DETAILED VIBRATION IMPACT ASSESSMENT
PROPOSED B-LINE LIGHT RAIL TRANSIT SYSTEM
CITY OF HAMILTON

FOR

HATCH MOTT MACDONALD

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1.0 Introduction and Background

The City of Hamilton has embarked on an aggressive plan to implement rapid transit, with a long-term vision encompassing five corridors connecting key destinations across the City. This proposed system is referred to as “B-L-A-S-T.” At present, the City’s focus is on implementing Light Rail Transit (LRT) along the City’s primary east/west B-Line corridor, Main/King between Eastgate Square and McMaster University, and defining a potential corridor and rapid transit mode for future rapid transit implementation along the City’s primary north/south A-Line corridor, James/Upper James between the waterfront and the airport.

Hatch Mott MacDonald retained J. E. COULTER ASSOCIATES LIMITED, on behalf of the City of Hamilton, to conduct a more detailed vibration impact assessment of the proposed City of Hamilton B-Line Light Rail Transit System (the project). The goal of the study is to more accurately determine the future LRT vibration levels in order to determine the costs of vibration control.

1.1 Project Description

The west terminus of the B-Line LRT is at McMaster University, just east of Cootes Drive. The route is as follows:

- The route runs east along Main Street, primarily in the centre of the roadway right-of-way. Near Highway 403, the route swings to the north side of Main Street.
- It will use a new bridge structure to cross Highway 403 and connect the route to King Street, east of the highway.
- It remains on the south side of King Street from Highway 403 to Main Street in the east.
- The route completely displaces road traffic on King Street between Catharine Street and Wellington Street.
- It follows Main Street east from King Street to Queenston Road, remaining on the south side of Main Street.
- After that it continues east on Queenston Road from Main Street, mainly remaining in the centre of the roadway right-of-way.
- The route then terminates at Eastgate Square at the intersection of Centennial Parkway and Queenston Road.

A key plan of the project route is provided in Figure 1 in Appendix A.

1.2 Scope of Work

The purpose of the detailed vibration assessment is to more accurately determine the areas of track where upgraded vibration isolation will be required. As a result, this assessment only considers the future operational vibration expected from LRT operations. Special track-work locations, such as crossovers and turnouts, have been only briefly reviewed, as their locations have not yet been finalized.
2.0 Vibration Assessment Criteria

The noise and vibration impact assessment criteria used to evaluate implications of the proposed LRT route are based on a set of draft protocols developed through the combined efforts of the Ministry of the Environment (MOE) and the Toronto Transit Commission (TTC). These protocols are used in the absence of any existing province-wide protocols for transit projects, specifically relating to light rail transit. The protocol that most directly relates to this project is the MOE/TTC Draft Protocol for Noise and Vibration Assessment for the Proposed Waterfront West Light Rail Transit Line (November 11, 1993). This protocol is similar to many of the other protocols developed by the TTC and the MOE for other rapid transit projects within Ontario. The vibration limit of 0.1mm/s rms (root-mean-square) from the MOE/TTC Draft Protocol for Noise and Vibration Assessment for the Proposed Scarborough Rapid Transit Extension is used, however, in lieu of the 0.14mm/s rms limit from the Waterfront LRT guidelines and ISO recommendations, as requested by the MOE.

The above protocols, created in the early 90s, have several outdated references. The protocols and other guidelines that are not easily accessible are provided in Appendix B. A more current list of references is provided in Appendix C. Additional definitions are provided in Appendix D.

The noise and vibration criteria, as outlined in the above-mentioned document, are summarized below.

2.1 Definition of Sensitive Receptors

As per the MOE/TTC protocol, sensitive receptors are identified as those existing or municipally-approved residential developments, nursing homes, group homes, hospitals, and other such institutional land uses where people reside. Within the project area, the primary sensitive receptors are residential developments. Though there are some institutional uses located along the corridor, the primacy of residential development in those same locations implies that any evaluation at the residential receptors will be representative of other sensitive receptors. For this reason, as the residential receptors are expected to be most representative of the effects of the proposed LRT system, the impacts at residential receptors will be used as a proxy for other sensitive receptors (land uses) in the same area. Henceforth, any references to receptors or receivers will be in regard to residential development, unless otherwise noted.

For the assessment, the protocols dictate that sound and vibration levels need to be calculated at the point of reception or point of assessment. The point of reception or point of assessment is described in the protocols as being a sensitive receptor located no less than 15m from the centre-line of the nearest track. There are many points along the route where the point of assessment, at a house or apartment, for example, would be significantly closer than 15m from the nearest track centre-line. As a result, the point of assessment for receptors along the corridor is taken to be the closest sensitive receptor, regardless of whether or not it is 15m or more from the nearest track centre-line. The calculations are adjusted accordingly for actual setbacks.
2.2 Vibration Impact Criteria

The vibration impact criteria attempt to address two potential impacts from vibration generated by the LRT.

- First, the criteria consider perceptible (ground-borne) vibration levels. This addresses vibration that can be felt by residents in a building.
- Secondly, the criteria document also mentions the sound caused by the vibration (vibration-induced sound) but does not set a limit.

The limit for perceptible vibration levels has been set to 0.1mm/s rms (root-mean-square) velocity. If absolute vibration levels are expected to exceed this limit, mitigation methods need to be determined during the LRT’s detailed design phase, to meet the criteria to the extent technologically, economically, and administratively feasible.

There are no specific criteria in Ontario that set limits for the sound resulting from vibration (vibration-induced sound). The relatively lesser limit of 0.1mm/s instead of 0.14mm/s (suitable for hospital vibration levels) attempts to reduce this discrepancy. The possibility of a noise impact as a result of vibration still exists. It is dependent on the frequency spectrum of the vibration as well as the levels. Based on the United States Federal Transit Administration (FTA) guidelines (FTA-VA-90-1003-06, May 2006), a guideline level of 35dBA is used in this report for residential rooms and other rooms (e.g., hospitals) where people generally sleep, for cases where the ground-borne, vibration-generated noise dominates the impression of the passby.

The vibration-induced noise criterion level of 35dBA should be taken in context along with the air-borne noise. New LRT vehicles typically exhibit maximum sound levels ranging from 78-80dBA at 7.5m while traveling at 40km/hr., similar to a medium-sized truck. For rooms with exposure to the LRT and other traffic, outdoor sound levels in this range would result in peak indoor sound levels of 48-50dBA, assuming a general 30dB noise reduction from closed windows. In this case, the contribution from vibration-induced noise would be negligible and often indistinguishable from the air-borne noise coming through the closed window. Thus, the criterion level for vibration-induced noise is mainly applicable to those rooms with little or no window exposure to the LRT. Examples of these would be flanking apartments/houses with little or no window exposure, inset bedrooms separated from the LRT exposure by another room, or basement apartments with small windows.

Figures 2 and 3 in Appendix A show the relative sensitivity for a house or apartment located next to the transit route.

3.0 Assessment Method

Vibration from transit sources depends on a number of variable factors. The soils, distance to the receptor, speed of the vehicle, mass of the LRV (light rail vehicle), suspension characteristics of the LRV, track support system (embedded rail or tie-on-ballast, for example), and the smoothness of the wheels and rails all affect the amount of vibration transmitted into the soil. On the receptor side, factors such
as the type of building construction, the number of floors, and the floor and wall spans affect the level of vibration felt inside the building and the level of the vibration-induced noise. Each of the preceding factors can significantly affect the amount of vibration felt or heard by occupants of sensitive buildings adjacent to the future LRT route.

Vibration levels are evaluated at the nearest point of a residential or sensitive-use building. The review of vibration-induced noise potential involves identifying the locations where the rail system passes close to buildings, or where there is special track work prone to creating vibration (switches). Next is the identification of the uses of the buildings and the proximity of sensitive rooms to the source of vibration. Then, the vibration levels are estimated and, where impacts are anticipated, a level of vibration control is specified.

Ontario does not promulgate a transit vibration assessment method. To some extent, existing streetcars in Toronto, operated by the TTC, can be used as an estimate of the future expected vibration levels from the LRVs. The un-sprung mass per axle of the typical Canadian Light Rail Vehicle (CLRV) and the Articulated Light Rail Vehicle (ALRV) is similar to that of the Bombardier Flexity Outlook LRV and similar LRVs. The other elements of the LRV, such as the suspension system, are unknown, as the vehicles have not yet been selected. While similar, the embedded rail system employed by the TTC could also be different than that used in Hamilton. Given these unknown factors, and in order to more accurately predict the future vibration levels from the project, elements of the FTA’s procedure for detailed vibration impact assessment have been adopted.

3.1 Current State of the Art

Before launching into this project, a review of the state of the technology was carried out. The prediction procedures for LRT and commuter rail transit in North America are mainly based on the procedures outlined in the FTA guidelines. Because the original FTA document was written about 35 years ago, it was felt that it should be applied with an eye to developments and experience gained since that time. In particular, the development and measurement of TTC vehicles of somewhat similar loads and dynamic action can inform the interpretation of the FTA results.

The sound and vibration from surface transit operating on encapsulated rail is a function of setback, soil conditions, speed of the vehicle, the state of rail and wheel maintenance and rubber or other insulation boots around the rail, as well as rail support and fastening systems. Most heavy rail runs on tie-on-ballast or an insulated tie arrangement. Most surface LRT runs on concrete embedded rail. Between the rails and the adjacent sensitive receivers of surface rail transit vibration could be asphalt or concrete pavement, soft soil, hard soil, and shallow or deep footings. Each of these details can affect the net result at the receiving location.

While the FTA procedure formed the basis of the approach taken in this case, we have made two adjustments based on experience with similar soils in the Toronto area that share many of the soil characteristics with the Hamilton area. First, there are problems in the 125 Hz octave band with the FTA approach. A review of the reports prepared by consultants working in various cities showed that this octave band, which is usually heard, not felt, resulted in a wide discrepancy among seemingly similar
types of vehicles. Site measurements in Hamilton showed that if the weight to simulate a transit vehicle was dropped directly on soil, the results at 125 Hz were quite different than what occurred if the impulse of force was applied to a paved surface. Therefore, for consistency, the testing was carried out after boring a hole in any pavement present at the test sites. In the end, it is expected that the encapsulated rail will always be on a concrete base when near housing or other sensitive receivers in the project. Therefore, our data will remain consistent. In any case, once when the lightest mitigation scheme was evaluated, it was found that the 125 Hz octave band was not a factor in vibration control decisions, as this band could be handled quite well with the most minimal of vibration control systems.

The second range of frequencies that caused concern was the 16 Hz octave band. After many measurements around Toronto, we have never found a site where 16 Hz is a problem. Also, 31.5 Hz is not usually the controlling band, although it is often significant. In most cases along the TTC streetcar lines, the controlling frequency band is 63 Hz octave band for both vibration and vibration induced sound purposes. We have checked the section of the Queensway TTC streetcar line that runs on ties with ballast and even there, 16 Hz has no appreciable effect. Consequently, the results of the mitigation project in the 16 Hz octave band, projected as necessary using the FTA method, have been downplayed in the analysis. The emphasis is on the 31.5 Hz and 63 Hz octave bands.

The vertical impact prediction procedure is a simplification of the complex interaction between the transit vehicle, the track bed, and the surrounding environment. The rail bed can vibrate vertically and horizontally, and is also capable of rocking. The impact test only induces a vertical displacement on the ground to simulate these various motions.

With regard to vibration control at the rail bed, we have noted that a number of models for the vibration mitigation use methods based on systems with no damping; they are assumed to bounce very easily and to keep bouncing when excited. This is in direct contrast to the results of researchers such as Bycroft who have found that surface mounted foundations have quite high damping coefficients due, in part, to the vibration energy radiated away from the foundation. The models then being used to calculate the vibration control effectiveness, without accounting for damping, predict dynamic amplification at frequencies in the range of 20-40 Hz. As one might have expected, the vibration isolation supplier CDM is now reporting they do not see this amplification effect in their installations and hence, in the conclusions of this report, none are assumed.

The source strength model used in this report is based on the current TTC CLRV streetcar, which operates on similar soils and speeds. The TTC has taken delivery of a new test streetcar that is based on very similar technology to the LRT. Thus, as the vibration isolation design is refined, there will be an opportunity to test a vehicle that even more closely resembles the specification of recent model LRTs. It is suggested the new unit be tested once it starts trials in the spring of 2013.

The following sections outline the progressive assessment method taken in evaluating the vibration impacts from the Hamilton LRT. As the type of soil plays a large factor in the vibration propagation, preliminary measurements were taken throughout the B-Line corridor in order to determine specific soil characteristics. Based on these measurements, 6 locations, including McMaster University, were selected for more detailed measurements, based partially on the FTA procedure.
3.2 Screening Measurements

Screening measurements were taken at 12 sites along the future LRT route. The purpose of these screening measurements was to measure the shear wave velocity in the soils. The 12 sites along the corridor were selected based on the geotechnical report submitted in the B-Line TPAP (Transit Project Assessment Process). The geotechnical report outlined the location and depth of various types of soil along the corridor. The testing sites were selected such that each type of soil was tested at least once for its shear-wave velocity. Figure 4 in Appendix A shows the locations of the screening measurements.

The shear-wave velocity at each site was determined by measuring the amount of time it takes for a vibration wave to pass between two points. Two accelerometers, typically spaced at 20m from each other, were mounted on the surface of the soil, but beneath the roots of the grass. A vibration impulse via a dropped sledgehammer was forced into the ground. The shear-wave velocity was determined from the amount of time it took the vibration wave to pass between the two accelerometers.

The shear-wave velocity indicates two things: the likelihood of efficient vibration propagation, and the probable effectiveness of any vibration mitigation measures to be used. Generally, high shear-wave velocities result in efficient vibration propagation. On the other hand, high velocities indicate a high shear modulus, especially in higher density soils. A high shear modulus indicates a stiff soil, where most vibration mitigation systems tend to perform better. The improved expected performance in the isolation characteristics somewhat offsets the negative vibration propagation implications of stiff soils.

Vibration attenuation in soil is dominated by the soil’s damping characteristics. The amount of damping is generally proportional to the number of wavelengths in soil between the source and the receiver. Thus, the total damping varies across different frequencies as well as across soils with different shear-wave velocities. Higher frequencies (shorter wavelengths) are damped out more quickly than lower frequencies (longer wavelengths).

More detailed damping measurements were conducted at 6 of the 12 sites previously tested for wave speeds. The damping tests consisted of vibrating the soil at a specific frequency and measuring the reduction in vibration levels between two accelerometers. Typically, the accelerometers were placed between 1 and 2 wavelengths apart, though this was not always possible. The locations of the damping measurements are shown in Figure 5 in Appendix A.

3.3 Detailed Vibration Measurements

Detailed vibration propagation measurements were conducted at 6 locations along the corridor. These sites were selected based on the results of the screening measurements, the type of soil in the area, and the proximity to the future LRT tracks. The detailed vibration testing is based on the FTA Detailed Assessment approach. This test characterizes how vibration would be transmitted from the LRT tracks to an adjacent building or point. The locations of the detailed measurements are shown in Figure 6 in Appendix A.

The propagation test consists of impacting the soil at a series of points along where the LRT route will operate. This test typically uses a dropped weight along with a force transducer to measure the force.
imparted into the soil by the dropped weight. In this case, a sledgehammer and strain gauge system were used to create and measure the force input, respectively. The medium used to transmit the force into the ground was a driven steel stake. In order to avoid the variability in road surface construction, a short borehole was drilled through the pavement at each impact point and the stake was driven below the surface into the subsoil. The drill hole was determined as necessary after testing showed that impacting the pavement surface lead to artifacts in the 125Hz octave band. Typically, 3 impact tests were performed at each test location at points directly in front of the measurement location and at points 10m and 20m further down the route. It was assumed the vibration propagation in the opposite direction would be fairly symmetrical. The assessment distances (between the impact point and the measurement location) in Hamilton were quite short, resulting in short delay times between the impact and receiver. This permitted the coherence determination used in other assessments to be dropped from the procedure.

At each impact, simultaneous measurements of the vibration levels at the test locations were recorded. The resultant function, of vibration level over the force, is referred to as the point source transfer mobility. The point source transfer mobility measurements are combined based on the overall length of the LRV, which is assumed to be approximately 33m or 110 ft. The resulting addition of the point source transfer mobility is the line source transfer mobility (LSTM). Longer LRVs will result in higher vibration levels at the receptor.

The second component of the vibration propagation testing is the force density function (FD). The force density function typifies the expected force imparted into the soil by the LRVs and the track. Typically, similar LRT systems in similar soil types are used to derive the force density function. As such a similar system is currently unavailable in Hamilton, and essentially in the rest of Ontario, the FTA’s example light rail average force density curve (Figure 11-2 in the FTA guidelines) is used as a conservative estimate of the future LRT’s force density curve. A copy of this curve is provided in Exhibit 1, below.
The force density function is combined with the LSTM in order to determine the resultant vibration level (Lv). This relationship is summarized below.

\[ \text{Lv} = \text{LSTM} \times \text{FD} \]

The force density is measured in Newtons and the LSTM is expressed in units of \( \frac{\text{mm/s}^2}{\text{N}} \). Lv (the resultant vibration level) is then expressed in units of mm/s.

Figure 7 in Appendix A summarizes the testing configuration.

**4.0 Identification of Critical Receptors**

In order to determine critical locations for detailed testing, the results of the screening vibration measurements were reviewed. The selection of the screening locations, however, was determined based on a review of the soils data available.

**4.1 Review of Soil Data**

At the time of the environmental assessment of the B-Line LRT, a geotechnical review of the project area was conducted. This review, dated September 2011, primarily summarized available borehole data to provide the expected geotechnical conditions along the corridor.

A portion of the geotechnical review is provided in Appendix E. To summarize, it seems that much of the project’s corridor runs through soils that are mostly glacial outwash and post glacier lake bottom deposits of tills, silts, and clays. East of the 403 and through much of the downtown Hamilton core are sand deposits laid down by former Lake Iroquois as a beach. Within the roadway right-of-way there also seems to be some fill of mixed matter.

Well-compacted sands tend to be efficient propagators of vibration. Less well-compacted sands and sands with interstitial layers of other soils (gravel, silt, till, clay, etc.) tend to attenuate vibration similar to the softer soils such as clay, silt, and till.

Generally, the soils along the corridor are relatively soft. These soft soils (slow speed propagation) provide good damping, typically resulting in rapid attenuation with distance. In close setbacks, however, the excellent damping characteristics of the soil are less beneficial and can make attenuating the vibration more difficult.

**4.2 Results of Screening Measurements**

Table 1 below outlines the shear-wave velocities at the 12 screening measurement locations. Also summarized is the type of soil on which the measurement location sits. The locations of the screening measurements are shown in Figure 4 in Appendix A.
Table 1: Wave Speed Testing Results

<table>
<thead>
<tr>
<th>Screening Test Site Number</th>
<th>Distance Between Accelerometers (m)</th>
<th>Wave Speed (m/s)</th>
<th>Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>150</td>
<td>Clay</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>178</td>
<td>Fill</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>170</td>
<td>Silt</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>160</td>
<td>Sand/Fill</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>190</td>
<td>Sand</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>173</td>
<td>Fill</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>269</td>
<td>Fill/Sand</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>168</td>
<td>Fill (Expected)*</td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td>128</td>
<td>Fill/Till</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>192</td>
<td>Fill</td>
</tr>
<tr>
<td>11</td>
<td>17.5</td>
<td>174</td>
<td>Sand/Till</td>
</tr>
<tr>
<td>12</td>
<td>20</td>
<td>132</td>
<td>Till (Expected)*</td>
</tr>
</tbody>
</table>

Notes: *Where no borehole information is available, the soil data from adjacent boreholes were extrapolated to obtain expected soil types.

As can be seen in Table 1, the wave speeds are quite variable throughout the corridor. This is attributable to both the type of soil and the location of the screening measurements. It was noted that whenever the screening measurements were conducted near solid surfaces, such as sidewalk or the roadway, the vibration wave would enter that structure and reach the measurement point at a faster rate than had the wave travelled through soil alone. Thus, some of the higher wave speeds in Table 1 may be slightly exaggerated when compared to a truly green-field situation.

Table 2 outlines the results of the damping test. Again, the results are variable from site-to-site but the damping per wavelength range across most sites is reasonable, when compared to those experienced at other sites with similar soils in Southern Ontario. The locations of the damping tests are shown in Figure 5 in Appendix A.
<table>
<thead>
<tr>
<th>Damping Test Site Number</th>
<th>Distance from Source to First Acc. (m)</th>
<th>Vibration Level at First Acc. (mm/s RMS)</th>
<th>Distance Between Acc. (m)</th>
<th>Vibration Level at Second Acc. (mm/s RMS)</th>
<th>Total Reduction (dB)</th>
<th>Reduction due to Distance (dB)</th>
<th>Reduction due to Damping (dB)</th>
<th>Damping Per Wavelength (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.6</td>
<td>0.04</td>
<td>3.3</td>
<td>0.02</td>
<td>6.02</td>
<td>1.8</td>
<td>4.26</td>
<td>3.2</td>
</tr>
<tr>
<td>2a</td>
<td>4</td>
<td>0.027</td>
<td>5.6</td>
<td>0.0074</td>
<td>11.24</td>
<td>3.8</td>
<td>7.44</td>
<td>3.8</td>
</tr>
<tr>
<td>2b</td>
<td>6.7</td>
<td>0.02</td>
<td>2.9</td>
<td>0.0077</td>
<td>8.29</td>
<td>1.6</td>
<td>6.73</td>
<td>6.6</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>0.007</td>
<td>3</td>
<td>0.0033</td>
<td>6.53</td>
<td>1.5</td>
<td>4.98</td>
<td>4.7</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>0.009</td>
<td>4</td>
<td>0.0026</td>
<td>10.79</td>
<td>2.2</td>
<td>8.57</td>
<td>6.1</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>0.0064</td>
<td>4</td>
<td>0.0034</td>
<td>5.49</td>
<td>1.8</td>
<td>3.73</td>
<td>2.96</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>0.012</td>
<td>3</td>
<td>0.007</td>
<td>4.68</td>
<td>2.4</td>
<td>2.25</td>
<td>1.63</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>0.0022</td>
<td>1.4</td>
<td>0.0017</td>
<td>2.24</td>
<td>1.3</td>
<td>0.94</td>
<td>1.4</td>
</tr>
</tbody>
</table>
The data for the damping testing at Site Number 4 and 5 seem very low. The soil was extremely hard and dry and this likely resulted in very low damping for the soil. It is also possible that the first accelerometer was placed in the near-field of the vibration source. In that case, the reduction due to distance would be more complicated to determine because of the interaction of the compression wave, surface wave, and shear waves, whereas normally only the surface wave is involved.

The above data, both wave speed and soil damping characteristics, are used in conjunction with the detailed testing to determine the expected vibration levels from the LRT at various setbacks, without the need to test each location. For example, a receptor near Damping Test Site 3 that is located a further 4m away would experience a reduction of approximately 4dB. If the detailed testing predicted a particularly level at a house located ‘X’ metres away from the LRT, the damping test would indicate that the vibration levels would be approximately 4dB lower at a house located X+4m away from the LRT. Vibration divergence losses only play a factor in setbacks greater than 50m.

### 4.3 Selection of Critical Receptors for Detailed Testing

Based on the measurements taken, the areas most sensitive to vibration from the future LRT were located between McMaster University in the west and where the LRT route starts to run onto Queenston Road in the east.

A total of 5 residential dwellings and the McMaster University campus grounds were selected for more detailed testing. The 5 detailed testing locations were selected based on the ability to use their testing results as an indication of the vibration levels that could be expected at different locations. A total of 2 apartments, 2 low-rise houses, and a 2nd-floor residential apartment (1st-floor commercial) were selected for detailed testing. These locations, as well as the specific area of the dwellings tested, are summarized in Table 3 below.

#### Table 3: Detailed Testing Location Descriptions

<table>
<thead>
<tr>
<th>Detailed Test Site Number</th>
<th>Street Address</th>
<th>Description of Building</th>
<th>Description of Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1028 Main Street West</td>
<td>2-storey residential dwelling</td>
<td>Vibration propagation tests conducted on ground floor and basement wall</td>
</tr>
<tr>
<td>2</td>
<td>595 King Street West</td>
<td>Mid-rise apartment building</td>
<td>Vibration propagation test conducted on ground floor</td>
</tr>
<tr>
<td>3</td>
<td>230 King Street East</td>
<td>Low-rise building with 2nd-floor apartments and 1st-floor retail</td>
<td>Vibration propagation test conducted on 2nd floor</td>
</tr>
<tr>
<td>4</td>
<td>2 Connaught Avenue</td>
<td>Mid-rise apartment building</td>
<td>Vibration propagation tests conducted on basement floor, wall, and ceiling</td>
</tr>
<tr>
<td>5</td>
<td>1262 Main Street East</td>
<td>2-storey residential dwelling</td>
<td>Vibration propagation tests conducted on basement floor and ground floor</td>
</tr>
</tbody>
</table>
In addition to the above tests, field-testing on McMaster Campus grounds was conducted on the southwest corner of the campus near Cootes Drive, where vibration-sensitive equipment is located. The locations of the detailed tests are shown in Figure 6 in Appendix A.

5.0 Detailed Vibration Impact Assessment Results

Once the testing at each site was completed, the LSTMs were derived from the recorded data and the general FTA force density for LRT systems was applied to generate the predicted vibration levels.

5.1 Vehicle/Track Characteristics and Expected Force Density

It is assumed the light rail vehicle chosen for the project will be approximately 30-35m in length and have an un-sprung mass per axle in the range of 750-820kg, which is similar to that of the streetcars (974kg) currently in use in Toronto. The majority of the system will operate on an embedded rail system, though the specifics of its construction are currently unknown. The maximum LRT speed is assumed to be 60km/hr. throughout the corridor, except between Catharine Street and Wellington Street where the maximum speed drops to 20km/hr. Until more detailed information is available, the FTA’s typical force density curve was used (provided in Appendix F). The force density function used is summarized in Table 4, expressed in metric units.

<table>
<thead>
<tr>
<th>1/3 Octave Band (Hz)</th>
<th>Force Density Function (N/√m)</th>
<th>Octave Band Force Density (N/√m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>143.03</td>
<td>239.01</td>
</tr>
<tr>
<td>16</td>
<td>143.03</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>127.47</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>113.61</td>
<td>153.16</td>
</tr>
<tr>
<td>31.5</td>
<td>80.43</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>63.89</td>
<td>176.09</td>
</tr>
<tr>
<td>50</td>
<td>63.89</td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>80.43</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>143.03</td>
<td>170.52</td>
</tr>
<tr>
<td>100</td>
<td>127.47</td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>101.26</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>50.75</td>
<td></td>
</tr>
</tbody>
</table>

The “√m” function indicates that the force density is a function of the square-root length of the LRV. The length of the vehicle is divided into segments based on the number of point transfer functions used to derive the LSTM. A total of 5 points are used in this assessment. Based on the force density and the measured transfer mobility, the overall expected vibration levels have been calculated. Details of the calculations are available in Appendix E.
The typical FTA force density curve for LRT vehicles is provided in Appendix F. Also provided are force density curves as measured in cities across the United States. It should be noted that the variability in force density functions is quite high considering that many of the vehicles tested share similar characteristics. Within the data supplied in the FTA guidelines, the width of the range of force density function varies between 10dB and 20dB. Relative to the average force density curve, this corresponds to a range of +77%/-56% to +216%/-31% in the absolute value of the forces imparted by LRT vehicles into the soil.

As provided in subsequent sections, measurements of the streetcar system in Toronto and also the measured LSTMs indicate that vibration in octave band frequencies below 16Hz and frequencies above 125Hz are not significant. As such, these frequencies are not considered in the assessment. As discussed in Sections 3.1 and 7.1, the vibration in the 16Hz and 125Hz octave band is not significant. These frequencies are carried through the calculations but are given little weight in the decisions on what type of vibration control to consider.

5.2 Predicted Vibration and Vibration-Induced Sound Levels

Table 5, below, summarizes the predicted vibration levels based on the detailed testing conducted and the typical FTA force density function for LRT vehicles, as summarized in Table 4, above. Table 6 summarizes the predicted vibration-induced sound levels based on the vibration levels predicted in Table 5.
Table 5: Predicted LRT Vibration Levels

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Configuration</th>
<th>Octave Band Vibration Levels (mm/s RMS)</th>
<th>Overall Vibration (mm/s RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>16Hz</td>
<td>31.5Hz</td>
</tr>
<tr>
<td>1</td>
<td>1028 Main Street West, House</td>
<td>Ground Floor, 17m from LRT</td>
<td>0.12</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Wall, 17m from LRT</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>2</td>
<td>595 King Street West, Apartment</td>
<td>Ground Floor, 6m from LRT</td>
<td>0.17</td>
<td>0.18</td>
</tr>
<tr>
<td>3</td>
<td>230 King Street, 2nd-storey Apartment</td>
<td>Second Floor, 5m from LRT</td>
<td>0.18</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Second Floor, 5m from LRT (with speed adjustment)</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>4</td>
<td>2 Connaught Avenue, Apartment</td>
<td>Basement Wall, 4.5m from LRT</td>
<td>0.11</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Floor, 4.5m from LRT</td>
<td>0.11</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Ceiling/Ground Floor, 4.5m from LRT</td>
<td>0.32</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Wall, 6.5m from LRT</td>
<td>0.08</td>
<td>0.15</td>
</tr>
<tr>
<td>5</td>
<td>1262 Main Street East, House</td>
<td>Ground Floor, 8m from LRT</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ground Floor, 10m from LRT</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Floor, 8m from LRT</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>6</td>
<td>McMaster University, Campus Grounds</td>
<td>Ground, 20m away from Impact</td>
<td>0.27</td>
<td>0.14</td>
</tr>
</tbody>
</table>
Table 6: Predicted Vibration-Induced Sound Levels

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Configuration</th>
<th>Octave Band Sound Levels (dB)</th>
<th>Overall Sound Level (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>16Hz</td>
<td>31.5Hz</td>
</tr>
<tr>
<td>1</td>
<td>1028 Main Street West, House</td>
<td>Ground Floor, 17m from LRT</td>
<td>68</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Wall, 17m from LRT</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>2</td>
<td>595 King Street West, Apartment</td>
<td>Ground Floor, 6m from LRT</td>
<td>71</td>
<td>71</td>
</tr>
<tr>
<td>3</td>
<td>230 King Street, 2nd-storey Apartment</td>
<td>Second Floor, 5m from LRT</td>
<td>71</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Second Floor, 5m from LRT (with speed adjustment)</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>4</td>
<td>2 Connaught Avenue, Apartment</td>
<td>Basement Wall, 4.5m from LRT</td>
<td>67</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Floor, 4.5m from LRT</td>
<td>67</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Ceiling/Ground Floor, 4.5m from LRT</td>
<td>76</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Wall, 6.5m from LRT</td>
<td>65</td>
<td>70</td>
</tr>
<tr>
<td>5</td>
<td>1262 Main Street East, House</td>
<td>Ground Floor, 8m from LRT</td>
<td>70</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ground Floor, 10m from LRT</td>
<td>68</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Floor, 8m from LRT</td>
<td>64</td>
<td>63</td>
</tr>
</tbody>
</table>
5.3 Analysis of Predicted Vibration Levels

As can be seen in Tables 5 and 6, the vibration levels and vibration-induced sound levels exceed the guideline levels of 0.10 mm/s and 35dBA, respectively, at all locations tested.

The vibration levels predicted in Tables 5 and 6 indicate that a significant increase in vibration levels can be expected when moving from short setbacks (6-7m) to even shorter setbacks (3-4m). This increase is significantly greater than one might expect given the relative change in distance of the testing. At close distances, however, the receiving structure (house or apartment) lies within the near-field of the surface wave. In addition, there are shear and compression wave components present and thus the overall energy transmitted into the receiving structure is greater.

At most sites, there seems to be a significant amount of vibration energy in the 16Hz and 31.5Hz octave bands. In measurements of the embedded rail portions of the TTC’s streetcar system, there is typically not a significant amount of vibration in the 16Hz band. The energy in the 31.5Hz band is also lower (by approximately 50%) than the energy found in the 63Hz octave band. This variation in expected vibration levels from the modeling versus measured vibration levels is likely a result of two factors.

First, the average FTA force density function likely includes measurements from all different track suspension systems associates with LRT. Lower frequency vibration tends to be more of an issue with tie-on-ballast track. This shifts the amount of force expected at those frequencies upwards relative to embedded rail systems. Measurements taken along the TTC’s tie-on-ballast track confirm this assumption, as there is a greater amount of 16Hz and 31.5Hz vibration at these locations. Table 7, below, summarizes vibration levels of streetcars measured at various sites in Toronto.

<table>
<thead>
<tr>
<th>Location</th>
<th>Track Configuration</th>
<th>Octave Band Vibration Levels (mm/s RMS)</th>
<th>Overall Vibration Level (mm/s RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet Street (Slow Moving Streetcars)</td>
<td>Embedded, 6m from nearest track</td>
<td>0.01 0.05 0.07 0.01</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>Embedded, 12m from nearest track</td>
<td>0.01 0.03 0.05 0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>Queensway (Fast Streetcars)</td>
<td>Tie-on-Ballast, 6m from nearest track</td>
<td>0.01 0.14 0.29 0.08</td>
<td>0.33</td>
</tr>
<tr>
<td>King Street East (Fast Streetcars)</td>
<td>Embedded, 12m from nearest track</td>
<td>0.02 0.07 0.13 0.01</td>
<td>0.16</td>
</tr>
<tr>
<td>Queen Street East (Fast)</td>
<td>Embedded, 6m from nearest track</td>
<td>0.02 0.10 0.17 0.01</td>
<td>0.20</td>
</tr>
<tr>
<td>King Street West (Fast)</td>
<td>Embedded, 12m from nearest track</td>
<td>0.01 0.03 0.08 0.01</td>
<td>0.09</td>
</tr>
</tbody>
</table>
Second, ambient traffic vibration often dominates the lower frequency ranges. As a result, vibration inputs into the soil adjacent to moving traffic may not stand out significantly (at least 10dB above) the ambient vibration level. While this was controlled as much as feasible during field-testing, the LSTM at 16Hz and to a lesser extent at 31.5Hz are affected by ambient traffic vibration.

Most of the streetcars measured in Table 7 travelled at speeds significantly below the maximum speed the B-Line LRT will operate at, with the exception of the streetcars running on tie-on-ballast track. Consequently, the overall vibration levels will be proportionately higher and more aligned with those values expected from the detailed testing (summarized in Table 5). Correspondence from Bombardier, the supplier of vehicles for Toronto’s Transit City network, indicates that the vibration levels should not exceed those of the current streetcar fleet and may actually produce lower vibration levels.

Given the above measurement data, it is concluded that the FTA prediction procedure significantly overestimates the low frequency component, with 16Hz being the most grossly overestimated octave band. As well, reviewing the measured streetcar data and other force density data measured from around the U.S., the mid-frequency components (63Hz and 125Hz) are slightly underestimated. As a result, the vibration mitigation recommendations made in this report are slightly conservative, to reflect the higher potential impact of vibration in the 63Hz and 125Hz octave bands. The levels next to Fleet Street in Toronto and at other sites are only 10% of the levels predicted by the average FTA force density function in the 16Hz octave band. The 31.5Hz band is significant, but measured levels are often not as high as the levels in the 63Hz octave band. The measured levels in the 31.5Hz octave band were approximately 60% of the levels predicted by the same force density function. The measured levels in the 63Hz band were doubled. The vibration and vibration-induced sound levels in Tables 5 and 6 have been adjusted to reflect the above discrepancies in the lower and higher frequencies. Tables 8 and 9 on the following pages summarize the revised predicted vibration levels.

Section 7.0 of this report discusses the mitigation recommendations for the expected vibration levels, based on the results of the above transfer mobility testing and the empirical results of the streetcar system in Toronto.
### Table 8: Predicted Vibration Levels (Adjusted)

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Configuration</th>
<th>Octave Band Vibration Levels (mm/s RMS)</th>
<th>Overall Vibration (mm/s RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>16Hz</td>
<td>31.5Hz</td>
</tr>
<tr>
<td>1</td>
<td>1028 Main Street West, House</td>
<td>Ground Floor, 17m from LRT</td>
<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Wall, 17m from LRT</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>595 King Street West, Apartment</td>
<td>Ground Floor, 6m from LRT</td>
<td>0.02</td>
<td>0.11</td>
</tr>
<tr>
<td>3</td>
<td>230 King Street, 2nd-storey Apartment</td>
<td>Second Floor, 5m from LRT</td>
<td>0.02</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Second Floor, 5m from LRT (with speed adjustment)</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>2 Connaught Avenue, Apartment</td>
<td>Basement Wall, 4.5m from LRT</td>
<td>0.01</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Floor, 4.5m from LRT</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Ceiling/Ground Floor, 4.5m from LRT</td>
<td>0.03</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Wall, 6.5m from LRT</td>
<td>0.01</td>
<td>0.09</td>
</tr>
<tr>
<td>5</td>
<td>1262 Main Street East, House</td>
<td>Ground Floor, 8m from LRT</td>
<td>0.02</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ground Floor, 10m from LRT</td>
<td>0.01</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Floor, 8m from LRT</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>6</td>
<td>McMaster University, Campus Grounds</td>
<td>Ground, 20m away from Impact</td>
<td>0.03</td>
<td>0.09</td>
</tr>
</tbody>
</table>
Table 9: Predicted Vibration-Induced Sound Levels (Adjusted)

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Configuration</th>
<th>Octave Band Sound Levels (dB)</th>
<th>Overall Sound Level (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1028 Main Street West, House</td>
<td>Ground Floor, 17m from LRT</td>
<td>48 62 71 58</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Wall, 17m from LRT</td>
<td>44 60 71 50</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>595 King Street West, Apartment</td>
<td>Ground Floor, 6m from LRT</td>
<td>51 67 67 61</td>
<td>46</td>
</tr>
<tr>
<td>3</td>
<td>230 King Street, 2nd-storey Apartment</td>
<td>Second Floor, 5m from LRT</td>
<td>51 66 71 58</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Second Floor, 5m from LRT (with speed adjustment)</td>
<td>45 60 65 52</td>
<td>41</td>
</tr>
<tr>
<td>4</td>
<td>2 Connaught Avenue, Apartment</td>
<td>Basement Wall, 4.5m from LRT</td>
<td>47 66 70 77</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Floor, 4.5m from LRT</td>
<td>47 60 77 67</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Ceiling/Ground Floor, 4.5m from LRT</td>
<td>56 74 78 70</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Wall, 6.5m from LRT</td>
<td>45 65 68 74</td>
<td>58</td>
</tr>
<tr>
<td>5</td>
<td>1262 Main Street East, House</td>
<td>Ground Floor, 8m from LRT</td>
<td>50 65 65 51</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ground Floor, 10m from LRT</td>
<td>48 64 64 50</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basement Floor, 8m from LRT</td>
<td>44 59 66 54</td>
<td>42</td>
</tr>
</tbody>
</table>
6.0 The Canadian Centre for Electron Microscopy at McMaster University

During the Environmental Assessment for the project, the Canadian Centre for Electron Microscopy (CCEM) at McMaster University was identified as having equipment especially sensitive to vibration. As part of this more detailed vibration assessment, the CCEM facility was reviewed to determine the potential impact on the sensitive equipment from the LRT operations. The building housing the CCEM facility is shown in Figure 8, attached.

Based on current plans, the terminus of the LRT line is approximately 100m away from the nearest corner of the building housing the CCEM. The nearest crossover (switches) is tentatively located 200m away.

6.1 Description of Sensitive Equipment

The primary types of sensitive equipment located within the CCEM are electron microscopes. Also housed in this facility are NMR (nuclear magnetic resonance) machines. Of the two types of equipment, electron microscopes are generally the most sensitive.

Electron microscopes’ sensitivity to vibration depends largely on their targeted image resolution. Higher resolution microscopes are more sensitive to vibration than lower resolution microscopes. Because of their sensitivity, the large electron microscopes are often mounted on vibration control systems and the equipment is located in areas of buildings with the lowest structural vibration.

The CCEM houses a number of electron microscopes with varying sensitivity. Some microscopes do not require vibration isolation systems of any kind whereas others have a relatively substantial investment in vibration isolation measures. The CCEM houses one of the most sensitive microscopes in the world capable if imaging individual atoms.

In order to determine whether or not the LRT would affect the operations of the CCEM, ambient vibration measurements were taken at the most sensitive equipment identified by the CCEM staff. These are compared to the predicted vibration levels from the LRT.

6.2 Ambient Vibration Levels

Ambient vibration measurements were conducted within 3 rooms housing electron microscopes. Measurements were conducted for approximately 10 to 15 minutes at each location to determine the ambient vibration levels within the building.

All 3 rooms tested were in the basement and located on slab-on-grade floors. As a result, footfall induced vibration is minimal. The ambient vibration would be dominated by building vibration (due to mechanical equipment, etc.) as well as vibration due to street traffic on Cootes Drive. Given the high traffic volumes and speeds on Cootes Drive, the short measurement window at each location was sufficient to obtain a representative sample of vehicular traffic’s impact on the ambient vibration levels.
Vibration measures were taken on the slab nearby each piece of equipment. Vibration measurements were taken both in one horizontal axis and in the vertical axis. It is assumed that for a symmetrically constructed room, the vibration levels in the other horizontal axis will be similar. A total of 3 rooms were measured: the rooms housing the Titan 30-800 ST, the Magellan 400, and the JEM 2010F.

Table 10 summarizes the peak octave band vibration levels measured during the observation period for each piece of equipment monitored.

Table 10: Sensitive Equipment Ambient Vibration Levels

<table>
<thead>
<tr>
<th>Location</th>
<th>Accelerometer Position</th>
<th>Octave Band Vibration Levels (mm/s RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>16Hz</td>
</tr>
<tr>
<td>Titan 30-800 ST</td>
<td>Vertical</td>
<td>0.0026</td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>0.0025</td>
</tr>
<tr>
<td>Magellan 400</td>
<td>Vertical</td>
<td>0.0024</td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>0.0012</td>
</tr>
<tr>
<td>JEM 2010F</td>
<td>Vertical</td>
<td>0.0033</td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>0.0016</td>
</tr>
</tbody>
</table>

The following exhibits show the one-second average of the overall vibration levels at each of the measured pieces of equipment. Additional data for the vertical movement in each room are available, but the following samples are representative of the remainder of the data collected.
As can be seen in the above exhibits, the overall vibration levels range from 0.002mm/s RMS to approximately 0.01mm/s RMS. Much of the ambient vibration that causes the spikes is in the lower frequencies such as 8Hz and 4Hz. This is likely due to internal sources within the building and enhanced by the building’s natural frequencies. Surface transit sources operating on embedded rail systems do not produce significant vibration at these low frequencies.
6.3 Prediction of Expected LRT Vibration Levels

The transfer mobility test becomes unreliable at large setbacks, especially in environments subject to relatively high background vibration such as near roadways. As a result, a transfer mobility test was conducted at a 20m setback from the impact point. The predicted vibration levels at 20m were then projected back to the CCEM facility using the previously measured soil data. Damping tests conducted on site confirmed the expected attenuation due to damping. Two scenarios were investigated; the vibration due to the crossover, located 200m away, and the vibration from the nearest point of the LRT line’s tangent track, located 100m away.

Table 11, below, summarizes the expected vibration levels at the CCEM facility as a result of the vibration due to the crossover. Table 12 summarizes the expected vibration levels at the CCEM due to the nearest track vibration.

| Table 11: Predicted Vibration Levels at the CCEM Due to Crossovers |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| | 16Hz | 31.5Hz | 63Hz | 125Hz | Overall |
| Predicted Vibration Level at 20m (mm/s) | 0.03 | 0.09 | 0.23 | 0.01 | 0.25 |
| Distance Correction (dB) | 10.00 | 10.00 | 10.00 | 10.00 | - |
| Number of Wavelengths | 14.55 | 28.64 | 57.27 | 113.64 | - |
| Damping per Wavelength (dB) | 4.00 | 4.00 | 4.00 | 4.00 | - |
| Total Damping Effect (dB) | 58.18 | 114.55 | 229.09 | 454.55 | - |
| Amplification Due to Crossovers | +10.00 | +10.00 | +10.00 | +10.00 | - |
| Total Adjustments (dB) | 58.18 | 114.55 | 229.09 | 454.55 | - |
| Expected Vibration Level at 200m (mm/s) | 3.37979E-05 | 1.63E-07 | 8.16E-13 | 2.15E-25 | 0.000034 |

Note: Corrections are negative unless otherwise noted

| Table 12: Predicted Vibration Levels at the CCEM Due to Tangent Track |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| | 16Hz | 31.5Hz | 63Hz | 125Hz | Overall |
| Predicted Vibration Level at 20m (mm/s) | 0.03 | 0.09 | 0.23 | 0.01 | 0.25 |
| Distance Correction (dB) | 6.99 | 6.99 | 6.99 | 6.99 | - |
| Number of Wavelengths | 6.46 | 12.73 | 25.45 | 50.51 | - |
| Damping per Wavelength (dB) | 4.00 | 4.00 | 4.00 | 4.00 | - |
| Total Damping Effect (dB) | 25.86 | 50.91 | 101.82 | 202.02 | - |
| Speed Correction (dB) | 12 | 12 | 12 | 12 | - |
| Total Adjustments (dB) | 44.89 | 69.94 | 120.85 | 221.05 | - |
| Expected Vibration Level at 100m (mm/s) | 0.000156 | 2.77E-05 | 2.11E-07 | 1.01E-13 | 0.0002 |

Note: Corrections are negative unless otherwise noted
Tables 11 and 12 summarize the vertical vibration levels that can be expected at the CCEM, assuming the coupling loss into the building and the dynamic amplification of the floors cancel each other out. This is a reasonable assumption for slab-on-grade construction. The levels calculated are also vertical vibration levels. For surface waves, the horizontal component of the wave is generally less significant and contains typically 2/3 of the vertical component’s energy and thus amplitude.

Based on the predicted vibration levels, the LRT’s operations from the crossover and the nearest section of tangent track will not affect the operations of the CCEM. The predicted levels from the LRT are well below the ambient vibration levels present in the CCEM. Additional vibration mitigation is thus not required to protect the CCEM facility. This is as expected given the relatively large setbacks involved and the soil’s propensity towards high damping. In any case, the tracks will be treated with at least a basic form of vibration isolation, which will reduce the expected vibration levels in Tables 11 and 12 a further 20 to 30%.

7.0 Vibration Control Recommendations

Based on the testing conducted throughout the corridor and the measurement of similar streetcar systems in Toronto, vibration impacts are expected at many points throughout the corridor. In some cases, the vibration excesses above the guidelines are expected to be minor. On other areas, the vibration excesses above the guidelines are expected to be significant and substantial vibration isolation will be required. Among the most recently completed transit projects in North America and in Europe, few LRT systems operate as close to sensitive receptors as the B-Line LRT route will run. Coupled with the street level speeds expected (50-60 km/hr.), the resultant requirements for vibration control are not surprisingly high.

This section outlines the various levels of vibration control considered, their expected performance based on the soil characteristics, and the areas in which the various forms of vibration control are required.

7.1 Recommended Levels of Vibration Control

Four different levels of vibration control have been considered for use in the project. The recommendations are based on products produced by CDM. Similar products from others suppliers as well as custom products are also available. These different levels are described in Table 13, below. Please see Figure 20 in Appendix A for a graphical representation of the floating slab products, which also shows the embedded rail isolation system.
Table 13: Description of Vibration Isolation Systems

<table>
<thead>
<tr>
<th>Isolation Level</th>
<th>Manufacturer’s Designation</th>
<th>Isolation Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CDM-QT-HP</td>
<td>Embedded Rail</td>
<td>A nominal performance embedded rail system, slightly more expensive than the rubber isolation required for electrical insulation.</td>
</tr>
<tr>
<td>2</td>
<td>CDM-QT-XP</td>
<td>Embedded Rail</td>
<td>A higher performance embedded rail system. A slightly thicker rubber layer around the rails.</td>
</tr>
<tr>
<td>3</td>
<td>CDM-FSM-L6 + CDM-QT-HP</td>
<td>Floating Slab</td>
<td>A floating slab construction used in conjunction with an embedded rail system to provide additional performance wherever needed.</td>
</tr>
<tr>
<td>4</td>
<td>CDM-FSM-L6 + CDM-QT-XP</td>
<td>Floating Slab</td>
<td>An upgraded floating slab solution as needed in especially close setbacks.</td>
</tr>
</tbody>
</table>

In order to determine the performance of the system, the manufacturer was supplied with the typical soil shear modulus along the corridor, derived from the wave speed measurements. The shear moduli along the corridor vary from approximately 35MPa to approximately 100MPa. The approximate weight per axle is assumed to be 10,000kg and the un-sprung mass per axle is assumed to be 1/10 of this amount, 1,000kg.

The theoretical insertion loss data, as supplied by the manufacturer, are provided in Table 14 below. Adjustments have also been made to the calculations to reflect the expected insertion losses. These are discussed further, below.

Table 14: Insertion Losses of Recommended Vibration Isolation Systems

<table>
<thead>
<tr>
<th>Isolation Level</th>
<th>Condition</th>
<th>16Hz</th>
<th>31.5Hz</th>
<th>63Hz</th>
<th>125Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Theoretical Performance</td>
<td>2</td>
<td>9</td>
<td>2</td>
<td>-20</td>
</tr>
<tr>
<td></td>
<td>Expected Performance</td>
<td>-1</td>
<td>2</td>
<td>-3</td>
<td>-21</td>
</tr>
<tr>
<td>2</td>
<td>Theoretical Performance</td>
<td>5</td>
<td>10</td>
<td>-2</td>
<td>-27</td>
</tr>
<tr>
<td></td>
<td>Expected Performance</td>
<td>1</td>
<td>3</td>
<td>-7</td>
<td>-28</td>
</tr>
<tr>
<td>3</td>
<td>Calculated Performance</td>
<td>11</td>
<td>1</td>
<td>-15</td>
<td>-39</td>
</tr>
<tr>
<td></td>
<td>Expected Performance</td>
<td>4</td>
<td>-3</td>
<td>-20</td>
<td>-40</td>
</tr>
<tr>
<td>4</td>
<td>Calculated Performance</td>
<td>9</td>
<td>-5</td>
<td>-21</td>
<td>-47</td>
</tr>
<tr>
<td></td>
<td>Expected Performance</td>
<td>2</td>
<td>-9</td>
<td>-26</td>
<td>-48</td>
</tr>
</tbody>
</table>

Note: Negative numbers indicate a reduction in vibration levels, while positive numbers indicate amplification of vibration levels.

The theoretical models used by suppliers of vibration isolation systems typically include a very conservative damping factor. This damping factor is typically significantly underestimated. Post-construction measurements of vibration isolation systems often yield better than expected results. At the 2012 APTA Rail Conference, Wilson, Ihrig & Associates conducted a presentation titled “The Benefits and Limitations of Floating Slab Track for Controlling Groundborne Noise and Vibration” (Gary M. Glickman, WIA, 2012). This presentation indicated that floating slab track performances were often
under-predicted, as they used relatively low damping factors (8% or so). In reality, when compared to measured results, a 40% damping factor yielded predicted results closer to the measured results. In systems such as these, the damping is often close to critical damping. Thus, the amount of radiation loss, especially at lower frequencies, is not accurately calculated within these models. The result is a higher than actual amplification, when in reality the dynamic amplification is small.

Table 14 includes the expected performance of vibration isolation systems. When going out to tender, it will be critical for the manufacturer to demonstrate equivalence with the above expected performance figures.

It should be noted that the floating slab systems evaluated above are substantial and the expected performance of those systems is amongst the highest of such systems in North America. There are, however, avenues to improve the vibration isolation performance of these systems. For example, there are discrete pad solutions that would provide another level of vibration isolation. Generally, the costs of such systems are slightly higher in terms of materials. The implementation costs of such systems are greater, however. Though there is less vibration isolation material required, the concrete construction required is more involved. Overall, the cost difference between such systems is likely within 10% over large stretches as is needed in Hamilton. The determination of which system to apply can be discussed with further detailed design.

In any case, the vibration isolation performance in the 63Hz band is most critical, given the relatively tight setbacks between the future LRT route and nearby sensitive receptors.

### 7.2 Predicted Vibration Levels with Vibration Control

The predicted vibration levels based on the testing results have been corrected for the expected performance of the various isolation measures, and have been adjusted based on measurements of the streetcar system. These predicted vibration levels with isolation are summarized in Table 15, below. The predicted vibration-induced sound levels are summarized in Table 16, following.
### Table 15: Predicted Vibration Levels with Recommended Vibration Control

<table>
<thead>
<tr>
<th>Location</th>
<th>Vibration Isolation Level</th>
<th>Description</th>
<th>Octave Band Vibration Levels (mm/s RMS)</th>
<th>Overall Vibration (mm/s RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>16Hz</td>
<td>31.5Hz</td>
</tr>
<tr>
<td>1</td>
<td>Level 2 Embedded</td>
<td>Ground Floor, 17m from LRT</td>
<td>0.01</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Level 2 Embedded</td>
<td>Basement Wall, 17m from LRT</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>2</td>
<td>Level 3 Floating</td>
<td>Ground Floor, 6m from LRT</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>3</td>
<td>Level 3 Floating</td>
<td>Second Floor, 5m from LRT (full speed)</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Level 1 Embedded</td>
<td>Second Floor, 5m from LRT (with speed adjustment)</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>Level 4 Embedded</td>
<td>Basement Wall, 4.5m from LRT</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Basement Floor, 4.5m from LRT</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Basement Ceiling/Ground Floor, 4.5m from LRT</td>
<td>0.04</td>
<td>0.08</td>
<td>0.02</td>
</tr>
<tr>
<td>5</td>
<td>Level 3 Embedded</td>
<td>Basement Wall, 6.5m from LRT</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Level 2 Embedded</td>
<td>Ground Floor, 8m from LRT</td>
<td>0.02</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>Ground Floor, 10m from LRT</td>
<td>0.01</td>
<td>0.10</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Basement Floor, 8m from LRT</td>
<td>0.01</td>
<td>0.05</td>
<td>0.04</td>
</tr>
</tbody>
</table>
### Table 16: Predicted Vibration-Induced Sound Levels with Recommended Vibration Control

<table>
<thead>
<tr>
<th>Location</th>
<th>Vibration Isolation Level</th>
<th>Description</th>
<th>Octave Band Sound Levels (dB)</th>
<th>Overall Sound Level (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>16Hz</td>
<td>31.5Hz</td>
</tr>
<tr>
<td>1</td>
<td>Level 2 Embedded</td>
<td>Ground Floor, 17m from LRT</td>
<td>49</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>Level 2 Embedded</td>
<td>Basement Wall, 17m from LRT</td>
<td>45</td>
<td>56</td>
</tr>
<tr>
<td>2</td>
<td>Level 3 Floating</td>
<td>Ground Floor, 6m from LRT</td>
<td>55</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>Level 3 Floating</td>
<td>Second Floor, 5m from LRT (full speed)</td>
<td>55</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>Level 1 Embedded</td>
<td>Second Floor, 5m from LRT (with speed adjustment)</td>
<td>43</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>Level 4 Embedded</td>
<td>Basement Wall, 4.5m from LRT</td>
<td>49</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Basement Floor, 4.5m from LRT</td>
<td></td>
<td>49</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Basement Ceiling/Ground Floor, 4.5m from LRT</td>
<td></td>
<td>58</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Level 3 Embedded</td>
<td>Basement Wall, 6.5m from LRT</td>
<td>49</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>Level 2 Embedded</td>
<td>Ground Floor, 8m from LRT</td>
<td>51</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>Ground Floor, 10m from LRT</td>
<td></td>
<td>49</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>Basement Floor, 8m from LRT</td>
<td></td>
<td>45</td>
<td>60</td>
</tr>
</tbody>
</table>
Table 15 indicates that the 0.10 mm/s target for vibration levels is readily achievable in most locations. Location 5 is slightly (less than 10%) above the guideline limit. This is within the tolerance of the prediction procedure and further upgrades are not recommended.

Table 16 indicates that the 35dBA target for indoor-levels is achievable with the recommended mitigation measures. The resulting vibration-induced sound levels are below the guideline and are conservative to reflect the higher 63Hz and 125Hz vibration levels expected.

The predicted vibration levels and vibration-induced sound levels have been extrapolated to other receptors along the corridor to determine the extents of vibration isolation required. The vibration control recommendations are shown in Figures 9 through 19 in Appendix A.

A cross-section of the floating slab track is shown in Figure 20 in Appendix A. This image also shows the embedded rail system, the Q-Track system.

### 7.3 Special Track Work

The exact locations of special track work within the corridor have not been finalized as yet. Currently there are at least 4 areas of special track work likely to be used: one at each of the two termini of the line; one at the turnout to the maintenance and storage facility; and one near the Scott Park stop. During the detailed design phase, other locations may be identified for crossovers, to facilitate operation of the LRT.

In general, per the FTA guidelines, the vibration levels near special track work increase by approximately 10dB (a factor of 3:1). Unlike the tangent track vibration, which is a semi-infinite line source, the vibration from special track work radiates like a point source. Hence, there is greater reduction in vibration levels due to distance.

It is assumed that low-impact frogs will be used throughout the project. The use of low-impact frogs can decrease the incremental effect of vibration by approximately 5dB (a factor of 1.8:1). The remaining expected increase in vibration due to special track work has been incorporated (see Figures 8, 14, and 19 in Appendix A) where their effects play a role in controlling the level of vibration isolation required. Because of the complexity of the track system, however, there is an incremental cost to the vibration isolation systems (discussed below) in each special case.

During the course of detailed design, it would be prudent not to locate any crossovers or turnouts wherever Level 4 mitigation has been recommended. As Level 4 mitigation is already quite complex and nearly at the limit of the performance of such systems, locating special track work in such areas would be problematic in terms of achieving the target vibration levels and vibration-induced sound levels.
7.3 Cost Estimates

Correspondence from the manufacturer of the reviewed vibration isolation systems has provided preliminary cost estimates for the materials required for the various vibration isolation systems. Table 17, below, summarizes the total length of each isolation system, the cost per unit length of that system, and the overall estimated vibration control material cost.

Table 17: Vibration Isolation Cost Estimates

<table>
<thead>
<tr>
<th>Vibration Isolation Level</th>
<th>Manufacturer’s Designation</th>
<th>Cost Per Metre of Dual Track</th>
<th>Total Length (m)</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1 – Embedded</td>
<td>CDM-QT-HP</td>
<td>$400</td>
<td>6100</td>
<td>$2,440,000</td>
</tr>
<tr>
<td>Level 2 – Embedded</td>
<td>CDM-QT-XP</td>
<td>$480</td>
<td>3700</td>
<td>$1,776,000</td>
</tr>
<tr>
<td>Level 3 – Floating Slab</td>
<td>CDM-FSM-L6 + CDM-QT-HP</td>
<td>$800</td>
<td>2700</td>
<td>$2,160,000</td>
</tr>
<tr>
<td>Level 4 – Floating Slab</td>
<td>CDM-FSM-L6 + CDM-QT-XP</td>
<td>$900</td>
<td>900</td>
<td>$810,000</td>
</tr>
</tbody>
</table>

The total cost for the above materials is estimated at approximately $7.2 million for the entire route. It is expected that the incremental costs due to crossovers will be approximately $80,000 per crossover. Assuming 5 crossovers/turnouts, the additional cost for the crossovers is estimated to be approximately $400,000. Other incidental supplies needed for the above systems, such as installation jigs and site delivery, will cost an additional $100,000 to $200,000. The budget price then for the vibration isolation required for the B-Line LRT is approximately $7.8 million.

The above estimates are for material only and do not include the labor required for installation, particularly the extra forming and materials for floating slab track.

7.4 Design Considerations

Although it is not the purpose of this report to design the vibration isolation systems, some consideration should be given to the design implications and associated details of the recommended systems.

The embedded rail systems are straight-forward installations and their design is straightforward. The CDM embedded rail systems, evaluated above, provide an added benefit in that they are thick enough to allow replacement of the steel rails without damaging the surrounding concrete. Future rail replacement is, therefore, much easier.

Floating slab systems are also fairly common occurrences, though few systems in North America demand as much floating slab as seems to be needed in Hamilton. The reason for the amount of floating slab track is the length of side running track. Unlike many areas in Europe and in the southern United States, the floating slab systems for surface track in Ontario must contend with the Canadian winter. During the design phase, the fact that the depth of the floating slab will not fall beneath the
average frost line will have to be considered. These systems will also stiffen in winter so low temperature elasticity will be a factor.

Finally, the sensitive receptors adjacent to the corridor vary quite substantially in a few factors. First, sensitive residential receptors requiring greater vibration control are often interspersed between less sensitive, commercial receptors requiring less vibration control. Additionally, based on the results of the testing, the difference in predicted vibration levels between a 4 or 5m setback from the LRT route and a 6 or 7m setback can be significant. Given these effects, the vibration control recommendations (discussed in Section 7.2 and shown in Figures 9 through 19) vary considerably and transition from one level to another.

In transitioning from one form of vibration control to another, the relative change in rail deflections should be considered. As the vibration isolation systems vary in their expected deflection, moving from one type to another without an appropriate transition can result in cracking of the surrounding concrete structure and significant damage to the tracks’ rails and the vehicles’ wheels. Moving from one level of embedded rail system to another should not require a significant length of transition. Therefore, the areas shown that transition from Level 1 isolation to Level 2 isolation should not be an issue. Moving from an embedded rail system to a floating slab system, however, will require an appropriate period of transition. Especially critical are the transitions from a Level 1 isolation system to a Level 4 isolation system. The details of transitions have not been specified as part of this vibration assessment, but typically require 1-2m of track to carry out.

In areas where the requirements change rapidly from one level to another, continuing the more strenuous vibration isolation system (i.e., the higher level of vibration isolation) may simplify the construction of the route.

7.5 Potential Future Refinement to the Model

In the absence of a definite vehicle selection, the vibration isolation recommendations outlined in this report have been based on the average FTA force density function for light rail systems, adjusted by measurements of the TTC streetcar operations. As outlined, there are some discrepancies in using this force density function when comparing the predicted vibration levels to those vibration levels measured of TTC streetcar systems. In order to account for this difference, the predicted vibration levels have been adjusted to reflect the expected vibration levels. Thus, a combination of the FTA prediction procedure and measurements of existing streetcar systems in Ontario have been used to obtain the vibration isolation recommendations needed to meet the MOE/TTC guideline of 0.10mm/s and the FTA recommended vibration-induced sound level guideline of 35dBA.

As mentioned earlier, the force density functions measured from across the United States vary considerably for systems of similar construction and design. Theoretically, the force density functions should be similar across vehicles with similar design, and track with similar construction. This indicates that the force density values calculated should be used with some caution.

In April 2013, the TTC is planning to begin testing its new streetcar vehicle on the streets of Toronto. These vehicles, Bombardier’s Flexity Freedom, are expected to share similar vehicle characteristics to J.E. COULTER ASSOCIATES LIMITED
the Bombardier Flexity Outlook, which is to be used in Toronto’s Transit City LRT network. This planned testing by the TTC would provide an opportunity to measure a similar system on the Lake Iroquois lacustrine deposits, which is not possible anywhere else. Measuring the force density function for this system in Toronto would provide further clarification on the expected vibration levels along the Hamilton corridor. Consideration should be given to approaching the TTC to coordinate such testing of their new vehicle. The cost of doing so at this point is minor.
EAST BEND AV S
HILDA AV
SPRINGER AV
ALBERT ST
PROSPECT ST S
BELVIEW AV

TRACKS:
SPEED VARIES
FROM 20-60 KM/H

VARIES
4m to 20+m

BASEMENT APARTMENT

VARIABLES
WOOD, MASONRY, CONCRETE, STEEL

MAIN WINDOWS

ADDITIONAL ROOMS AND
FLOORS

CLOSEST SECOND FLOOR ROOM
FAR SECOND FLOOR ROOM

CLOSEST FIRST FLOOR ROOM
FAR FIRST FLOOR ROOM

SURFACES OF PAVEMENT,
CONCRETE, SOIL, OR A
COMBINATION

SMALL WINDOW
TO BASEMENT
APARTMENT

VARIABLE SOILS: CLAY, TILL, SAND, SILT,
FILL, SOMETIMES IN LAYERS TOGETHER

FIGURE 2
SOURCE-RECEIVER
CONFIGURATION
DECREASING VIBRATION AND VIBRATION-INDUCED NOISE WITH INCREASING HEIGHT

CLOSEST SECOND FLOOR ROOM: MODERATE SENSITIVITY TO VIBRATION AND LOW SENSITIVITY TO VIBRATION-INDUCED NOISE DUE TO HIGH STREET NOISE

FAR SECOND FLOOR ROOM: LOW SENSITIVITY TO VIBRATION AND MODERATE SENSITIVITY TO VIBRATION-INDUCED NOISE

CLOSEST FIRST FLOOR ROOM: HIGH SENSITIVITY TO VIBRATION LOW SENSITIVITY TO VIBRATION-INDUCED NOISE DUE TO STREET NOISE

FAR FIRST FLOOR ROOM: MODERATE SENSITIVITY TO VIBRATION AND MODERATE SENSITIVITY TO VIBRATION-INDUCED NOISE

BASEMENT APARTMENT: HIGH SENSITIVITY TO BOTH VIBRATION AND VIBRATION-INDUCED NOISE

FIGURE 3 RESIDENTIAL RECEIVER SENSITIVITY
LEGEND:
- DAMPING TEST
- SCREENING TEST

FIGURE 5
DAMPING MEASUREMENT LOCATIONS
Testing AT McMaster

Location 1
1028 Main Street West

Location 2
595 Main Street West

Location 3
230 Main Street East

Location 4
2 Connaught Avenue

Location 5
1262 Main Street East

Figure 6
Detailed Measurement Locations
FIGURE 7
TESTING CONFIGURATION
FIGURE 10
VIBRATION ISOLATION

Embedded Rail (3dB)
- $400/m of dual track
- Floating Slab (13-17dB)
- $700/m of dual track

Embedded Rail (5-6dB)
- $500/m of dual track
- Floating Slab (18+ dB)
- $800/m of dual track
FIGURE 11
VIBRATION ISOLATION
Figure 15
Vibration Isolation
EMBEDDED RAIL (3dB)
- $400/m of dual track
- FLOATING SLAB (13-17dB)
- $600/m of dual track
- EMBEDDED RAIL (5-6dB)
- $500/m of dual track
- FLOATING SLAB (18+ dB)
- $800/m of dual track

FIGURE 16
VIBRATION ISOLATION
Figure 17
Vibration Isolation

- Embedded Rail (3dB): $400/m of dual track
- Embedded Rail (5-6dB): $500/m of dual track
- Floating Slab (13-17dB): $700/m of dual track
- Floating Slab (18+ dB): $800/m of dual track
FIGURE 18
VIBRATION ISOLATION
EMBEDDED RAIL (3dB) $400/m of dual track
FLOATING SLAB (13-17dB) $700/m of dual track
EMBEDDED RAIL (5-6dB) $480/m of dual track
FLOATING SLAB (18+ dB) $800/m of dual track

FIGURE 19
VIBRATION ISOLATION
APPENDIX B: GUIDELINES AND PROTOCOLS
APPENDIX B
MOE/TTC PROTOCOLS

MOEE/TTC
DRAFT
PROTOCOL FOR NOISE AND
VIBRATION ASSESSMENT FOR THE
PROPOSED SCARBOROUGH RAPID
TRANSIT EXTENSION

May 11, 1993
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PROTOCOL FOR NOISE AND VIBRATION ASSESSMENT

PART A. PURPOSE

The Toronto Transit Commission (TTC) and the Ministry of the Environment and Energy (MOE) recognize that transit facilities produce noise and vibration which may affect neighbouring properties within urbanized areas. This document identifies the framework within which criteria will be applied for limiting way-side air-borne noise and ground-borne noise and vibration from the TTC’s proposed Scarborough Rapid Transit Line Extension (the “Line”). The proposed extension is to run from Mccowan station to Markham Road and Sheppard Avenue East. The framework presented in this document is to be applied for planning purposes only, in order to address the requirements of the Environmental Assessment Act and to be utilized during implementation of the Line.

The passage sound levels and vibration velocities in this protocol have been developed specifically for the Line and this protocol is not to be applied retrospectively to existing TTC transit lines, routes or facilities, including the existing SRT Line, nor to transit authorities other than TTC. Further, the criteria specified for this project are not precedent setting for future projects.

Prediction and measurement methods are being developed by the TTC. This will be done in consultation with MOE and the Ministry of Transportation (MTO). Studies pertaining to noise and vibration levels are also being conducted by TTC. Upon completion of these studies, the TTC may review the assessment criteria and methods in this protocol to modify them as required in consultation with MOE and the Ministry of Transportation (MTO).

PART B. GENERAL

During design of the Line, predicted way-side sound levels and vibration velocities are to be compared to criteria given in this protocol. This will permit an impact assessment and help determine the type and extent of mitigation measures to reduce that impact. Sound levels and vibration velocities will be predicted from sound levels and velocities of TTC’s existing rail technologies.

The criteria presented in this document are based on good operating conditions and the impact assessment assumes this condition. Good operating conditions exist when well maintained vehicles operate on well maintained continuous welded rail without significant rail corrugation. It is recognized that wheel flats or rail corrugations will inevitably occur and will temporarily increase sound and vibration levels until they are corrected. Levels in this protocol do not reflect these occasional events, nor do they apply to maintenance activities on the line. TTC recognizes that wheel rail squeal is a potential source of noise which may pose a concern to the community. TTC is investigating and will continue to investigate measures to mitigate wheel rail squeal and will endeavour to mitigate this noise source. TTC endeavours to minimize the noise and vibration impacts associated with its transit operations and is committed to providing good operating conditions to the extent technologically, economically and administratively feasible.
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It is recognized that levels of sound and vibration at special trackwork, such as at crossovers and turnouts, are invariably higher than along tangent track. Also, there is a limit to the degree of mitigation that is feasible at special trackwork areas. This is to be taken into account in predicting sound and vibration levels near these features and in applying the levels in this protocol. Special trackwork, such as at crossovers and turnouts, is encompassed within the framework of this document.

This protocol applies to existing and proposed residential development having municipal approval on the date of this protocol. The protocol also applies to existing and municipally approved proposed residential development, group homes, hospitals and other such institutional land uses where people reside. This protocol does not apply to commercial and industrial land uses.

This protocol does not apply closer than 15 m to the centreline of the nearest track. Any such cases shall be assessed on a case by case basis.

Part D of this document deals with airborne noise from the Line and its construction. Part E deals with groundborne noise and vibration from the Line.

PART C. DEFINITIONS

The following definitions apply to both parts D and E of this document.

Auxiliary Facilities:

Subsidiary locations associated with either the housing of personnel or equipment engaged in TTC activities or associated with mainline revenue operations. Examples of auxiliary facilities include, but are not limited to, subway stations, bus terminals, emergency service buildings, fans, fan and vent shafts, substations, mechanical equipment plants, maintenance and storage facilities, and vehicle storage and maintenance facilities.

Passby Time Interval:

The passby time interval of a vehicle or train is given by its total length and its speed. The start of the pass-by is defined as that point in time when the leading wheels pass a reference point. The end of the pass-by is defined as that point in time when the rear wheels of the vehicle or train pass the same reference point. The reference point is to be chosen to give the highest level at the point of reception or point of assessment, i.e., usually at the point of closest approach. From a signal processing perspective, the passby time interval will be defined in the prediction and measurement methods being developed.

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PART D. AIRBORNE NOISE

1.0. DEFINITIONS

The following definitions are to be used only within the context of Part D of this document.

Ambient:

The ambient is the sound existing at the point of reception in the absence of all noise from the Line. In this protocol the ambient is taken to be the noise from road traffic and existing Industry. The ambient specifically excludes transient noise from aircraft and railways, except for pre-existing TTC rail operations.

Daytime Equivalent Sound Level:

L_{eq, Day} is the daytime equivalent sound level. The definition of equivalent sound level is provided in Reference 2. The applicable time period is from 07:00 to 23:00 hours.

Nighttime Equivalent Sound Level:

L_{eq, Night} is the nighttime equivalent sound level. The applicable time period is from 00:01 to 07:00 hours.

Point of Reception:

Daytime: 07:00 - 23:00 hours

Any outdoor point on residential property, 15 m or more from the nearest track's centreline, where sound originating from the Line is received.

Nighttime: 23:00 - 07:00 hours

The plane of any bedroom window, 15 m or more from the nearest track's centreline, where sound originating from the Line is received. At the planning stage, this is usually assessed at the nearest facade of the premises.

Passby Sound Level, L_{passby}

Within the context of this document, the passby sound level is defined as the A-weighted equivalent sound level, L_{eq} (Reference 2) over the passby time interval.

2.0. RAIL TRANSIT

In the assessment of noise impact, rail transit is considered to include the movement of trains between stations, the movement and idling of trains inside stations as well as the movement of trains between the mainline and ancillary facilities. Ancillary facilities are not considered part of the rail transit and are assessed as stationary
sources. Trains idling in maintenance yards and storage facilities are part of the stationary source.

The assessment of noise impact resulting from Line L is to be performed in terms of the following sound level descriptors:

1. Daytime equivalent sound level, $L_{eq, day}$
2. Nighttime equivalent sound level, $L_{eq, night}$
3. Passby Sound Level, $L_{passby}$

The predicted daytime and nighttime equivalent sound levels include the effects of both passby sound level and frequency of operation and are used to assess the noise impact of the Line. The Passby Sound Level criterion is used to assess the sound levels received during a single train passby. The criteria and methods to be used are discussed in Sections 2.1 and 2.2.

2.1 Criteria

Noise impact shall be predicted and assessed during design of the Line using the following sound level criteria:

**DAYTIME EQUIVALENT SOUND LEVEL**:

The limit at a point of reception for the predicted daytime equivalent sound levels for rail transit operating alone (excluding contributions from the ambient) is 55 dBA or the ambient $L_{ambient}$, whichever is higher.

**NIGHTTIME EQUIVALENT SOUND LEVEL**:

The limit at a point of reception for the predicted nighttime equivalent sound levels for rail transit operating alone (excluding contributions from the ambient) is 50 dBA or the ambient $L_{ambient}$, whichever is higher.

**PASSBY SOUND LEVEL**:

The limit at a point of reception for predicted $L_{passby}$ for a single train operating alone and excluding contributions from other sources is 80 dBA. This limit is based on vehicles operating on tangent track. It does not apply within 100m of special trackwork and excludes wheel rail squeal.

Mitigating measures will be incorporated in the design of the Line when predictions show that any of the above limits are exceeded by more than 5 dB. All mitigating measures shall ensure that the predicted sound levels are as close to, or lower than, the respective limits as is technologically, economically, and administratively feasible.

2.2 Prediction

In most cases, a reasonable estimate of the ambient sound level can be made using a road traffic noise prediction method such as that described in Reference 9, and the minimum sound levels in Table 106-2 of Reference 6. Prediction of road traffic $I_{road}$ is preferred to individual measurements in establishing the ambient. Prediction techniques for the $I_{road}$ from road traffic and the $I_{rail}$ from transit shall be compatible with one another. Any impact assessment following this protocol shall include a description of the prediction method and the assumptions and sound level data inherent in it. Prediction and measurement methods compatible with MOEE guidelines and procedures are being developed by the TTC at the time of this protocol in consultation with MTO and MOEE.

3.0 AUXILIARY FACILITIES

Predicted noise impacts from auxiliary facilities shall be assessed during the design of the Line in accordance with the stationary source guidelines detailed in Reference 5. The predictions shall be compatible with and at least as accurate as CEA Standard 2107.55.

4.0 BUSES IN MIXED TRAFFIC

Where buses are part of the road traffic there are no additional criteria requirements beyond those presented in the Ministry of Transportation of Ontario Protocol for dealing with noise concerns during the preparation, review and evaluation of Provincial Highways Environmental Assessments (Reference 11). Buses should be considered as medium trucks in the traffic noise prediction models.

5.0 CONSTRUCTION

Noise impacts from the construction of the Line are to be examined. For the purposes of impact assessment and identifying the need for mitigation, the Ministry of the Environment and Energy guidelines for construction presented in Reference 7 are to be referred to.
PART II. GROUND-BORNE VIBRATION

The assessment of ground-borne vibration impact is confined to the vibration that is produced by the operation of the Line and excludes vibration due to maintenance activities.

In recognition of the fact that the actual vibration response of a building is affected by its own structural characteristics, this document deals with the assessment of ground-borne vibration only on the outside premises. Structural characteristics of buildings are beyond the scope of this protocol and beyond the control of the TTC.

1.6 DEFINITIONS

The following definitions are to be used only within the context of Part E of this document.

Pole of Assessment:
A point of assessment is any outdoor point on residential property 15 m or more from the nearest track's centerline, where vibration engineering from the Line is received.

Vibration Velocity:
Vibration Velocity is the root-mean-square (rms) vibration velocity assessed during a train pass-by. The unit of measure is metres per second (m/s) or millimetres per second (mm/s). For the purposes of this protocol only vertical vibration is assessed. The vertical component of transit vibration is usually higher than the horizontal. Human sensitivity to horizontal vibration at the frequencies of interest is significantly less than the sensitivity to vertical vibration.

2.0 VIBRATION ASSESSMENT

Vibration velocities at points of assessment shall be predicted during design of the Line. If the predicted rms vertical vibration velocity from the Line exceeds 0.1 m/s, mitigation methods shall be applied during the detailed design to meet this criterion to the extent technologically, economically, and administratively feasible.

Any impact assessment following this protocol shall include a description of the prediction methods and the assumptions and data inherent in it. Prediction and measurement methods are being developed by the TTC as the date of this protocol in cooperation with NFO and MCEE.
MOEE/TTC
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PROTOCOL FOR NOISE AND VIBRATION ASSESSMENT FOR THE PROPOSED WATERFRONT WEST LIGHT RAIL TRANSIT LINE

November 11, 1993

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PROTOCOL FOR NOISE AND VIBRATION ASSESSMENT

PART A: PURPOSE

The Toronto Transit Commission (TTC) and the Ministry of the Environment and Energy (MOEE) recognize that transit facilities produce noise and vibration which may affect neighbouring properties within urbanized areas. This document identifies the framework within which criteria will be applied for limiting roadway, air-borne noise, ground-borne noise and vibration from the TTC’s proposed front street light rail transit line (the “Line”). The proposed line is to run from Spadina and Queen’s Quay West to the GTR Don Mills Station and from the Harbour Loop to Agincourt West. The framework contained in this document is to be applied for planning purposes in order to address the requirements of the Environmental Assessment Act and is to be utilized during implementation of the Line.

The assessed sound levels and vibration velocities in this protocol have been developed specifically for the Line and this protocol is not to be applied retrospectively to existing TTC transit lines, routes or facilities, including the existing lines with which this Line will interact, nor to transit authorities other than TTC. Further, the criteria specified for this project are not precedent setting for future projects.

Prediction and measurement methods are being developed by the TTC. This will be done in consultation with MOEE and the Ministry of Transportation (MTO). Subsequently, to measure noise and vibration levels are also being conducted by TTC. Upon completion of these studies, the TTC may adapt the assessment criteria and methods in this protocol to modify them as required in consultation with MOEE and the Ministry of Transportation (MTO).

PART B: GENERAL

During design of the Line, predicted roadway sound levels and vibration velocities are to be considered, as are given in this protocol. This will permit an impact assessment and help determine the type and extent of mitigation measures to reduce that impact. Sound levels and vibration velocities will be predicted from sound levels and velocities of TTC’s existing rail technologies.

The criteria presented in this document are based on good operating conditions and the impact assessment assumes this condition. Good operating conditions exist when well maintained vehicles operate on well maintained continuous welded rail without significant rail corrugation. It is recognized that when line or rail corrugation will inevitably occur and will transiently increase sound and vibration levels until they are corrected. Levels in this protocol do not reflect these occasional events, nor do they apply to maintenance activities on the Line. TTC recognizes that such rail corrugation is a potential source of noise which may pose a concern to the community. TTC is investigating and will continue to investigate measures to mitigate wheel rail squeal and will endeavour to mitigate this noise source. TTC endeavours to minimize the noise and vibration impacts associated with its transit operations and is committed to providing good operating conditions to the extent technologically, economically and administratively feasible.

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It is recognized that levels of sound and vibration at special trackwork, such as at crossovers and turnouts, are inevitably higher than along tangent basis. Also, there is a limit to the degree of mitigation that is feasible at special trackwork areas. This is to be taken into account in predicting sound and vibration levels near these features and in applying the levels in this protocol. Special trackwork, such as at crossings, crossovers and crossings, is not considered within the framework of this document.

This protocol applies to existing and proposed residential development having municipal approval on the site of this protocol. The protocol also applies to existing and municipally approved proposed nursing homes, group homes, hospitals and other such institutional land uses where people reside. This protocol does not apply to commercial and industrial land uses.

This protocol does not apply closer than 15 m to the centreline of the nearest track. Any such cases shall be assessed on a case by case basis.

Part D of this document deals with air-borne noise from the Line and its construction. Part E deals with ground-borne noise and vibration from the Line.

PART C: DEFINITIONS

The following definitions apply to both Parts D and E of this document.

Auxiliary Facilities:

Subsidary locations associated with either the building of personnel or equipment engaged in TTC activities or associated with maintenance operations. For example, auxiliary facilities includes, but are not limited to, subway stations, bus terminals, emergency service buildings, fire, police and transit shelters, substations, mechanical equipment plants, maintenance and storage facilities, and vehicle storage and maintenance facilities.

Passby Time Interval:

The passby time interval of a vehicle is given by its total length and its speed. The start of the passby is defined as that point in time when the leading wheels pass a reference point. The end of the passby is defined as that point in time when the last wheels of the vehicle pass the same reference point. The reference point is to be chosen to give the highest level at the point of reception or point of assessment, i.e., usually the point of closest approach. From a signal processing perspective, the passby time interval will be defined in the prediction and measurement methods being developed.
PART D. AERODROME NOISE

5.0 DEFINITIONS

The following definitions are to be used only within the context of Part D of the document.

Ambient:

The ambient is the sound existing at the point of reception in the absence of all noise from the Line. In this regard the ambient is taken to be the noise from road traffic and existing industry. The ambient specifically excludes transient noises from aircraft and railways, except for pre-existing TRG rail operations.

Daytime Equivalent Sound Level:

\( L_{eq,day} \)

is the daytime equivalent sound level. The definition of equivalent sound level is provided in Reference 2. The applicable time period is from 0700 to 2100 hours.

Nighttime Equivalent Sound Level:

\( L_{eq,night} \)

is the nighttime equivalent sound level. The applicable time period is from 2100 to 0700 hours.

Point of Reception:

Daytime:

\[ 0700 \text{ to } 2100 \text{ hours} \]

Nighttime:

\[ 2100 \text{ to } 0700 \text{ hours} \]

Any outdoor point on residential property, 10 m or more from the nearest residential boundary, where sound originating from the Line is received.

Passby Sound Level, \( L_{p,day} \)

Within the context of this document, the passby sound level is defined as the A-weighted equivalent sound level, \( L_{eq} \) [Reference 2] over the passby sound level time interval.

2.0 RAIL TRANSIT

In the assessment of noise impact, rail transit is considered to include the movement of vehicles between stations, the movement and idling of vehicles behind tracks as well as the movement of vehicles between the mainline and ancillary facilities. Ancillary facilities are not considered part of the rail transit and are assessed as stationary sources. Vehicles idling in maintenance yards and storage facilities are part of the stationary source.

2.1 Criteria

Noise impact shall be predicted and assessed during design of the Line using the following sound level criteria:

**DAYTIME EQUIVALENT SOUND LEVEL:**

The limit at a point of reception for the predicted daytime equivalent sound levels for rail transit operating alone (excluding contributions from the ambient) is 55 dB(A) or the ambient \( L_{eq} \), whichever is higher.

**NIGHTTIME EQUIVALENT SOUND LEVEL:**

The limit at a point of reception for the predicted nighttime equivalent sound levels for rail transit operating alone (excluding contributions from the ambient) is 50 dB(A) or the ambient \( L_{eq} \), whichever is higher.

**PASSBY SOUND LEVEL:**

The limit at a point of reception for predicted \( L_{p,day} \) for a single vehicle operating alone and excluding contributions from other sources is 90 dB(A).

This limit is based on vehicles operating on tangent track. It does not apply within 100 m of roundwork and excludes wheel rail squeal.

Mitigating measures will be incorporated in the design of the Line when predictions show that any of the above limits are exceeded by more than 5 dB.

All mitigating measures shall ensure that the predicted sound levels are as close to, or lower than, the respective limits as is technologically, economically, and administratively feasible.

2.2 Predictions

In most cases, a reasonable estimate of the ambient sound level can be made using a road traffic noise prediction method such as that described in Reference 3, and the...
minimum sound levels in Table 160-2 of Reference 6. Prediction of road traffic noise is performed by individual measurements in establishing the amplitudes. Prediction techniques for the $L_n$ from road traffic and the $L_n$ of traffic noise shall be compatible with one another. Any impact assessment following this protocol shall include a description of the prediction method and the assumptions and sound level data inherent in it. Predictive and measurement methods compatible with MOEE guidelines and procedures are being developed by the TTC at the time of this protocol in consultation with MTO and MOEE.

3.0. ANCILLARY FACILITIES

Predictive noise impacts from ancillary facilities shall be assessed during the design of the Line in accordance with the stationary source guidelines detailed in Reference 6. The predictions used shall be compatible with and at least as accurate as CSA Standard Z767-91.

4.0. BUSES IN MIXED TRAFFIC

Where buses are part of the road traffic there are no additional criteria requirements beyond those presented in the Ministry of Transportation of Ontario Protocol for dealing with noise contours during the preparation, review, and evaluation of Provincial Highways Environmental Assessments (Reference 1). Buses should be considered as medium trucks in the traffic noise prediction methods.

5.0. CONSTRUCTION

Noise impacts from the construction of the Line are to be examined. During the purposes of impact assessment and identifying the needs for mitigation, the Ministry of the Environment and Energy guidelines for construction presented in Reference 7 are to be referred to.

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5.2. VIBRATION ASSESSMENT

Vibration velocities at points of assessment shall be predicted during design of the Line. If the predicted and vertical vibration velocity from the Line exceeds 0.25 mm/s, mitigation measures shall be applied during the design process to reduce this vibration to levels that are environmentally and economically feasible.

Any impact assessment following this protocol shall include a description of the prediction method and the assumptions and data inherent in it. Predictive and measurement methods are being developed by the TTC at the time of this protocol in consultation with MTO and MOEE.

6.0. DEFINITIONS

The following definitions are to be used only within the context of Part E of this document:

Point of Assessment:

A point of assessment is any outdoor point on residential property, 15 m or more from the nearest sound barrier, where vibration originating from the Line is received.

Vibration Velocity:

Vibration velocity is the root-mean-square (RMS) vibration velocity measured in a plane perpendicular to the Line. The unit of measure is meters per second (m/s) or millimeters per second (mm/s). For the purposes of this protocol only vertical vibration is assessed. The vertical component of total vibration is usually higher than the horizontal. Human sensitivity to horizontal vibration at the frequencies of interest is significantly less than the sensitivity to vertical vibration.
APPENDIX C: REFERENCES


There are limited numbers of publications clarifying the basics of surface-mounted vibration sources. The subsequent published works of those involved in references 5 and 6 are among the more useful for the purposes of understanding the physics of vibration from transit.
APPENDIX D: DEFINITIONS

Ground-borne Vibration

Ground-borne vibration is vibration transmitted through the soil that is felt, rather than heard. Typically, vibration levels are most felt at frequencies below 50Hz.

Vibration-induced Noise

Vibration-induced noise is a result of ground-borne vibration being transmitted into the structure of a building and radiating as a “rumbly” sound that is more audible than “feelable” to the touch. Generally, vibration-induced noise is a concern at frequencies greater than 50Hz.

Vibration Velocity

Vibration velocity is the speed at which the building or ground moves up and down or sideways as it oscillates. It does not relate to how fast the vibration wave is moving along in the soil.
APPENDIX E: GEOTECHNICAL DATA
For preliminary configuration west of this point please see Figure 2.1 in main body of Report.
APPENDIX F: CALCULATIONS
1262 King Street East - First Floor
Point Source Transfer Mobility Function

1262 King Street East - Basement Floor
Point Source Transfer Mobility Function
1028 Main Street West - First Floor
Point Source Transfer Mobility Function

2 Connaught Avenue - Basement Floor
Point Source Transfer Mobility Function
2 Connaught Avenue - Basement Wall
Point Source Transfer Mobility Function

Octave Band Force Density Function
(FTA Average for LRT)
1/3 Octave Band Force Density Function (FTA Average for LRT)

FORCE DENSITY CURVES FROM OTHER SITES IN THE UNITED STATES

1/3 Octave Band Force Density Function
Generic Track Condition
(40 mph Average FTA Force Density)
1/3 Octave Band Force Density Function
Embedded Rail
(33 mph Central Corridor Extension)

1/3 Octave Band Force Density Function
Embedded Rail
(33 mph Central Mesa LRT Extension)
1/3 Octave Band Force Density Function
Ties-on-Balast
(35 mph Portland TriMet Extension)

[Bar chart showing force density function for Ties-on-Balast at 35 mph Portland TriMet Extension]

1/3 Octave Band Force Density Function
Ties-on-Concrete
(53 mph Metro Gold Line Foothill Extension)

[Bar chart showing force density function for Ties-on-Concrete at 53 mph Metro Gold Line Foothill Extension]
CALCULATION PROCEDURE

Following is the calculation procedure interpreted from the FTA guidelines:

1. Impact the soil; measure the force input (F)
2. Measure the vibration levels within the building (V)
3. Compute the point source transfer mobility function (V/F)
4. Apply the force density function (FD * V/F)
5. Apply the distance for which the point source transfer mobility is applicable.

Note that the distance for which the point source transfer mobility applies can be incorporated at Step 3 in the above procedure. The LRT vehicle length of 33m or 100 ft. has been divided into 5 sections based on the testing completed.

Equipment used during the testing included the following:

1. Custom-built equipment such as vibration amplifiers and force transducers (from strain gauges)
2. Bruel and Kjaer Model 4366 Accelerometer
3. PCB Model 393B05 Accelerometer
4. Function generator and custom-built speaker system
5. The vibration measurement apparatus used for all outdoor measurements has a functional range of 2Hz to 200Hz. The accelerometers and computer software are capable of a wider range than this. The limitation at the higher frequencies lies within the ability to couple to the soil effectively.

Equipment was calibrated continuously during the testing procedures.