LOW FREQUENCY VIBRATION FROM LIGHT RAIL VEHICLES

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ABSTRACT

The question of how much low-frequency vibration is generated by operations of typical light rail vehicles is an important issue when a proposed light rail system will be in close proximity to vibration sensitive research facilities. In this paper we define low-frequency vibration to be vibration radiated at frequencies below 25 Hz because rail transit vibration often is lower than the vibration from buses and trucks at frequencies below 25 Hz. This paper is largely based on vibration measurements performed in support of the vibration monitoring system that was installed in the University-Link extension of the Seattle Link LRT system. The monitoring system is designed to protect vibration sensitive research facilities that are relatively close to the subway. The testing has shown that there is substantial low-frequency vibration at the vibration monitors from traffic on nearby roadways and that this vibration is often greater than the vibration generated by train operations. In other words, at low frequencies, the vibration from trains passing about 10 ft from the monitors is often less than the vibration created by traffic that is at least 200 ft from the monitors. This is a non-intuitive result, and the primary purpose of this paper is to examine possible reasons for this result and what factors contribute to the low-frequency traffic vibration being greater than the low-frequency train vibration. The results of this analysis are applicable to other rail transit projects where low frequency vibration interfering with research equipment is a concern.
INTRODUCTION

This paper is basically a case history of a detailed exploration of low-frequency vibration from train operations in a subway, the University Link (U-Link) extension of the Sound Transit Link light rail system. Researchers at the University of Washington (UW) Seattle campus have been concerned that vibration from the light rail extension through the campus would cause problems with various vibration sensitive research facilities that are distributed throughout the campus. The departments concerned about the low frequency vibration from rail operations affecting their research equipment ranged from the Fisheries Center to the Forest Sciences Laboratory to various physics, engineering, and materials science laboratories.

Negotiations between UW and Sound Transit led to several accommodations by Sound Transit to minimize the potential for vibration and electromagnetic fields (EMF) to interfere with the research equipment. This paper focuses on vibration and does not cover the EMF issue. The negotiations led to a Master Implementation Agreement (MIA) signed by the CEO of Sound Transit and the President of the University. This agreement includes specific requirements for a vibration monitoring system located in the subway that provides real-time alerts whenever the vibration levels in nearby buildings may exceed the maximum allowed vibration levels. The MIA provides vibration limits in terms of 1/3 octave band velocity levels over the 2 to 100 Hz range for 24 buildings.

The MIA limits are based on measurements of ambient vibration that were performed prior to the start of construction of the U-Link extension. The test results presented in this report were performed as part of the effort to estimate the relationships between vibration at the monitoring system stations in the subway and the train vibration inside the 24 buildings identified in the MIA. The buildings covered by the MIA limits are labeled in red in Figure 1. The four buildings where vibration measurements were performed are the Center for Human Development and Disability (CHDD), the University of Washington Medical Center Cyclotron facility (UWMC), Winkenwerder Forest Sciences Laboratory, and Wilcox Hall that is used by a variety of engineering departments. As seen in Figure 1, the horizontal distances from the subway to these buildings ranged from approximately 600 ft to 1,000 ft. The subway is approximately 100 ft deep.

The vibration monitoring system was supplied by International Electronic Machines, Corp. Relevant to this paper are the nine monitoring stations in the subway segment near the UW campus. The monitors are at 150 ft intervals alternating between the northbound and southbound tunnels. Monitors 4-1 through 4-3 are in the bored tunnels, Monitors 5-1 through 5-3 are adjacent to the crossover structure south of the UW Station, and Monitors 5-4 through 5-6 are in the UW Station. Each of the nine monitors are programmed to collect data every time a train is within a set distance of the monitor and to report the maximum 8-second RMS vibration velocity level (Lmax) during the period that the train is within the set distance of the monitor. The data are collected at 1-second intervals and the 8-second RMS levels are calculated from the 1-second data. The 1/3 octave band Lmax spectra of are provided by the monitor software for each train event.

The system allows specifying adjustment factors that are used to estimate the building vibration levels from the Lmax levels for each train event. In this report the adjustment factors are referred to as Vibration Adjustment Estimates (VAEs). The monitoring system software adds the
The remainder of this paper outlines the measurement programs, discusses the results of the measurement programs, and presents a discussion of the theoretical considerations relative to when and at what amplitudes vibration in the 2 to 6 Hz range will occur.

Figure 1. University of Washington Campus Map.

Buildings identified by UW as sensitive buildings are labeled in red. Measurements were performed at CHDD, the UW Medical Center Cyclotron, Winkenwerder, and Wilcox. The distance to the subway is shown adjacent to each of the measurement buildings.

CHALLENGES TO ESTIMATING VAES

The program to develop valid estimates of the VAEs began in July 2015 and needed to be completed in time for the U-Link extension to open in March 2016. Before the system could open the VAE values had to be uploaded to the monitoring system software and tested to confirm that ambient vibration did not generate alarms and that the sum of the measured Lmax at the monitors and the VAEs did not underestimate the train vibration levels at the sensitive buildings. Some of the challenges to developing reasonable estimates for the VAEs were:
• As seen in Figure 1, the closest sensitive buildings were 600 ft to 1,000 ft from the subway. Ground vibration tends to attenuate relatively rapidly, which meant that relatively low vibration levels at the buildings could be expected.

• There are a number of structures in the paths between the subway and the buildings. The structures include an underground parking structure, and various buildings, utilities, and roadways.

• There was considerable interest in the results of the measurements and analysis. The stakeholders included the managers of the vibration sensitive facilities, the UW executives and department heads who wanted to maintain the University’s reputation as a world class research facility that could accommodate modern nanotechnology research, and Sound Transit that wanted to both avoid false alarms and avoid exceeding the MIA vibration limits. Another consideration is that this exercise was basically a dry run for the analysis that will be required for the Northgate Link that is currently under construction. The Northgate Link route will be considerably closer to a number of vibration sensitive laboratories and will include a low-frequency floating slab system to control the vibration levels.

• In many cases, the train vibration was lower than the ambient inside buildings. The ambient was due to equipment and activities within the buildings, traffic on nearby streets, and various unidentified sources. The low levels of train vibration were due to the distances of the buildings from the subway and the various vibration mitigation measures that were used (e.g. soft fasteners and low impact frogs at the crossover).

• Limited time to perform measurements and provide results.

A key issue is that UW and Sound Transit needed to mutually agree that the approach to and the results were reasonable before the U-Link extension could open, which it did in March 2016.

MEASUREMENT PROGRAMS
The data available for evaluating ambient vibration at the U-Link subway monitors includes:

1. Measurements of train vibration and ambient vibration performed in August 2015. The results of these measurements are documented in Reference 1.
2. Certification measurements that were performed by Wilson, Ihrig & Associates (WIA) on August 18 and 19, 2015. These measurements are documented in Ref. 2.
3. Continuous monitoring at three VMS monitors from Monday November 23 through Friday November 27, 2015. Thanksgiving Day was Thursday November 26, 2015 and a football game was played at Husky Stadium on Friday November 27, 2015. The data were provided by IEM.
4. Measurements performed on February 2016 to further investigate and document the ambient vibration at the monitor sites in the subway and the train vibration levels at the buildings. The results from those measurements are documented in Ref. 4.

The locations where train vibration measurements were performed in August 2015 are shown in Figure 2. The measurements were performed on two mornings between midnight and 4 AM. The first morning was focused on locations west of the subway and the second morning focused on
sites northwest of the subway. The measurements were performed with up to 20 seismic accelerometers, four RION DA-20 four channel data recorders, plus a National Instruments LabVIEW recording system with 12-channels.

The measurements west of the subway during the first morning of testing consisted of:

- Four channels between the subway and Montlake Boulevard.
- Three channels west of Montlake Boulevard.
- Inside and outside measurements at CHDD and UWMC.
- Vibration at each of the monitors.

The measurements the second morning of testing consisted of:

- Four channels parallel to the north end of the station and Montlake Boulevard.
- Two channels in a UW utility tunnel that was approximately halfway between the station and Winkenwerder Hall.
- Inside and outside measurements at Winkenwerder and Wilcox.

![Figure 2: Surface Measurement Locations for Train and Ambient Testing (August 2015)](image-url)

The supplementary measurements performed in February 2016 were just a few weeks prior to the opening in March. Those measurements consisted of two phases:
(1) Measuring ambient vibration at three of the monitors, at the ground surface above the monitors and close to Montlake Boulevard, and on one of the footings of the Montlake Draw Bridge. These measurements were performed during the daytime to obtain vibration from normal traffic. Videotaping of traffic also was performed to allow accurate identification the trucks and buses that caused vibration events.

(2) Supplementary train vibration measurements using a test train that was purposely selected because it had one or more wheel flats.

The purpose of the February measurements was to identify the source of the ambient vibration at the monitors and to pin down the levels of train vibration in two of the buildings (CHDD and UWMC).

A key feature of the test program was time synching the recording systems. This was achieved by assembling all of the systems in the same location and then triggering record simultaneously on all of the devices using an electronic signal. The recording systems were then run continuously until the end of the measurements, which ranged from 30 minutes to several hours. There was some drift in the time synching between the five systems, but it was on the order of 10 msec or less, which was small enough to ignore.

Accelerometers were used for the measurements performed in August 2015 and geophones were used for the February 2016 measurements. The accelerometers used had sensitivities of 1 V/g and 10 V/g. In general, the 10 V/g accelerometers were used at the more distant locations. The accelerometers used in the subway were all 1 V/g units. Due to instrumentation noise, the results of the tunnel are not valid at frequencies below 10 to 20 Hz, which is the frequency range focused on in this report. Therefore, the analysis was based on data from the VMS monitors and the surface measurement positions. The geophones used for the February 2016 measurements were similar to those used by IEM at the monitoring stations.

The accelerometer and geophone data were processed to obtain 1/3 octave band spectra at 1/2 second intervals. The acceleration data were then integrated in the frequency domain to obtain vibration velocity levels.

### MEASUREMENT RESULTS

Figure 3 illustrates typical data from the August 2016 measurements. On all five spectrograms the horizontal axis is time from 1:10:30 to 1:20:30, the vertical axis is frequency from 2 to 40 Hz. Color indicates vibration amplitude. The vertical lines show when the test train passed Monitor 5-1. Figure 3(a) shows the vibration at Monitor 5-1. The measurement at Monitor 5-1 was performed with an accelerometer that was not capable of accurately characterizing vibration below 10 to 20 Hz and is included to show when the test train passed Monitor 5-1. In general, we used the 40 Hz 1/3 octave band to identify when trains passed the monitors. The odd numbers (T1-T7) are the test train operating in the northbound direction at speeds of 20 to 30 mph. The even numbers (T2-T8) are trains operating in the southbound direction speed of 40 mph.

Observations from the results shown in Figure 3 are:

Figure 3(b): This position was directly above the tunnel. There are peaks at 40 Hz and 10 Hz for all of the trains and a weaker peak at 20 Hz for trains in the southbound direction. At frequencies below 8 Hz, the vibration appears to be largely uncorrelated to the train operations.
Figure 3(c): This measurement position was on the east sidewalk of Montlake approximately centered on the crossover box. Now the vibration shows substantially less correlation to the train events although there is still an indication that train vibration caused a measurable increase in the vibration levels in the 8 to 40 Hz range, although the variations between the test trains suggests that traffic contributed to the vibration during train events.

Figure 3(d): This measurement position was west of Montlake approximately 30 ft from the northbound traffic lane. The 10 volts/g accelerometer was used at this position compared to the 1 volt/g accelerometers used east of Montlake. There is very little change in the vibration levels during trains T1, T4, and T6. T1 was a northbound run at 20 to 30 mph and T4 and T6 were southbound runs at 40 mph. The other trains have vibration level increases that are almost simultaneous with the train events, but offset by 10 to 30 seconds. Because these vibration events are not synchronized with the train events and similar vibration signals are not evident during the other train events, it is unlikely that these events are associated with train operations.

Figure 3(e): This is the most distant surface accelerometer for this series of vibration tests. There is very little indication of vibration increases during the train events although there are other vibration events that generally are not synchronized with the trains. One interesting observation in Figures 3(d) and 3(e) is about 3 minutes of vibration in the 2 and 3.15 Hz bands starting at 01:13. This vibration fluctuates between about 25 to 40 dB and is not seen for the remainder of the period shown in Figure 3. Similar periods of intermittent low-frequency vibration occurred during most of the measurements. We have not identified the source of this vibration.

The key conclusion drawn from this close inspection of the vibration data at the ground surface is that there is no indication that the train operations caused any vibration at frequencies of 8 Hz and lower that was greater than the normal, middle of the night, background vibration.
Figure 3. Example Spectrograms of Surface Train Vibration

The vertical lines indicate when the test train passed Monitor 5-1. Odd numbers are northbound runs at 20 to 30 mph. Even numbers are northbound runs at a speed of 40 mph.
Figure 4 shows the vibration from the two-car test train measured at Monitor 4-2. Figure 4a shows the vibration from all the test runs that did not have simultaneous vibration from traffic (blue lines), the average train vibration in red, and the L1, L5, and L10 exceedance levels during the train testing. The periods of the train operations were removed before determining the exceedance levels. Train testing was performed between 1 AM and 4 AM when traffic on Montlake was at a minimum. Figure 4a shows that even in the early morning hours when traffic was at a minimum, train vibration was often lower than the ambient vibration at frequencies below about 16 Hz. Figure 4b compares the average level of train vibration at Monitor 4-2 with the measured levels of truck and bus vibration measured at Monitor 4-2 as the vehicles passed over the Montlake Bridge. From Figure 4b, it is evident that vibration from trucks and buses passing over the Montlake Bridge usually exceed the train vibration at Monitor 4-2 over the 2 to 25 Hz 1/3 octave bands.

Because the vibration from traffic on Montlake Boulevard is lower than the vibration from vehicles passing over the Montlake Bridge, the ambient vibration at the other monitors is lower than at Monitor 4-2. As a result, train vibration in the 12 Hz and higher 1/3 octave bands could be determined without subtracting out the effects of ambient vibration.

Figure 4. SB train vibration at Monitor 4-2 vs. ambient vibration

**COMPARISON OF BUS AND LRV VIBRATION**

In past projects when potential for interference with vibration sensitive equipment has been a concern, the vibration from existing automobiles, buses, and trucks often has been overlooked. Figure 5 shows a comparison of the force density levels derived from vibration testing that was performed for the Central Corridor LRT project in Minneapolis (Ref. 3). The measurements were performed in a corridor where both light rail trains and buses operated in parallel. Figure 5 shows that bus vibration can be expected to be equivalent to and frequently greater than LRT vibration at lower frequencies. The testing in Minneapolis shows that the crossover is in the 20 to 30 Hz range.

Of course there are a number of factors that will affect the relationship between vibration generated by buses and LRVs. These include speed, roadway condition, roadway construction, track construction, track condition, wheel condition, and localized geology.
THEORETICAL CONSIDERATIONS, MOVING LOAD IN TUNNEL

This section presents some theoretical considerations relative to the vibration in the tunnel and when the quasi-static deflection of the tunnel by the train would cause measurable low-frequency tunnel motion at the U-Link monitors.

The ground vibration displacement response to a sinusoidal load is essentially uniform or slightly increasing with frequency for an infinite half-space. Thus, the velocity response of the ground increases with increasing frequency at the rate of at least 6 dB per octave. Ignoring the effects of soil layering, the displacement response of the ground is roughly inversely proportional to the shear stiffness. For sources below grade, the dominant wave types are shear waves, compression waves, and non-radiating near-field responses. Rayleigh surface waves form at a horizontal distance of roughly five times the tunnel depth. Because the U-Link tunnel is approximately 100 ft deep, Rayleigh surface waves are not expected to be significant for the vibration in the tunnel due to surface traffic along Montlake Blvd. Most of the vibration energy is carried in shear. Thus, the ground vibration propagates through increasing depths of the ground with decreasing frequency. The shear stiffness of the ground tends to increase with increasing depth due to confining stress, further decreasing the response with decreasing frequency.

At the UW campus, the geologic materials consist of over-consolidated sands and gravels, glacial tills, and silts that were deposited by glaciers. These overlay sediments at depth that also have high shear stiffness, though slightly less than the overlying glacial deposits, as indicated by shear wave velocity data for the Sound Transit alignment on the UW campus illustrated in Figure 6. The shear stiffness increases with depth down to about 50 feet below grade, below which the shear wave velocity lessens slightly. At some depth, an increase of shear stiffness with increasing depth is expected due to increasing confining stress.

The shear stiffness of the ground is proportional to the product of soil density and the square of the shear wave velocity. As shown in Figure 6, the shear wave velocity on the UW campus is about 1,500 feet per second, roughly twice the shear wave velocity of alluvial soils where over-consolidation has not occurred. Thus, shear stiffness is roughly four times that of typical alluvial
soils, which means that the response of the ground at low frequencies is perhaps 12 dB lower
than the response of alluvial materials in locations such as the Central Valley of California
assuming that all other factors are unchanged. The increased density of over-consolidated soils
also increases the shear stiffness and reduces the response.

The compression wave velocities shown in Figure 6 are generally much higher than the shear
wave velocities, reaching 7,500 feet per second, which is about 60% greater than the speed of
sound in water (4,700 feet per second). The high compression wave velocity relative to shear
wave velocity is typical of saturated soils. The soil is virtually incompressible. As a result, the
amplitude of the compression wave is very low compared to the shear wave amplitude.

These over-consolidated materials exhibit low material loss factor, with the result that dissipation
of propagating wave energy on the UW campus is low compared with alluvial or sandy materials
not subject to over-consolidation. This is one of the reasons that the vibration velocity at
frequencies above 30 Hz is more apparent than at frequencies below 20 Hz at the UW campus.

Observed vibration energy dissipation at low frequencies was negligible due to masking by
vibration from traffic on Montlake Boulevard and other sources within several hundred feet of
the tunnel.

The response at the ground surface is dominated by the non-propagating near-field at low
frequencies, where the source-receiver distance is roughly less than a wavelength. At 10 Hz, the
shear wavelength is about 150 feet, so that vibration at receivers at the ground surface above the
tunnel or at the tunnel bench adjacent to the track are significantly affected by the near-field. The
near-field is inversely proportional to the square or cube of the source receiver distance, and thus
attenuates rapidly with distance, and is non-propagating. The static deflection field of the moving
loads of the vehicle also produces a very low frequency non-radiating ground motion at very low
frequencies (see below).
Figure 6. Seismic velocities at various borings on the UW campus

Figure 7 illustrate the line source responses (LSR) measured at the tangent track south of the UW cross-over box. A shaker was used at frequencies below 20 Hz and impact forces above 10 Hz. The shaker data were taken at 1/3 octave band center frequencies, while the impact data involve a continuous spectrum over the entire frequency range. Impact test results below 12.5 Hz are not shown, due to poor coherence in the impact data. These data indicate that the LSR decreases rapidly with decreasing frequency below 50 Hz, for the reasons cited above. At frequencies below 8 Hz, the response is much less uniform, possibly due to near field effects, but also due to the response of the ground, which may involve nodes in the response function related to layering, or tunnel/soil dynamics. Background vibration may have also affected the data at some geophones.
Vibration forces produced by transit vehicles are roughly proportional to the acceleration of the mass of the vehicle truck at frequencies between the primary resonance frequency of about 8 to 10 Hz and secondary suspension resonance frequency of around 2 Hz. Above the primary resonance frequency, the un-sprung mass of the wheel set is expected to dominate the load up to the resonance frequency of the resilient wheels, axle and direct fixation of the rail, which is about 40 to 60 Hz depending on rail fastener stiffness. The track forces due to a sinusoidal roughness between the wheel and rail will thus decrease at a rate of 12 dB per octave with decreasing frequency at frequencies between the primary resonance frequency and the wheelset/track resonance frequency.

A peak occurs at the primary resonance frequency, which is controlled by the truck mass and the parallel combination of the primary and secondary suspension stiffnesses. The frequency appears to be about 8 to 10 Hz for the Kinkysharyo vehicle. Below this frequency, the track loading again decreases with decreasing frequency at 12 dB per octave decrease in frequency until the secondary suspension resonance frequency is encountered at about 2 Hz. These characteristics are illustrated in Figure 8. In this figure of the theoretical invert force estimate for a one micro-in amplitude sinusoidal roughness, the secondary, primary, and wheelset/track resonances are at 2, 9, and 36 Hz, respectively.

The rail roughness tends to decrease with increasing frequency at a rate of 3 to 6 dB or more per doubling of frequency. This is partially compensated by the increasing bandwidth of one-third octave band filters. The bandwidth is approximately 23% of the nominal center frequency, so that the response of the third-octave filter increases by 3 dB per doubling of frequency.
In view of the above, one may expect rates of attenuation of the vibration velocity at the ground surface to be of the order of 18 dB per halving of frequency, notwithstanding peaks in the spectrum at the wheelset/track resonance, primary resonance, and secondary resonance frequencies.

The roughness of asphalt or concrete road surfaces is generally much greater than the roughness of high quality steel rails used on transit systems. The static load of the LRV at AW4 loading is about 160,000 lbs, which may be compared with the static load of a heavily loaded tractor-trailer of around 80,000 lbs. If the LRV were operated on rails with roughness equal to that of asphalt or concrete pavement surfaces, the low frequency vibration produced by the LRV would likely be substantially greater than that produced by trucks and buses. The smoothness of the wheels and rails relative to that of the road surface is a major factor in the difference between vibration produced by road vehicles and transit vehicles.

Tunnel motion due to the moving static loads of the vehicle trucks may be very apparent within the tunnel in which the train travels, with spectral peaks at frequencies below 4 Hz. The estimated 1/3 octave velocity levels for a 2-car train with three trucks per vehicle traveling at 40 mph are shown in Figure 9 along with the estimated train vibration levels observed at monitor 4-2. The peak at 1.6 Hz is due to the static loads of the individual trucks passing by. The estimated levels of train vibration at monitor 4-2 that are included in Figure 9 are in the same general range as the predictions based on static loading analysis over the 2 to 5 Hz range. At higher frequencies, the estimated values from the measurements diverge sharply from the theoretical value. This is the frequency range that the vibration shifts from non-radiating vibration related to the moving static load to radiating vibration that is caused by the interaction of the rolling wheels with the rail roughness. The ground motion due to moving static loads attenuate rapidly with distance and are unobservable beyond roughly 50 ft.

Discrepancies between the measured and predicted vibration due to a moving static load may be related to the distances between the trucks, here assumed to be 30 feet, and the actual distances and various other factors. The secondary and primary suspension resonances should not be factors for moving static loads. One may also expect the vibration response of an actual tunnel wall to differ from the response of a semi-infinite half space with a vertical load as modeled here. The moving loads are assumed to be at 100 feet below the surface. The receiver is assumed to be 10 feet from the track center and at mid tunnel height, 10 feet above the load application point. The load of each truck is assumed to be 50,000 lbs. The soil parameters are assumed to be similar to those found at the UW station. The calculations are based on an exact theory (R. D. Mindlin, Physics, v7. 1936, pg. 195) for a uniform half-space.
Figure 8 Transmitted Force for Relative Roughness of $10^{-6}$ in.
CONCLUSIONS

1. There is not much low frequency train vibration evident in the U-Link measurements. The results show that ambient vibration from traffic and other sources at the monitor locations on the tunnel safety walk often exceeded the low frequency vibration generated by test trains. This non-intuitive result indicates that the Sound Transit LRVs do not generate much low-
frequency vibration and trucks and buses tend to generate higher levels of low-frequency vibration. Similar results have been observed at other transit systems.

2. The limited low-frequency vibration energy observed at the subway monitoring stations in and south of the UW Station are consistent with other measurements of train vibration measured in locations with overly consolidated soils.

3. Based on the soil properties in UW area, this result is consistent with the models that would be used to predict the vibration properties.

4. Although this report focuses on when low-frequency vibration is not observed, it is important to recognize that there are situations when low-frequency energy will be generated by LRV operations. This report does not include specific examples of this because the focus is on why low-frequency vibration from LRV operations has not been observed at the ground surface at the north end of the U-Link extension.

5. For the U-Link extension in the University of Washington area, at frequencies below 10 to 20 Hz, we expect the ground vibration from buses and trucks to exceed the vibration generated by LRVs. The observation includes the following qualifiers: (1) LRVs with good condition wheels, (2) similar distances between the measurement positions and the vehicles, and (3) the buses/trucks and LRVs operate at similar speeds.

6. The trigger thresholds for the U-Link vibration monitoring system should be set so that they not are triggered by the vibration caused by the moving static loads of the LRVs, as these are non-radiating vibration sources, nor by background vibration from external sources.

REFERENCES


