THEORETICAL ESTIMATES OF GROUNDBORNE RAILWAY VIBRATION

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1 Introduction

The United States (U.S.) Federal Rail and Transit Administrations (FTA/FRA) publish guidelines [1, 2] for railway noise and vibration purposes showing generic curves for estimating vibration from various transportation modes with distance. The data that were applied by the U.S. FTA/FRA towards creating these generic curves are not readily available. This paper compares the generic FTA curves to theoretical estimates based upon independent contributions from three parametric components of groundborne vibration: surface waves, longitudinal/pressure waves, and shear waves. Utilizing a theoretical equation that is comprised of these three components, it has been found that it is not possible to recreate the generic curves that are promulgated by the U.S. FTA; a prior review suggests that the U.S. FTA curves greatly overpredict groundborne vibration at distances beyond about 30 m [3]. As such, this paper presents explorations of a new theoretical equation that is comprised of surface, spherical, and shear waves, which is thought to provide more accurate estimates of groundborne vibration from railways as a function of distance.

2 Literature Review

The U.S. FTA guideline [1, pp.10-3 – 10-4] has the following to say about the generic curves, "The curves in [Figure 1] were developed from many measurements of ground-borne vibration. Experience with ground-borne vibration data is that, for any specific type of transit mode, a significant variation in vibration levels under apparently similar conditions is not uncommon. The curves in [Figure 1] represent the upper range of the measurement data from well-maintained systems. Although actual levels fluctuate widely, it is rare that ground-borne vibration will exceed the curves in [Figure 1] by more than one or two decibels unless there are extenuating circumstances, such as wheel- or running-surface defects." Further adjustments can be made for speed, wheel and rail type and condition, type of track support system, type of building foundation, and number of floors [within a building] above basement level. The interpretation of these generic curves for the purposes of "General Assessment" is such that projected vibrations are compared to a vibration-velocity-impact criterion; for example, 65 VdB re: 1 microinch/sec is the criterion for vibration-sensitive instrumentation, such as electron microscopes. When projected vibrations are: (1) below the criterion, vibration impact is unlikely; (2) 0 to 5 VdB above the criterion, site-specific "Detailed Analysis" is recommended; and (3) 5 VdB or more above the criterion, "Detailed Analysis" is required for environmental study that complies with U.S. FTA regulation. The generic curves within U.S. FRA regulation [2] are specifically for trains traveling at speeds of 150 mph and are not subject to analysis within the scope of this paper.

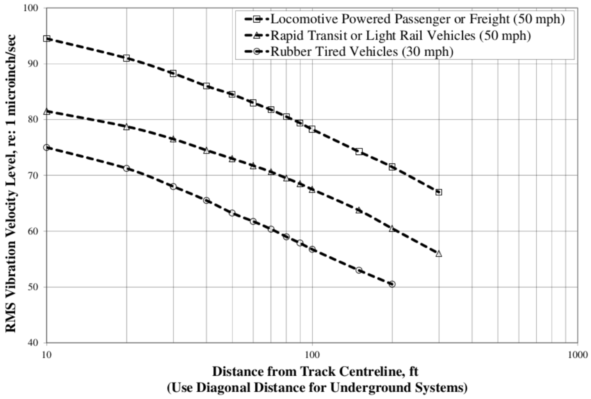

Figure 1: U.S. FTA Generic Vibration Curves .

Richart, Hall and Woods [4, pp. 88–92] note that Rayleigh/surface waves, spherical/pressure waves, and shear waves display different behaviors at the horizontal surface of an ideal, elastic half-space than within the elastic media itself. For a vertical force loading due to a small circular footing vibrating as a sinusoid at the elastic half-space boundary, Rayleigh/surface waves decay along the surface as $r^{-0.5}$; with longitudinal/pressure and shear waves as r^{-2} with distance. Below the horizontal surface, Rayleigh/surface waves diminish in amplitude exponentially; longitudinal/spherical pressure and shear waves as r^{-1} with distance. Wave velocities are such the longitudinal/pressure wave arrives first, followed by the shear wave, and Rayleigh/surface wave. Miller and Pursey [5] reported the percentage of energy that is distributed amongst the three wave types for displacement waves from a circular footing on a homogeneous, isotropic, elastic half-space, as follows: Rayleigh/surface 67%; shear 26%; and longitudinal/pressure 7%. Klein and Rainer [6] explore wave propagation within elastic, homogeneous, isotropic media, and provides an Attenuation Formula that varies based upon: (1) geometry of the vibration source (point versus line); (2) type of excitation (stationary versus impulsive); and (3) predominant type of wave (Rayleigh on the surface, longitudinal/pressure waves at depth (i.e., body waves)). Exponents are described that are specific to each of the possible variations as summarized in Table 1.

Source Geometry	**Surface Wave**		**Body Wave**	
	Stationary	**Impulsive**	**Stationary**	**Impulsive**
Point	**0.5**	**1.0**	**1.0**	**1.5**
Line	**0.0**	**0.5**	**0.5**	**1.0**

Table 1: Exponents for use within Attenuation Formula

3 Results

3.1 Stationary Line Source

Figure 2 shows the results of curve fitting using an exponent of 0.0 for a stationary line source and 0.5 for a stationary body source. Stationary within the context of these results refers to the stability of vibration emissions over time. The variable is the distance-dependent propagation loss due to material properties. As shown, it is possible to match the closest and furthest points of the calculated curves relative to the U.S. FTA curve, but at the expense of greater overprediction at intermediate distances. As such, this does suggest that the U.S. FTA curves, based on measurements, are indicative of vibration propagation that is neither a line geometry nor is stationary in time.

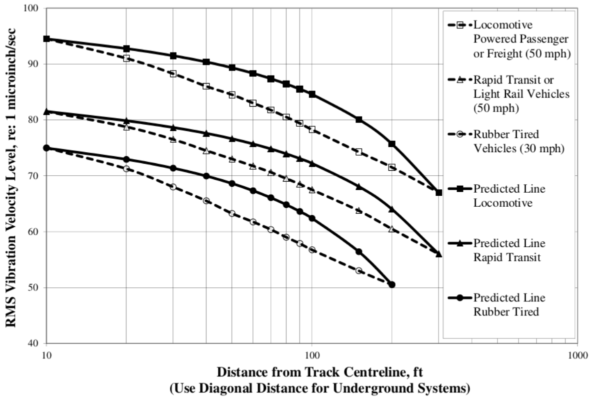

Figure 2: U.S. FTA Generic Vibration Curves versus Stationary Line Source Predictions .

3.2 Impulsive Line Source / Stationary Point Source

Figure 3 shows the results of curve fitting using an exponent of 0.5 for the Rayleigh/surface wave type and 1.0 for the body wave type. The only variable in question is the distance-dependent propagation losses due to material properties. As can be seen, it is possible to match of the calculated curves relative to the U.S. FTA curve at both the closest point at a distance of 100 ft (30 m), but at the expense of some error at other distances of interest. The improved match does suggest that the transportation modes of interest are generating vibrations in more complicated ways in terms of behaving as an impulsive line source and/or stationary point source.

4 Discussion

The U.S. FTA generic vibration curves are to be applied for situations involving both surface transportation and underground sources. As such, the combination of these two data sets to develop a single set of generic curves may be a factor limiting the prospects for matching measurement data to the parametric equations developed for this paper; the differences from within Figure 3 being 3.8 VdB or less. Comparing new theoretical predictions to the 38 data points used to construct the generic curves, the agreement is within 1.0 VdB or less for 30 of those data points, with the largest discrepancies at the greatest distances.

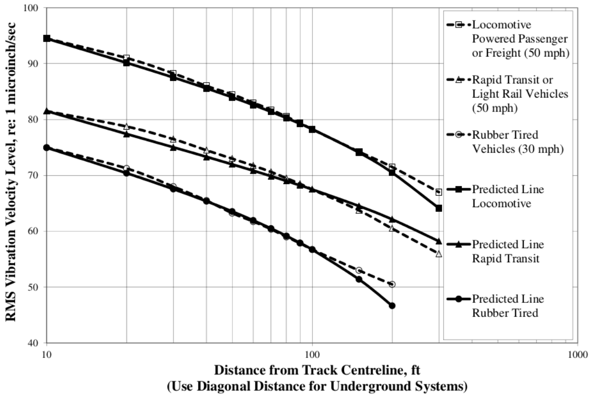

Figure 3: U.S. FTA Generic Vibration Curves versus Impulsive Line Source / Stationary Point Source Predictions .

5 Conclusion

This paper presented explorations of a parametric theoretical equation comprised of surface, spherical, and shear wave types. The results indicate an improved match between U.S. FTA generic curves for estimating vibration velocity level as a function of distance and underlying parameters for each wave type within a new theoretical equation.

Acknowledgments

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References

[1] Transit Noise and Vibration Impact Assessment, U.S Department of Transportation, Federal Transit Administration, Office of Planning and Environment, Washington, D.C.,.May 2006.

[2] High-Speed Ground Transportation Noise and Vibration Impact Assessment, U.S Department of Transportation, Federal Rail Administration, Washington, D.C.,.September 2012.

[3] Todd Busch, Michael Gendreau and Hal Amick, "*Vibration and Noise Criteria used to Evaluate Environmental Impacts of Transportation Projects on Sensitive Facilities*", Proc. SPIE 5933, Buildings for Nanoscale Research and Beyond, 593306, San Diego, August 29, 2005.

[4] F.E. Richart Jr., R.D. Woods, and J.R. Hall Jr., Vibrations of Soils and Foundations, Prentice-Hall of Canada Ltd, Toronto, 1970.

[5] G.F. Miller and H. Pursey, " *On the Partition of Energy between Elastic Waves in a Semi-Infinite Solid* ", Proc. Royal Society, v.233, pp. 55–69, 1955.

[6] Gunter K. Klein and Johan H. Rainer, Chapter 6: " *Wave Propagation*", Vibration Problems in Structures: Practical Guidelines, Ed. Hugo Bachman, Birkhauser Verlag, Boston, 1995.