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Street-running LRT may not affect a neighbour's sleep

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Abstract

A comprehensive dynamic finite difference model and analysis was conducted simulating LRT running at the speed of 24 km/h on a city street. The analysis predicted ground borne vibration (GBV) to remain at or below the FTA criterion of a RMS velocity of 72 VdB (0.004 in/s) at the nearest residence. In the model, site-specific stratography and dynamic soil and rock properties were used that were determined from in situ testing. The dynamic input load from LRT vehicle running at 24 km/h was computed from actual measured data from Portland, Oregon's West Side LRT project, which used a low floor vehicle similar to the one proposed for the NJ Transit project.

During initial trial runs of the LRT system, vibration and noise measurements were taken at three street locations while the vehicles were running at about the 20–24 km/h operating speed. The measurements confirmed the predictions and satisfied FTA criteria for noise and vibration for frequent events.

This paper presents the analytical model, GBV predictions, site measurement data and comparison with FTA criterion.

1. Introduction

The Hudson-Bergen Light Rail Transit System (HBLRTS) is a 20.5-mile light rail transit (LRT) system providing local transit service along New Jersey's Hudson River Waterfront. A portion of the alignment runs through the streets of downtown Jersey City, including Essex Street. Situated along the north side of Essex Street is a row of brownstone houses that are well over 100 years old (Fig. 1). The Claremont Condominiums are located on the north side of Essex Street, just north of the tracks (Fig. 2).

Concerns were raised by the residents of Essex Street and the NJ State Historic Site Council regarding effects of vibration resulting from HBLRTS operation on the existing historic

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Fig. 1. Brownstone houses.

Fig. 2. Claremont Condominiums.

brownstone and condominium residences. NJ Transit requested Parsons Brinckerhoff (PB) to conduct the assessment and evaluation of potential vibration impacts on the residential buildings along Essex Street.

Operating light rail vehicles (LRVs) on street-running tracks supported by a track slab creates vibration as the trains move over the tracks. This vibration energy is transmitted through the ground to adjacent structures by surface waves that propagate in a zone relatively close to the surface. The scope of this study was to determine the level of vibration that LRVs would produce and to evaluate the impacts of this on the residences.

2. Study methodology

PB thoroughly evaluated the study area and conducted investigations to determine the nature of the vibration that would be produced by the HBLRTS. A three-pronged approach was used to collect all appropriate data and analyze what it would mean to the residents of Essex Street.

PB's analysis of potential impacts was based on:

- seismic characterization of the subsurface soils and shallow rock [1,2],
- monitoring of on-site vibration produced by a bus,
- dynamic finite difference modelling of vibration effects caused by passing of LRVs.

Site-specific data were collected by performing subsurface drilling, dynamic cone penetration tests, and spectral analysis of surface wave investigations at various Essex Street locations. These Analyses produced a site-specific geological profile (Fig. 3) of the composition of the zone through which the vibration energy would travel, as well as the velocity of shear waves as they pass through this zone to the adjacent buildings. This site-specific data was then input into the numerical analysis to obtain more accurate predictions of the models used.

Initial vibration measurements, during the design phase, were taken at three representative residential sites to determine the rate at which vibration decreased with distance from the source. An empty NJ Transit bus travelling at 40 km/h was run past monitors set up at different distances from the bus at these sites to record vibration levels as the bus passed by. The results of these measurements provided an indication of how the vibration changed as a function of distance for ground conditions existing in the area of the Essex Street properties.

In addition, vibration velocity measurements were taken during operation of the Westside Corridor LRT System in Portland, Oregon. This system, which runs on embedded track similar to those used on the HBLRTS, provided an opportunity to simulate, as closely as possible, actual operations of the HBLRTS. Monitors were placed at various distances from the track centreline with two-car vehicles operating at 24 km/h and resulting vibration levels were recorded.

The numerical finite difference analysis performed was based on site-specific geophysical data, and the actual measured vibration source model predictions were compared to on-site vibration measurements, vibration measurements from the Westside Corridor LRT, and published FTA data to validate the accuracy of the results.

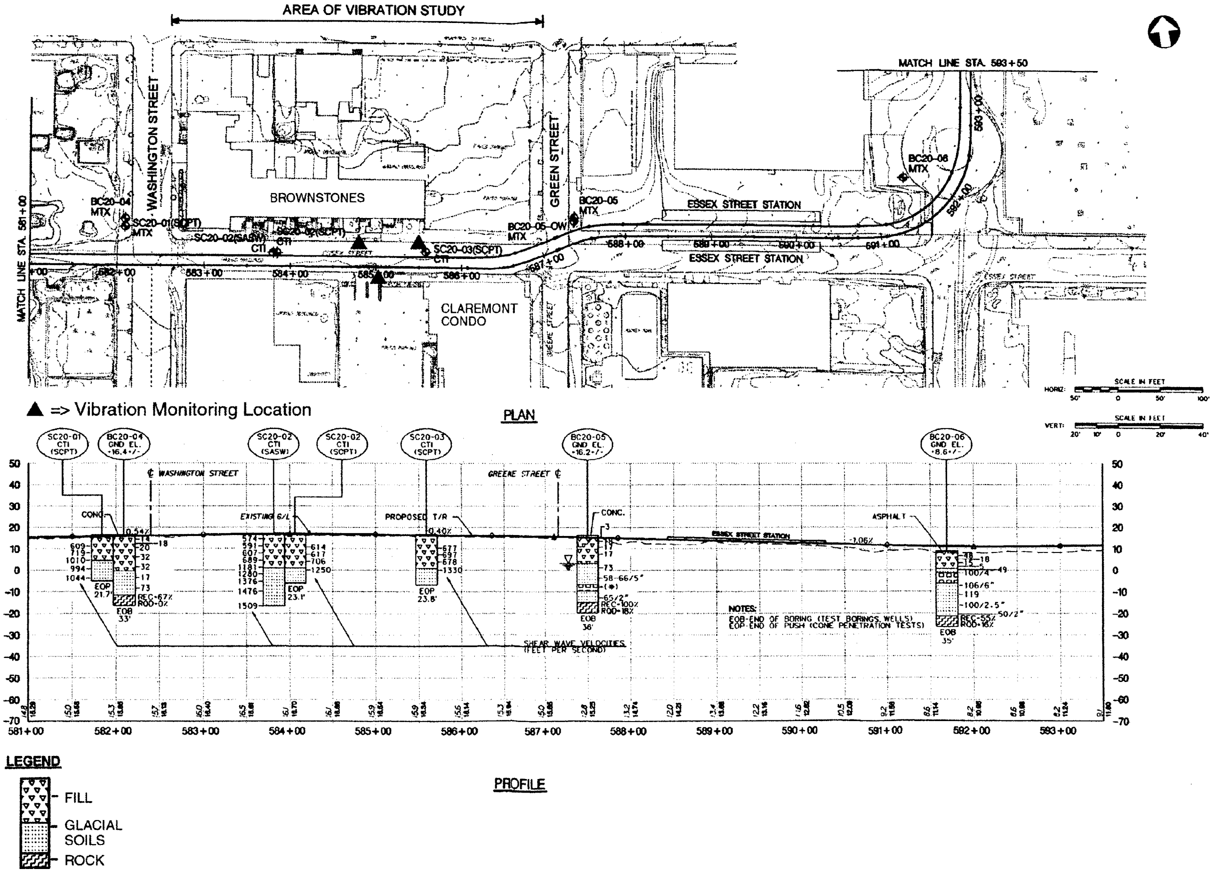

Fig. 3. Plan and subsurface profile.

3. Site conditions

Subsurface investigations consisting of conventional soil and rock drilling were performed to identify the geological profile of the study area. Subsurface materials encountered at the site have been categorized for engineering purposes into three generalized strata, identified with increasing depth from the ground surface, as follows:

- Stratum 1—fill.
- Stratum 2—glacial soils.
- Stratum 3—bedrock.

3.1. Stratum 1—fill

Fill materials encountered at the ground surface contained brown, grey, and multi-coloured sand with varying amounts of gravel, cinders, silt, clay, and miscellaneous debris. The thickness of this stratum is about 5 m. The Standard Penetration Test (SPT) N-values obtained in this stratum ranged from 15 to over 300 blows per metre, representative of the diversity of the materials encountered.

3.2. Stratum 2—glacial soils (sand and silt with gravel)

This stratum contained brownish red silty sand of glacial origin. Typical fines content (percentage of particles passing through the US No. 200 sieve) is 25 per cent. At some locations the stratum included zones of clayey silt with sand, gravel, and/or cobbles. The SPT N-values range from 50 to over 300 blows per foot. The general consistency of the materials in Stratum 2 ranges from medium dense to very dense. The soil samples obtained from Stratum 2 generally classify as SM in the Unified Soil Classification System.

3.3. Stratum 3—bedrock

At the Essex Street site, bedrock consisted of a mica schist encountered at typical depths of 8–11 m. The mica schist is dark grey, medium grained, weathered medium to hard rock. Fractures were closely to very closely spaced in the cores obtained. The inclination of fractures observed in rock cores was typically less than 20°. Rock quality designation (RQD) values for core samples of the schist obtained from six borings in the Essex and Hudson Street area ranged from 0 to 58 per cent with a typical value of about 20 per cent.

3.4. Groundwater

Groundwater depths were monitored periodically from May through December 1995. Results indicate that the groundwater table is located from 3.5 to 3.9 m below the ground surface.

3.5. Geophysical programme

Following the conventional soil and rock borings, geophysical site investigations were performed consisting of conventional cone penetration testing (CPT), seismic cone penetration testing (SCPT), and spectral analysis of surface waves (SASW).

The results of the SCPT and SASW tests provided site-specific data on vibration velocity at various depths below the surface, which was used as input into the models employed in the finite difference analysis performed for this study.

3.6. On-site vibration

On-site vibration measurements were performed on December 27, 1995 at 3 representative residential sites. Vibration was created by an empty NJ Transit bus travelling at a speed of approximately 40 km/h. Two devices that measure vibration velocity were mounted at each location, one 1.5 m from the bus and another near the front of the residences, where measurements were recorded and differences were noted. These measurements were intended to determine the rate at which ground vibration would decrease with distance from the source.

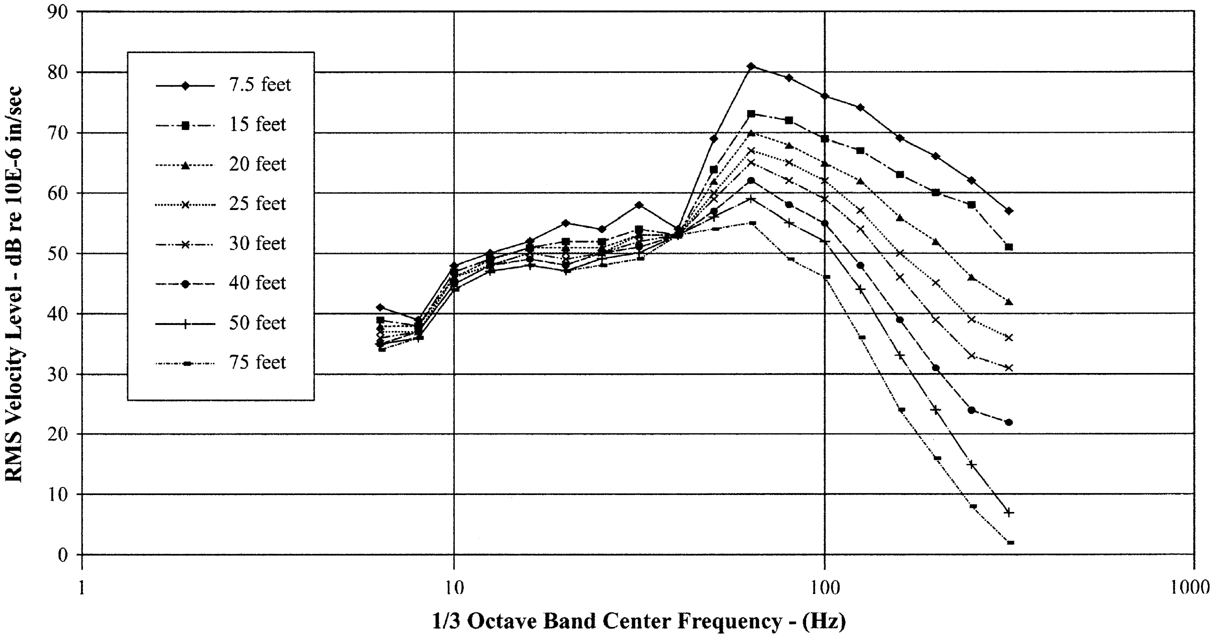

Fig. 4. Embedded track ground vibration for 2-car Tri-Met trains at 24 km/h.

For the bus operating on Essex Street, there was approximately a 6 VdB drop in vibration velocity between sensors placed 6 m apart at two locations (see Fig. 7 later). A significantly larger drop was recorded at another location, which was not used for comparison with the predictions.

4. Measurements from Westside Corridor LRT

Operations of the Tri-Met Westside Corridor LRT System in Portland, Oregon is a similar LRT system under similar structural configurations (e.g., the type of track support system) and operational conditions (e.g., the train speed). Taking vibration measurements of operations of this system afforded the best opportunity to simulate the vibration levels that would result from operation of the HBLRTS. For comparison purposes, GVB levels were measured at various distances from the track centreline with a 2-car (28 m long) Tri-Met train operating on embedded track at 24 km/h (Fig. 4).

5. Prediction of ground borne vibration

The construction industry has established building damage criteria for various types of building damage (e.g., damage to architectural elements/facades, and structural elements/slabs, beams, etc.). These values are expressed as peak particle velocities measured in inches per second.

The FTA is concerned with people's perceptions; that is, will people be able to detect vibration and has established a vibration criteria expressed as $\frac{1}{3}$ octave band root mean square (RMS) velocity levels in decibels (re: 25–15 cm/s). The FTA established an impact threshold of 72 VdB (0.01 cm/s) as the frequent event residential limit [3].

Numerical analyses were conducted using the Fast Lagrangian Analysis of Continua (FLAC) [4] finite difference numerical model. Site-specific data obtained from the borings and geophysical tests described earlier were used to predict the propagation of ground vibration caused by the proposed LRT along Essex Street.

6. FLAC numerical analysis

FLAC is a two-dimensional finite difference code that permits full dynamic analysis of ground vibration, including the consideration of soil–structure interaction. The analysis was performed in the time domain instead of in the frequency domain. In this type of modelling the ground is divided into small elements, or zones, that form a mesh that can be adjusted by the users to fit the problem domain. Each element in this mesh is characterized according to its response to input excitations, in this case the shear waves resulting from LRT operations.

Fig. 5 shows the finite difference mesh used for this study. The bottom boundary represents the underlying bedrock and was conservatively assumed to be fixed (i.e., rigid). The left boundary of the mesh represents the centreline of the track and was assumed to be fixed in the horizontal direction and free to move in the vertical direction to simulate the symmetric loading condition

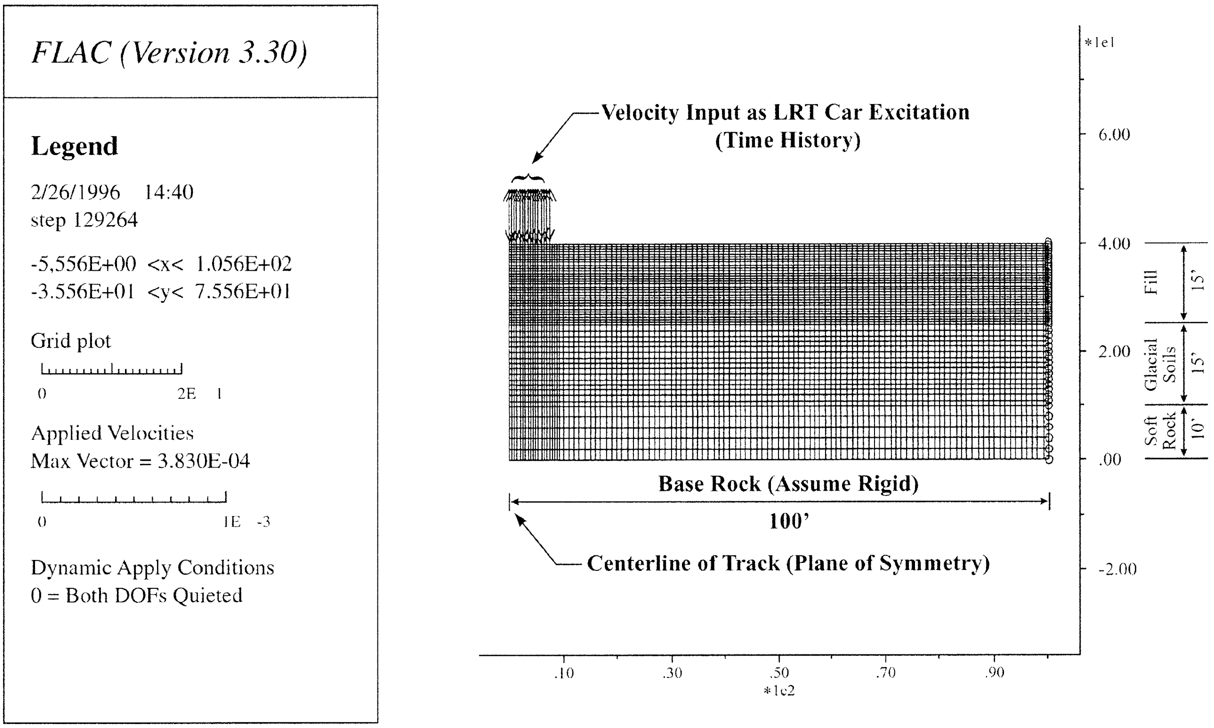

Fig. 5. Finite difference mesh in FLAC analysis.

there. The figure shows a 30.5 m zone from the centreline of the track, where a viscous boundary was assumed through which vibration waves were able to radiate. The soil elements were broken down into very small pieces to allow proper transmission of high-frequency waves in the soil layers. The input source excitations were applied at the track location. For this study, the input source excitations were represented as a velocity time history.

7. Dynamic soil and rock properties

The following input data for each of the strata found at the Essex Street site are: (1) total unit weight; (2) the dynamic shear modulus; (3) damping; and (4) the Poisson ratio.

The dynamic shear modulus represents the stiffness of the ground. The dynamic stiffness of a soil differs significantly from the value obtained under static loading conditions, and can be best quantified by measuring the wave propagation velocities in the field. The measured wave propagation velocities can then be converted to soil modulus values. For this study, the shear wave velocities of the soil strata at the site were measured in the SCPT and SASW test conducted at the site. Based on these data, the shear modulus and the corresponding shear velocity used in the analyses were derived. The values for the highly fractured and weathered rock stratum were based on local experience. It was further assumed in the analyses that the underlying bedrock at the site is rigid. This assumption is conservative in that the vibration energy is confined within the soil layers (particularly within the softer fill layer) and cannot be radiated through the bottom boundary.

8. Numerical simulations of input source excitations

In order to simulate the source excitations of trains running over the tracks at Essex Street, the measured vibration levels from the Westside LRT System were used. These measurements were taken in the frequency domain. To overcome this incompatibility, the frequency data was converted were to a velocity time history using the SIMQKE microcomputer program [5]. The energy of the train excitations was concentrated in the frequency range between 50 and 120 Hz.

Fig. 6 shows a typical velocity time history input at a track centreline generated by SIMQKE using the spectral density function. The time history covers a duration of about 2 s because preliminary analyses suggested that steady state vibration of the adjacent ground can be reached within a fairly short duration (less than 1 s). The corresponding $RMS(t)$ values varying as function of time were computed and plotted. The time-dependent RMS values were obtained by moving an averaging time window of 0.5 s along the velocity time axis. By examining the time-dependent $RMS(t)$, it was verified that the simulated source excitations produced by SIMQKE agree with the maximum measured value (0.04 cm/s).

9. Numerical analysis prediction results

Ground vibration associated with a train is a complex phenomenon. Due to the significant uncertainties involved in the characterizations of the wave transmission media and the input

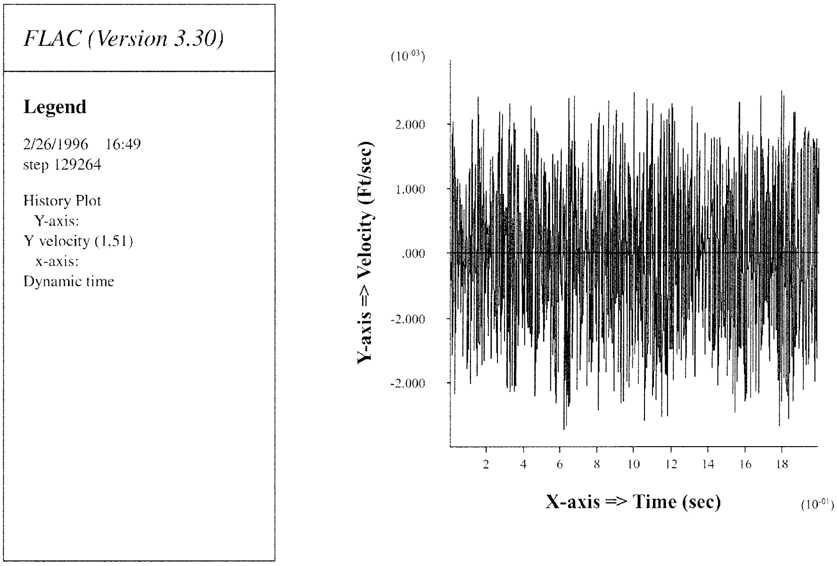

Fig. 6. Simulated velocity time history excitation input at track centreline (typical).

source excitations, an accurate prediction is difficult either by empirical methods or by numerical analyses. Numerical modelling, however, allows analyses to be conducted using site-specific data to identify site-specific issues. It also allows parametric analyses to be performed to establish a range of predictions that can be reasonably expected. For this study, a numerical analysis was performed using site-specific input data compared with measured input data from another project having similar LRVs and on-site vibration measurements.

The numerical analysis was performed under axisymmetric loading conditions where the vibration of passing trains was simulated by applying the input velocity time history derived from computer simulations over an area of 4.6 m in diameter to represent an enlarged wheel loading area. Because the closest vibration measurements from Tri-Met project were taken at a distance of 2.3 m from track centreline, and it is reasonable to assume that the vibration excitations are symmetrical about the track centreline, the source excitations were represented by a circular loading area of 14.6 m in diameter (i.e., $2 \times 2.3\,\text{m}^2$).

It was further assumed that the input motions are in complete synchronous phase. The assumption of a localized area instead of a continuous strip area to simulate the wheel loading provides a more realistic representation of the ground vibration caused by the LRT vehicles. Predicted vibration levels were plotted as a function of distance from the track centreline in Fig. 7. The prediction was based on a speed of 15 m/h. Superimposed (for comparison) on the figure area:

- the FTA's ground borne vibration threshold criteria (72 VdB),
- FTA generalized ground vibration data for LRT trains,
- measured ground vibration data from the Westside Corridor LRT on embedded track running at 24 km/h,

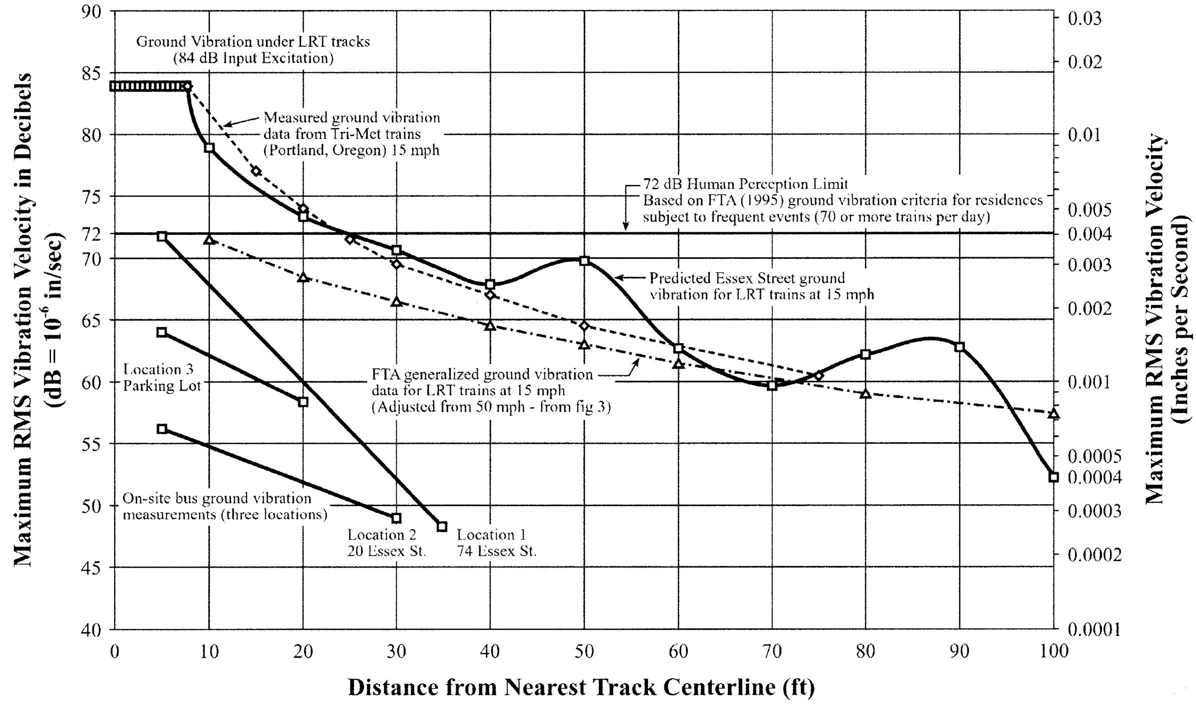

Fig. 7. Predicted GBV vs. distance from centreline of the nearest LRT track.

- on-site vibration measurements of an empty NJ Transit bus running at a speed of about 40 km/h on Essex Street.

The following results are noted from the predicted vibration curve:

- Predicted vibration at 24 km/h speed is below the FTA criterion of 72 VdB for residences located at a distance of 7.5 m or more from the track centreline. Most residences along the north side of Essex Street are located more than 7.5 m from the track centreline. However, the multi-storey Claremont Condominium is only 4.5 m from the track centreline and vibration predicted at a speed of 24 km/h is slightly over the FTA criterion.

However, one should note that the numerical predictions at this study were conservative because of the following factors:

- Input motions were assumed to be in a complete synchronous phase.
- HBLRTS used reduced weight vehicles compared to existing Portland vehicles, which were used as a source of input vibration in the numerical model.
- The base rock is assumed rigid in the FLAC analyses, allowing complete reflection of vibration waves back to ground surface.

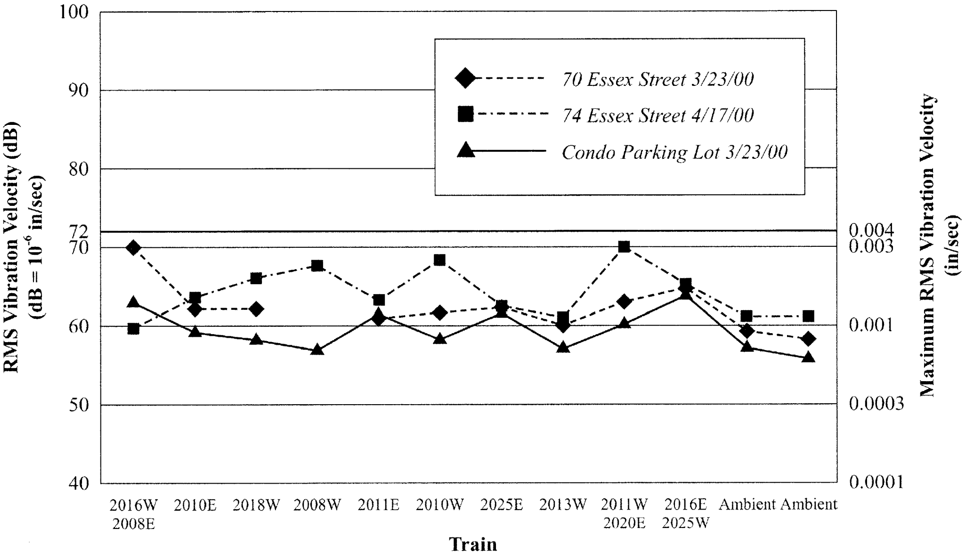

Fig. 8. Measured ground borne vibration from LRV test runs at Essex Street.

10. Measurement of ground borne vibration during LRT operation

During initial test runs of the HBLRTS, vibrations were monitored by seismographs at three locations (Fig. 1), approximately the same locations used for original impact study, 14.6–12 m away from the track, in March and April 2000 to determine vibration impact. All readings were below the FTA criterion of 72 VdB (Fig. 8). Measured speed at monitoring locations varied between 20 and 24 km/h. These minor changes in speed did not appear to affect the vibration levels significantly. For three of the events recorded, two vehicles (NB and SB) passed simultaneously; however, the readings were virtually identical to those for single vehicle passage. Noise measurements were made along with vibration measurements. However, noise data are not presented in this paper.

11. Conclusion

It has been demonstrated using sophisticated site-specific analysis and by monitoring during trial runs, that operation of the HBLRTS along Essex Street in New Jersey will neither create an annoyance to residents inside their homes nor cause even minor structural damage to the historic homes due to vibration generated by the LRVs.

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