Sound Transit U-Link Light Rail Project

Vibration Threshold Compliance Testing at the University of Washington

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EXECUTIVE SUMMARY

Vibration measurements have been conducted on the University of Washington (UW) campus to ascertain whether vibration from Sound Transit operations on the fully constructed U-Link extension (Segment 1) complies with thresholds established by the Master Implementation Agreement (MIA) between the transit agency and the university.¹ These tests largely paralleled the systems tests that were made in June of this year, though the earlier testing was beneficial in that several logistical issues were identified and resolved prior to this testing. The most important of these was that some of the ambient vibration levels in some of the buildings exceeded the MIA thresholds and train vibration was not discernable when the trains were moving, thus resulting in an indeterminate situation with respect to assessing train vibration. This was resolved by jointly by Sound Transit and the UW by developing a protocol for estimating the upper bound of train vibration for assessment in this situation (established in Operating Agreement OA-2015.001).²

Vibration measurements were made in four University buildings while Sound Transit LRV test trains were operated under controlled conditions in the University of Washington Station and in

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¹ Master Implementation Agreement for Sound Transit Entry to the University of Washington Seattle Campus, July 2, 2007; as amended June 5, 2014.

the track structures south of the station. The buildings were Wilcox Hall, Winkenwerder Hall, UW Medical Center (near the Cyclotron), and CHDD.

Ambient vibration measurements (i.e., with no train moving) were interspersed with measurements made while trains were moving.

During systems check testing, it was not possible to discern train vibration in any building under any conditions. During the current testing, we find that train vibration may be discernable in one frequency band in one building, namely, in the 40 Hz band at CHDD, when two trains were leaving the station simultaneously at 40 mph. This condition was not possible to run during systems testing and will not actually be possible to run during revenue service, so it is truly a worst case scenario. Even accepting that train vibration is discernable, the calculated train-only vibration level is 18 dB below the MIA threshold.

As before, the vibration levels in some band in some buildings (both with and without trains) exceed the MIA thresholds. For this reason, upper bound estimates have been made of train vibration in all buildings per the OA-2015.001 procedure. The upper bound estimates of train vibration are lower than the applicable MIA thresholds in all buildings under all conditions tested.

INTRODUCTION

Section 4.1.3 of the Master Implementation Agreement for Sound Transit Entry to the University of Washington Seattle Campus (MIA), executed on June 29, 2007 and amended on June 5, 2014 states that "... Revenue Service shall not commence until such time as Sound Transit demonstrates to the University that operation of that segment of the Light Rail Transit System on University Property will not exceed the Thresholds contemplated in Section 4.1.1 for at least a two (2) year period following commencement of Revenue Service." The first major component of the demonstration process is field measurement of vibration while trains are operating, a task that has come to be known as "vibration certification testing".

Testing was conducted on 18 and 19 August 2015 in accordance with the Vibration Certification Testing at the University of Washington Test Plan, 31 July 2015 (Exhibit 1 of OA-2015.001).

MEASUREMENTS

Locations. Measurements were made in four UW buildings. Exact measurement locations were initially identified jointly by Sound Transit, UW, and their advisors in February 2015. However, upon return for systems testing in June, the pre-selected location in CHDD was affected by mechanical equipment that was not running in February, so this location was relocated to a nearby stairwell. The stairwell location was used again for certification testing. Also, after systems testing found high ambient levels in Wilcox Hall, an alternative location was sought, but none more suitable was found, so the certification measurements were made in the same location as the system check measurements.
The measurement locations used were:

1. Wilcox Hall [Y]  
   *In Room 39G on and off isolated floor*
2. Winkenwerder Hall [Z]  
   *At base of southeast stairwell*
3. UW Medical Center – Cyclotron [X]  
   *In basement at the base of Stairwell NW-1*
4. Center on Human Development and Disability (CHDD) [E]  
   *In stairwell near Room CD-010K*

The letters in brackets refer to the building designation in MIA Exhibit A2 (reproduced herein as Figure 1). Photographs of the measurement equipment in the four buildings are shown on Photographic Plate 1.

**Equipment.** Vertical vibration measurements were made in each of the four buildings using a Wilcoxon Research 731A Seismic Accelerometer connected to WIA Power Supply and a Mark Products Model L-28B Geophone connected to a WIA Type 116 Geophone Pre-Amplifier. The signals were recorded using a WIA Type 222 Voltage Amplifier and a Sony PCM-D50 Digital Recorder, or simply a Rion DA-20 or DA-21 Recorder.

Simultaneously, vibration was measured in the box structure that houses the double-crossover south of the University of Washington Station. This area is referred to by the train crews as the "interlock". Vibration measurements in this area were made using R. T. Clark Model RTC-4.5 Geophones, WIA Type 116 Geophone Pre-Amplifiers, and a TEAC LX-10 Digital Recorder.

The clocks of all five recording devices were synchronized immediately prior to the measurements so that times when a train or trains were moving as measured in the box structure would be known and transferrable to the data recorded in the UW buildings.

**Test Trains.** All tests were conducted with 4-car consists comprised of the following Light Rail Vehicles (LRVs):

Train 50: 137 – 116 – 156 – 140

Train 51: 118 – 144 – 146 – 104

None of the vehicles had audible wheel flats.

The trains were unloaded during testing (AW0).

**Train Movements.** Four train movements into and out of the University of Washington Station were used at the time of testing:
The various moves are illustrated in Figure 2.

The two diverging moves, Move 2 and Move 4, involved both tracks and the common crossover diamond, so they are *exclusive* movements — no other movement can take place when a train is making either Move 2 or Move 4. Move 1 and Move 3, however, are not exclusive. A train could be entering the station on the northbound track while another is departing on the southbound track. For testing purposes, passing trains (one entering, one exiting the station) were simulated by running two trains side-by-side (Moves 1 & 3 together).

Until Northgate Link tracks are functional, it will be unsafe for northbound trains to approach the University of Washington Station through the interlock at speeds greater than 20 mph, so this was the test speed for Moves 1 and 3 in the northbound direction. The design speed through the interlock upon traveling southbound from the University of Washington Station platforms (either tunnel) is 40 mph for non-diverging moves and the actual operating speed is expected to be in the range of 25 to 30 mph. For southbound runs of Moves 1 and 3, both trains began from the platform and accelerated to 40 mph as quickly as possible through the interlock.

The trains traversed the crossover diamond (Moves 2 and 4) at 10 mph, which is the operational speed limit. Because of the impact forces generated when the wheel set hits the crossover diamond, this is likely the "worst case" vibration source for U-Link operation (if one disregards the two trains exiting the station southbound at 40 mph, a scenario which is very unlikely to occur during normal service).

Table I presents the number of runs for each speed and train movement.

<table>
<thead>
<tr>
<th>Move No.</th>
<th>Description</th>
<th>Track South of UWS</th>
<th>Track/Platform at UWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Arriving UWS, non-diverging</td>
<td>NB</td>
<td>NB</td>
</tr>
<tr>
<td>2.</td>
<td>Arriving UWS, diverging</td>
<td>NB</td>
<td>SB</td>
</tr>
<tr>
<td>3.</td>
<td>Departing UWS, non-diverging</td>
<td>SB</td>
<td>SB</td>
</tr>
<tr>
<td>4.</td>
<td>Departing UWS, diverging</td>
<td>SB</td>
<td>NB</td>
</tr>
</tbody>
</table>

SB = Southbound track
NB = Northbound track
Table I  Summary of Test Runs

<table>
<thead>
<tr>
<th>Move(s)</th>
<th>Description</th>
<th>Test Train(s)</th>
<th>Speed</th>
<th>No. of Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 3</td>
<td>“Passing” trains, northbound</td>
<td>Train 50 &amp; 51 ‡</td>
<td>20 mph</td>
<td>20</td>
</tr>
<tr>
<td>1 &amp; 3</td>
<td>“Passing” trains, southbound</td>
<td>Train 50 &amp; 51 ‡</td>
<td>40 mph</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>Northbound tunnel to southbound platform</td>
<td>Train 50</td>
<td>10 mph</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>Northbound platform to southbound tunnel</td>
<td>Train 51</td>
<td>10 mph</td>
<td>20</td>
</tr>
</tbody>
</table>

‡ Train 50 was in the SB bore; Train 51 was in the NB bore.

Data were collected in both directions of travel for any given train movement. For example, Move 2 is the crossover move between the northbound tunnel and the southbound platform in the University of Washington Station. For the 20 data runs for this move, ten were made with the train running northbound from the tunnel to the platform, and ten were made with the train running from the platform to the tunnel.

Ambient Data. To enable ambient samples to be taken throughout the testing period, the train was directed to sit for a period of 1 minute after each test run before making the return trip.

DATA ANALYSIS PROCEDURES

The vibration transducers were all calibrated with a Kistler Type 808K accelerometer that is sent annually to an ISO-9001-2008-certified calibration facility. The NIST-traceable calibration test number is 683/281893-12-BK255.

A watch synchronized to the recorders worn by a person on a test train was used to establish the timing of each run. The "run" would start at first motion and end when the test train came to a full stop. The train or trains would remain stopped for an interval of at least 1 minute between runs.

Using the vibration recordings in each building, moving, 8-second, root-mean-square, 1/3-octave band energy averages were calculated at 1 second intervals for the entire duration of each run and each ambient rest period. Then, the highest level in each 1/3-octave band was obtained over the each run and rest period. This effectively treats each 1/3-octave band individually in the compliance assessment.

The spectra calculated for periods when trains were running are referred to herein as “with train samples” or "samples concurrent with trains". The spectra calculated for periods when the trains were not running are called "ambient samples".
Following is a general description of the process by which the data were assessed and analyzed. A detailed explanation of the data processing for Room 39G in Wilcox Hall is given in Appendix A. The processing of data from the other buildings is not discussed in detail because it is very similar. However, summary results from all of the buildings will be discussed.

Data Processing Procedure:

1. Plot and assess ambient samples. The main goal of this part of the process is to determine the range of fluctuating ambient levels throughout the testing period. For clarity and because of restrictions in the data plotting software, the 20 ambient samples are plotted in groups of 6 or 7 on three plots (see, for example, Appendix A, Figure A-1-1-1A). Any 1/3-octave band spectrum that exhibits any particularly high and unusual characteristics is discarded for the purpose of determining the energy average ambient level. Spectra used for the energy average calculation are indicated in the plots with a solid line type (▬▬▬▬). A plot summarizing the characteristics of the ambient samples for each building and move combination is presented; the plot includes the range of all samples and the energy average of the retained samples (e.g., Appendix A, Figure A-1-1-2). The applicable MIA threshold spectrum for the building is also shown on each plot for reference.

2. Plot and assess samples with trains. The main goal of this part of the process is to determine if the data collected during any given train movement was overly influenced by other transient sources. Again, for clarity and because of plotting limitations, the spectra with trains are presented in three sets of 6 or 7 with a gray background indicating the range of the ambient vibration levels (e.g., Appendix A, Figure 1-1-3A). The vibration produced by a test train traveling at a controlled speed is very consistent, typically varying by less than 2 or 3 dB over many runs. Figures 3-1 to 3-3 show the vibration for various train movements measured during systems check testing in the crossover box structure. Given the consistency of vibration from trains moving under controlled conditions, a large, positive deviation in a given spectrum is a clear indication that another source or sources created vibration during the measurement. Using this physical reasoning, only samples concurrent with trains that do not include large positive deviations from the preponderance of samples are used to calculate the energy average of "with train" samples. The samples used for the energy average calculations are those shown with a solid line (▬▬▬▬) in the plots in Appendix A.

3. Compare ambient samples and samples with trains to determine if train vibration is discernable. The energy averages of the ambient samples and the "with train" samples are plotted, compared, and assessed. For the most part, the differences are very small, and, except in rare instances, less than 1 dB, the standard measurement tolerance. There are some instances where the differences are slightly larger than 1 dB, but in some of these cases, the ambient average is actually higher than the "with train" average, lending credence to the assertion that differences less than 2 dB are more likely due to statistical variation than deterministic train vibration at low frequencies. In one band at CHDD, the "with train" level is 1.7 dB higher than the ambient level, and both groups of data are very consistent. This is the only instance in which the increase in vibration may, in fact,
be due to train movement (two trains leaving the station at 40 mph). The comparison of the energy average ambient spectrum to the energy average spectrum with trains for each building/move analysis will be discussed in conjunction with the data plots below. Also, the levels will be discussed in the context of the applicable MIA threshold.

4. Calculate and assess upper bound train vibration levels. The upper bounds of train vibration levels in each building were calculated in accordance with Exhibit 2 (Approach to Estimate Train Vibration) of OA-2015.001:

To estimate train vibration when it is not discernable over the ambient vibration, Sound Transit proposes the following approach:

- Step 1: When the average vibration level of samples taken while trains are running are not distinguishable from the average ambient vibration level, use the measurement location that has the lowest ambient vibration level as the starting point to estimate the upper bound for train vibration by subtracting 10 dB from the ambient level. Assuming the results during “Certification Tests” are similar to those during the “Pre-Certification Tests,” at the vibration levels at CHDD would be used as the starting point for determining the upper bound of train vibration levels.

- Step 2: Use the previously developed line source transfer functions from the diamond crossover to each of the buildings to calculate the difference in transfer functions between CHDD and the other three buildings (See Exhibit 2 Figure 1 and Figure 2).

- Step 3: Add the upper bound train vibration estimate from CHDD data and the transfer function difference for the each of the other buildings. This will produce the upper bound train vibration estimate for each building.

Upper bound estimates were calculated using the typical train vibration in every building, and the results are presented two ways:

1. The estimate based only on CHDD vibration (since this is specifically named in the OA protocol). This is identified in the data plots as “Upper Bound Estimate of Train Vibration (CHDD)”.

2. The lowest calculated upper bound estimate based on information from all buildings. In general, vibration in lower frequency bands was not lowest in CHDD. This is identified in the data plots as “Upper Bound Estimate of Train Vibration (Lowest)”.

For Moves 1 & 3 at 40 mph, the upper bound estimate in CHDD in the 40 Hz band was found by logarithmically subtracting the average ambient level from the average “with train” level. In all other bands and all other buildings, the upper bound estimate was obtained by subtracting 10 dB from the average “with train” level. For all buildings and scenarios other than Moves 1 & 3 at 40 mph, the “with train” levels for all types of train movements were energy averaged together to produce a generic result. Bear in mind that trains were not discernable in any of these situations, so this is effectively an energy average of ambient vibration levels. The upper bound for each building/move
combination is presented along with the energy averages and the applicable MIA threshold.

VIBRATION IN UW BUILDINGS

Wilcox Hall, Room 39G, Off Isolated Floor

**Moves 1 & 3 (Passing), SB, 40 mph.** Figure 4-1-1 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient spectra. The gray area shows the range of ambient vibration level which is considerable at low frequencies. With respect to the MIA 1/3-octave band thresholds, the energy average during train movements are less than the thresholds in the 3.15 to 16 Hz and 80 and 100 Hz bands. In the 20 to 63 Hz bands, the "with train" and ambient averages are virtually identical, indicating that ambient vibration is dominating and that train vibration is not discernable in any band. The upper bound estimates for train vibration are well below the MIA threshold levels.

**Moves 1 & 3 (Passing), NB, 20 mph.** Figure 4-1-2 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient spectra. With respect to the MIA 1/3-octave band thresholds, the energy average during train movements are less than the thresholds in the 3.15 to 16 Hz and 80 and 100 Hz bands. In the 20 to 63 Hz bands, the "with train" and ambient averages are virtually identical, indicating that ambient vibration is dominating and that train vibration is not discernable in any band. Even though the “with train” average is higher than the ambient average in the 3.15 and 4 Hz bands, given the volatility of the ambient vibration at these frequencies, we do not believe this is due to train movements. Note that the same two trains going 40 mph (rather than 20 mph) are less than the ambient in Figure 4-1-1. The upper bound estimates for train vibration are well below the MIA threshold levels.

**Move 2 (Crossover), 10 mph.** Figure 4-1-3 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient spectra. With respect to the MIA 1/3-octave band thresholds, the energy average during train movements are less than the thresholds in the 3.15 to 16 Hz and 80 and 100 Hz bands. In the 20 to 63 Hz bands, the "with train" and ambient averages are virtually identical, indicating that ambient vibration is dominating and that train vibration is not discernable in any band. The slightly higher “with train” levels in the 4, 10, and 12.5 Hz bands are considered ambient fluctuation and not evidence of train vibration. The upper bound estimates for train vibration are well below the MIA threshold levels.

**Move 4 (Crossover), 10 mph.** Figure 4-1-4 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient spectra. With respect to the MIA 1/3-octave band thresholds, the energy average during train movements are less than the thresholds in the 3.15 to 16 Hz and 80 and 100 Hz bands. In the 20 to 63 Hz bands, the "with train" and ambient averages are virtually identical, indicating that ambient vibration is dominating and that train vibration is not discernable in any band. The upper bound estimates for train vibration are well below the MIA threshold levels.
Wilcox Hall, Room 39G, On Isolated Floor

**Moves 1 & 3 (Passing), SB, 40 mph.** Figure 4-2-1 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient spectra. With respect to the MIA 1/3-octave band thresholds, the energy average during train movements are less than the thresholds in the 3.15 to 16 Hz and 80 and 100 Hz bands. In the 20 to 63 Hz bands, the "with train" and ambient averages are virtually identical, indicating that ambient vibration is dominating and that train vibration is not discernable in any band. Note that the “with train” vibration levels are noticeably lower than the ambient levels in the 3.15 to 5 Hz bands; again, this is considered to be the result of ambient level fluctuation at these levels. Upper bound estimates were not made atop the isolated floor in Room 39G.

**Moves 1 & 3 (Passing), NB, 20 mph.** Figure 4-2-2 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient spectra. With respect to the MIA 1/3-octave band thresholds, the energy average during train movements are less than the thresholds in the 3.15 to 16 Hz and 80 and 100 Hz bands. In the 20 to 63 Hz bands, the "with train" and ambient averages are virtually identical, indicating that ambient vibration is dominating and that train vibration is not discernable in any band. The differences in the 3.15 and 4 Hz bands are attributed to ambient fluctuation. Upper bound estimates were not made atop the isolated floor in Room 39G.

**Move 2 (Crossover), 10 mph.** Figure 4-2-3 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient spectra. With respect to the MIA 1/3-octave band thresholds, the energy average during train movements are less than the thresholds in the 3.15 to 16 Hz and 80 and 100 Hz bands. In the 20 to 63 Hz bands, the "with train" and ambient averages are very similar and with the range of ambient vibration, indicating that ambient vibration is dominating and that train vibration is not discernable in any band. Upper bound estimates were not made atop the isolated floor in Room 39G.

**Move 4 (Crossover), 10 mph.** Figure 4-2-4 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient spectra. With respect to the MIA 1/3-octave band thresholds, the energy average during train movements are less than the thresholds in the 3.15 to 16 Hz and 80 and 100 Hz bands. In the 20 to 63 Hz bands, the "with train" and ambient averages are virtually identical, indicating that ambient vibration is dominating and that train vibration is not discernable in any band. Upper bound estimates were not made atop the isolated floor in Room 39G.

Winkenwerder Hall

**Moves 1 & 3 (Passing), SB, 40 mph.** Figure 4-3-1 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient background spectra. The energy average during train movements is less than the MIA threshold in all but the 12.5, 40, and 50 Hz bands, however, even in these bands the "with train" levels are
the same or less than the ambient levels indicating that train vibration is not discernable. The lowest upper bound estimate of train vibration for this move is well below the MIA threshold in every band. The estimate based on CHDD is approaching the MIA threshold, but as noted previously the very low frequency vibration levels in CHDD are higher than in the other buildings.

**Moves 1 & 3 (Passing), NB, 20 mph.** Figure 4-3-2 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient background spectra. The energy average during train movements is less than the MIA threshold in all but the 2.5, 3.15, 12.5, 40, and 50 Hz bands. In the 12.5, 40, and 50 Hz bands, the "with train" levels are essentially identical to the ambient levels indicating that train vibration is not discernable. In the 2.5 and 3.15 Hz bands, the “with train” levels are higher than the average ambient level, but this is ascribed to the fluctuating ambient levels, not trains. Note that the ambient levels in these bands for every other move (Figure 4-3-1, 4-3-3, and 4-3-4) are generally the same or higher than the “with train” levels for Move 2 (Figure 4-3-2) in the 2.5 and 3.15 Hz bands. The lowest upper bound estimate of train vibration in for this move is well below the MIA threshold in every band.

**Move 2 (Crossover), 10 mph.** Figure 4-3-3 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient background spectra. The energy average during train movements is less than the MIA threshold in all but the 2, 2.5, 3.15, 12.5, 40, and 50 Hz bands, however, even in these bands the "with train" levels are either identical to or comparable with the ambient levels (considering ambient fluctuation) indicating that train vibration is not discernable. The largest difference is in the 2.5 Hz band in which the "with train" average is about 1 dB higher than the ambient average. In general, a 1 dB difference is considered insignificant, but this is particularly true in these very low frequency bands where the fluctuation in the ambient is on the order of 10 dB. The upper bound estimate of train vibration in for this move is below the MIA threshold in every band.

**Move 4 (Crossover), 10 mph.** Figure 4-3-4 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient background spectra. The energy average during train movements is less than the MIA threshold in all but the 3.15, 12.5, 40, and 50 Hz bands, however, even in these bands the "with train" levels are the same or less than the ambient levels indicating that train vibration is not discernable. In the 2 to 4 Hz bands, the "with train" average levels are 1 to 2 dB less than the average ambient levels, a consequence of the large ambient fluctuations at these frequencies. The upper bound estimate of train vibration in for this move is below the MIA threshold in every band.

**UW Medical Center**

**Moves 1 & 3 (Passing), SB, 40 mph.** Figure 4-4-1 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient background spectra. The energy average during train movements is less than the MIA threshold in all but the 6.3, 25 and 31.5 Hz bands. However, in these bands, the two energy averages are
virtually identical, indicating that ambient vibration is dominating and that train vibration is not discernable. The upper bound estimate of train vibration is well below the MIA threshold.

**Moves 1 & 3 (Passing), NB, 20 mph.** Figure 4-4-2 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient background spectra. The energy average during train movements is less than the MIA threshold in all but the 6.3, 25 and 31.5 Hz bands. However, in these bands, the two energy averages are virtually identical, indicating that ambient vibration is dominating and that train vibration is not discernable. The upper bound estimate of train vibration is well below the MIA threshold.

**Move 2 (Crossover), 10 mph.** Figure 4-4-3 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient background spectra. The energy average during train movements is less than the MIA threshold in all but the 6.3, 25, 31.5 and 63 Hz bands. However, in these bands, the two energy averages are virtually identical, indicating that ambient vibration is dominating and that train vibration is not discernable. The upper bound estimate of train vibration is well below the MIA threshold.

**Move 4 (Crossover), 10 mph.** Figure 4-4-4 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient background spectra. The energy average during train movements is less than the MIA threshold in all but the 6.3, 25, 31.5 and 63 Hz bands. However, in these bands, the two energy averages are virtually identical, indicating that ambient vibration is dominating and that train vibration is not discernable. The upper bound estimate of train vibration is well below the MIA threshold.

**CHDD**

**Moves 1 & 3 (Passing), SB, 40 mph.** Figure 4-5-1 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient background spectra. The energy average during train movements is less than the MIA threshold in all bands. The "with train" level is also less than or equal to the ambient level in all but the 40 Hz band. The difference in the 40 Hz band is 1.7 dB which may be attributable to train movement given the consistency of the both the "with train" data (Figures A-5-1-3A/B/C) and ambient samples (note range in plot) in this band and the fact that the “with train” level exceeds the tight range of ambient vibration. It should be noted that the level is 18 dB below the applicable MIA threshold and that this train movement – two trains simultaneously leaving UWS in the southbound direction at maximum acceleration to 40 mph – will very likely never occur during normal operations. In this band, the upper bound estimate for train-only vibration was not determined by subtracting 10 dB, but rather by logarithmically subtracting the ambient level (21.1 dB) from the "with train" level (22.9 dB), resulting in 18.3 dB. The upper bound estimate in all bands, including the 40 Hz band, are well below the MIA threshold.

**Moves 1 & 3 (Passing), NB, 20 mph.** Figure 4-5-2 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient background spectra. The energy average during train movements is less than the MIA threshold in all bands. The "with train" level is also essentially equal to the ambient level in all bands,
indicating that train vibration is not discernable. The upper bound for train vibration is well below the MIA threshold in every band.

**Move 2 (Crossover).** Figure 4-5-3 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient background spectra. The energy average during train movements is less than the MIA threshold in all bands. The "with train" level is also less than or equal to the ambient level in all bands, indicating that train vibration is not discernable. The upper bound for train vibration is well below the MIA threshold in every band.

**Move 4 (Crossover).** Figure 4-5-4 compares the energy average of consistent spectra measured during train movements with the energy average of consistent ambient background spectra. The energy average during train movements is less than the MIA threshold in all bands. The "with train" level is also equal to or less than the ambient level in all bands, indicating that train vibration is not discernable. The upper bound for train vibration is well below the MIA threshold in every band.

**CONCLUSIONS**

1. Train vibration is only discernable in one frequency band (40 Hz) in one building (CHDD) under the worst case running conditions (two trains leaving the station simultaneously at 40 mph). This train vibration level is well below the MIA threshold.

2. Train vibration is not discernible under any other circumstance in CHDD nor in any other building under any conditions.

3. Per the procedures established by OA-2015.001, Exhibit 2, upper bound estimates of train vibration were calculated for every building and every train movement scenario. All upper bound estimates are below the MIA thresholds.

4. In all of the UW buildings tested, the ambient vibration levels were higher than the MIA thresholds in some frequency bands. "Typical ambient vibration" means vibration when trains were not moving and with anomalously high ambient levels removed. Ambient vibration is due to sources other than trains, most likely UW mechanical equipment.
Photographic Plate 1  Measurement Locations in Four UW Buildings
Figure 1  Campus Map with Tested Buildings Highlighted
Figure 2  Train Movements Into And Out Of University Of Washington Station
Figure 3-1  Consistency of Vibration during Moves 1 & 3 Testing
Figure 3-2  Consistency of Vibration during Move 2 Testing
Figure 3-3  Consistency of Vibration during Move 4 Testing
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Figure 4-1-2  Wilcox (Off Isolated Floor) – Moves 1 & 3, NB, 20 mph
Figure 4-1-3  Wilcox (Off Isolated Floor) – Move 2, 10 mph
Figure 4-1-4  Wilcox (Off Isolated Floor) – Move 4, 10 mph
Figure 4-2-1  Wilcox (On Isolated Floor) – Moves 1 & 3, SB, 40 mph
Figure 4-2-2  Wilcox (On Isolated Floor) – Moves 1 & 3, NB, 20 mph
Figure 4-2-3  Wilcox (On Isolated Floor) – Move 2, 10 mph
Figure 4-2-4  Wilcox (On Isolated Floor) – Move 4, 10 mph
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Figure 4-3-3  Winkenwerder – Move 2, 10 mph
Figure 4-3-4  Winkenwerder – Move 4, 10 mph
Figure 4-4-1  UWMC – Moves 1 & 3, SB, 40 mph
Figure 4-4-2  UWMC – Moves 1 & 3, NB, 20 mph
Figure 4-4-3   UWMC – Move 2, 10 mph
Figure 4-4-4  UWMC – Move 4, 10 mph
Figure 4-5-1  CHDD – Moves 1 & 3, SB, 40 mph
Figure 4-5-2  CHDD – Moves 1 & 3, NB, 20 mph
Figure 4-5-3  CHDD – Move 2, 10 mph
Figure 4-5-4  CHDD – Move 4, 10 mph
Appendix A

Complete Set of Measured Vibration Spectra
Detailed Analysis Discussion:

Wilcox Hall, Room 39G, Off Isolated Floor, Moves 1 & 3 (Passing), SB, 40 mph.

Figures A-1-1-1A to A-1-1-1C show the ambient samples collected in between test train runs. All of these samples were used in determining the range of ambient levels during testing, and seven were excluded for the purpose of calculating the ambient average spectrum.

Figure A-1-1-2 summarizes the ambient analysis. The range shown is for all 20 samples, whereas the energy average is for a smaller set of samples that do not contain any large, positive deviations. The MIA threshold spectrum for Wilcox is also shown. In the 20 to 63 Hz 1/3-octave bands, inclusive, the ambient vibration levels were consistently higher than the MIA threshold spectrum. The very small range in these bands indicates that mechanical equipment or some other steady-state source was dominating the vibration environment.

Figures A-1-1-3A to 1-1-3C show the samples collected while the two test trains were leaving the University of Washington Station (Moves 1 & 3) at maximum acceleration through the interlock up to a speed of 40 mph. The spectra shown with a solid line are included in the energy average calculation for “consistent” samples whereas spectra shown with dashed lines are excluded. All but a few data points are within the range of ambient vibration during testing (shown by the gray area). Note that 5 of the first 6 runs have been excluded because of the anomalously high levels in the 4 to 8 Hz bands. Interestingly, this was seen at all four buildings, indicating a large scale vibration source in the area. However, given the lower levels during later runs, we unequivocally assert that these levels were not due to trains.

Please see Figure 4-1-1 for the culmination of this analysis.

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3 The samples are labeled by run number, train direction, and (top) speed. In the case of Moves 1 & 3, southbound runs at 40 mph were interspersed with northbound runs at 20 mph. That is why it appears than 41 runs were made – the odd numbered run are at 40 mph, and the even number runs are at 20 mph. Excluding scrub, there were 20 valid runs in each direction, though one or two of these may have been subsequently disregarded during data analysis due to, for example, local interference at the transducer (beyond normal ambient conditions).
Figure A-1-1-1A: Wilcox - Unisolated, Ambient During Moves 1&3, 40 mph, Testing (Group 1)
Figure A-1-1-1B: Wilcox - Unisolated, Ambient During Moves 1&3, 40 mph, Testing (Group 2)
Figure A-1-1-1C: Wilcox - Unisolated, Ambient During Moves 1&3, 40 mph, Testing (Group 3)
Figure A-1-1-2: Wilcox - Unisolated, Ambient During Moves 1&3, 40 mph, Testing - Summary
Figure A-1-1-3A: Wilcox - Unisolated, Samples During Moves 1&3 SB, 40 mph (Group 1)
Figure A-1-1-3B: Wilcox - Unisolated, Samples During Moves 1&3 SB, 40 mph (Group 2)
Figure A-1-1-3C: Wilcox - Unisolated, Samples During Moves 1&3 SB, 40 mph (Group 3)
Figure A-1-2-1A: Wilcox - Unisolated, Ambients w/ Moves 1&3 NB, 20 mph, Testing (Group 1)
Figure A-1-2-1B: Wilcox - Unisolated, Ambients w/ Moves 1&3 NB, 20 mph, Testing (Group 2)
Figure A-1-2-1C: Wilcox - Unisolated, Ambients w/ Moves 1&3 NB, 20 mph, Testing (Group 3)
Figure A-1-2-2: Wilcox - Unisolated, Ambients w/ Moves 1&3 NB, 20 mph, Testing - Summary
Figure A-1-2-3A: Wilcox - Unisolated, Samples During Moves 1 & 3 NB, 20 mph (Group 1)
Figure A-1-2-3B: Wilcox - Unisolated, Samples During Moves 1&3 NB, 20 mph (Group 2)
Figure A-1-2-3C: Wilcox - Unisolated, Samples During Moves 1&3 NB, 20 mph (Group 3)
Figure A-1-3-1A: Wilcox - Unisolated, Ambients During Move 2, 10 mph, Testing (Group 1)
Figure A-1-3-1B: Wilcox - Unisolated, Ambients During Move 2, 10 mph, Testing (Group 2)
Figure A-1-3-1C: Wilcox - Unisolated, Ambients During Move 2, 10 mph, Testing (Group 3)
Figure A-1-3-2: Wilcox - Unisolated, Ambients During Move 2, 10 mph, Testing - Summary
Figure A-1-3-3A: Wilcox - Unisolated, Samples Concurrent with Move 2, 10 mph (Group 1)
Figure A-1-3-3B: Wilcox - Unisolated, Samples Concurrent with Move 2, 10 mph (Group 2)
Figure A-1-3-3C: Wilcox - Unisolated, Samples Concurrent with Move 2, 10 mph (Group 3)
Figure A-1-4-1A: Wilcox - Unisolated, Ambients During Move 4, 10 mph, Testing (Group 1)
Figure A-1-4-1B: Wilcox - Unisolated, Ambients During Move 4, 10 mph, Testing (Group 2)
Figure A-1-4-1C: Wilcox - Unisolated, Ambients During Move 4, 10 mph, Testing (Group 3)
Figure A-1-4-2: Wilcox - Unisolated, Ambients During Move 4, 10 mph, Testing - Summary
Figure A-1-4-3A: Wilcox - Unisolated, Samples Concurrent with Move 4, 10 mph (Group 1)
Figure A-1-4-3B: Wilcox - Unisolated, Samples Concurrent with Move 4, 10 mph (Group 2)
Figure A-1-4-3C: Wilcox - Unisolated, Samples Concurrent with Move 4, 10 mph (Group 3)
Figure A-2-1-1A: Wilcox - Isolated, Ambients During Moves 1&3 SB, 40 mph, Testing (Group 1)
Figure A-2-1-1B: Wilcox - Isolated, Ambients During Moves 1&3 SB, 40 mph, Testing (Group 2)
Figure A-2-1-1C: Wilcox - Isolated, Ambients During Moves 1&3 SB, 40 mph, Testing (Group 3)
Figure A-2-1-2: Wilcox - Isolated, Ambients During Moves 1&3 SB, 40 mph, Testing - Summary
Figure A-2-1-3A: Wilcox - Isolated, Samples Concurrent with Moves 1&3 SB, 40 mph (Group 1)
Figure A-2-1-3B: Wilcox - Isolated, Samples Concurrent with Moves 1&3 SB, 40 mph (Group 2)
Figure A-2-1-3C: Wilcox - Isolated, Samples Concurrent with Moves 1&3 SB, 40 mph (Group 3)
Figure A-2-2-1A: Wilcox - Isolated, Ambients During Moves 1&3 NB, 20 mph, Testing (Group 1)
Figure A-2-2-1B: Wilcox - Isolated, Ambients During Moves 1 & 3 NB, 20 mph, Testing (Group 2)
Figure A-2-2-1C: Wilcox - Isolated, Ambients During Moves 1&3 NB, 20 mph, Testing (Group 3)
Figure A-2-2-2: Wilcox - Isolated, Ambients During Moves 1&3 NB, 20 mph, Testing - Summary
Figure A-2-2-3A: Wilcox - Isolated, Samples During Moves 1&3 NB, 20 mph (Group 1)
Figure A-2-2-3B: Wilcox - Isolated, Samples Concurrent with Moves 1&3 NB, 20 mph (Group 2)
Figure A-2-2-3C: Wilcox - Isolated, Samples Concurrent with Moves 1&3 NB, 20 mph (Group 3)
Figure A-2-3-1A: Wilcox - Isolated, Ambients During Move 2, 10 mph, Testing (Group 1)
Figure A-2-3-1B: Wilcox - Isolated, Ambients During Move 2, 10 mph, Testing (Group 2)
Figure A-2-3-1C: Wilcox - Isolated, Ambients During Move 2, 10 mph, Testing (Group 3)
Figure A-2-3-2: Wilcox - Isolated, Ambients During Move 2, 10 mph, Testing - Summary
Figure A-2-3-3A: Wilcox - Isolated, Samples Concurrent with Move 2, 10 mph (Group 1)
Figure A-2-3-3B: Wilcox - Isolated, Samples Concurrent with Move 2, 10 mph (Group 2)
Figure A-2-3-3C: Wilcox - Isolated, Samples Concurrent with Move 2, 10 mph (Group 3)
Figure A-2-4-1A: Wilcox - Isolated, Ambients During Move 4, 10 mph, Testing (Group 1)
Figure A-2-4-1B: Wilcox - Isolated, Ambients During Move 4, 10 mph, Testing (Group 2)
Figure A-2-4-1C: Wilcox - Isolated, Ambients During Move 4, 10 mph, Testing (Group 3)
Figure A-2-4-2: Wilcox - Isolated, Ambients During Move 4, 10 mph, Testing - Summary
Figure A-2-4-3A: Wilcox - Isolated, Samples Concurrent with Move 4, 10 mph (Group 1)
Figure A-2-4-3B: Wilcox - Isolated, Samples Concurrent with Move 4, 10 mph (Group 2)
Figure A-2-4-3C: Wilcox - Isolated, Samples Concurrent with Move 4, 10 mph (Group 3)
Figure A-3-1-1A: Winkenwerder, Ambients During Moves 1&3 SB, 40 mph, Testing (Group 1)
Figure A-3-1-1B: Winkenwerder, Ambients During Moves 1&3 SB, 40 mph, Testing (Group 2)
Figure A-3-1-1C: Winkenwerder, Ambients During Moves 1&3 SB, 40 mph, Testing (Group 3)
Figure A-3-1-2: Winkenwerder, Ambients During Moves 1&3 SB, 40 mph, Testing - Summary
Figure A-3-1-3A: Winkenwerder, Samples Concurrent with Moves 1 & 3 SB, 40 mph (Group 1)
Figure A-3-1-3B: Winkenwerder, Samples Concurrent with Moves 1&3 SB, 40 mph (Group 2)
Figure A-3-1-3C: Winkenwerder, Samples Concurrent with Moves 1&3 SB, 40 mph (Group 3)
Figure A-3-2-1A: Winkenwerder, Ambients During Moves 1&3 NB, 20 mph, Testing (Group 1)
Figure A-3-2-1B: Winkenwerder, Ambients During Moves 1&3 NB, 20 mph, Testing (Group 2)
Figure A-3-2-1C: Winkenwerder, Ambients During Moves 1&3 NB, 20 mph, Testing (Group 3)
Figure A-3-2-2: Winkenwerder, Ambients During Moves 1&3 NB, 20 mph, Testing - Summary
Figure A-3-2-3A: Winkenwerder, Samples Concurrent with Moves 1&3 NB, 20 mph (Group 1)
Figure A-3-2-3B: Winkenwerder, Samples Concurrent with Moves 1&3 NB, 20 mph (Group 2)
Figure A-3-2-3C: Winkenwerder, Samples Concurrent with Moves 1&3 NB, 20 mph (Group 3)
Figure A-3-3-1A: Winkenwerder, Ambients During Move 2, 10 mph, Testing (Group 1)
Figure A-3-3-1B: Winkenwerder, Ambients During Move 2, 10 mph, Testing (Group 2)
Figure A-3-3-1C: Winkenwerder, Ambients During Move 2, 10 mph, Testing (Group 3)
Figure A-3-3-2: Winkenwerder, Ambients During Move 2, 10 mph, Testing - Summary
Figure A-3.3.3A: Winkenwerder, Samples Concurrent with Move 2, 10 mph (Group 1)
Figure A-3-3-3B: Winkenwerder, Samples Concurrent with Move 2, 10 mph (Group 2)
Figure A-3-3-3C: Winkenwerder, Samples Concurrent with Move 2, 10 mph (Group 3)
Figure A-3-4-1A: Winkenwerder, Ambients During Move 4, 10 mph, Testing (Group 1)
Figure A-3-4-1B: Winkenwerder, Ambients During Move 4, 10 mph, Testing (Group 2)
Figure A-3-4-1C: Winkenwerder, Ambients During Move 4, 10 mph, Testing (Group 3)
Figure A-3-4-2: Winkenwerder, Ambients During Move 4, 10 mph, Testing - Summary
Figure A-3-4-3A: Winkenwerder, Samples Concurrent with Move 4, 10 mph (Group 1)
Figure A-3-4-3B: Winkenwerder, Samples Concurrent with Move 4, 10 mph (Group 2)
Figure A-3-4-3C: Winkenwerder, Samples Concurrent with Move 4, 10 mph (Group 3)
Figure A-4-1-1A: UWMC, Ambients During Moves 1&3 SB, 40 mph, Testing (Group 1)
Figure A-4-1-1B: UWMC, Ambients During Moves 1&3 SB, 40 mph, Testing (Group 2)
Figure A-4-1-1C: UWMC, Ambients During Moves 1&3 SB, 40 mph, Testing (Group 3)
Figure A-4-1-2: UWMC, Ambients During Moves 1&3 SB, 40 mph, Testing - Summary
Figure A-4-1-3A: UWMC, Samples Concurrent with Moves 1&3 SB, 40 mph (Group 1)
Figure A-4-1-3B: UWMC, Samples Concurrent with Moves 1&3 SB, 40 mph (Group 2)
Figure A-4-1-3C: UWMC, Samples Concurrent with Moves 1&3 SB, 40 mph (Group 3)
Figure A-4-2-1A: UWMC, Ambients During Moves 1&3 NB, 20 mph, Testing (Group 1)
Figure A-4-2-1B: UWMC, Ambients During Moves 1&3 NB, 20 mph, Testing (Group 2)
Figure A-4-2-1C: UWMC, Ambients During Moves 1&3 NB, 20 mph, Testing (Group 3)
Figure A-4-2-2: UWMC, Ambients During Moves 1&3 NB, 20 mph, Testing - Summary
Figure A-4-2-3A: UWMC, Samples Concurrent with Moves 1&3 NB, 20 mph (Group 1)
Figure A-4-2-3B: UWMC, Samples Concurrent with Moves 1&3 NB, 20 mph (Group 2)
Figure A-4-2-3C: UWMC, Samples Concurrent with Moves 1&3 NB, 20 mph (Group 3)
Figure A-4-3-1A: UWMC, Ambients During Move 2, 10 mph, Testing (Group 1)
Figure A-4-3-1B: UWMC, Ambients During Move 2, 10 mph, Testing (Group 2)
Figure A-4-3-1C: UWMC, Ambients During Move 2, 10 mph, Testing (Group 3)
Figure A-4-3-2: UWMC, Ambients During Move 2, 10 mph, Testing - Summary
Figure A-4-3-3A: UWMC, Samples Concurrent with Move 2, 10 mph (Group 1)
Figure A-4-3-3B: UWMC, Samples Concurrent with Move 2, 10 mph (Group 2)
Figure A-4-3-3C: UWMC, Samples Concurrent with Move 2, 10 mph (Group 3)
Figure A-4-4-1A: UWMC, Ambients During Move 4, 10 mph, Testing (Group 1)
Figure A-4-4-1B: UWMC, Ambients During Move 4, 10 mph, Testing (Group 2)
Figure A-4-4-1C: UWMC, Ambients During Move 4, 10 mph, Testing (Group 3)
Figure A-4-4-2: UWMC, Ambients During Move 4, 10 mph, Testing - Summary
Figure A-4-4-3A: UWMC, Samples Concurrent with Move 4, 10 mph (Group 1)
Figure A-4-4-3B: UWMC, Samples Concurrent with Move 4, 10 mph (Group 2)
Figure A-4-4-3C: UWMC, Samples Concurrent with Move 4, 10 mph (Group 3)
Figure A-5-1-1A: CHDD, Ambients During Moves 1&3 SB, 40 mph, Testing (Group 1)
Figure A-5-1-1B: CHDD, Ambients During Moves 1&3 SB, 40 mph, Testing (Group 2)
Figure A-5-1-1C: CHDD, Ambients During Moves 1&3 SB, 40 mph, Testing (Group 3)
Figure A-5-1-2: CHDD, Ambients During Moves 1&3 SB, 40 mph, Testing - Summary
Figure A-5-1-3A: CHDD, Samples Concurrent with Moves 1&3 SB, 40 mph (Group 1)
Figure A-5-1-3B: CHDD, Samples Concurrent with Moves 1&3 SB, 40 mph (Group 2)
Figure A-5-1-3C: CHDD, Samples Concurrent with Moves 1&3 SB, 40 mph (Group 3)
Figure A-5-2-1A: CHDD, Ambients During Moves 1&3 NB, 20 mph, Testing (Group 1)
Figure A-5-2-1B: CHDD, Ambients During Moves 1&3 NB, 20 mph, Testing (Group 2)
Figure A-5-2-1C: CHDD, Ambients During Moves 1&3 NB, 20 mph, Testing (Group 3)
Figure A-5-2-2: CHDD, Ambients During Moves 1&3 NB, 20 mph, Testing - Summary
Figure A-5-2-3A: CHDD, Samples Concurrent with Moves 1&3 NB, 20 mph (Group 1)
Figure A-5-2-3B: CHDD, Samples Concurrent with Moves 1&3 NB, 20 mph (Group 2)
Figure A-5-2-3C: CHDD, Samples Concurrent with Moves 1&3 NB, 20 mph (Group 3)
Figure A-5-3-1A: CHDD, Ambients During Move 2, 10 mph, Testing (Group 1)
Figure A-5-3-1B: CHDD, Ambients During Move 2, 10 mph, Testing (Group 2)
Figure A-5-3-1C: CHDD, Ambients During Move 2, 10 mph, Testing (Group 3)
Figure A-5-3-2: CHDD, Ambients During Move 2, 10 mph, Testing - Summary
Figure A-5-3-3A: CHDD, Samples Concurrent with Move 2, 10 mph (Group 1)
Figure A-5-3-3B: CHDD, Samples Concurrent with Move 2, 10 mph (Group 2)
Figure A-5-3-3C: CHDD, Samples Concurrent with Move 2, 10 mph (Group 3)
Figure A-5-4-1A: CHDD, Ambients During Move 4, 10 mph, Testing (Group 1)
Figure A-5-4-1B: CHDD, Ambients During Move 4, 10 mph, Testing (Group 2)
Figure A-5-4-1C: CHDD, Ambients During Move 4, 10 mph, Testing (Group 3)
Figure A-5-4-2: CHDD, Ambients During Move 4, 10 mph, Testing - Summary
Figure A-5-4-3A: CHDD, Samples Concurrent with Move 4, 10 mph (Group 1)
Figure A-5-4-3B: CHDD, Samples Concurrent with Move 4, 10 mph (Group 2)
Figure A-5-4-3C: CHDD, Samples Concurrent with Move 4, 10 mph (Group 3)