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TECHNICAL MEMORANDUM

DATE: 15 November 2011

TO: Dan Adams, NTP

CC: Tracy Reed, Sound Transit

FROM: Thom Bergen, Jim Nelson, Derek Watry

SUBJECT: Summary of Supply Train Vibration Measurements
Sound Transit U-LINK, Shelby/Hamlin Neighborhood, NB and SB Tunnels

This memorandum provides a summary of vibration levels measured on Shelby Street south of the Montlake Cut in Seattle on the evening of October 12, 2011. The purpose of the measurements was to characterize vibration levels at the ground surface produced by the TBM supply train in the U-Link southbound (SB) and northbound (NB) tunnels. During these measurements, the SB tunnel had the original supply train track system with steel sleepers bolted directly into the tunnel liner. In the NB tunnel, the steel sleepers had been unbolted and thicker oak wood ties supported by sections of conveyor mat had been installed between each of steel ties.

Vibration Measurement Set-up

The measurement instrumentation and set-up were the same as previous measurements on Shelby Street. The Wilcoxon 731 seismic accelerometer signals were recorded on the TEAC LX-10 digital data recorder. The acceleration signals were integrated and both vibration acceleration and velocity were recorded. The accelerometer string followed the south curb of Shelby Street with the stakes driven approximately 1 foot from the south edge of the curb. This location on Shelby Street is estimated to be approximately Station No. 1194+20. Data recordings were made between 9:00 PM and 12:00 midnight.

For these measurements, five surface measurement locations were used. Because the distances from most of the locations to the two tunnels are different (the exception being the "midpoint" location), each location is identified by a letter from A to E. Location A was directly over the southbound tunnel, and the lettering proceeded eastward from there. The distances between the measurement locations and the various accelerometers are:

Location	Dist to SB Tunnel	Dist to NB Tunnel
A	0.0 ft	63.0 ft
B	31.5 ft	31.5 ft

C	63.0 ft	0.0 ft
D	163.0 ft	100.0 ft
E	263.0 ft	200.0 ft

Unfortunately, the accelerometer set-up at Location E was damaged by a local resident while exiting their vehicle (they had parked next to the accelerometer), and we were not able to repair the set-up in time for the test. Consequently, there is no data from Location E.

Supply Train Operation
During the measurement of ground vibration at the surface, a fully loaded supply train was run back and forth below Shelby Street through both the northbound and southbound tunnels. A minimum of three round-trips were made at full speed (about 5 to 6 mph) and also at half speed. An additional test was performed by locating the loci directly below the measurement location and revving the engine for several seconds. The muck conveyor systems in both tunnels operated intermittently during the recordings.

Vibration Data Analysis
The vibration acceleration and velocity signals were analyzed into one-third octave band levels with 6th order filters and 1-second contiguous integrations. The vibration velocity data are of primary interest and only those are reported herein. To identify samples for analysis, the time series was carefully observed while listening to the recorded data through headphones. For the sustained vibration produced by the supply train, statistical levels of L_1, L_{10}, L_{50}, L_{90}, and L_{99} were computed for a few selected samples. In addition, samples of the ambient vibration environment were analyzed for each location.

The energy equivalent vibration level (L_{eq}) was computed for all of the test train passbys for samples 20 to 30 seconds in length. As demonstrated by previous measurements, the vibration levels and frequency spectra are remarkably repeatable from one train to the next. For each test condition, three to six supply train samples were energy-averaged to give a representative sample for comparison with other scenarios. Samples that were contaminated with vehicles passing on Shelby Street were not included in the averages.

Summary of Results
As in previous measurements, the variations in statistical levels were found to be similar for all loci passbys. The maximum levels (L_1) are typically 5 to 7 dB higher than the L_{eq}, the L_{10} levels are typically 3 to 4 dB higher, and the L_{90} levels are typically 4 to 6 lower. Vibration levels in the 10 to 16 Hz frequency bands are likely to include a contribution from traffic on Montlake Blvd, which is unavoidable. The primary frequency range of vibration associated with the supply trains is in the audible range of 31.5 to 100 Hz as previously reported. Vibration produced by the loci engine revving test and the muck conveyor systems were not detectable above the ambient.

In Figure 1, the average 1/3 octave band vibration velocity levels for supply trains moving in the SB tunnel at full speed are plotted for the four measurement locations. Similarly, the vibration levels due to trains in the SB tunnel at *half* speed are presented in Figure 2. Vibration velocity levels for trains in the NB tunnel at full and half speeds are included in Figures 3 and 4, respectively. The overall vibration levels are summarized in Table 1.[1]

Table 1 Average Overall Vibration Levels

Supply Train Location	Train Speed	Overall Vibration Velocity Level [1]		
		Location A	Location B	Location C
SB Tunnel	Full	62	55	60
	Half	57	51	55
NB Tunnel	Full	58	52	59
	Half	55	50	55

[1] In VdB re 1 micro-inch/second. Energy averaged L_{eq} of 3 to 6 loci passbys.

These data indicate that the vibration levels are significantly lower at Location B (the midpoint between the two tunnels) relative to the other nearby locations. Although care is taken in selecting suitable mounting locations for the accelerometers, it appears that Location B was at a "dead spot" meaning the absolute ground vibration levels measured there do not fit well in the cluster of other data points. However, as long as the measured vibration levels are above the background vibration levels, the *relative* changes in the measured curb vibration levels due to changes in conditions (e.g., full speed vs half speed) still provide useful and valid information.

Two pertinent questions may be answered using the data collected at Locations A, B, and C:

> What was the effect of replacing steel sleepers with wooden sleepers?
>
> What is the effect of slowing the supply train down?

In terms of overall vibration levels, these questions can be answered from the information in Table 1. For a train at full speed, vibration levels from the northbound tunnel (wooden sleepers) relative to the southbound tunnel (steel sleepers) were typically 2 to 3 VdB less. Vibration levels from a half speed train relative to a full speed train were typically 4 to 5 VdB less on steel ties and 2 to 4 VdB less on wooden ties.

Equally important to these reductions are the reductions in the A-weighted, groundborne noise levels inside residences. These reductions may be estimated by conducting a similar analysis on the vibration spectra after they have been A-weighted. The absolute noise levels estimated this way will not be accurate, but the relative differences should provide a good indication of the

[1] The "overall level" sums the vibration energy at all frequencies.

noise reduction inside the homes. The estimated decrease in groundborne noise levels from the northbound tunnel (wooden sleepers) relative to the southbound tunnel (steel sleepers) is 5 to 7 dBA for a full speed train and 2 to 4 dBA for a half speed train. The estimated decrease in groundborne noise levels from slowing the train down to half speed is 3 to 5 dBA on wood ties and 6 to 7 dBA on steel ties. We are not providing the spectral details of these calculations. Table 2 summarizes the reductions afforded by replacing the sleepers and slowing the trains down.

Table 2 Effects of Sleepers and Train Speed on Noise and Vibration

Action	Decrease in Overall Vibration Level	Decrease in A-weighted Noise Level
Replacing Steel Sleepers with Wooden Sleepers	0 to 3 VdB	2 to 7 dBA
Slowing Train Down to Half Speed	2 to 5 VdB	3 to 7 dBA

Conclusions

Overall vibration levels measured on Shelby Street during loci passbys are generally consistent with previous measurements. However, there was one “dead spot” at the midpoint between the two tunnels. The cause of the relatively low vibration levels at this spot is now known.

The wood tie system provides a modest reduction in vibration of 2 to 3 VdB for trains moving at full speed. The estimated reduction in groundborne noise is 5 to 7 dBA for full speed train. This is somewhat larger than we would have expected from the wooden ties and conveyor belt rubber pads, so it most likely due to the 1/4" resilient Pandrol rail pad between the rail and the tie.[2] At half speed, both the noise and vibration reduction provided by installing wood ties is somewhat less.

Reducing the speed by half is slightly more effective on the steel ties than with the wood tie system. Speed reduction for trains in the SB tunnel (steel ties) reduced the vibration by 4 to 5 VdB, while speed reduction for the NB tunnel (wood ties) trains reduced vibration by 2 to 4 VdB. Reducing the speed likely reduces the groundborne noise level by 3 to 5 dBA on wood ties and 6 to 7 dBA on steel ties.

The combined effect of installing wood ties and slowing the train down would be somewhat greater than either action alone, but would not be the sum of the individual effects because of non-linearities in the mechanical system.

[2] This has been called the "AirBoss" pad by some, but the technical information we received indicates it is a Pandrol pad.

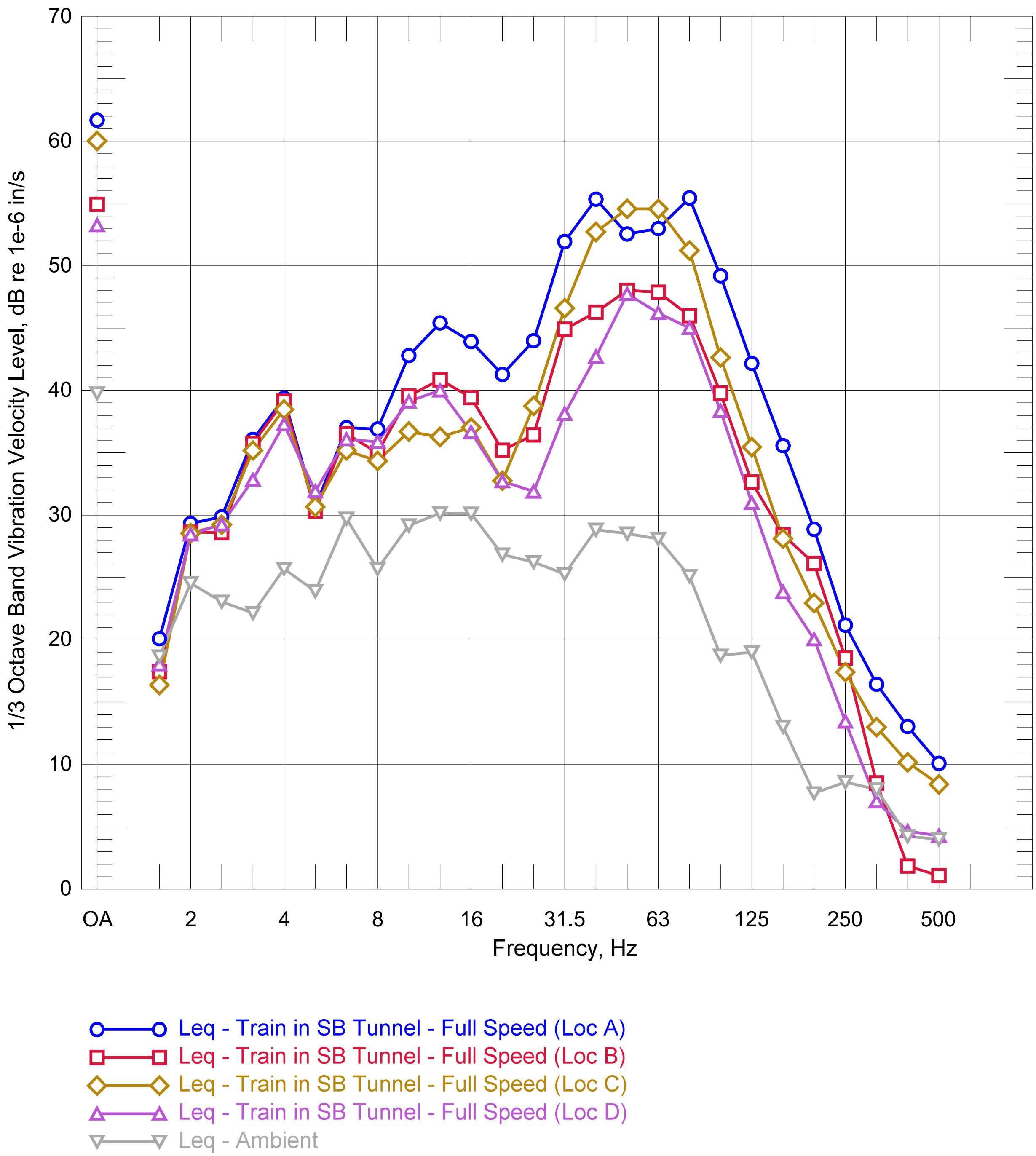

Figure 1 Average vibration velocity levels – train in SB tunnel at full speed

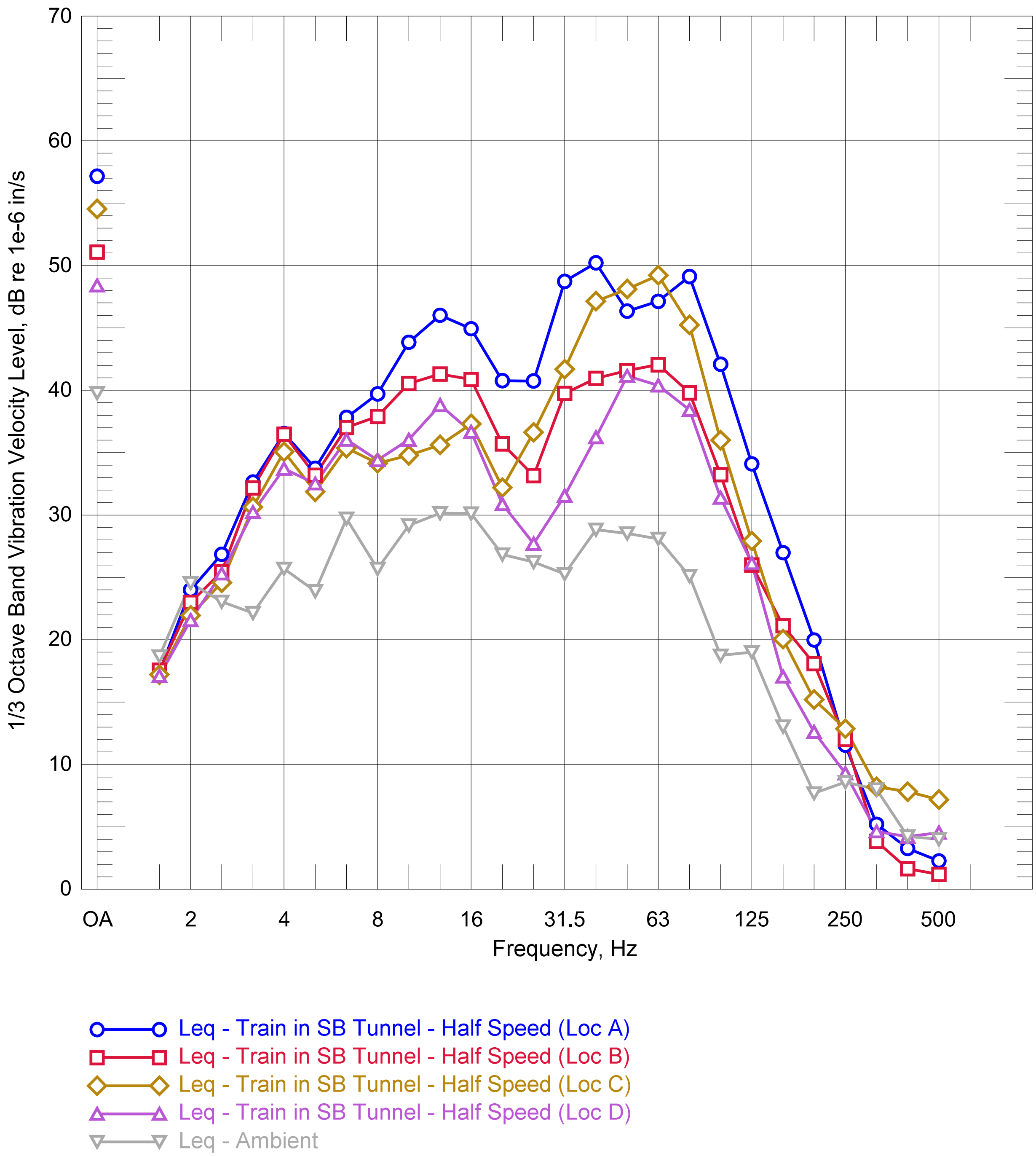

Figure 2 Average vibration velocity levels – train in SB tunnel at half speed

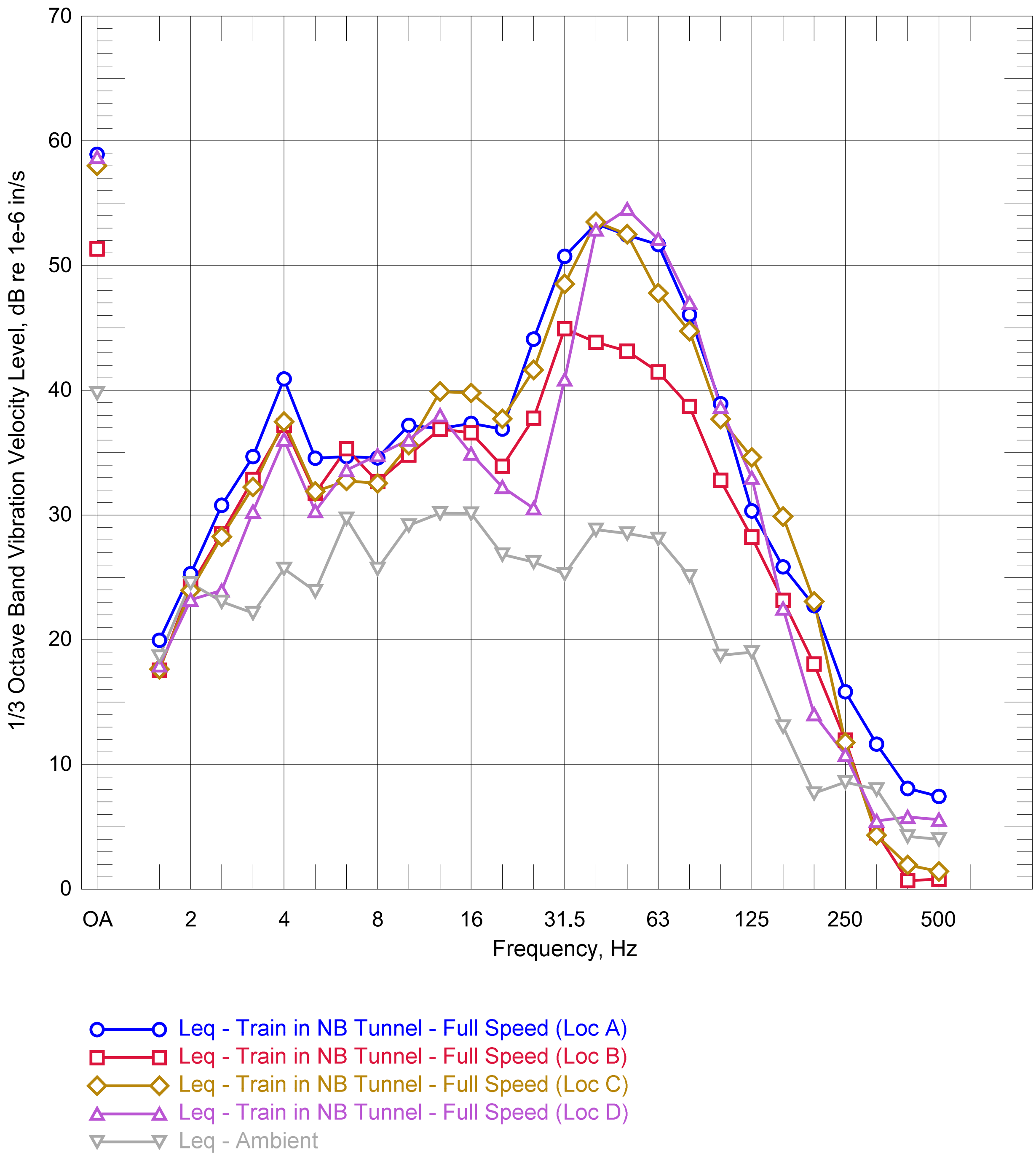

Figure 3 Average vibration velocity levels – train in NB tunnel at full speed

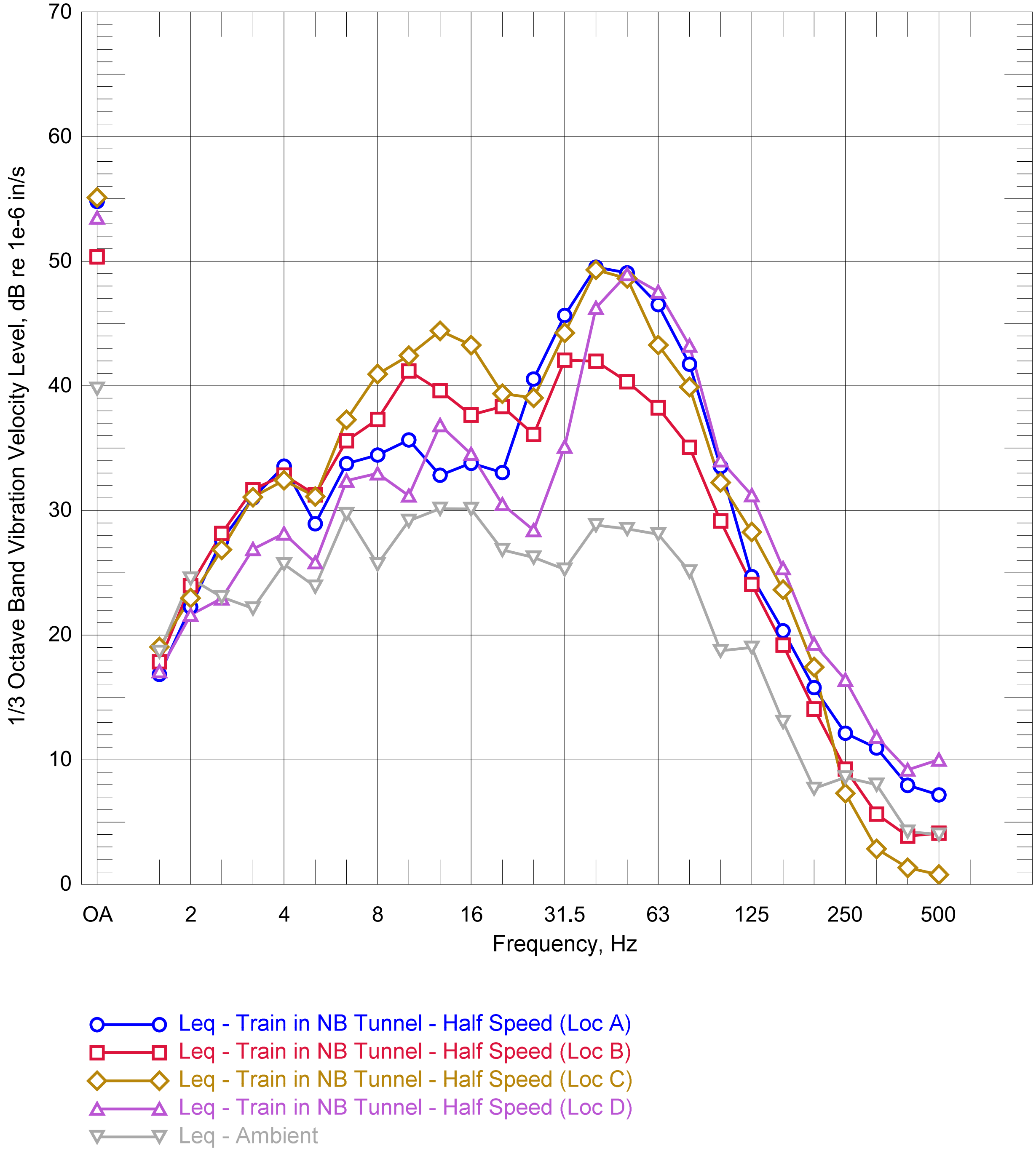

Figure 4 Average vibration velocity levels – train in NB tunnel at half speed