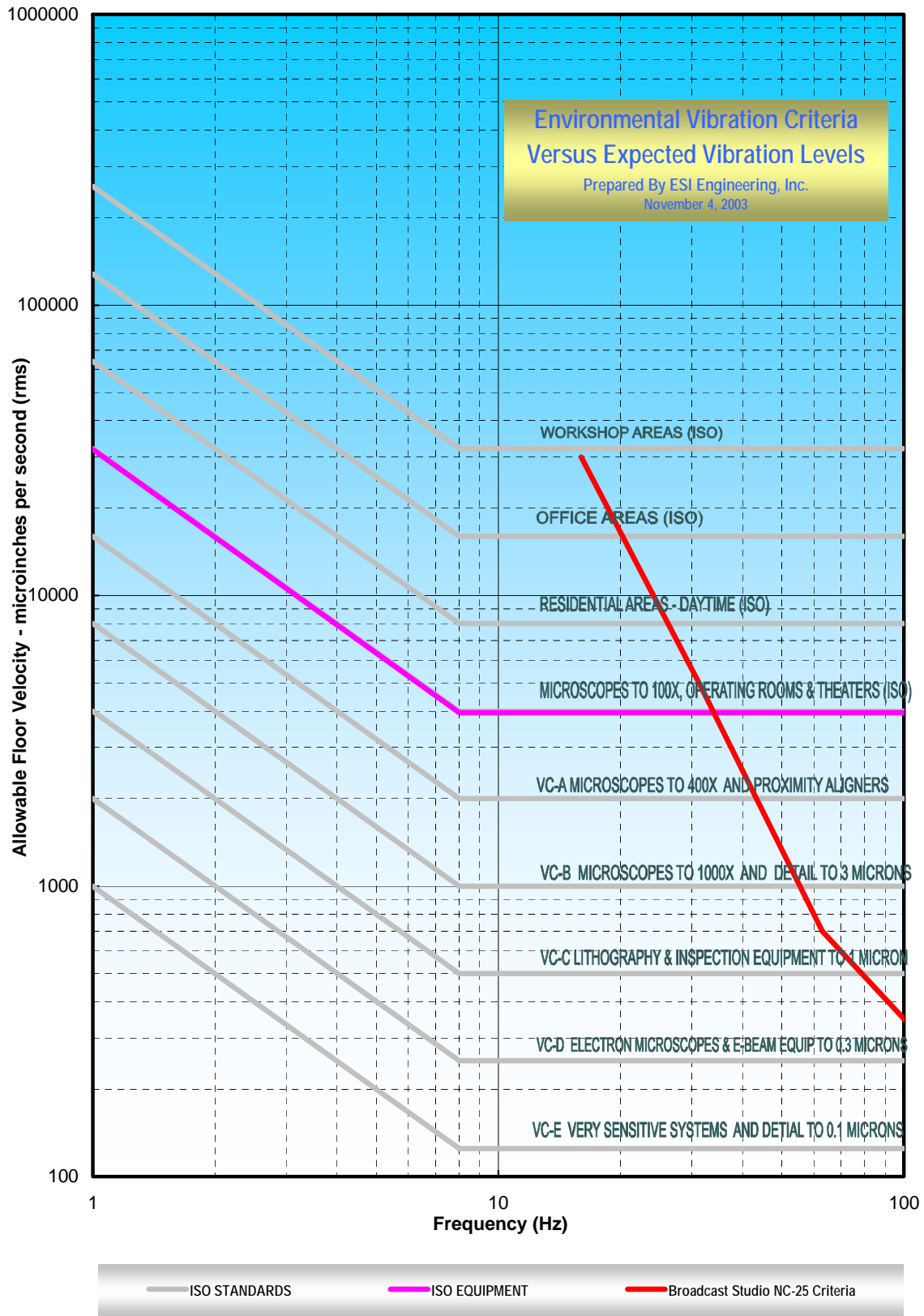


Figure 2.2-1 Environmental Vibration Criteria For People and Equipment In Buildings

Table 2.2-2 shows criteria for some equipment that may be used in this building (Reference 6). It should be noted that all of the equipment criteria discussed in this section pertain to the instantaneous maximum or "peak" vibration to which the equipment is exposed and not the average over time. The dominant adverse effect of vibrations on sensitive equipment generally is independent of the time variation. Overall, the office criteria is recommended for this facility and the operating room criteria is recommended for the broadcast studio floors as shown in Figure 2.2-1.

Table 2.2-2 – Vibration Criteria For Sensistive Equipment

Facility Equipment or Use	Vibration Sensitivity	Permissible Vibration	
		(min/sec)	(mm/sec)
Workshops (ISO Criteria)	Vibration is distinctly felt by people	32,000	400
Offices (ISO Criteria)	Vibration is felt by people	16,000	200
Residential Daytime; Computer systems; 20x Microscopes (ISO Criteria)	Vibration is barely felt by people	8,000	200
Operating rooms; Surgery; Bench microscopes up to 100x magnification; Laboratory robots; Residential (Nighttime) (ISO Criteria)	Vibration is not felt by people but starts to affect equipment	4,000	100
Bench microscopes up to 400x magnification; Optical and other precision balances; Coordinate measuring machines; Metrology labs; Optical comparators; Microelectronics manufacturing equipment - Class A	Vibration affects precision equipment	2,000	50
Micro-surgery, eye-surgery, neuro-surgery; Bench microscopes at magnification greater than 400x; Optical equipment on isolation tables; Microelectronics manufacturing equipment – Class B	Vibration affects microelectronics equipment	1,000	25
Electron microscopes up to 30,000x magnification; Microtomes; Magnetic resonance imagers; Microelectronics manufacturing equip - Class C	Vibration affects electron microscopes equipment	500	12
Electron microscopes at greater than 30,000x mag.; Mass Spectrometers; Cell implant & Microelectronics manufacturing equip – Class D	Vibration affects high powered electron microscopes equipment	250	6
Microelectronics manufacturing equipment; Unisolated laser and optical research systems - Class E	Vibration criteria very difficult to achieve	130	3
Notes:			
Class A: Inspection, probe test, and other manufacturing support equipment.			
Class B: Aligners, steppers and other critical equipment for photolithography with line widths of 3 microns or more.			
Class C: Aligners, steppers and other critical equipment for photolithography with line widths of 1 micron.			
Class D: Aligners, steppers and other critical equipment for photolithography with line widths of 1/2 micron; includes electron-beam systems.			
Class E: Aligners, steppers and other critical equipment for photolithography with line widths of 1/4 micron; includes electron-beam systems.			

3.0 VIBRATION IMPACT ASSESSMENT FROM LIGHT-RAIL TRANSIT

There are different levels of detail for determining vibration impact assessment from light-rail transit. The first level is a screening procedure using a table of distances to determine whether vibration-sensitive land uses are close enough to the rail line for impact from ground-borne vibration to be possible. The second method is a general assessment using generalized data to develop a curve of vibration data as a function of distance from the track. Vibration levels are estimated based on a series of adjustments and factors accounting for train speed, track condition and type of building. The third method is a detailed assessment based on actual measurements, specific soil information and characteristics of the building structure.

3.1 Preliminary Screening Procedure

The screening method allows a quick check to identify whether and where impacts from ground-borne vibration are likely. Table 3.1-1 shows screening distances in feet for steel-wheel trains traveling less than 100 mph. Some vibration impact should be expected.

Table 3.1-1 Screening Distances for Preliminary Vibration Assessment

Land Use	Train Frequency	Screening Distance – ft
Residential	Frequent	120
	Infrequent	60
Institutional	Frequent	100
	Infrequent	20

3.2 Generalized Vibration Assessment Procedure

The Generalized Assessment procedure uses a base curve of overall ground-surface vibration as a function of distance from the source. Adjustments are applied to this curve to account for factors such as track support system, train speed, track and wheel condition, building type, and receiver location within the building.

3.2.1 Baseline Vibration Curve for Rapid Transit or Light-Rail Vehicles

The generalized ground surface vibration curve for steel-wheeled train vibration shown in Figure 3.2-1 applies to rapid transit and light-rail vehicles. This curve represents typical ground-surface vibration levels assuming equipment is in good condition and traveling at speeds of 50 mph. The levels are adjusted to account for factors such as different train speeds, train equipment and geologic conditions than those assumed in the figure. The curve is based on measurements of ground-borne vibration data at a number of North American transit systems and is the upper range of measurement data. Baseline data can fluctuate by 10 dB below this curve.

It is our understanding the light-rail vehicles for the Hiawatha Line were manufactured by Bombardier Transportation Systems and we have assumed vehicles in the Central Corridor will be similar. Details of vehicles for the Hiawatha light-rail line are as follows:

Length: 94 feet Height: 13 feet Width: 9 feet
Weight: 107,000 pounds Wheel Diameter: 28 inches

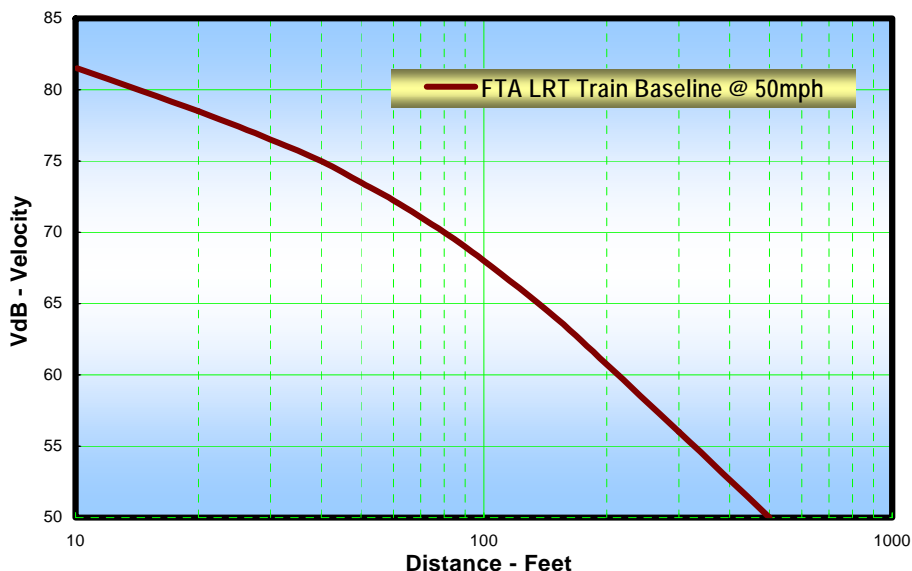


Figure 3.2-1 Generalized Ground-Borne Vibration Baseline Curve

3.2.2 Adjustments to Baseline Vibration

Adjustments from the baseline curve were made to develop vibration projections for specific receiver positions inside buildings. All of the adjustments are given as single numbers added or subtracted from the base level. The adjustment parameters are speed, wheel and rail type and condition, type of track support system, type of building foundation, and number of floors above the basement level.

Train Speed - The levels of ground-borne vibration vary approximately 20 times the logarithm of speed. Doubling train speed increases the vibration level approximately 6 decibels and halving the train speed reduces the level by 6 decibels. The following relationship was used to calculate the adjustments for other speeds:

$$\text{Train Speed Adjustment (dB)} = 20 \times \log(\text{train speed}/\text{speed}_{\text{ref}})$$

Train Condition - The most important factors for the train condition are the suspension system, wheel condition, and wheel type. It was assumed that the Central Corridor light-rail will have wheels in good condition at startup. However, when older vehicles are used on new track, it may be appropriate to include an adjustment for wheel condition. Wheels with flats or corrugations can cause vibration levels that are as much as 10 decibels higher than normal. It was assumed that there would be some vehicles with flats on the wheels going past the site in the future.

Track System and Support - This category includes the type of rail (welded, jointed or special trackwork), the track support system and the condition of the rail. The base curves all assume good condition welded rail. It was assumed the track through the Central Corridor would be welded rail.

Ground Propagation Characteristics – Some very important factors that must be accounted for in a General Assessment are the vibration propagation characteristics. It is well known that there are situations where ground-borne vibration propagates much more efficiently than normal. One possibility is that shallow bedrock acts to keep the vibration energy near the surface. Much of the energy that would normally radiate down is directed back towards the surface by the rock layer with the result that the ground surface vibration is higher than normal.

In the General Assessment procedure it is necessary to make a selection among propagation characteristics. It is usually appropriate to consider soft siltstone and sandstone to be more similar to soil than hard rock. Whether the track system is founded in soil or rock makes up to a 15 decibel difference in the vibration levels. Here the sandstone appears to be hard.

When considering at-grade vibration sources, the selection is between "normal" vibration propagation and "efficient" vibration propagation. Efficient vibration propagation results in approximately 10 decibels higher vibration levels. Some geologic conditions are repeatedly associated with efficient propagation. Shallow bedrock, less than 30 ft below the surface, is likely to have efficient propagation. When a building foundation is directly on the rock layer, there is no "coupling loss" due to the weight and stiffness of the building. Efficient vibration propagation was assumed at the MPR Expansion site.

Type of Building and Receiver Location in Building - Since annoyance from ground-borne vibration and noise is an indoor phenomenon, the effects of the building structure on the vibration must be considered. Wood frame buildings, such as the typical residential structure, are more easily excited by ground vibration than heavier buildings. In contrast, large masonry buildings such as this structure with spread footings have a low response to ground vibration.

Vibration generally reduces in level as it propagates through a building. A 1-2 decibel attenuation per floor is usually assumed. Counteracting this, resonances of the building structure, particularly the floors, cause some amplification of the vibration.

3.2.3 Generalized Vibration Impact Assessment

The generalized curve for surface vibration along with adjustments for specific operating conditions and buildings is compared with the criteria in Section 2.0 to determine whether vibration impact is likely. Usually, results of the general assessment are expressed in terms of an inventory of all sensitive land uses where ground-borne vibration from the light-rail may exceed the impact thresholds. The general assessment includes a discussion of mitigation measures that would likely be needed to reduce vibration to acceptable levels. These conservative assessments of the impact are shown in Table 3.2.3-1. See Appendix A.

Table 3.2.3-1 – General Assessment of Ground-Borne Vibration

Impact Inventory	Assumptions	New Expansion			Existing Building		
		New MPR Broadcast Floor	Private Office Floors	Open Office Floors	Existing MPR Broadcast Floor	Private Office Floors	Open Office Floors
Category		Special Buildings	Cat 3 - Institutional	Cat 3 - Institutional	Special Buildings	Cat 3 - Institutional	Cat 3 - Institutional
Distance Away -ft		40	22	40	50	40	40
Baseline Curve - VdB	50 mph	75	78	75	73	75	75
Adjustments							
Speed	30 mph ⁽¹⁾	-4.44	-4.44	-4.44	-4.44	-4.44	-4.44
Train Condition	Worn Wheels/Flats ⁽⁴⁾	10	10	10	10	10	10
Track System	Using Ballast Mats	0	0	0	0	0	0
Track Structure	At Grade on Soil	0	0	0	0	0	0
Propagation	Bedrock < 30 ft ⁽²⁾	10	10	10	10	10	10
Coupling	See Note 3	0	0	0	0	0	0
Receiver	2nd Flr Amplification	6	6	6	6	6	6
Estimated Vibration at Startup (VdB)		87	90	87	85	87	87
Estimated Vibration in the Future (VdB)		97	100	97	95	97	97
Vibration Impact Criteria (VdB)		65	75	75	65	75	75
Vibration Impact Expected		Very High	Very High	High	Very High	High	High

- Notes:
1. Maximum speed assumed is 30 mph
 2. Bedrock is less than than 30 feet below ground.
 3. Large multi-store concrete structure with footings on bedrock
 4. Worn wheels and/or flats were assumed to develop over time and into the future.

3.3 Detailed Vibration Assessment

A detailed assessment is appropriate because the General Assessment indicates that light-rail will create vibration impact at the building adjacent to the alignment. This would be the case along the west side of the building where the general assessment indicates vibration levels more than 5 VdB over the impact threshold.

The detailed assessment provides a means to determine general vibration propagation conditions along the corridor and develop specific projections for buildings where vibration impact is predicted by a general assessment. The goal of the detailed assessment is to develop a more accurate projection of ground-borne vibration using vibration analysis or monitoring that can analyze the magnitude and frequency spectrum of the vehicle traffic.

It should be recognized that many of the general assessment adjustments are strongly dependent on the frequency spectrum of the vibration source and the frequency dependence of the vibration propagation. The single number values are suitable for generalized evaluation of the vibration impact and vibration mitigation measures since they are based on typical vibration spectra. However, the single number adjustments are not adequate for detailed evaluations of impact of sensitive buildings or for detailed specification of mitigation measures. Detailed analysis requires consideration of the relative importance of different frequency components.

Local geologic conditions can have a very large effect on the impact of ground-borne vibration. Projections using the general assessment procedures are based on the high range of data from sites that appear to have "normal geology". This means that the actual levels of ground-borne vibration will usually be 5 VdB or more lower than projections developed using the general assessment curve and adjustments, and will rarely exceed projections developed using the general assessment approach. However, an important qualification is that there will be some, apparently rare, conditions where the actual levels of ground-borne vibration will be substantially higher than those projected using the general assessment procedures.

A detailed vibration assessment consists of three main steps:

Step 1 - Monitoring Existing Vibration and/or Analyzing Soil-Structure Interaction

Step 2 - Predicting Future Vibration and Vibration Impact

Step 3. Developing Mitigation Measures

A survey of the existing vibration may be valuable in documenting existing background vibration at sensitive buildings and measuring the vibration levels created by existing rail lines. All of the available analytical tools should be applied in a detailed assessment to develop the best possible estimates of the potential for vibration impact.

Controlling the impact from ground-borne vibration requires developing cost-effective measures to reduce the vibration levels. The detailed assessment can identify practical vibration control measures that will be effective at the dominant vibration frequencies and compatible with the given trackway structure and track support system.

3.3.1 Monitoring Existing Vibration and/or Analyzing Soil-Structure Interaction

For supporting information for Step 1, vibration monitoring was completed at the MDA/MDH site for the new Minnesota Departments of Agriculture and Health building along 12th Street in St. Paul, Minnesota on October 2, 2002. The test was done to determine the nature and magnitude of vibration levels in the ground from surrounding activities and vehicular traffic.

The tests were performed during the daytime hours between 6 a.m. and 9 a.m. to capture typical traffic and normal daytime activity. Accelerometers were positioned in the vertical and horizontal directions for the test. Vibration data were taken in 1-minute samples for an hour at a

time. Monitoring was completed at one location on the building site on the concrete curb of the parking lot approximately 25 feet north of the 12th Street curb.

The maximum vibration amplitudes measured from traffic on 12th Street were below the criteria for the MPR building for all tests taken. The tests showed resonant frequencies of the soil ranged between 10-15 Hz.

Vibration monitoring uses a transducer such as an accelerometer to sense motion. When the accelerometer is moved an electrical signal proportional to the acceleration is produced. The signal is amplified and analyzed with a spectrum analyzer to show the motion in terms of frequency and acceleration, velocity or displacement. The following instrumentation was used:

1. **Accelerometers** - PCB Peizotronics, Inc., Model 393C seismic accelerometer. These accelerometers produce 1 volt/g over a frequency range of .025 to 800 Hz.
2. **Amplifiers** - PCB signal conditioning amplifiers provide variable voltage amplification for each of the accelerometers.
3. **Spectrum Analyzer** - A Data Physics Corp. dual-channel, Fast Fourier Transform (FFT) spectrum analyzer was used to capture and analyze the vibration data.
4. **Personal Computer** - The data from the FFT spectrum analyzer is transferred directly to a PC that provides data analysis, output, and storage capabilities.

The spectrum analyzer was set up with 1600 lines of resolution. Peakhold was used in conjunction with the flattop window over the entire spectrum. The magnitude is shown in terms of rms velocity in units of inches per second. The amplitude at each frequency was retained. All measurements were narrow-band, Fast Fourier Transforms (FFT's) taken over the frequency range of 0-125 Hz.

The tests were performed during the daytime hours to capture typical traffic and normal daytime activities. Most traffic passing by the site was easily detected on the monitor. Several larger trucks passed by during the tests creating some of the higher vibration amplitudes.

Accelerometers were positioned in both the vertical and horizontal directions. Half of the testing was done with the horizontal accelerometer in the north-south and half with the horizontal accelerometer in the east-west direction. The maximum vibration displacement at each frequency in each group was determined and then plotted over the vibration criteria recommended for sensitive equipment operations. See Figure 3.3.1-1

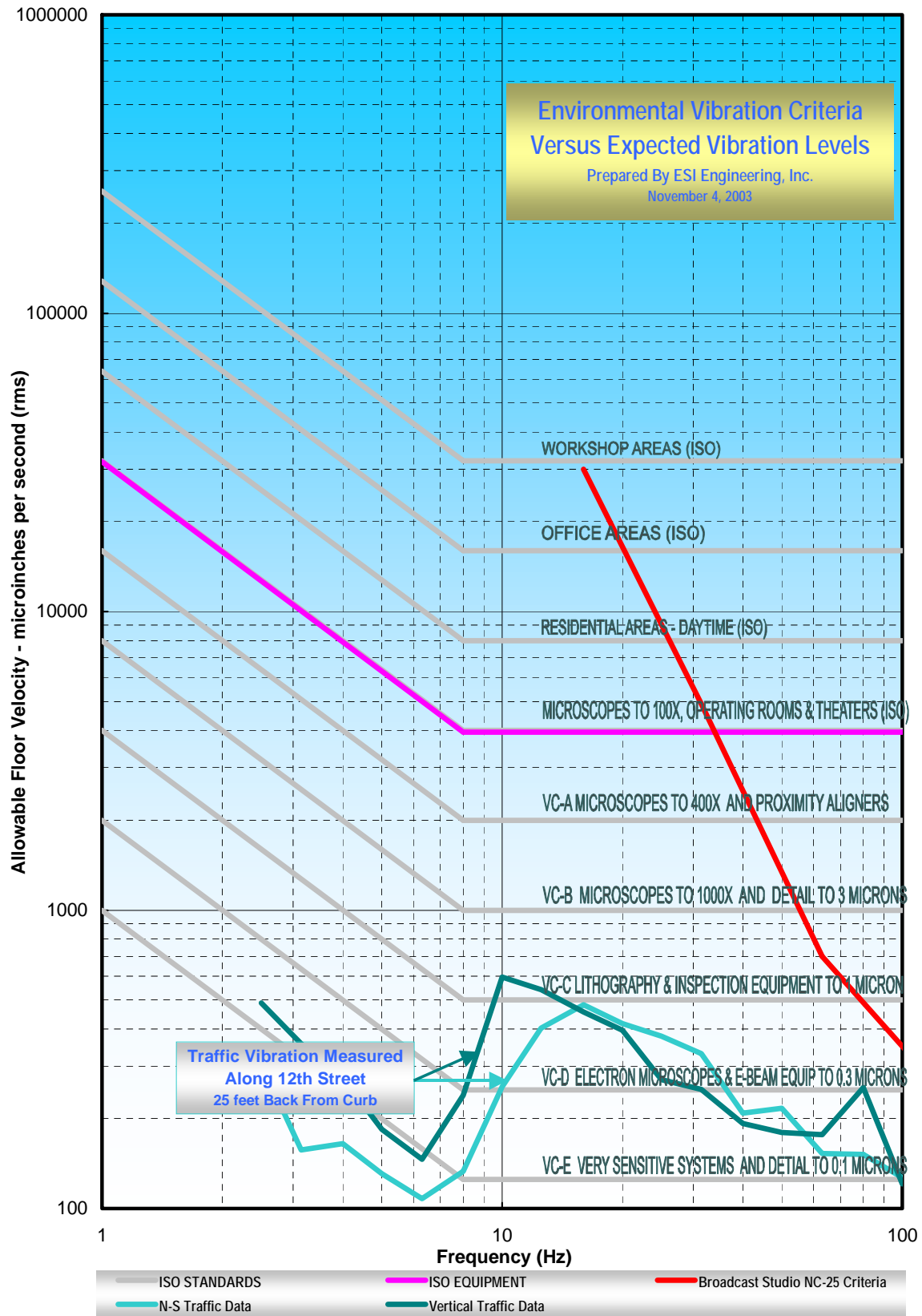


Figure 3.3.1-1 – Existing Vibration Monitored At The Site

3.3.2 Predicting Current and Future Vibration Impact From Structural Modeling

Vibration analyses of the building frame were completed using finite element analysis (FEA) and other computational methods to predict the impact of the LRT as part of Step 2. The structure and soil characteristics were modeled with finite element analysis beam, plate and boundary elements to determine the natural frequencies and mode shapes of the soil-structure interaction.

The site is underlain by (in descending order), Platteville Limestone, Glenwood Shale, and St. Peter Sandstone. The top of the bedrock (limestone) is close to existing site grades on the north side of the site, but the limestone and shale has been eroded away on the south side of the site forming a bedrock valley that has been filled by existing fill and alluvial sediments.

The top soils are silty sands down to 2-5 feet below the surface. Limestone and shale layers are below with blow counts ranging from 50-60. It is our understanding that the footings for most of the new expansion will be directly on sandstone bedrock just below the parking slab. Approximations for the dynamic shear modulus range from 15,000 psi for the upper silty sand layer to over 600,000 psi for the lower sandstone layer.

Computational methods developed by Richart, Hall and Woods (Reference 7) were used to predict ground-borne vibration attenuation through the ground and rock. Figure 3.3.2-1 shows the expected geometric attenuation of the LRT versus distance in the upper blue curve. The combined expected geometric and damping attenuation versus distance is shown in the lower red curve. The damping attenuation is based on the characteristics at the site. Notice the ground vibration does not attenuate very quickly with distance and is well above the limit for special buildings. Ground vibration from the LRT from Figure 3.3.1-2 was superimposed to determine the amplitudes of building vibration. See Appendix B for the computations.

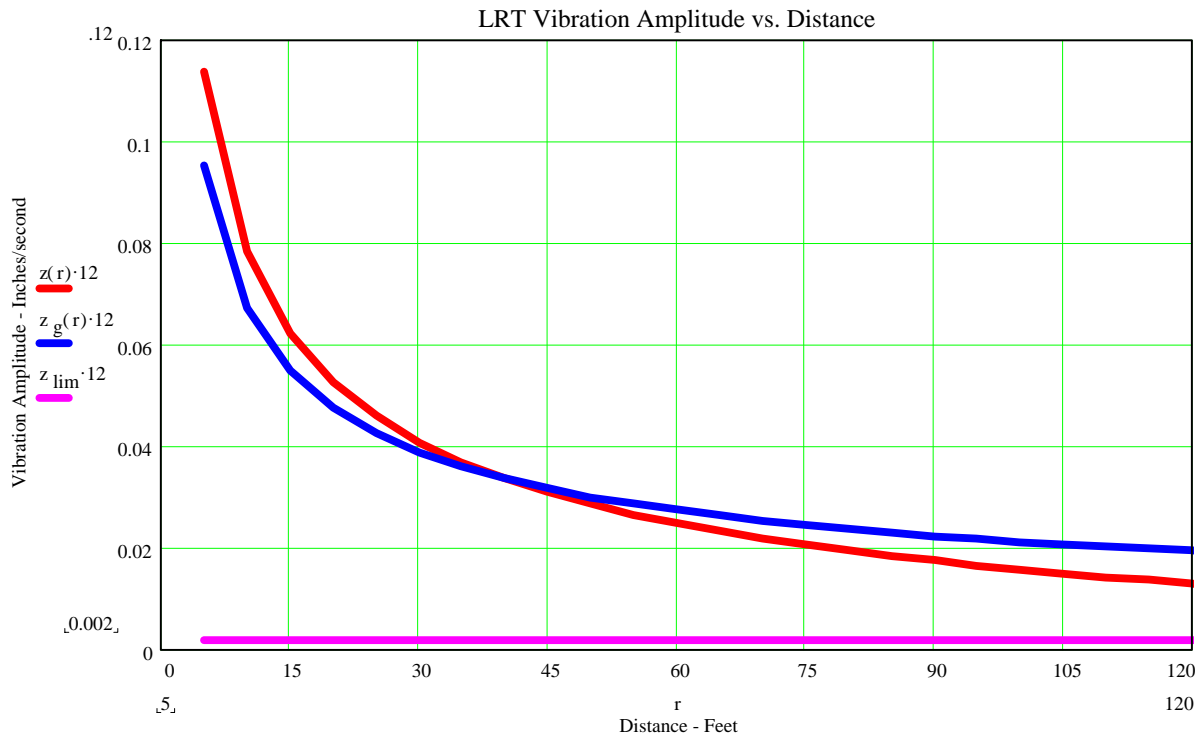


Figure 3.3.2-1 – Geometric and Damping Attenuation of the LRT for the New Expansion

3.3.2.1 Structural Modeling of New Expansion

An elevation of the structural framing system for the new expansion is shown in Figure 3.3.2-2. The floors are primarily a one-way structural concrete pan-joist system spanning in the east-west direction. The spans are short except for the open office area with 50 ft spans. Alignment of the LRT is expected to come closest to the west side of the building, approximately ± 22 feet from the west wall.

Three adjacent bays in the building represent all its structural and functional characteristics. Consequently, a three bay width E-W strip was modeled using FEA to extract stiffness, frequencies and amplitude information. Complete continuity was assumed from bay to bay including the columns below. Floor stiffness was based on the assumption of moments of inertia with uncracked concrete sections.

The FEA was completed to determine frequencies, modes and amplitudes. The natural frequencies of the soil-structure interaction show that light-rail vehicles passing at speeds of 30 mph will excite the structure and cause high vibration in the long spans and in the editing rooms.

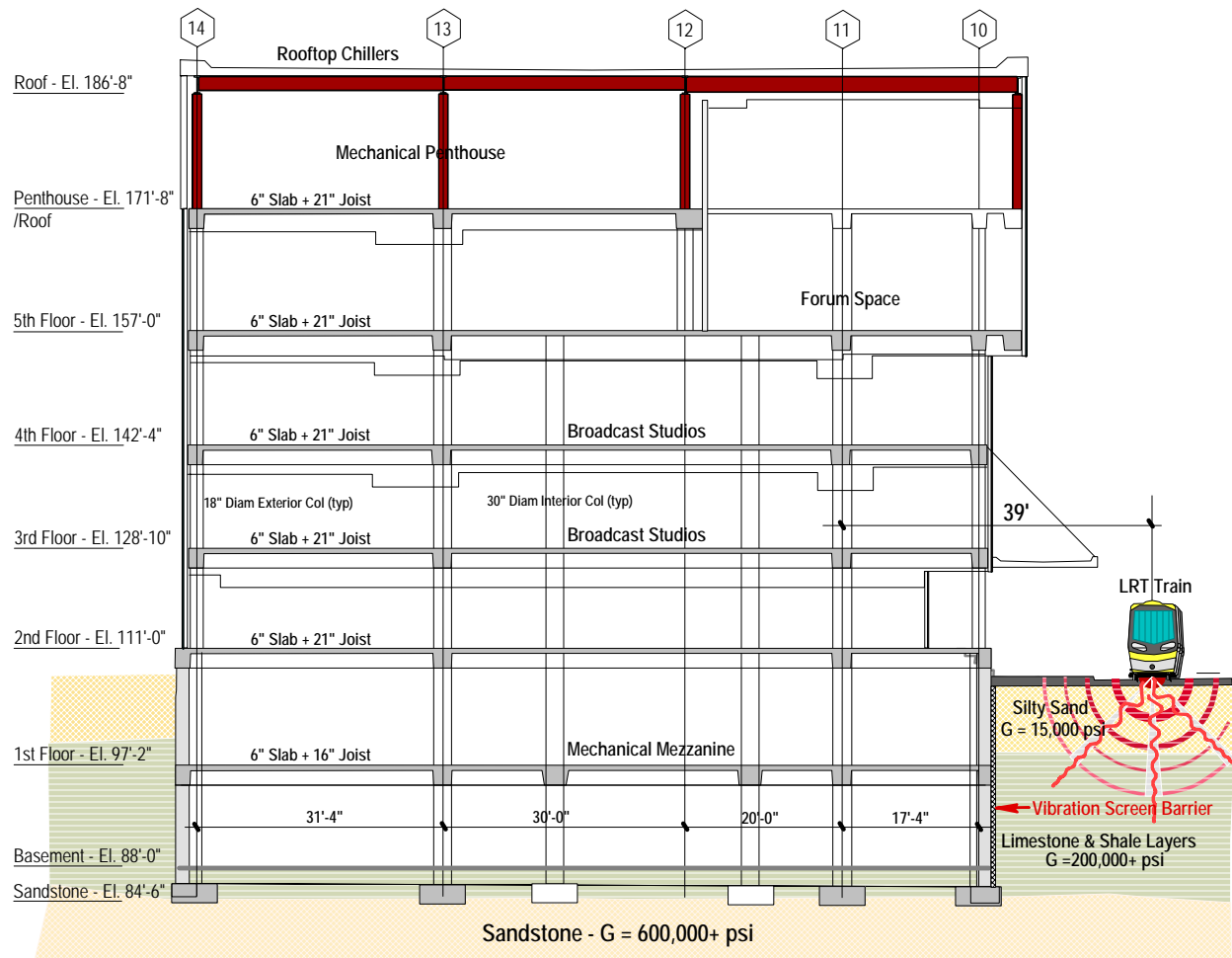


Figure 3.3.2-2 – MPR New Expansion - Section From Grids DD and GG

The predicted amplitude levels will exceed the criteria most notably in the 50-ft long spans and in the editing rooms. This suggests the floor should be stiffened to raise the natural frequency further above the resonant condition with the LRT speed. Four possible solutions for mitigation were studied as follows:

1. Increase the concrete strength of the floor system to 8,000 psi to increase the stiffness
2. Increase the depth of the long span beams and joists by 16 inches to increase the stiffness
3. Widen the long span beams of the floor system to 66 inches to increase the stiffness
4. Install ballast Mats under the LRT tracks

Results of the vibration analysis at the MPR Expansion are shown in Table 3.3.3 -1 below for the original design and four possible solutions for mitigation as follows:

Table 3.3.2-1 Results of Vibration From Light Rail – New Expansion

Key Point	Node Point	Floor Level	Grid Location		Floor Vibration - microinches/sec For Each Scheme - See Notes**					Allowable Vibration ips
			NS	EW	Original	Strength	Depth	Width	Ballast	
Open Office - Center of Long Span	1181	2	12.2	GG	41,846	29,852	15,512	32,011	13,273	16,000
Open Office - Center of Long Span	1681	3	12.2	GG	49,149	33,530	19,590	37,528	15,539	16,000
Open Office - Center of Long Span	2181	4	12.2	GG	49,442	35,022	19,937	38,354	15,619	16,000
Open Office - Center of Long Span	2681	5	12.2	GG	47,629	37,075	48,082	49,362	15,059	16,000
Shop Space	1186	2	12.2	EE.8	2,052	2,585	2,026	1,866	653	32,000
Broadcast Studio - Mid Span	1686	3	12.2	EE.8	4,371	4,824	4,504	4,131	1,378	4,000
Broadcast Studio - Mid Span	2186	4	12.2	EE.8	5,304	5,784	5,491	5,091	1,679	4,000
Forum Space	2686	5	12.2	EE.8	7,703	8,396	7,463	7,036	2,452	8,000
Conference Room/Shop Space	1204	2	11.8	EE	1,732	2,052	1,466	1,519	560	16,000
Broadcast Studio - Near Column	1704	3	11.8	EE	2,852	3,332	2,452	2,505	906	4,000
Broadcast Studio - Near Column	2204	4	11.8	EE	3,651	4,238	3,145	3,252	1,146	4,000
Forum/Prefunction Space	2704	5	11.8	EE	4,478	5,117	3,891	3,998	1,413	8,000
Editing Suites - Middle on Column line	1565	3	13.5	GG	18,844	17,884	19,350	18,871	5,944	8,000
Editing Suites - Middle on Column line	2065	4	13.5	GG	24,414	22,575	24,894	24,521	7,729	8,000
Editing Suites - Middle of Span	1567	3	13.5	GG.5	22,469	20,869	24,947	23,002	7,116	8,000
Editing Suites - Middle of Span	2067	4	13.5	GG.5	29,692	28,039	32,650	30,385	9,382	8,000
Private Office - Mid Span	1277	2	10.5	EE.5	2,479	2,959	1,546	1,653	800	16,000
Private Office - Mid Span	1777	3	10.5	EE.5	5,544	6,264	3,598	3,785	1,759	16,000
Private Office - Mid Span	2277	4	10.5	EE.5	6,663	7,756	4,238	4,531	2,132	16,000
Forum Space	2777	5	10.5	EE.5	9,622	10,741	5,944	6,157	3,038	16,000

**Notes:

1. Original - Original DD Structural Design Concept
2. Strength - Increase Concrete Strength of Floor (joists, beams, slab) to 8,000 psi
3. Depth - Increase Depth of 50 ft Long Span Bays from 30 inches to 46 inches
4. Width - Widen Beams of 50 ft Long Span at Columns from 22 inches to 66 inches
5. Ballast - Get Agreement from Central Corridor Planners for Ballast Mats on Cedar Street

The simplest solution to mitigating vibration from the LRT would be to get an agreement from the Central Corridor Planners (Ramsey County) to declare the MPR building a vibration sensitive site and have ballast mats installed under the tracks.

Figure 3.3.2-3 shows the variation in the expected second floor vibration for the original design. Figure 3.3.2-4 shows the response for the ballast mat condition.

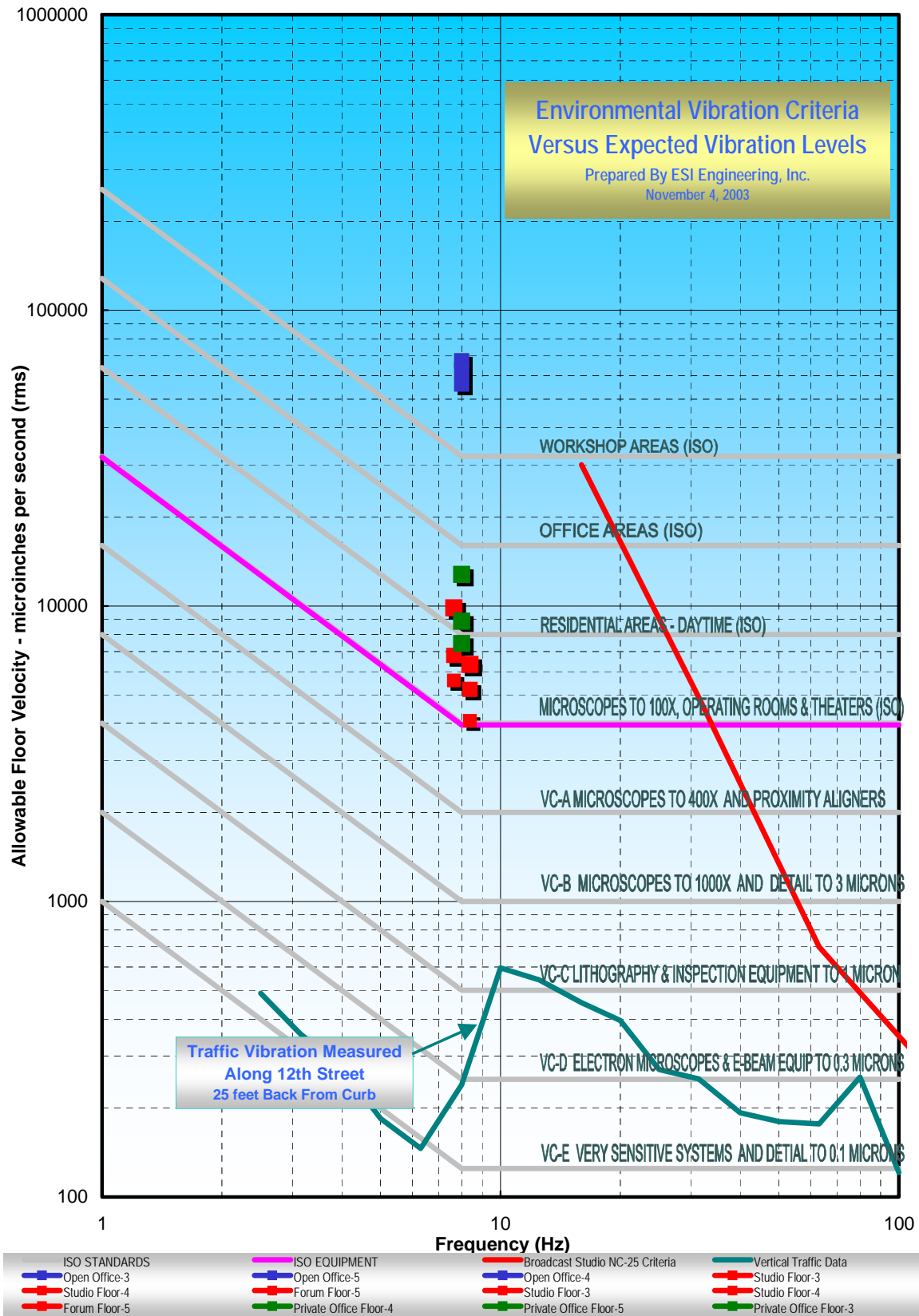


Figure 3.3.2-3 - Expected Floor Vibration From LRT With Original DD Concept

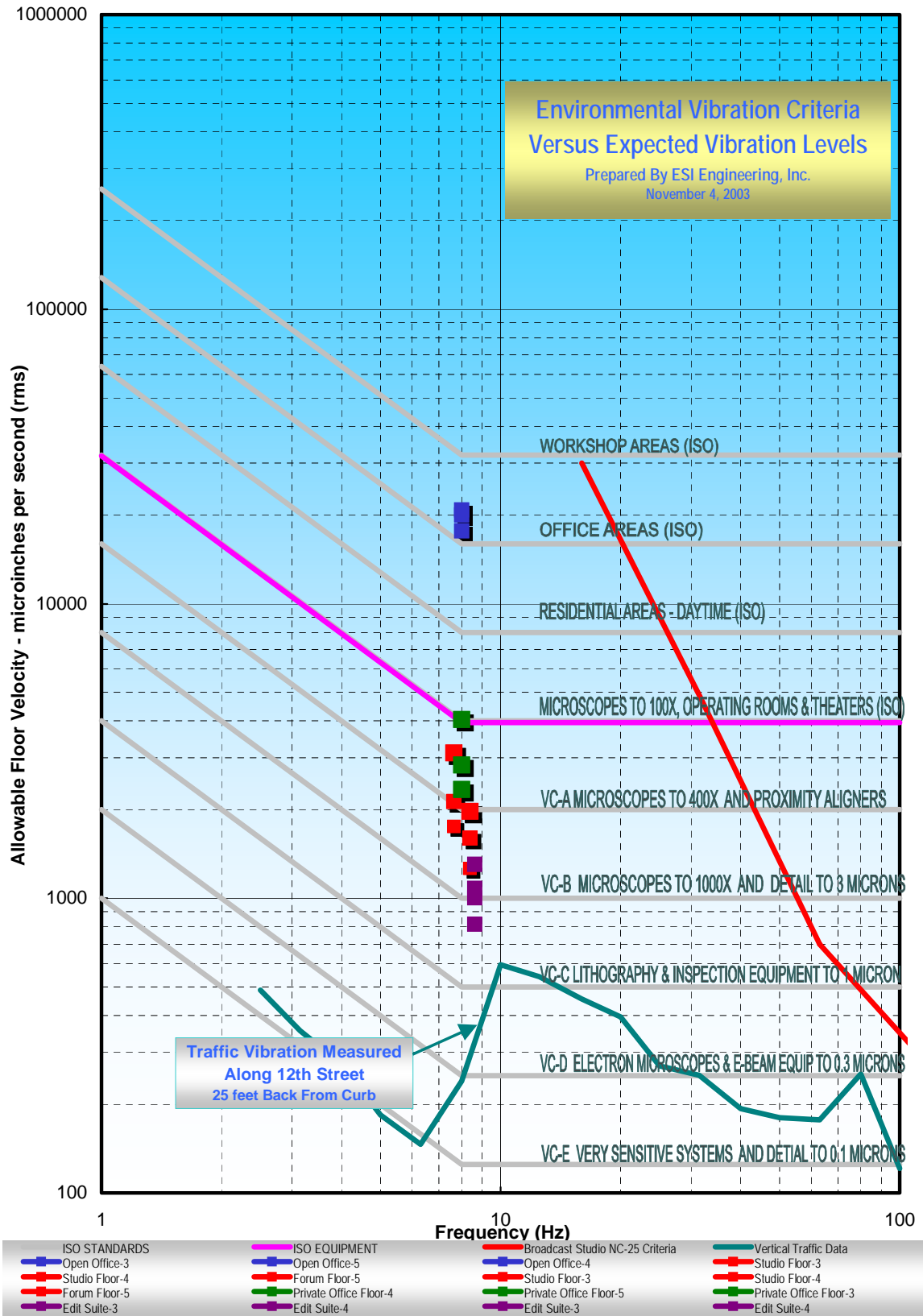


Figure 3.3.2-4 - Expected Floor Vibration From LRT With Ballast Mats

3.3.2.2 Structural Modeling of Existing Building

An elevation of the structural framing for the existing building is shown in Figure 3.3.2-5. The floors are primarily a one-way structural concrete pan-joist system spanning 21'-0" in the east-west direction. Alignment of the LRT is expected to come closest to the west side of the building, approximately ± 30 feet from the west wall.

Three adjacent bays in the building represent all its structural and functional characteristics. Consequently, a three bay width E-W strip was modeled using FEA to extract stiffness, frequencies and amplitude information. Complete continuity was assumed from bay to bay including the columns below. Floor stiffness was based on the assumption of moments of inertia with uncracked concrete sections. The foundation was assumed to be on 30-50 ft caissons piles into bedrock.

The FEA was completed to determine frequencies, modes and amplitudes. The natural frequencies of the soil-structure interaction show that light-rail vehicles passing at speeds of 30 mph will excite the structure and cause high vibration.

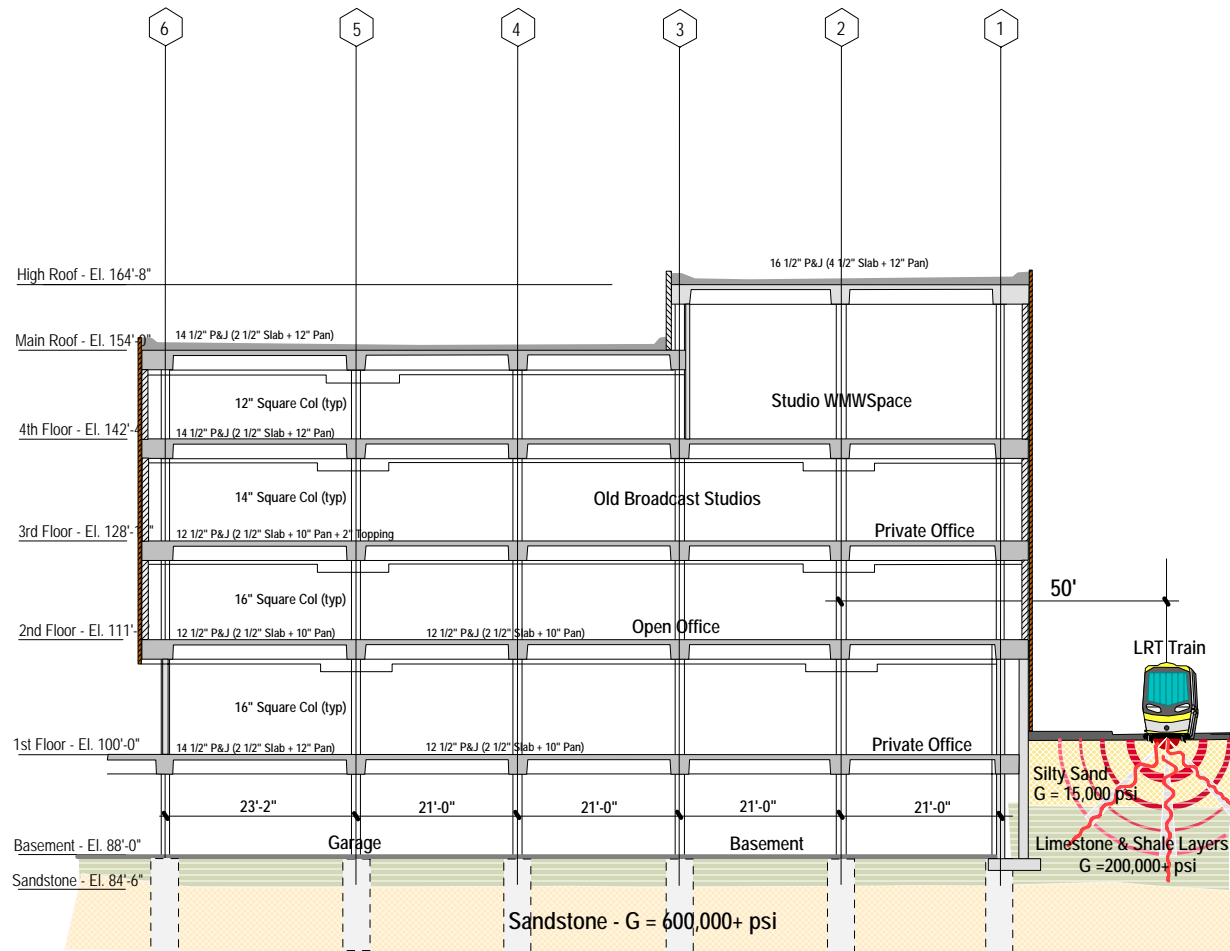


Figure 3.3.2-5 – MPR Existing Building - Section From Grids B to E

The results show a slight amplification from the ground vibration of the LRT. The vibration will not be significant if all the existing studios will be moved to the new expansion and the existing space will be converted to private and open offices. However, vibration will be an issue if the Maud Moon Weyerhauser studio continues to be a vibration sensitive floor. Results of the vibration analysis in the existing space are shown in Table 3.3.2-2.

Table 3.3.2-2 Results of Vibration From Light Rail – Existing Building

Key Point	Node Point	Floor Level	Grid Location		Floor Vibration microsinches/sec		Vibration Limit ips
			NS	EW	No Isolation	With Isolation	
Open Office	1476	1	1.5	CD	2,639	924	16,000
Private Office	2476	2	1.5	CD	5,197	1,819	16,000
Open Office	2771	2	2.5	BC	6,637	2,323	16,000
Open Office	3176	3	1.5	DE	13,433	4,702	16,000
Private Office	3476	3	1.5	CD	11,221	3,927	16,000
Existing Broadcast Studio	3766	3	3.5	BC	10,528	3,685	4,000
Existing Broadcast Studio	3771	3	2.5	BC	12,607	4,412	4,000
Existing Maud Moon Weyerhauser Studio	4171	4	2.5	DE	20,976	7,342	4,000
Existing Maud Moon Weyerhauser Studio	4176	4	2.5	CD	20,336	7,118	4,000
Existing Maud Moon Weyerhauser Studio	4471	4	1.5	DE	15,006	5,252	4,000
Existing Maud Moon Weyerhauser Studio	4476	4	1.5	CD	10,102	3,536	4,000
Existing Control Room	4455	4	5.5	DE	11,994	4,198	8,000
Existing Studio	4761	4	4.5	BC	25,934	9,077	4,000

3.3.3 Developing Mitigation Measures

The projected vibration impact at the site is expected to be high to very high based on the General Assessment procedure. The estimated vibration impact at startup of the LRT line should be minimal with new equipment. Over time the train condition may cause the vibration impact to exceed the criteria if wheels become worn and flats occur.

MPR Radio needs assurances that the LRT train condition will remain good. Otherwise, the maximum speeds when passing the site will need to be lower than currently planned.

The projected ground-borne vibration is much more than 5 decibels greater than the impact threshold. Very high Vibration impact is probable and some type of vibration control should be planned for the final design of the project.

3.3.5 Mitigation with Trench and Sheet-Wall Barriers

One possible mitigation concept sometimes discussed is to control vibration with trenches and sheet-wall barriers. This method of mitigation should be used as a means of last resort in a large-scale project because of the difficulty of construction, maintenance and cost. However, this method may work well at site.

Vibration isolation by trench barriers is based on reflection, scattering, and diffraction of the soil particle waves. Barriers may consist of solid, fluid, or void zones in the ground. No soil particle waves are transmitted with an open trench; thus it is the most effective vibration barrier but the most difficult to construct and maintain.

In this case, it may be rather easy to construct an isolation barrier with air space or with friable material to form a vibration control mat along the foundation wall with the building structure founded in bedrock.

Experimental studies have been conducted over the years to determine the effectiveness of trenches and sheet-wall barriers as vibration isolators and guidelines have been developed for the design of these barriers (Reference 7). The results of these studies and tests show:

- Sheet-wall barriers are not as effective in reducing amplitude of vertical ground motion as the trench barriers.
- Width of an open trench is not an important variable, in fact, a small crack or slit is sufficient to screen vibration waves. Trench width is determined solely on the basis of the trench-construction requirements.
- A trench can be considered effective if the amplitude of vertical surface motion is reduced to 50 per cent of the motion without the trench.
- The depth of a trench is based on wave velocity of the soil and frequency of the vibration source. For soils in this area, a depth of 20-25 feet would be required to effectively isolate train vibration.
- Soil layering, water table, and other foundation or building details can alter the vibration propagation phenomena and require additional considerations in the selection of a trench barrier

There are many problems and hazards associated with keeping trenches open for depths of 25 feet or greater. One promising possibility is to fill a trench with single or multiple rows of thin shell-lined cylindrical pipe such as PVC. These could be placed in vertical or horizontal rows with 6-inch diameter pipe. They must be capped on both ends to keep out water.

Because of the high vibration impact at this site, ESI does recommend trench isolation barriers be installed for controlling LRT vibration at this site. MPR would also be best served if the LRT train condition remains good and if the maximum speeds past the site were limited to 20 mph.

4.0 VIBRATION IMPACT ASSESSMENT FROM FOOTFALL EFFECTS

Vibration analysis of the structure was also completed using the same finite element model (FEA) and other computational methods to predict the impact of footfall.

A recommended procedure for designing a structural floor appropriate for sensitive equipment subjected to footfall effects is as follow:

- use a live load slightly greater than the building code requirements
- determine the maximum velocity due to walking-induced vibrations
- compare maximum velocities to the appropriate criteria in Figure 2.2-1
- make adjustments to the structure as necessary to satisfy the criteria

4.1 FEA Modeling Floor Vibration For Footfall Effects

Methods developed by Murray, Allen and Unger (References 6 and 8) were used to model dynamic footfall effects from walking. They have developed an idealized footfall pulse with characteristics of maximum force, pulse rise time that depend on walking speed and on the person's weight. Floor vibration from footfall effects for MPR Expansion was obtained using the following footfall pulse data:

Weight of Walker - 185 lbs
Walking Speed - 100 steps/minute

Footfall vibration rises dramatically with faster walking speeds in the range of 90-110 steps/minute. Typically, speeds below 75 steps/minute are not a concern for most floors. However, it has been our experience that the criteria needs to be met at walking speeds that are close to 90-100 steps per minute in long corridors or open spaces such as in the center of this building.

4.2 Results of Vibration Effects from Footfall Vibration

Footfall effects in the open office will not excite floors beyond the recommended criteria at the fastest walking speeds for the studios or the open office as shown in Figure 4.2-1 below. See Appendix C for calculations of footfall vibration.

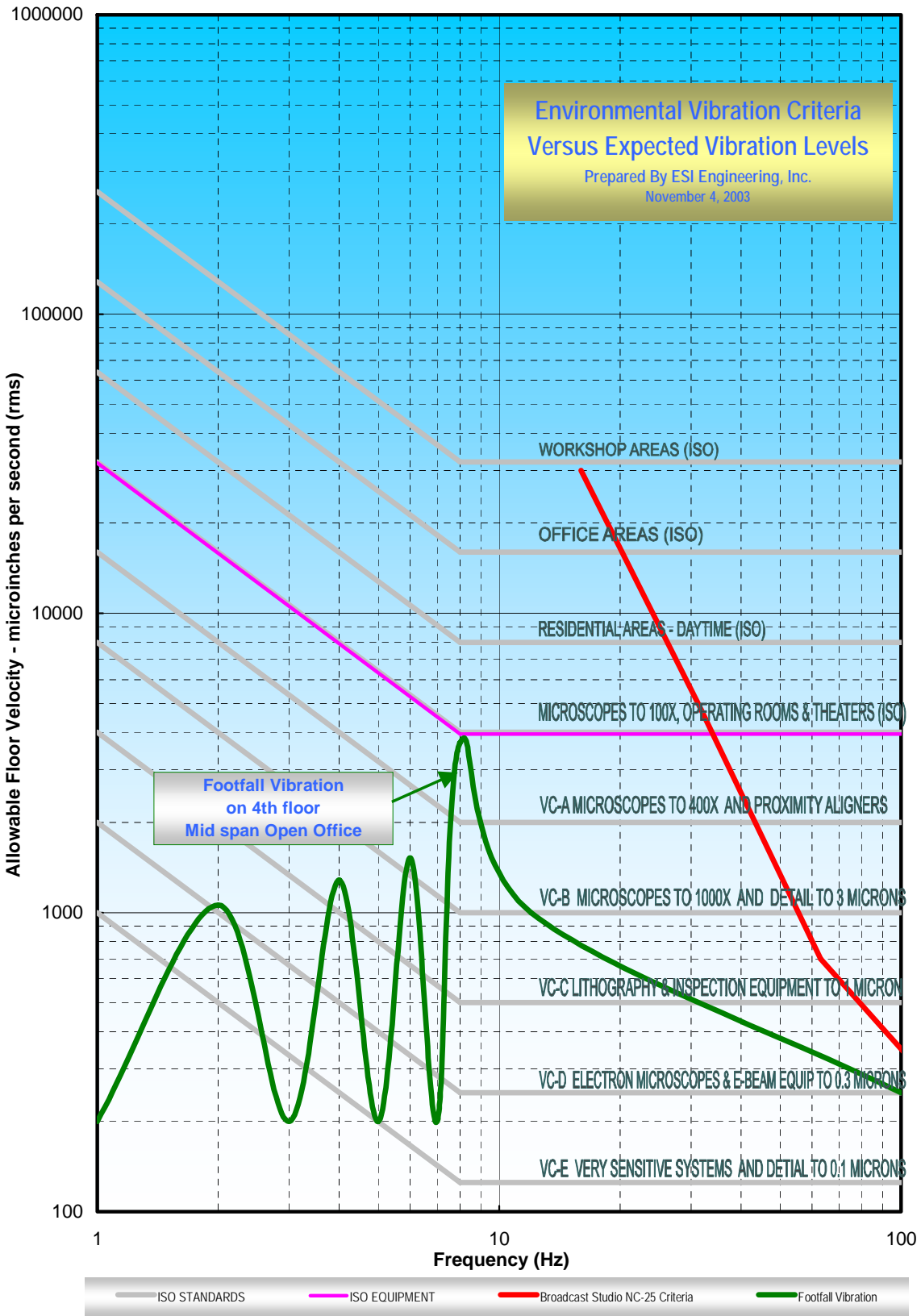


Figure 4.2-1 Results of Vibration From Footfall At 100 Steps/Minute

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Appendix A – Generalized Vibration Assessment

Appendix B – Geometric & Material Damping Computations

Appendix C – Footfall Vibration Assessment

