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

FOR

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Table of Contents

List of Tables

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.

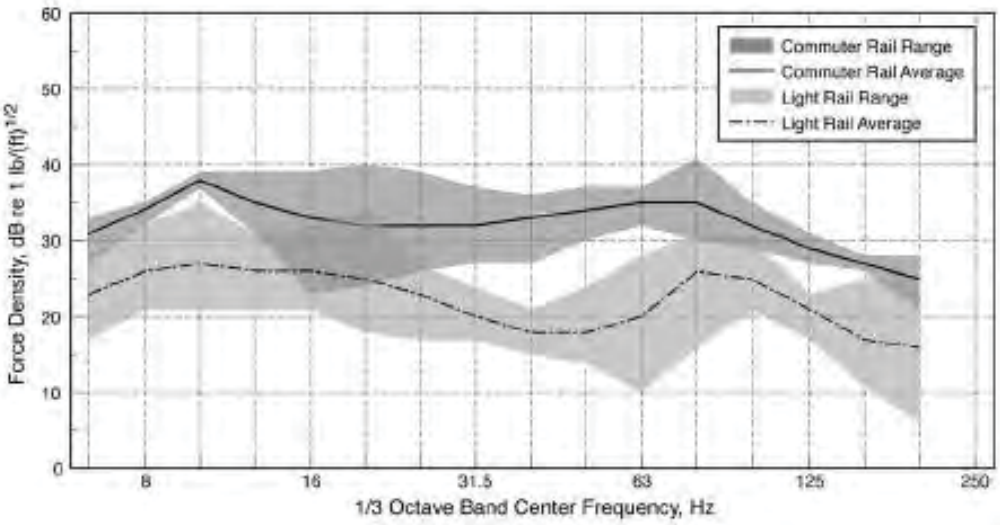


Figure 11-2. Typical Force Densities for Rail Transit Vehicles, 40 mph

Exhibit 1: FTA Typical Force Density Curves

The force density function is combined with the LSTM in order to determine the resultant vibration level (Lv). This relationship is summarized below.

$$Lv = LSTM \times FD$$

The force density is measured in Newtons and the LSTM is expressed in units of $\frac{mm/s}{N}$. 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

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

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 2: Vibration Damping Testing Results at 60Hz

Damping Test Site Number	Distance from Source to First Acc. (m)	Vibration Level at First Acc. (mm/s RMS)	Distance Between Acc. (m)	Vibration Level at Second Acc. (mm/s RMS)	Total Reduction (dB)	Reduction due to Distance (dB)	Reduction due to Damping (dB)	Damping Per Wavelength (dB)
1	6.6	0.04	3.3	0.02	6.02	1.8	4.26	3.2
2a	4	0.027	5.6	0.0074	11.24	3.8	7.44	3.8
	6.7	0.02	2.9	0.0077	8.29	1.6	6.73	6.6
2b	7	0.007	3	0.0033	6.53	1.5	4.98	4.7
	6	0.009	4	0.0026	10.79	2.2	8.57	6.1
3	8	0.0064	4	0.0034	5.49	1.8	3.73	2.96
4	4	0.012	3	0.007	4.68	2.4	2.25	1.63
5	4	0.0022	1.4	0.0017	2.24	1.3	0.94	1.4

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

Detailed Test Site Number	Street Address	Description of Building	Description of Tests
1	1028 Main Street West	2-storey residential dwelling	Vibration propagation tests conducted on ground floor and basement wall
2	595 King Street West	Mid-rise apartment building	Vibration propagation test conducted on ground floor
3	230 King Street East	Low-rise building with 2nd-floor apartments and 1st-floor retail	Vibration propagation test conducted on 2nd floor
4	2 Connaught Avenue	Mid-rise apartment building	Vibration propagation tests conducted on basement floor, wall, and ceiling
5	1262 Main Street East	2-storey residential dwelling	Vibration propagation tests conducted on basement floor and ground floor

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 4: FTA Average LRT Force Density Function

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

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

Location	Description	Configuration	Octave Band Vibration Levels (mm/s RMS)				Overall Vibration (mm/s RMS)
			16Hz	31.5Hz	63Hz	125Hz	
1	1028 Main Street West, House	Ground Floor, 17m from LRT	0.12	0.10	0.09	0.04	0.19
		Basement Wall, 17m from LRT	0.08	0.08	0.08	0.02	0.14
2	595 King Street West, Apartment	Ground Floor, 6m from LRT	0.17	0.18	0.05	0.05	0.26
3	230 King Street, 2nd-storey Apartment	Second Floor, 5m from LRT	0.18	0.17	0.09	0.04	0.27
		Second Floor, 5m from LRT (with speed adjustment)	0.09	0.08	0.04	0.02	0.13
4	2 Connaught Avenue, Apartment	Basement Wall, 4.5m from LRT	0.11	0.17	0.08	0.35	0.41
		Basement Floor, 4.5m from LRT	0.11	0.09	0.18	0.11	0.26
		Basement Ceiling/Ground Floor, 4.5m from LRT	0.32	0.43	0.19	0.15	0.59
		Basement Wall, 6.5m from LRT	0.08	0.15	0.06	0.12	0.22
5	1262 Main Street East, House	Ground Floor, 8m from LRT	0.15	0.15	0.04	0.02	0.22
		Ground Floor, 10m from LRT	0.13	0.14	0.04	0.01	0.19
		Basement Floor, 8m from LRT	0.08	0.07	0.05	0.03	0.12
6	McMaster University, Campus Grounds	Ground, 20m away from Impact	0.27	0.14	0.12	0.01	0.33

Table 6: Predicted Vibration-Induced Sound Levels

Location	Description	Configuration	Octave Band Sound Levels (dB)				Overall Sound Level (dBA)
			16Hz	31.5Hz	63Hz	125Hz	
1	1028 Main Street West, House	Ground Floor, 17m from LRT	68	66	65	58	44
		Basement Wall, 17m from LRT	64	64	65	50	40
2	595 King Street West, Apartment	Ground Floor, 6m from LRT	71	71	61	61	45
3	230 King Street, 2nd-storey Apartment	Second Floor, 5m from LRT	71	71	65	58	44
		Second Floor, 5m from LRT (with speed adjustment)	65	65	59	52	38
4	2 Connaught Avenue, Apartment	Basement Wall, 4.5m from LRT	67	71	64	77	61
		Basement Floor, 4.5m from LRT	67	65	71	67	52
		Basement Ceiling/Ground Floor, 4.5m from LRT	76	79	72	70	54
		Basement Wall, 6.5m from LRT	65	70	62	68	52
5	1262 Main Street East, House	Ground Floor, 8m from LRT	70	69	59	51	38
		Ground Floor, 10m from LRT	68	69	58	50	37
		Basement Floor, 8m from LRT	64	63	60	54	40

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 7: Toronto Streetcar Vibration Levels

Location	Track Configuration	Octave Band Vibration Levels (mm/s RMS)				Overall Vibration Level (mm/s RMS)
		16Hz	31.5Hz	63Hz	125Hz	
Fleet Street (Slow Moving Streetcars)	Embedded, 6m from nearest track	0.01	0.05	0.07	0.01	0.08
	Embedded, 12m from nearest track	0.01	0.03	0.05	0.01	0.06
Queensway (Fast Streetcars)	Tie-on-Ballast, 6m from nearest track	0.01	0.14	0.29	0.08	0.33
King Street East (Fast Streetcars)	Embedded, 12m from nearest track	0.02	0.07	0.13	0.01	0.16
Queen Street East (Fast)	Embedded, 6m from nearest track	0.02	0.10	0.17	0.01	0.20
King Street West (Fast)	Embedded, 12m from nearest track	0.01	0.03	0.08	0.01	0.09

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)

Location	Description	Configuration	Octave Band Vibration Levels (mm/s RMS)				Overall Vibration (mm/s RMS)
			16Hz	31.5Hz	63Hz	125Hz	
1	1028 Main Street West, House	Ground Floor, 17m from LRT	0.01	0.06	0.18	0.04	0.19
		Basement Wall, 17m from LRT	0.01	0.05	0.17	0.02	0.18
2	595 King Street West, Apartment	Ground Floor, 6m from LRT	0.02	0.11	0.11	0.05	0.16
3	230 King Street, 2nd-storey Apartment	Second Floor, 5m from LRT	0.02	0.10	0.18	0.04	0.21
		Second Floor, 5m from LRT (with speed adjustment)	0.01	0.05	0.09	0.02	0.10
4	2 Connaught Avenue, Apartment	Basement Wall, 4.5m from LRT	0.01	0.10	0.16	0.35	0.41
		Basement Floor, 4.5m from LRT	0.01	0.05	0.37	0.11	0.43
		Basement Ceiling/Ground Floor, 4.5m from LRT	0.03	0.26	0.38	0.15	0.48
		Basement Wall, 6.5m from LRT	0.01	0.09	0.12	0.24	0.28
5	1262 Main Street East, House	Ground Floor, 8m from LRT	0.02	0.09	0.09	0.02	0.13
		Ground Floor, 10m from LRT	0.01	0.08	0.08	0.01	0.12
		Basement Floor, 8m from LRT	0.01	0.04	0.10	0.03	0.11
6	McMaster University, Campus Grounds	Ground, 20m away from Impact	0.03	0.09	0.23	0.01	0.25

Table 9: Predicted Vibration-Induced Sound Levels (Adjusted)

Location	Description	Configuration	Octave Band Sound Levels (dB)				Overall Sound Level (dBA)
			16Hz	31.5Hz	63Hz	125Hz	
1	1028 Main Street West, House	Ground Floor, 17m from LRT	48	62	71	58	47
		Basement Wall, 17m from LRT	44	60	71	50	45
2	595 King Street West, Apartment	Ground Floor, 6m from LRT	51	67	67	61	46
3	230 King Street, 2nd-storey Apartment	Second Floor, 5m from LRT	51	66	71	58	47
		Second Floor, 5m from LRT (with speed adjustment)	45	60	65	52	41
4	2 Connaught Avenue, Apartment	Basement Wall, 4.5m from LRT	47	66	70	77	61
		Basement Floor, 4.5m from LRT	47	60	77	67	54
		Basement Ceiling/Ground Floor, 4.5m from LRT	56	74	78	70	56
		Basement Wall, 6.5m from LRT	45	65	68	74	58
5	1262 Main Street East, House	Ground Floor, 8m from LRT	50	65	65	51	41
		Ground Floor, 10m from LRT	48	64	64	50	40
		Basement Floor, 8m from LRT	44	59	66	54	42

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

Location	Accelerometer Position	Octave Band Vibration Levels (mm/s RMS)			
		16Hz	31.5Hz	63Hz	125Hz
Titan 30-800 ST	Vertical	0.0026	0.0012	0.0007	0.0001
	Horizontal	0.0025	0.0011	0.0008	0.0002
Magellan 400	Vertical	0.0024	0.0012	0.0014	0.0006
	Horizontal	0.0012	0.0003	0.0002	0.0001
JEM 2010F	Vertical	0.0033	0.0016	0.0023	0.0011
	Horizontal	0.0016	0.0004	0.0002	0.0003

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.

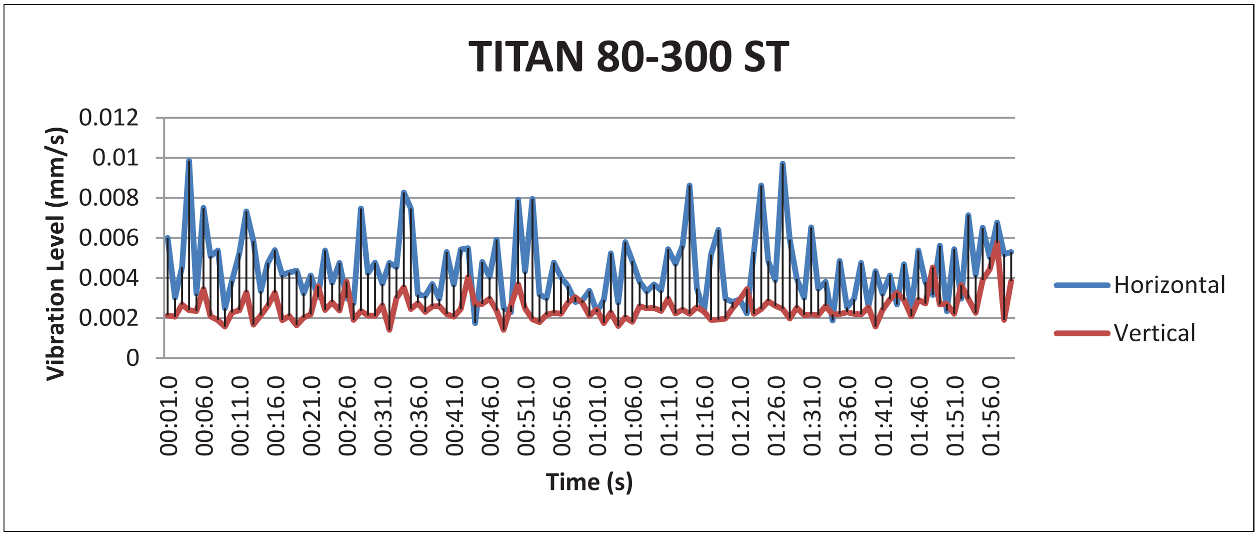


Exhibit 2: TITAN 80-300 ST Ambient Vibration

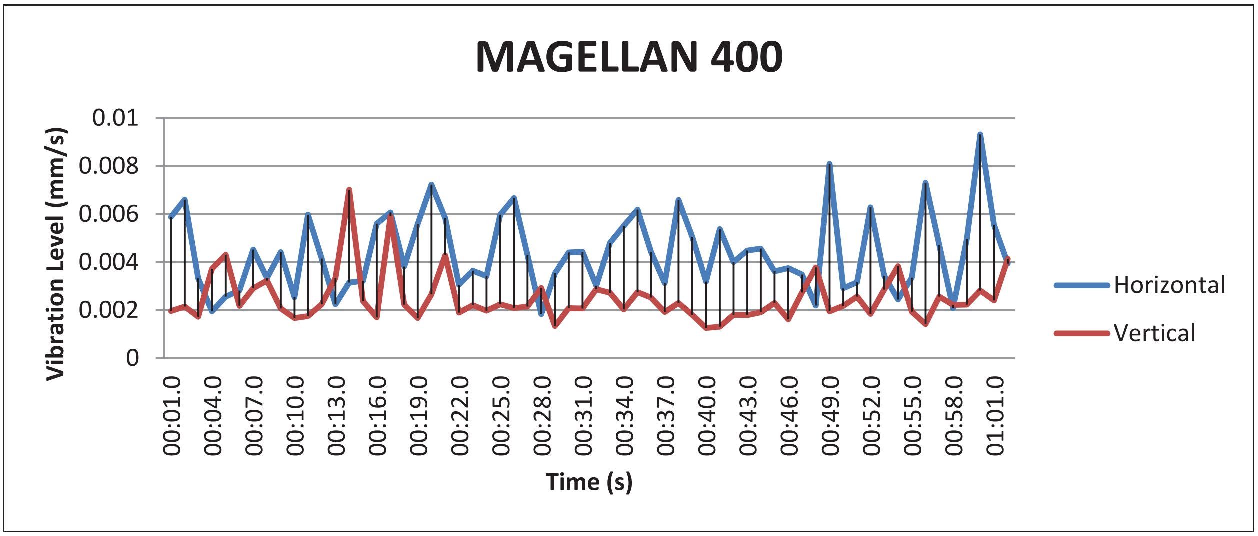


Exhibit 3: MAGELLAN 400 Ambient Vibration

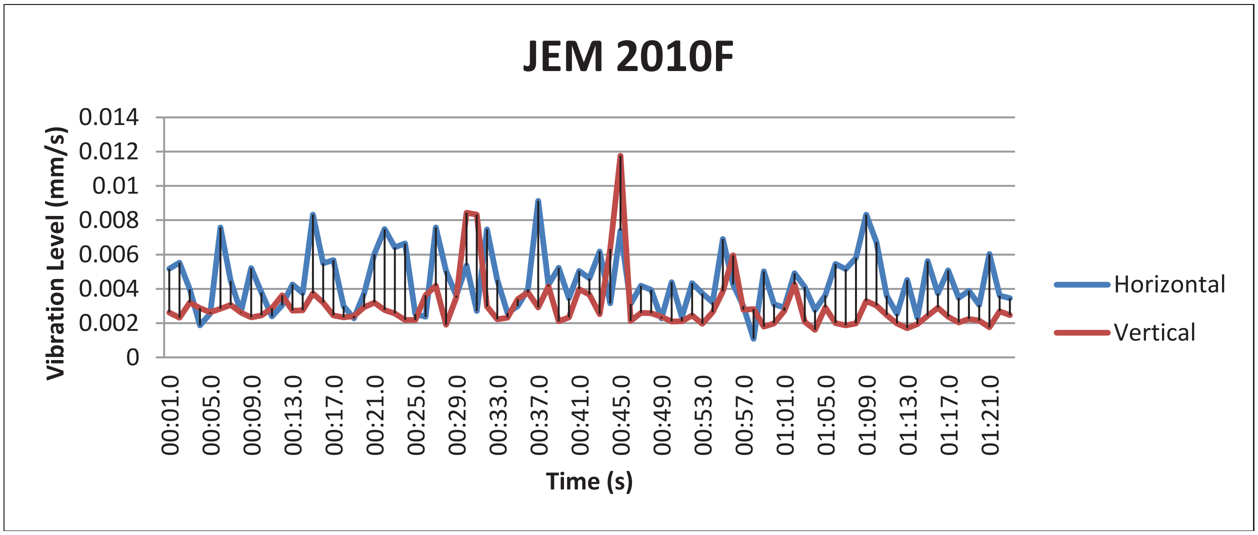


Exhibit 4: JEM 2010F Ambient Vibration

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

	Octave Band				Overall
	16Hz	31.5Hz	63Hz	125Hz	
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

	Octave Band				Overall
	16Hz	31.5Hz	63Hz	125Hz	
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

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

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

Isolation Level	Condition	Octave Band Insertion Loss (dB)			
		16Hz	31.5Hz	63Hz	125Hz
1	Theoretical Performance	2	9	2	-20
	Expected Performance	-1	2	-3	-21
2	Theoretical Performance	5	10	-2	-27
	Expected Performance	1	3	-7	-28
3	Calculated Performance	11	1	-15	-39
	Expected Performance	4	-3	-20	-40
4	Calculated Performance	9	-5	-21	-47
	Expected Performance	2	-9	-26	-48

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

Location	Vibration Isolation Level	Description	Octave Band Vibration Levels (mm/s RMS)				Overall Vibration (mm/s RMS)
			16Hz	31.5Hz	63Hz	125Hz	
1	Level 2 Embedded	Ground Floor, 17m from LRT	0.01	0.07	0.04	0.00	0.08
	Level 2 Embedded	Basement Wall, 17m from LRT	0.01	0.03	0.04	0.00	0.05
2	Level 3 Floating	Ground Floor, 6m from LRT	0.03	0.07	0.01	0.00	0.07
3	Level 3 Floating	Second Floor, 5m from LRT (full speed)	0.03	0.06	0.02	0.00	0.07
	Level 1 Embedded	Second Floor, 5m from LRT (with speed adjustment)	0.01	0.05	0.06	0.00	0.08
4	Level 4 Embedded	Basement Wall, 4.5m from LRT	0.01	0.03	0.01	0.00	0.03
		Basement Floor, 4.5m from LRT	0.01	0.02	0.02	0.00	0.03
		Basement Ceiling/Ground Floor, 4.5m from LRT	0.04	0.08	0.02	0.00	0.09
	Level 3 Embedded	Basement Wall, 6.5m from LRT	0.01	0.05	0.01	0.00	0.05
5	Level 2 Embedded	Ground Floor, 8m from LRT	0.02	0.10	0.04	0.00	0.11
		Ground Floor, 10m from LRT	0.01	0.10	0.04	0.00	0.10
		Basement Floor, 8m from LRT	0.01	0.05	0.04	0.00	0.07

Table 16: Predicted Vibration-Induced Sound Levels with Recommended Vibration Control

Location	Vibration Isolation Level	Description	Octave Band Sound Levels (dB)				Overall Sound Level (dBA)
			16Hz	31.5Hz	63Hz	125Hz	
1	Level 2 Embedded	Ground Floor, 17m from LRT	49	63	58	30	33
	Level 2 Embedded	Basement Wall, 17m from LRT	45	56	58	22	32
2	Level 3 Floating	Ground Floor, 6m from LRT	55	62	47	27	25
3	Level 3 Floating	Second Floor, 5m from LRT (full speed)	55	62	51	24	27
	Level 1 Embedded	Second Floor, 5m from LRT (with speed adjustment)	43	60	61	36	35
4	Level 4 Embedded	Basement Wall, 4.5m from LRT	49	56	44	35	23
		Basement Floor, 4.5m from LRT	49	50	51	25	25
		Basement Ceiling/Ground Floor, 4.5m from LRT	58	64	52	28	28
	Level 3 Embedded	Basement Wall, 6.5m from LRT	49	60	42	28	22
5	Level 2 Embedded	Ground Floor, 8m from LRT	51	66	58	29	33
		Ground Floor, 10m from LRT	49	66	57	28	32
		Basement Floor, 8m from LRT	45	60	59	32	33

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

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

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 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.

JEC:SNK:pt

APPENDIX A: FIGURES

Cartography by Steer Davies Gleave 2010
Source: OpenStreetMap

FIGURE 1
B-LINE LRT
KEY PLAN

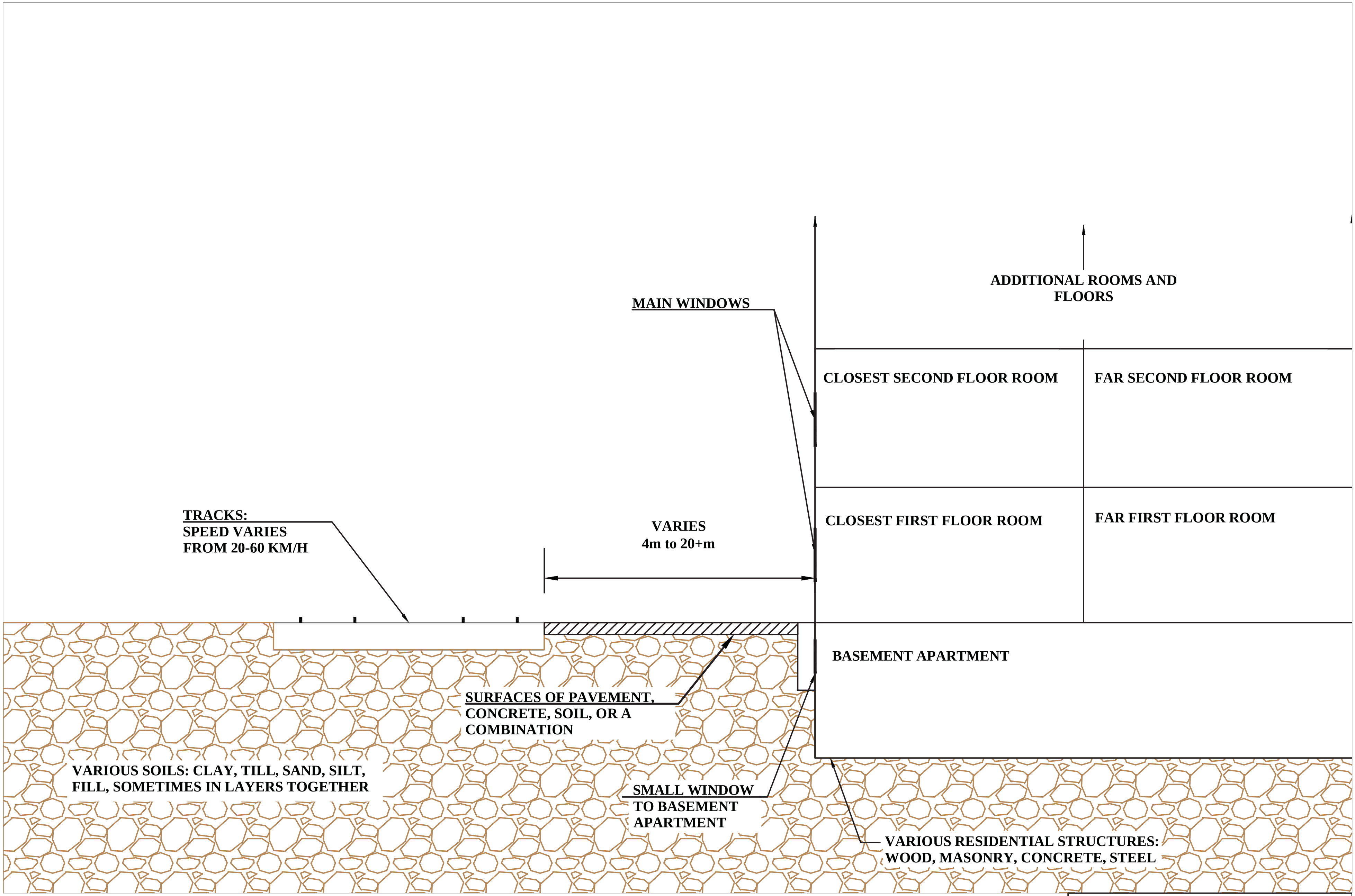


FIGURE 2
SOURCE-RECEIVER CONFIGURATION

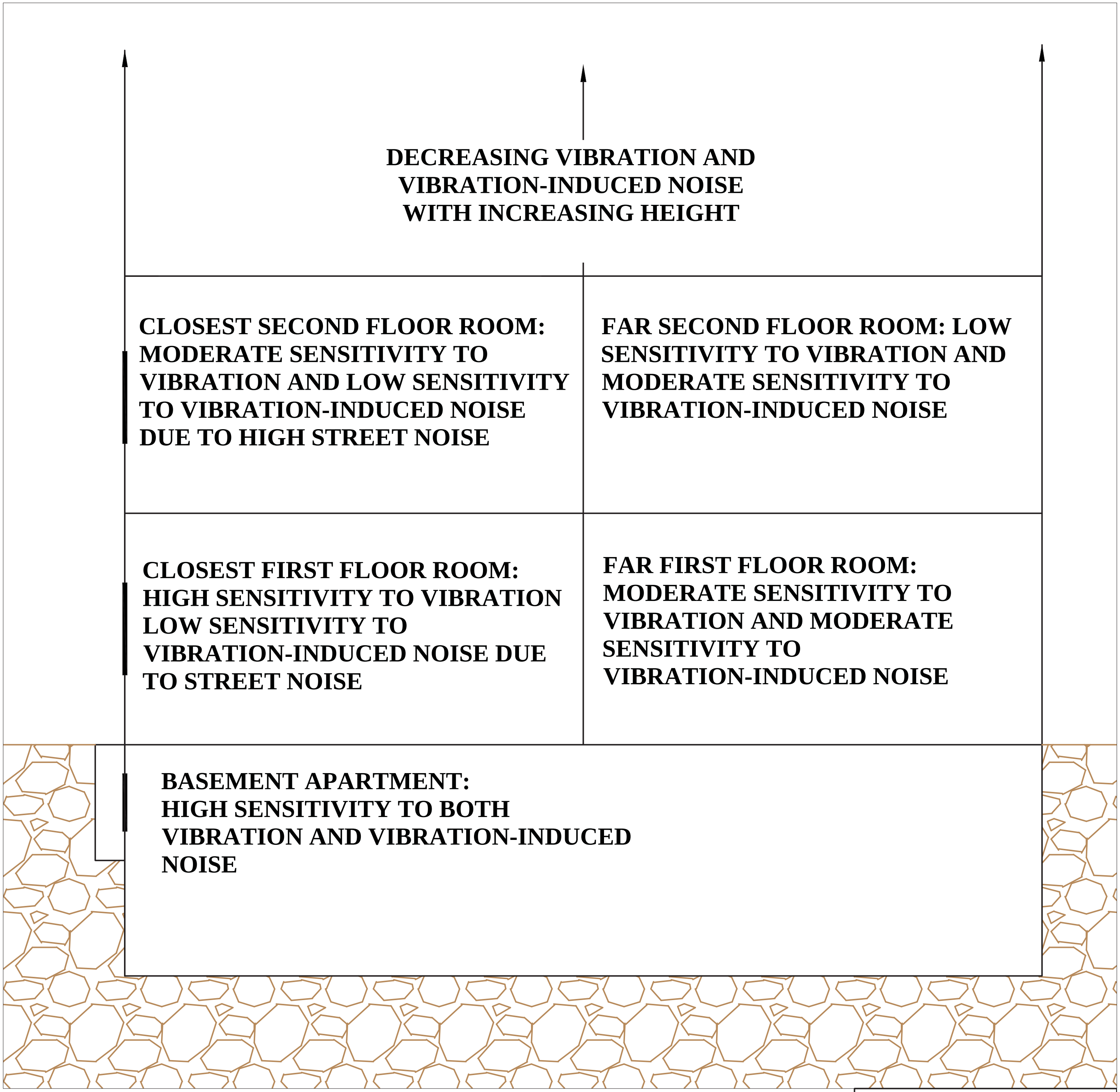


FIGURE 3
RESIDENTIAL RECEIVER SENSITIVITY

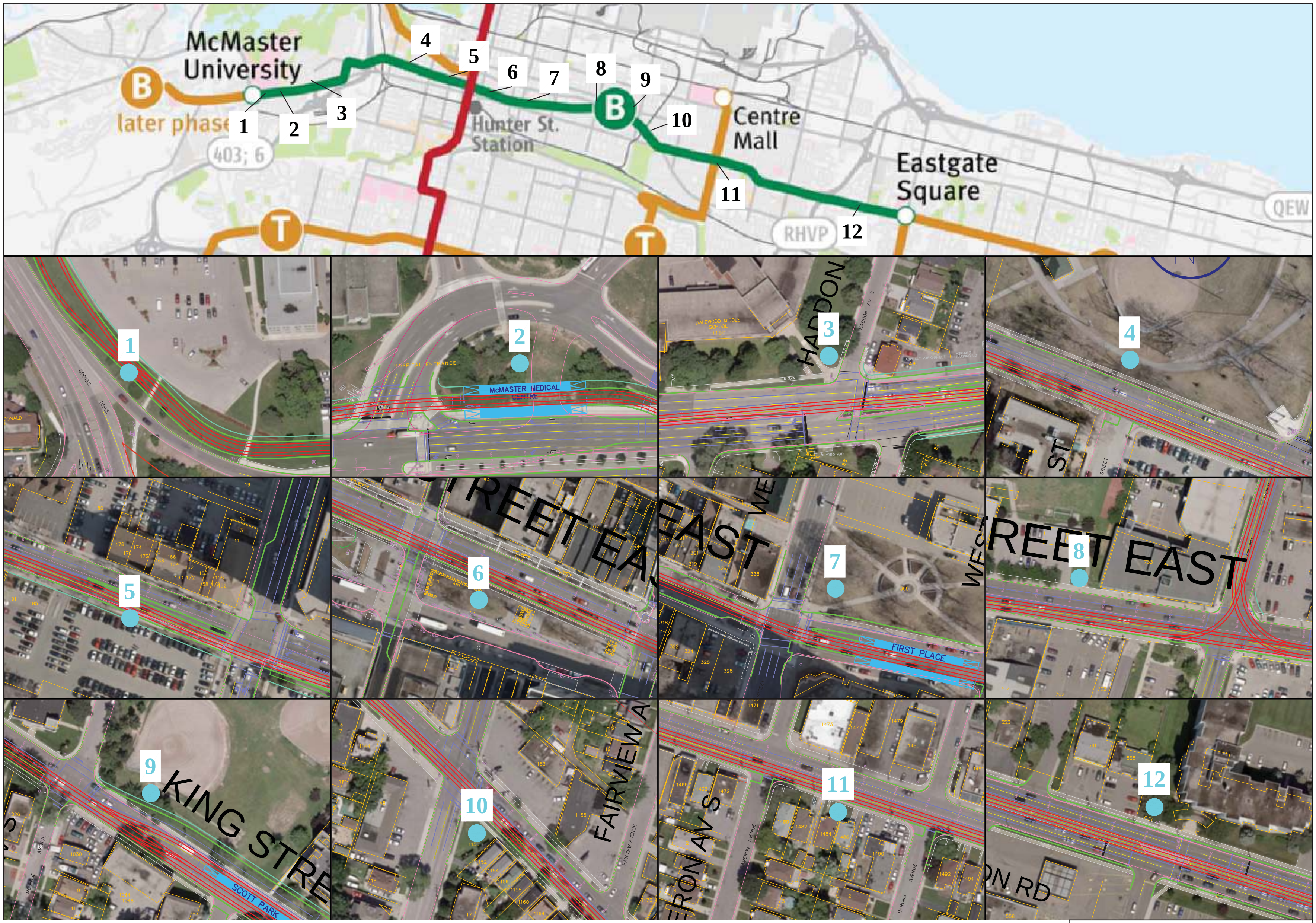


FIGURE 4
SCREENING MEASUREMENT LOCATIONS

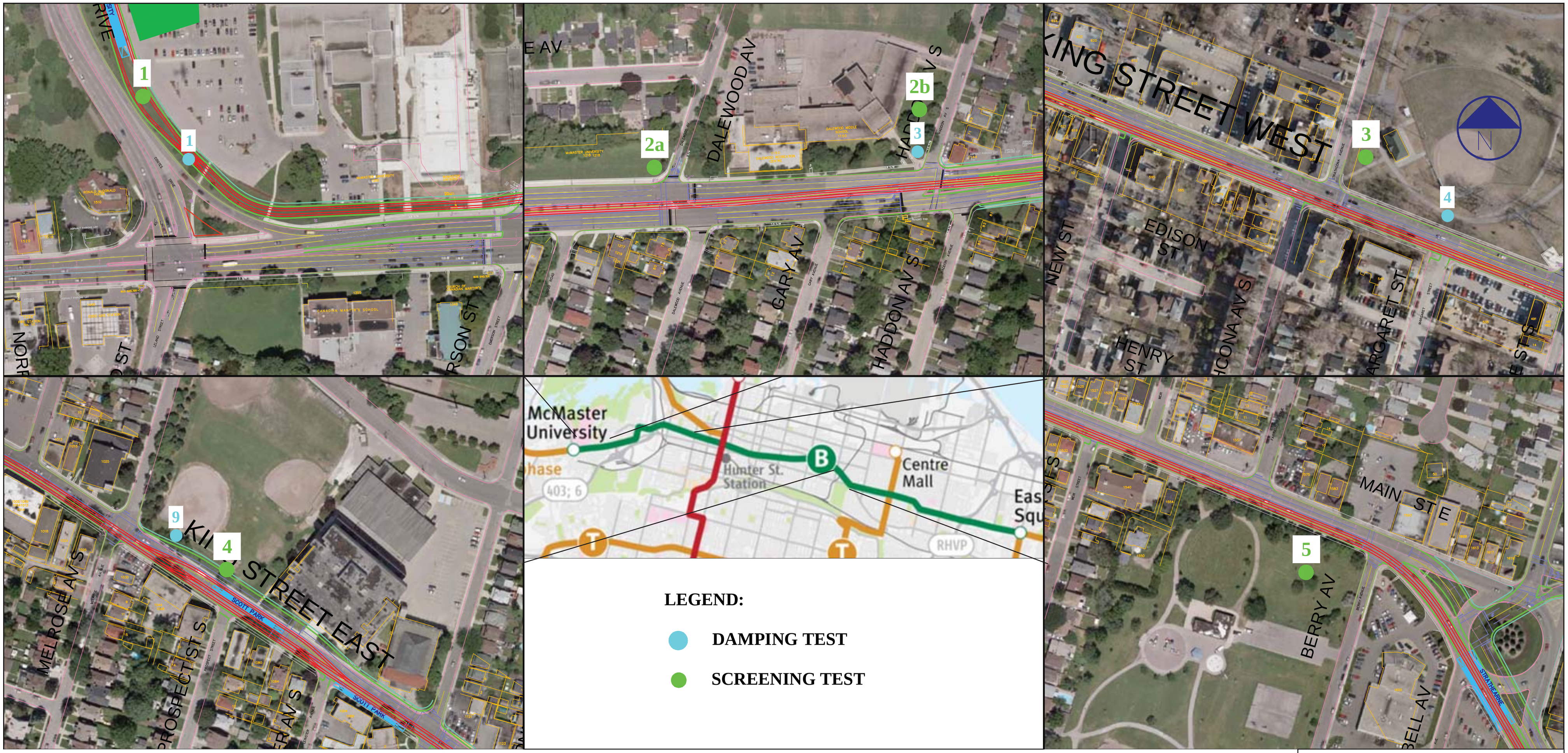


FIGURE 5
DAMPING MEASUREMENT
LOCATIONS

FIGURE 6
DETAILED MEASUREMENT LOCATIONS

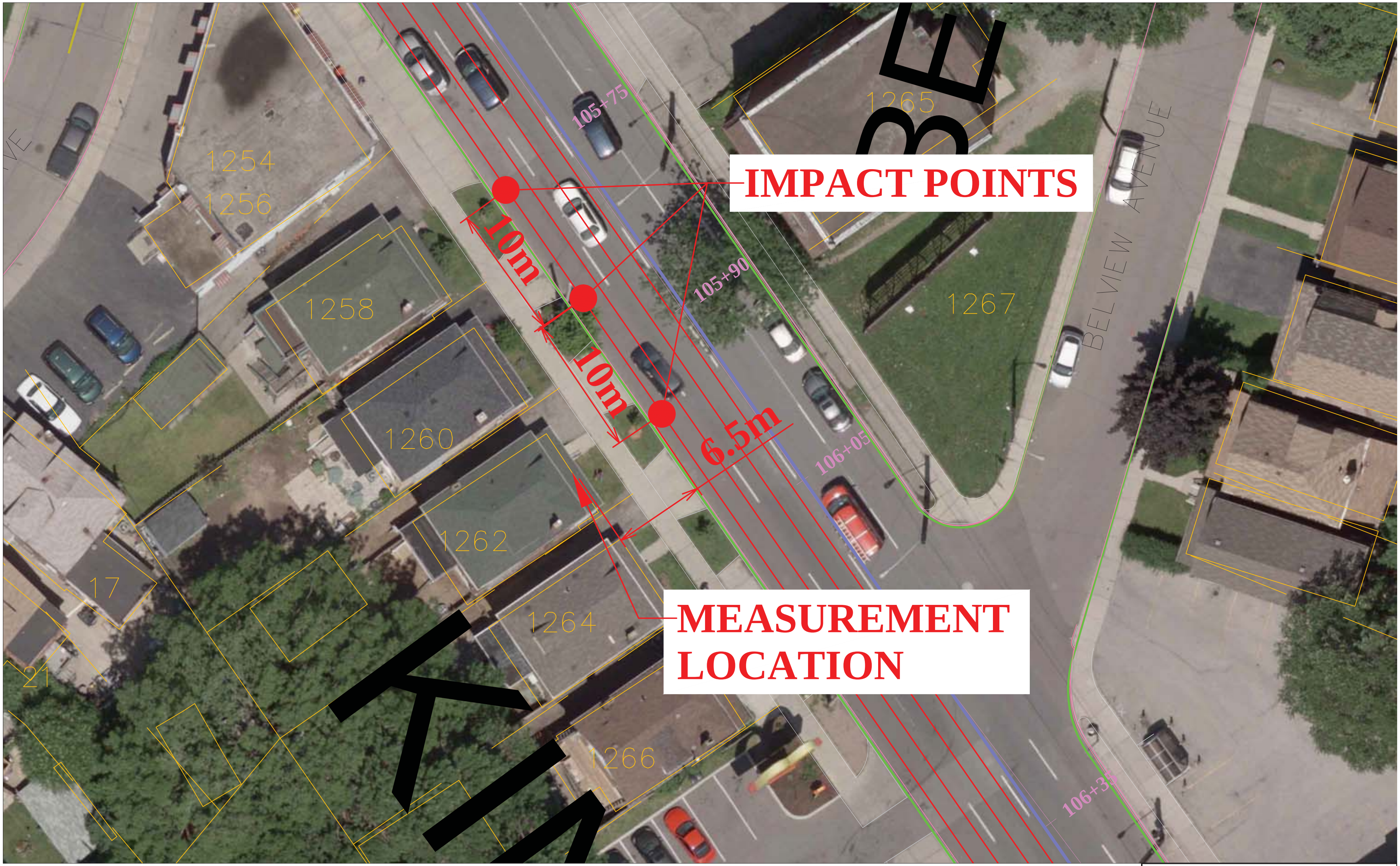


FIGURE 7
TESTING
CONFIGURATION

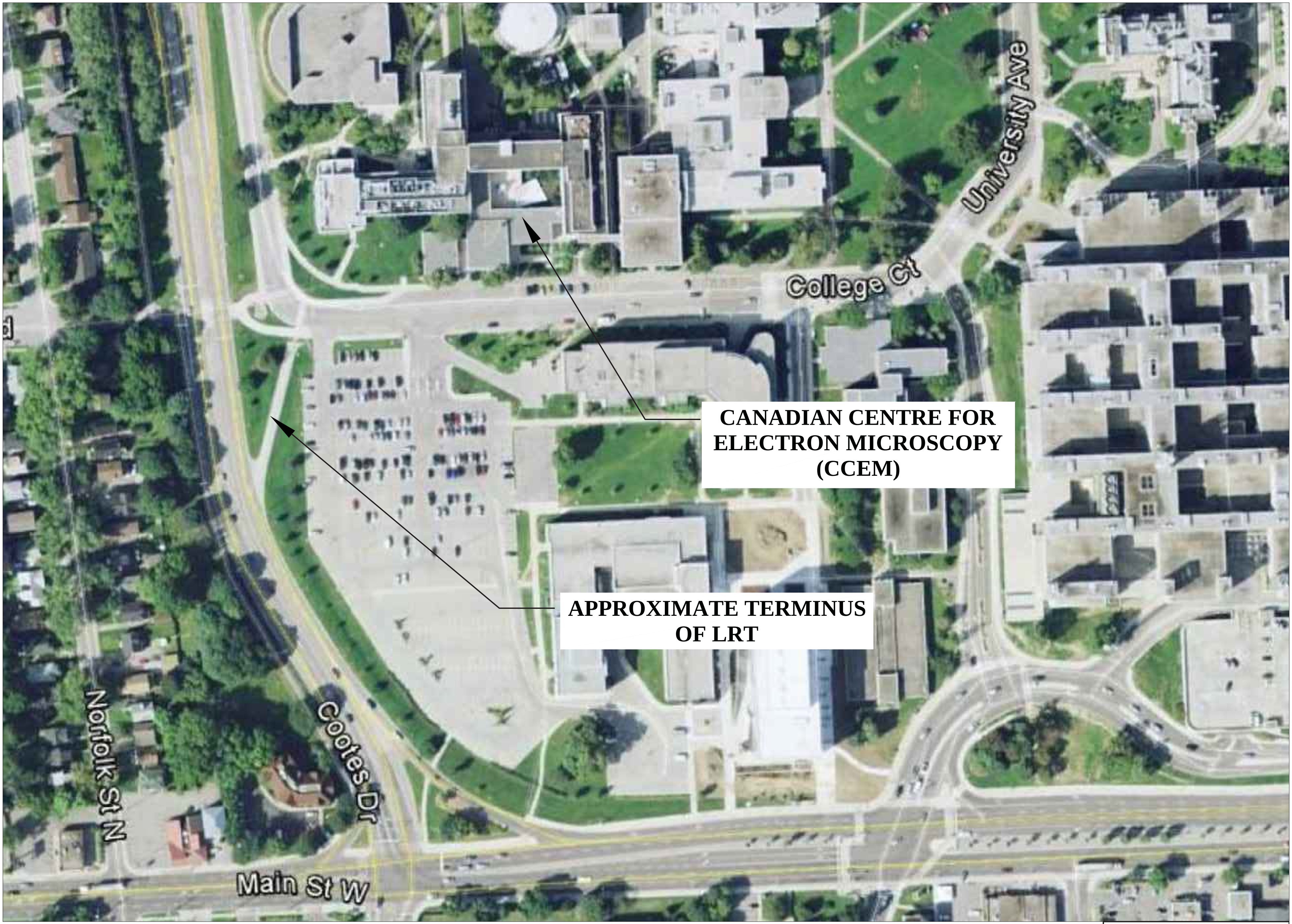
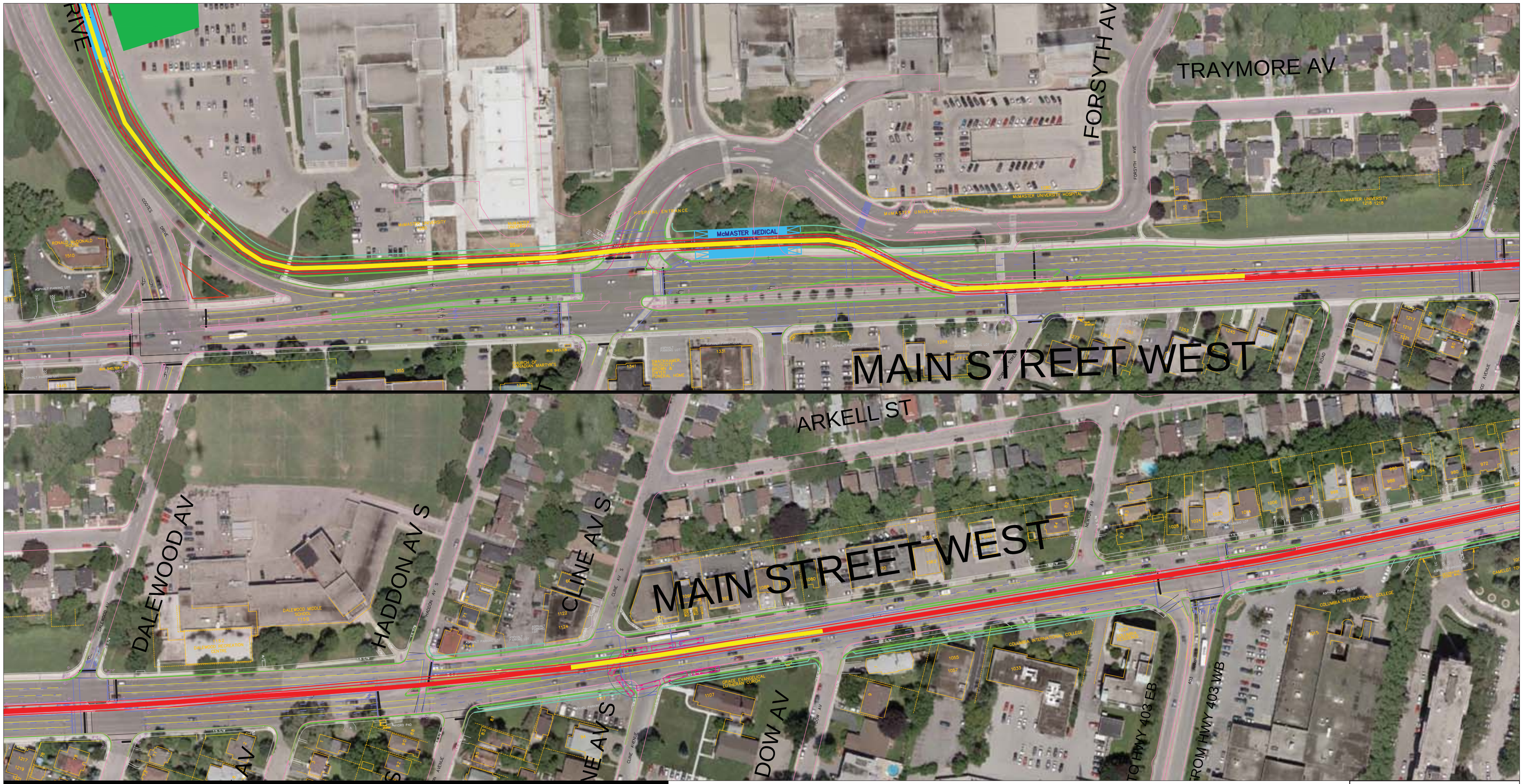


FIGURE 8
MCMASTER UNIVERSITY CCEM



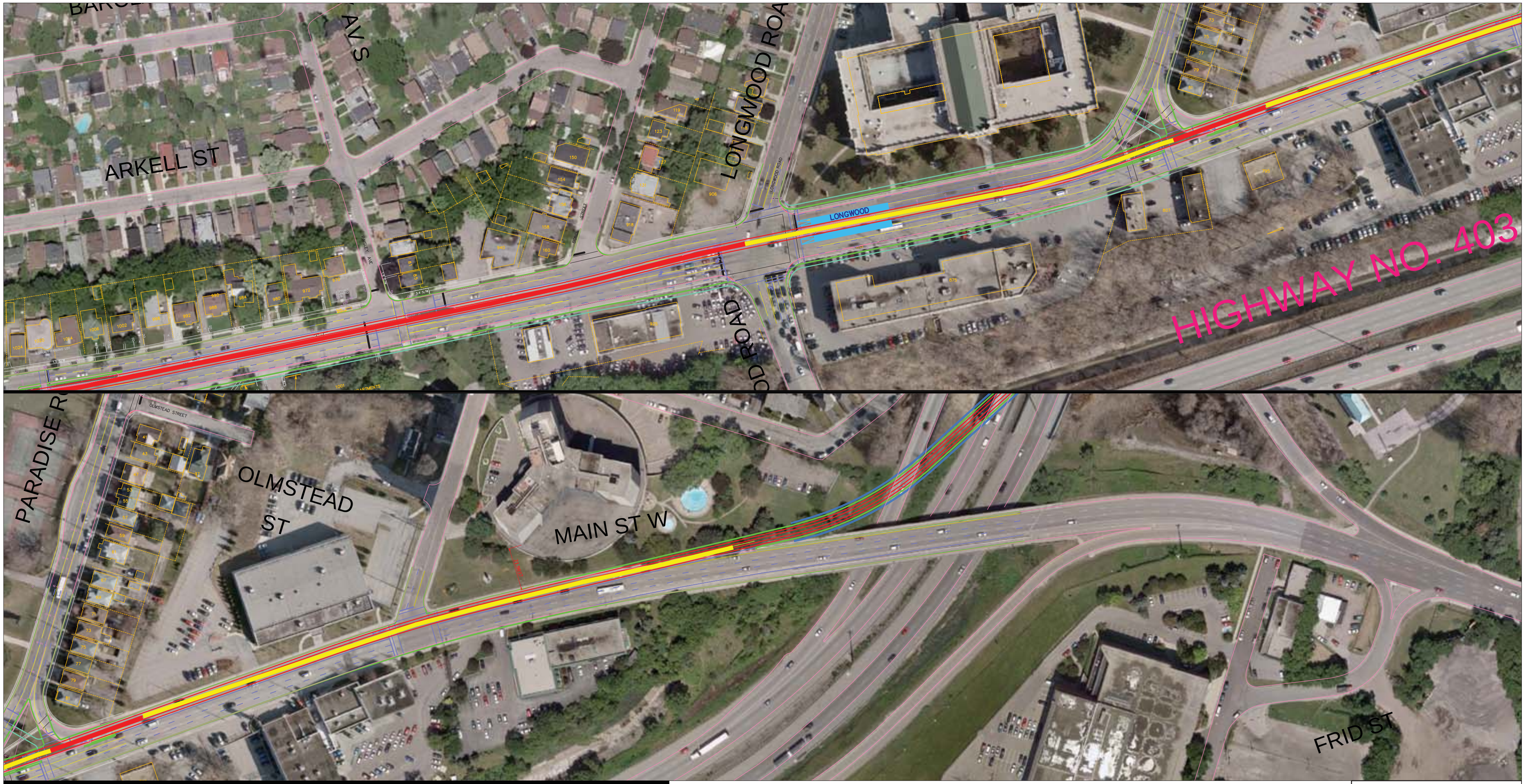
EMBEDDED RAIL (3dB)
$400/m of dual track

EMBEDDED RAIL (5-6dB)
$480/m of dual track

FLOATING SLAB (13-17dB)
$700/m of dual track

FLOATING SLAB (18+ dB)
$800/m of dual track

FIGURE 9 VIBRATION ISOLATION



🟨 EMBEDDED RAIL (3dB)
$400/m of dual track

🟥 EMBEDDED RAIL (5-6dB)
$480/m of dual track

🟩 FLOATING SLAB (13-17dB)
$700/m of dual track

🟦 FLOATING SLAB (18+ dB)
$800/m of dual track

FIGURE 10
VIBRATION
ISOLATION

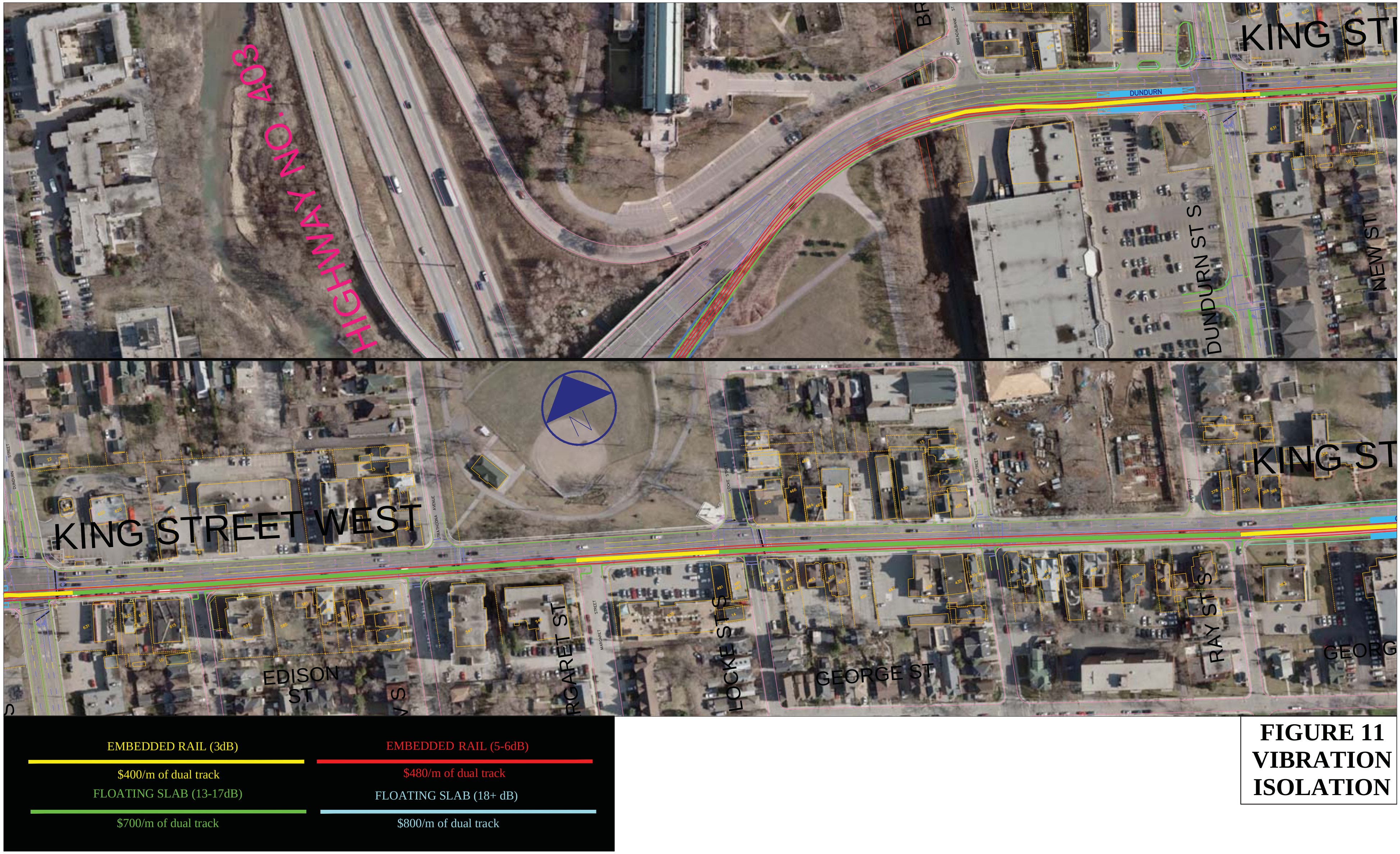


FIGURE 11
VIBRATION ISOLATION

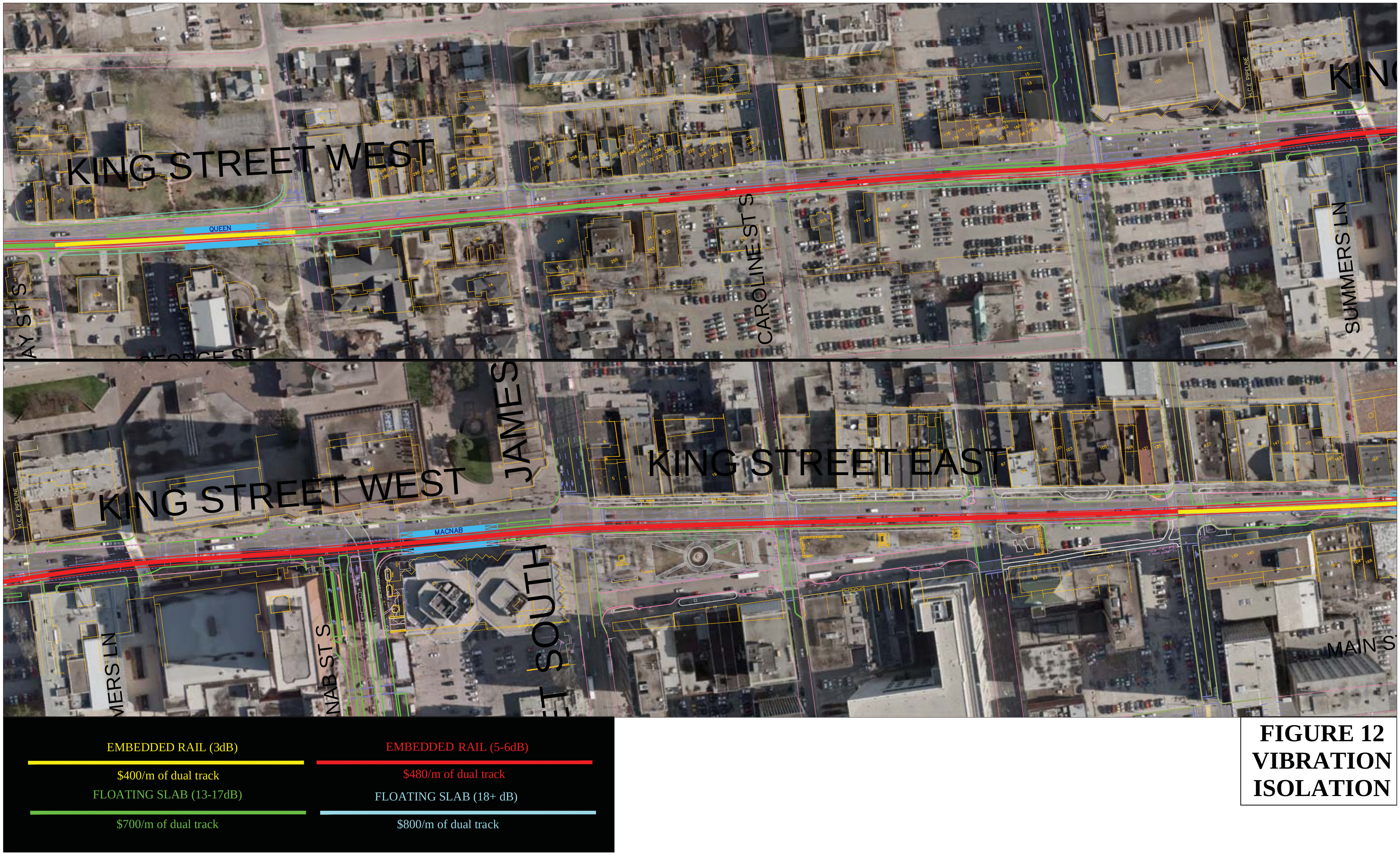
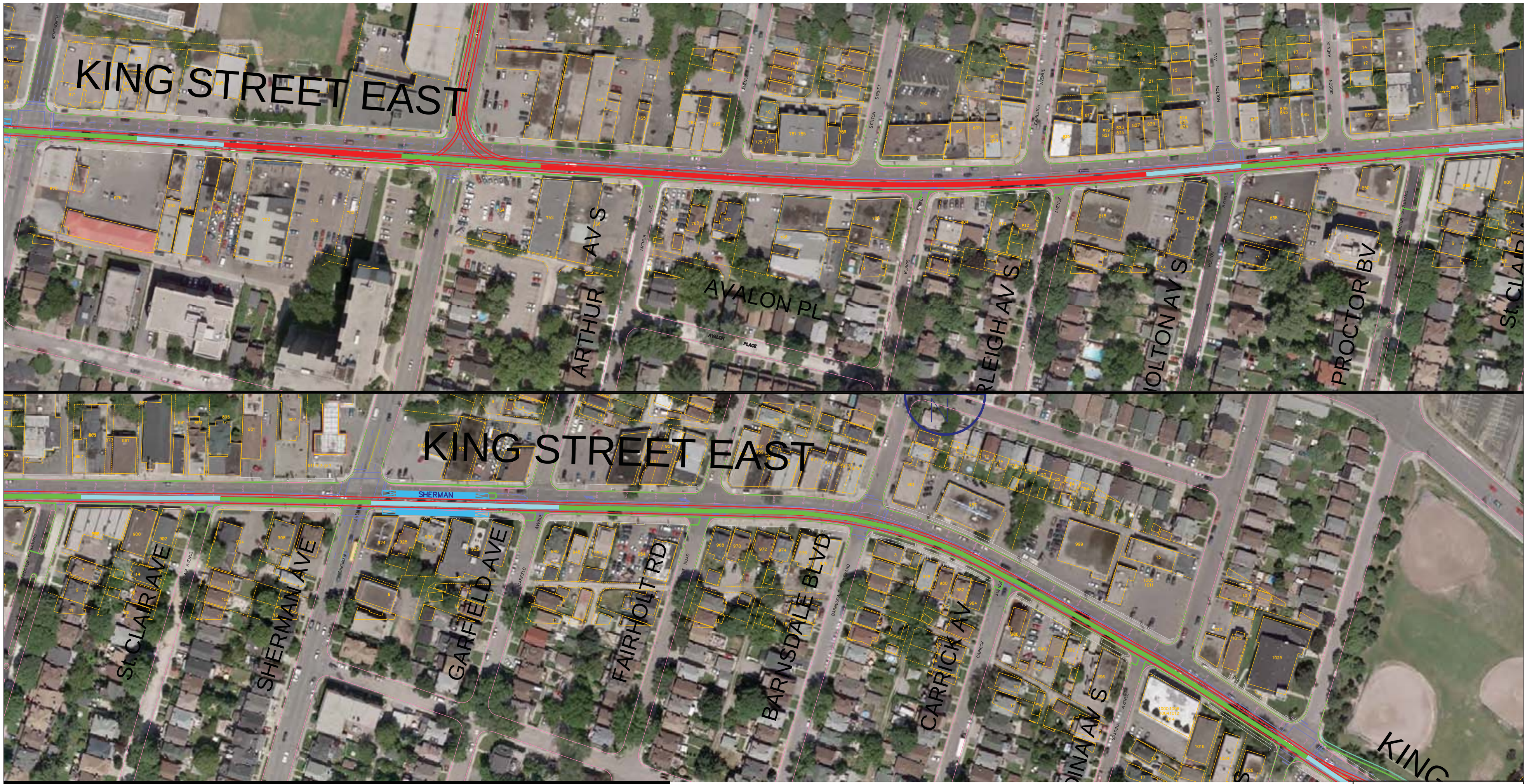


FIGURE 12
VIBRATION ISOLATION

FIGURE 13
VIBRATION ISOLATION



EMBEDDED RAIL (3dB)
🟨 $400/m of dual track

EMBEDDED RAIL (5-6dB)
🟥 $480/m of dual track

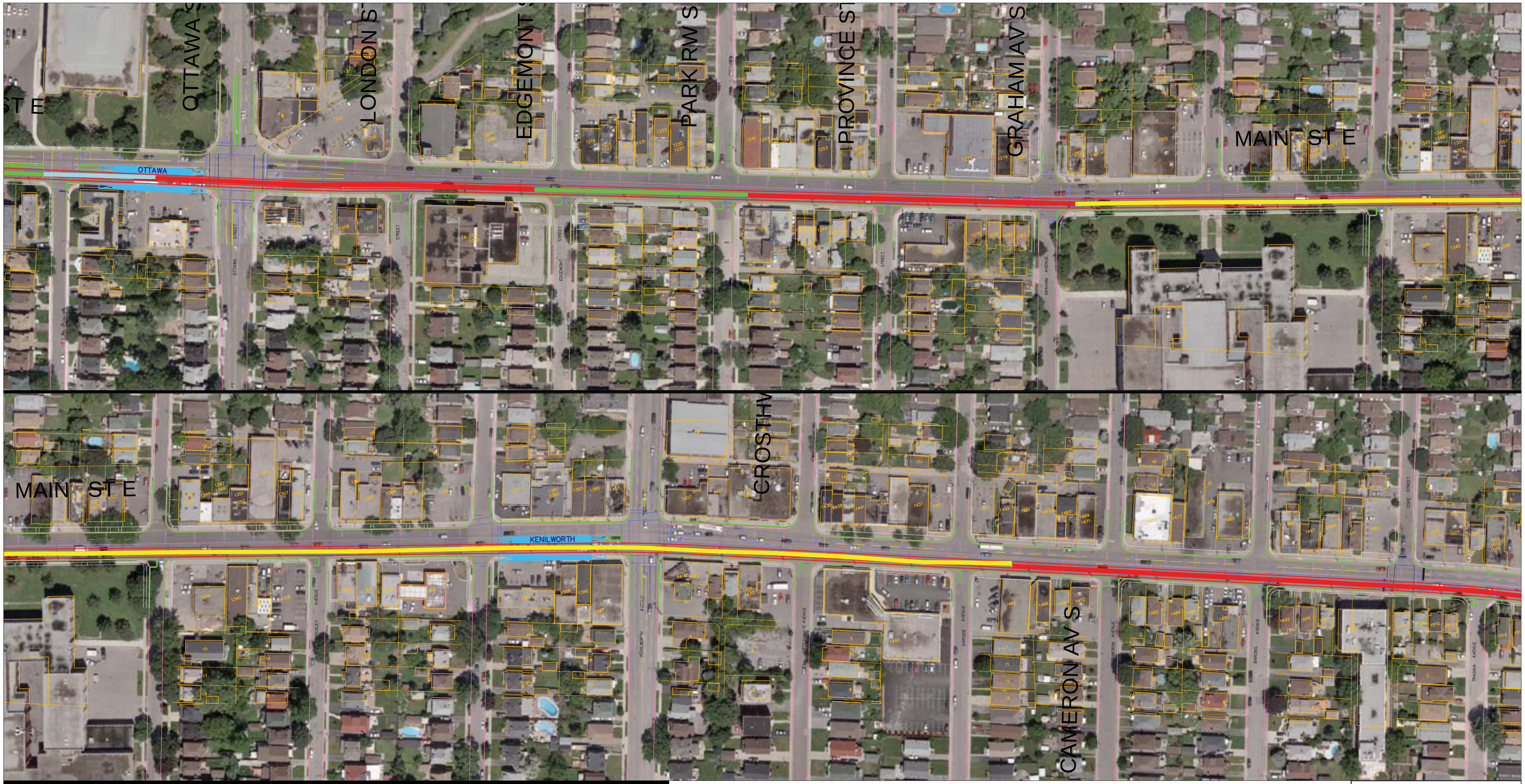
FLOATING SLAB (13-17dB)
🟩 $700/m of dual track

FLOATING SLAB (18+ dB)
🟦 $800/m of dual track

FIGURE 14
VIBRATION
ISOLATION

EMBEDDED RAIL (3dB)	EMBEDDED RAIL (5-6dB)
$400/m of dual track	$480/m of dual track
FLOATING SLAB (13-17dB)	FLOATING SLAB (18+ dB)
$700/m of dual track	$800/m of dual track

FIGURE 15 VIBRATION ISOLATION



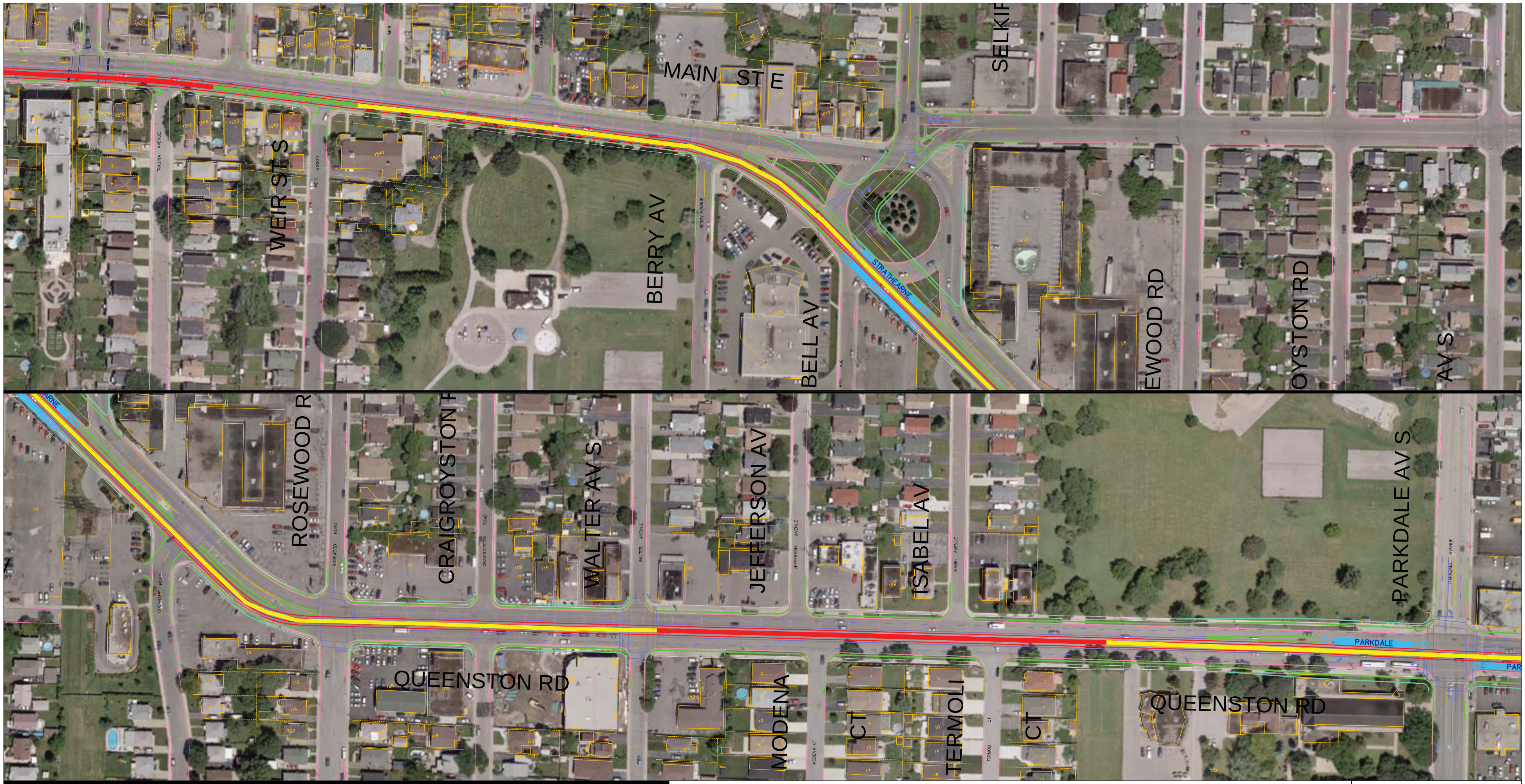
🟨 EMBEDDED RAIL (3dB)
$400/m of dual track

🟥 EMBEDDED RAIL (5-6dB)
$480/m of dual track

🟩 FLOATING SLAB (13-17dB)
$700/m of dual track

🟦 FLOATING SLAB (18+ dB)
$800/m of dual track

FIGURE 16
VIBRATION ISOLATION



EMBEDDED RAIL (3dB)	EMBEDDED RAIL (5-6dB)
🟨	🟥
$400/m of dual track	$480/m of dual track
FLOATING SLAB (13-17dB)	FLOATING SLAB (18+ dB)
🟩	🟦
$700/m of dual track	$800/m of dual track

FIGURE 17
VIBRATION ISOLATION

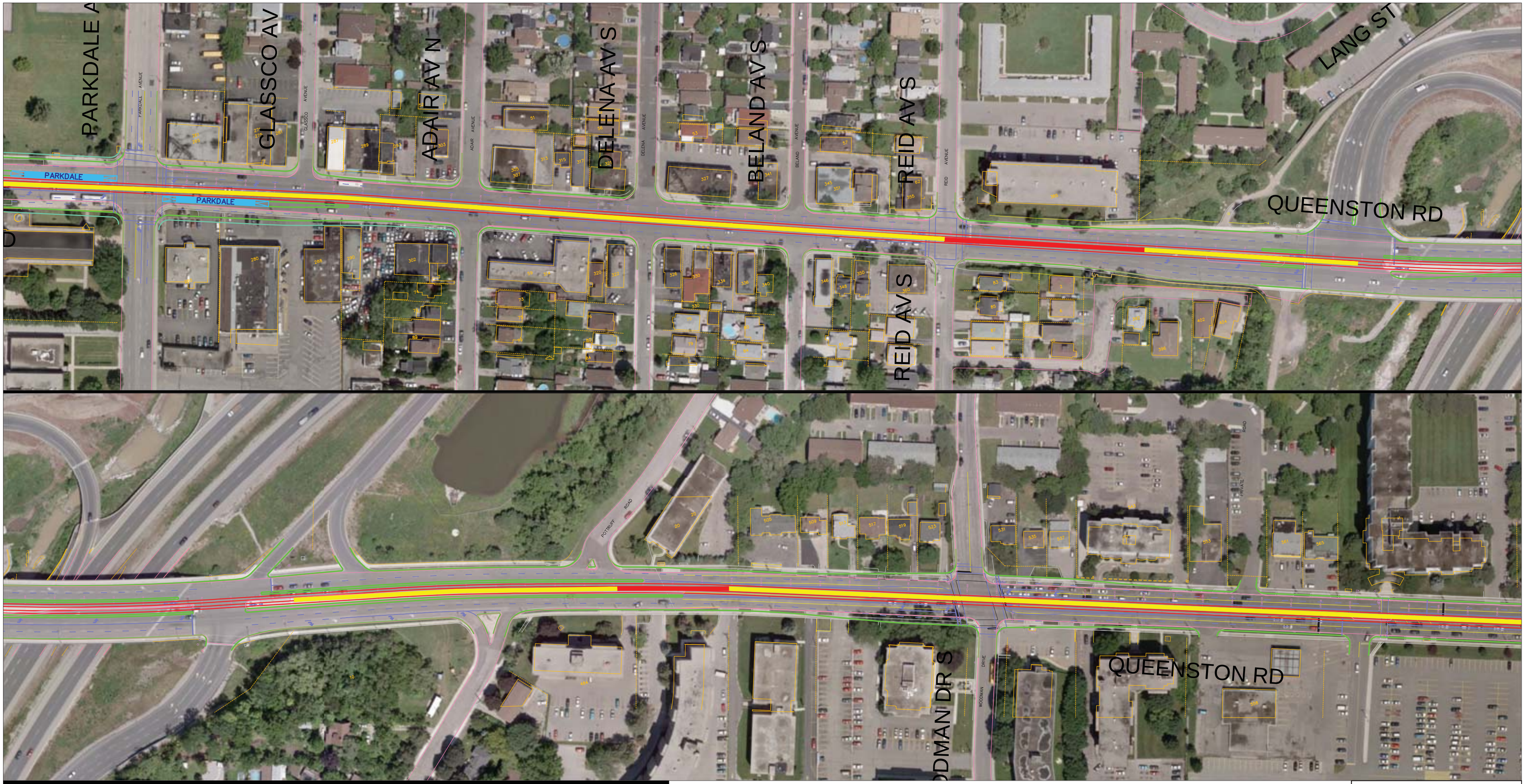


FIGURE 18
VIBRATION
ISOLATION

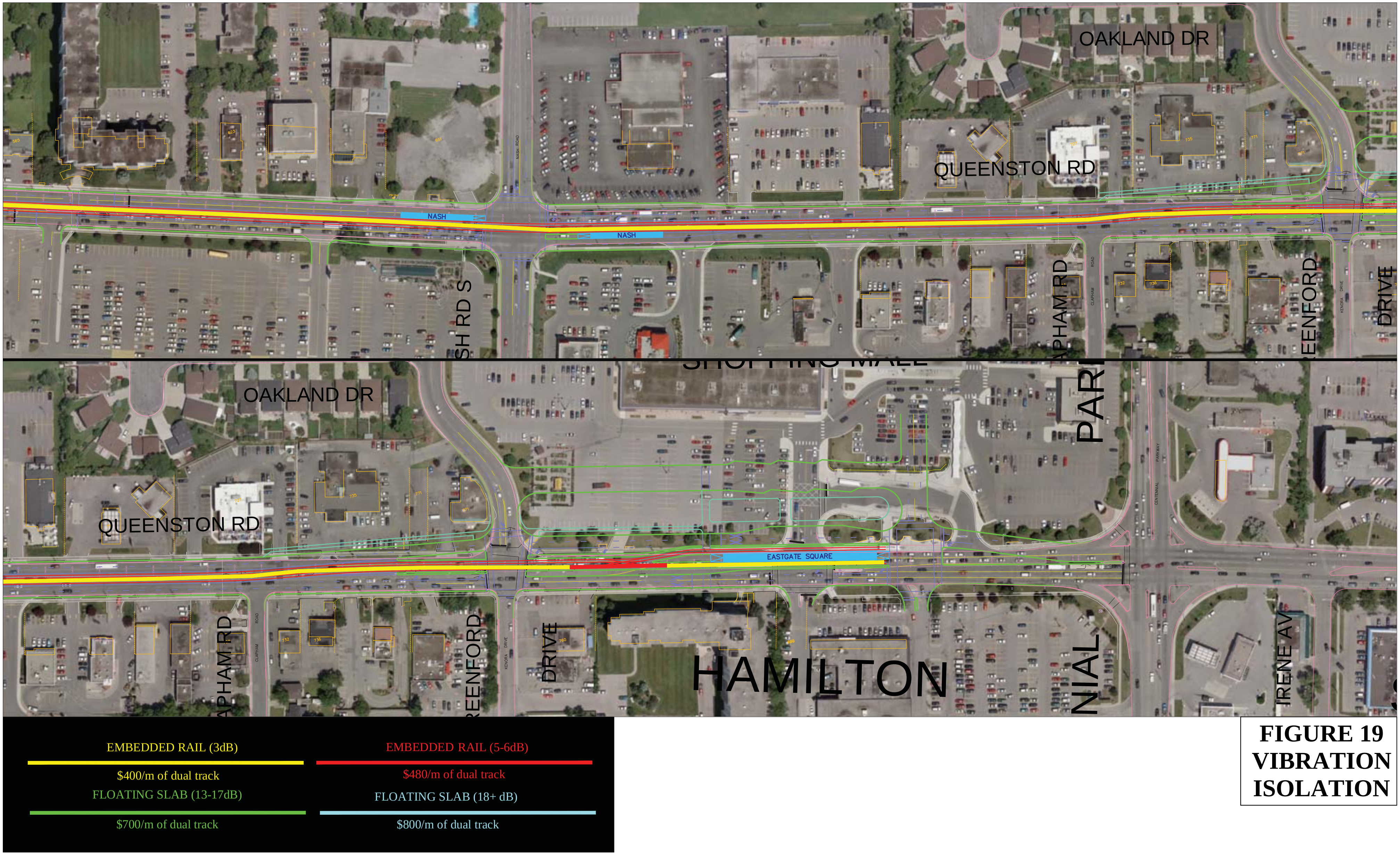


FIGURE 19
VIBRATION ISOLATION

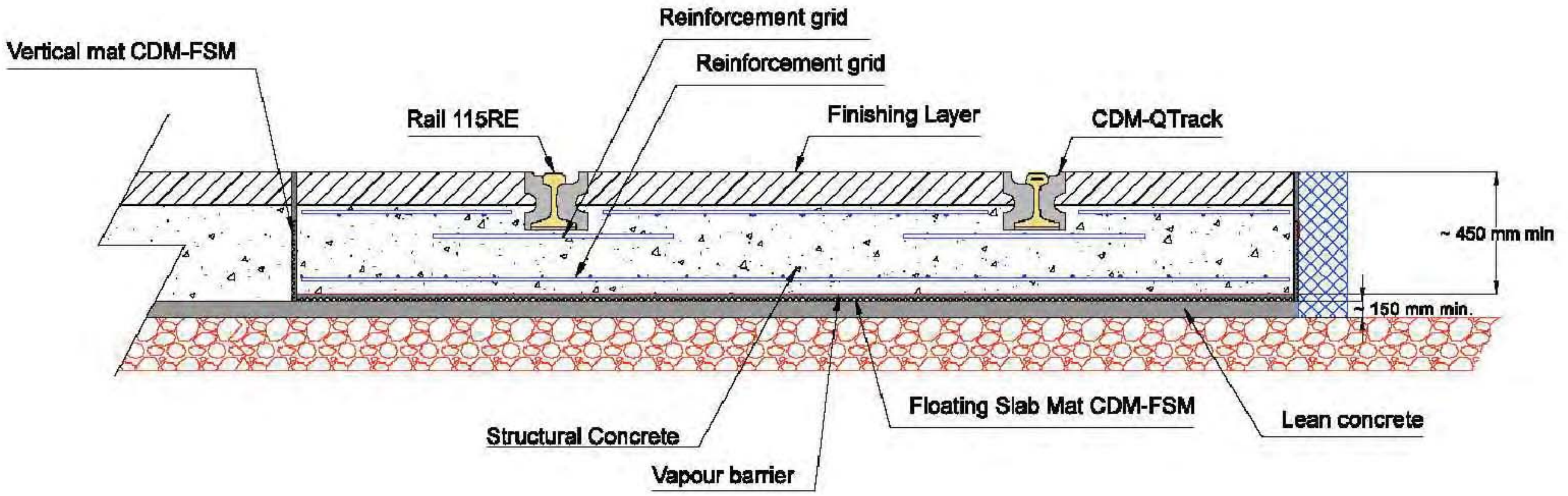


FIGURE 20
TYPICAL FLOATING
SLAB CROSS SECTION

APPENDIX B: GUIDELINES AND PROTOCOLS

MOEE/TTC
DRAFT

PROTOCOL FOR NOISE AND VIBRATION ASSESSMENT FOR THE PROPOSED SCARBOROUGH RAPID TRANSIT EXTENSION

May 11, 1993

TABLE OF CONTENTS

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 wayside air-borne noise and ground-borne noise and vibration from the TTC's proposed Scarborough Rapid Transit Line Extension (the "Line"). This 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 in order to address the requirements of the Environmental Assessment Act and is to be utilized during implementation of the Line.

The passby sound levels and vibration velocities in this protocol have been developed specifically for the Line and this protocol is not to be applied retroactively 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 MOEE 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 revisit 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 wayside 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 or 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 recognised 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.

It is recognised that levels of sound and vibration at special trackwork, such as at crossovers and turnouts, are inevitably 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 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 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.

Ancillary Facilities:

Subsidiary locations associated with either the housing of personnel or equipment engaged in TTC activities or associated with mainLine revenue operations. Examples of ancillary facilities include, but are not limited to, subway stations, bus terminals, emergency services 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 last 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.

PART D. AIR BORNE 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:

$L_{eq,16h}$ 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:

$L_{eq,8h}$ is the nighttime equivalent sound level. The applicable time period is from 23:00 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 facilitities are part of the stationary source.

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

1) Daytime equivalent sound level, $L_{eq,16h}$,
2) Nighttime equivalent sound level, $L_{eq,8h}$,
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 $L_{eq,16h}$, 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 $L_{eq,8h}$, 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 L_{eq} is preferred to individual measurements in establishing the ambient. Prediction techniques for the L_{eq} from road traffic and the L_{eq} or L_{passby} 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 date of this protocol in consultation with MTO and MOEE.

3.0 ANCILLARY FACILITIES

Predicted noise impacts from ancillary facilities shall be assessed during the design of the Line in accordance with the stationary source guideLines detailed in Reference 5. The predictions used shall be compatible with and at least as accurate as CSA Standard Z107.55.

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 1]. 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 E. 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.

1.0 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 track's centreLine, where vibration originating 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 mm/sec, 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 method and the assumptions and data inherent in it. Prediction and measurement methods are being developed by the TTC at the date of this protocol in cooperation with MTO and MOEE.

References

1)**A Protocol for Dealing With Noise Concerns During the Preparation, Review and Evaluation of Provincial Highways Environmental Assessments**, Ministry of Transportation, February 1986.

2)**Model Municipal Noise Control By-Law, Final Report, Publication NPC-101 Technical Definitions**, Ministry of the Environment, August 1978.

3)**Model Municipal Noise Control By-Law, Final Report, Publication NPC-103 Procedures**, Ministry of the Environment, August 1978.

4)**Model Municipal Noise Control By-Law, Final Report, Publication NPC-104 Sound Level Adjustments**, Ministry of the Environment, August 1978.

5)**Model Municipal Noise Control By-Law, Final Report, Publication NPC-105 Stationary Sources**, Ministry of the Environment, August 1978.

6)**Model Municipal Noise Control By-Law, Final Report, Publication NPC-106 Sound Levels of Road Traffic**, Ministry of the Environment, August 1978.

7)**Noise Control GuideLine For Class Environmental Assessment of Undertakings**, February 1980, Ministry of the Environment.

8)**Toronto Subway System Track Vibration Isolation System (Double Tie) - Technical Report**, TTC Engineering Department, June 1982.

9)**STAMSON 4.1**, Ontario Ministry of the Environment Road and Rail Noise Prediction Software

MOEE/TTC

DRAFT

PROTOCOL FOR NOISE AND VIBRATION ASSESSMENT FOR THE PROPOSED WATERFRONT WEST LIGHT RAIL TRANSIT LINE

November 11, 1993

TABLE OF CONTENTS

PROTOCOL FOR NOISE AND VIBRATION ASSESSMENT

PART A. PURPOSE

The Toronto Transit Commission (TTC) and the Ministry of the Environment and Energy (MOEE) recognise that transit facilities produce noise and vibration which may affect neighbouring properties within urbanised areas. This document identifies the framework within which criteria will be applied for limiting wayside air-borne noise, ground-borne noise and vibration from the TTC's proposed Waterfront West Light Rail Transit Line (the "Line"). The proposed line is to run from Spadina and Queen's Quay West to the CNE Dufferin Street Gate and from the Humber Loop to Legion Road. The framework presented 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 passby sound levels and vibration velocities in this protocol have been developed specifically for the Line and this protocol is not to be applied retroactively to existing TTC transit lines, routes or facilities, including the existing lines with which this line will intersect, 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). Studies pertaining to noise and vibration levels are also being conducted by TTC. Upon completion of these studies, the TTC may revisit 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 wayside 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 or 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.

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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 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.

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The passby time interval of a vehicle 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 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 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.

PART D. AIR-BORNE NOISE

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$L_{eq,16h}$ 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:

$L_{eq,8h}$ is the nighttime equivalent sound level. The applicable time period is from 23:00 to 07:00 hours.

Point of Reception:

<u>Daytime:</u> 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.

<u>Nighttime:</u> 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 vehicles between stations, the movement and idling of vehicles inside stations 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.

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

1) Daytime equivalent sound level, $L_{eq,16h}$,
2) Nighttime equivalent sound level, $L_{eq,8h}$,
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 vehicle 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 $L_{eq,16h}$, 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 $L_{eq,8h}$, whichever is higher.

PASSBY SOUND LEVEL:

The limit at a point of reception for predicted L_{passby} for a single vehicle 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 8, and the minimum sound levels in Table 106-2 of Reference 6. Prediction of road traffic L_{eq} is preferred to individual measurements in establishing the ambient. Prediction techniques for the L_{eq} from road traffic and the L_{eq} or L_{passby} 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 date of this protocol in consultation with MTO and MOEE.

3.0 ANCILLARY FACILITIES

Predicted noise impacts from ancillary facilities shall be assessed during the design of the Line in accordance with the stationary source guidelines detailed in Reference 5. The predictions used shall be compatible with and at least as accurate as CSA Standard Z107.55.

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 1]. 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 E. 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.

It is recognised that ground-borne vibration can produce air-borne noise inside a structure and there is a direct correlation between the two. The TTC can only control ground-borne noise by controlling ground-borne vibration. Accordingly, ground-borne noise will be predicted and assessed in terms of vibration measured at a point of assessment using the limit in Section 2.0, Vibration Assessment.

1.0 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 track's centreline, where vibration originating from the Line is received.

Vibration Velocity:

Vibration Velocity is the root-mean-square (rms) vibration velocity assessed during a vehicle 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 0.14 mm/sec, 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 method and the assumptions and data inherent in it. Prediction and measurement methods are being developed by the TTC at the date of this protocol in cooperation with MTO and MOEE.

APPENDIX C: REFERENCES

1. Model Municipal Noise Control By-Law, Final Report, Publication *NPC-101* Technical Definitions, Ministry of the Environment, August 1978.

2. Model Municipal Noise Control By-Law, Final Report, Publication *NPC-102* Instrumentation, Ministry of the Environment, August 1978.

3. Model Municipal Noise Control By-Law, Final Report, Publication *NPC-103* Procedures, Ministry of the Environment, August 1978.

4. Transit Noise and Vibration Impact Assessment, Federal Transit Administration, May 2006.

5. Forced vibrations of a rigid circular plate on a semi-infinite elastic space and on an elastic stratum, Bycroft G.N., 1956.

6. Vibrations of soils and foundations, F.E. Richart, J.R. Hall, R.D. Woods, 1970.

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.

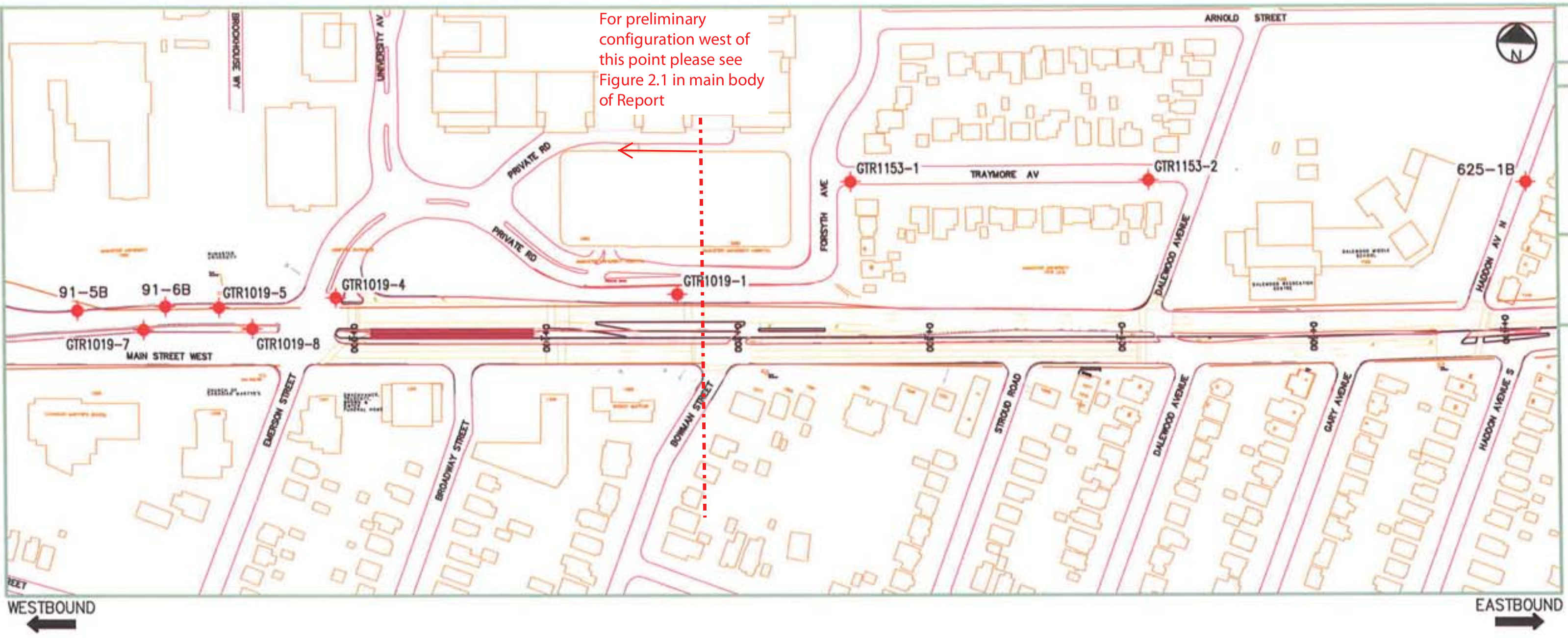
Vibration Velocity

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

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

DIMENSIONS SHOWN ON THIS PLAN ARE IN METRES UNLESS OTHERWISE NOTED

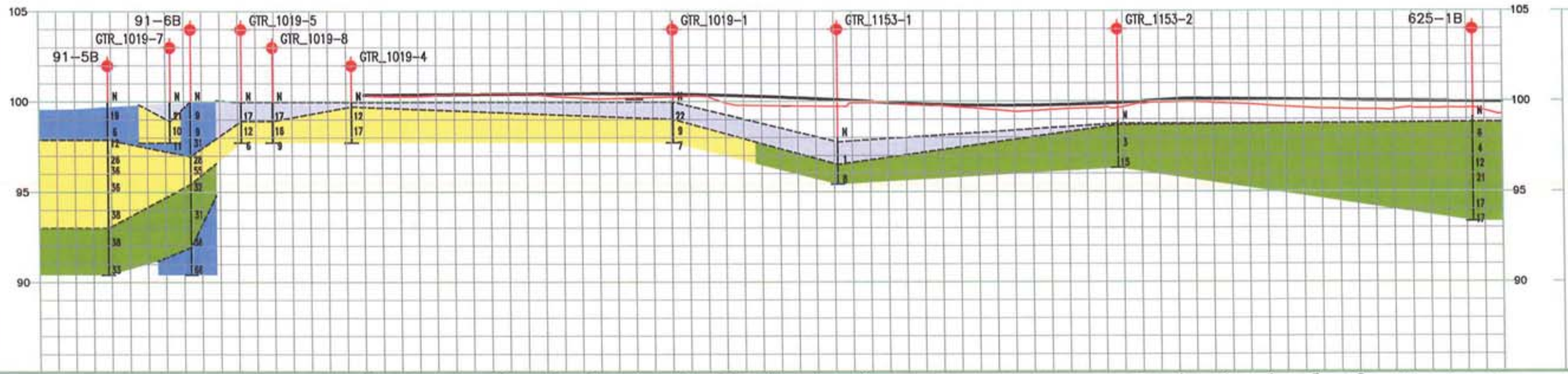


For preliminary configuration west of this point please see Figure 2.1 in main body of Report

LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)
- ● EXISTING BOREHOLE LOCATION
- FILL
- CLAY
- SILT
- SAND
- TILL
- SHALE

DRAFT



PROPOSED TOP OF RAIL PROFILE	100.344	100.361	100.379	100.396	100.413	100.428	100.420	100.387	100.329	100.245	100.136	100.004	99.875	99.789	99.752	99.764	99.826	99.938	100.094	100.104	100.076	100.048	100.020	99.992	99.964	99.936
EXISTING GROUND ELEVATION	100.346	100.278	100.380	100.416	100.334	100.187	100.112	100.240	99.923	99.760	99.735	99.913	99.836	99.720	99.523	99.501	99.617	99.805	99.955	99.883	99.759	99.609	99.543	99.616	99.614	99.326
CONSTRUCTION ℄ CHAINAGE	0+000				0+100				0+200				0+300				0+400				0+500				0+600	

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials | DATE:

REFERENCE MATERIAL:
Surveyed By :
Sewer Plans :
Water Plans :
Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report —

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 1.25m 2.5m 5m
VERTICAL 1:250

Project Manager (Design)
NAME
Manager of Design
NAME

SNC·LAVALIN
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HAMILTON LRT 'B' LINE BOREHOLE PLAN AND STRATIGRAPHIC PROFILE

SHEET 1 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

DIMENSIONS SHOWN ON THIS PLAN ARE IN METRES UNLESS OTHERWISE NOTED

LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)

● EXISTING BOREHOLE LOCATION

▨	FILL
🟦	CLAY
🟩	SILT
🟨	SAND
🟩	TILL
▨	SHALE

DRAFT

PROPOSED TOP OF RAIL PROFILE	99.852	99.824	99.796	99.768	99.740	99.712	99.685	99.657	99.629	99.601	99.573	99.545	99.517	99.489	99.461	99.433
EXISTING GROUND ELEVATION	99.523	99.480	99.483	99.507	99.486	99.451	99.419	99.339	99.258	99.333	99.441	99.469	99.507	99.505	99.459	99.317
CONSTRUCTION ℄ CHAINAGE	0+700				0+800				0+900				1+000			

PROPOSED TOP OF RAIL PROFILE	99.405	99.377	99.349	99.322	99.294	99.267	99.240	99.213	99.187	99.161	99.135	99.108	99.082	99.056	99.030	99.003
EXISTING GROUND ELEVATION	99.207	99.128	99.089	99.107	99.307	99.111	99.044	99.043	99.035	99.155	99.172	99.018	99.170	99.140	98.900	98.860
CONSTRUCTION ℄ CHAINAGE	1+100				1+200				1+300				1+400			

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials DATE:

REFERENCE MATERIAL:
Surveyed By :
Sewer Plans :
Water Plans :
Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report =

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 1.25m 2.5m 5m
VERTICAL 1:250

Project Manager (Design)
NAME
Manager of Design
NAME

SNC·LAVALIN
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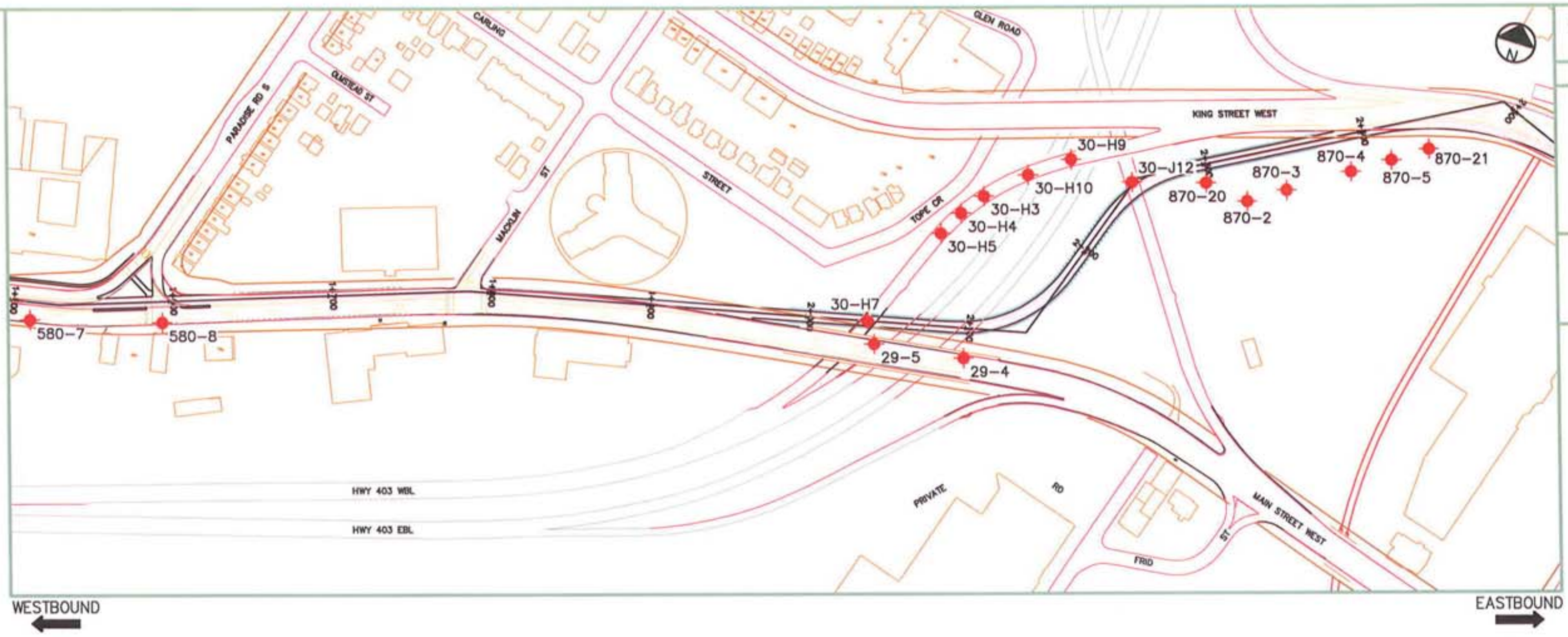
HAMILTON LRT 'B' LINE
BOREHOLE PLAN AND STRATIGRAPHIC PROFILE

SHEET 2 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

DIMENSIONS SHOWN ON THIS PLAN ARE IN METRES UNLESS OTHERWISE NOTED



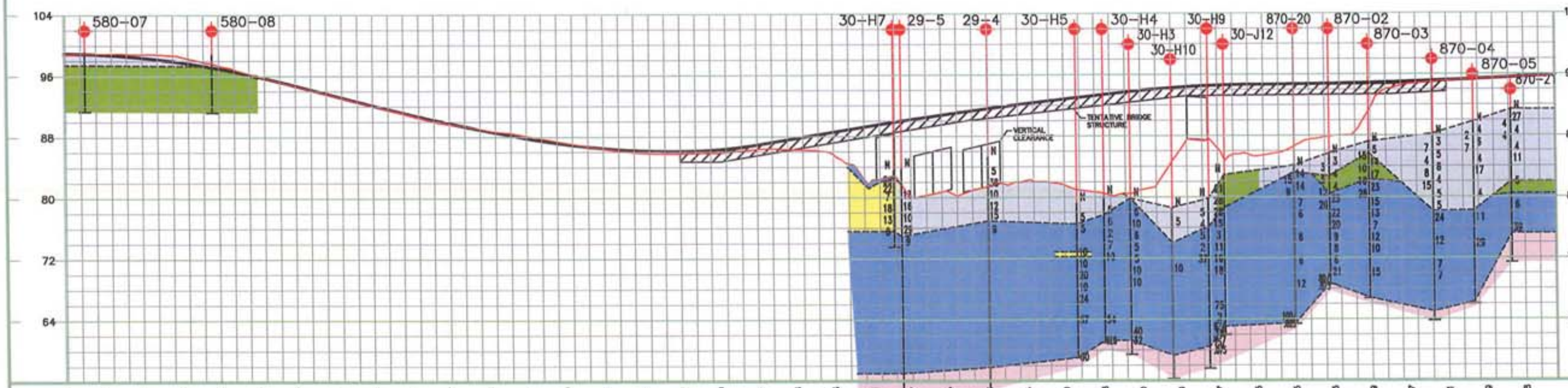
LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)

● EXISTING BOREHOLE LOCATION

- ▭ FILL
- 🟦 CLAY
- 🟩 SILT
- 🟨 SAND
- 🟩 TILL
- ▭ SHALE

DRAFT



CONSTRUCTION ℄ CHAINAGE	EXISTING GROUND ELEVATION	PROPOSED TOP OF RAIL PROFILE
1+500	[illegible]	[illegible]
	98.932	98.798
	98.889	98.409
	98.617	97.808
1+600	97.428	96.993
	96.044	95.966
	94.681	94.730
	93.354	93.426
1+700	92.071	92.129
	90.775	90.910
	89.663	89.787
	88.865	88.759
1+800	88.148	87.821
	87.265	87.050
	86.421	86.510
	85.902	86.201
1+900	85.810	86.120
	85.881	86.330
	86.364	86.916
	86.312	87.738
2+000	85.687	88.563
	82.331	89.381
	79.817	90.157
	80.733	90.887
2+100	81.422	91.57
	82.235	92.214
	81.657	92.810
	80.519	93.368
2+200	80.961	93.910
	85.977	94.319
	88.390	94.567
	85.340	94.655
2+300	86.642	94.695
	87.933	94.765
	91.670	94.869
	94.686	95.007
2+400	95.095	95.181
	95.396	95.389
	95.613	95.628

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials DATE:

REFERENCE MATERIAL:
Surveyed By :
Sewer Plans :
Water Plans :
Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report –

SCALES
HORIZONTAL 1:3000 (0 15m 30m 60m)
VERTICAL 1:600 (0 3m 6m 12m)

Project Manager (Design)
NAME
Manager of Design
NAME

SNC·LAVALIN
steer davies gleave
DIALOG
THURBER ENGINEERING LTD.
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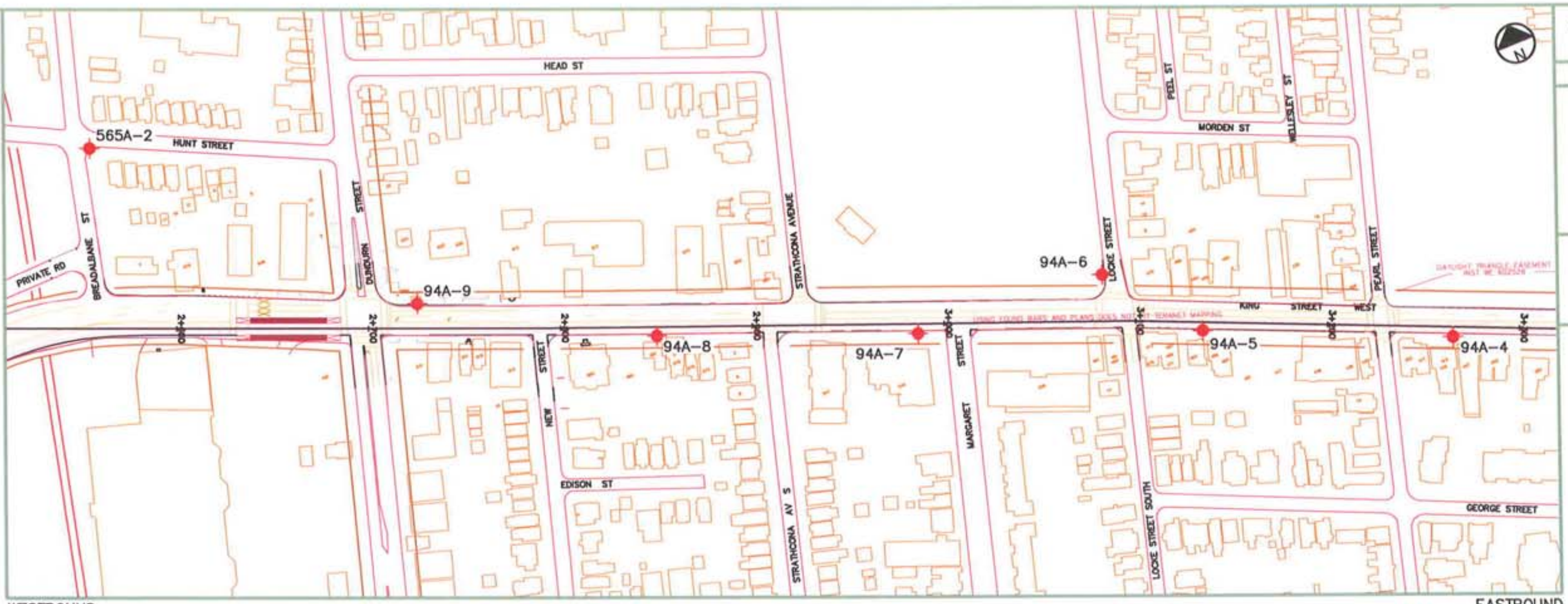
HAMILTON LRT 'B' LINE
BOREHOLE PLAN AND STRATIGRAPHIC PROFILE
SHEET 3 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

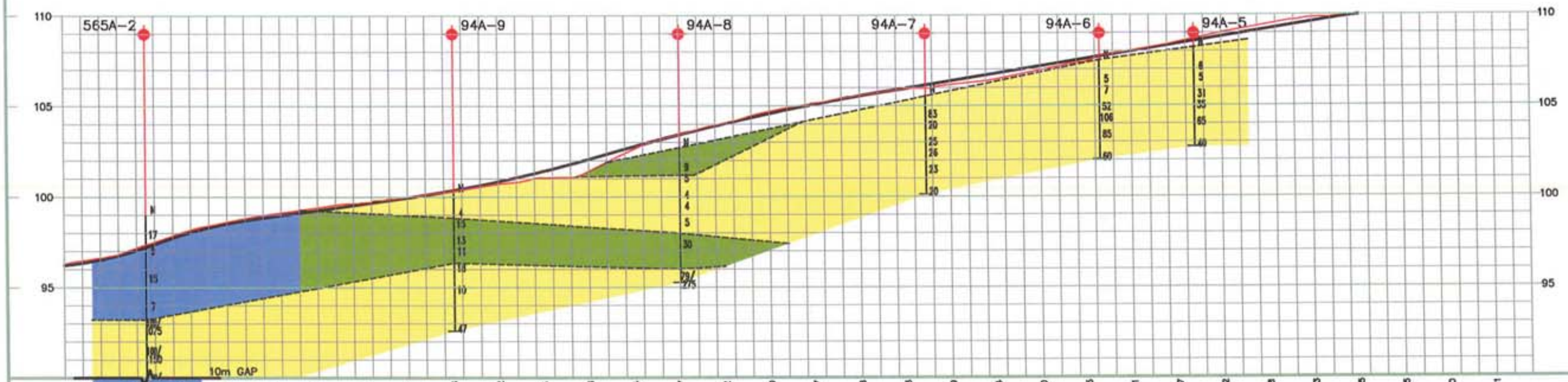
DIMENSIONS SHOWN ON THIS PLAN ARE IN METRES UNLESS OTHERWISE NOTED



LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)
- ● EXISTING BOREHOLE LOCATION
- ▭ FILL
- ▭ CLAY
- ▭ SILT
- ▭ SAND
- ▭ TILL
- ▭ SHALE

DRAFT



PROPOSED TOP OF RAIL PROFILE	EXISTING GROUND ELEVATION	CONSTRUCTION ℄ CHAINAGE
96.422	96.555	
97.035	97.183	
97.883	98.025	
98.509	98.611	2+600
98.893	99.059	
99.243	99.409	
99.594	99.685	
99.945	99.989	2+700
100.346	100.311	
100.832	100.722	
101.405	101.067	
102.063	101.422	2+800
102.754	102.597	
103.407	103.425	
104.012	104.052	
104.569	104.704	2+900
105.077	105.130	
105.538	105.579	
105.953	105.934	
106.359	106.170	3+000
106.764	106.469	
107.170	106.971	
107.575	107.489	
107.981	108.020	3+100
108.387	108.483	
108.792	109.018	
109.198	109.473	
109.603	109.843	3+200
109.975	110.088	
110.245	110.388	
110.410	110.579	
110.471	110.619	3+300

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials DATE:

REFERENCE MATERIAL:
Surveyed By :
Sewer Plans :
Water Plans :
Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report –

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 1.25m 2.5m 5m
VERTICAL 1:250

Project Manager (Design)
NAME
Manager of Design
NAME

SNC·LAVALIN steer davies gleave DIALOG
THURBER ENGINEERING LTD.

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APPROVED

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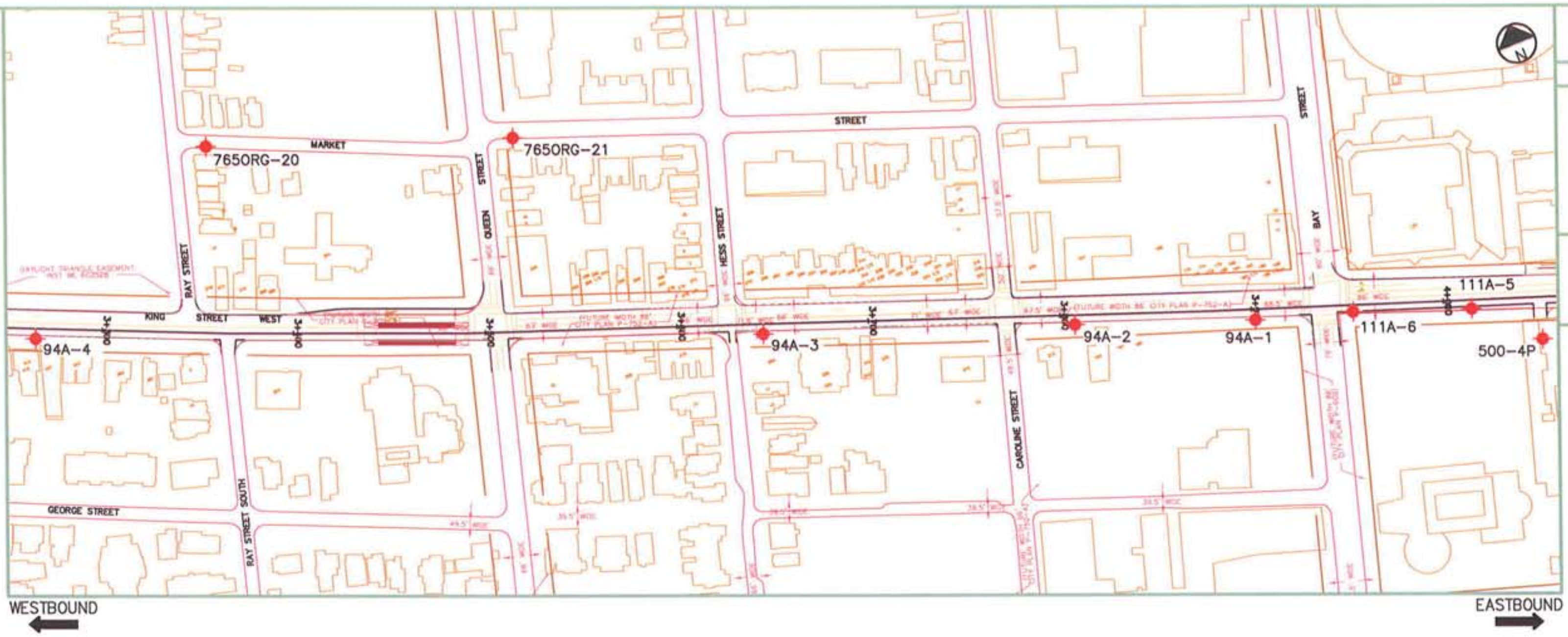
METROLINX

HAMILTON LRT 'B' LINE
BOREHOLE PLAN AND STRATIGRAPHIC PROFILE
SHEET 4 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

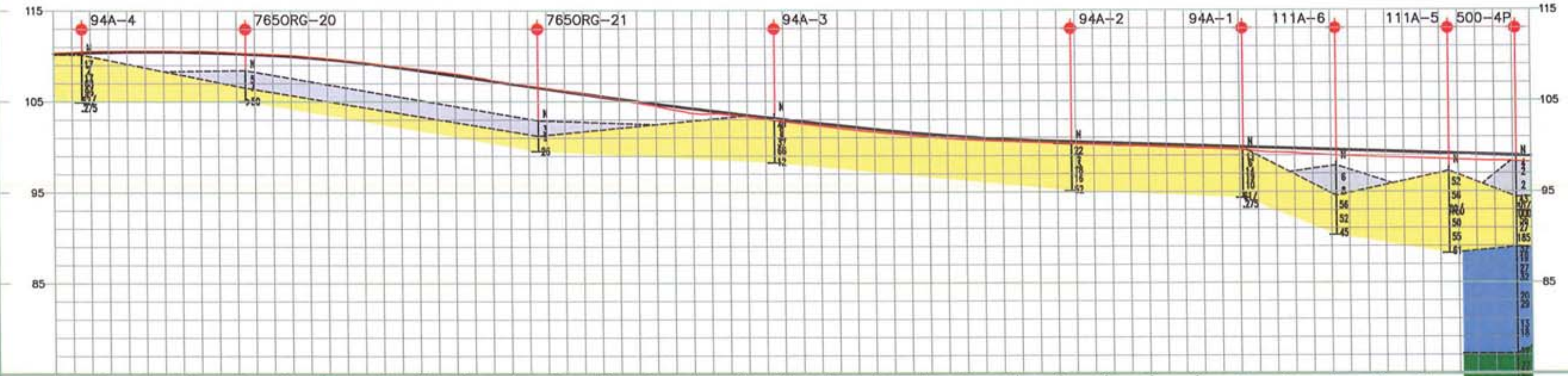
DIMENSIONS SHOWN ON THIS PLAN ARE IN METRES UNLESS OTHERWISE NOTED



LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)
- ● EXISTING BOREHOLE LOCATION
- FILL
- CLAY
- SILT
- SAND
- TILL
- SHALE

DRAFT



CONSTRUCTION ℄ CHAINAGE	EXISTING GROUND ELEVATION	PROPOSED TOP OF RAIL PROFILE
	110.579	110.410
3+300	110.619	110.471
	110.596	110.428
	110.385	110.279
	110.167	110.039
3+400	109.765	109.658
	109.224	109.114
	108.587	108.422
	107.931	107.694
3+500	107.038	106.965
	106.313	106.237
	105.502	105.523
	104.705	104.841
3+600	103.889	104.192
	103.409	103.575
	102.792	102.990
	102.191	102.437
3+700	101.628	101.902
	101.188	101.425
	100.773	101.041
	100.541	100.752
3+800	100.318	100.555
	100.185	100.395
	100.005	100.234
	99.848	100.074
3+900	99.643	99.914
	99.308	99.753
	99.022	99.593
	98.813	99.433
4+000	98.663	99.272
	98.477	
	98.317	

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials DATE:

REFERENCE MATERIAL:
Surveyed By :
Sewer Plans :
Water Plans :
Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report –

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 2.5m 5m 10m
VERTICAL 1:500

Project Manager (Design)
NAME
Manager of Design
NAME

SNC·LAVALIN steer davies gleave DIALOG
THURBER ENGINEERING LTD.

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HAMILTON LRT 'B' LINE BOREHOLE PLAN AND STRATIGRAPHIC PROFILE

SHEET 5 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

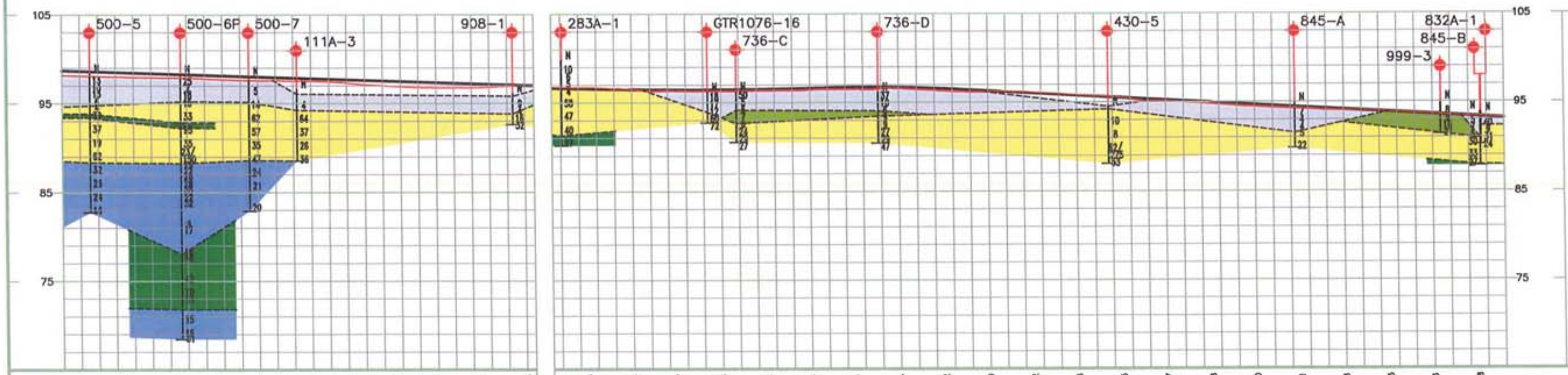
DIMENSIONS SHOWN ON THIS PLAN ARE IN METRES UNLESS OTHERWISE NOTED

LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)
- EXISTING BOREHOLE LOCATION

- 🟪 FILL
- 🟦 CLAY
- 🟩 SILT
- 🟨 SAND
- 🟩 TILL
- 🟪 SHALE

DRAFT



CONSTRUCTION ℄ CHAINAGE	PROPOSED TOP OF RAIL PROFILE	EXISTING GROUND ELEVATION
4+100	98.631	98.154
	98.471	98.022
	98.310	97.928
	98.150	97.776
4+200	97.990	97.627
	97.829	97.550
	97.669	97.354
	97.509	96.970
4+300	97.349	96.788
	97.188	96.819
	97.028	96.977
	96.573	96.747
	96.486	96.501
	96.447	96.332
4+500	96.456	96.299
	96.512	96.362
	96.616	96.450
	96.714	96.513
4+600	96.694	96.605
	96.552	96.314
	96.300	96.190
	96.032	96.136
4+700	95.763	95.839
	95.495	95.476
	95.227	95.101
	94.958	94.814
4+800	94.690	94.479
	94.421	94.245
	94.153	94.040
	93.885	93.878
4+900	93.616	93.594
	93.348	93.361

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials
DATE:

REFERENCE MATERIAL:
Surveyed By :
Sewer Plans :
Water Plans :
Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report –

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 2.5m 5m 10m
VERTICAL 1:500

Project Manager (Design)
NAME
Manager of Design
NAME

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DIALOG
THURBER ENGINEERING LTD.

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HAMILTON LRT 'B' LINE BOREHOLE PLAN AND STRATIGRAPHIC PROFILE

SHEET 6 OF 17

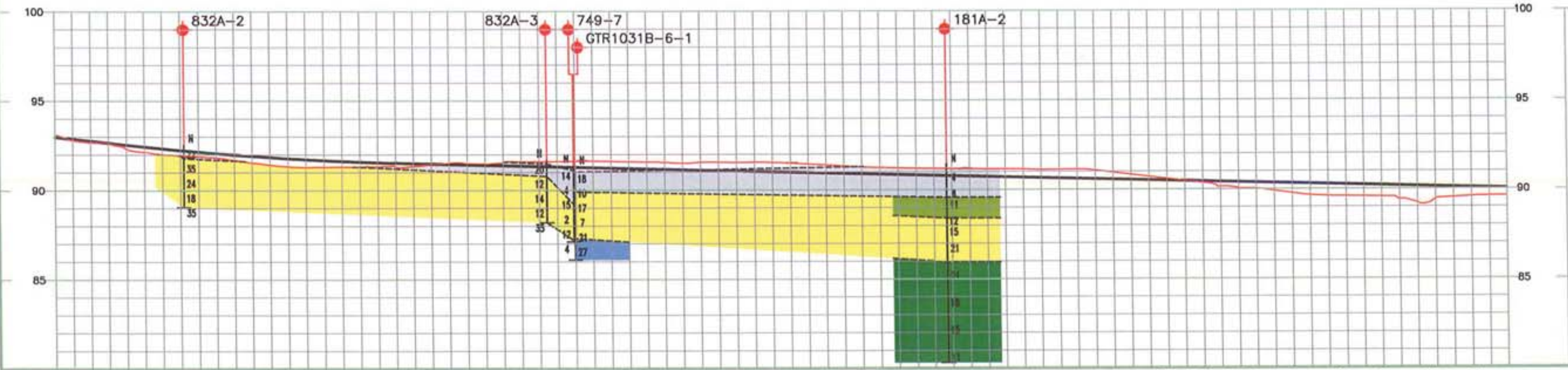
FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

DIMENSIONS SHOWN ON THIS PLAN ARE IN METRES UNLESS OTHERWISE NOTED

LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)
- ● EXISTING BOREHOLE LOCATION
- ▨ FILL
- 🟦 CLAY
- 🟩 SILT
- 🟨 SAND
- 🟩 TILL
- ▨ SHALE

DRAFT



PROPOSED TOP OF RAIL PROFILE	EXISTING GROUND ELEVATION	CONSTRUCTION ℄ CHAINAGE
92.811	92.738	
92.543	92.349	5+000
92.288	91.992	
92.063	91.823	
91.874	91.497	
91.720	91.299	5+100
91.601	91.309	
91.517	91.315	
91.458	91.483	
91.396	91.477	5+200
91.335	91.601	
91.275	91.627	
91.215	91.609	
91.155	91.550	5+300
91.095	91.567	
91.035	91.550	
90.975	91.490	
90.914	91.347	5+400
90.854	91.237	
90.794	91.189	
90.734	91.175	
90.674	91.139	5+500
90.614	91.122	
90.553	90.964	
90.493	90.844	
90.433	90.344	5+600
90.373	90.042	
90.313	89.775	
90.253	89.593	
90.193	89.566	5+700
90.132	89.169	
90.072	89.564	

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials DATE:

REFERENCE MATERIAL:
Surveyed By :
Sewer Plans :
Water Plans :
Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report —

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 1.25m 2.5m 5m
VERTICAL 1:250

Project Manager (Design)
NAME
Manager of Design
NAME

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CHECKED
APPROVED

Hamilton Public Works
RAPIDTransit
METROLINX

HAMILTON LRT 'B' LINE BOREHOLE PLAN AND STRATIGRAPHIC PROFILE

SHEET 7 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

DIMENSIONS SHOWN ON THIS PLAN ARE IN METRES UNLESS OTHERWISE NOTED

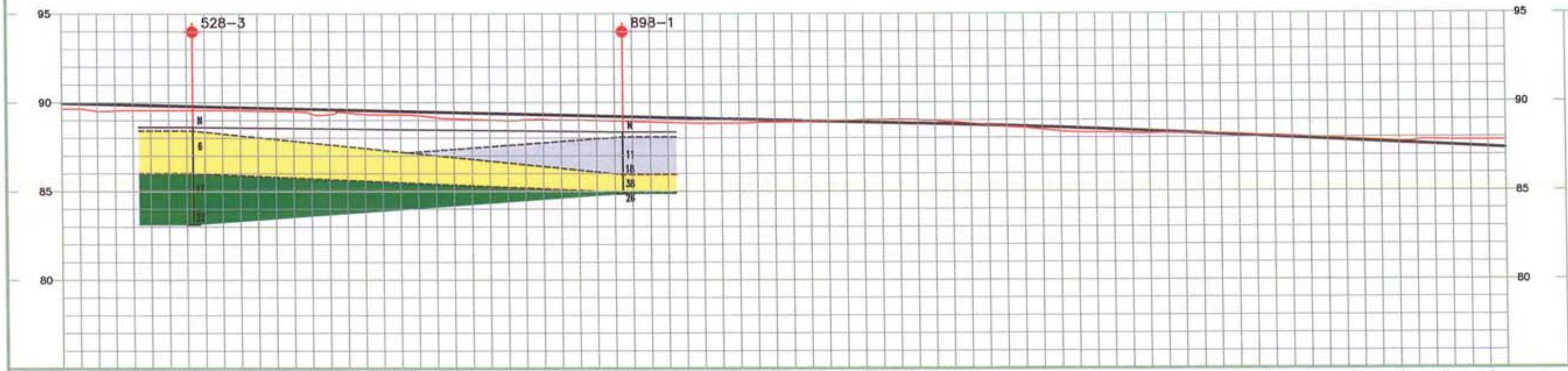
WESTBOUND

EASTBOUND

LEGEND

—	NEW CONSTRUCTION
—	EXISTING
—	PROPERTY LINE (ROAD ALLOWANCE)
●	EXISTING BOREHOLE LOCATION
▭	FILL
🟦	CLAY
🟩	SILT
🟨	SAND
🟩	TILL
▭	SHALE

DRAFT



PROPOSED TOP OF RAIL PROFILE	EXISTING GROUND ELEVATION	CONSTRUCTION ℄ CHAINAGE
89.892	89.520	
89.832	89.566	
89.772	89.565	
89.711	89.558	5+900
89.651	89.509	
89.591	89.301	
89.531	89.317	
89.471	89.268	6+000
89.411	89.077	
89.350	88.974	
89.290	89.016	
89.230	88.988	6+100
89.170	88.920	
89.110	88.849	
89.050	88.831	
88.990	88.876	6+200
88.929	88.920	
88.869	89.001	
88.809	89.025	
88.746	88.884	6+300
88.673	88.847	
88.589	88.459	
88.498	88.288	
88.392	88.236	6+400
88.277	88.225	
88.156	88.207	
88.034	88.101	
87.912	88.003	6+500
87.790	87.889	
87.668	87.769	
87.546	87.834	
87.424	87.817	6+600

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials DATE:

REFERENCE MATERIAL:
Surveyed By :
Sewer Plans :
Water Plans :
Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report –

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 1.25m 2.5m 5m
VERTICAL 1:250

Project Manager (Design)
NAME
Manager of Design
NAME

SNC-LAVALIN
steer davies gleave
DIALOG
THURBER ENGINEERING LTD.

DRAWN
CHECKED
APPROVED

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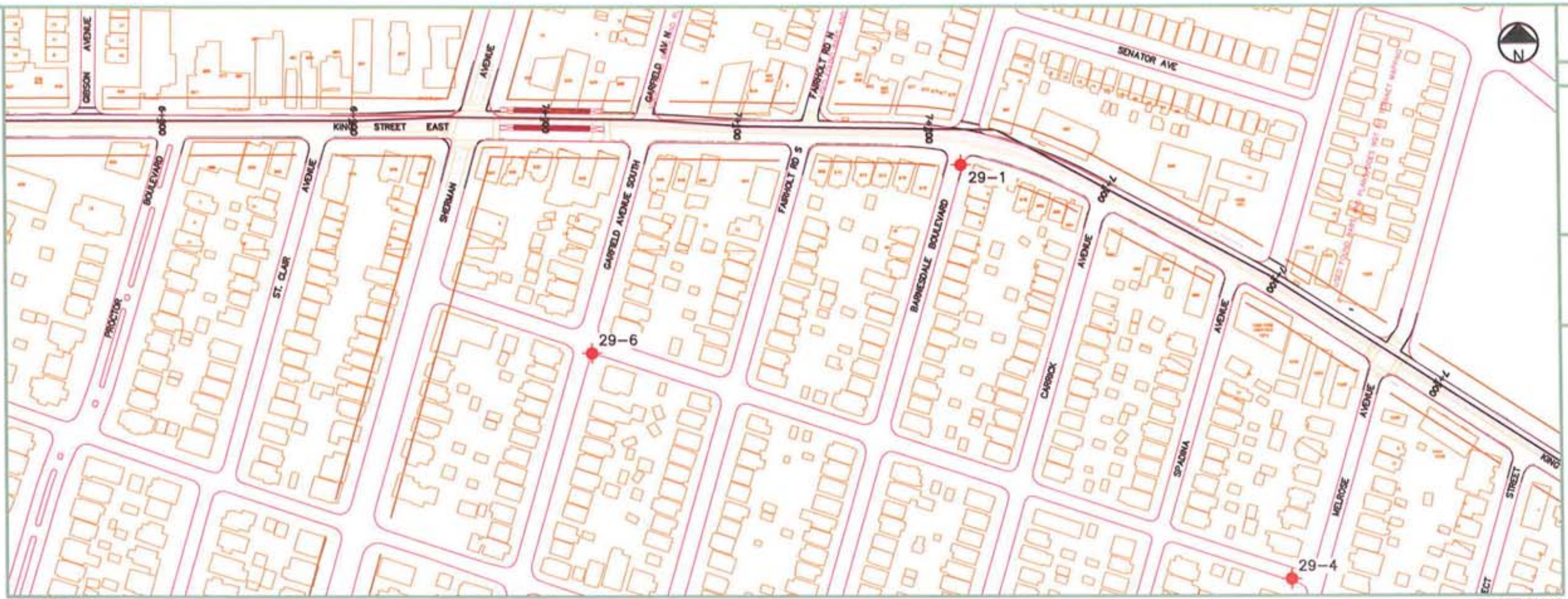
RAPIDTransit moving HAMILTON forward
METROLINX

HAMILTON LRT 'B' LINE BOREHOLE PLAN AND STRATIGRAPHIC PROFILE

SHEET 8 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

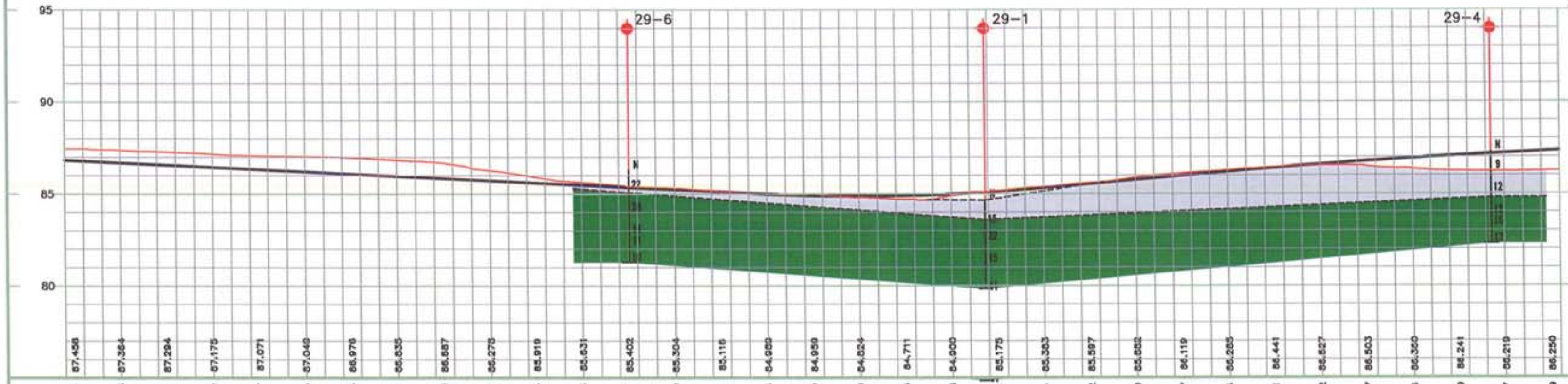
DIMENSIONS SHOWN ON THIS PLAN ARE IN METRES UNLESS OTHERWISE NOTED



LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)
- ● EXISTING BOREHOLE LOCATION
- ▨ FILL
- 🟦 CLAY
- 🟩 SILT
- 🟨 SAND
- 🟩 TILL
- ▨ SHALE

DRAFT



PROPOSED TOP OF RAIL PROFILE	86.814	86.693	86.571	86.449	86.327	86.205	86.083	85.961	85.839	85.717	85.595	85.473	85.351	85.229	85.107	84.986	84.899	84.869	84.895	84.978	85.118	85.314	85.532	85.749	85.967	86.185	86.391	86.582	86.757	86.916	87.059	87.187	87.309
EXISTING GROUND ELEVATION	87.458	87.364	87.294	87.175	87.071	87.049	86.976	86.835	86.687	86.278	85.919	85.631	85.402	85.304	85.116	84.989	84.959	84.824	84.711	84.900	85.175	85.383	85.597	85.882	86.119	86.285	86.441	86.527	86.503	86.360	86.241	86.219	86.250
CONSTRUCTION ℄ CHAINAGE				6+800				6+900				7+000				7+100				7+200				7+300				7+400				7+500	

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials
DATE:
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Sewer Plans :
Water Plans :
Survey Plan :
Geodetic Bench Mark Index Elevation=
Borehole Report –

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 1.25m 2.5m 5m
VERTICAL 1:250

Project Manager (Design)
NAME
Manager of Design
NAME

SNC·LAVALIN
steer davies gleave
DIALOG
THURBER ENGINEERING LTD.
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CHECKED . . . . .
APPROVED . . . . .

Hamilton
Public Works
RAPIDTransit
METROLINX

HAMILTON LRT 'B' LINE
BOREHOLE PLAN AND STRATIGRAPHIC PROFILE

SHEET 9 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

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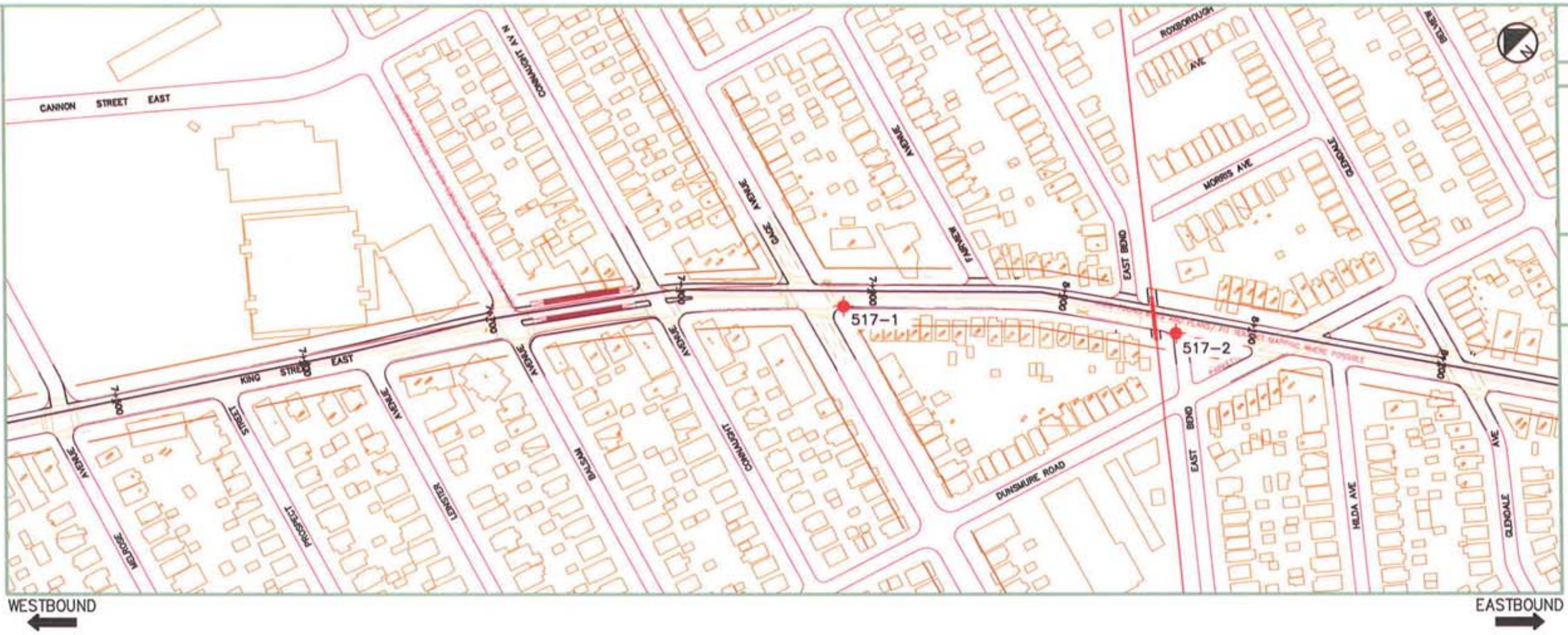


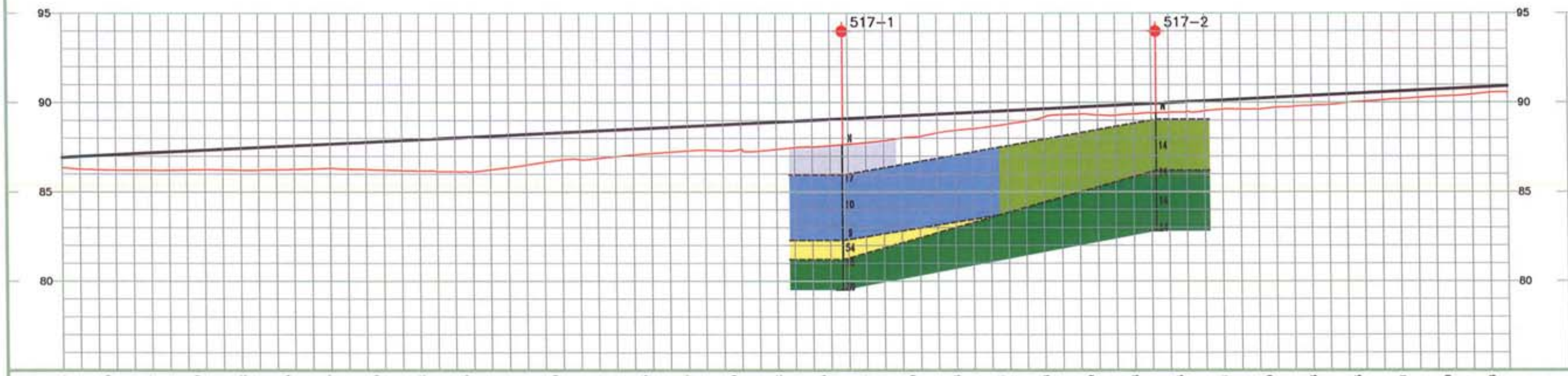
LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)

- EXISTING BOREHOLE LOCATION

- FILL
- CLAY
- SILT
- SAND
- TILL
- SHALE

DRAFT



CONSTRUCTION ℄ CHAINAGE	PROPOSED TOP OF RAIL PROFILE	EXISTING GROUND ELEVATION
	[illegible]	[illegible]
	87.059	86.241
7+500	87.187	86.219
	87.309	86.250
	87.432	86.228
	87.555	86.256
7+600	87.677	86.296
	87.800	86.246
	87.922	86.185
	88.045	86.145
7+700	88.167	86.372
	88.290	86.740
	88.412	86.885
	88.535	87.121
7+800	88.657	87.301
	88.780	87.302
	88.902	87.384
	89.025	87.552
7+900	89.147	87.763
	89.270	88.078
	89.393	88.444
	89.515	88.738
8+000	89.638	89.175
	89.760	89.318
	89.883	89.368
	90.005	89.463
8+100	90.128	89.622
	90.250	89.667
	90.373	89.833
	90.495	90.035
8+200	90.618	90.204
	90.740	90.360
	90.863	90.557

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials DATE:

REFERENCE MATERIAL:
Surveyed By :
Sewer Plans :
Water Plans :
Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report –

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 1.25m 2.5m 5m
VERTICAL 1:250

Project Manager (Design)
NAME
Manager of Design
NAME

SNC·LAVALIN
steer davies gleave
DIALOG
THURBER ENGINEERING LTD.

DRAWN . . . . .
CHECKED . . . . .
APPROVED . . . . .

Hamilton Public Works
RAPIDTransit
METROLINX

HAMILTON LRT 'B' LINE
BOREHOLE PLAN AND STRATIGRAPHIC PROFILE

SHEET 10 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

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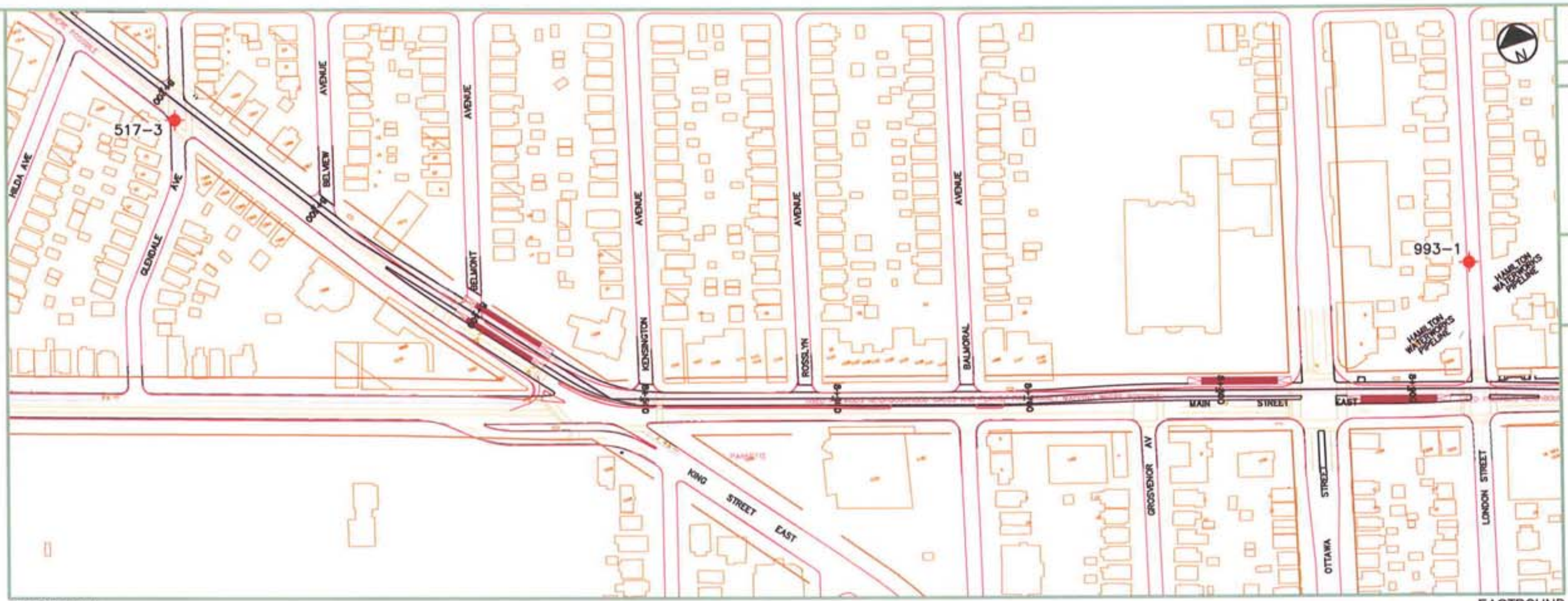


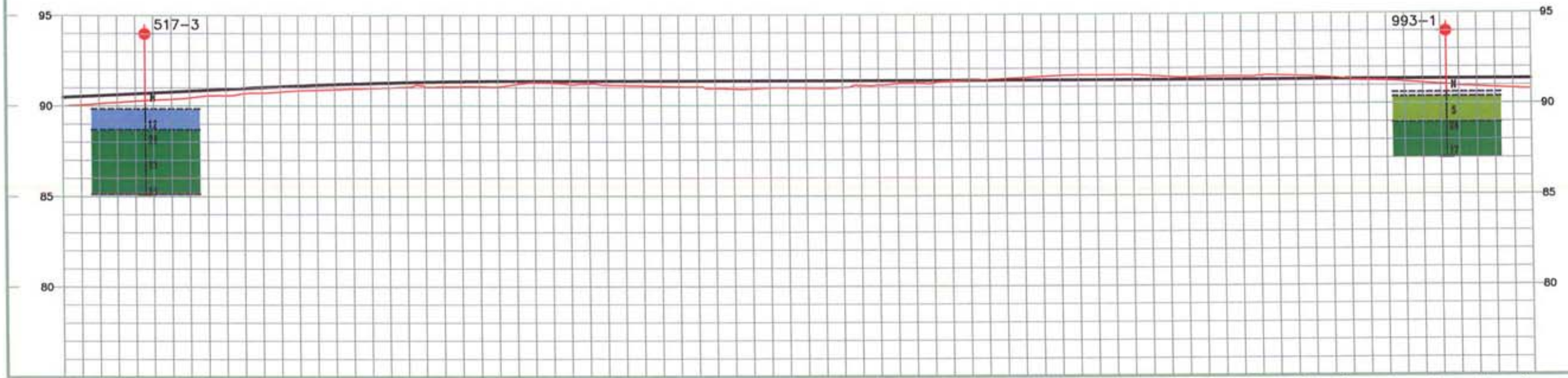
WESTBOUND ← → EASTBOUND

LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)
- ● EXISTING BOREHOLE LOCATION

- ▭ FILL
- 🟦 CLAY
- 🟩 SILT
- 🟨 SAND
- 🟩 TILL
- ▭ SHALE

DRAFT



PROPOSED TOP OF RAIL PROFILE	90.495	90.618	90.740	90.863	90.985	91.096	91.186	91.256	91.306	91.335	91.343	91.343	91.343	91.343	91.343	91.343	91.343
EXISTING GROUND ELEVATION	90.035	90.204	90.360	90.557	90.711	90.842	90.921	90.988	91.031	91.066	91.234	91.175	91.139	91.074	90.947	90.916	90.964
CONSTRUCTION ℄ CHAINAGE		8+200				8+300				8+400				8+500			

PROPOSED TOP OF RAIL PROFILE	91.343	91.343	91.343	91.343	91.343	91.343	91.343	91.343	91.343	91.343	91.343	91.343	91.343	91.343	91.343	91.343
EXISTING GROUND ELEVATION	90.982	91.149	91.217	91.371	91.505	91.620	91.625	91.557	91.529	91.531	91.563	91.397	91.260	91.100	90.922	90.797
CONSTRUCTION ℄ CHAINAGE	8+600				8+700				8+800				8+900			

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials | DATE:

REFERENCE MATERIAL:
Surveyed By :
Sewer Plans :
Water Plans :
Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report --

SCALES
0 12.5m 25m 50m HORIZONTAL 1:2500
0 1.25m 2.5m 5m VERTICAL 1:250

Project Manager (Design)
NAME
Manager of Design
NAME

SNC·LAVALIN steer davies gleave DIALOG THURBER ENGINEERING LTD. GEOTECHNICAL • ENVIRONMENTAL • MATERIALS

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CHECKED . . . . .
APPROVED . . . . .

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HAMILTON LRT 'B' LINE
BOREHOLE PLAN AND
STRATIGRAPHIC PROFILE
SHEET 11 OF 17

FILE No. | CONTRACT No. PW 00-00 (-) | SHEET No.

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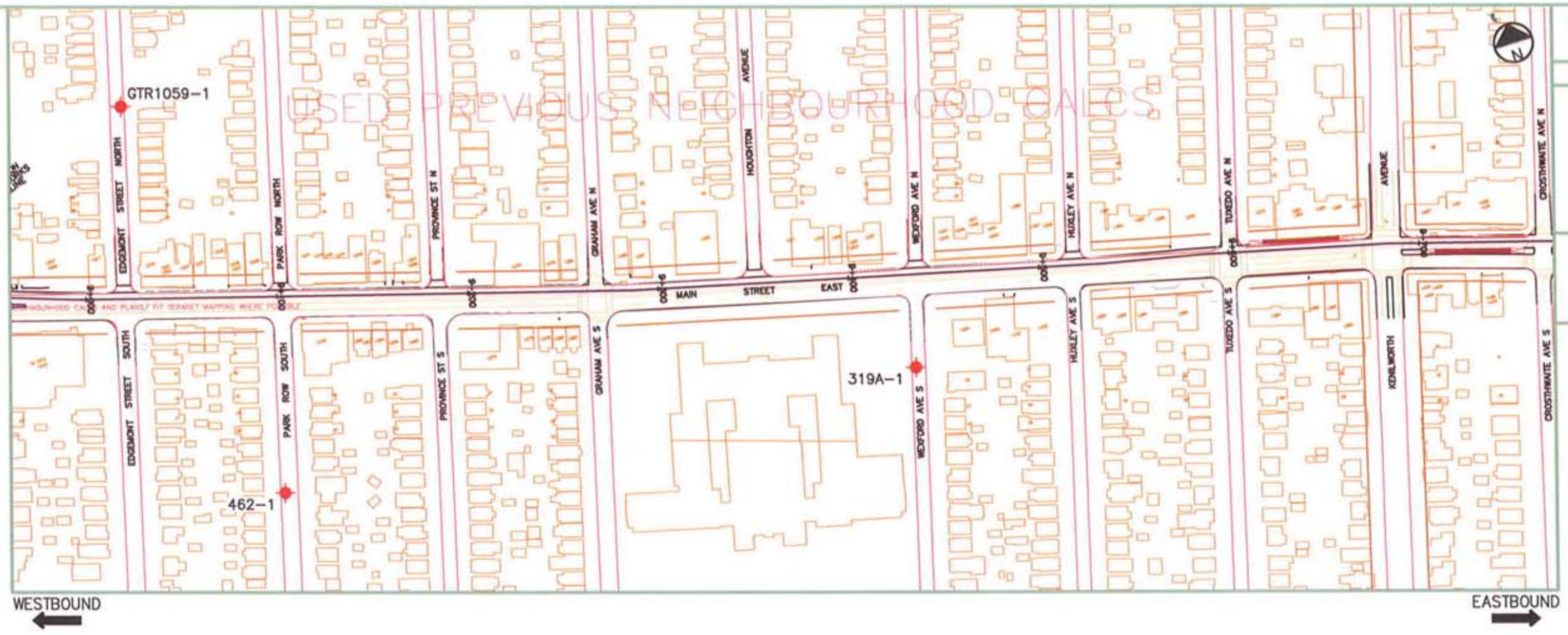


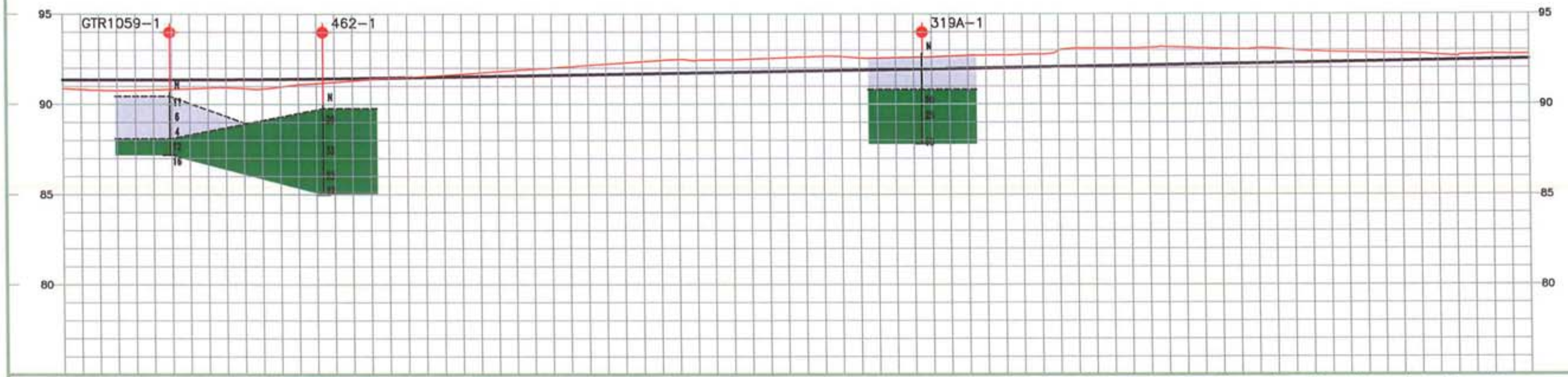
LEGEND

NEW CONSTRUCTION
EXISTING
PROPERTY LINE (ROAD ALLOWANCE)

● EXISTING BOREHOLE LOCATION

- ▨ FILL
- 🟦 CLAY
- 🟩 SILT
- 🟨 SAND
- 🟩 TILL
- ▨ SHALE

DRAFT



PROPOSED TOP OF RAIL PROFILE	91.343	91.343	91.348	91.356	91.372	91.396	91.426	91.463	91.504	91.545	91.586	91.628	91.669	91.710	91.751	91.792
EXISTING GROUND ELEVATION	90.797	90.783	90.852	90.934	90.909	91.156	91.337	91.484	91.641	91.820	91.972	92.185	92.338	92.486	92.479	92.514
CONSTRUCTION ℄ CHAINAGE		9+000				9+100				9+200				9+300		

PROPOSED TOP OF RAIL PROFILE	91.833	91.874	91.915	91.956	91.997	92.039	92.080	92.121	92.162	92.203	92.244	92.285	92.326	92.367	92.408	92.449
EXISTING GROUND ELEVATION	92.634	92.563	92.600	92.658	92.725	92.773	93.100	93.098	93.155	93.071	93.102	92.921	92.857	92.805	92.693	92.775
CONSTRUCTION ℄ CHAINAGE		9+400				9+500				9+600				9+700		

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials DATE:
REFERENCE MATERIAL:
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Sewer Plans :
Water Plans :
Survey Plan :
Geodetic Bench Mark Index Elevation=
Borehole Report –

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 1.25m 2.5m 5m
VERTICAL 1:250

Project Manager (Design)
NAME
Manager of Design
NAME

SNC·LAVALIN
steer davies gleave
DIALOG
THURBER ENGINEERING LTD.

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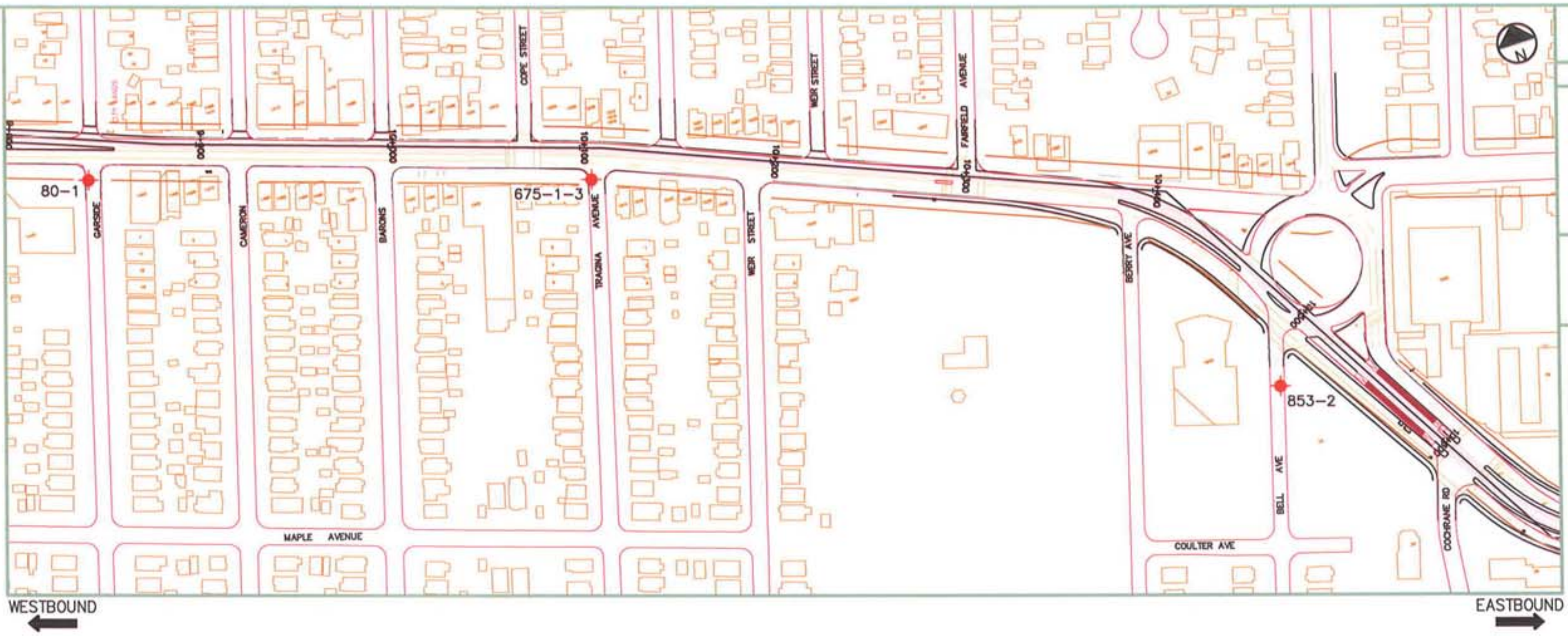
APPROVED

Hamilton Public Works
RAPIDTransit
METROLINX

HAMILTON LRT 'B' LINE
BOREHOLE PLAN AND STRATIGRAPHIC PROFILE
SHEET 12 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

DIMENSIONS SHOWN ON THIS PLAN ARE IN METRES UNLESS OTHERWISE NOTED

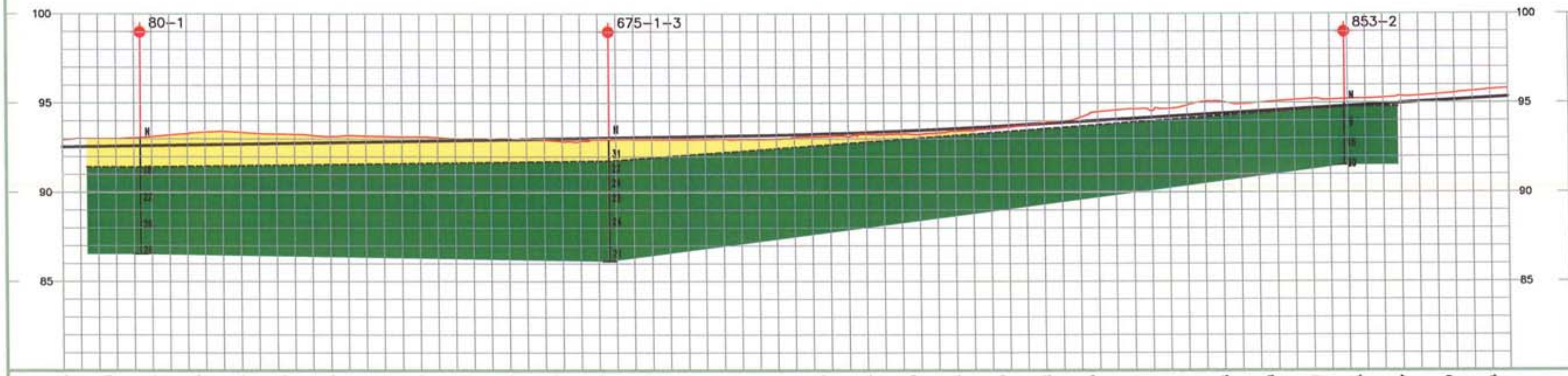


LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)
- EXISTING BOREHOLE LOCATION

- FILL
- CLAY
- SILT
- SAND
- TILL
- SHALE

DRAFT



CONSTRUCTION ℄ CHAINAGE	EXISTING GROUND ELEVATION	PROPOSED TOP OF RAIL PROFILE
[illegible]	[illegible]	[illegible]
	93.008	92.573
	93.130	92.614
	93.360	92.655
9+900	93.370	92.696
	93.265	92.737
	93.140	92.778
	93.151	92.819
10+000	93.121	92.860
	93.011	92.901
	93.012	92.943
	92.896	92.984
10+100	92.955	93.025
	92.965	93.066
	92.954	93.107
	92.947	93.148
10+200	93.019	93.196
	93.123	93.260
	93.241	93.342
	93.250	93.440
10+300	93.438	93.556
	93.597	93.689
	93.881	93.832
	94.356	93.975
10+400	94.660	94.118
	94.728	94.261
	95.059	94.405
	95.050	94.548
10+500	95.217	94.691
	95.227	94.834
	95.379	94.977
	95.507	95.120
10+600	95.740	95.264

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials
DATE:
REFERENCE MATERIAL:
Surveyed By :
Sewer Plans :
Water Plans :
Survey Plan :
Geodetic Bench Mark Index Elevation=
Borehole Report –

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 1.25m 2.5m 5m
VERTICAL 1:250

Project Manager (Design)
NAME
Manager of Design
NAME

SNC·LAVALIN
steer davies gleave
DIALOG
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CHECKED . . . . .
APPROVED . . . . .

Hamilton Public Works
RAPIDTransit
METROLINX

HAMILTON LRT 'B' LINE
BOREHOLE PLAN AND STRATIGRAPHIC PROFILE
SHEET 13 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

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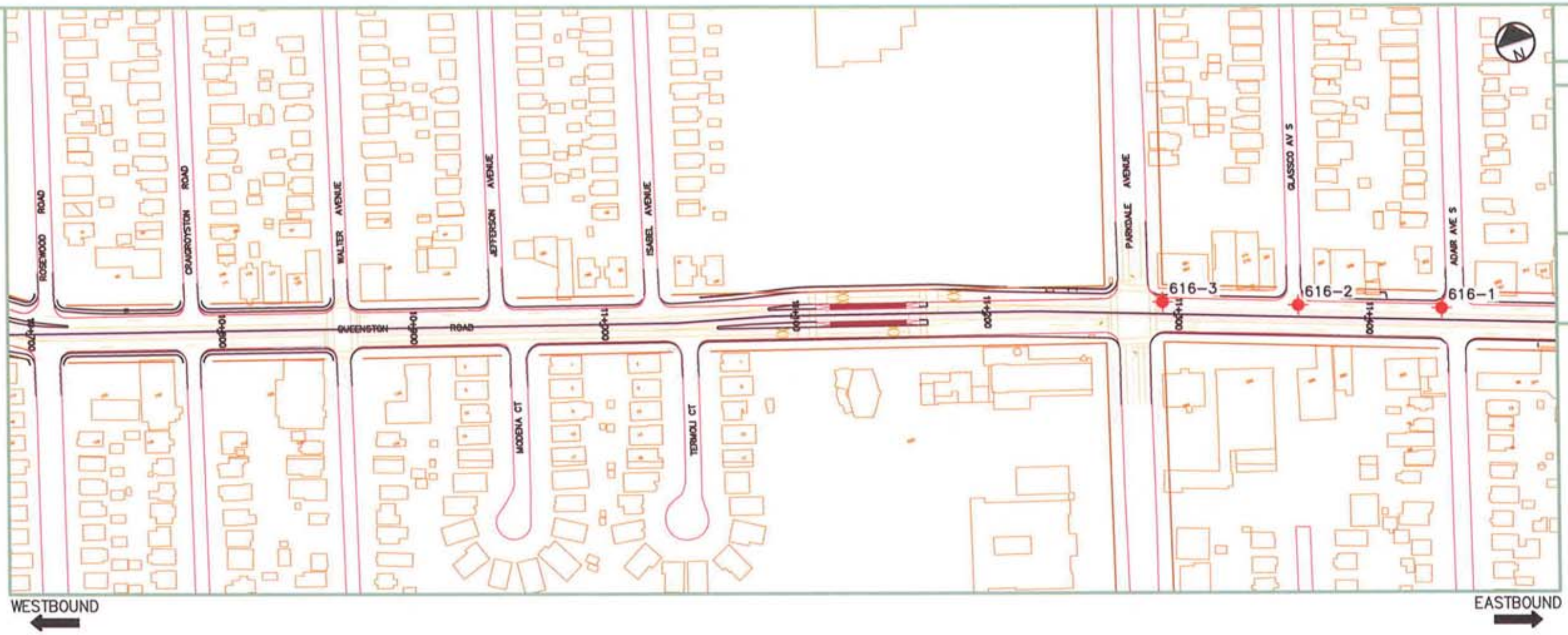

LEGEND
- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)

● EXISTING BOREHOLE LOCATION

- ▨ FILL
- ▨ CLAY
- ▨ SILT
- ▨ SAND
- ▨ TILL
- ▨ SHALE

DRAFT

PROPOSED TOP OF RAIL PROFILE	95.836	95.979	96.123	96.266	96.409	96.552	96.695	96.839	96.982	97.125	97.268	97.411	97.554	97.698	97.841	97.984
EXISTING GROUND ELEVATION	95.889	95.907	95.973	96.150	96.304	96.357	96.335	96.297	96.412	96.546	96.659	96.643	96.678	97.019	97.241	97.620
CONSTRUCTION ℄ CHAINAGE	10+700				10+800				10+900				11+000			

PROPOSED TOP OF RAIL PROFILE	98.127	98.270	98.413	98.557	98.700	98.843	98.986	99.128	99.224	99.251	99.211	99.103	98.927	98.684	98.420	98.155
EXISTING GROUND ELEVATION	97.945	98.199	98.402	98.565	98.757	98.848	98.942	99.041	99.163	99.092	98.953	98.845	98.810	98.744	98.626	98.541
CONSTRUCTION ℄ CHAINAGE	11+100				11+200				11+300				11+400			

No.	REVISIONS	INITIAL	DATE

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DATE:
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Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report —

SCALES
0 12.5m 25m 50m
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0 1.25m 2.5m 5m
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Manager of Design
NAME

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Hamilton Public Works
RAPIDTransit moving HAMILTON forward
METROLINX

HAMILTON LRT 'B' LINE
BOREHOLE PLAN AND STRATIGRAPHIC PROFILE
SHEET 14 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

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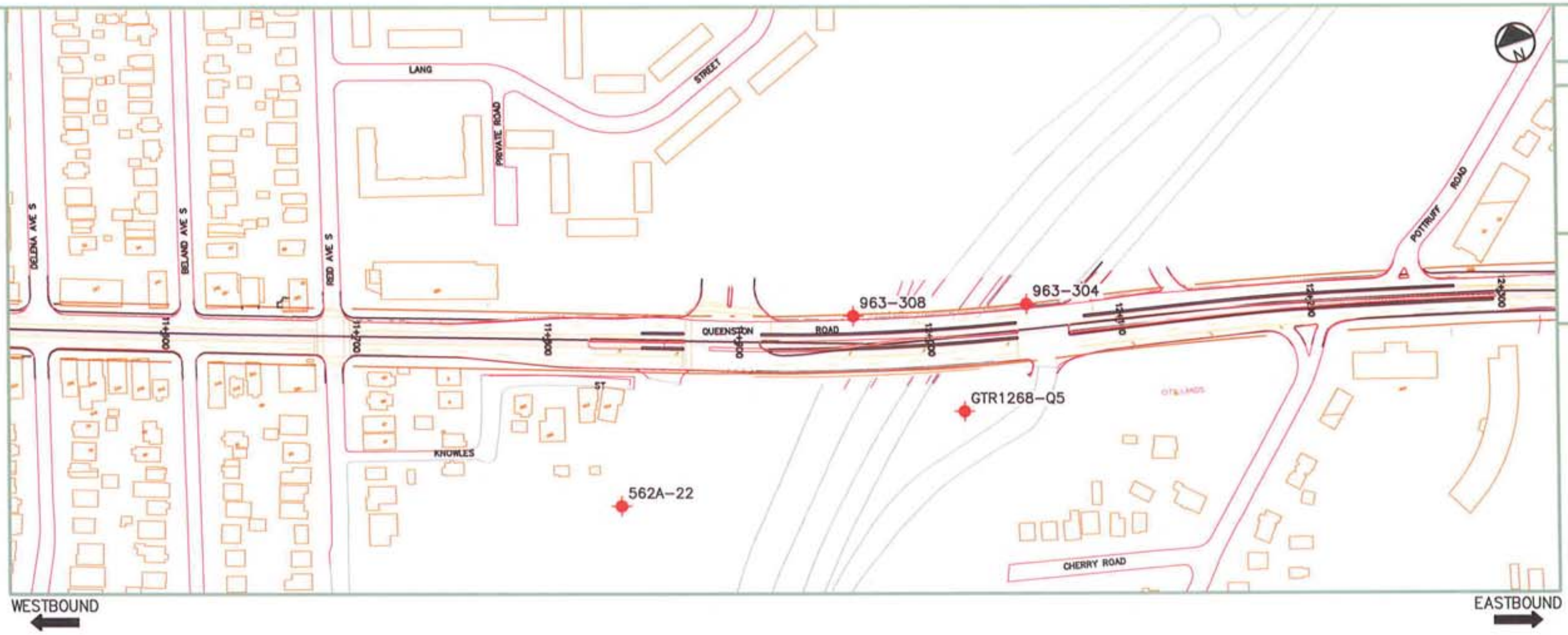
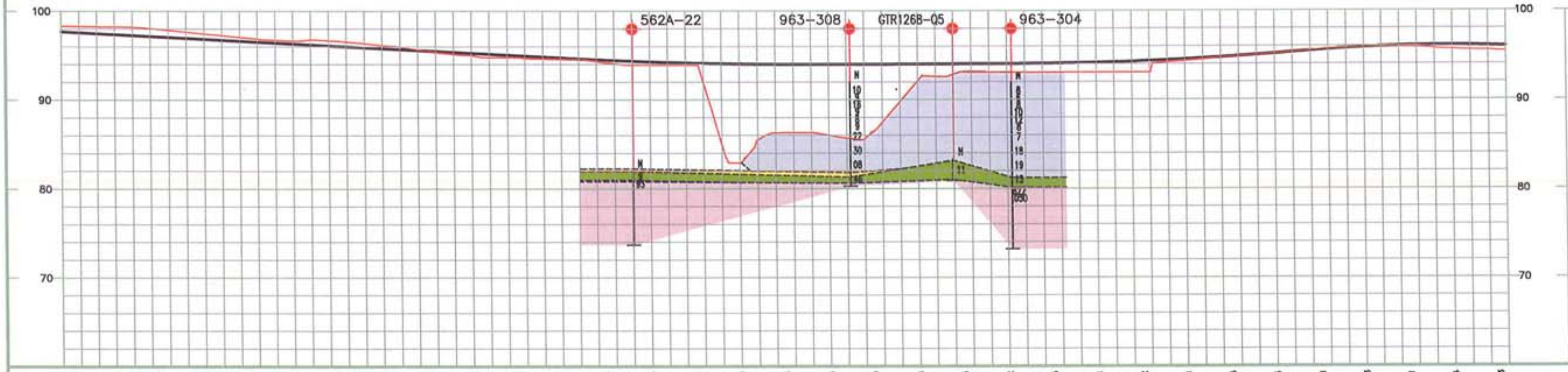


LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)
- ● EXISTING BOREHOLE LOCATION
- ▨ FILL
- ▨ CLAY
- ▨ SILT
- ▨ SAND
- ▨ TILL
- ▨ SHALE

DRAFT



CONSTRUCTION ℄ CHAINAGE	EXISTING GROUND ELEVATION	PROPOSED TOP OF RAIL PROFILE
	98.347	97.626
	98.263	97.362
	97.980	97.097
11+600	97.481	96.833
	97.014	96.568
	96.672	96.304
	96.651	96.040
11+700	96.176	95.775
	95.507	95.511
	95.040	95.246
	94.784	94.982
11+800	94.573	94.717
	94.195	94.473
	93.926	94.275
	93.905	94.124
11+900	82.935	94.020
	86.306	93.963
	88.040	93.953
	88.445	93.970
12+000	92.689	93.988
	93.133	94.005
	93.083	94.022
	93.082	94.055
12+100	93.055	94.148
	93.071	94.302
	94.355	94.518
	94.759	94.795
12+200	95.099	95.135
	95.600	95.518
	95.824	95.823
	95.890	96.001
12+300	95.838	96.054
	95.491	95.983

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials DATE:

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Water Plans :
Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report –

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 2.5m 5m 10m
VERTICAL 1:500

Project Manager (Design)
NAME
Manager of Design
NAME

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DIALOG
THURBER ENGINEERING LTD.

DRAWN
CHECKED
APPROVED

Hamilton Public Works
RAPIDTransit
METROLINX

HAMILTON LRT 'B' LINE BOREHOLE PLAN AND STRATIGRAPHIC PROFILE

SHEET 15 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

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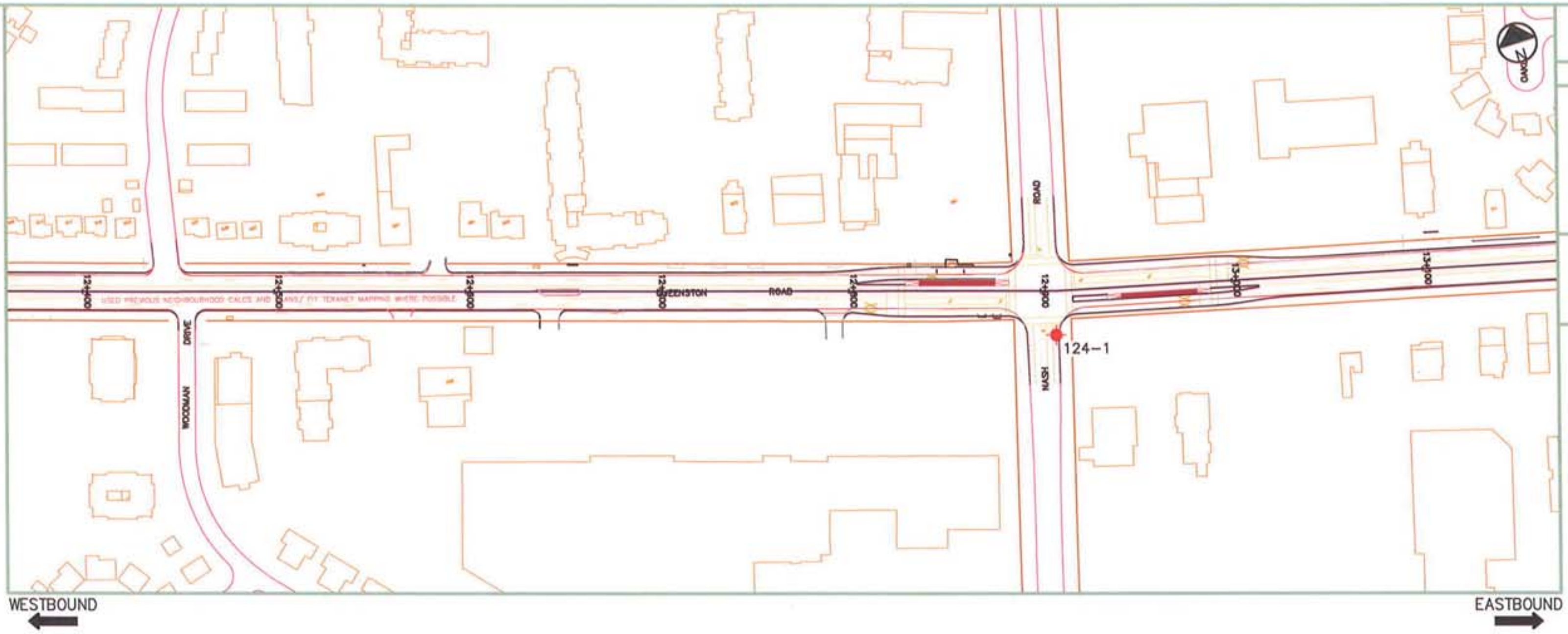
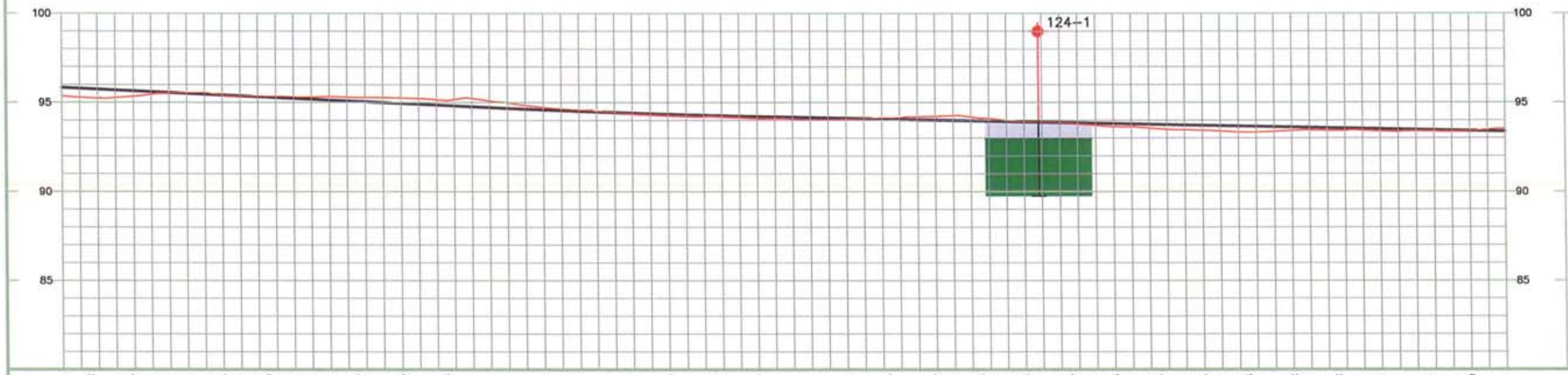


LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)
- ● EXISTING BOREHOLE LOCATION
- ▭ FILL
- 🟦 CLAY
- 🟩 SILT
- 🟨 SAND
- 🟩 TILL
- ▭ SHALE

DRAFT



CONSTRUCTION ℄ CHAINAGE	EXISTING GROUND ELEVATION	PROPOSED TOP OF RAIL PROFILE
	95.278	95.752
12+400	95.354	95.637
	95.537	95.521
	95.400	95.406
	95.347	95.290
12+500	95.313	95.174
	95.284	95.059
	95.263	94.943
	95.127	94.828
12+600	95.084	94.712
	94.779	94.601
	94.579	94.501
	94.384	94.412
12+700	94.256	94.333
	94.224	94.266
	94.100	94.209
	94.048	94.158
12+800	94.042	94.108
	94.121	94.057
	94.234	94.007
	94.125	93.956
12+900	93.905	93.906
	93.825	93.855
	93.649	93.805
	93.529	93.754
13+000	93.430	93.704
	93.330	93.653
	93.433	93.602
	93.426	93.552
13+100	93.391	93.501
	93.389	93.451
	93.389	93.400

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials
DATE:

REFERENCE MATERIAL:
Surveyed By :
Sewer Plans :
Water Plans :
Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report –

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 1.25m 2.5m 5m
VERTICAL 1:250

Project Manager (Design)
NAME
Manager of Design
NAME

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Hamilton
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moving HAMILTON forward
METROLINX

HAMILTON LRT 'B' LINE
BOREHOLE PLAN AND STRATIGRAPHIC PROFILE

SHEET 16 OF 17

FILE No.	CONTRACT No. PW 00-00 (-)	SHEET No.

DIMENSIONS SHOWN ON THIS PLAN ARE IN METRES UNLESS OTHERWISE NOTED

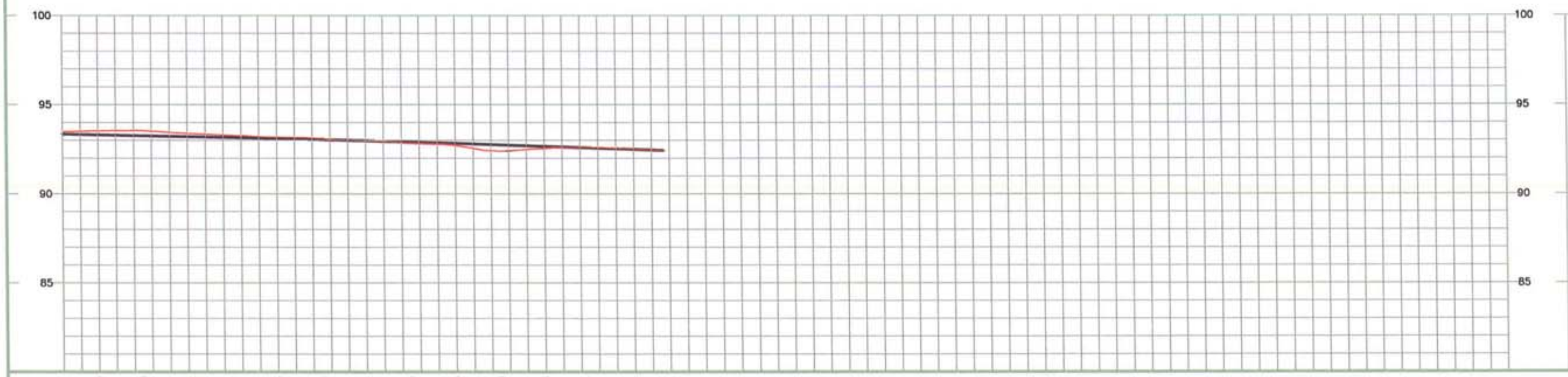
LEGEND

- NEW CONSTRUCTION
- EXISTING
- PROPERTY LINE (ROAD ALLOWANCE)

● EXISTING BOREHOLE LOCATION

▨	FILL
🟦	CLAY
🟩	SILT
🟨	SAND
🟩	TILL
▨	SHALE

DRAFT



PROPOSED TOP OF RAIL PROFILE	93.299	93.249	93.198	93.148	93.095	93.038	92.971	92.900	92.823	92.740	92.653	92.567	92.481	
EXISTING GROUND ELEVATION	93.531	93.539	93.399	93.289		93.116	92.979	92.832	92.715	92.403	92.544	92.597	92.503	
CONSTRUCTION ℄ CHAINAGE	13+200				13+300				13+400				13+500	13+600

No.	REVISIONS	INITIAL	DATE

DRAWN BY: Initials DATE:

REFERENCE MATERIAL:
Surveyed By :
Sewer Plans :
Water Plans :
Survey Plan :

Geodetic Bench Mark Index Elevation=
Borehole Report —

SCALES
0 12.5m 25m 50m
HORIZONTAL 1:2500
0 1.25m 2.5m 5m
VERTICAL 1:250

Project Manager (Design)
NAME
Manager of Design
NAME

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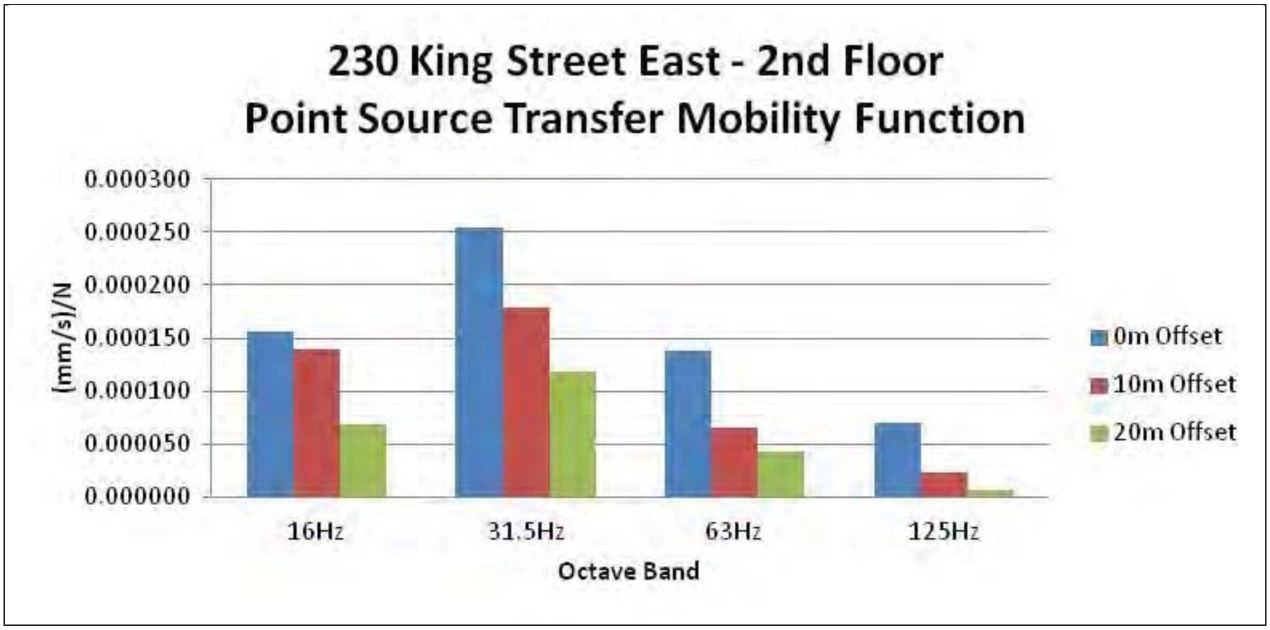
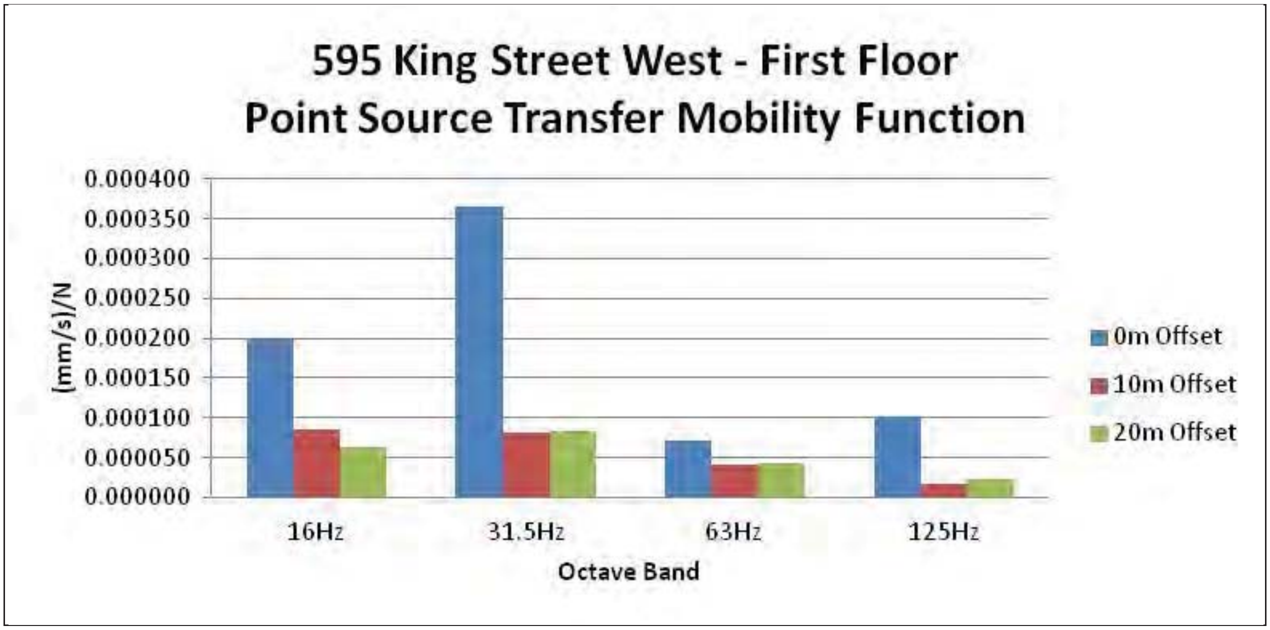
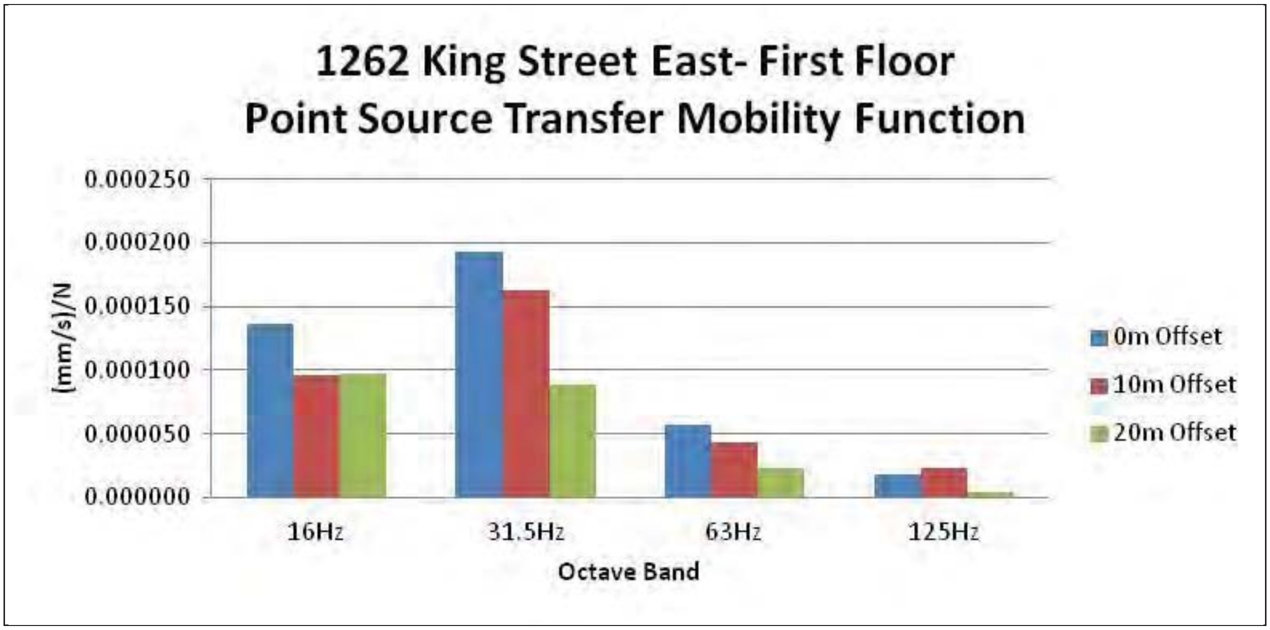
HAMILTON LRT 'B' LINE
BOREHOLE PLAN AND
STRATIGRAPHIC PROFILE
SHEET 17 OF 17

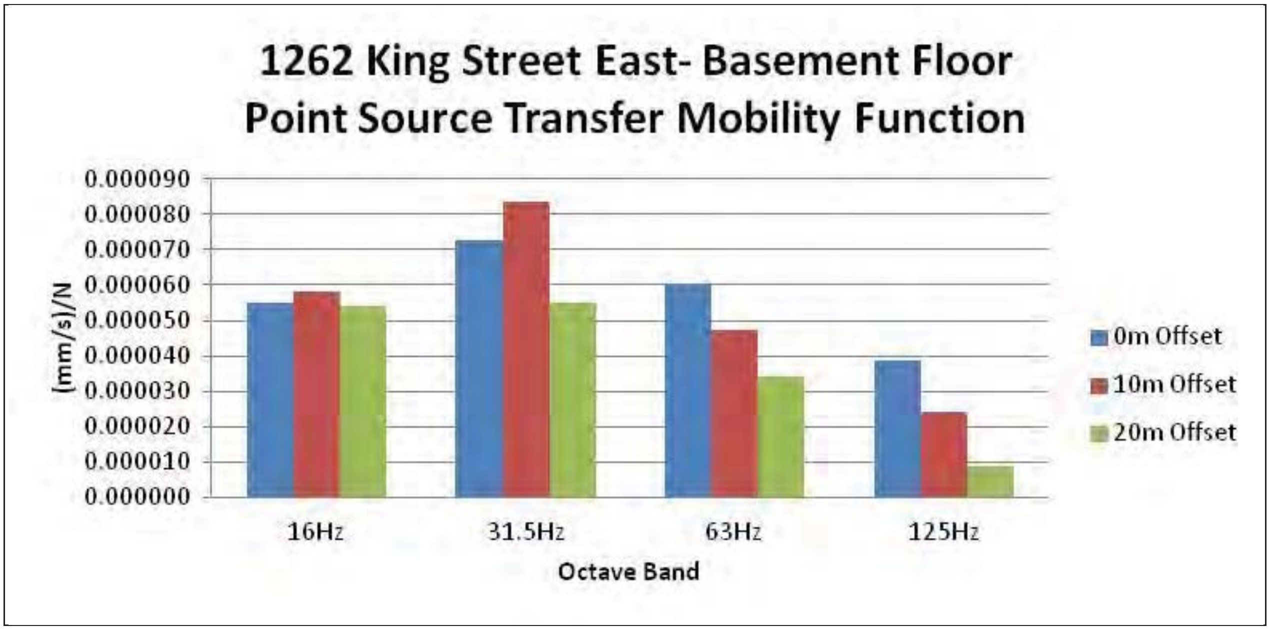
APPENDIX F: CALCULATIONS

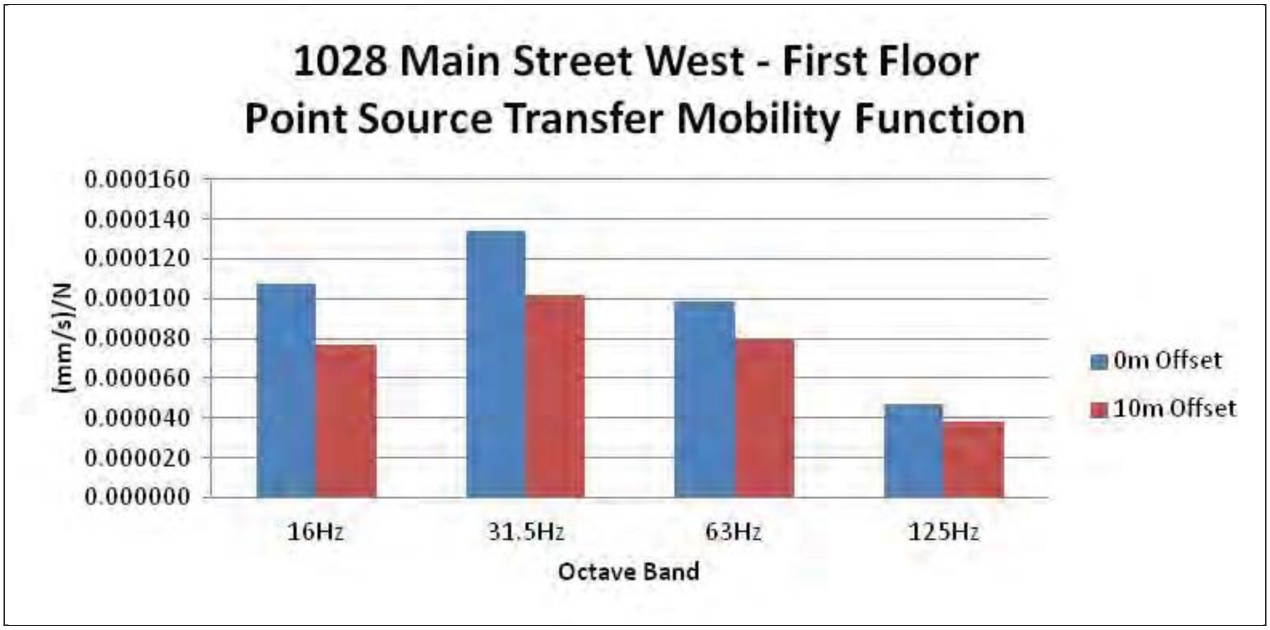
POINT SOURCE TRANSFER MOBILITY FUNCTIONS AND USED FORCE DENSITY CURVES

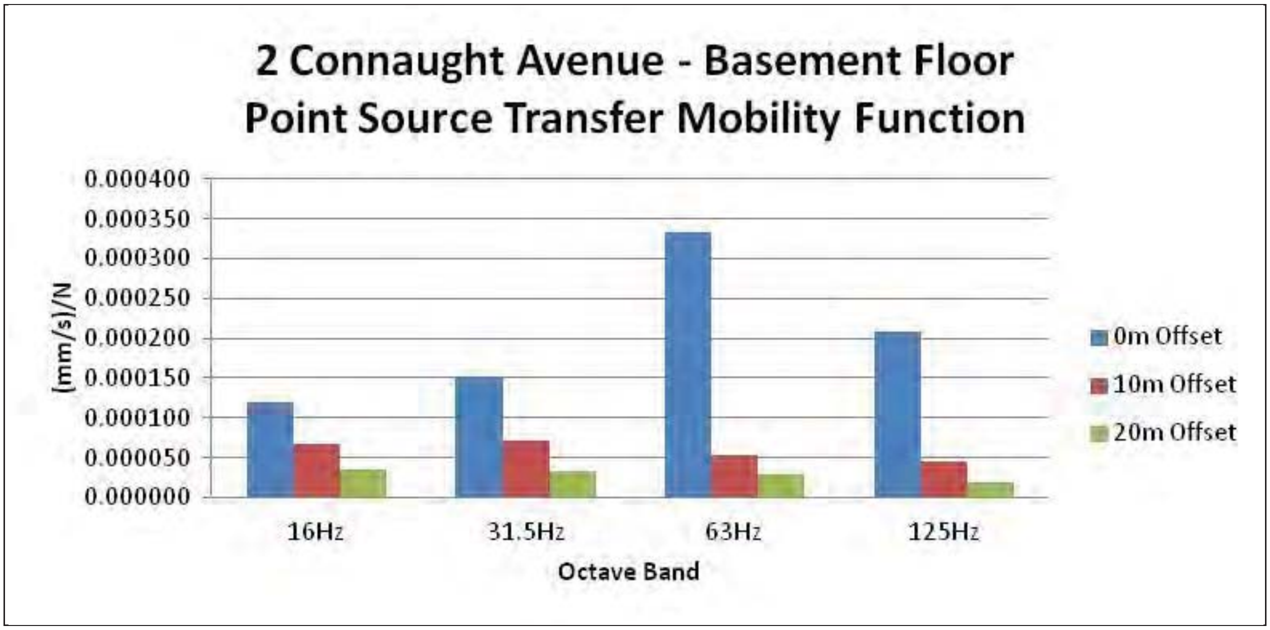


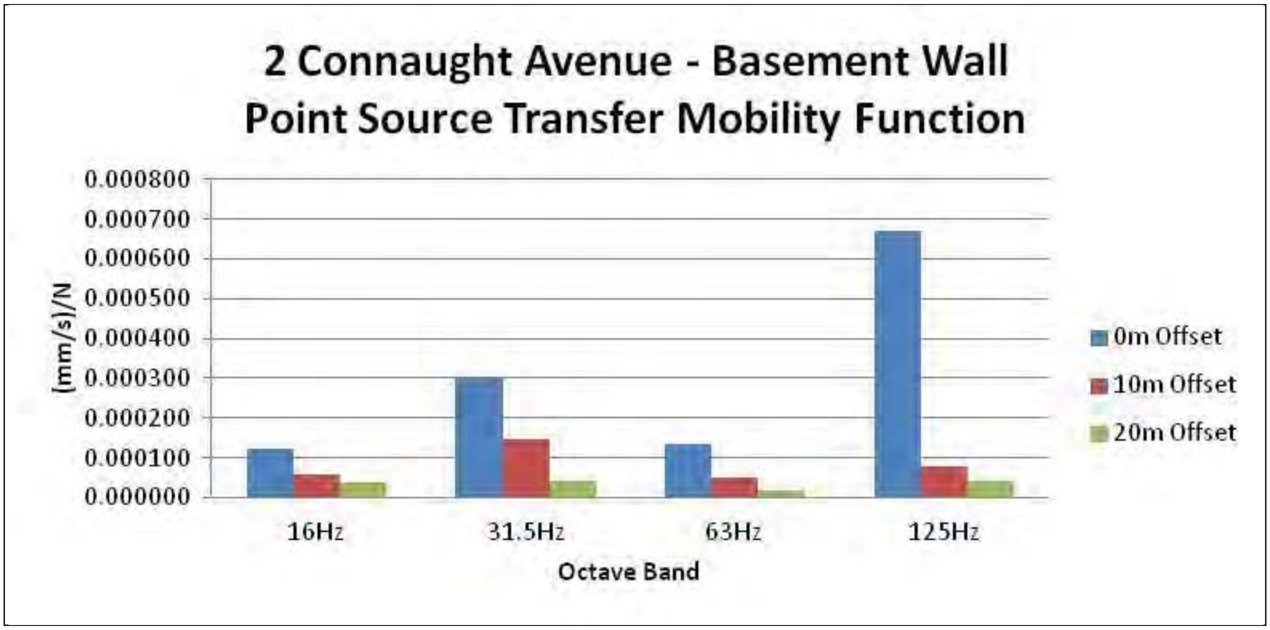


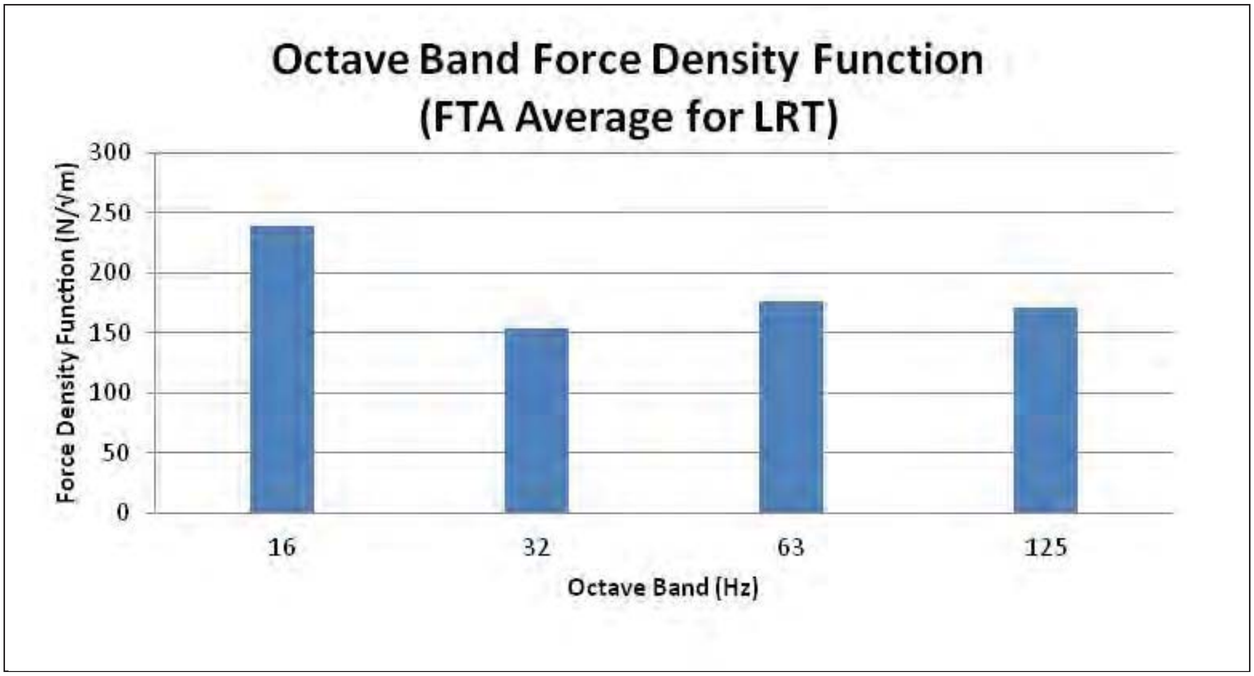

1262 King Street East- First Floor
Point Source Transfer Mobility Function
0.000250
0.000200
0.000150
0.000100
0.000050
0.000000
[mm/s]/N
16Hz
31.5Hz
63Hz
125Hz
Octave Band
0m Offset
10m Offset
20m Offset

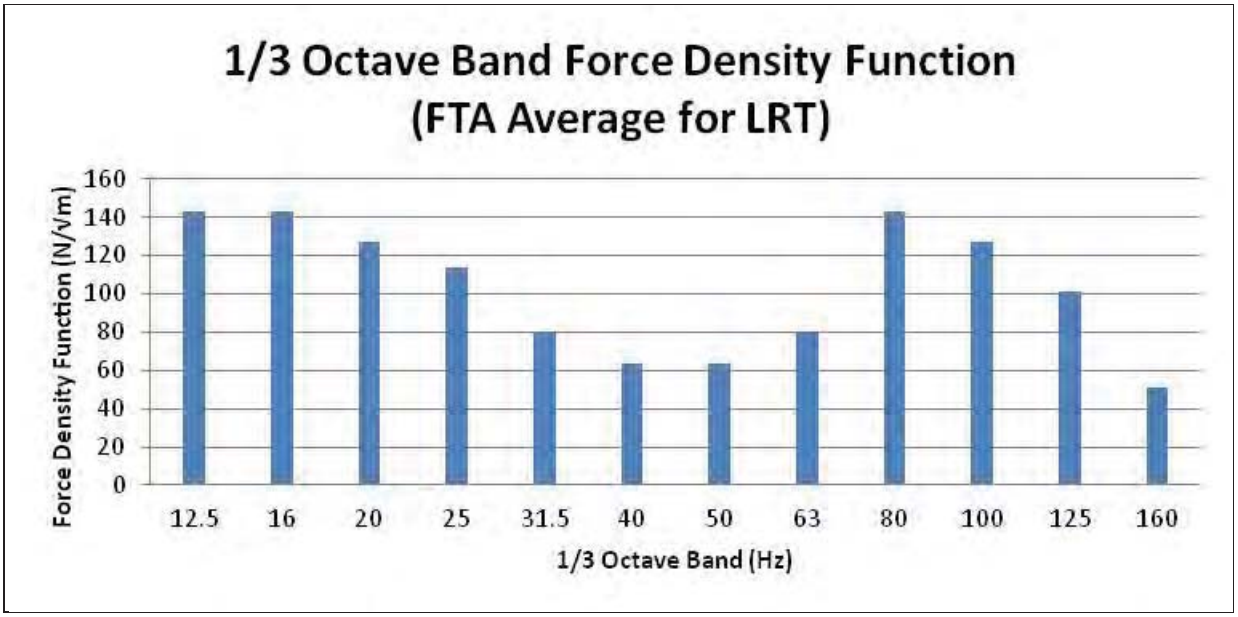

1262 King Street East- Basement Floor
Point Source Transfer Mobility Function
0.000090
0.000080
0.000070
0.000060
0.000050
0.000040
0.000030
0.000020
0.000010
0.000000
[mm/s]/N
16Hz
31.5Hz
63Hz
125Hz
Octave Band
0m Offset
10m Offset
20m Offset


1028 Main Street West - First Floor
Point Source Transfer Mobility Function
0.000160
0.000140
0.000120
0.000100
0.000080
0.000060
0.000040
0.000020
0.000000
(mm/s)/N
16Hz
31.5Hz
63Hz
125Hz
Octave Band
0m Offset
10m Offset

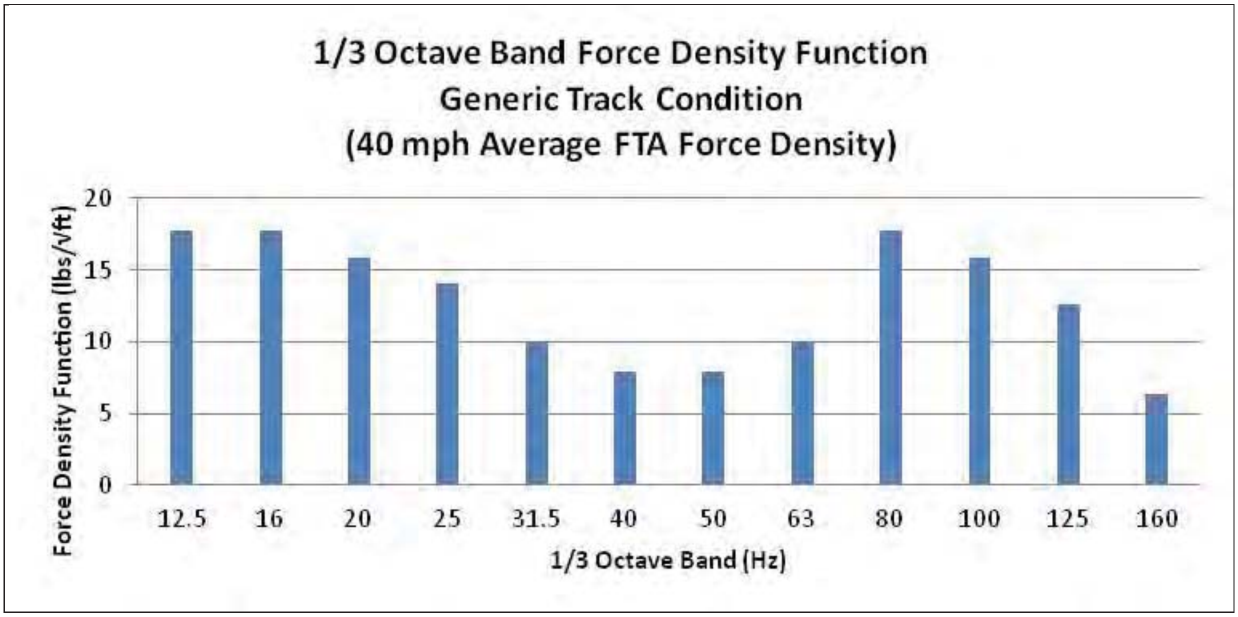

2 Connaught Avenue - Basement Floor
Point Source Transfer Mobility Function
0.000400
0.000350
0.000300
0.000250
0.000200
0.000150
0.000100
0.000050
0.000000
(mm/s)/N
16Hz
31.5Hz
63Hz
125Hz
Octave Band
0m Offset
10m Offset
20m Offset

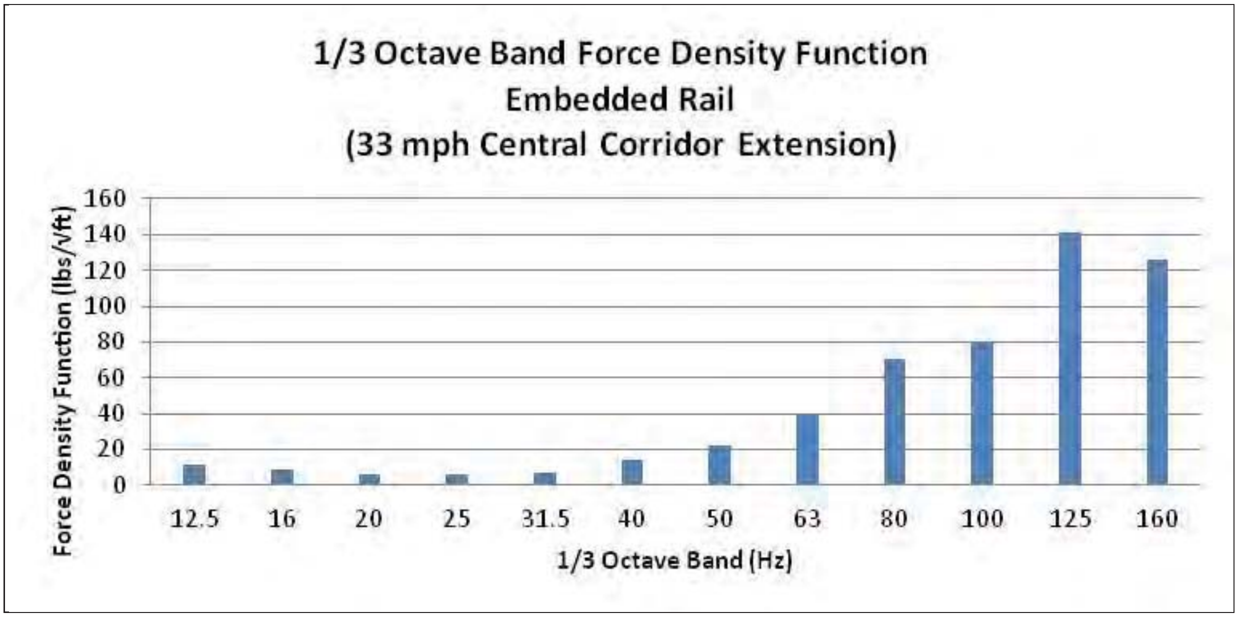

2 Connaught Avenue - Basement Wall
Point Source Transfer Mobility Function
(mm/s)/N
0.000800
0.000700
0.000600
0.000500
0.000400
0.000300
0.000200
0.000100
0.000000
16Hz
31.5Hz
63Hz
125Hz
Octave Band
0m Offset
10m Offset
20m Offset

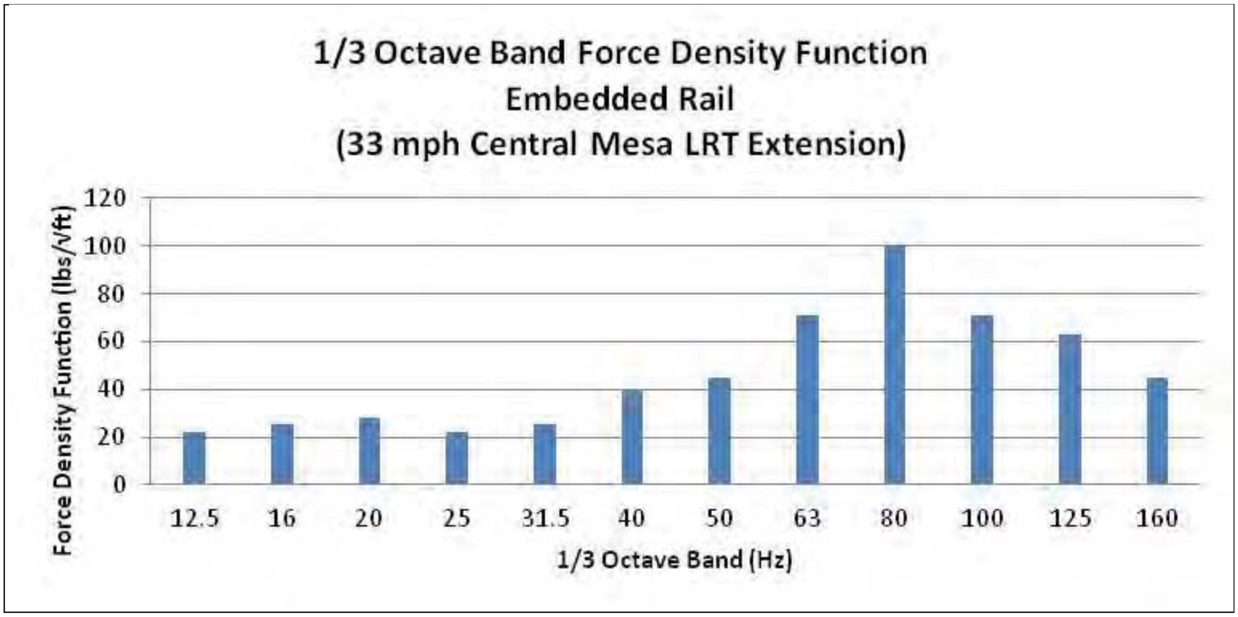

Octave Band Force Density Function
(FTA Average for LRT)
Force Density Function (N/√m)
300
250
200
150
100
50
0
16
32
63
125
Octave Band (Hz)

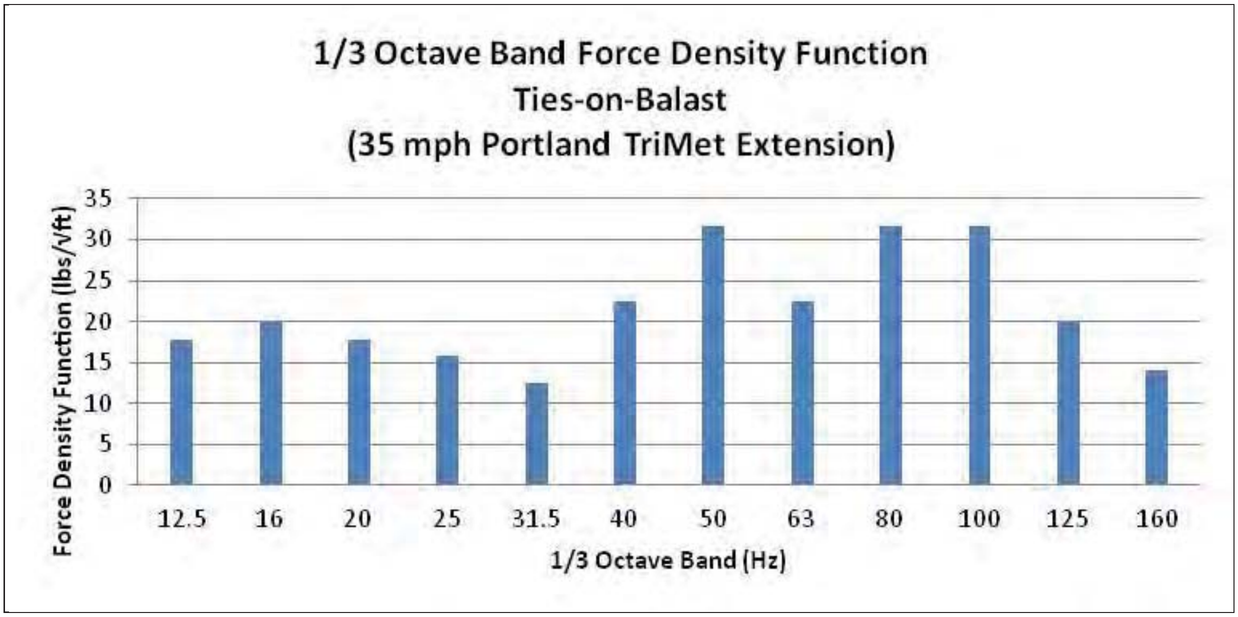


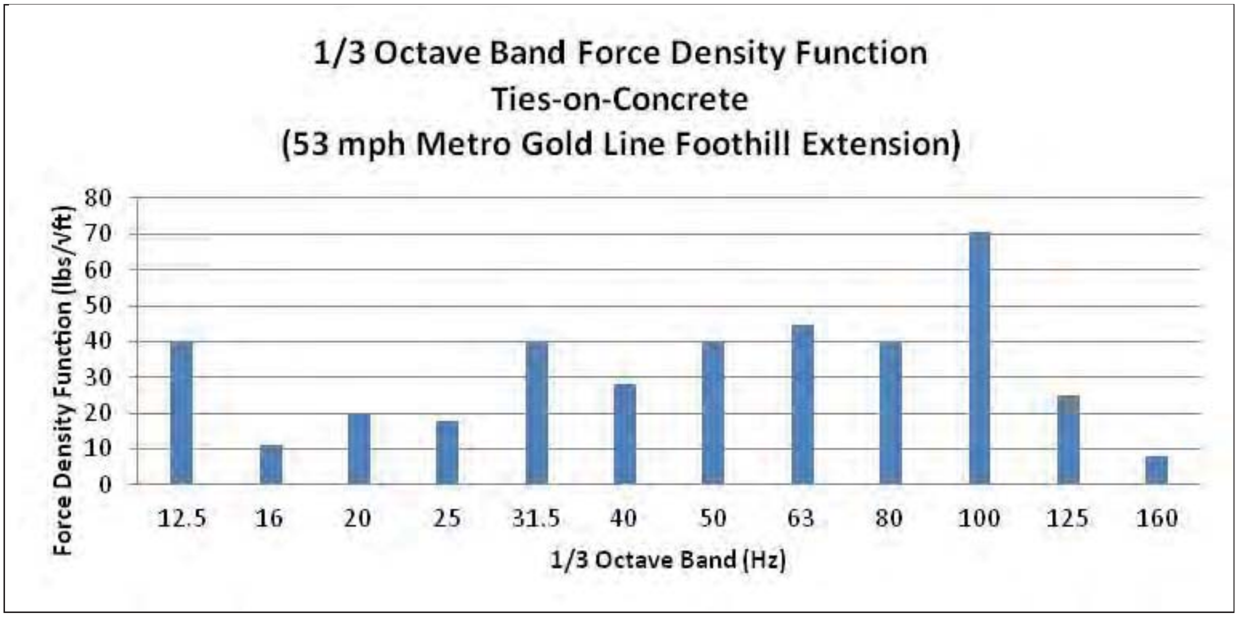
FORCE DENSITY CURVES FROM OTHER SITES IN THE UNITED STATES




1/3 Octave Band Force Density Function
Embedded Rail
(33 mph Central Corridor Extension)
Force Density Function (lbs/√ft)
160
140
120
100
80
60
40
20
0
12.5
16
20
25
31.5
40
50
63
80
100
125
160
1/3 Octave Band (Hz)


1/3 Octave Band Force Density Function
Embedded Rail
(33 mph Central Mesa LRT Extension)
Force Density Function (lbs/√ft)
120
100
80
60
40
20
0
12.5
16
20
25
31.5
40
50
63
80
100
125
160
1/3 Octave Band (Hz)


1/3 Octave Band Force Density Function
Ties-on-Balast
(35 mph Portland TriMet Extension)
Force Density Function (lbs/√ft)
35
30
25
20
15
10
5
0
12.5
16
20
25
31.5
40
50
63
80
100
125
160
1/3 Octave Band (Hz)


1/3 Octave Band Force Density Function
Ties-on-Concrete
(53 mph Metro Gold Line Foothill Extension)
Force Density Function (lbs/√ft)
80
70
60
50
40
30
20
10
0
12.5
16
20
25
31.5
40
50
63
80
100
125
160
1/3 Octave Band (Hz)

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 Accelormeter
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.