Reprinted from Proceedings of SPIE Conference 5933: Buildings for Nanoscale Research and Beyond
San Diego, CA, 31 Jul 2005 to 1 Aug 20

Vibration and Noise Criteria used to Evaluate Environmental Impacts of Transportation Projects on Sensitive Facilities

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ABSTRACT

The paper examines the methodologies and evaluation criteria advocated by the U.S. Federal Transit Administration (FTA) and Federal Rail Administration (FRA) used to determine whether or not a proposed alignment for a transportation project adversely impacts affected land uses, such as research & development and high-technology manufacturing. The criteria in question are applied as limits on vibration and noise at sensitive receiver locations. Both short-term construction and long-term transportation operations are typically considered, with the latter being the focus of this paper. A case study is presented of a proposed transit system that passes through four different soil zones, the operational characteristics that are required to generate a vibration level equal to the FTA/FRA advocated level of 65 VdB re: 1 micro-inch/sec, and the range of variability of the acceptability of the vibration conditions when considered in terms of third-octave bands compared to vibration criterion (VC) curves that are used as the design performance targets of vibration-sensitive facilities.

Keywords: Vibration, noise, transportation, environmental, criteria, impact, force density, transfer mobility

1. INTRODUCTION

The continued functionality of existing facilities utilizing vibration and noise sensitive equipment is placed at risk when changes to transportation infrastructure and operations are proposed. A lack of appropriate detail often results when environmental studies of vibration and noise impacts are prepared without regard to the needs of research instrumentation and processes. This paper illustrates the manner and extent of these technical issues.

When project sponsors seek funding from U.S. Federal sources, environmental impacts are evaluated and disclosed consistent with regulatory interpretations of the National Environmental Protection Act (NEPA). Both the Federal Rail Administration (FRA) and Federal Transit Administration (FTA) have developed guidance manuals in which calculation methods are promulgated for initial screening, general assessment and detailed analysis. Greater accuracy is claimed as operational alternatives, alignment, technologies, and site specific propagation information is established.

The impact criteria adopted by FRA and FTA are essentially the same and have two notable shortcomings when applied to sensitive facilities: they are based on summations without frequency-specific thresholds; and the levels of impact are too high relative to the sensitivity of critical research instrumentation. For example: the potential for vibration damaging structures is evaluated via comparisons to peak particle velocity (PPV); vibration impacts on people are evaluated in terms of various maximum root-mean-square (RMS) velocity levels; and noise impacts on people are evaluated in terms of various A-weighted sound pressure levels. Deliberate effort is required on the part of facility owners and technical experts to ensure that the parameters of environmental studies address the needs of critical research instrumentation and processes so that adequate mitigation is designed into viable projects.

2. ENVIRONMENTAL IMPACT CRITERIA

Ground-borne vibration from any type of transportation vehicle will rarely be high enough to cause any sort of building damage, even minor cosmetic damage, when evaluated in terms of single events. A real concern is that the vibration will be intrusive to building occupants and/or interfere with vibration sensitive equipment at levels that are considered imperceptible. Ground-borne noise (i.e. interior noise arising due to vibrations traveling through intervening soil as opposed to an airborne propagation path) could be a potential impact for underground transit operations. The significance depends upon the noise level relative to that due to air-borne propagation to the building façade, that transmits through the window/wall construction of a building typically exceed the ground-borne noise within a building.

Table 1 shows FTA/FRA[1,2] impact criteria as a function of maximum RMS level for ground-borne vibration as a function of land use. Similar approaches have been adopted for application to projects subject to FRA review and approval. The RMS value can be calculated from time series samples by energy averaging the data for a period of +/- 0.5 seconds about each sample. In practice, measurements of existing conditions or calculations of future vibration conditions are sometimes restricted to the vertical axis, resulting in lower values than would be the case for a three-axis summation. There is no explicit commentary within FTA guidance documents on this aspect of the methodology. No discussion is given within the FTA/FRA documents regarding band-pass filtering of data to eliminate low- or high-frequency data, although in practice a range of 1–100 Hz is a range is utilized when band-pass filtering is employed.

A high sensitivity Category 1 land use is one for which low vibration levels are essential for operations within, regardless of human perception or annoyance, including laboratories, high-tech manufacturing, and some medical facilities. Some buildings, such as concert halls, TV studios, and recording studios can be very sensitive to vibration and are evaluated as Category 1 properties with sensitivity to ground-borne noise. Other Category 1 properties, with less stringent thresholds, include auditoriums and theaters. For the purposes of this paper the 65 VdB re: 1 micro-inch/sec FTA/FRA criterion is of interest and will be assumed applied as a restriction on vibration for a single axis. Moderate sensitivity Category 2 land uses include anywhere that people sleep, such as residences, hotels, hospitals, and apartments. Moderate sensitivity uses include conference/convention centers. Low sensitivity Category 3 land uses include day-use facilities without sensitive equipment, but housing activities that may be vibration sensitive. Includes schools, offices, some laboratories, and institutions. For this technical noise and vibration study, warehouse and heavy industrial uses that might otherwise be overlooked are considered to be Category 3 land uses.

3. THIRD-OCTAVE BAND VIBRATION CRITERION CURVES

Figure 1 and Table 2 illustrate the third-octave band criterion curves that are most commonly applied[3,4] to each orthogonal axis when designing a vibration sensitive facility. Each third-octave band is considered independently of the others, and no time-domain restriction is given on the total vibration velocity level. In principal this means that a vibration-inducing event that has all of its energy restricted to a single third-octave band is as acceptable as an event having energy at or below the curves shown for every third-octave band where a given curve is applied.

4. REPRESENTATIVE VIBRATION VELOCITY LEVELS

On steel-wheel, steel-rail train systems, ground-borne vibration is produced by the dynamic loading of the passing train and also due to the interaction of the steel wheels rolling on the steel rails. Factors that influence the potential impacts of ground-borne vibration include vehicle speed, vehicle suspension characteristics, wheel-rail maintenance, track type, track fixation, track support, soil and rock properties, soil-foundation interaction, building mass and number of floors. A continuously welded rail minimizes wheel impacts at rail joints and results in significantly lower vibration levels than with jointed rail, and isolated switches and crossovers. The scale of roughness and state of wear of wheels and rails influence vibration impacts at the wheel-rail interface. The mitigation of ground-borne vibration usually requires modifications to the track support system to improve the vibration isolation characteristics of the system.

Figure 2 shows the curves advocated by FTA (Figure 10–1 of referenced document) for estimating the vibration level as a function of distance from a particular class of transportation vehicle that carries passengers as part of a transit network. For purposes of this paper the level is assumed to be restricted to a single axis. From this information, the distance to a 65 VdB total level is about 135 ft for a speed of 50 mph. Variations from the curves shown for rail vehicles often display a dependency 20 $\log_{10}$ (actual speed / reference speed) given the role that variations of kinetic energy play in determining the vibration velocity level. From this, the distance to 65 VdB is estimated to be 80 ft at 29 mph.

The FTA curves are reportedly intended to represent an upper range of measurement data for various systems under apparently similar conditions (although the underlying data is not shown), with an excess of more than 1–2 VdB claimed within the FTA guidance document to be unlikely unless there is a maintenance issue, such as rail corrugations or wheel flats that can increase vibration levels substantially, on the order of 10 VdB above a well-maintained condition. The rapid transit curve may be considered to represent either an embedded or direct fixation track system, without the benefits of resilient fasteners, ballast mats, or floating slab. Soil-structure coupling losses/gains are another area of interest for estimating vibration impacts.

A variant of a parametric model[5] incorporating Rayleigh, body, and surface waves was utilized to generate the approximations shown in Figure 2. This is, of necessity, an approximation of an FTA advocated curve for which data are not publicly available. A discussion of the accuracy of the curves is outside of the scope of this paper but involves the incoherent summation of these three components and modifications of the divergence to accommodate line-source versus point-source propagation issues, with the sole objective of matching the FTA reference curves.

5. TRANSFER MOBILITY CONCEPTS

Whereas noise emissions from automobiles, medium trucks, and heavy trucks are audibly different, ground-borne vibration for these same vehicles is typically most energetic at frequencies below the 20 Hz frequency that represents the typical lower limit for human audibility of sounds. Structural vibrations below this frequency may thus be perceived as vibration. Structural vibrations above this frequency may be perceived as both vibration and as sound. The frequency content and amplitudes of vibration is characterized at the source using force density (L_f in logarithmic terms).

The propagation of vibration through the ground is more complicated than the propagation of sound through air, and subject to a greater range of variability due to the diversity of ground types. The propagation loss through ground can be determined using ambient sources such as vehicular traffic and trains. It can also be measured using a controlled source of vibration energy, frequently consisting of either an impulsive sources or steady state oscillatory sources. An impulsive source such as a seismic hammer of known weight and drop height can produce impulses in the ground. The frequency dependent propagation loss can be determined using a line of vibration measuring transducers and equipment to record and analyze the measured response. Alternately, an oscillatory source of excitation like an electro-dynamic “shaker” can be employed. The raw field data obtained are in the form of point-source transfer mobility measurements, as the impacting force is applied over a limited area of the ground. Post-processing software numerically integrates the data in order to estimate the line-source transfer mobility (to approximate the effect of a passing train, approximated as a line source) for each frequency band as a function of distance for each site. The line-source transfer mobility represents the response of the ground to a linear vibration source of a known length, such as a train with a length of 261 ft, as a function of increasing perpendicular distance away from the tracks.

To infer the force density of a train, measurements of the transfer mobility using the controlled source of vibration (for instance, a seismic hammer) are performed along a line perpendicular to the track. The decay of vibration with distance is thus known, and when a train passes by the event can be used to estimate the force density input of the train having a known speed and overall length. With this information at hand, it is possible to characterize the general efficiency of ground vibration propagation at representative sites and to estimate future projected vibration levels caused by trains on a site-specific basis. The decrease of vibration with increasing distance over a wide frequency range (a transfer function) can be determined from this transducer array measurement. The terminology employed within the FTA manual to describe this transfer function for a line source like a train, is transfer mobility (TM_{line}). Adjustments to account for building characteristics can be considered (C_{build}) such as ground-foundation coupling.

The vibration velocity level, L_v, in VdB, as a function of frequency and distance from the track is the sum of the force density and transfer mobility. Ground-borne noise levels can also be calculated as an A-weighted noise level, L_{pA}, from this information by applying a correction to estimate the sound radiated by walls and the effects of absorptive surfaces within a room (K_{rad}) and applying an A-weighting to the un-weighted vibration velocities ($K_{A\text{-}weight}$). The logarithmically based equations for these calculations are shown below:

$$L_v = L_f + TM_{line} + C_{build} \qquad (1)$$

$$L_{pA} = L_v + K_{rad} + K_{A\text{-}weight} \qquad (2)$$

The combination of the force density curves and transfer mobility, functions provides an estimate of vibration at the ground surface as a function of distance from the tracks, the horizontal distance for surface tracks and the diagonal distance in the case of subways. Adjustments are used to account for train speed, mitigation measures, and building foundation. The projections are based on characterizing the magnitude of the vibration forces caused by a transit train in terms of a force density and characterizing the propagation through the soil with a transfer mobility function. The force density is assumed to represent the combined effects of the vehicle suspension, the wheel and rail condition, and the track support system and is assumed to be independent of the local geologic conditions.

Given the frequency-dependent characteristics of a vibration source (i.e. force density) for the train source of arbitrary length, the vibration level can be calculated at a distance. For this calculation, actual train vibration data are gathered at a reference site where trains are already operating with a comparable number of cars, known speed, and track conditions (for instance, continuous welded rail that is either at-grade embedded or elevated slab track with direct fixation).

6. CASE STUDY

Vibration propagation from the source to nearby receivers depends on many geological factors such as soil type and bedrock depth below grade. Normal vibration propagation is expected if the bedrock is more than 30 feet below the surface. In areas of shallow rock, vibration propagation is more efficient due to the constraints imposed by the transition from soil to rock. In areas of saturated ground or alluvial soil types, concentrations of vibratory energy near the ground surface can result in vibration problems at greater distances from the source of vibration. In general, wetland areas with silty soils have a higher than typical response at higher frequency, but the resulting vibrations diminish rapidly with distance. Areas with shallow rock or shallow, stiff soil have a high, narrow peak in the high frequencies, which may result in high vibration levels relatively close to the track. Areas with sandy soil or deep rock have an increased response at lower frequencies and the vibrations tend to diminish more slowly with distance. Table 3 summarizes the characteristics of four soil zones where tests of vibration propagation to determine the transfer mobility were performed[6] to facilitate an environmental study of a proposed light-rail transit project.

Figure 3 shows the expected variability of vibration velocity level, L_v, at a distance of 200 ft from the track centerline at an exterior location. The speed has been adjusted uniformly to 29 mph until the total vibration velocity level of each of the four soil zones is at or below 65 VdB at the 200 ft distance, which contrasts with the FTA assertion that the propagation curves in Figure 2 are conservative. The force density is derived from measurements[6] of a system operating Sumitomo Nippon Sharyo P865 technology with concrete ties and exposed rock ballast. The assumed train length with three 87 ft cars is 261 ft. Each 94,000 lb car is articulated, double-ended, and has six axles. Figure 3 contains a fifth soil zone as present at the site of the Blue Line force density testing, although the characteristics of this soil are not known in detail. Table 4 summarizes the results including the 56 VdB to 65 VdB range of the total RMS level due to soil variations alone. The 10 Hz and 12.5 Hz third-octave band shows the highest vibration velocities with a range of variability on the order of 11 VdB and 9 VdB, respectively. For the 50 Hz third-octave band the range of variation is 28 VdB. The linear range is from 500 to 1400 micro-inch/sec, assuming that the FTA criterion of 65 VdB for total vibration velocity level is applied to a single axis, such as the vertical. The VC compatibility therefore ranges from VC-A down to VC-C, without consideration of soil-structure interaction.

7. CONCLUSION

The results shown above illustrate that soil type is a significant factor when evaluating vibration propagation. In terms of the application of the VC to the evaluation of facility design, the results ranged from VC-A down to VC-C for operations of a representative light-rail transit system at 29 mph and 200 ft offset distance. To arrive at VC-D or lower conditions would require increased distance due to a change of transit alignment, reduced speed operation, reliance upon losses due to soil-structure interaction, or inclusion of vibration reducing features into the track such as resilience fasteners, ballast mats, or floating slab. Poor track maintenance or track features such as switches would generally increase vibration levels, perhaps interfering with the continued viability of the nearby facility of concern.

REFERENCES

1. U.S. Federal Transit Administration, “Transit Noise and Vibration Assessment,” DOT–T–94–16, Washington, D.C., 1995.
2. U.S. Federal Rail Administration, “High Speed Ground Transportation Noise and Vibration Impact Assessment,” DTFR53–94–A–00056, Washington, DC, 1998.
3. Institute of Environmental Sciences (IEST), Appendix C in Recommended Practice RP-012, “Considerations in Clean Room Design,” IES-RP-CC012.2, Institute of Environmental Sciences, Rolling Meadows, IL, 2005
4. International Standards Organization, ISO 2631 “Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration, Parts 1 and 2,” Part 1 was updated 15 July 1997 and Part 2 was updated 1 April 2003.
5. Hal Amick and Michael Gendreau, “Construction Vibrations and their Impact on Vibration-Sensitive Facilities,” ASCE Construction Congress 6, Orlando, Florida, 2000.
6. Acentech Report No. 334, “Noise and Vibration Technical Report The Orange County CenterLine Project,” 2003. The principal author of this report is Todd Busch, formerly of Acentech. Acknowledgement is owed to Jeff Zapfe and Jonathan Kemp of Acentech for their fundamental contributions determining the transfer mobility for each of the four soil zones and determination of the force density of light-rail vehicle operating on the Los Angeles County Metropolitan Transportation Authority Blue Line. The latter data on force mobility data was not ultimately employed for the CenterLine evaluation since the proposed technology involved sufficiently different rail vehicles and methods of track fixation.

Table 1: FTA/FRA 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 (1) Events	**Infrequent (2) Events**	**Frequent (1) Events**	**Infrequent (2) Events**
Category 1: Buildings where low ambient vibration is essential for interior operations.	65 VdB (3)	65 VdB (3)	(4)	(4)
Category 1: Concert Halls, TV Studios, Recording Studios	65 VdB (5)	65 VdB (5)	25 dBA	25 dBA
Category 1: Auditoriums	72 VdB	80 VdB	30 dBA	38 dBA
Category 1: Theaters	72 VdB	80 VdB	35 dBA	43 dBA
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

1. “Frequent Events” is defined as more than 70 vibration events per day.
2. “Infrequent Events” is defined as fewer than 70 vibration events per day. This category includes most commuter rail systems.
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.
4. Vibration-sensitive equipment is not influenced by ground-borne noise.
5. If the buildings 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.

Figure 1: Generic Vibration Criterion (VC) Curves for Vibration-Sensitive Equipment (showing also the ISO guidelines for people in buildings)

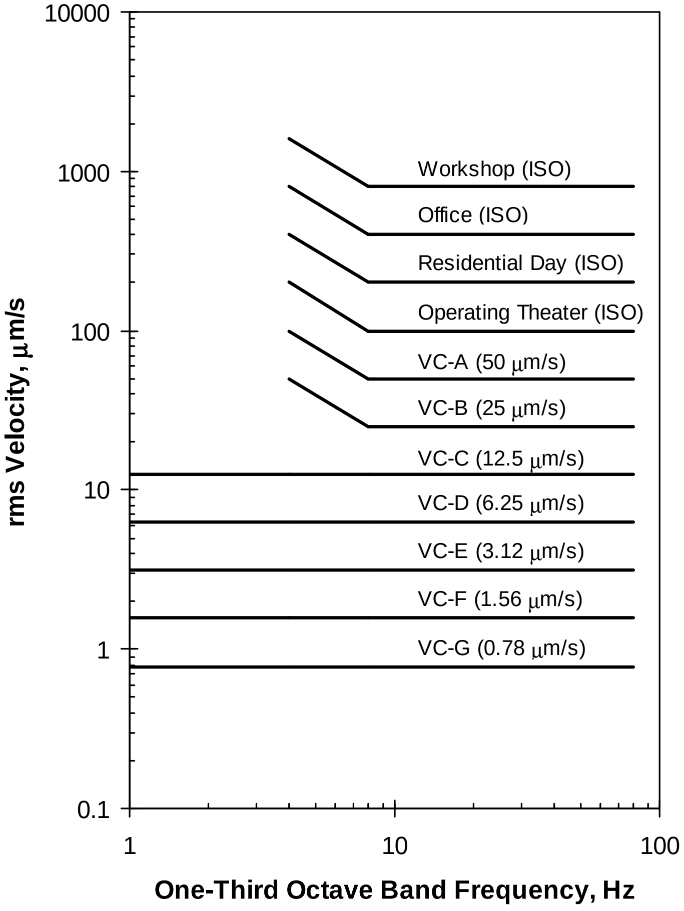


Table 2: Numerical Definition of VC Curves shown in Figure 1

Criterion	Definition
VC-A	260 μg between 4 Hz and 8 Hz; 50 μm/s (2000 μin/s) between 8 Hz and 80 Hz
VC-B	130 μg between 4 Hz and 8 Hz; 25 μm/s (1000 μin/s) between 8 and 80 Hz
VC-C	12.5 μm/s (500 μin/s) between 1 and 80 Hz
VC-D	6.25 μm/s (250 μin/s) between 1 and 80 Hz
VC-E	3.1 μm/s (125 μin/s) between 1 and 80 Hz
VC-F	1.6 μm/s (62.5 μin/s) between 1 and 80 Hz
VC-G	0.78 μm/s (31.3 μin/s) between 1 and 80 Hz

Figure 2: Comparison of FTA Generalized Ground Surface Vibration Curves versus Calculations from Parametric Model

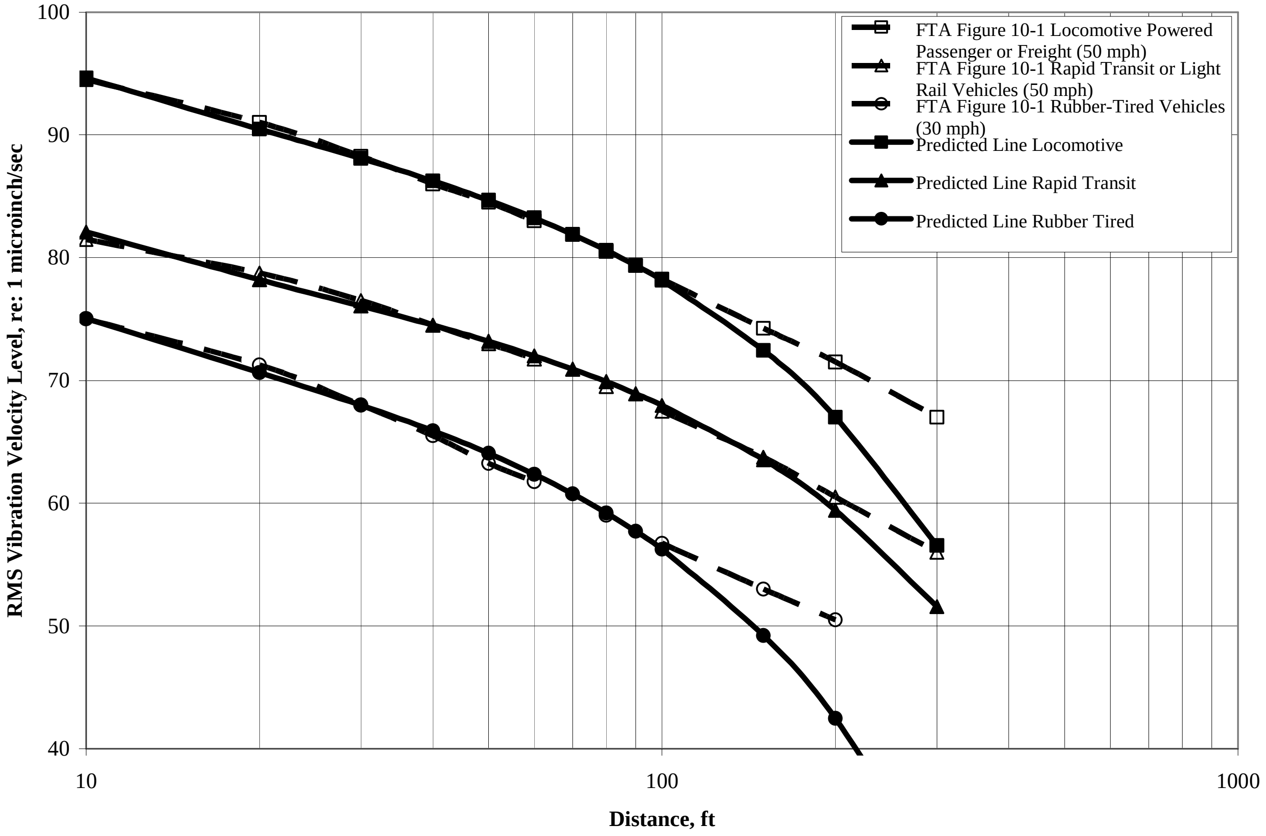
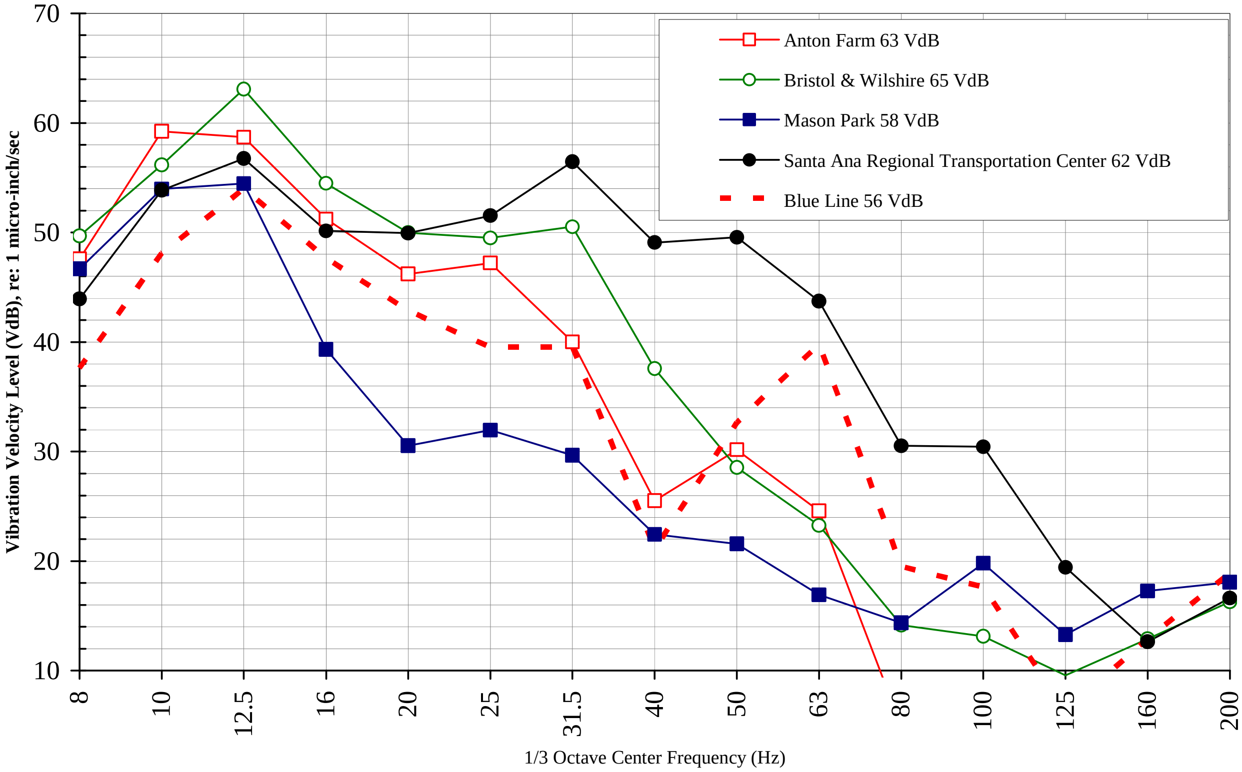


Table 3: Vibration Propagation Test Site Locations

ID	City	Site Description	Soil Type	Water Table (below grade)
TM1	Santa Ana	Near Santa Ana Transportation Center	Holocene Alluvium (silt)	50+ ft.
TM2	Santa Ana	Near intersection of Bristol St. and Wilshire	Holocene Alluvium (silt)	20 ft.
TM3	Costa Mesa	Anton Farm	Holocene Alluvium (silt)	≤5 ft.
TM4	Irvine	Mason Park, Near UC Irvine	Pleistocene Alluvium (silt)	10 ft.

Figure 3: Predicted Light Rail Transit Vibration Velocity Level using Force Density of Los Angeles County Metropolitan Transportation Authority Blue Line Light Rail Vehicles



Predicted Vibration Spectra, D = 200 ft, V = 29 mph

Table 4: Summary of Results shown in Figure 3

ID	Site Description	Total Vibration Velocity Level re: 1 micro-inch/sec	Vibration Criterion (VC) Comparison
TM1	Near Santa Ana Transportation Center	62	700 micro-inch/sec @12.5 Hz VC-B
TM2	Near intersection of Bristol St. and Wilshire	65	1400 micro-inch/sec @ 12.5 Hz VC-A
TM3	Anton Farm	63	900 micro-inch/sec @ 10 Hz VC-B
TM4	Mason Park, Near UC Irvine	58	500 micro-inch/sec @ 12.5 Hz VC-C
TM5	Blue Line between Wardlow and Del Amo stations	56	500 micro-inch/sec @ 12.5 Hz VC-C