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TECHNICAL MEMORANDUM

DATE: 1 November 2011

TO: Dan Adams, NTP

CC: Tracy Reed, Sound Transit

FROM: Thom Bergen, Jim Nelson, Derek Watry

SUBJECT: Summary of Supply Train Ground-borne Noise and Vibration Measurements
Sound Transit U-LINK, Shelby/Hamlin Neighborhood, Interior of Three Homes

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This memorandum provides a summary of ground-borne noise and vibration (GBNV) measurements made inside three Shelby/Hamlin residences on the evening of 24 October 2011. The purpose of the measurements is to characterize noise and vibration levels inside the homes produced by the TBM supply trains (locis) in the U-Link southbound and northbound tunnels.

Test Condition

During the measurements, a fully loaded supply train was run back and forth through both tunnels between the shaft and approximately Ring 257 south of Hamlin St. Two round-trips were made at full speed (about 5 mph) in each tunnel in addition to regular trains supplying the TBM. The supply train tracks in both tunnels were supported with oak ties on thin rubber mats between, roughly, Rings 105 and 260.

Test Locations

Measurements were made in three residences: [redacted] (2[redacted] E. Hamlin Street; near Ring 226), [redacted] (2[redacted] E. Hamlin Street; near Ring 196), and [redacted] (2[redacted] E. Shelby Street; near Ring 166). All three homes are located in the vicinity of the northbound tunnel with [redacted] and [redacted] located directly over the tunnel. The resident of each home indicated that the disturbance they are experiencing is perceived to be worst in the basement of their home. Thus, all measurements were made in the basements of the homes, all three of which have been built out to be useable rooms.

The three rooms vary in size with [redacted] being smallest (8' x 20' approx.) and [redacted] the largest (15' x 30' approx.). All are carpeted and contain upholstered furniture. The [redacted] basement includes a raised wooden floor beneath the carpet. All three basements have windows of varying size near the ceiling; all windows were closed during the measurements.

Test Equipment and Set-up

Noise and vibration data were recorded on a two-channel Sony PCM-D50 digital data recorder. A high-fidelity audio recording was recorded on one of the channels using a B&K Type 2230 Sound Level Meter for a microphone and gain control. An electronic signal proportional to vibration acceleration was recorded on the other channel. This signal was generated by an Endevco 7707-1000 piezoelectric accelerometer with a WIA charge amplifier and conditioned by a WIA gain amplifier. Both the audio and vibration signals were listened to live with high-fidelity headphones during data collection. All equipment was calibrated before and after the measurements.

The accelerometer was fastened to the floor at each location to measure vertical vibration. In the [redacted] residence, the accelerometer was located on a section of linoleum tile near the center of the room. In the [redacted] residence, a set of "carpet spikes" were used to attach the accelerometer firmly to the raised subfloor through the carpet in the center of the room. In the [redacted] home, the accelerometer was adhered to the tile floor in a bathroom adjacent to the open basement area. In all of the rooms, the sound level measurement was made by locating the microphone in an open area of the room (away from the walls) and 4 to 5 feet above the floor.

Noise and Vibration Data Analysis Methodology

The vibration acceleration data were first converted to velocity by time-integration. Then, the velocity and sound pressure data were analyzed into one-third octave band levels with 6th order filters and 1-second contiguous integrations. To identify samples for analysis, the time series was carefully observed on the computer screen while listening to the recorded data through headphones. This enables us to identify loci passage and distinguish the trains from other sources. Samples were specifically extracted from the recordings when there was minimal interference from other sources. For the purposes of this study, the average noise and vibration levels (L_{eq}) for each supply train passby were computed for 30 second samples (the typical duration that the trains are audible). Statistical noise levels were also computed for representative noise samples (discussed below in detail).

Analysis Results

The 1/3 octave band vibration velocity levels associated with several loci passbys in both tunnels as measured on the [redacted] residence basement floor are plotted in Figure 1. This figure shows that the vibration produced by the supply trains is remarkably consistent for trains moving in either direction and in either tunnel. The frequency distribution is highest in the 31.5 to 100 Hz range which is characteristic of the supply trains as determined previously with exterior (street) measurements. Peaks in the spectrum in the 8 to 16 Hz frequency bands are associated with car, bus, and truck traffic on surrounding roadways, not the supply train.

The energy average vibration spectra of all loci passbys is plotted with the ambient spectra in Figure 2. The supply train movements clearly increase the floor vibration in the 20 Hz and higher bands, but the resulting *overall* level (the level obtained by summing all of the frequency components) is still less than 60 VdB indicating that it should not be perceptible, and we did not observe vibration to be perceptible.

The 1/3 octave band noise levels from several loci passbys measured in the center of the [redacted] basement are shown in Figure 3. These noise spectra correspond to the same times as the vibration spectra in Figure 1. The energy average supply train passby noise spectrum is plotted in Figure 4 along with the ambient noise spectrum. The peak in the ambient spectrum at 63 Hz is most likely associated with electrically powered equipment in the house (e.g, the refrigerator, but the actual source is not known).

Similar to Figures 1 through 4 for the [redacted] residence, the supply train vibration and noise levels for the [redacted] residence are presented in Figures 5 through 8 and for the [redacted] residence in Figures 9 through 12. The patterns and observations made with respect to the [redacted] residence all hold for the other two residences, as well.

Finally, for ease of comparison, the average loci vibration levels for the three basement floor locations are shown in Figure 13, and the average noise levels during train passage for the three residences are shown in Figure 14.

A few representative samples of other noise sources were selected for analysis. These include jet aircraft passing over the houses and vehicular traffic on adjacent roadways. The times of the events were correlated with the notes taken by Sound Transit personnel stationed on the street outside the house. For comparison, the noise levels produced by aircraft and vehicles are plotted with the supply train groundborne noise levels in Figures 15, 16, and 17 for each of the three residences. Note that traffic noise may also include a groundborne component.

For [redacted] all exterior noise sources produce approximately the same A-weighted noise level inside the house. In the [redacted] basement, the supply trains clearly produce higher noise levels in the 31.5 to 100 Hz range relative to the other sources, but the same A-weighted noise level as aircraft because the jet noise has more energy at higher frequencies (above 200 Hz) which are emphasized by the A-weighting. At [redacted] it was noted that large trucks and buses are clearly audible in noise recording (not so at the other homes) and characterized by the peak centered at 16 Hz (which is itself below the audible range). However, as with [redacted] the aircraft are clearly audible and produce the same A-weighted noise level as the trains.

Table I summarizes some pertinent measures of groundborne noise and vibration due to supply trains in the three homes, as well as noise levels from other sources.

For a typical loci passby in each residence, statistical descriptors of the 1/3 octave band noise levels were computed for 30 second samples. In each frequency band, the L50 represents a level where half of the samples are above and half are below. Similarly, the L10 is the level where 90% of the samples are below and 10% above. The Lmax is the maximum level is highest sample computed for each 1/3 octave band. For the supply trains, the Lmax is associated with the "thump-thump" produced at the rail joints. The L50, L10, and Lmax noise levels for the [redacted] [redacted] and [redacted] basements are plotted in Figures 18, 19, and 20, respectively. Table II summarizes the A-weighted statistical noise levels (see the attached Description of Acoustical Terms at the ends of this memo).

TABLE I Summary Of Time-Averaged Noise And Vibration Levels

	[redacted]	[redacted]	[redacted]
Trains: Floor Vibration	53 VdB	54 VdB	57 VdB
Trains: Groundborne Noise	27 - 30 dBA	29 - 33 dBA	28 - 32 dBA
Other Sources: Ground- and Air-borne			
Jet Aircraft	30 dBA	30 dBA	30 dBA
Cars on Hamlin/Shelby	29 dBA	25 dBA	25 dBA
Trucks/Buses on Montlake	--	--	22 dBA
Background (no sources)	19 dBA	21 dBA	22 dBA

Note: [redacted] background noise level adjusted for 63 Hz electrical tone.

TABLE II Summary Of Statistical Noise Levels

	[redacted]	[redacted]	[redacted]
Lmax	32 dBA	37 dBA	33 dBA
L10	32 dBA	35 dBA	33 dBA
L50	30 dBA	32 dBA	31 dBA
L90	29 dBA	29 dBA	27 dBA
L99	28 dBA	27 dBA	26 dBA
Background (no train)	19 dBA	21 dBA	22 dBA

Note: [redacted] background noise level adjusted for 63 Hz electrical tone.

Observations

In the [redacted] residence, supply trains were subjectively observed to be barely audible for a brief period during each passby. At this location, noise and vibration levels were noted to be slightly higher (1 to 2 dB) for loci moving in the northbound tunnel. The data presented in Figures 1 through 4 indicate that the floor vibration levels due to supply trains are well above the ambient, but the associated air-borne noise is partially masked by other sources within and outside the home. Frequent aircraft and traffic noise were observed (transmitted through closed windows).

Floor amplification is evident in the [redacted] basement, which is expected because the wooden floor is raised, and the amplification results in higher noise and vibration levels from trains relative to the other two residences (see Figures 13 and 14). The peak at 40 Hz is likely associated with a resonance of the raised floor. Here, the trains were clearly audible and characterized by a low-level low-frequency “rumble” with an intermittent higher level “thump-thump”. For each loci passby, the noise is present for 20 to 50 seconds per train. Listening carefully to the recording, it is clear that much of the vibration and “thumping” noise is associated with the loci passing over joints and other discontinuities in the rail.

As with the [redacted] residence, both trains and aircraft were clearly audible in the [redacted] residence. Several of the train samples in [redacted] were made when heavy trucks or busses were passing on Montlake Blvd. The road vehicles are responsible for the vibration seen in the 8 to 16 Hz bands in Figure 9, not the trains (as evidenced by the other train samples). Even with the trucks and/or busses, the overall vibration level during a train passby is dominated by the train vibration, but is still below the typical threshold of perceptibility. The truck and/or bus vibration below 20 Hz should not be audible to humans, although higher frequency components from these noise sources are audible.

Assessment Using Standard Criteria

Groundborne noise from activities in a tunnel is essentially the audible manifestation of groundborne vibration. As such, it is generally addressed in conjunction with vibration. The Federal Transit Administration (FTA) *Transit Noise and Vibration Impact Assessment Manual* states "[f]or evaluating potential annoyance . . . due to construction vibration, the criteria for General Assessment . . . can be applied."[1] The General Assessment criteria for groundborne noise and vibration for residences depends on the number of events per day, and the most stringent is for *frequent events*, defined as more than 70 events per day. Because these criteria were developed for rail transit systems and because there are on the order of 70 supply trains per day, these criteria are well suited for assessing the situation in the Shelby/Hamlin neighborhood.

The respective criteria are:

Groundborne noise: 35 dBA re 20 micro-Pa
Groundborne vibration: 72 VdB re 1 micro-in/sec

Neither of these criteria is predicated upon "imperceptibility." In fact, supply train noise or vibration at the respective criteria level would be distinctly perceptible if the respective background levels were lower, which they are in this situation.

The measured floor vibration levels in all three houses are well below the 72 VdB criterion. In addition, they are also well below 65 VdB which is the threshold of perception for most people.

The background noise levels in the homes when there are no discernible exterior or interior sources is 19 to 22 dBA, so it would not be surprising to learn that a noise on the order of 30 or 35 dBA is distinctly audible. Furthermore, as discussed above, the rail joints introduce a "thumping" nature to the audible supply train noise which makes it even more distinctive. In contrast, the increase and decrease of noise from an airplane passing overhead is smoother.

The thumping nature of the noise raises the question as to how best represent the "typical" noise level during the train passage which is audible for approximately 20 to 50 seconds.

The levels averaged over the entire train passage as reported in Table I are all below the FTA criterion and similar to the noise levels from aircraft. On upper floors of the residences, train

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[1] , FTA-VA-90-1003-06, May 2006.

noise levels would be similar or slightly less and aircraft noise likely slightly higher due to the larger windows upstairs. Therefore, the A-weighted, average train noise and aircraft noise levels are very likely equal upstairs, but still beneath the FTA criterion.

The statistical noise levels presented in Table II indicate to some degree how the rail joints cause the noise level to vary during a train passage. To a person listening, the thumping would be also be detectable by its characteristic sound. At [redacted] and [redacted] even the maximum noise levels are below the FTA criteria. At [redacted] the loci passby produces noise levels which exceed the 35 dBA criterion for 10% of the duration of the passby. For a train that is audible for 30 seconds, the rail joint "thumping" noise levels is greater than 35 dBA for about 3 seconds.

Conclusions

- Vibration levels are well below the threshold of perceptibility in the three homes tested.
- The vibration levels are well below the level that could cause damage to homes. The residents should be assured of this.
- Groundborne noise is distinctly audible in [redacted] and [redacted] and somewhat audible in [redacted] above the background. The average A-weighted noise level during a train passage is 8 to 10 dBA higher than the background.
- The rail joints introduce a "thumping" character to the supply train noise, distinguishing it from other exterior, transportation noise sources.
- The average noise level during a train passage is 29 to 31 dBA, depending on the residence. This is below the FTA groundborne noise criterion.
- The maximum noise levels during a train passage attributable to rail joint thumping is 32 to 37 dBA depending on the residence. It only exceeds the FTA criterion of 35 dBA at the [redacted] residence, and there about 10% of the time during the train passage.
- In all three basements, the A-weighted noise level is similar for aircraft and supply trains, but the sound of these two sources are distinctly different (difference frequency content). We do not know how many airplanes fly over these homes per hour or per day, but the number of "events" does affect how people react to noise sources.
- The reaction of people to noise also depends on their emotions or beliefs about the noise source. In this case, the residents may be anxious or upset about having a tunnel beneath their neighborhood, and their reaction to the audibility of the supply trains colored by their beliefs or emotions. They could also be reacting to a new and unusual noise source.

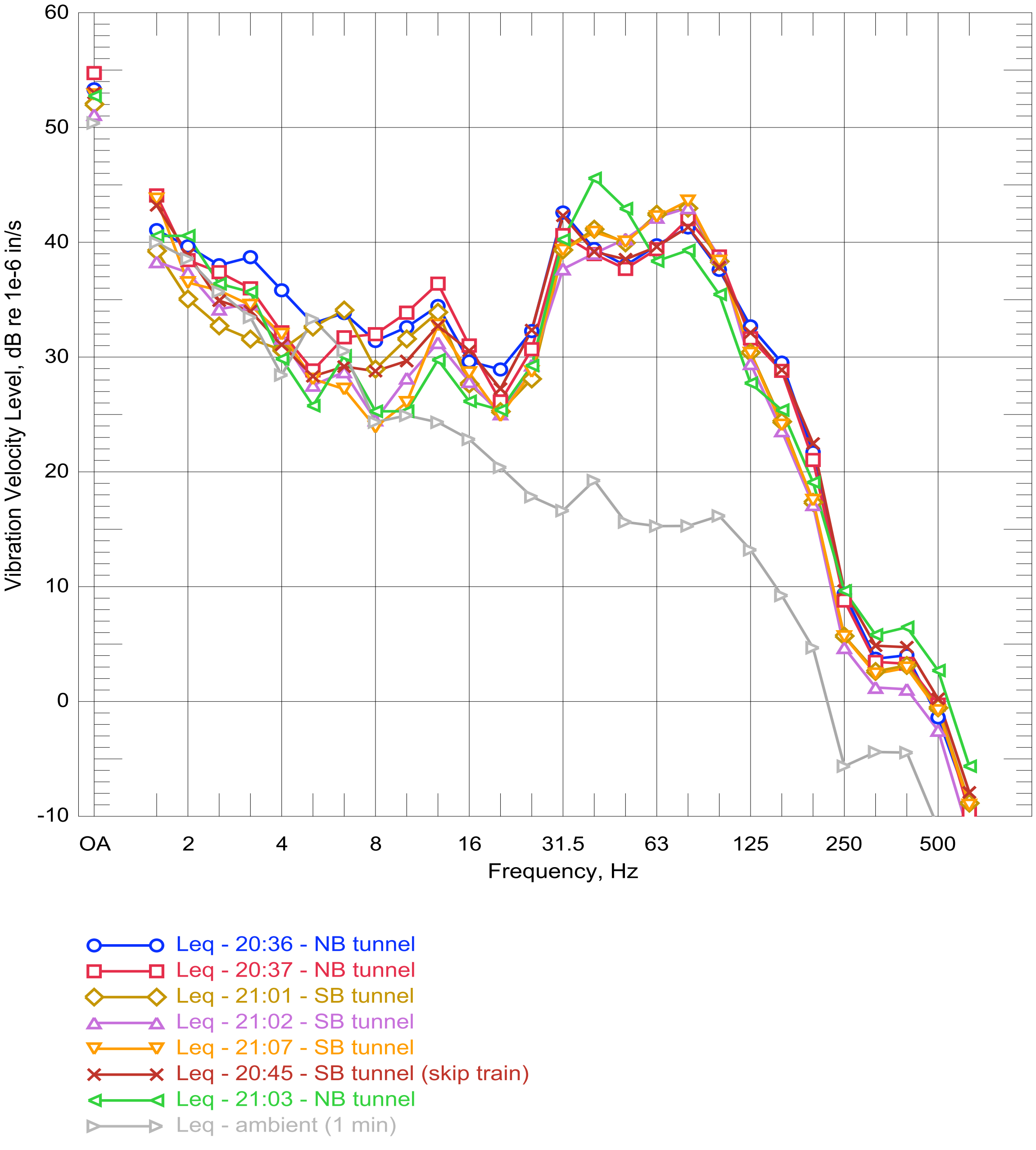


Figure 1 Average vibration velocity levels on basement floor in [redacted] residence ! Hamlin Street ! eight loci passbys ! both tunnels

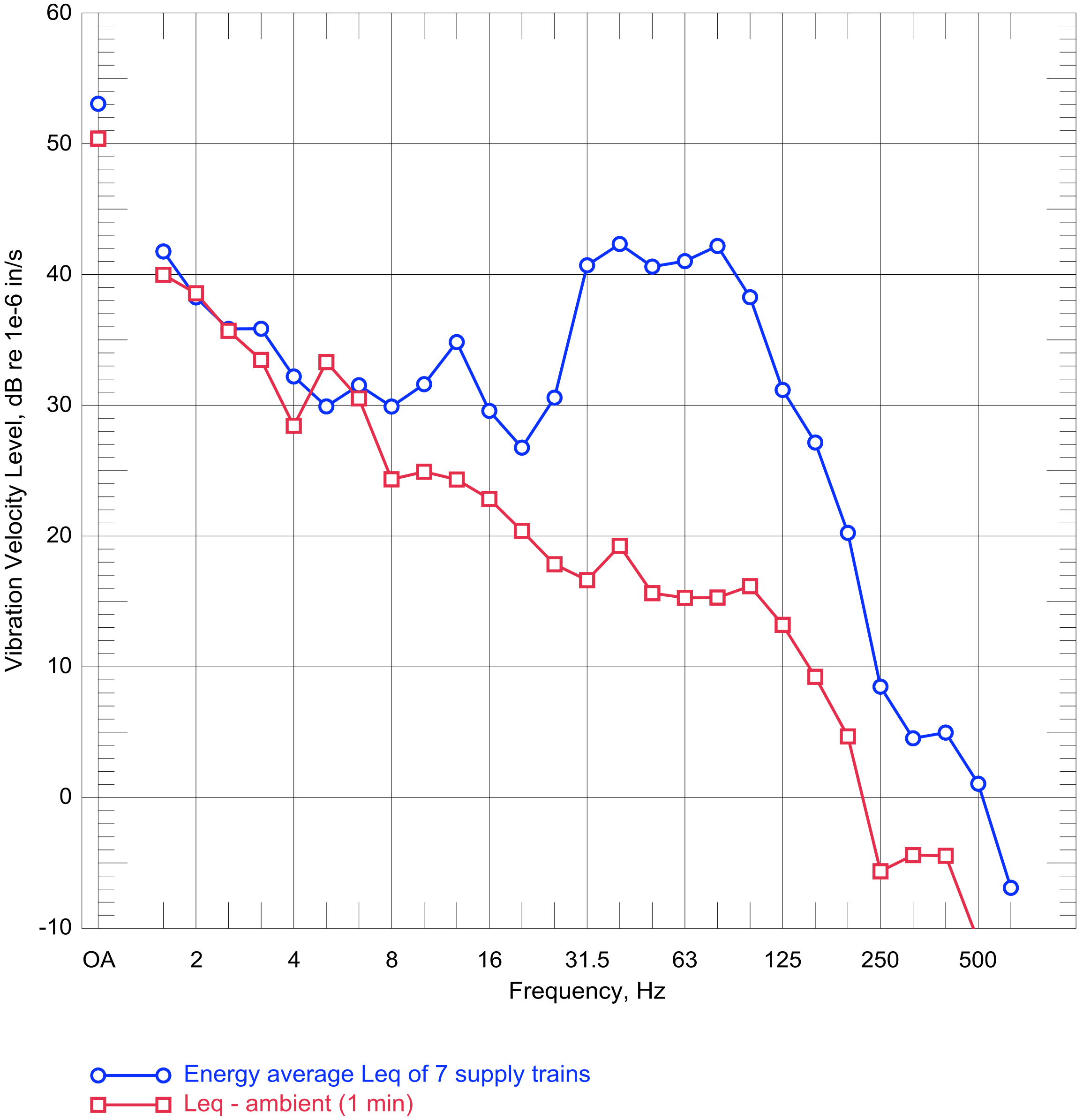


Figure 2 Energy average of eight supply trains vibration levels - [redacted] residence basement floor - Hamlin Street

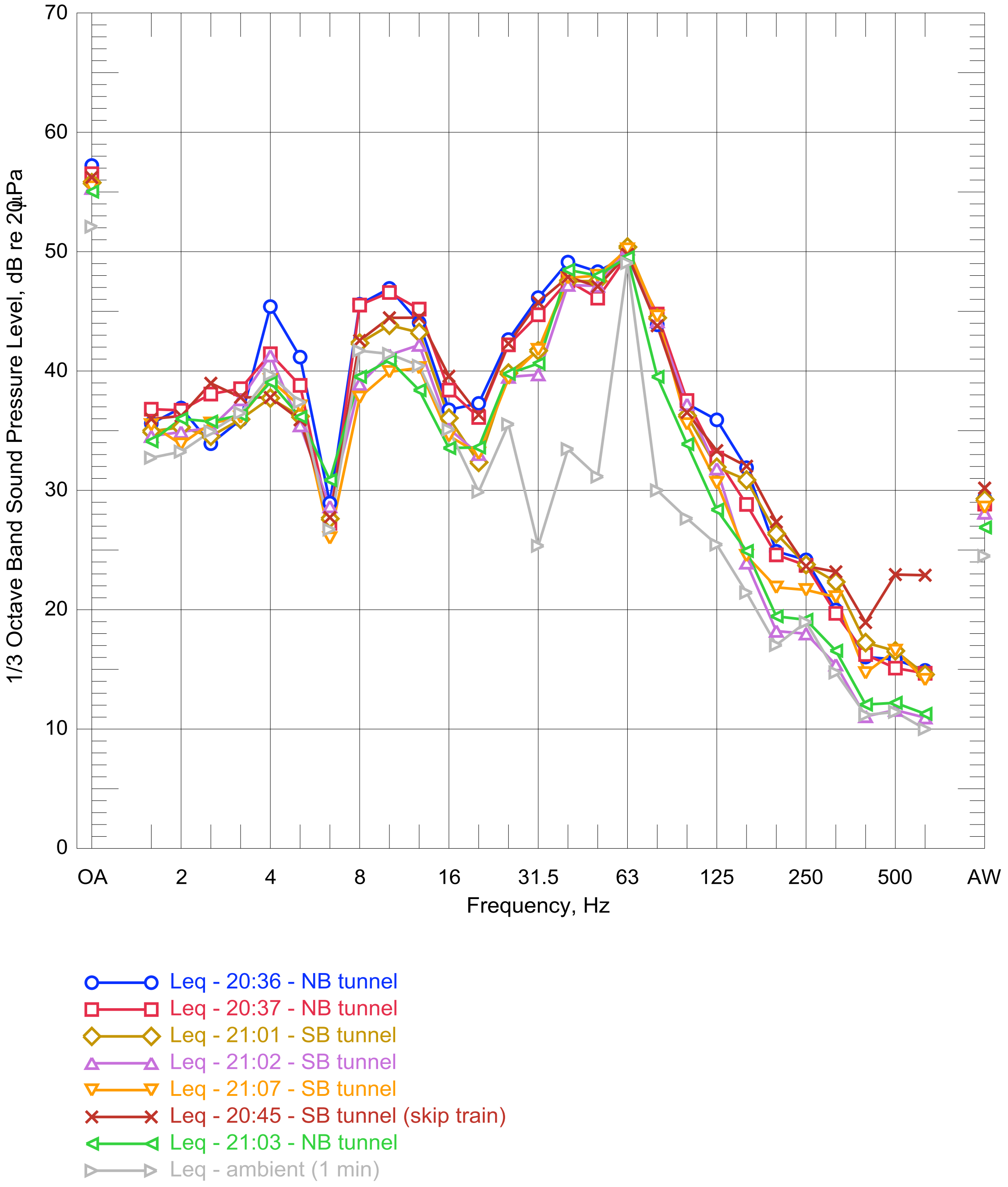


Figure 3 Noise levels measured during seven loci passbys - [redacted] basement - Hamlin Street

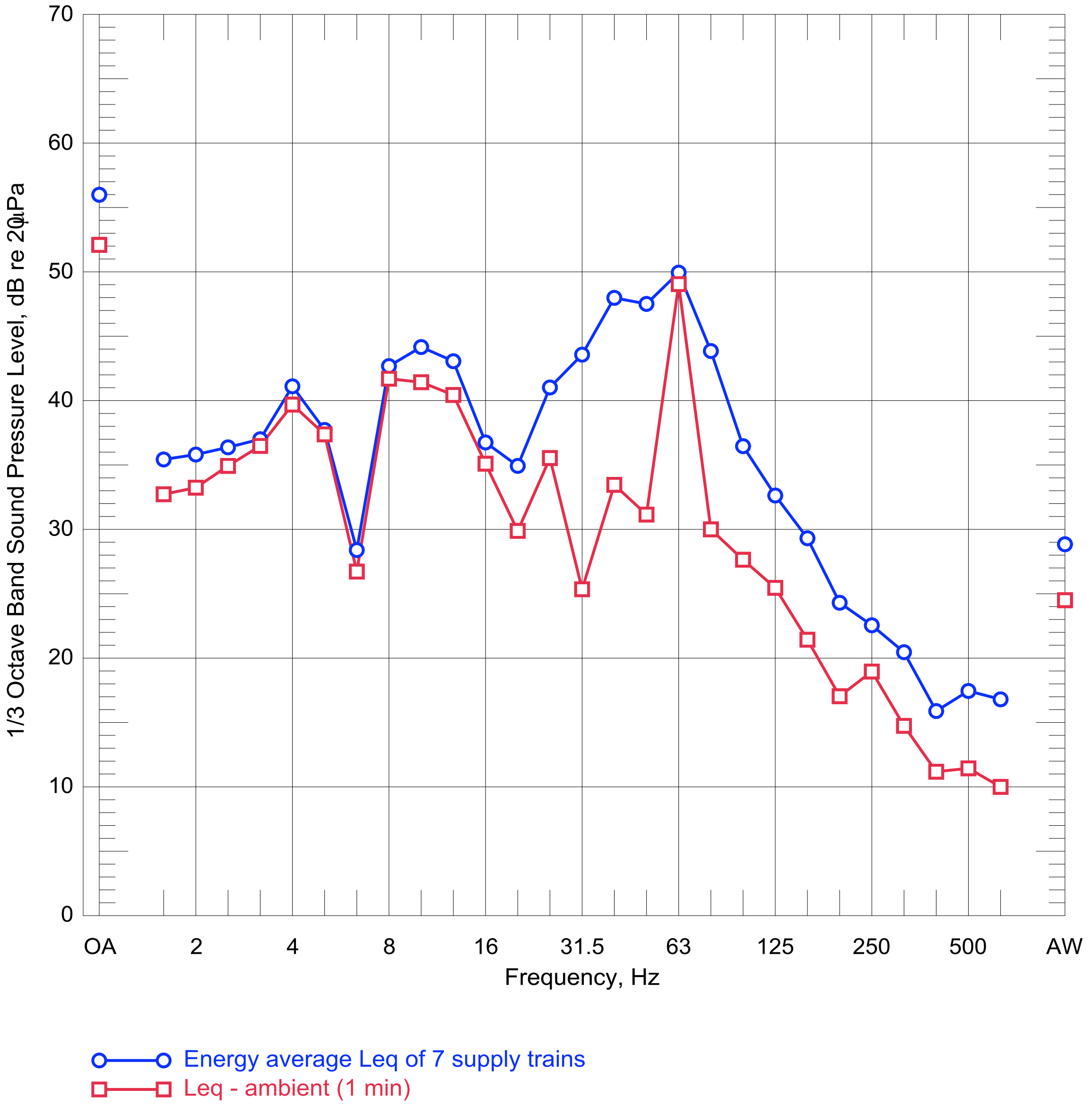


Figure 4 Energy average of eight supply trains noise levels - [redacted] residence basement - Hamlin Street

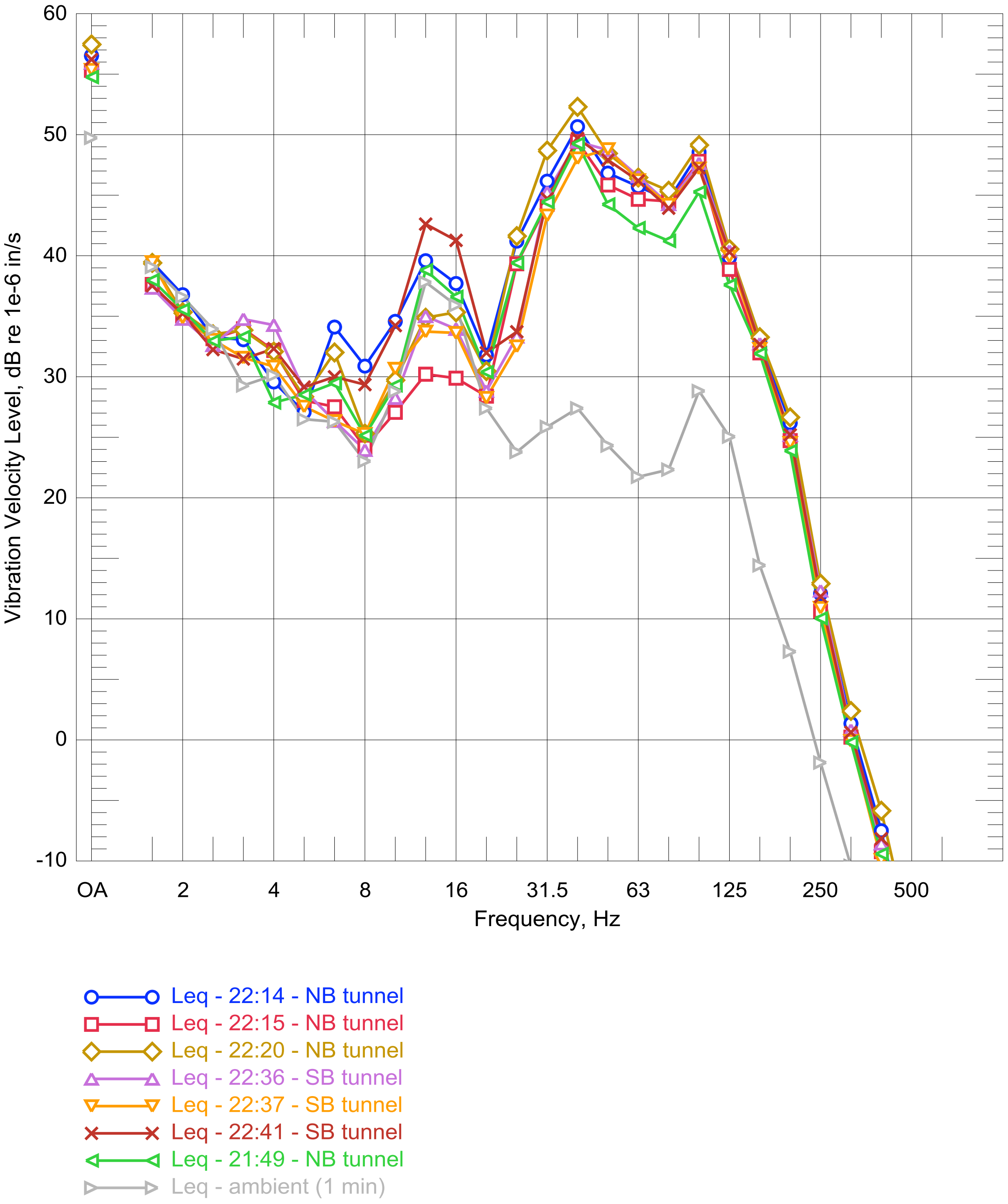


Figure 5 Average vibration velocity levels on basement floor in [redacted] residence ! Hamlin Street ! six loci passbys ! both tunnels

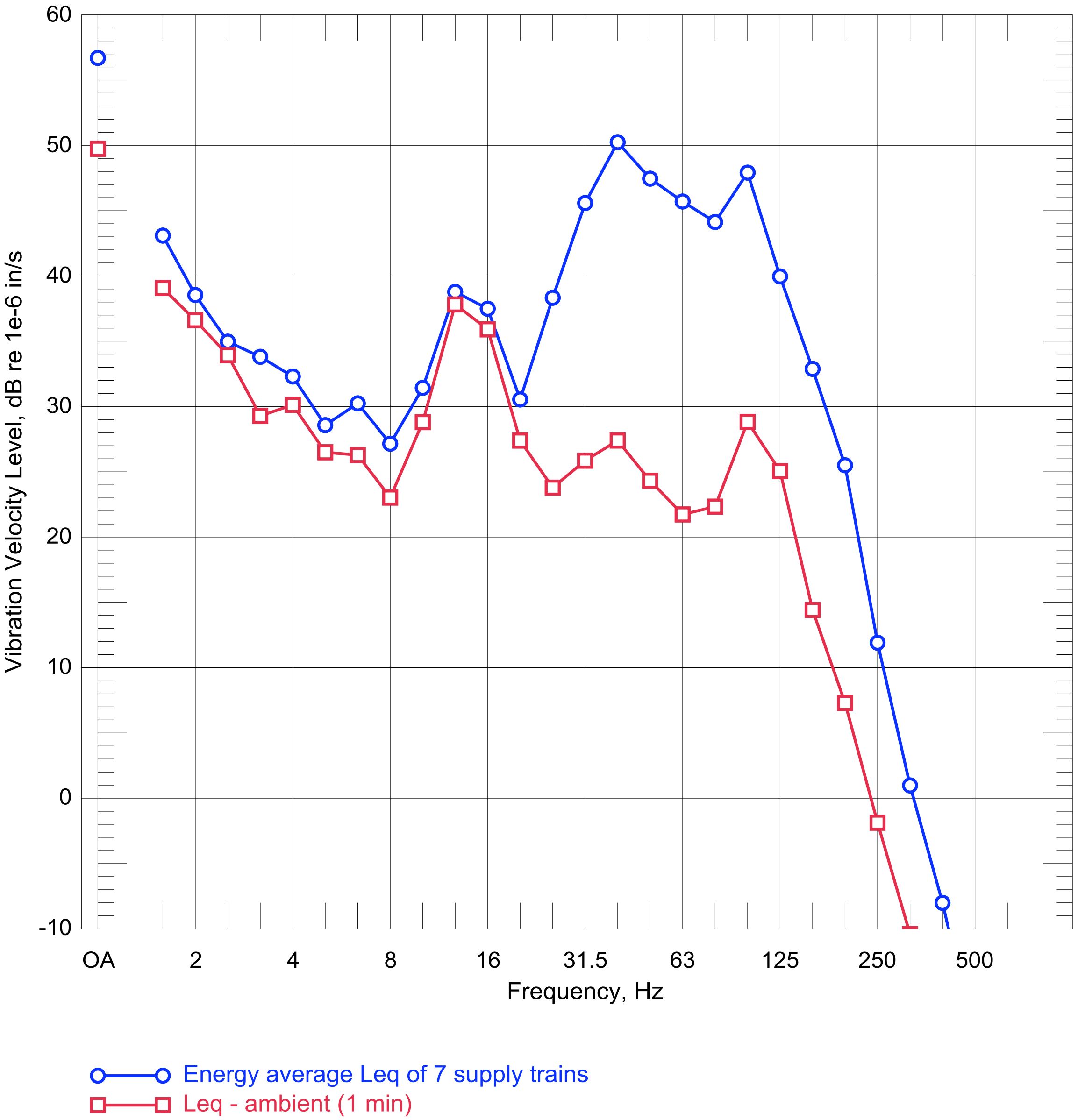


Figure 6 Energy average of six supply trains vibration levels - [redacted] residence basement floor - Hamlin Street

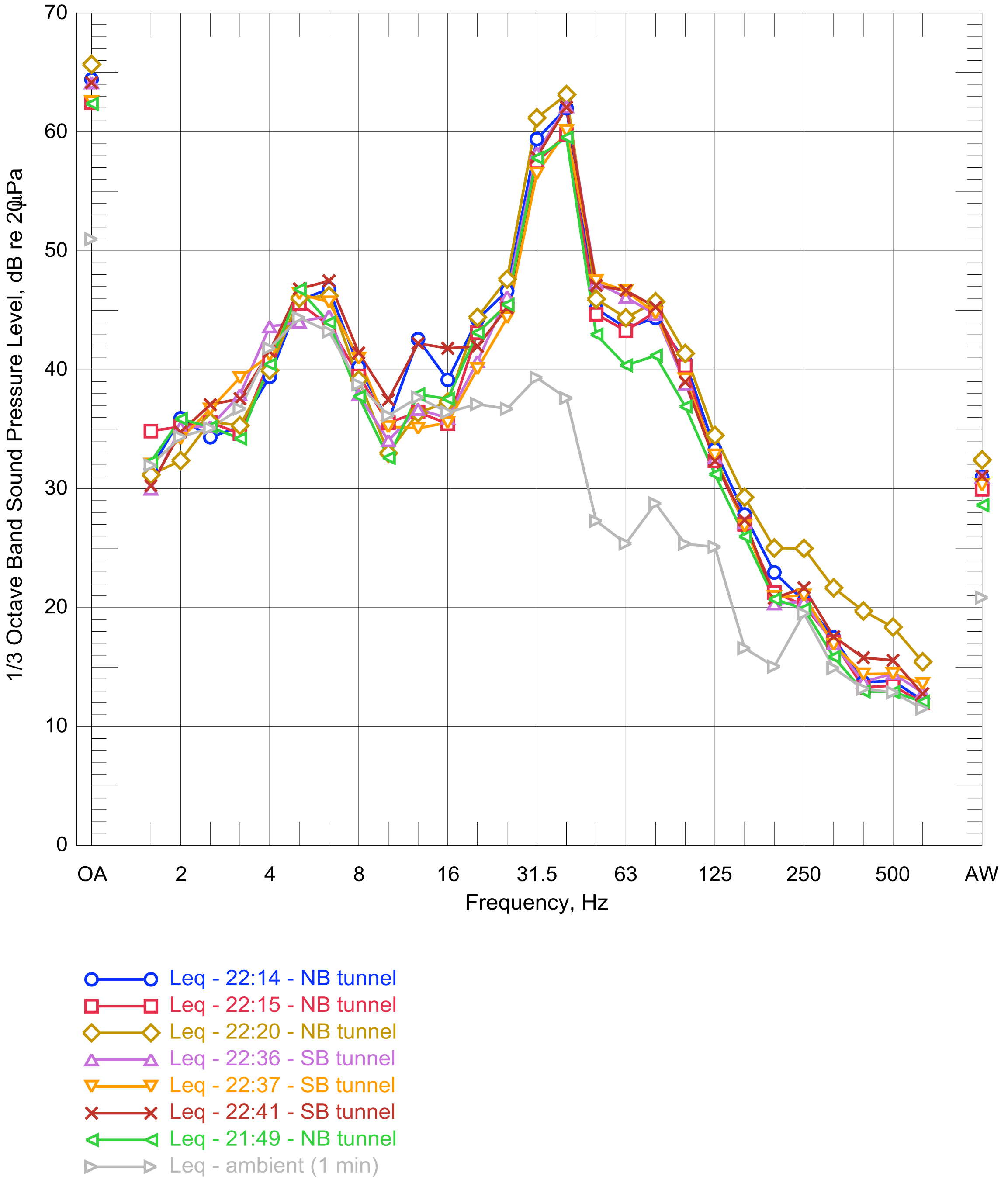


Figure 7 Noise levels measured during six loci passbys - [redacted] residence basement - Hamlin Street

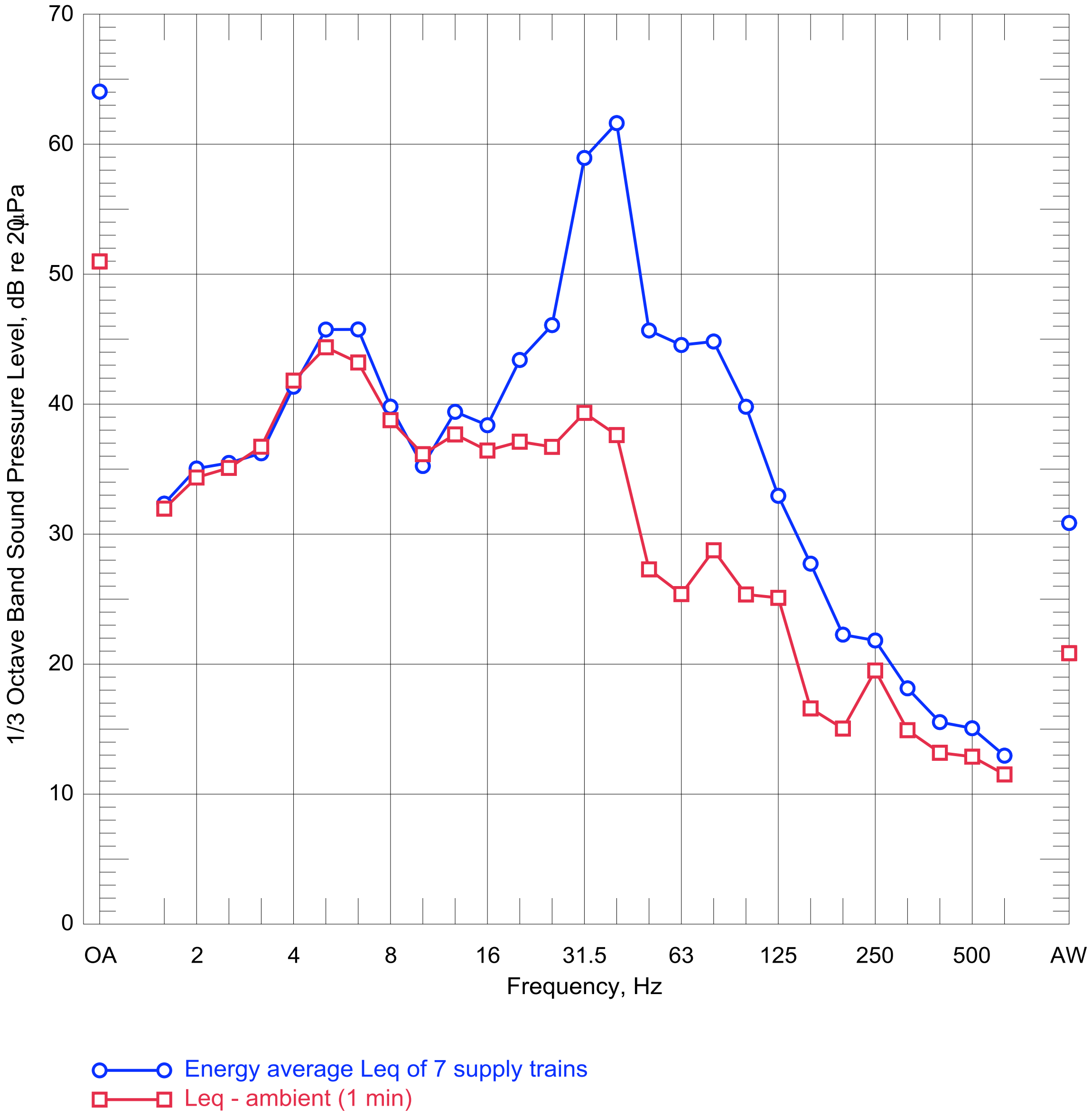


Figure 8 Energy average of six supply trains noise levels - [redacted] residence basement - Hamlin Street

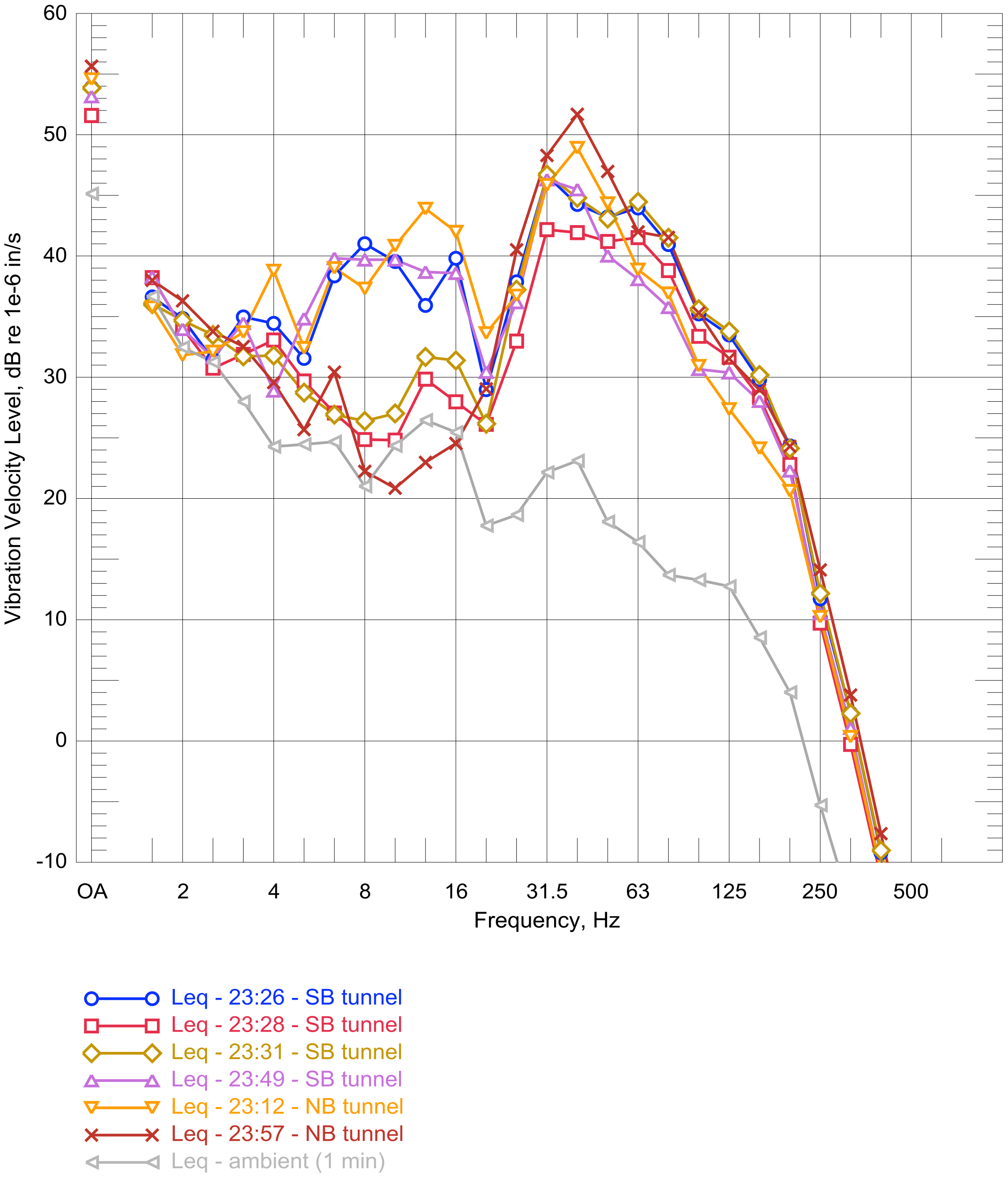


Figure 9 Average vibration velocity levels on basement floor in [redacted] residence ! Shelby Street ! six loci passbys ! both tunnels

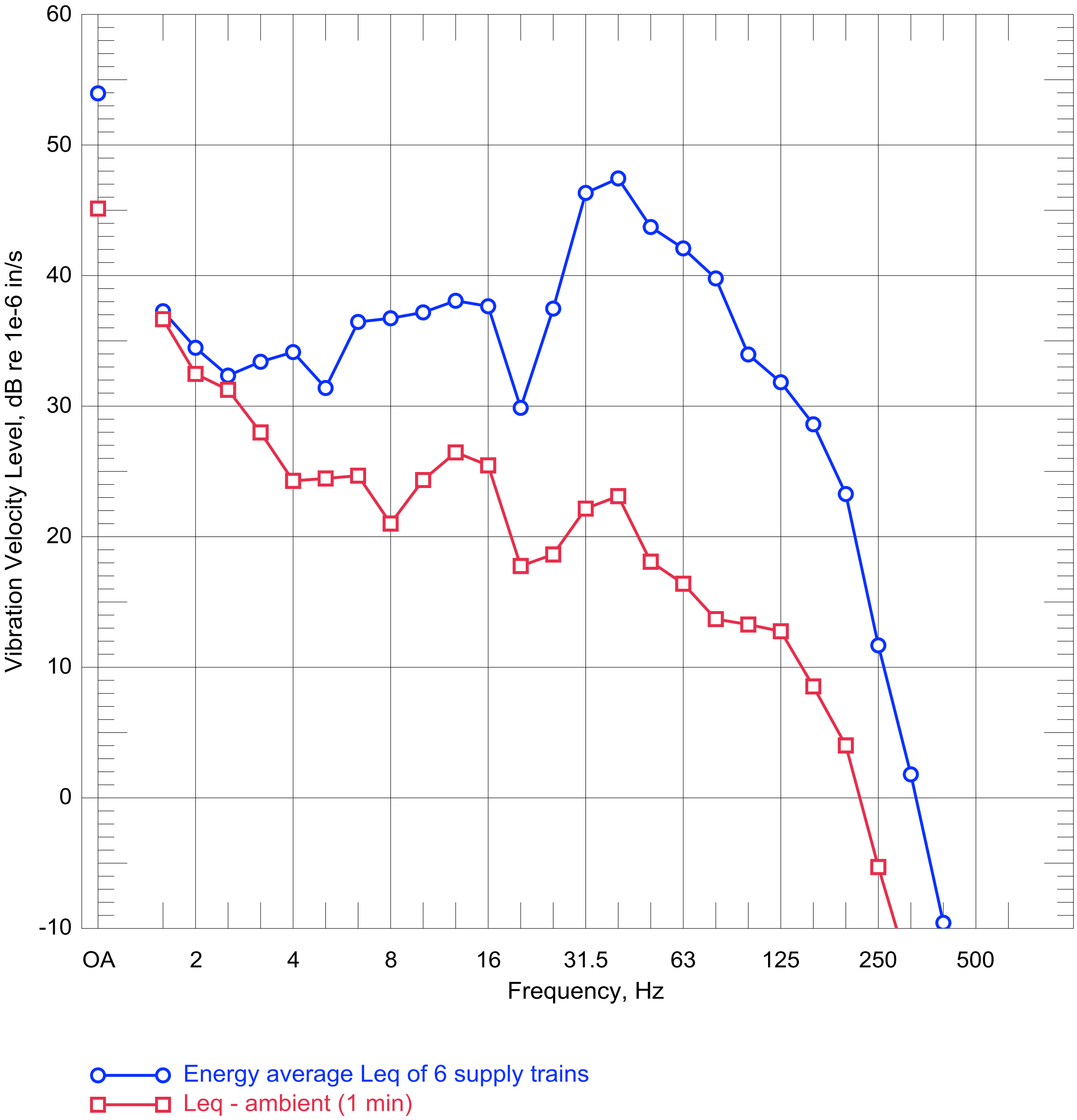


Figure 10 Energy average of six supply trains vibration levels - [redacted] residence basement floor - Shelby Street

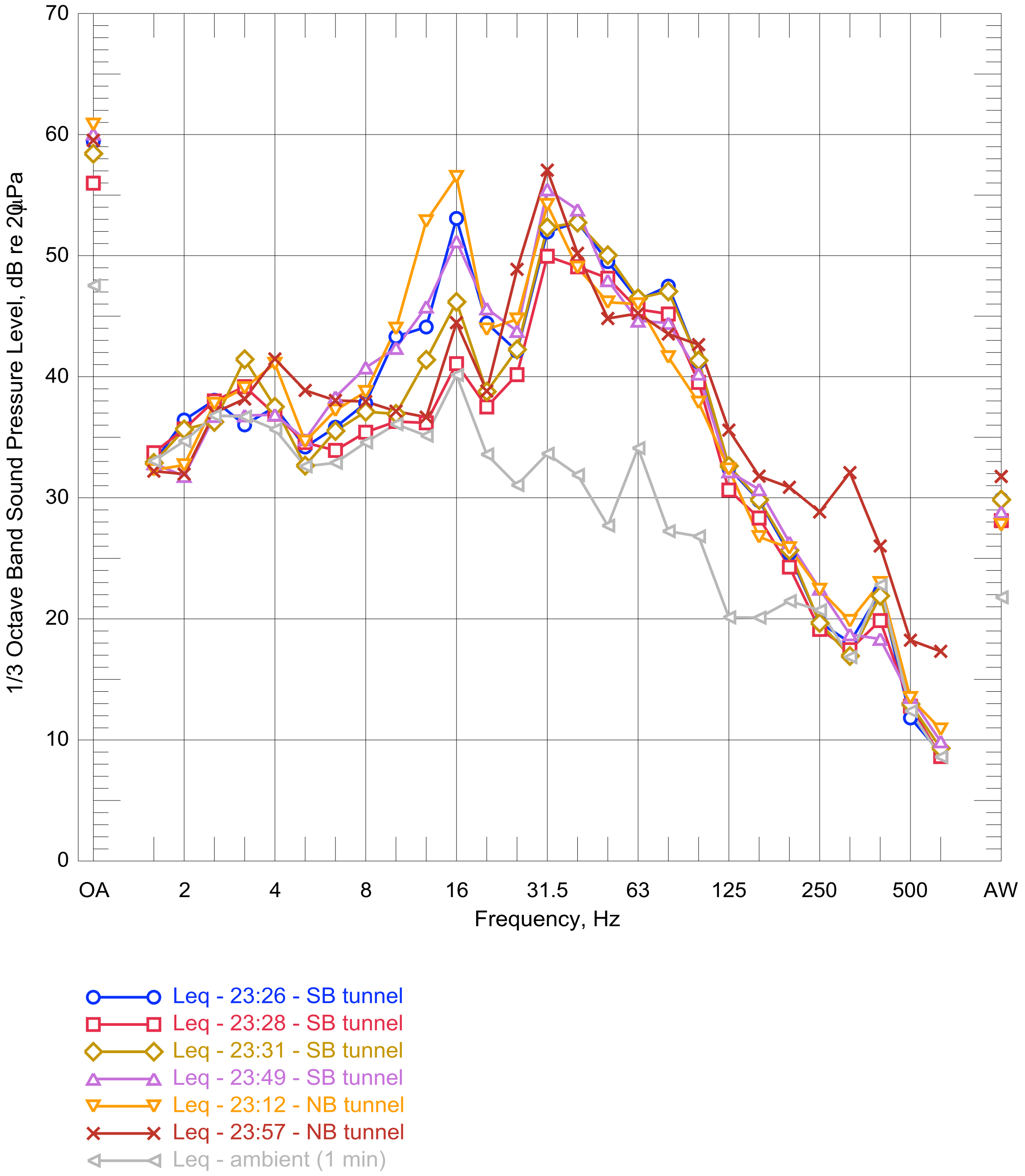


Figure 11 Noise levels measured during six loci passbys ! [redacted] residence basement - Shelby Street

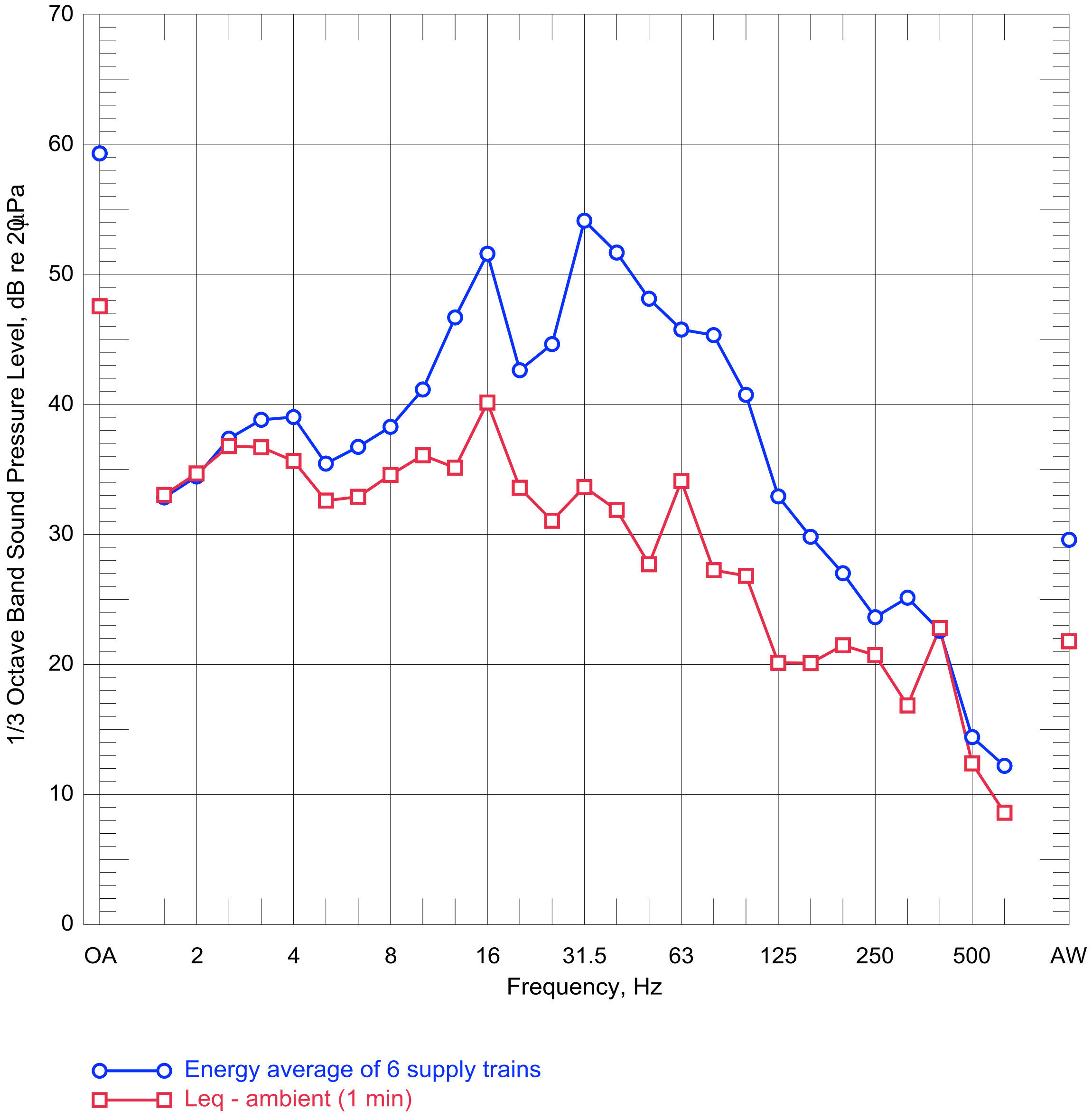


Figure 12 Energy average of six supply trains noise levels - [redacted] residence basement - Shelby Street

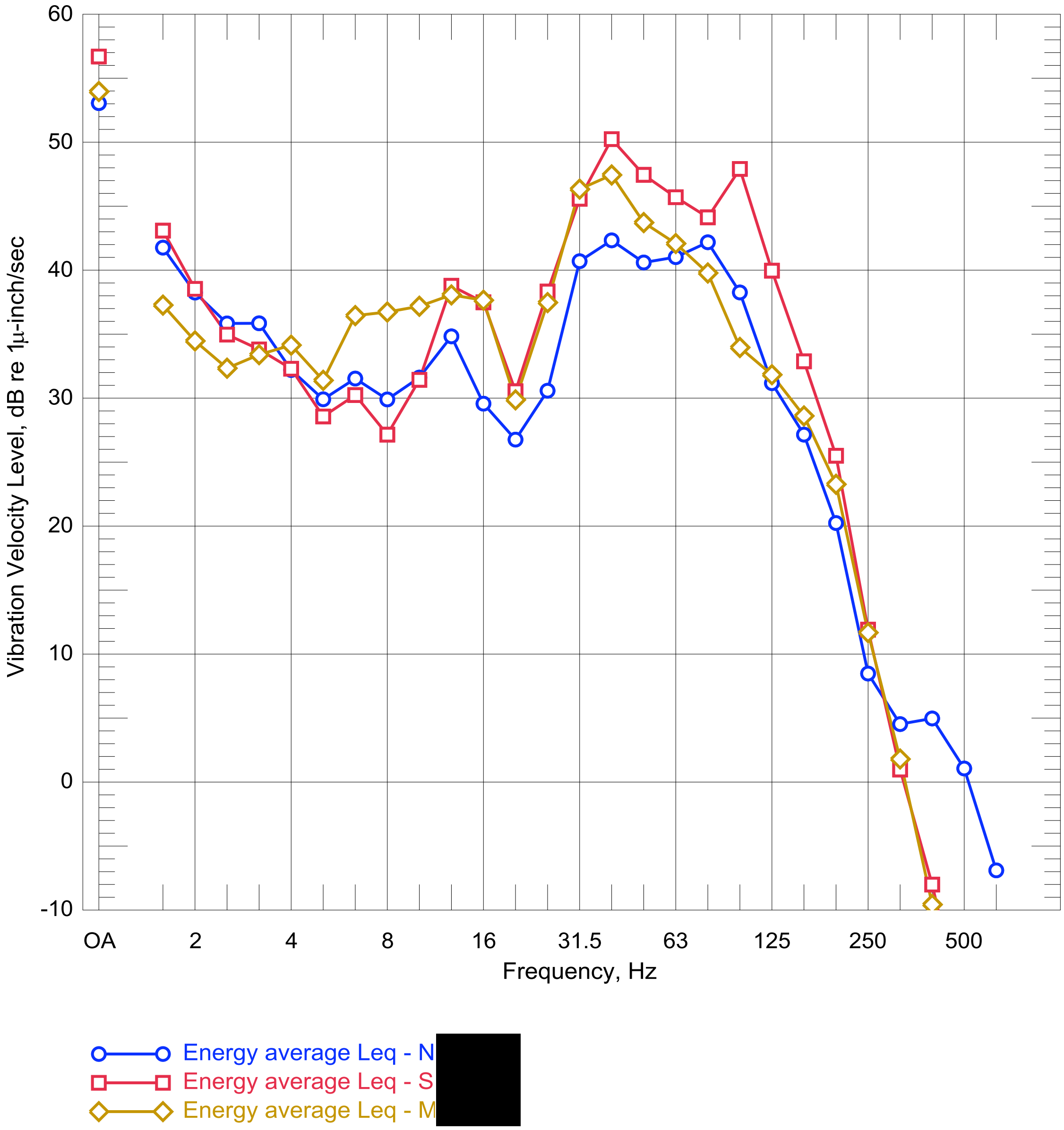
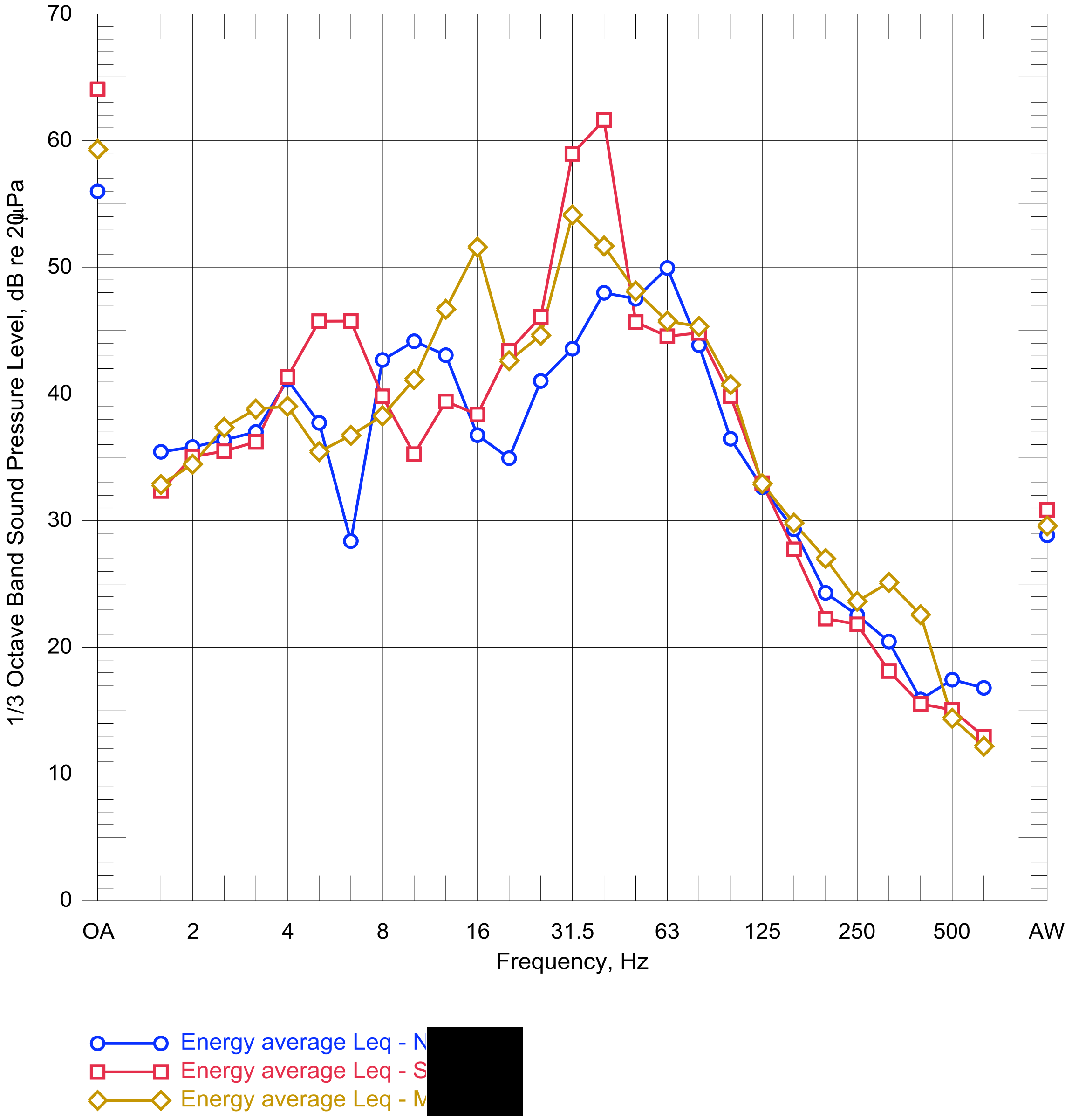


Figure 13 Comparison of energy average vibration levels due to supply train passbys at basement floors of three residences



[redacted]

Figure 14 Comparison of energy average noise levels due to supply train passbys in basements of three residences

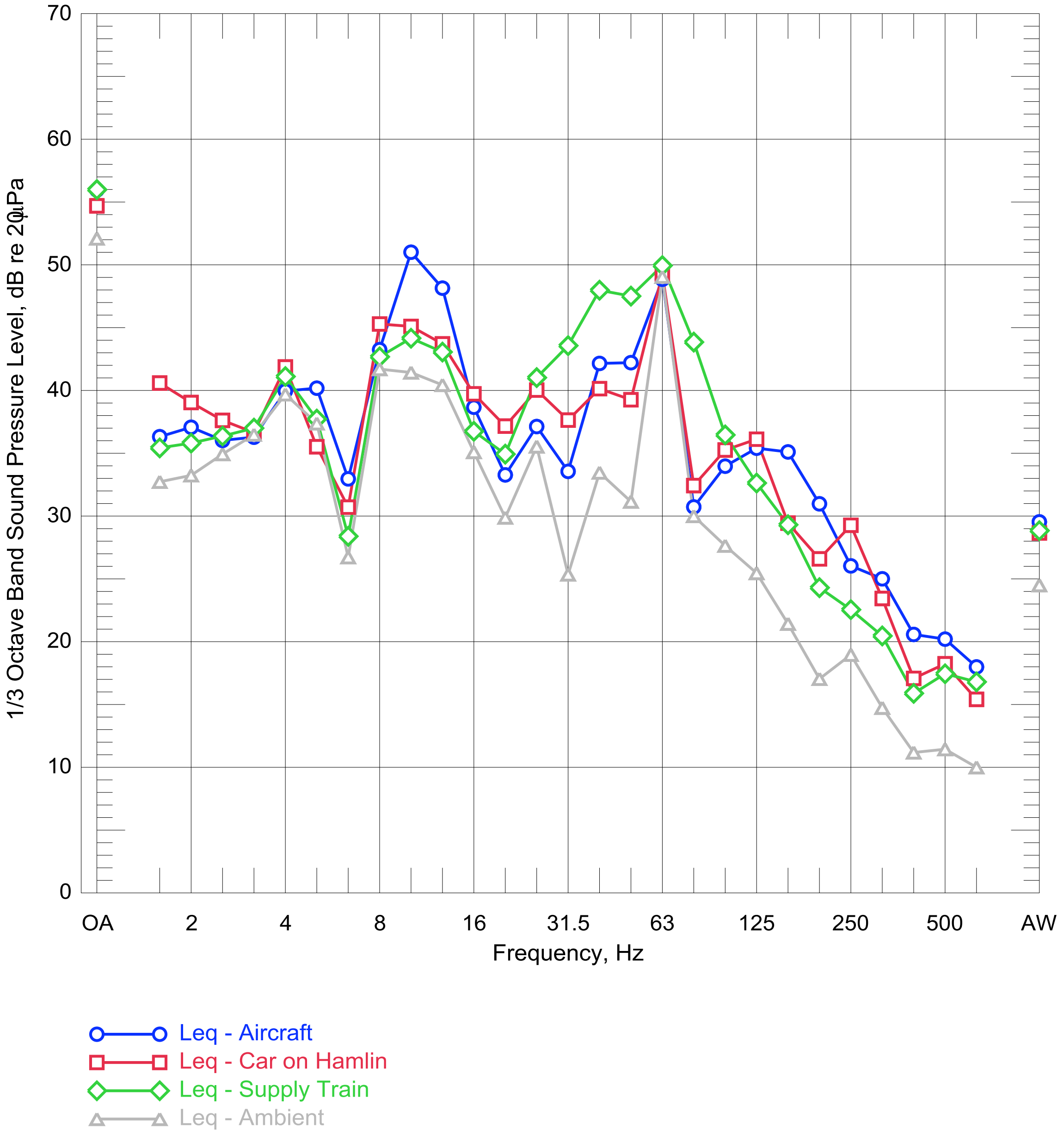


Figure 15 Comparison of interior noise levels due to air-borne and ground-borne sources - [redacted] residence

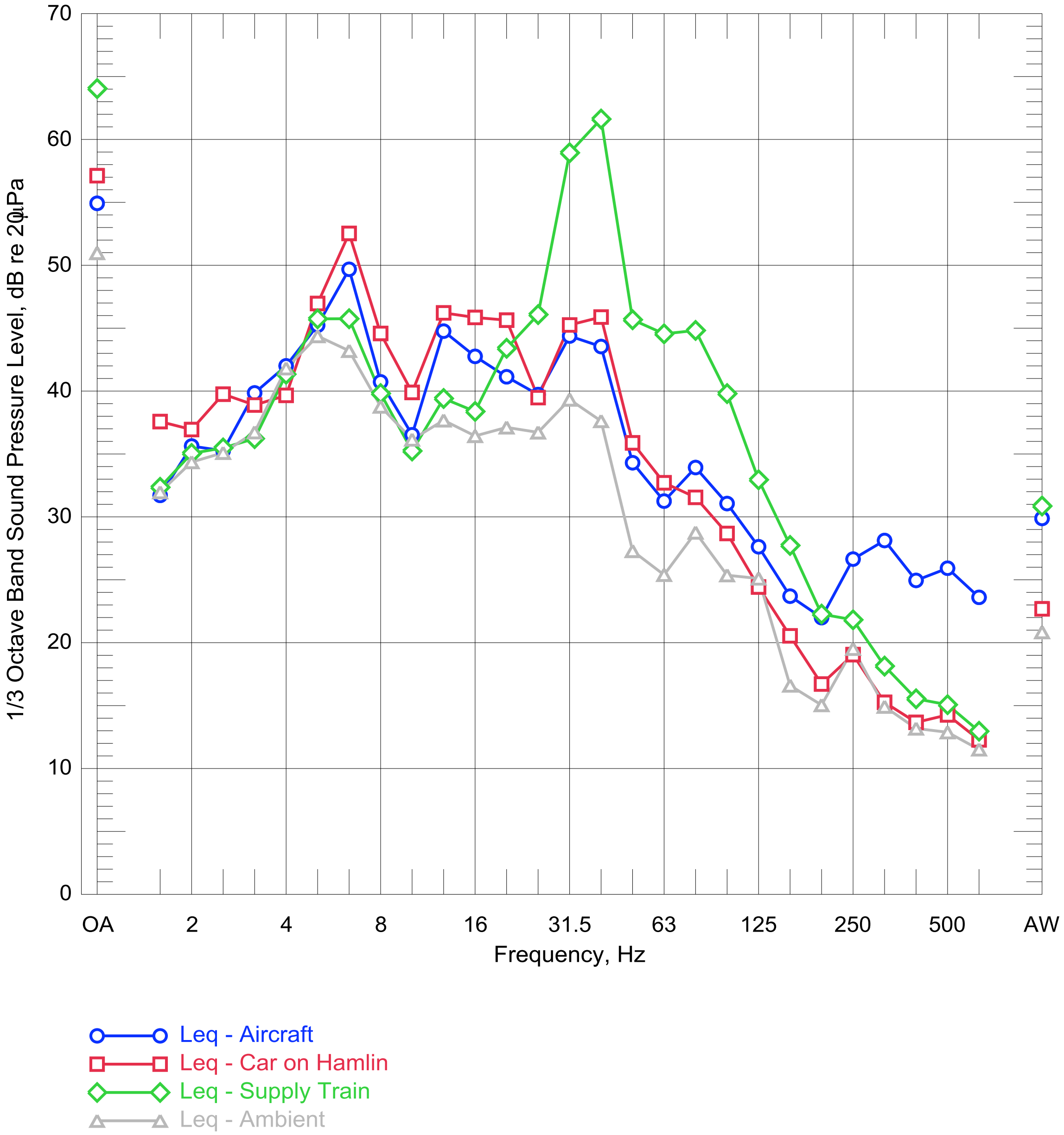


Figure 16 Comparison of interior noise levels due to air-borne and ground-borne sources
! [redacted] residence

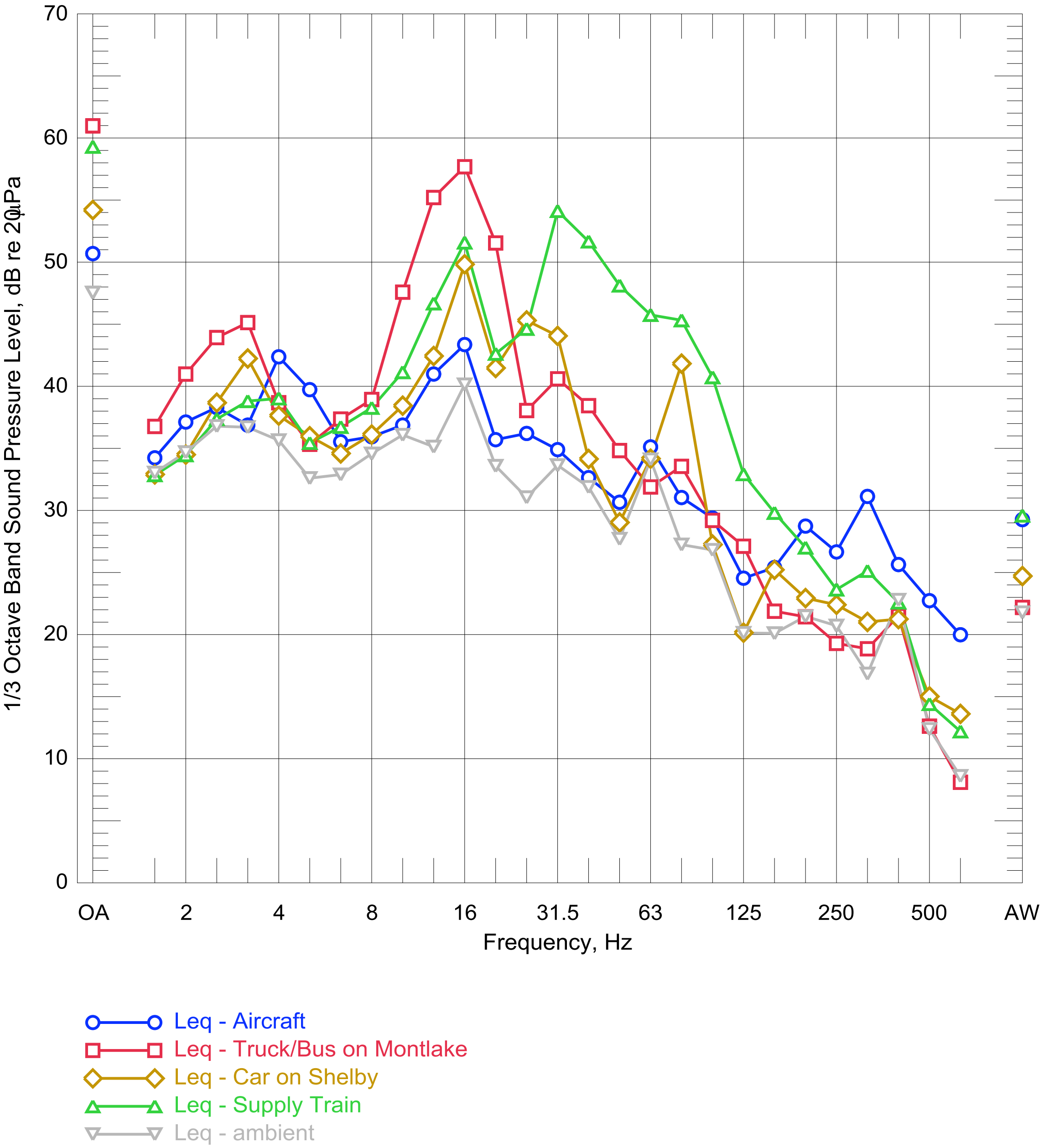


Figure 17 Comparison of interior noise levels due to air-borne and ground-borne sources - [redacted] residence

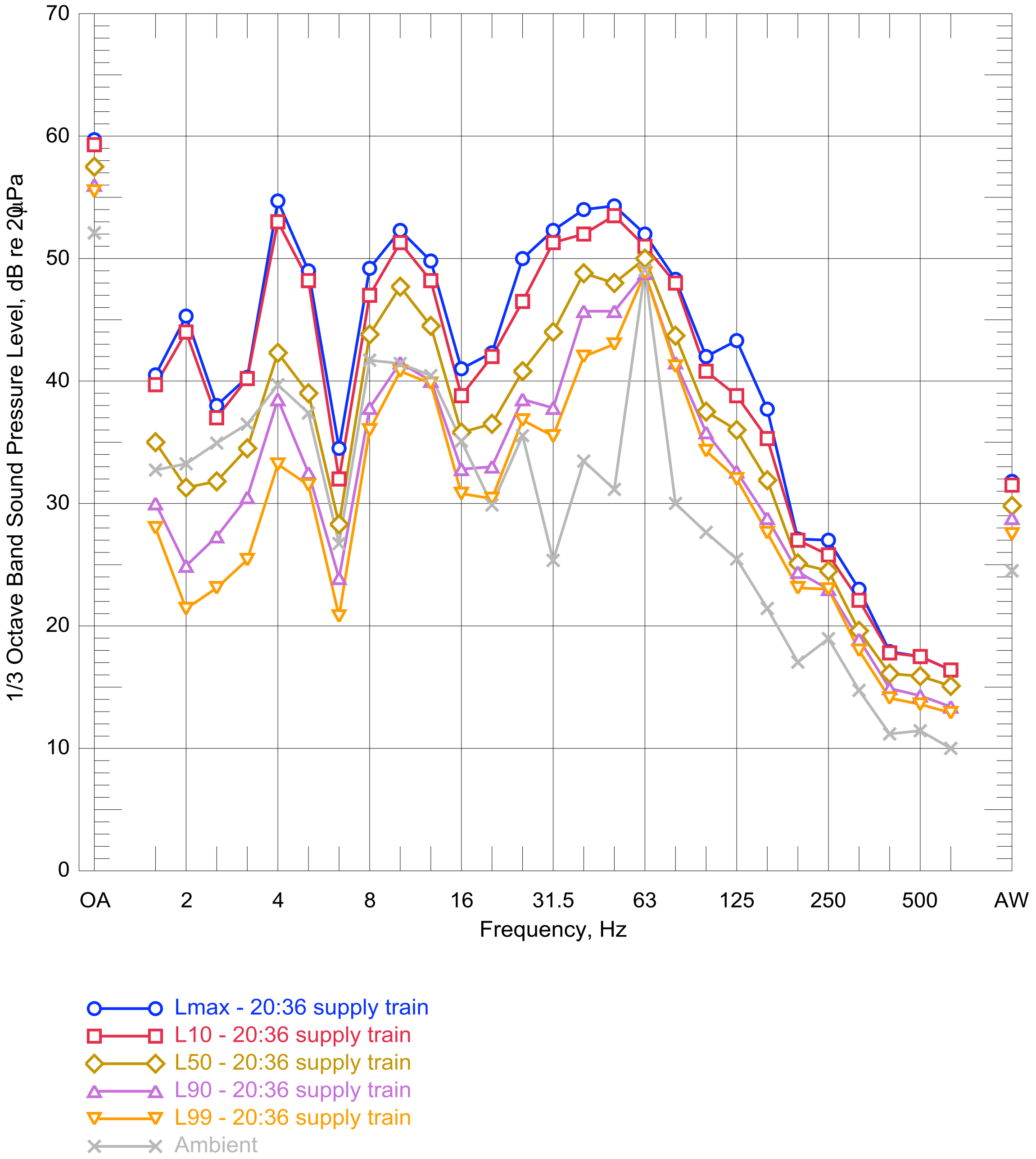


Figure 18 Supply train noise statistical descriptors - [redacted] residence

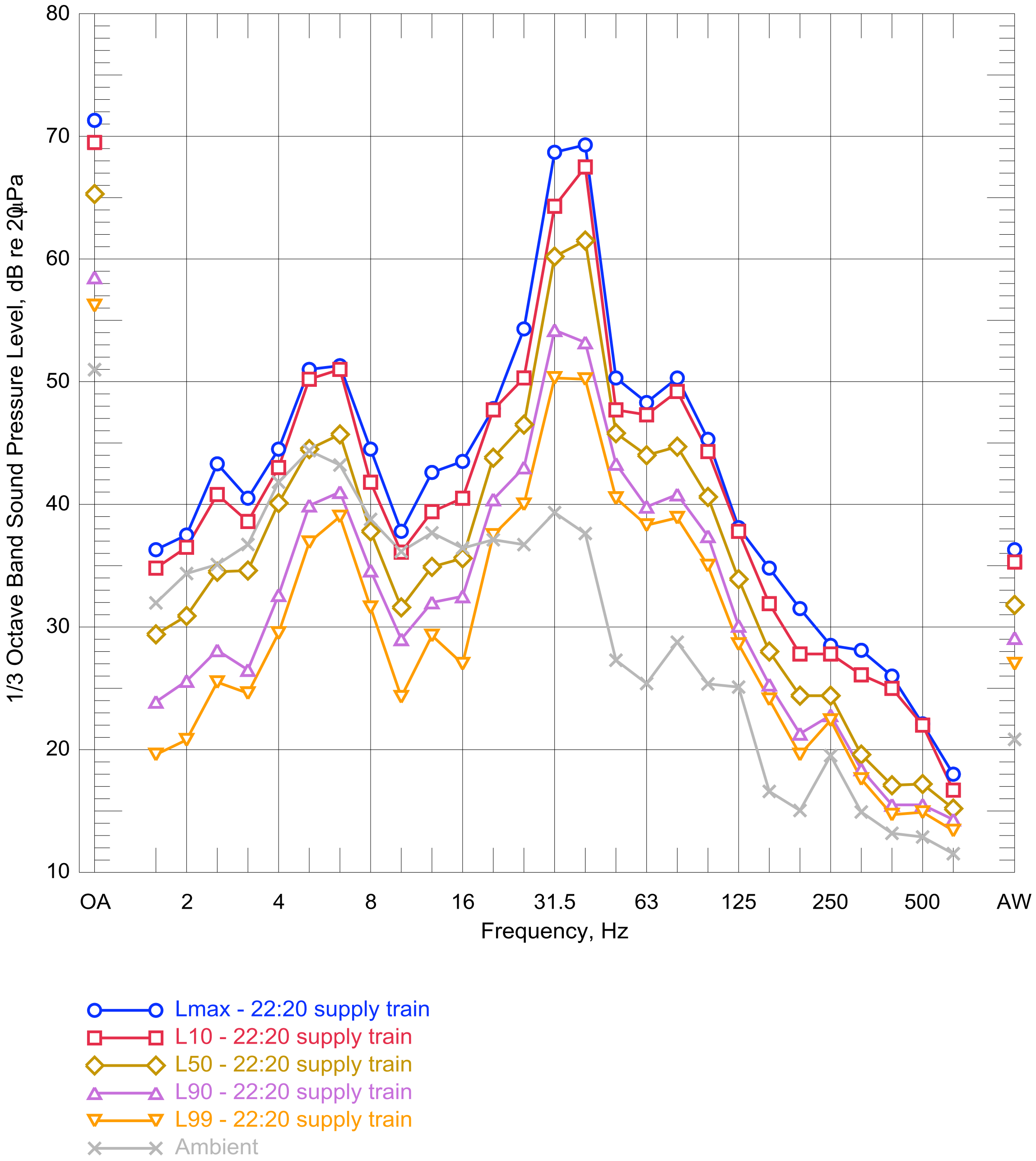


Figure 19 Supply train noise statistical descriptors - [redacted] residence

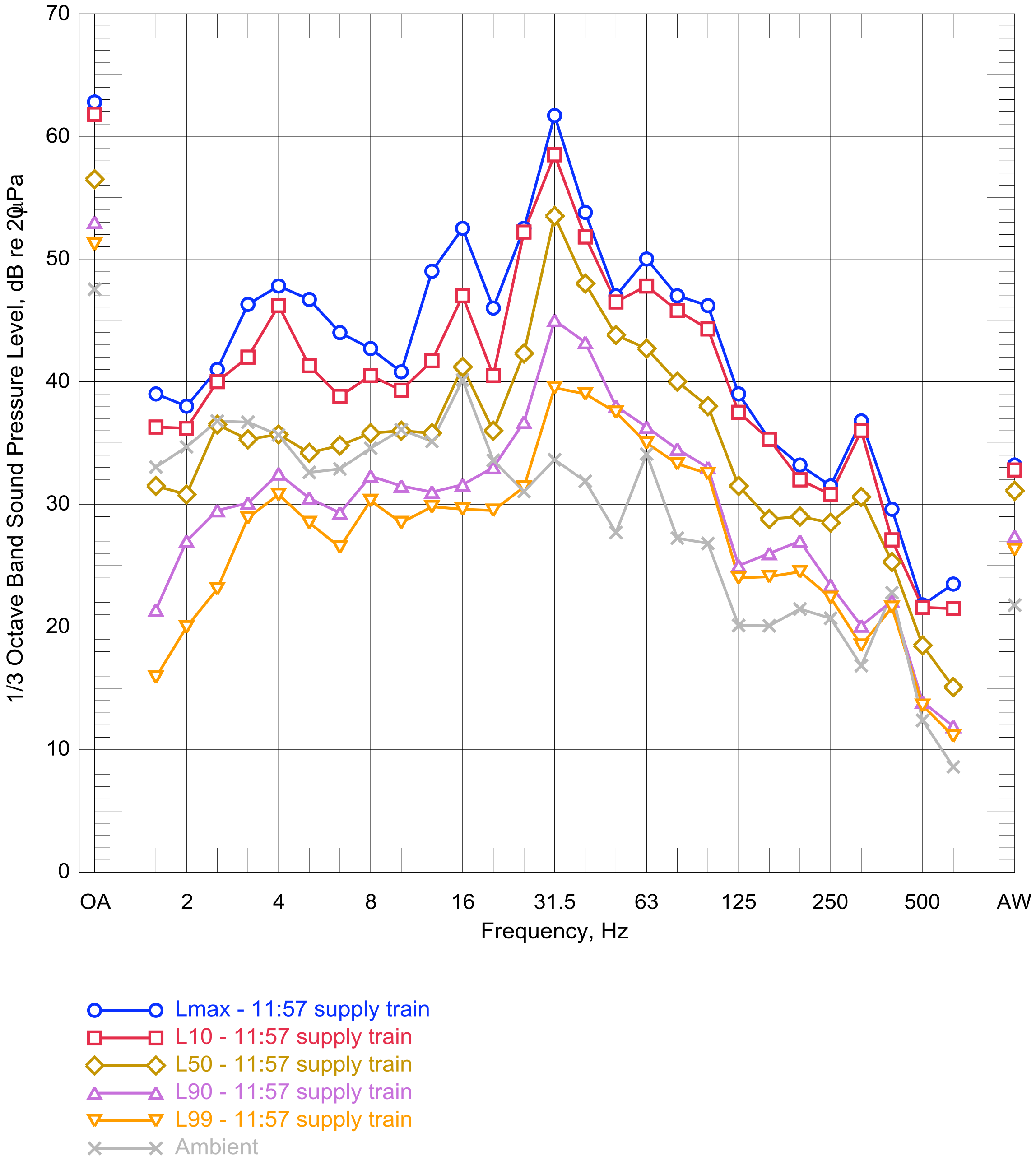


Figure 17 Supply train noise statistical descriptors - [redacted] residence

DESCRIPTION OF ACOUSTICAL TERMS

A-Weighted Sound Level (dBA):

The sound pressure level in decibels as measured on a sound level meter using the internationally standardized A-weighting filter or as computed from sound spectral data to which A-weighting adjustments have been made. A-weighting de-emphasizes the low and very high frequency components of the sound in a manner similar to the response of the average human ear. A-weighted sound levels correlate well with subjective reactions of people to noise and are universally used for community noise evaluations.

Airborne Sound:

Sound that travels through the air, as opposed to structure-borne or ground-borne sound.

Ambient Noise:

The prevailing general noise existing at a location or in a space, which usually consists of a composite of sounds from many sources near and far.

Decibel (dB):

The decibel is a measure on a logarithmic scale of the magnitude of a particular quantity (such as sound pressure, sound power, sound intensity) with respect to a standardized quantity.

Energy Equivalent Level / Equivalent Noise Level (Leq):

The level of a steady noise which would have the same energy as the fluctuating noise level integrated over the time period of interest. Leq is widely used as a single-number descriptor of environmental noise. Leq is based on the logarithmic or energy summation and it places more emphasis on high noise level periods than does L50 or a straight arithmetic average of noise level over time. This energy average is not the same as the average sound pressure levels over the period of interest, but must be computed by a procedure involving summation or mathematical integration.

Frequency (Hz):

The number of oscillations per second of a periodic noise (or vibration) expressed in Hertz (abbreviated Hz). Frequency in Hertz is the same as cycles per second.

Noise Level:

See Sound Pressure Level.

Octave Band - 1/3 Octave Band:

One octave is an interval between two sound frequencies that have a ratio of two. For example, the frequency range of 200 Hz to 400 Hz is one octave, as is the frequency range of 2000 Hz to 4000 Hz. An octave band is a frequency range that is one octave wide. A standard series of octaves is used in acoustics, and they are specified by their center frequencies. In acoustics, to increase resolution, the frequency content of a sound or vibration is often analyzed in terms of 1/3 octave bands, where each octave is divided into three 1/3 octave bands.

Sound Pressure Level (SPL):

The sound pressure level of sound in decibels is 20 times the logarithm to the base of 10 of the ratio of the RMS value of the sound pressure to the RMS value of a reference sound pressure. The standard reference sound pressure is 20 micro-pascals as indicated in ANSI S1.8-1969, "Preferred Reference Quantities for Acoustical Levels".

Structure-Borne Sound:

Sound propagating through building structure. Rapidly fluctuating elastic waves in gypsum board, joists, studs, etc.

Statistical Distribution Terms:

L99 and L90 are descriptors of the typical minimum or "residual" background noise (or vibration) levels observed during a measurement period, normally made up of the summation of a large number of sound sources distant from the measurement position and not usually recognizable as individual noise sources. Generally, the prevalent source of this residual noise is distant street traffic. L90 and L99 are not strongly influenced by occasional local motor vehicle passbys. However, they can be influenced by stationary sources such as air conditioning equipment.

L50 represents a long-term statistical median noise level over the measurement period and does reveal the long-term influence of local traffic.

L10 describes typical levels or average for the maximum noise levels occurring, for example, during nearby passbys of trains, trucks, buses and automobiles, when there is relatively steady traffic. Thus, while L10 does not necessarily describe the typical maximum noise levels observed at a point, it is strongly influenced by the momentary maximum noise level occurring during vehicle passbys at most locations.

L1, the noise level exceeded for 1% of the time is representative of the occasional, isolated maximum or peak level which occurs in an area. L1 is usually strongly influenced by the maximum short-duration noise level events which occur during the measurement time period and are often determined by aircraft or large vehicle passbys.