WILSON IHRIG
ACOUSTICS, NOISE & VIBRATION

CALIFORNIA
WASHINGTON
NEW YORK

MEMORANDUM

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Addressed to: Kyle Pepin, GFP

Prepared by: James T. Nelson, Ph.D., P.E. License DC #: PE920122

Subject: Building damage potential – Final Draft
WMATA Green Line
Task Order N0. 17-FQ15191-TSFA-005

DISTRICT OF COLUMBIA JAMES NELSON No. PE920122 Exp. 8/31/2018 LICENSED PROFESSIONAL ENGINEER

Peak particle velocities (PPV) produced by WMATA revenue service trains, road traffic, and internal residential sources were measured at various homes along the WMATA Green Line. The maximum observed peak particle velocities are summarized below in Table 1, which has been extracted from the report "Ground-Borne Noise and Vibration Evaluation." This table lists the maximum peak particle velocities observed during extended measurement periods over several hours, and thus includes data for several passbys by various types of trains, vibration caused by road traffic, and vibration caused by internals sources such as door closures and footfalls.

The highest events were observed at Site 1 (0.0801 ips PPV Longitudinal), and Site 2 (0.034 ips PPV Transverse). The highest vertical components were generally less than either the longitudinal or transverse. These magnitudes are anomalous relative to maximum particle velocities listed for Sites 3 through 15. Inspection of the logged data for Site 1 and 2 indicate that these events occurred either at the very beginning of the test period or at the very end of the test period. Review of these data indicate that the typical maximum peak particle velocities observed during periods involving numerous train passbys and other sources were of the order of 0.001 to perhaps 0.01 ips PPV. This is typical of ground vibration produced by rapid trains operating in tunnels.

Criteria for cosmetic and structural damage to buildings are generally much higher than the peak particle velocities observed at these homes. A peak particle velocity of 0.5 ips is considered the threshold of cosmetic cracking damage for transient vibration such as blasting, for which some modest cracking of plaster might occur. Further, the strains associated with incident ground vibration with peak magnitude 0.5 ips are comparable with the seasonal and diurnal strains due to temperature changes, and are also comparable with the strains induced by door slams.[1] Cosmetic cracking is a naturally occurring process in buildings. Whiffin[2] identifies a limit of 0.2 ips PPV for residences with plastered walls and ceiling, above which there is a risk of architectural damage but no structural damage. Whiffin further identifies a magnitude of 0.1 ips PPV below which there is

[1] Dowding, C. H., ., **Construction Vibrations**, Prentice Hall, Upper Saddle River, NJ., 1996, Pg. 186

[2] Whiffin, A. C. 1971. **A survey of traffic-induced vibrations**. (Report LR419.) Crowthorne, Berkshire, England: United Kingdom Department of Environment, Road Research Laboratory.

"virtually" no risk of architectural damage to normal buildings, and a limit of 0.08 ips PPV below which there is no risk to ruins or ancient monuments. These criteria given by Whiffin are the most conservative of building damage criteria that have been recently listed, for example, by the California Department of Transportation.[3] The damage criterion employed by WMATA for new construction is 0.12 ips PPV. The WMATA damage criterion is thus conservative with respect to accepted damage criteria for threshold cracking. Vibration velocities in excess of these limits do not necessarily induce cracking, as pointed out by Dowding.[4]

Table 1: PPV Vibration Data for Residential Survey Sites

Potential for Building Vibration Damage Assessment							
Site #[1]	> 0.12 in/sec PPV in any direction?	Average PPV (in/sec)			Highest PPV (in/sec)		
		Tran	Vert	Long	Tran	Vert	Long
1	NO	0.0012	0.0008	0.0005	0.0236	0.0062	0.0801
2	NO	0.0034	0.0034	0.0021	0.0340	0.0250	0.0120
3	NO	0.0012	0.0005	0.0004	0.0016	0.0071	0.0016
6	NO	0.0031	0.0032	0.0021	0.0050	0.0130	0.0070
7	NO	0.0006	0.0005	0.0003[2]	0.0012	0.0118	0.0016
9	NO	0.0029	0.0029	0.0020	0.0030	0.0070	0.0040
10	NO	0.0031	0.0032	0.0027	0.0110	0.0230	0.0170
12	NO	0.0032	0.0030	0.0021	0.0180	0.0080	0.0270
13	NO	0.0005	0.0006	0.0003[2]	0.0022	0.0115	0.0102
15	NO	0.0030	0.0029	0.0020	0.0080	0.0140	0.0070

[1] PPV vibration was only measured at residential measurement sites.
[2] Resolution of monitoring equipment is 0.00031 inches per second.
PPV = peak particle velocity, inches per second

None of the data collected along the WMATA Green Line for operating trains approach or exceed even the most conservative of threshold damage criteria. Thus, the probability of cosmetic damage, or, for that matter, structural or foundation damage, to buildings along the WMATA Green Line, caused by vibration from rail transit trains is virtually nil.

[3] **Transportation- and Construction-Induced Vibration Guidance Manual**, California Department of Transportation, September 2013

[4] Dowding, C. H., **Construction Vibrations**, Prentice Hall, Upper Saddle River, NJ., 1996, Pg. 168

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Ground-Borne Noise and Vibration Evaluation

Final Draft

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Prepared for:
Washington Metropolitan Area Transit Authority (WMATA)

GFP
A Gannett Fleming/Parsons
JOINT VENTURE
800 I ST, NW - 6th Floor
Washington, DC 20001

Questions about this report should be directed to WMATA's office of External Relations

WI Project 17-009

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1 Executive Summary

Introduction. Wilson Ihrig conducted an extensive measurement program to investigate reports by residents about increased levels of noise and vibration along subway portions of the Washington Metropolitan Area Transit Authority (WMATA) Green Line. Some residents have inquired about the potential for building damage due to train vibration.

This study addresses the following questions:

1. Are ground-borne noise and/or vibration levels inside homes exceeding design criteria?

2. Is vibration causing any damage to residential structures along the alignment?

3. Have any recent changes to the system caused an increase in noise and/or vibration?

These questions are addressed below.

Method. WMATA compiled a list of reports pertaining to ground-borne noise and vibration from residents along the Green Line. In this area, the Green Line tracks are located underground, generally along New Hampshire Avenue. Of the 48 residences from which reports have been received, ten were selected for field measurements by Wilson Ihrig to cover the geographic range of reports and combinations of tunnel and track construction. In addition to the measurements at selected residences, ground vibration was also measured at six outdoor locations to assess areas where no home was surveyed and to measure the rate of vibration attenuation with distance.

The survey was conducted in June and August 2017. Measurements in the homes typically covered a three- to four-hour period of rail operations. In most cases, vibration was measured in two to four rooms inside the home and at one or two locations outside the home. Noise was typically measured in one or two rooms inside the home. At the outdoor-only locations, vibration was measured at multiple distances from the tunnels. In addition to measuring noise and vibration, the rails in the areas near the ten residences were inspected and the rail head surface roughness was measured at most locations using a device made specifically for this purpose.

Assessment Against Design Criteria. The criteria used for this assessment are those that were established when the Mid-City Segment of the Green Line was designed in the late 1980s and early 1990s. The ground-borne noise criteria were not exceeded in any residence. The vibration criteria were exceeded at four residences by 8% to 29% of train passbys. There were no exceedances of the vibration criteria at the other six residences.

Assessment of Potential for Building Damage. All measured vibration levels are well below that at which structural or architectural (cosmetic) damage, such as the propagation of existing cracks in plaster and drywall, could occur. There is a large difference between vibration levels that can be felt and vibration levels that can cause even minor damage.

Assessment of Changes in Noise and/or Vibration Levels. Because numerous homeowner reports were received in a relatively short period of time after years of operation, it is plausible that a change in the system has resulted in a noticeable increase in noise and/or vibration.

Although rail roughness can change over time, the change is typically not abrupt. Rail roughness measurements indicate that the rails are wearing consistently along the alignment. No major rail defects such as spalls, which can occur precipitously, were observed.

WMATA is currently operating five series of trains from four different manufacturers on the Green Line. Data collected inside residences indicate that the noise levels from all train series, including the 7000 Series, are below the design criteria. On average, the 7000 Series noise levels are noticeably louder than the other series cars in eight of the nine homes in which train noise was detectable, although some individual vehicles of the older series do produce comparable levels. See Table 10 for a summary of the ground-borne noise measurement results. Transit system design criteria are not intended to make transit systems inaudible, but, rather, to make the noise levels acceptable in the context of an urban setting that includes traffic, aircraft, and other transportation noise sources.

Although vibration levels from the 7000 Series are also higher, on average, than those from the other vehicles, the vibration levels in most of the residences are still below the level that is widely considered to be the threshold of perceptibility. Trains that generate vibration above the design criteria include cars from most series, not just the 7000 Series. See Table 11 for a summary of the vibration measurement results.

2 Introduction

Wilson Ihrig conducted a survey of ground-borne noise and vibration levels generated by trains operating along the Washington Metropolitan Area Transit Authority (WMATA) Green Line (E Route) in response to reports of vibration and noise by homeowners. The homeowners have indicated that the ground-borne noise and vibration from subway trains is annoying and that this is a relatively recent occurrence (beginning mid- to late-2016). Further, some homeowners have expressed concern regarding the potential for vibration damage to their homes.

2.1 Purpose

The primary purpose of the survey is to measure ground-borne noise and vibration levels during normal revenue operations and compare them to relevant criteria. A secondary purpose is to ascertain which factors, if any, produce more vibration than the others.

2.2 Background

WMATA compiled a list of residences where homeowners have reported elevated noise and/or vibration levels. Candidate residences for measurement were identified based on homeowner reports of noise and vibration, proximity of the residence to the subway or stations, side of the track (outbound or inbound side), and track design details. The locations of the residences were reviewed in conjunction with track and tunnel design details. Candidate measurement locations were identified to cover the geographic range of reports and the distance from the tunnels as well as combinations of tunnel type and rail fixation type. The survey program was designed to provide a broad set of data documenting the noise and vibration levels inside residences. Vibration data were also collected at outdoor-only locations to investigate areas where no residence was available for measurements and to provide a better understanding of how vibration propagates away from the subway tunnels.

3 Introduction to Decibel Scales

Most people equate decibel readings with sound levels, but both noise and vibration levels may be quantified using a decibel scale.

Sound, or noise, levels are expressed in terms of decibels (dB) using the root mean square (RMS) pressure as measured by a microphone. All noise levels in this report use a decibel scale reference of 20 micro-Pascals (20 μPa). Because human hearing does not respond equally to all frequencies (e.g., humans cannot hear a dog whistle), the sound signal is often passed through a frequency filter that approximates typical human hearing response. This process is called A-weighting, and the resulting, single-number sound level reading is denoted by "dBA", meaning decibels that have been A-weighted. It is also possible to analyze the sound signal into constituent frequency components. While there are many ways this can be done, the most common way when dealing with transportation noise is to resolve the sound data into 1/3-octave bands. When plots of 1/3-octave band spectra are presented in this report, the individual band levels are not A-weighted.

In this report, vibration levels are expressed in terms of decibels using the root mean square (RMS) vibration velocity. All vibration decibels in this report use a decibel reference of 1 micro-inch per second (1 μin/sec). To avoid confusion with sound level decibels, vibration decibels are denoted by "VdB". No weighting is used when calculating the *overall* vibration level, the single-number level that includes the contributions of all frequencies (denoted "OA"). Like sound levels, vibration levels can be resolved into constituent parts expressed as 1/3-octave band levels.

4 Ground-Borne Noise and Vibration Assessment Criteria

4.1 WMATA Design Criteria

WMATA first adopted design criteria to guide the engineering work for new facilities in 1970. By the late 1980s, when the Mid-City Segment of the Green Line was designed, criteria had been developed to minimize annoyance from airborne noise, ground-borne noise, and vibration. The criteria at that time did not include damage criteria. In 2016, WMATA issued its current design criteria. For single-family residences, the current WMATA ground-borne noise criteria are the same as those in use when the Mid-City Segment of the Green Line was designed, whereas the current vibration criteria are slightly (2 VdB) higher. In other words, the vibration design criterion in homes along the Mid-City Segment is 2 VdB less than it would be if that segment were being designed today.

Most locations assessed in this report are in Columbia Heights and Petworth in Northwest Washington D. C., along the Green Line E-Route Mid-City Segment that was designed in the late 1980s and early 1990s. For these locations, the assessment levels used in this analysis are the design criteria taken directly from the environmental study *Noise and Vibration Impact Analysis, Green Line E-Route Mid-City Segment, Design Sections E-2c, E-3, and E-4*[1]. Because the measured ambient noise levels along New Hampshire Avenue NW were fairly high at the time of that study, that corridor was treated as a "commercial" community area category, so the ground-borne noise criterion for single-family homes was 40 dBA and the vibration criterion was 70 VdB.

The residences in Michigan Park in Northwest Washington, D. C. are along sections of tunnel that were constructed prior to the Mid-City Segment. The documentation containing the noise and vibration analyses originally conducted for these tunnels is not currently available; however, the design criteria used for the Michigan Park sections are known. As the design was completed before the first transit-specific criteria were developed, the designers utilized criteria that had been developed for heating, ventilation, and air-conditioning (HVAC) systems to assess ground-borne noise. Since this accommodation is outdated, the WMATA design criteria used in the Mid-City Segment study are being applied to the Michigan Park locations. It is assumed that the community area category for this area is either "average residential" or "high density residential", either of which results in a ground-borne noise criterion of 35 dBA and a vibration criterion of 70 VdB.

[1] Wilson, Ihrig & Associates, Inc., Noise and Vibration Impact Analysis, Green Line E-Route Mid-City Segment, Design Sections E-2c, E-3, and E-4, Washington Metropolitan Transit Authority (WMATA), Revised November 1990.

The applicable ground-borne noise and vibration criteria for each site are presented in Section 7, Site-Specific Field Studies.

4.2 FTA Criteria

The Federal Transit Administration (FTA), developed guidelines to comply with federal laws related to the assessment of ground transportation noise and vibration impacts for federal or federally supported projects. The FTA published guidelines, titled *Transit Noise and Vibration Impact Assessment*[2] (FTA guidance manual), contain methodology and criteria to assess noise and vibration impacts from mass transit.

The FTA criteria are presented here as reference information only to provide context for the reader. The FTA methodology includes three levels of detail for assessing ground-borne noise and vibration: Screening, General Assessment, and Detailed Analysis. The General Assessment deals only with the overall vibration velocity level and A-weighted sound level. The General Assessment criteria are presented in Table 1. The ground-borne vibration criterion for residences adjacent to a transit line with more than 70 trains per day is 72 VdB. The ground-borne noise criterion for residences adjacent to a transit line with more than 70 trains per day is 35 dBA.

[2] U.S. Federal Transit Administration, "Transit Noise and Vibration Impact Assessment" (Final Report No. FTA-VA-90-1003-06, May 2006)

Table 1: FTA Ground-Borne Vibration and Ground-Borne Noise Impact Criteria for General Assessment

Land Use Category	GBV Impact Levels (VdB re: 1 µin/sec)			GBN Impact Levels (dB re: 20 µPa)		
	Frequent Events[1]	Occasional Events[2]	Infrequent Events[3]	Frequent Events[1]	Occasional Events[2]	Infrequent Events[3]
Category 1: Buildings where vibration would interfere with interior operations.	65 VdB[4]	65 VdB[4]	65 VdB[4]	N/A[5]	N/A[5]	N/A[5]
Category 2: Residences and buildings where people normally sleep.	72 VdB	75 VdB	80 VdB	35 dBA	38 dBA	43 dBA
Category 3: Institutional land uses with primarily daytime use.	75 VdB	78 VdB	83 VdB	40 dBA	43 dBA	48 dBA

Source: FTA 2006

1 "Frequent Events" is defined as more than 70 vibration events of the same kind per day.

2 "Occasional Events" is defined as between 30 and 70 vibration events of the same kind per day.

3 "Infrequent Events" is defined as fewer than 30 vibration events of the same kind per day.

4 This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. Vibration-sensitive manufacturing or research will require detailed evaluation to define the acceptable vibration levels. Ensuring lower vibration levels in a building often requires special design of the HVAC systems and stiffened floors.

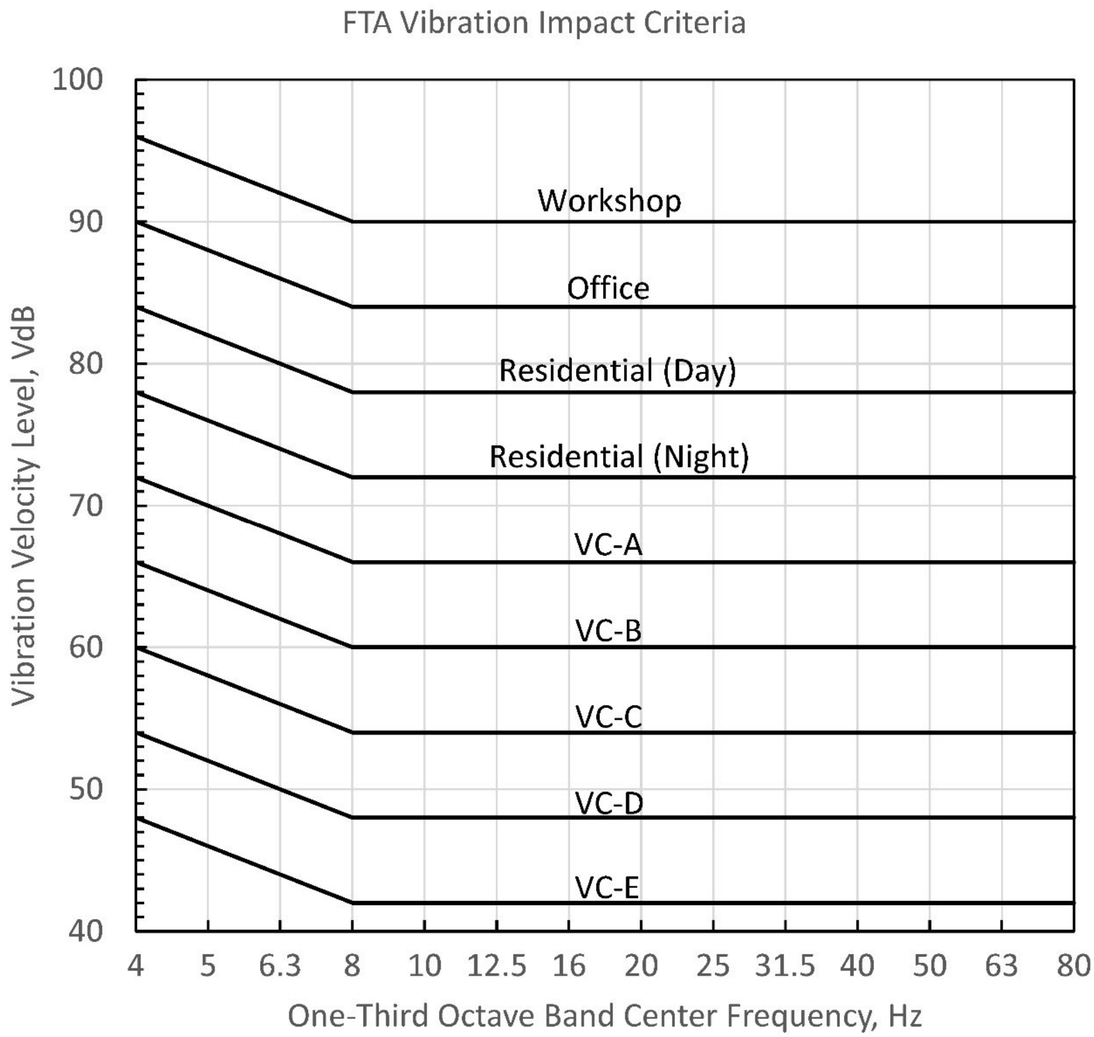
5 Vibration-sensitive equipment is not sensitive to ground-borne noise.

GBV = ground-borne vibration

GBN = ground-borne noise

N/A = not applicable

The FTA Detailed Analysis is more complex and also considers the frequency spectrum of the noise and vibration. The Detailed Analysis ground-borne vibration criteria are expressed in terms of 1/3-octave band velocity spectra as shown in Figure 1. The criterion for residences, indicated as Residential (Night), is 72 VdB in the 1/3-octave bands between 8 to 80 Hz. The ground-borne noise criteria for a Detailed Analysis are the same as those in Table 1.



Source: FTA 2006

Figure 1: FTA Criteria for Detailed Vibration Analysis

5 Building Vibration Damage Thresholds

Vibration annoyance criteria such as those presented above are an order of magnitude lower than vibration damage thresholds, so if the annoyance criteria are not exceeded, there is no possibility of physical damage.

WMATA vibration building damage criteria were not in place when the Mid-City Segment of the Green Line was designed. In the absence of such criteria, the current WMATA vibration damage thresholds for minimizing risk of physical damage to buildings during construction are presented below in Table 2. The WMATA vibration damage criteria are expressed in terms of the peak particle velocity (PPV) vibration, which is the appropriate metric for assessing building damage.

Table 2: WMATA Building Damage Assessment Criteria

Maximum Ground Vibration Magnitude	Application
0.20 in/sec PPV in any direction	For buildings that are in generally sound condition.
0.12 in/sec PPV in any direction	For buildings or historical monuments that are considered particularly fragile (as determined by a competent structural engineer) due either to the method of construction or a weakened condition resulting from the age of the structure.

Source: WMATA Manual of Design Criteria, Release 9, Revision 3, November 2016
PPV = peak particle velocity, inches per second

The FTA guidance manual also provides guideline vibration damage criteria for various building structural categories. Those are provided for reference purposes in Table 3. The FTA vibration damage criteria are presented in terms of PPV. The table also includes the approximate RMS level based on a crest factor of 4, representing a PPV to RMS difference of 12 VdB. These approximate RMS vibration damage levels can be useful as a point of reference.

Table 3: FTA Construction Vibration Damage Criteria

Building Category	PPV (in/sec)	Approximate L_v[1]
I. Reinforced-concrete, steel or timber (no plaster)	0.5	102
II. Engineered concrete and masonry (no plaster)	0.3	98
III. Nonengineered timber and masonry buildings	0.2	94
IV. Buildings extremely susceptible to vibration damage	0.12	90

Source: FTA 2006
[1] RMS velocity in VdB (re: 1 µin/sec).
PPV = peak particle velocity
L_v = vibration velocity level

6 Measurement and Analysis Methodology

6.1 Instrumentation and Calibration

All measurement instrumentation was calibrated with National Institute of Standards and Technology (NIST) traceable calibration signals. Refer to Appendix A for a summary of all instrumentation and calibration documentation.

6.2 Residential Measurements

WMATA and Wilson Ihrig coordinated access to ten residential survey locations for measurements. Measurements were performed in the morning/daytime or afternoon/evening. Our understanding is that WMATA was operating normally during all of the measurement periods.

Most data were collected with measurement personnel on-site to monitor field recordings and observe train passby noise and vibration. Observations of outside street traffic were also made during the measurements to note heavy trucks, buses, and other road vehicles that might cause interfering vibration. Activity by residents within the houses were also observed and noted. The measurements made at residential locations are referred to as *attended measurements*.

The attended measurement objective was to obtain data for approximately ten passbys of 7000 Series trains and ten passbys of non-7000 Series trains in each direction during both rush hour and non-rush hour service. Special attention was paid to the 7000 Series vehicles because the reports from residents began around the same time as these vehicles were introduced to the system. This objective was not always possible at each location due to the relative numbers of each type of vehicle put into service on the day of the measurement.

Three types of attended measurements were conducted at each residential site, as described below.

- **RMS Vibration**: The typical setup included one vibration sensor in the basement or lowest floor, one vibration sensor on the first floor, one vibration sensor on the second floor (if applicable), and one vibration sensor outside of the building. Based on feedback from residents about where vibration from trains is of concern and the layouts of some residences, additional vibration sensors were positioned at other locations. These sensors measure actual vibration signals (analogous to audio signals) used to determine passby vibration levels for assessing annoyance. Refer to Section 6.4.3 for vibration analysis details.

- **Ground-Borne Noise**: One microphone was positioned on the lowest habitable floor in a room where the resident indicated ground-borne noise from trains is of concern. Based on feedback from residents and the layouts of some residences, an additional microphone was positioned at another location. Refer to Section 6.4.3 for ground-borne noise analysis details.

- **Peak Particle Velocity (PPV)**: One specialized PPV vibration monitor was placed in the basement or on lowest floor to log PPV vibration data. PPV vibration data are used to assess the propensity for cosmetic or architectural damage. Refer to Section 6.5 for PPV vibration data analysis details.

The vibration sensors were connected with cables to portable data recorders at a central location on the building property where the data was monitored for quality during the recording process. During the measurement period within each residence, movement within the residence was avoided or kept to a minimum.

The microphones recorded sound in the residence for post-processing. The microphones recorded all sounds, including voices and other noises within the residence; residents were advised of this prior to measurements. During the measurement period within each residence, conversation was avoided or kept to a minimum.

At most residences, Wilson Ihrig also deployed one long-term vibration monitor in the basement or lowest floor for unattended overnight logging of vibration data. The purpose of the overnight monitor was to provide supplemental RMS vibration data and to document fleet variability.

6.3 Outdoor-Only Vibration Measurements

In addition to the residential survey locations, vibration was measured at six outdoor-only locations on public rights-of-way such as sidewalks or roadways. The intent of the outdoor-only measurements was to measure vibration levels near additional residential report locations and to determine the attenuation of vibration levels with distance from the subway tunnels at various locations. Each outdoor-only site consisted of two to eight vibration sensors connected by cables to data recorders. Where possible, the sensors were placed along cross streets in a line at various distances from the tunnels. The measurements were usually focused on areas close to the WMATA tunnels with sensors near the closest residences; however, locations for outdoor-only measurements also included locations where WMATA had received reports from residences that were located beyond the first row of buildings from the alignment.

6.4 Data Analysis

The amount of vibration and ground-borne noise generated by a given rail vehicle depends on many factors, including its design and its speed. Because there are several types of vehicles currently operating simultaneously on the WMATA system, it is important to know which vehicle type(s) passed the measurement site so the noise and vibration levels could be properly attributed. Knowing the train speeds is useful because faster trains typically, though not always, generate more vibration and noise.

The amount of vibration and ground-borne noise also depends on the distance to the track and depth of the tunnel along with the specific track configuration and rail fixation type near each measurement site. Sites near sections of similar track configuration often provided data with similar train passby noise and vibration frequency content but the levels are unique to each site.

6.4.1 Train Speeds

Trains speeds were provided by WMATA in the form of velocity profile charts showing speed as a function of clock time and track location. These charts were used to determine the train speed for passbys on the near track for the date and time duration of the attended measurement period for each residence site. An example of the velocity profile charts is shown in Figure 2.

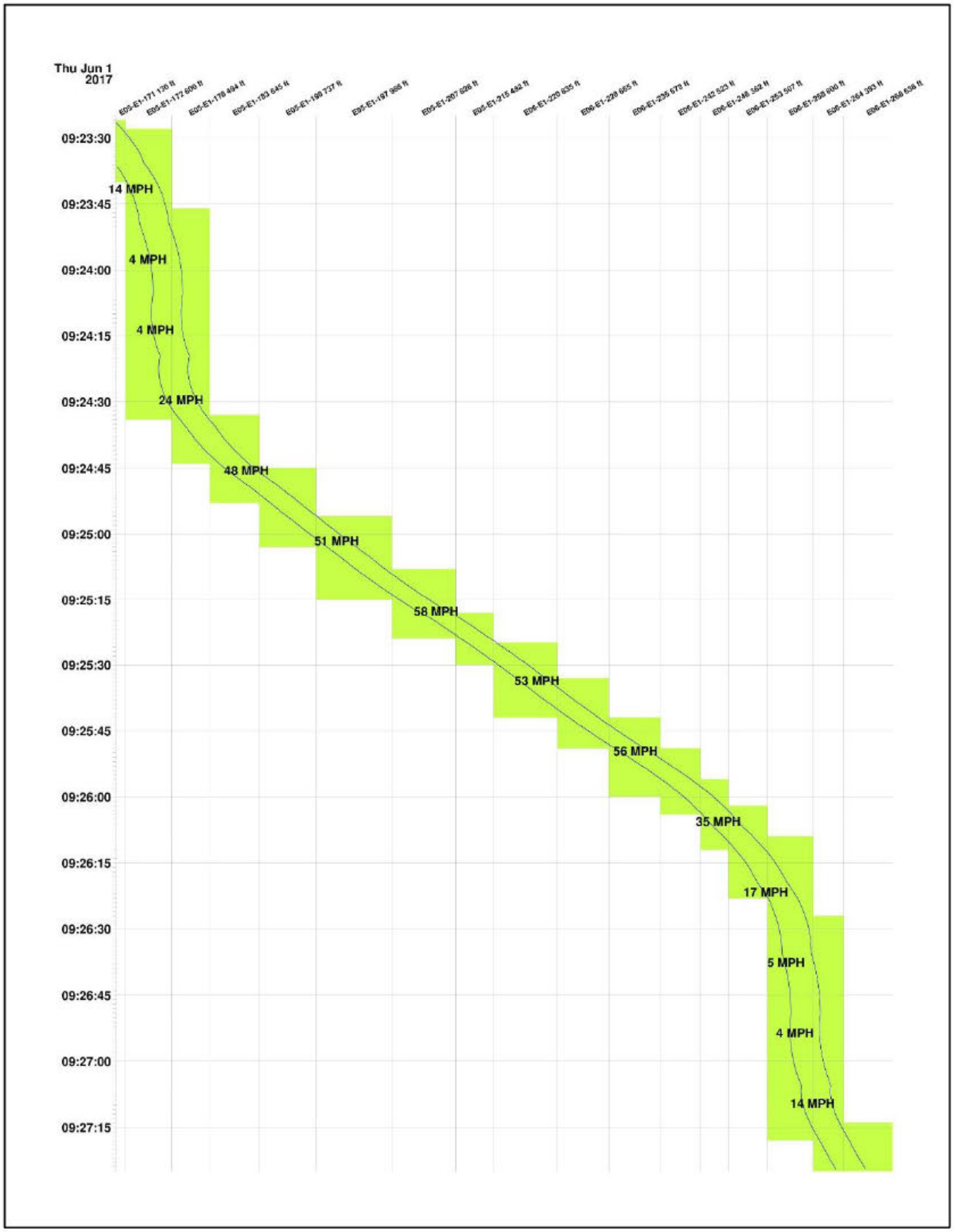


Figure 2: Example of WMATA Velocity Profile Chart

6.4.2 Train Vehicles

Rail performance charts and SPOTS reports were provided by WMATA that were used to identify individual train passby events and vehicle type for correlation with measured noise and vibration data. Examples of the rail performance charts and accompanying SPOTS reports are shown in Figure 3 and Figure 4.

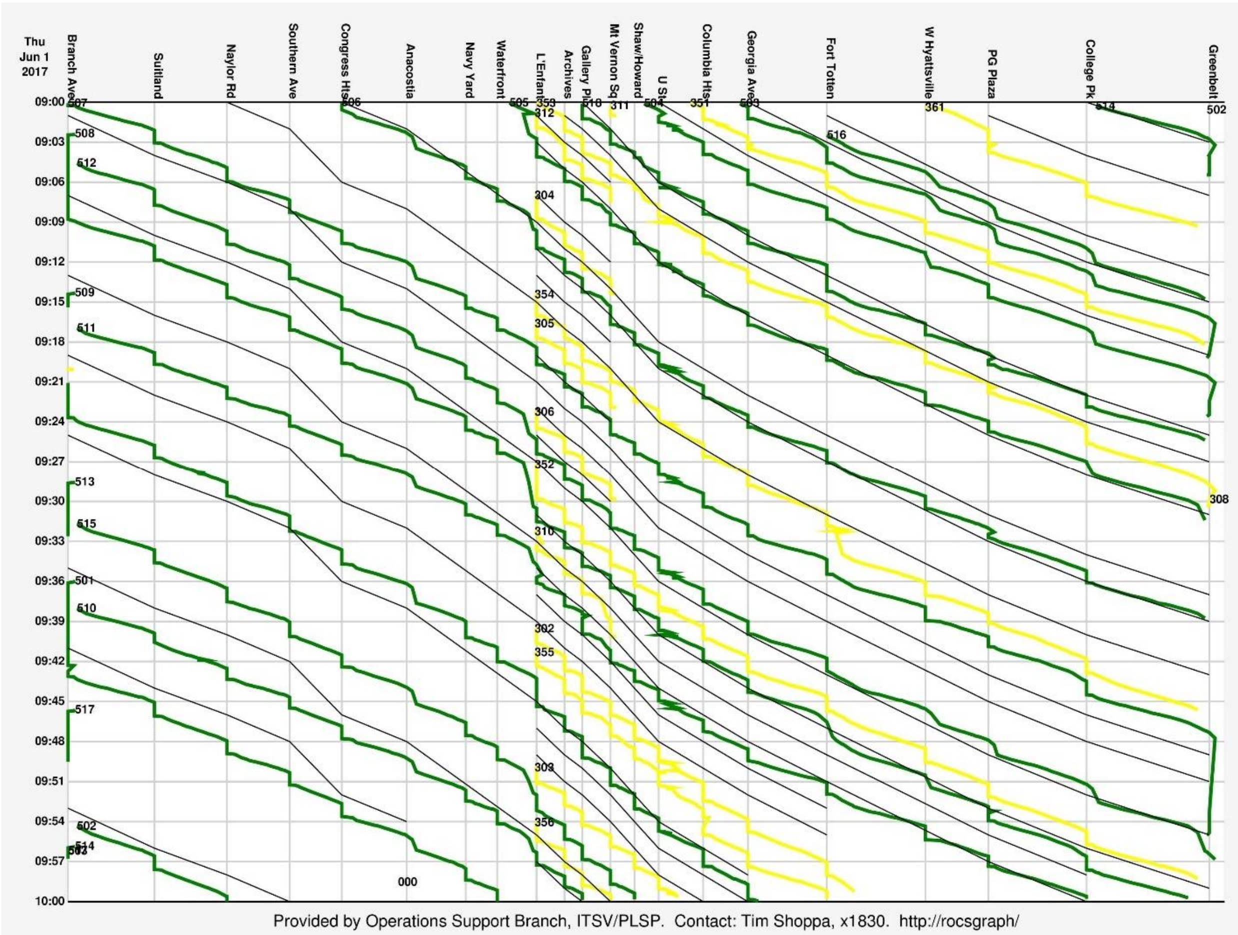


Figure 3: Example of WMATA Rail Performance Chart

Select Platform: E05-1 **and/or Select ID:** Leave blank to remove criteria
and/or Select 4-digit car number: Leave blank to remove criteria
Select Date: Jun 1 2017 **Select Times (0-24HRS): From** 09:00 **To** 20:00

Generate Report

ID	Platform	length	dcode	Right door open	Right door close	dwell	Left door open	Left door close	dwell	Head Arrived	Tail cleared	cars	Headway door open to door open
503	E05-1	8	44				09:00:48	09:01:01	13	09:00:22	09:01:14	7332-7333.7335-7334.7304-7305.7275-7274	-
351	E05-1	6	24				09:03:08	09:03:11	3	09:02:39	09:03:11	3290-3291.5097-5096.5038-5039	2:20
351	E05-1	6	24				09:03:15	09:03:21	6	09:03:15	09:03:32	3290-3291.5097-5096.5038-5039	0:07
504	E05-1	6	44				09:05:36	09:05:59	23	09:05:10	09:06:10	3276-3277.3210-3211.3084-3085	2:21
518	E05-1	6	44				09:10:10	09:10:23	13	09:09:42	09:10:35	3092-3093.1060-1061.5126-5127	4:34
353	E05-1	6	24				09:13:09	09:13:18	9	09:12:41	09:13:29	6033-6032.5033-5032.6055-6054	2:59
505	E05-1	6	44				09:16:16	09:16:31	15	09:15:52	09:16:44	3222-3223.1168-1169.3122-3123	3:07
506	E05-1	6	44				09:23:59	09:24:14	15	09:23:30	09:24:24	6005-6004.6117-6116.6171-6170	7:43
354	E05-1	6	24				09:28:24	09:28:37	13	09:27:55	09:28:48	3250-3251.3235-3234.3243-3242	4:25
507	E05-1	6	44				09:32:12	09:32:25	13	09:31:45	09:32:34	unknown	3:48
512	E05-1	8	44				09:39:34	09:39:45	11	09:39:01	09:39:57	7122-7123.7301-7300.7234-7235.7139-7138	7:22
352	E05-1	6	24				09:42:09	09:42:35	26	09:41:39	09:42:46	3009-3008.5135-5134.6115-6114	2:35
508	E05-1	6	44				09:43:54	09:44:08	14	09:43:24	09:44:18	unknown	1:45
511	E05-1	8	44				09:49:01	09:49:15	14	09:48:36	09:49:26	3073-3072.6119-6118.6066-6067.6081-6080	5:07
302	E05-1	6	29				09:54:25	09:54:38	13	09:53:53	09:54:46	3153-3152.3175-3174.3188-3189	5:24

Figure 4: Example of WMATA SPOTS Report

6.4.3 Ground-Borne Noise and Vibration Levels

The ground-borne noise and RMS vibration levels for each individual train were calculated over the duration of the passby, typically 3 to 5 seconds. As described above, the residential criteria are based on the RMS levels.

Reasonable effort has been made to exclude from train passby samples any data contaminated by street traffic, resident activity within the house, or other clearly discernable sources not related to the trains. Ambient background noise and vibration spectra (in the absence of trains) were analyzed for comparison. The ambient background spectra shown are averages of multiple samples taken during steady quiet lulls in between train events.

6.5 PPV Vibration Data Analysis

At each residential measurement site, PPV vibration was logged during the entire attended measurement duration using triaxial instruments designed just for that purpose. For this analysis, individual train passages were not analyzed. Rather, the highest and average PPV readings during the entire attended measurement period at each residence are reported. No effort was made to distinguish train vibration from other vibration with the PPV vibration data. The analysis is, thus, inherently conservative because it includes all sources of vibration, not just trains.

6.6 Rail Roughness Measurements

Roughness in the running surface of the rail can lead to increased ground-borne noise and vibration levels. The acoustic roughness of the rail can be measured to determine the variation in height of the rail running surface associated with train wheel rolling noise excitation.

The rail roughness measurement locations are summarized in Table 4. These locations can be found on Figure 6 through Figure 12. Each measurement location is denoted by the rail section over which rail roughness was measured (start and end position), track direction, and specific rail upon which the roughness trace was measured. The individual rail for the roughness trace is denoted by L for left rail and R for right rail. The left and right designations relate to the direction of train travel. The corresponding ground-borne noise and vibration measurement sites that are covered by the rail roughness measurement sections are included in the table. Rail roughness was not measured at all sections corresponding to the noise and vibration measurement sites because the rail roughness measurement equipment is not suitable for use through sections of special track work (such as crossovers and turnouts) or through curved sections of track. However, the rail in all sections corresponding to residential measurement sites was visually inspected for signs of corrugation and/or mechanical defects. No visual evidence of rail corrugation, chips, spalls, etc., was observed at any location.

Table 4: Rail Roughness Measurements Locations

Location #[1]	Rail Roughness Measurement Designation[2, 3]	Start Position (Track Chainage)	End Position (Track Chainage)	Noise and Vibration Measurement Site[4]
1	T1-R-188	188+00 (T1)	196+00 (T1)	Site 6
2	T1-L-196	196+00 (T1)	188+00 (T1)	Site 6
3	T1-R-201	201+00 (T1)	205+00 (T1)	Sites 7, 8, 9
4	T1-L-205	205+00 (T1)	201+00 (T1)	Sites 7, 8, 9
5	T2-L-201	201+00 (T2)	205+00 (T2)	Sites 7, 8, 9
6	T2-R-205	205+00 (T2)	201+00 (T2)	Sites 7, 8, 9
7	T2-R-194	194+00 (T2)	188+00 (T2)	Site 6
8	T2-L-188	188+00 (T2)	194+00 (T2)	Site 6
9	T2-R-186	186+00 (T2)	180+00 (T2)	Site 5
10	T2-L-180	180+00 (T2)	186+00 (T2)	Site 5
11	T1-R-286	286+40 (T1)	290+00 (T1)	Sites 14, 15
12	T1-L-290	290+00 (T1)	286+40 (T1)	Sites 14, 15
13	T2-L-286	286+44 (T2)	290+00 (T2)	Sites 14, 15
14	T2-R-290	290+00 (T2)	286+44 (T2)	Sites 14, 15
15	T2-L-213	213+00 (T2)	218+00 (T2)	Sites 11, 12, 13
16	T2-R-218	218+00 (T2)	213+00 (T2)	Sites 11, 12, 13
17	T1-R-213	213+00 (T1)	218+00 (T1)	Sites 11, 12, 13
18	T1-L-218	218+00 (T1)	213+00 (T1)	Sites 11, 12, 13

[1] Measurements are listed in the order that they were conducted.

[2] T1 refers to Track 1, the Outbound track. T2 refers to Track 2, the Inbound track.

[3] L and R denote left and right rail, respectively, with respect to the direction of train travel.

[4] The noise and vibration measurement sites located near each rail roughness measurement location are listed.

Roughness was measured with a Corrugation Analysis Trolley (CAT)[3] in conformance with reference standard EN 15610:2009(E) Railway Applications – Noise emission – Rail Roughness Measurement Related to Rolling Noise Generation.[4] Measurements were made over distances in the range of 400 to 800 feet depending on location.

Roughness data were post-processed with the CAT software version 12.01.18805. The software produced the 1/3-octave band roughness spectra as a function of wavelength for each trace.

[3] Manufactured by Rail Measurement, Ltd.

[4] EN 15610 specifies a direct method for characterizing the surface roughness of the rail associated with rolling noise ("acoustic roughness"), in the form of a 1/3-octave band spectrum.

7 Site-Specific Field Studies

Table 5 provides a summary of the measurement sites and the dates and times for the attended measurement period. Measurements were conducted at ten residences and six outdoor-only locations. The table includes the applicable ground-borne noise and vibration assessment criteria for each residential site. Detailed measurement information and data summaries for each site are provided in Appendix B. At the residential sites, the measurements included RMS vibration, ground-borne noise, and PPV vibration. At outdoor-only sites, only RMS vibration was measured.

Figure 5 shows an overview of the area studied and measurement locations. Figure 6 through Figure 12 show closer views of all 16 measurement sites as well as all reporting homeowner locations. The residential measurement sites are indicated in red and the outdoor vibration sites are indicated in yellow. The figures also show track chainage, track type, tunnel type, and the locations of Georgia Avenue-Petworth Station and Fort Totten Station.

Table 5: Measurement Sites & Annoyance Criteria

Site #	Address	Type[1]	Chainage T1 = Track 1 T2 = Track 2	Attended Measurement Period (Day, Date, Hours)	Criteria	
					GBN (dBA)	Vibr (VdB)
1	1300 block of Park Rd NW	Residence	143+75 (T2)	Mon, 5 June 2017 16:43 to 20:45	40	70
2	3600 block of New Hampshire Ave NW	Residence	163+90 (T2)	Wed, 16 August 2017 09:05 to 12:56	40	70
3	700 block of Princeton Pl	Residence	169+00 (T1)	Tue, 6 June 2017 15:50 to 19:15	40	70
4	Rock Creek Church Rd NW & 9th St NW	Outdoor-Only	169+00 to 170+00 (T2)	Fri, 2 June 2017 12:22 to 15:23	N/A	N/A
5	New Hampshire Ave NW & Randolph St NW	Outdoor-Only	181+50 to 184+00 (T1)	Fri, 2 June 2017 08:37 to 11:00	N/A	N/A
6	4100 block of New Hampshire Ave NW, Unit [redacted]	Residence	191+75 (T2)	Tue, 15 August 2017 09:01 to 13:02	40	70
7	4300 block of New Hampshire Ave NW	Residence	203+50 (T1)	Wed, 7 June 2017 08:30 to 12:40	40	70
8	New Hampshire Ave NW & Webster St NW	Outdoor-Only	203+50 to 206+00 (T1 & T2)	Thu, 1 June 2017 09:12 to 11:40	N/A	N/A
9	4400 block of 5th St NW	Residence	204+50 (T2)	Wed, 9 August 2017 10:07 to 14:00	40	70
10	4400 block of New Hampshire Ave NW	Residence	206+75 (T1)	Tue, 8 August 2017 10:03 to 13:59	40	70
11	New Hampshire Ave NW & Buchanan St NW	Outdoor-Only	213+00 to 215+00 (T1 & T2)	Thu, 1 June 2017 13:10 to 15:21	N/A	N/A
12	4600 block of 4th St NW	Residence	214+75 (T2)	Mon, 14 August 2017 14:35 to 18:36	40	70
13	4600 block of New Hampshire Ave NW	Residence	216+10 (T2)	Thu, 8 June 2017 14:58 to 19:26	40	70
14	Gallatin St NE & 8th St NE	Outdoor-Only	284+50 to 287+50 (T1)	Thu, 1 June 2017 16:45 to 19:55	N/A	N/A
15	800 block of Gallatin St NE	Residence	288+00 (T1)	Wed, 16 August 2017 17:00 to 20:15	35[2]	70[2]
16	1200 block of Gallatin St NE	Outdoor-Only	303+50 to 304+50 (T1)	Wed, 16 August 2017 17:45 to 19:45	N/A	N/A

[1] At residences, RMS (root mean square) vibration, ground-borne noise, and PPV (peak particle velocity) vibration were all measured. At outdoor-only locations, only RMS vibration was measured.

[2] The criteria shown for Site 15 are provided for reference only. See Section 4 of this report for further information.

N/A = Not Applicable. Design criteria only apply to indoor spaces. There are no criteria for outdoor locations.

GBN = ground-borne noise, dBA

Vibr = vibration, VdB

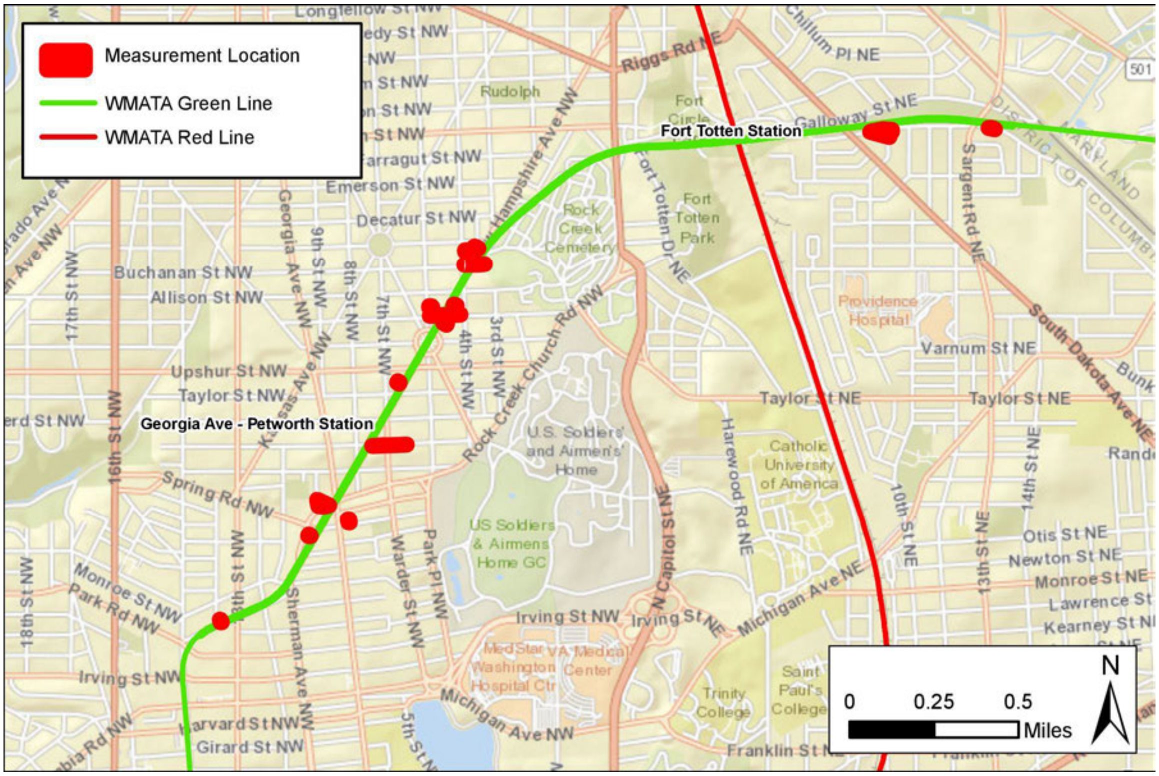


Figure 5: Study Area and Measurement Locations

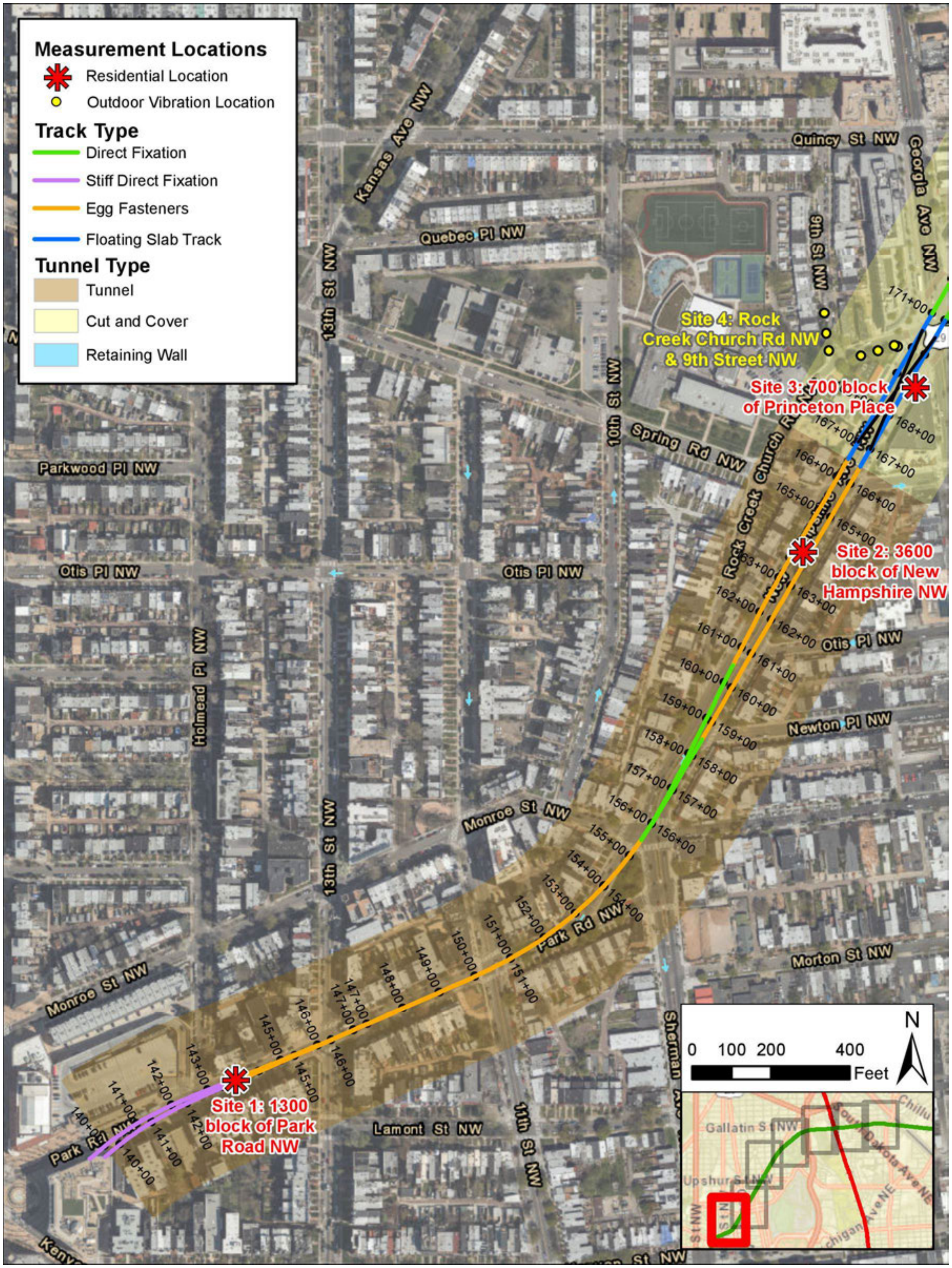


Figure 6: Green Line Alignment and Measurement Sites (1 of 7)

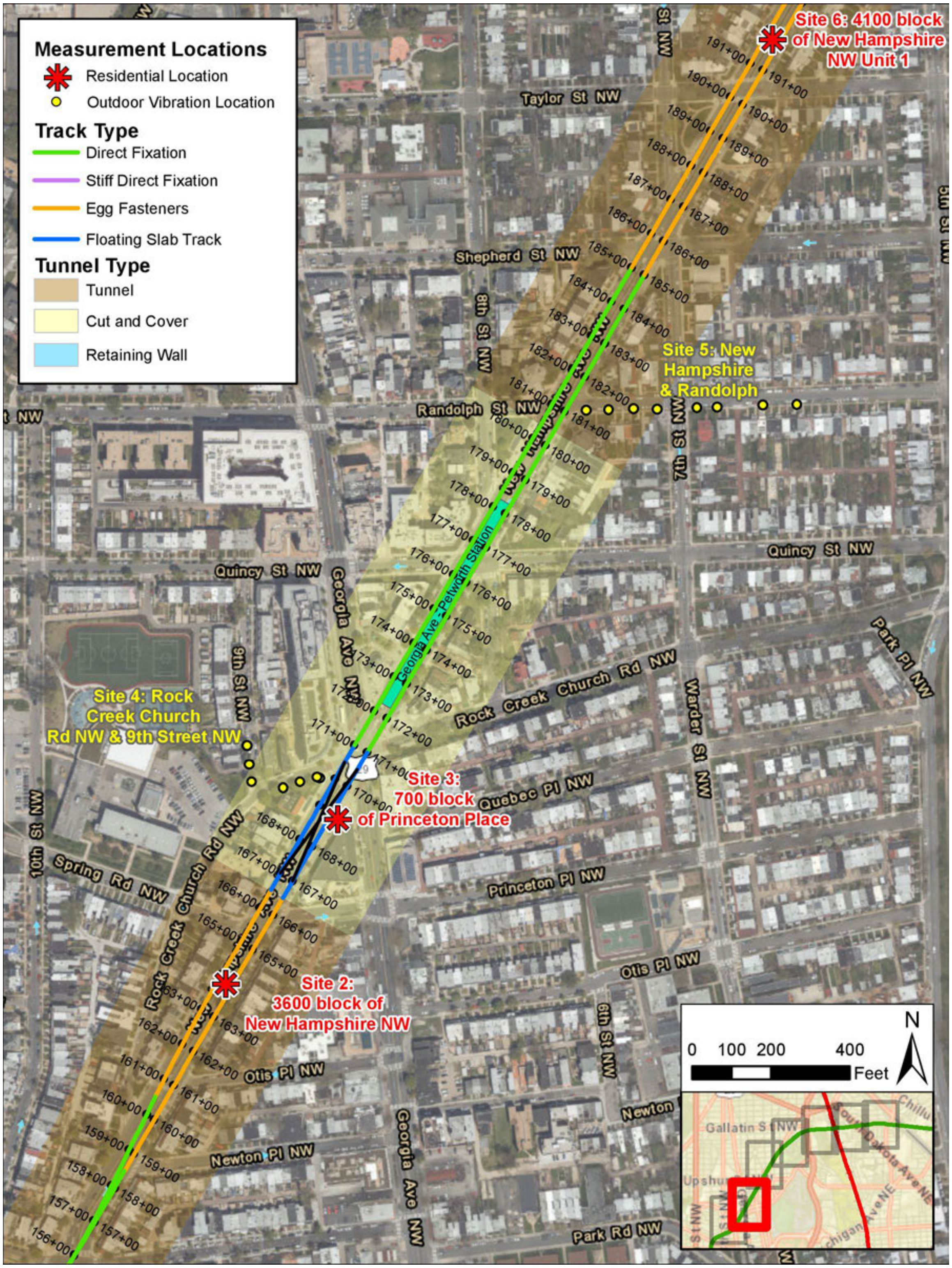


Figure 7: Green Line Alignment and Measurement Sites (2 of 7)

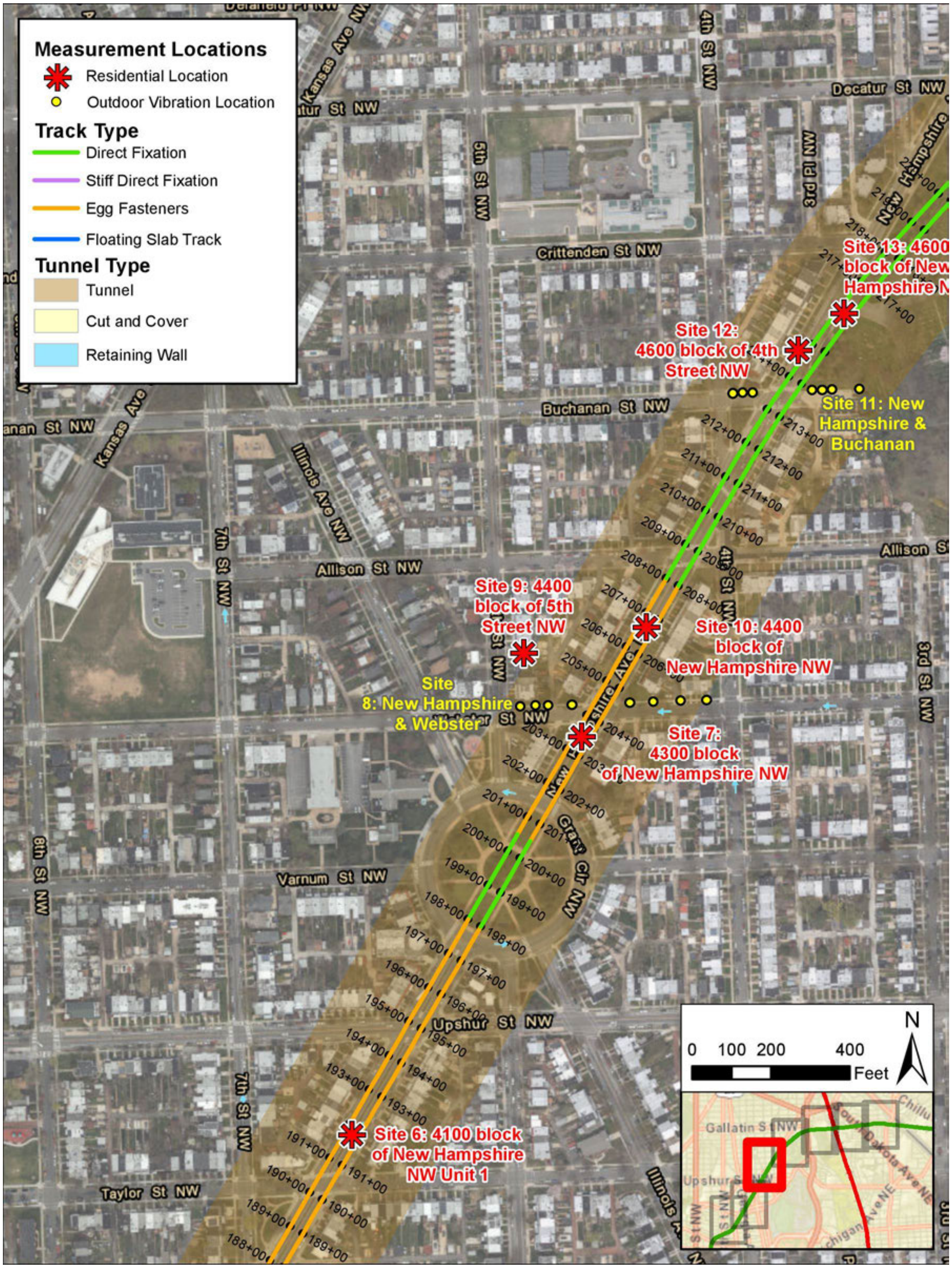


Figure 8: Green Line Alignment and Measurement Sites (3 of 7)

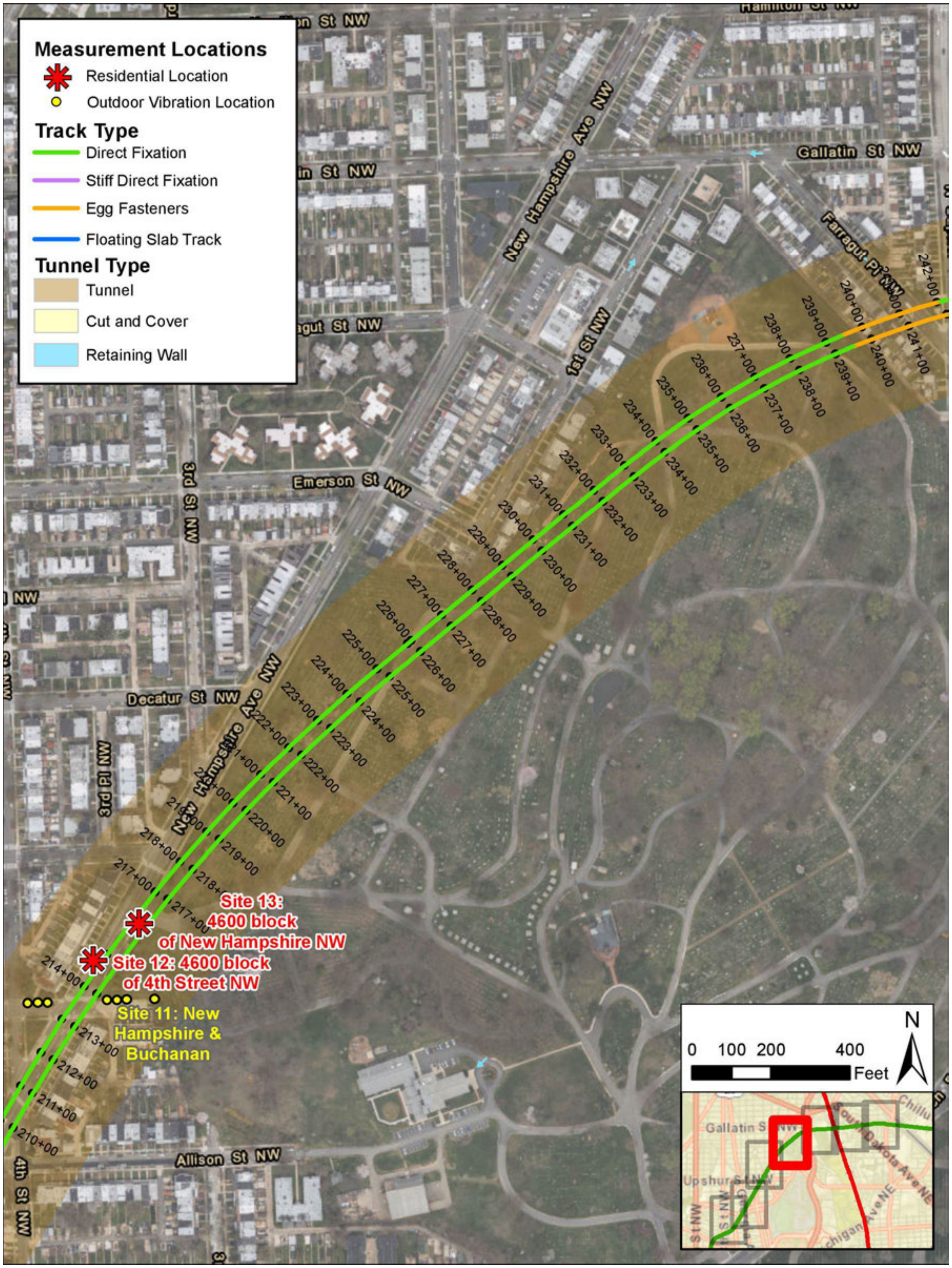


Figure 9: Green Line Alignment and Measurement Sites (4 of 7)

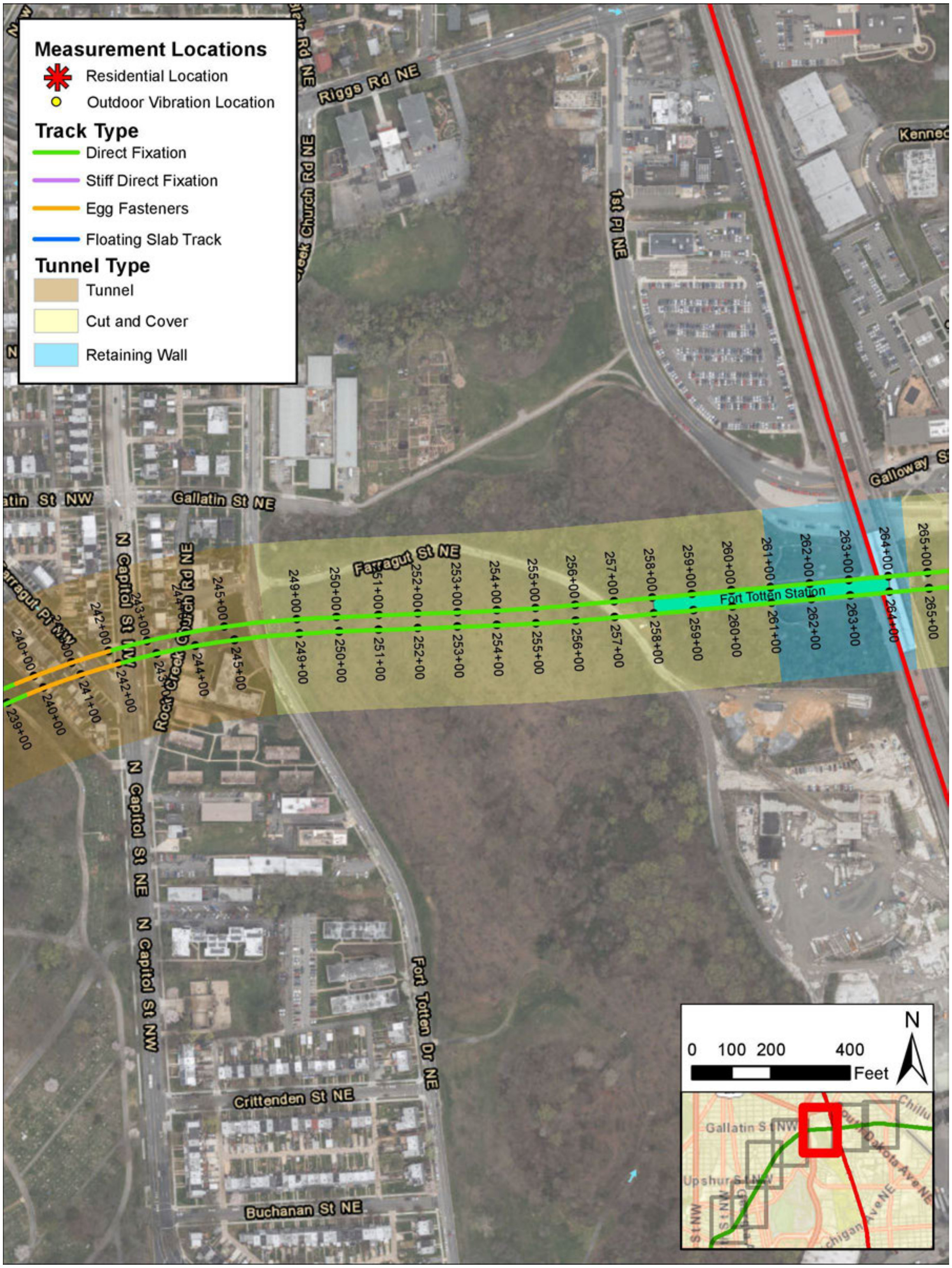


Figure 10: Green Line Alignment and Measurement Sites (5 of 7)

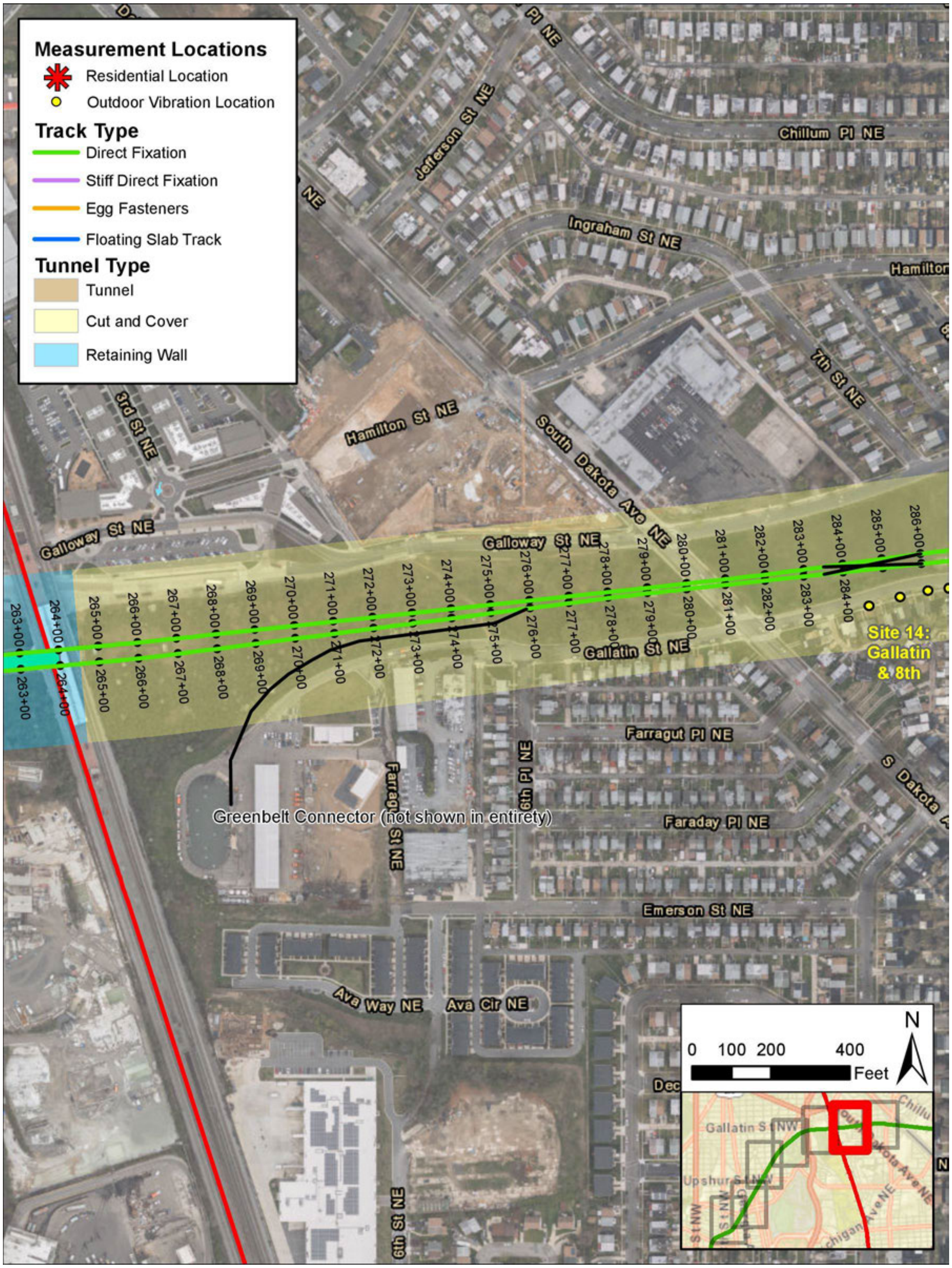


Figure 11: Green Line Alignment and Measurement Sites (6 of 7)

Figure 12: Green Line Alignment and Measurement Sites (7 of 7)

The following sections presents a sample of the ground-borne noise and vibration survey data at one residential location, Site 1, 1300 block of Park Road NW, and one outdoor-only location, Site 8, New Hampshire Avenue NW & Webster Street NW. Refer to Appendix B for detailed measurement information and survey data summaries for each site.

7.1 Sample Residential Survey Site – Site 1, 1300 block of Park Road NW

7.1.1 Site 1 - Building and Tunnel Notes

Location:	Inbound, Track 2, at 143+75
Building Notes:	Residential townhouse, 4 floors comprised of partial underground basement plus 3 upper floors, exterior wall of brick construction
Tunnel Structure:	Earth Tunnel
Track Type:	Transition from stiff DF to soft Egg Fasteners
T/R Depth:	73 to 74 feet (Track 2) / 45 feet (Track 1)
Train Speed:	34 to 42 mph
Measurement Period:	Monday, 5 June 2017, 16:43 to 20:45
Field Observations:	Homeowners present during the measurements, children playing inside the home on the first and second floors.

7.1.2 Site 1 - Measurement Positions

The following table lists the sensor positions and distances to the tunnels for Site 1.

Table 6: Site 1 Measurement Positions

Sensor[a,b,c]	Location / Room Occupancy	INBOUND TRACK 2			OUTBOUND TRACK 1		
		Horizontal Distance[d] (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)	Horizontal Distance (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)
Triaxial Geo.	Basement Bedroom	31	74	80	38	45	59
V1	Basement Bedroom	31	74	80	38	45	59
N1	Basement Bedroom	31	74	80	38	45	59
N2	Basement Bedroom	31	74	80	38	45	59
V2	1st Floor Livingroom	31	74	80	38	45	59
V3	2nd Floor Playroom	31	74	80	38	45	59
V4	Outside House	25	74	78	32	45	55
V5	Across Street	28	73	78	21	45	50
V6	Across Street	26	74	78	19	45	49

Notes:

a) Triaxial geophone mounted on floor, logging peak particle velocity
b) V# vibration locations with accelerometer mounted on floor in vertical direction
c) N# noise locations with microphone/sound level meter mounted on tripod 48 inches above floor
d) Horizontal distance from track to building façade for indoor locations, not accounting for tunnel depth.
e) T/R depth = top-of-rail depth
f) Total slant distance to T/R = total distance from building to track, accounting for tunnel depth

The following figure presents an aerial map showing track centerlines and the residential measurement location for Site 1.

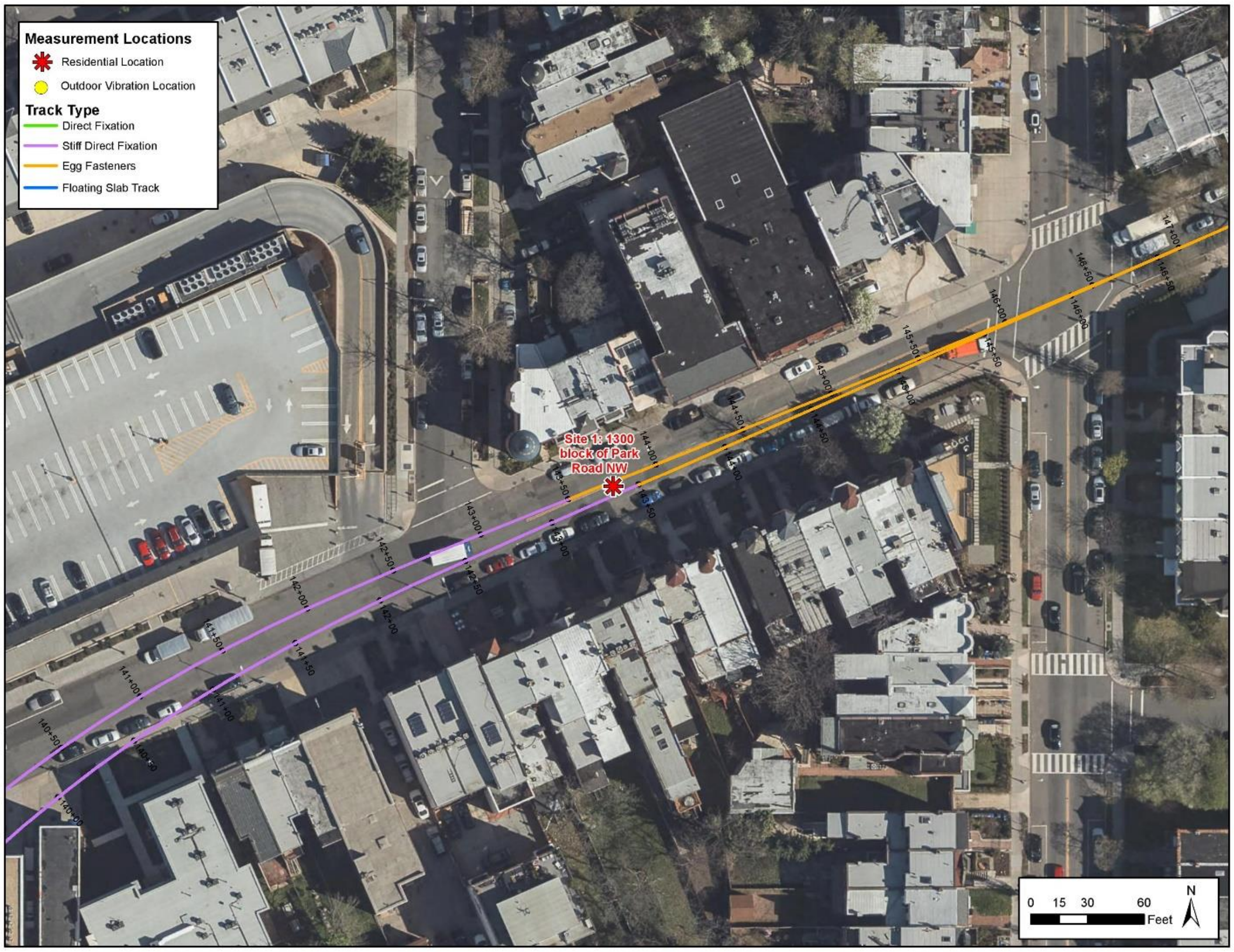


Figure 13: Site 1 Aerial Map Residence and Exterior Measurement Locations

The following figure presents a cross-section sketch to illustrate the multi-story sensor locations and arrangement with respect to the tunnels.

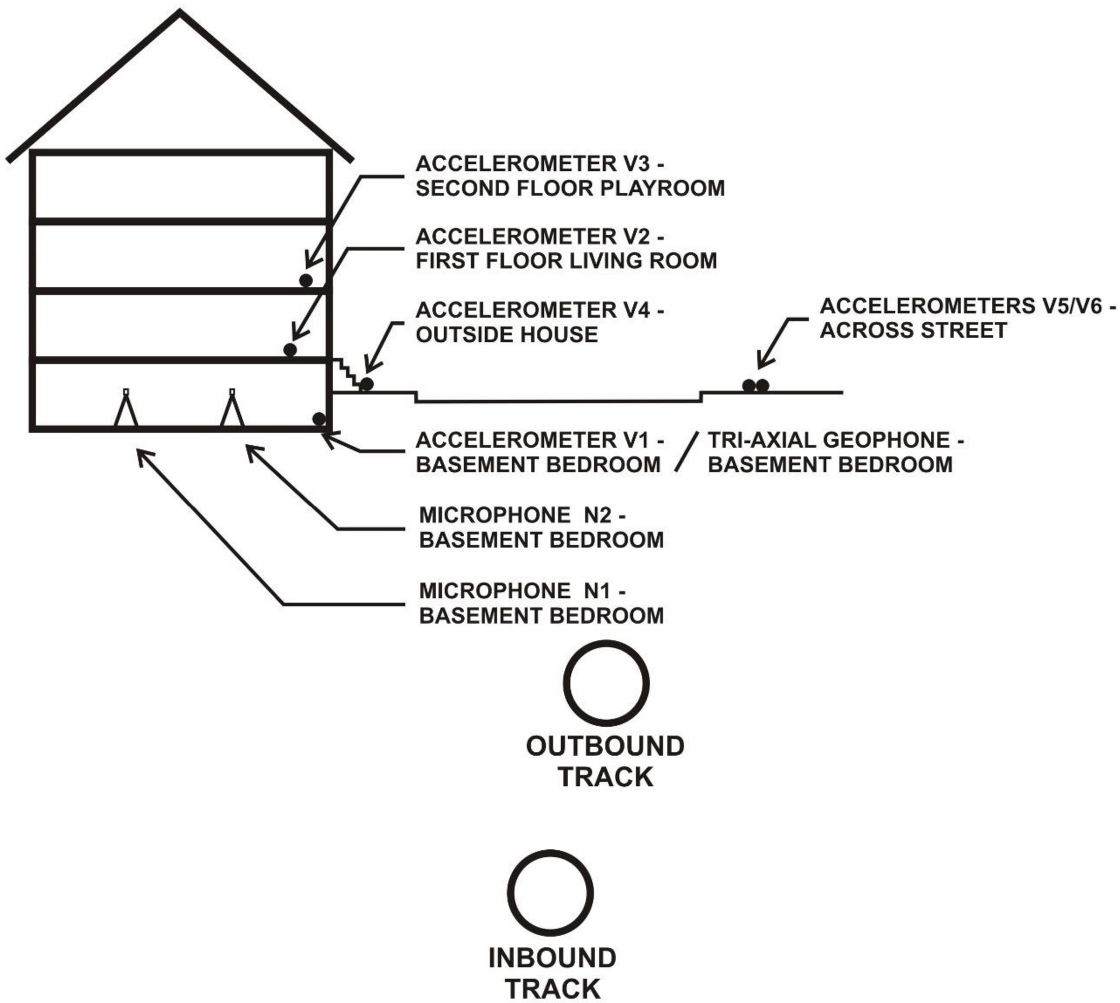


Figure 14: Site 1 Cross-section Sketch (not to scale) of Indoor and Exterior Measurement Locations

7.1.3 Site 1 - Vibration and Ground-Borne Noise Assessment Summary

The following table presents a summary of whether or not the passby vibration and ground-borne noise data exceeded the applicable assessment criteria. As can be seen in the table, no passbys exceeded the assessment criteria for vibration or ground-borne noise at Site 1.

Table 7: Site 1 Vibration and Ground-Borne Noise Assessment Summary

SITE 1	**1300 BLOCK OF PARK ROAD NW – ATTENDED PASSBY MEASUREMENT ASSEMENT**	
	Vibration	**>70 VdB?**
	7000 Series - Average of Multiple Passbys	NO
	6000 Series - Average of Multiple Passbys	NO
	3000 Series - Average of Multiple Passbys	NO
	Mixed Legacy with 4000 Series (Single Passby)	NO
	Mixed Legacy without 4000 Series - Average of Multiple Passbys	NO
	7000 Series - Individual Train with Highest Overall Vibration	NO
	6000 Series - Individual Train with Highest Overall Vibration	NO
	3000 Series - Individual Train with Highest Overall Vibration	NO
	Mixed Legacy - Individual Train with Highest Overall Vibration	NO
	Ground-borne Noise (GBN)	**>40 dBA?**
	7000 Series - Average of Multiple Passbys	NO
	6000 Series - Average of Multiple Passbys	NO
	3000 Series - Average of Multiple Passbys	NO
	Mixed Legacy without 4000 Series (Average of Multiple Passbys)	NO
	7000 Series - Individual Train with Highest A-weighting	NO
	6000 Series - Individual Train with Highest A-weighting	NO
	3000 Series - Individual Train with Highest A-weighting	NO
	Mixed Legacy - Individual Train with Highest A-weighting	NO

7.1.4 Site 1 - PPV Results

The following table presents a summary of the building vibration damage assessment. As can be seen in the table, the PPV vibration data did not exceed the threshold for vibration damage at Site 1 for the entire duration of the measurement period.

Table 8: Site 1 PPV Results

SITE 1	**1300 BLOCK OF PARK ROAD NW – POTENTIAL FOR BUILDING VIBRATION DAMAGE ASSESSMENT**						
	>0.2 in/sec PPV in any direction?	Average PPV (in/s)			Highest PPV (in/s)		
		Tran	Vert	Long	Tran	Vert	Long
	NO	0.0012	0.0009	0.0006	0.0326	0.0360	0.0801
Basement 5-Jun-17, 4:58:00 PM to 9:10:50 PM							

7.1.5 Site 1 - Passby Vibration Spectra and Overall Levels

The section presents samples of the passby vibration spectra and overall levels measured at Site 1. Each chart shows the 1/3-octave band velocity spectra for each measured train series compared against the ambient background vibration in the absence of trains.

The vertical axis is the 1/3-octave band velocity level in VdB. The horizontal axis is the 1/3-octave band center frequency (Hz). The overall level (denoted “OA” on the left-hand side of the chart) is the energy sum of the 1/3-octave band velocity levels over the range of frequencies shown.

There are four plots for each sensor as follows:

1. Average by Vehicle Type, Track 1
2. Average by Vehicle Type, Track 2
3. Highest Individual Train by Vehicle Type, Track 1
4. Highest Individual Train by Vehicle Type, Track

In this summary section, only the data from one vibration sensor are shown for brevity. The complete set of data is included in Appendix B for this and every other location.

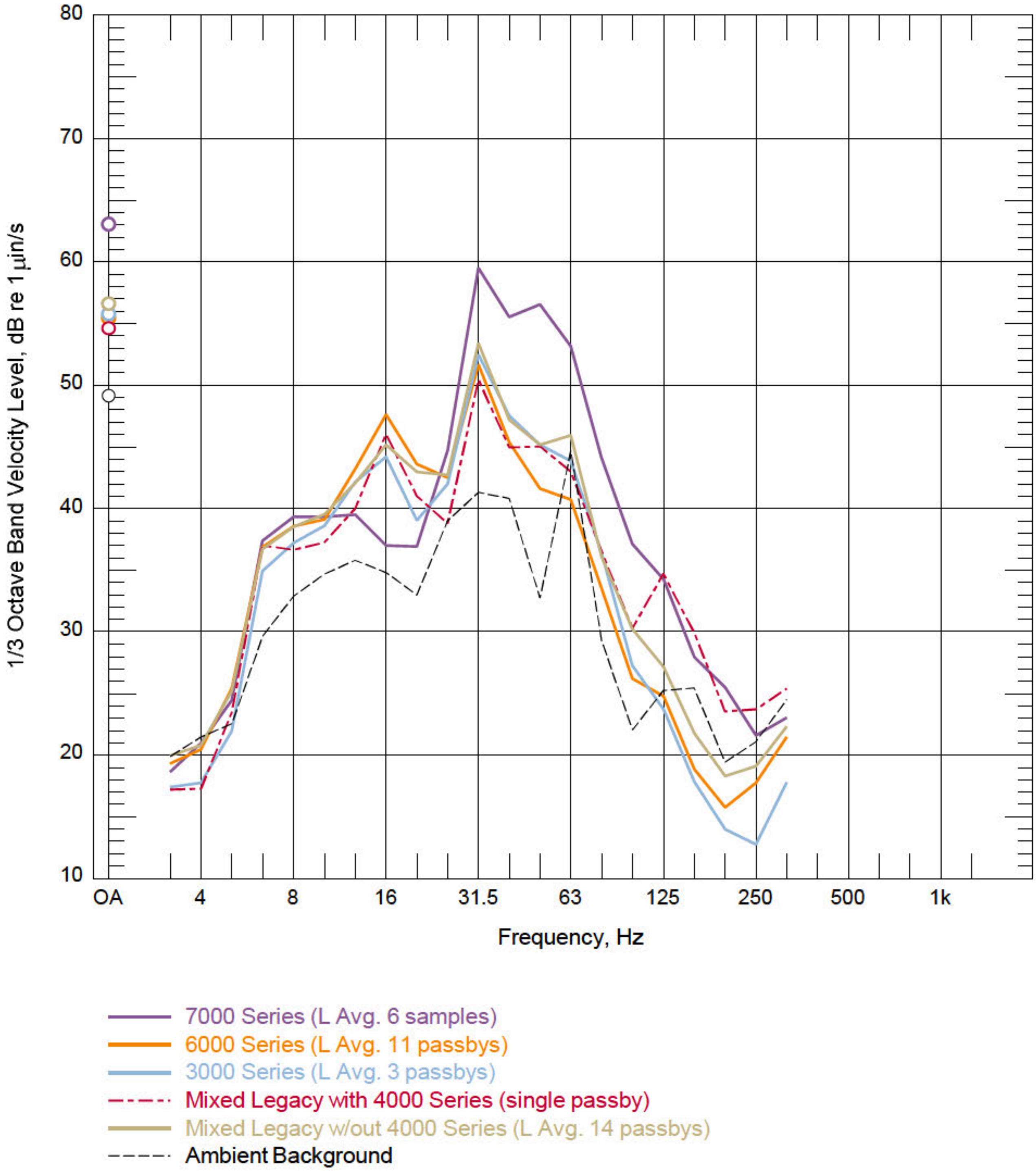


Figure 15: Site 1 at Location V2 1st Floor Living Room
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

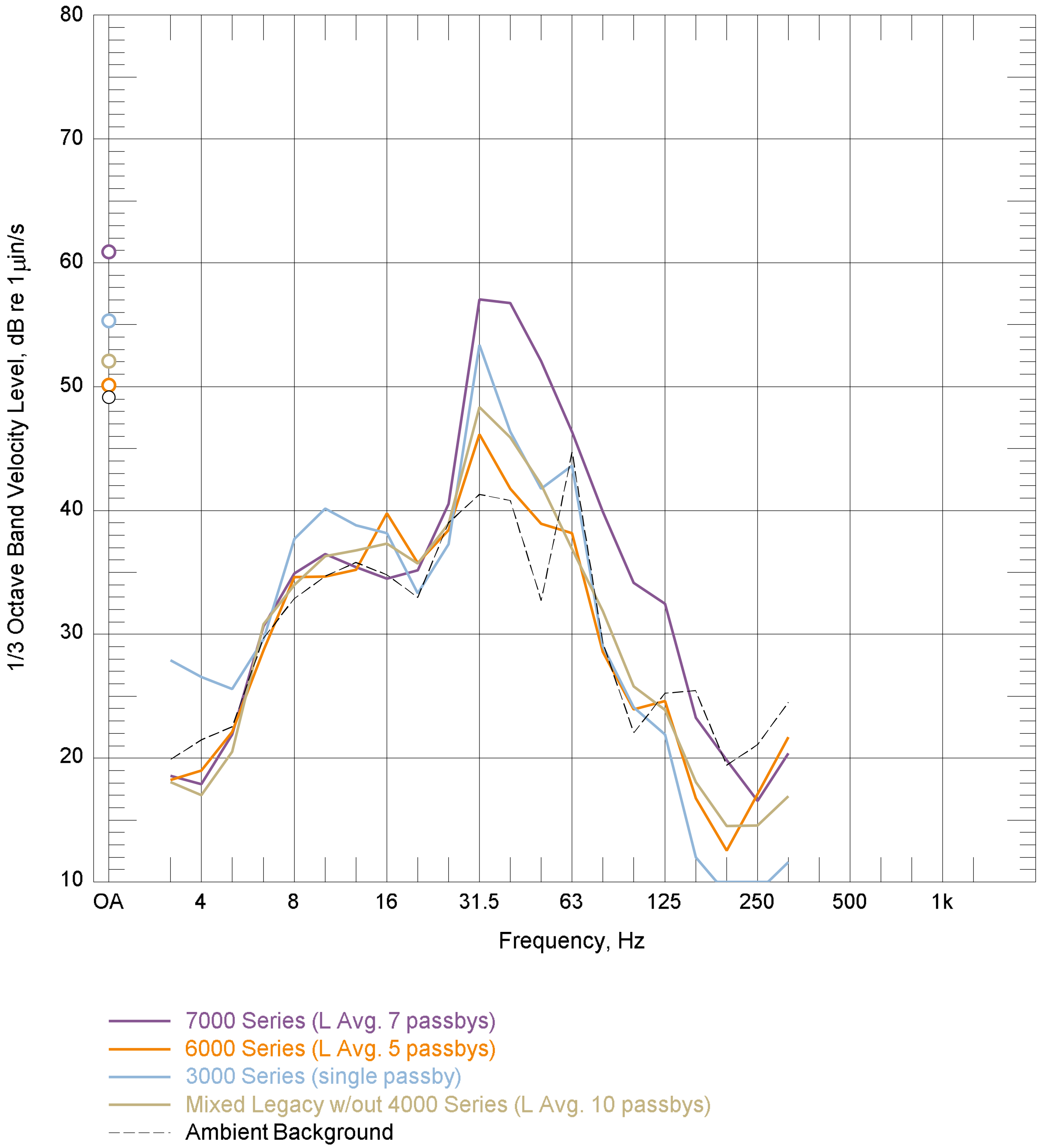


Figure 16: Site 1 at Location V2 1st Floor Living Room
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

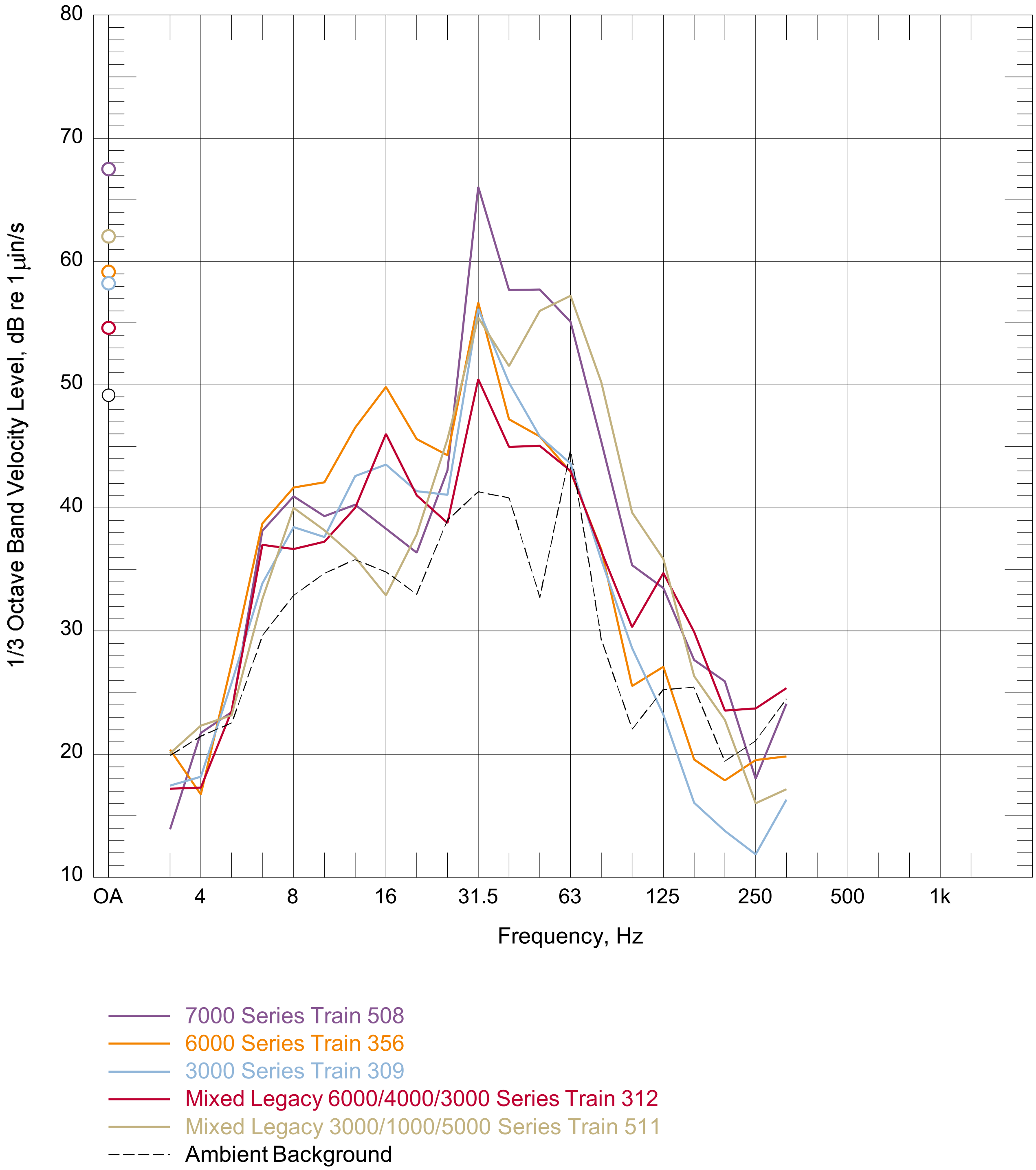


Figure 17: Site 1 at Location V2 1st Floor Living Room
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

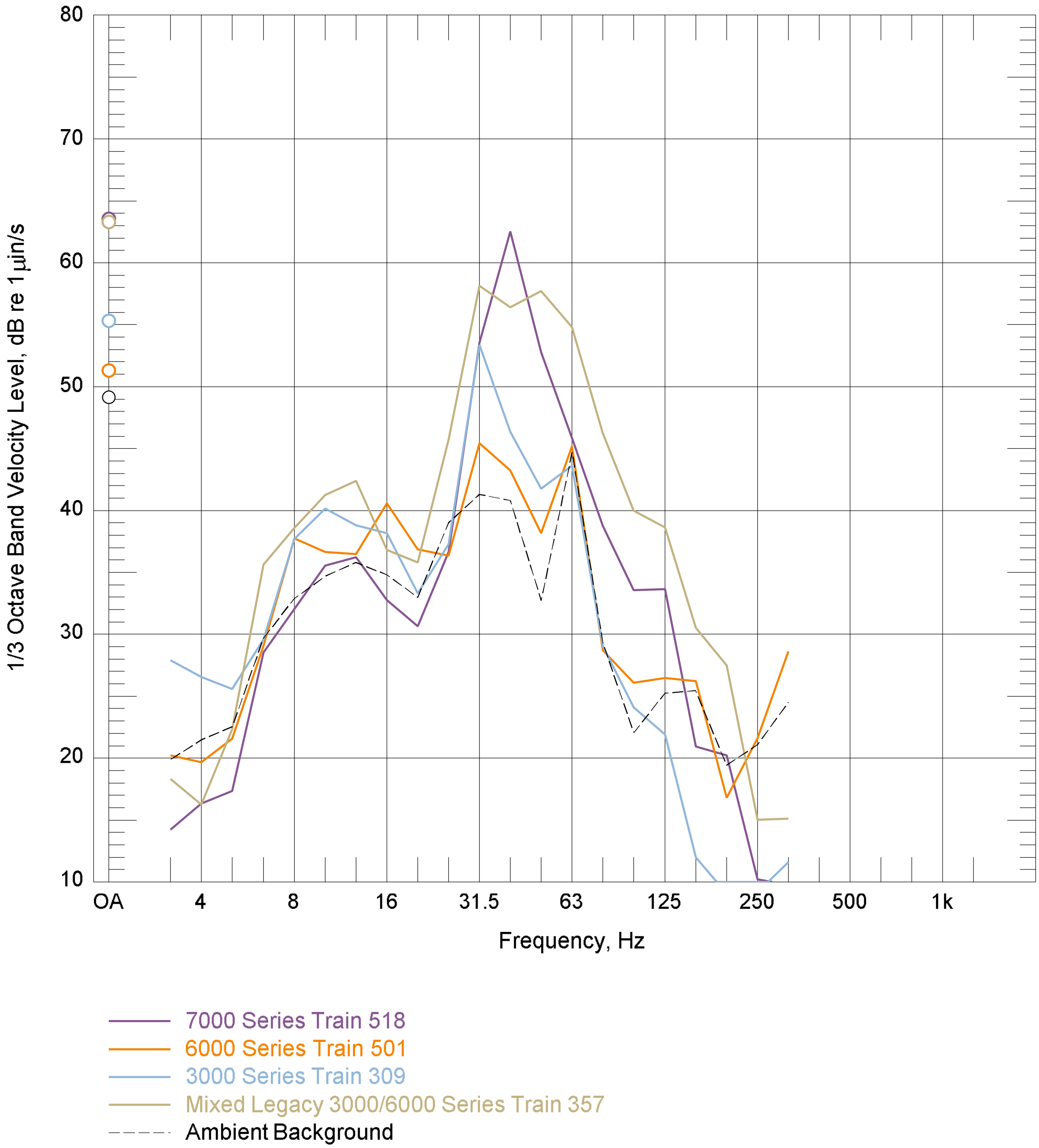


Figure 18: Site 1 at Location V2 1st Floor Living Room
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

Passby Ground-borne Noise Spectra and A-weighted Levels

The section presents samples of the passby noise spectra and A-weighted noise levels measured at Site 1. Each chart shows the 1/3-octave band noise spectra for each measured train series compared against the ambient background noise in the absence of trains.

The vertical axis is the 1/3-octave band sound pressure level in dB re 20 μPa. The horizontal axis is the 1/3-octave band center frequency (Hz). The A-weighted noise level (denoted "AW" on the right-hand side of the chart) is the A-weighted energy sum of the 1/3-octave band sound pressure levels over the range of frequencies shown.

There are four plots for each sensor as follows:

1. Average by Vehicle Type, Track 1
2. Average by Vehicle Type, Track 2
3. Highest Individual Train by Vehicle Type, Track 1
4. Highest Individual Train by Vehicle Type, Track 2

In this summary section, only the data from one microphone are shown for brevity. The complete set of data is included in Appendix B for this and every other location.

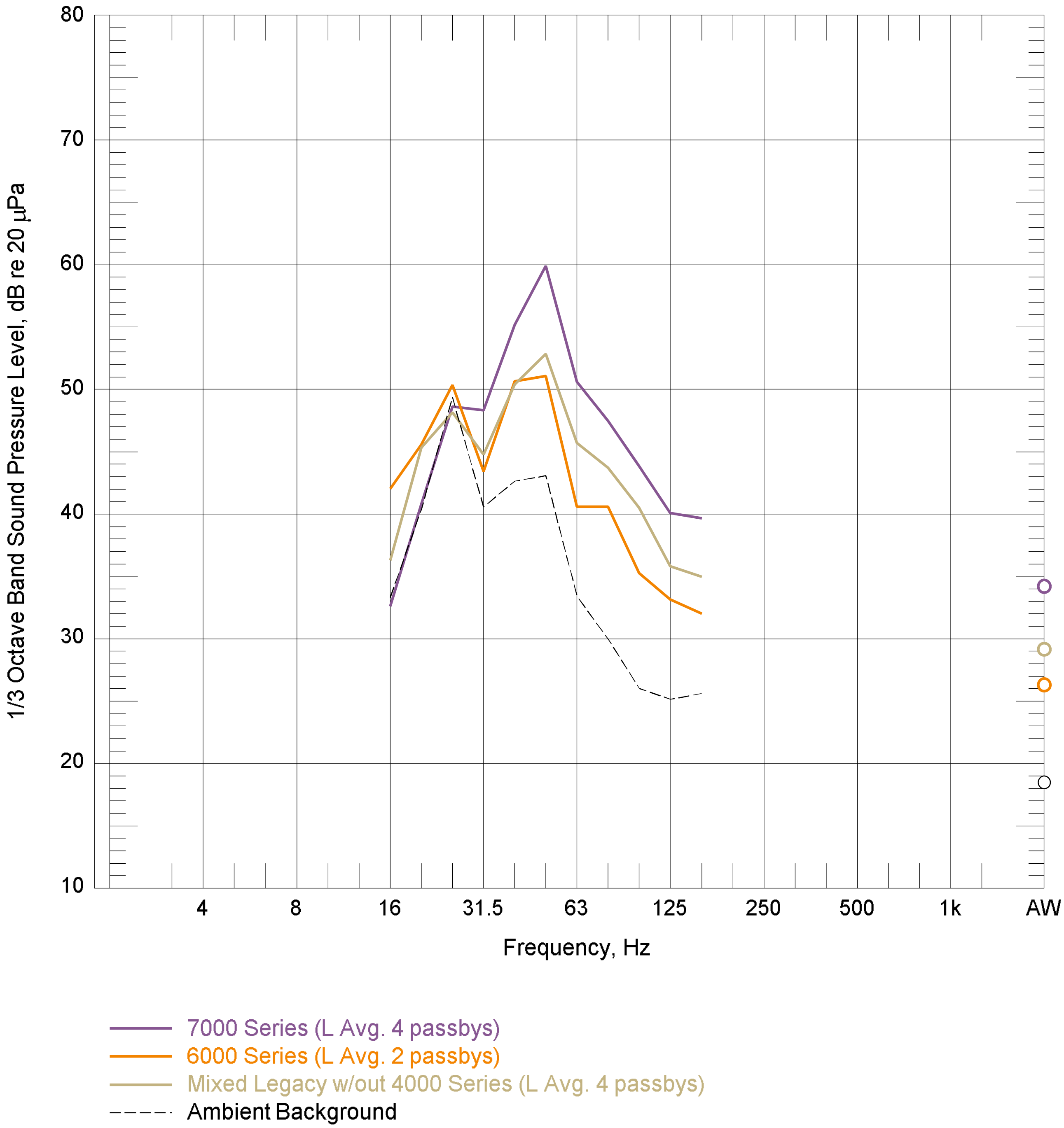


Figure 19: Site 1 at Microphone N1 in Basement Bedroom
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

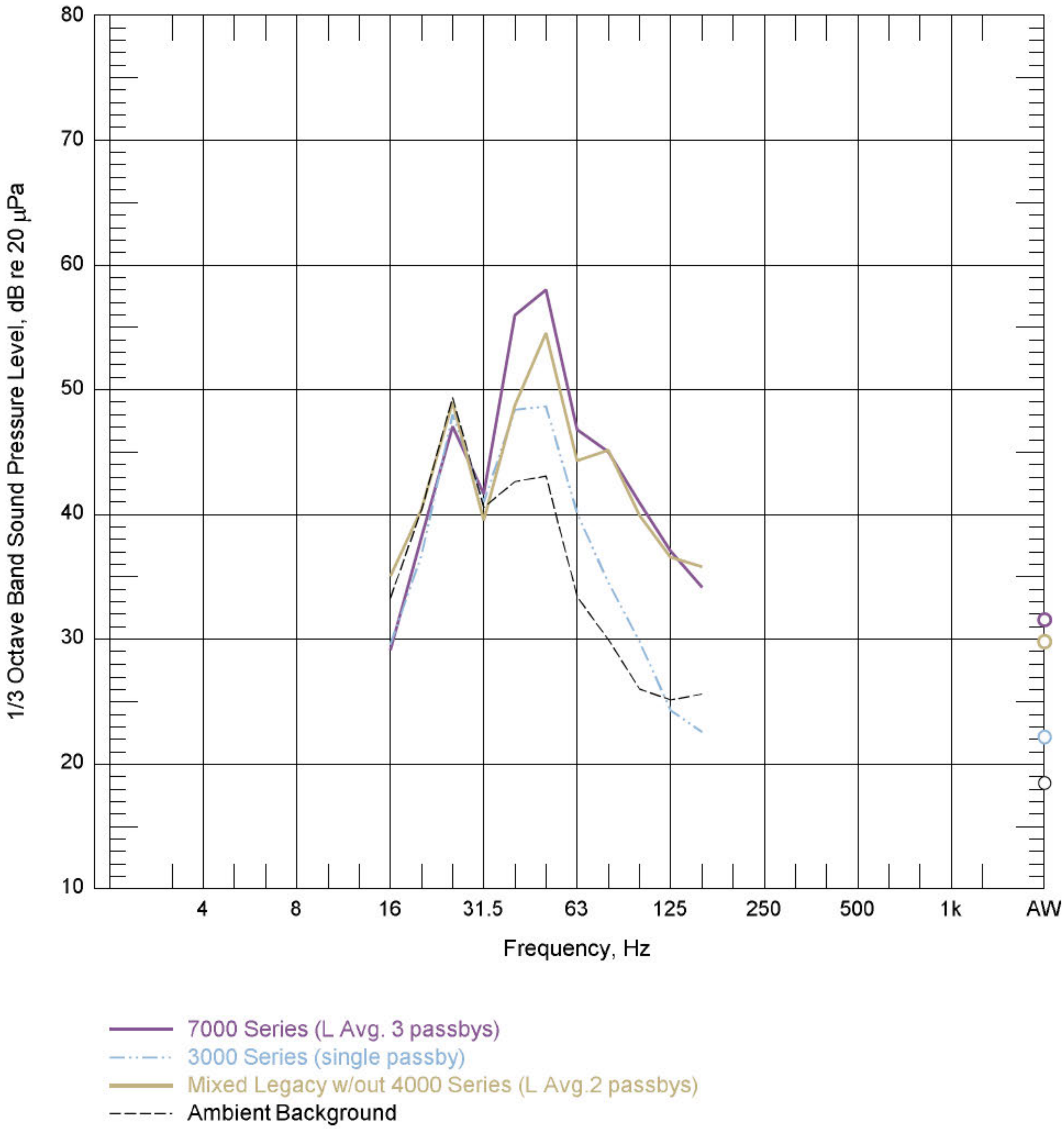


Figure 20: Site 1 at Microphone N1 in Basement Bedroom
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

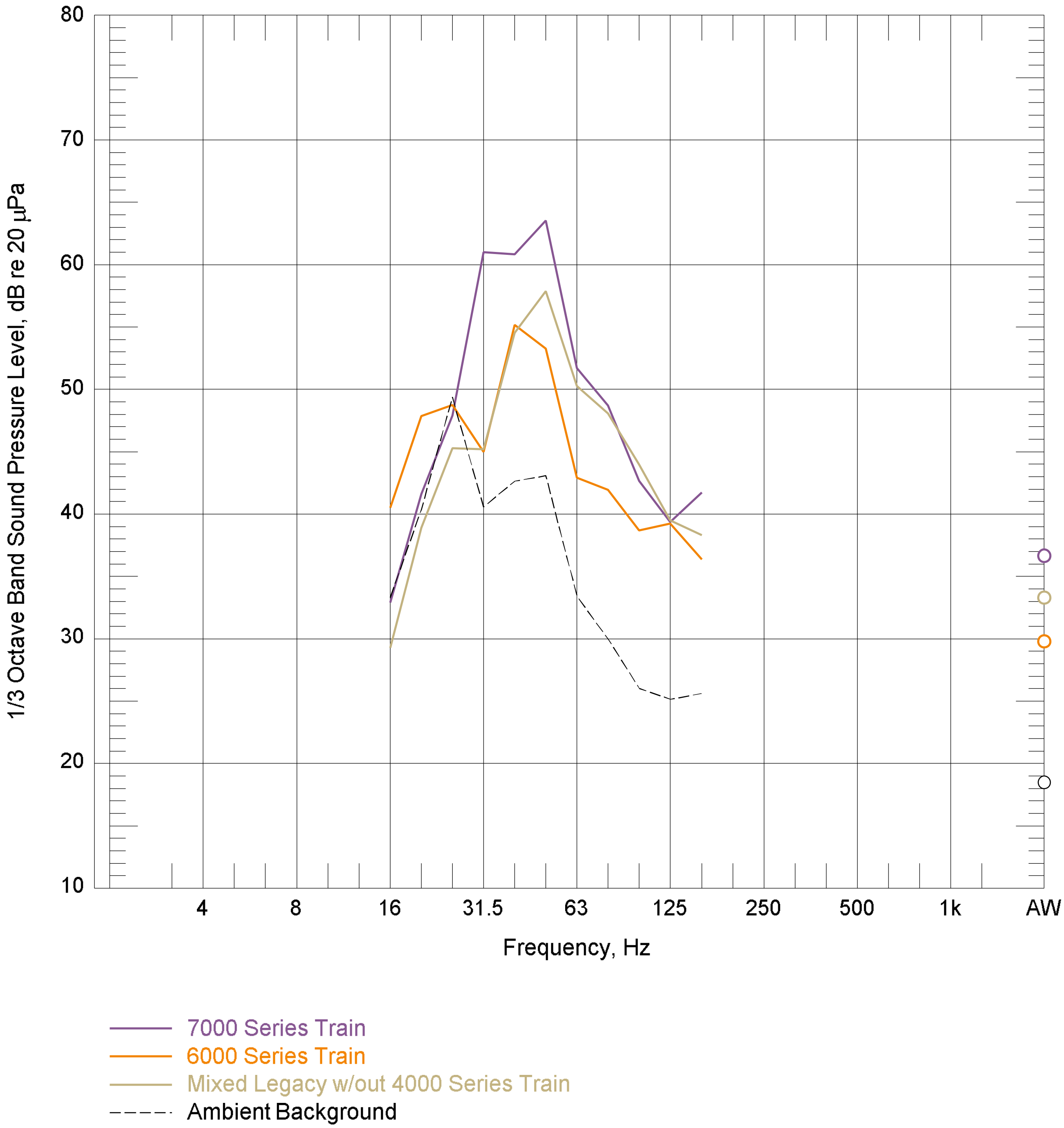


Figure 21: Site 1 at Microphone N1 in Basement Bedroom
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

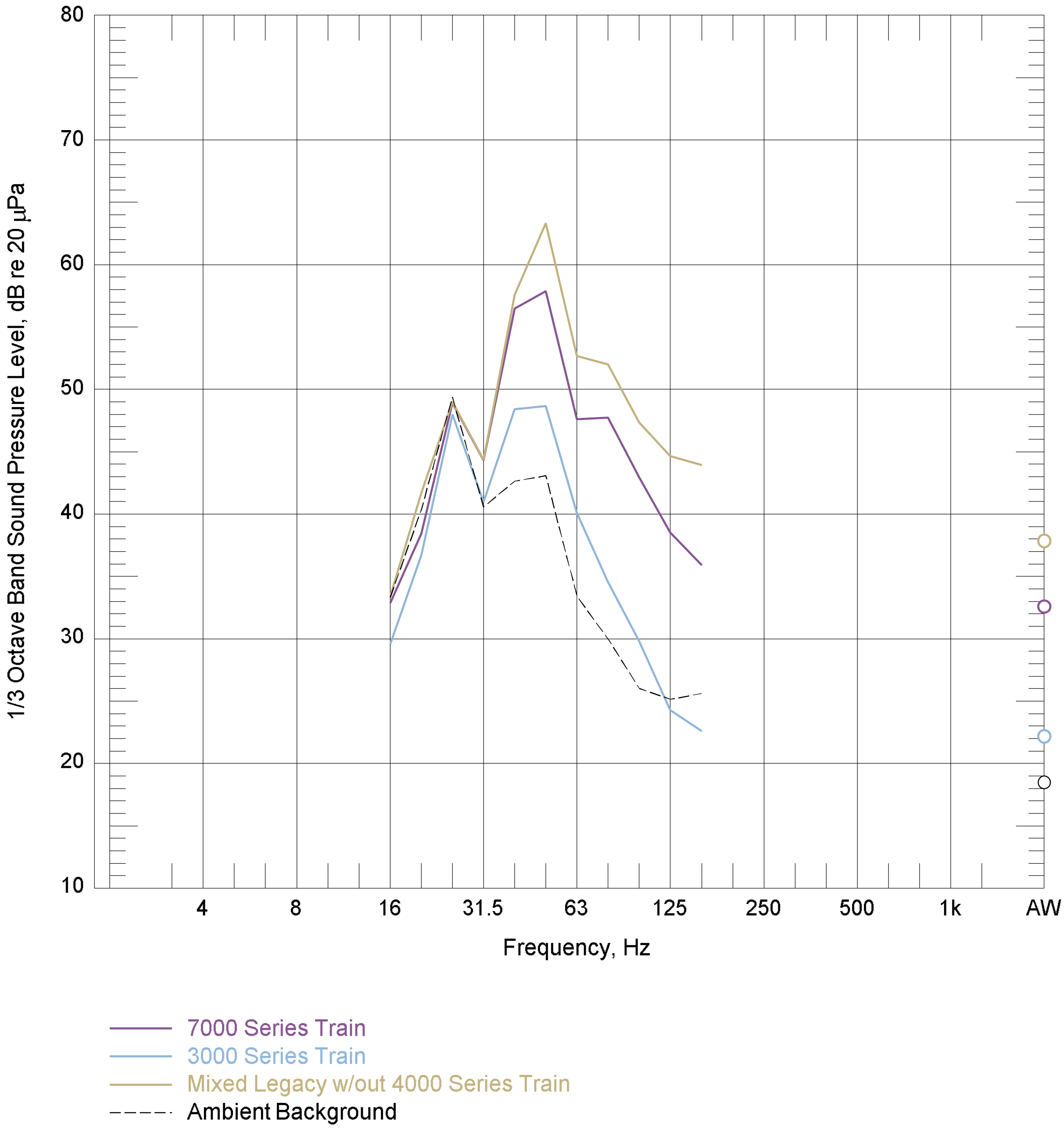


Figure 22: Site 1 at Microphone N1 in Basement Bedroom
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

7.2 Sample Outdoor Survey Site – Site 8, New Hampshire Avenue NW & Webster Street NW

7.2.1 Tunnel Notes

The following notes pertain to the tunnel and track at Site 8.

Tunnel Structure: Earth Tunnel

Track Type: Egg Fasteners

T/R Depth: 65 to 70 feet

Measurement Period: Thursday, 1 June 2017, 9:12 to 11:40

7.2.2 Measurement Positions

The following table lists the horizontal distances, top-of-rail depth, and total slant distance for each sensor with respect to the inbound and outbound tracks.

Table 9: Site 8 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Recorder Channel	Chainage	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)
A1	205+00	80	67	104	43	67	80
A2	205+00	130	67	146	94	67	115
A3	205+50	189	69	201	153	69	168
A4	206+00	244	70	254	208	70	219
B1	204+00	45	65	79	81	65	104
B2	203+50	96	66	116	133	66	148
B3	203+50	124	66	140	161	66	174
B4	203+50	156	66	169	192	66	203

Perp. distance = perpendicular distance to track, not accounting for tunnel depth
T/R depth = top-of-rail depth
Total slant distance = total distance to track, accounting for tunnel depth

The following figure presents an aerial map showing the track centerlines and measurement locations.

Figure 23: Site 8 Aerial Map of Measurement Positions

7.2.3 Overall Level vs Distance Plot

The following chart presents the overall vibration level (VdB) on the vertical axis vs the distance to track centerline on the horizontal axis. Each data point is an average of the overall vibration levels for 7000 Series passbys (purple color symbol) and non-7000 Series (pink color symbol) for each sensor position as a function of horizontal plan distance from track centerline. The data are sorted by 7000 Series and non-7000 Series vehicles on each track. The circle symbol denotes Track 1 data and the square symbol denotes Track 2 data. Distance shown on the graph represents the horizontal distance from the track centerline to the measurement location.

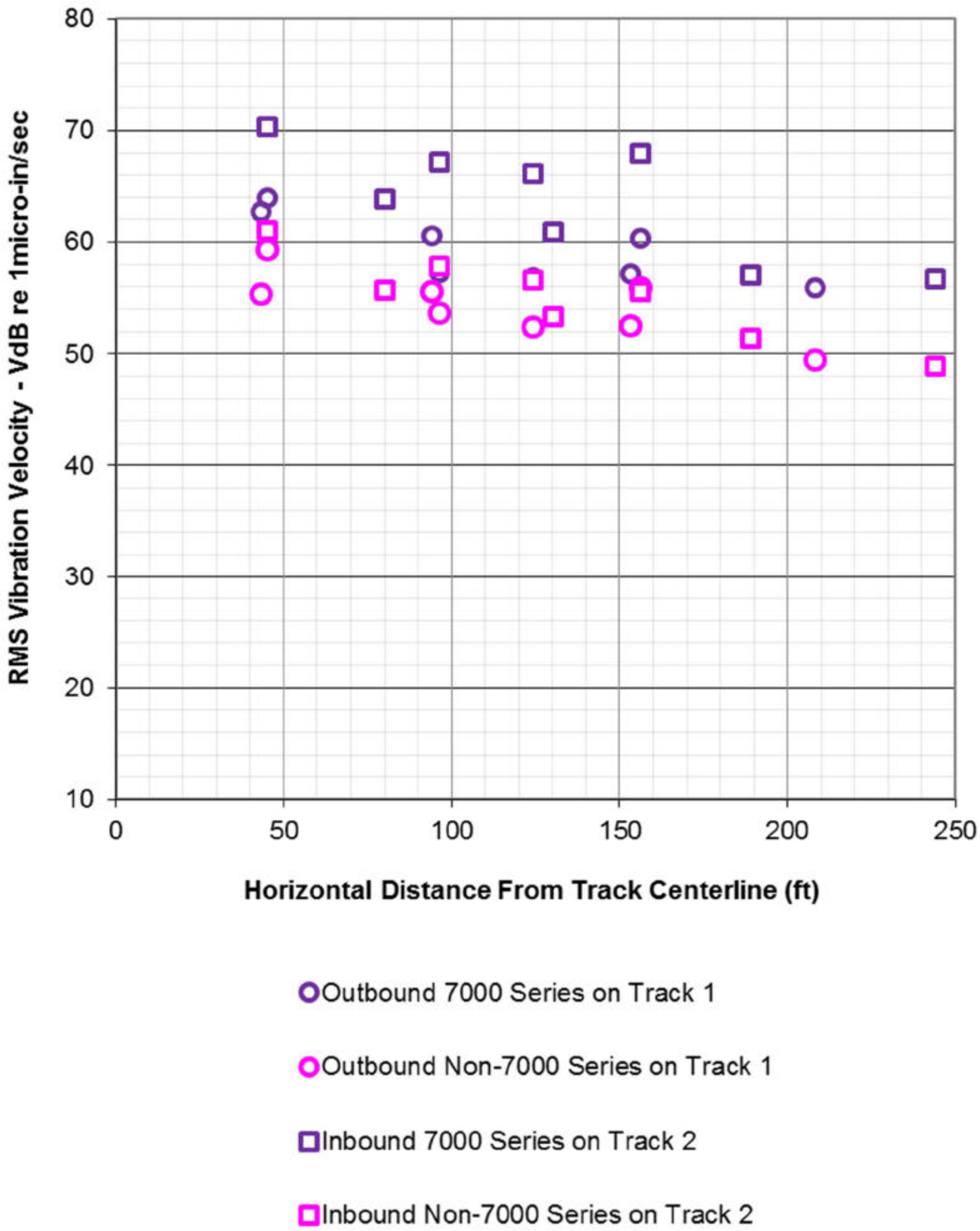


Figure 24: Site 8 Average Overall Level vs Distance

8 Discussion of Findings

8.1 Passby Ground-Borne Noise and Vibration Assessment

Since the ground-borne noise and vibration criteria are only assessed inside buildings, only interior results are presented for each location. Even though measurements were made in multiple rooms in each residence, the criterion apply to every room. Therefore, only the data from the room where the ground-borne noise and vibration levels were highest are presented in this section. All data may be found in Appendix B.

At each site, the data are summarized by both the average and the highest vibration level. Both types of data are presented by vehicle type. For sites where data were collected at multiple locations (the norm), the data presented is that from the location that provided the highest levels.

By way of an example, at Site 1, vibration measurements were made in the Basement Bedroom, the Living Room, and 2nd floor Playroom; and data were collected from trains running on both Track 1 and Track 2. For this site, the highest Average and Highest vibration levels were measured at the 1st floor Living Room location from passbys on the outbound track (Track 1), so these are the levels presented in Table 11. For this site, the outbound track (Track 1) is actually closer to the residence than the inbound track (Track 2) due to the depth of the tunnels, even though the residence is on the inbound T2 side of the alignment.

For rooms where some trains generated noise over the criteria, the "% >" column indicates the percentage of train passbys that exceeded the criterion calculated as a percent of all passbys analyzed for that location on the dominant track. The percentage provides a rough indication of passbys that currently exceed the design criteria to the extent that the fleet mix at the time of the measurements is representative of current operations.

8.1.1 Ground-Borne Noise

Table 10 summarizes the results of the ground-borne noise criteria assessment. Table 10 indicates that all trains generated noise levels below the respective design criterion. The average ground-borne noise level from the 7000 Series vehicles is noticeably higher than the non-7000 vehicles, but the maximum level is often similar for both 7000 and non-7000 vehicles. Ground-borne noise from the trains could be heard except at Site 3. Train noise below 25 dBA is usually difficult to discern from the ambient.

Table 10: Ground-Borne Noise Assessment Summary

Site #	Ground-Borne Noise (dBA) 7000 Series[5]			Ground-Borne Noise (dBA) Non-7000 Series[5]		
	Average	Highest	% > 40 dBA	Average[2]	Highest	% > 40 dBA
1	38	39	---	30	40	---
2	29	30	---	23	31	---
3	---[4]	---[4]	---	---[4]	---[4]	---
4	N/A	N/A	---	N/A	N/A	---
5	N/A	N/A	---	N/A	N/A	---
6	30	35	---	26	30	---
7	32	35	---	24	28	---
8	N/A	N/A	---	N/A	N/A	---
9	24[1]	24	---	22	31	---
10	32	37	---	25	34	---
11	N/A	N/A	---	N/A	N/A	---
12	29	32	---	18	22	---
13	31	32	---	32	33	---
14	N/A	N/A	---	N/A	N/A	---
15[3]	30[1]	30	---	25	30	---
16	N/A	N/A	---	N/A	N/A	---

[1] Single passby.
[2] Average of all non-7000 Series trains measured at the site. Refer to site-specific field studies in Appendix B for all data.
[3] Ground-borne noise criterion for Site 15 of 35 dBA is provided for reference only. See Section 4 of this report for further information.
[4] Ground-borne train noise was not discernable at Site 3. All train noise was below the criterion at Site 3.
[5] This table does not include data from any train passbys where the ROCS SPOTS reports indicated an "unknown" train type.
N/A = Not Applicable. Design criteria only apply to indoor spaces. There are no criteria for outdoor locations.

8.1.2 Vibration

Table 11 presents the summary assessment for vibration annoyance. As with the ground-borne noise assessment, only the data from the room with the highest levels are presented.

As can be seen in Table 11, the average vibration level from 7000 Series train passbys was above the design criterion at one residence, Site 10. The average from the other series did not exceed the criterion at any residence.

Individual trains, some of which were 7000 Series and others of which consisted of other series vehicles, exceeded the vibration criteria in four residences. In all likelihood, these trains had rougher than average wheels or wheels with flat spots formed during hard braking. Wheel flats and rough wheels are the most common cause of higher than average vibration levels.

At Site 10, 4400 block of New Hampshire Ave NW, 7000 Series trains exceeded the criterion of 70 VdB during 6 of 9 passbys on both tracks. The highest vibration level measured for the 7000 Series was 7 VdB over the criterion, which is a noticeable amount. The highest vibration level measured at Site 10 was from a 3000 Series vehicle. This vehicle was 10 VdB over the criterion, which is a noticeable amount. Non-7000 Series trains exceeded the criterion at Site 10 during 7 of 60 passbys on both tracks.

Table 11: Ground-Borne Vibration Assessment Summary

Site #	Ground-Borne Vibration (VdB) 7000 Series[7]			Ground-Borne Vibration (VdB) Non-7000 Series[7]		
	Average (VdB)	**Highest** (VdB)	**% > 70 VdB[6]**	**Average[2]** (VdB)	**Highest** (VdB)	**% > 70 VdB[6]**
1	63	68	---	57	64	---
2	70	**71**[4]	1 of 2 50%	59	**71**[4]	2 of 21 10%
3	--- [3]	--- [3]	---	--- [3]	--- [3]	---
4	N/A	N/A	---	N/A	N/A	---
5	N/A	N/A	---	N/A	N/A	---
6	62	64	---	62	69	---
7	67	69	---	59	64	---
8	N/A	N/A	---	N/A	N/A	---
9	61[1]	61	---	55	63	---
10	**74**[4]	**77**[4]	6 of 9 67%	66	**80**[4]	7 of 60 12%
11	N/A	N/A	---	N/A	N/A	---
12	60	62	---	63	**71**[4]	2 of 22 9%
13	66	**72**[4]	1 of 8 13%	68	**79**[4]	9 of 28 32%
14	N/A	N/A	---	N/A	N/A	---
15[5]	64	64	---	61	65	---
16	N/A	N/A	---	N/A	N/A	---

[1] Single passby.
[2] Average of all non-7000 Series trains measured at the site. Refer to site-specific field studies in Appendix B for all data.
[3] Train vibration detectable in 63 Hz 1/3-octave band but overall vibration levels dominated by non-train ambient sources. All train vibration was below the criterion at Site 3.
[4] Vibration levels in **boldface** font exceed the applicable criterion.
[5] Ground-borne vibration criterion for Site 15 of 70 VdB are provided for reference only. See Section 4 of this report for further information.
[6] At sites where passby event levels exceeded the criterion, the number of passbys that exceeded, the total number of passbys, and the resulting percentage that exceeded the criterion are provided. These numbers are specific to the vehicle series.
[7] This table does not include data from any train passbys where the ROCS SPOTS reports indicated an "unknown" train type.
N/A = Not Applicable. Design criteria only apply to indoor spaces. There are no criteria for outdoor locations.

Table 12 provides a summary of all the individual train car consists that caused exceedances of vibration criterion at the residential measurement sites. The table lists the specific sensor locations at each site, the date and time, and the overall vibration level of the exceedances. The table also includes the train ID, the track the train was traveling on, and the train consist individual car numbers. Our understanding is that WMATA checked the maintenance records for each train car that caused an exceedance on the day of testing as well as the days preceding and following the testing and did not find any maintenance logs pertaining to those cars.

Table 12: Summary of Train Consists That Exceeded Applicable Vibration Criteria

Site #	Sensor	Location	Day	Time	Overall Vibration (VdB)	Track	Train ID	Consist
2	V5	First Floor Dining Room	Wed, 16 Aug 2017	10:49 AM	71	Inbound Track 2	304	3012-3013.3165-3164.3062-3063
	V5	First Floor Dining Room	Wed, 16 Aug 2017	09:19 AM	71	Inbound Track 2	512	7352-7353.7011-7010.7390-7391.7389-7388
	V4	First Floor Living Room	Wed, 16 Aug 2017	10:13 AM	71	Inbound Track 2	301	3057-3056.2000-2001.2049-2048
10	V2	First Floor Living Room	Tue, 8 Aug 2017	11:46 AM	73	Outbound Track 1	302	2014-2015.2062-2063.2008-2009
	V2	First Floor Living Room	Tue, 8 Aug 2017	01:24 PM	73	Outbound Track 1	302	2014-2015.2062-2063.2008-2009
	V2	First Floor Living Room	Tue, 8 Aug 2017	10:55 AM	80	Outbound Track 1	306	3067-3066.3222-3223.3019-3018
	V2	First Floor Living Room	Tue, 8 Aug 2017	12:38 PM	71	Outbound Track 1	306	3067-3066.3222-3223.3019-3018
	V2	First Floor Living Room	Tue, 8 Aug 2017	11:10 AM	71	Outbound Track 1	307	6147-6146.6127-6126.6181-6180
	V2	First Floor Living Room	Tue, 8 Aug 2017	10:42 AM	77	Outbound Track 1	501	7076-7077.7383-7382.7112-7113.7099-7098
	V2	First Floor Living Room	Tue, 8 Aug 2017	12:41 PM	76	Outbound Track 1	501	7076-7077.7383-7382.7112-7113.7099-7098
	V2	First Floor Living Room	Tue, 8 Aug 2017	11:02 AM	72	Outbound Track 1	503	7172-7173.7225-7224.7184-7185.7103-7102
	V2	First Floor Living Room	Tue, 8 Aug 2017	11:26 AM	75	Outbound Track 1	308	7218-7219.7371-7370.7170-7171.7381-7380
	V2	First Floor Living Room	Tue, 8 Aug 2017	11:33 AM	75	Outbound Track 1	301	2016-2017.2029-2028.2064-2065
	V2	First Floor Living Room	Tue, 8 Aug 2017	10:49 AM	74	Outbound Track 1	305	unknown (WMATA ROCS SPOTS did not provide)
	V2	First Floor Living Room	Tue, 8 Aug 2017	12:22 PM	71	Outbound Track 1	305	unknown (WMATA ROCS SPOTS did not provide)

Site #	Sensor	Location	Day	Time	Overall Vibration (VdB)	Track	Train ID	Consist
	V2	First Floor Living Room	Tue, 8 Aug 2017	01:57 PM	72	Inbound Track 2	304	2053-2052.6151-6150.2021-2020
	V2	First Floor Living Room	Tue, 8 Aug 2017	11:29 AM	72	Inbound Track 2	501	7098-7099.7113-7112.7382-7383.7077-7076
	V2	First Floor Living Room	Tue, 8 Aug 2017	01:27 PM	72	Inbound Track 2	501	7098-7099.7113-7112.7382-7383.7077-7076
12	V4	First Floor Dining Room	Mon, 14 Aug 2017	03:51 PM	71	Inbound Track 2	504	6103-6102.6044-6045.6111-6110.6141-6140
	V4	First Floor Dining Room	Mon, 14 Aug 2017	05:34 PM	71	Inbound Track 2	504	6103-6102.6044-6045.6111-6110.6141-6140
13	V3	Second Floor Bedroom	Thu, 8 Jun 2017	03:25 PM	75	Inbound Track 2	304	3033-3032.6020-6021.6028-6029
	V3	Second Floor Bedroom	Thu, 8 Jun 2017	03:22 PM	71	Inbound Track 2	505	3092-3093.1060-1061.5126-5127
	V3	Second Floor Bedroom	Thu, 8 Jun 2017	05:00 PM	72	Inbound Track 2	504	3092-3093.1060-1061.5126-5127
	V3	Second Floor Bedroom	Thu, 8 Jun 2017	06:20 PM	71	Inbound Track 2	360	5016-5017.1226-1227.3034-3035
	V3	Second Floor Bedroom	Thu, 8 Jun 2017	03:40 PM	73	Inbound Track 2	358	5135-5134.1214-1215.1137-1136.5058-5059
	V3	Second Floor Bedroom	Thu, 8 Jun 2017	04:55 PM	74	Inbound Track 2	353	6027-6026.6107-6106.3278-3279
	V3	Second Floor Bedroom	Thu, 8 Jun 2017	06:50 PM	75	Inbound Track 2	300	6078-6079.1118-1119.4038-4039.3068-3069
	V3	Second Floor Bedroom	Thu, 8 Jun 2017	04:40 PM	75	Inbound Track 2	352	6134-6135.6172-6173.6053-6052
	V3	Second Floor Bedroom	Thu, 8 Jun 2017	05:07 PM	79	Inbound Track 2	354	6169-6168.5032-5033.5114-5115
	V3	Second Floor Bedroom	Thu, 8 Jun 2017	04:10 PM	72	Inbound Track 2	501	7340-7341.7343-7342.7304-7305.7275-7274

8.2 Potential for Building Damage Assessment

Table 13 presents the average and highest PPV vibration data measured at each residential site in comparison to the building vibration damage threshold of 0.12 in/sec PPV that applies to fragile buildings. No structural survey of any residence was conducted as part of this study, so there is no basis for determining whether or not any of the buildings along the Green Line route are actually fragile enough to warrant application of the more conservative threshold.

As seen in Table 13, not a single PPV reading exceeded the conservative threshold for cosmetic damage to a fragile building. Therefore, the measurement data indicates that WMATA's operations are not causing any physical damage to any residences.

Table 13: PPV Vibration Data for Residential Survey Sites

Potential for Building Vibration Damage Assessment							
Site #[1]	> 0.12 in/sec PPV in any direction?	Average PPV (in/sec)			Highest PPV (in/sec)		
		Tran	Vert	Long	Tran	Vert	Long
1	NO	0.0012	0.0008	0.0005	0.0236	0.0062	0.0801
2	NO	0.0034	0.0034	0.0021	0.0340	0.0250	0.0120
3	NO	0.0012	0.0005	0.0004	0.0016	0.0071	0.0016
6	NO	0.0031	0.0032	0.0021	0.0050	0.0130	0.0070
7	NO	0.0006	0.0005	0.0003[2]	0.0012	0.0118	0.0016
9	NO	0.0029	0.0029	0.0020	0.0030	0.0070	0.0040
10	NO	0.0031	0.0032	0.0027	0.0110	0.0230	0.0170
12	NO	0.0032	0.0030	0.0021	0.0180	0.0080	0.0270
13	NO	0.0005	0.0006	0.0003[2]	0.0022	0.0115	0.0102
15	NO	0.0030	0.0029	0.0020	0.0080	0.0140	0.0070

[1] PPV vibration was only measured at residential measurement sites.
[2] Resolution of monitoring equipment is 0.00031 inches per second.
PPV = peak particle velocity, inches per second

8.3 WMATA Rail Roughness Measurement Results

Wilson Ihrig conducted rail roughness measurements at locations adjacent to residential measurement sites during the week of 7 August 2017. The intent of the measurements was to benchmark rail roughness when and where the passby measurements were performed. No rail grinding occurred between the time of the residential measurements and the time of the rail roughness measurements. The rail was last ground in March 2017 to remove corrugation according to [redacted] (email correspondence, 3 April 2017).

The RMS spectra for each site and all measurement traces are plotted below in Figure 25. Wavelength can be related to frequency relative to train speed by the formula, $\lambda = v / f$, where v is the train speed and *f* is the frequency. For a given wavelength, as train speed increases, the vibration frequency increases. Table 14 shows the approximate wavelength ranges of interest for 15 miles per hour (mph) to 60 mph train speeds.

Table 14: Audible Ground-borne Noise – Approximate Wavelength Ranges of Interest

Train Speed (mph)	Acoustic Frequency Range (Hz)	Rail Roughness Wavelength Range (mm)
15	25 to 250	315 to 31.5
30	25 to 250	630 to 63
45	25 to 250	800 to 80
60	25 to 250	1,000 to 100

mph = miles per hour
Hz = Hertz (cycles per second)
mm = millimeter

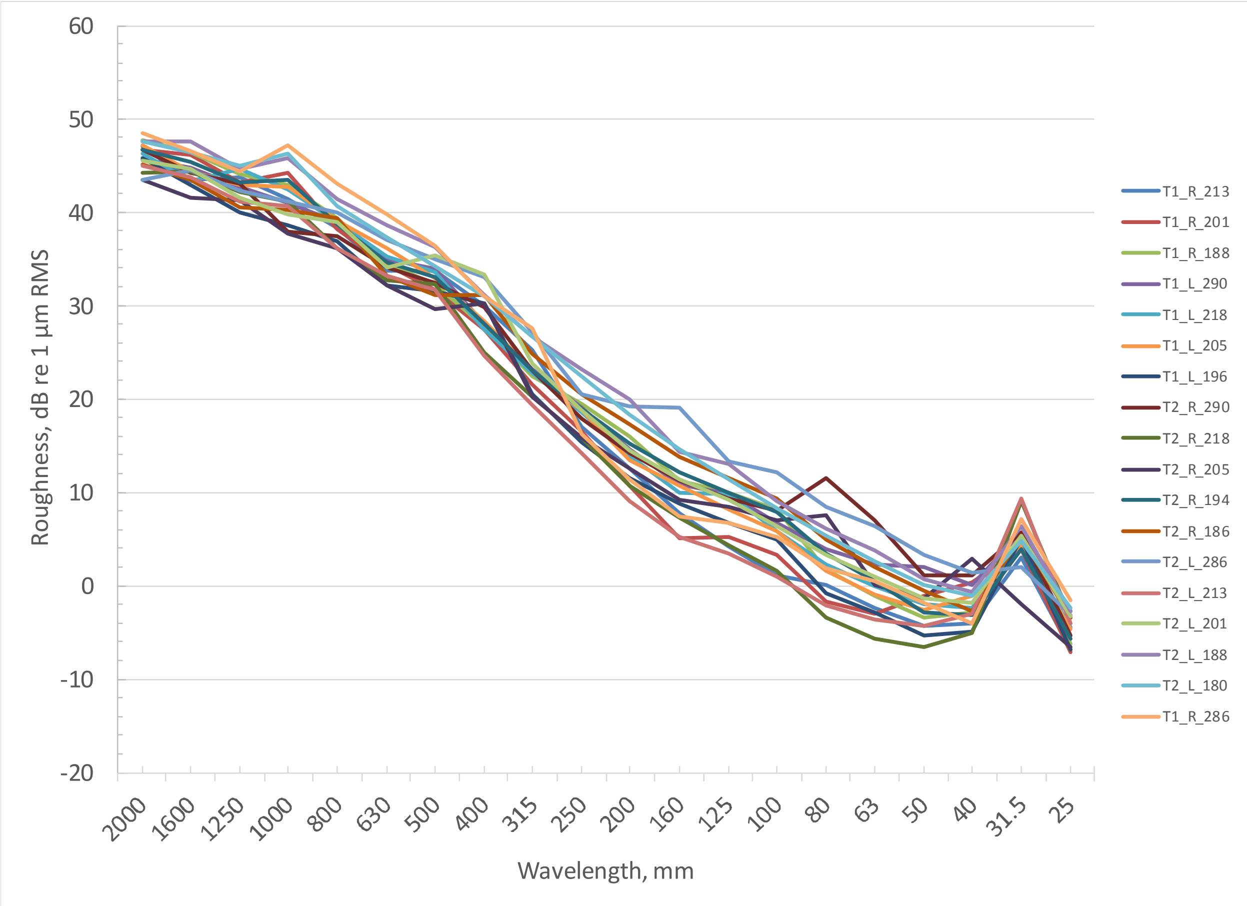


Figure 25: WMATA Rail Roughness Data

For this study, the main interest was to see if one or a few of the locations had significantly rougher rails than the others. The roughness data collected from all measurement sites are consistent and group together within about 7 dB. The only strong peak seen in the spectra occurs in the 31.5 mm band, which peak is associated with grinding patterns left by the rail grinder and is typical. This wavelength would not result in audible ground-borne noise at train speeds observed during the measurements.

Reducing rail roughness could be explored further as a means to reduce wayside ground-borne noise. However, the rails were ground in March 2017, and significant roughness or rail corrugation would not likely have developed between then and the measurements. Even if it had, additional rail grinding alone would not be expected to reduce vibration if wheel roughness is the primary cause. Wheels get rough through normal wear and from braking events that can cause flat spots to form on the metal tread. The RMS roughness is the square root of the sum of the squares of wheel roughness and rail roughness, and both roughnesses must be reduced to achieve low vibration and noise.

8.4 7000 Series Fleet Compared to Other Fleets

8.4.1 Comparison of Single-Number Decibel Metrics

Table 15 compares the average ground-borne noise and vibration levels from the 7000 Series passbys to the average levels of all other types at each residence. As with Table 10 and Table 11, the summary is based on the indoor location at each residence with the highest levels.

While certain passbys of non-7000 Series vehicles generated levels comparable to 7000 Series vibration, on average the 7000 Series produced higher ground-borne noise and vibration levels than the older series vehicles did.

The ground-borne noise produced by earlier series trains was either not noticeable or barely noticeable, and ground-borne noise produced by the 7000 Series cars is typically noticeable. The difference in most residences surveyed is distinctly perceptible and would explain why residents have noticed and expressed concern about the passby ground-borne noise whereas they had not expressed concern prior to the introduction of the vehicles. Perceptibility does not equate with exceeding design criteria, and 7000 Series ground-borne noise levels are within the design criteria.

The average ground-borne noise levels from the 7000 Series vehicles relative to those from older series vehicles ranges from minus (-) 1 dBA to plus (+) 11 dBA. “Relative” in this sense means the level from the 7000 Series compared to the non-7000 Series, i.e., the difference. For example, if the 7000 Series level were 38 dBA and the non-7000 Series were 30 dBA, the relative level would be +8 dBA.

Vibration levels from 7000 Series vehicles are higher, on average, than for older series vehicles, but they are also still largely below generally accepted criteria for floor vibration in residences, except perhaps at Site 10, where the level was above 74VdB. The average overall vibration levels from the 7000 Series relative to the older series ranges from -3 VdB (meaning the 7000 Series produces less vibration) to +11 VdB (meaning the 7000 Series produces more vibration).

Table 15: Increase in Ground-Borne Noise and Vibration due to 7000 Series Vehicles

Site #	Ground-Borne Noise (dBA)			Ground-Borne Vibration (VdB)		
	7000 Series	All Others	Increase	7000 Series	All Others	Increase
1	38	30	8	63	57	6
2	29	23	6	70	59	11
3	--- [1]	--- [1]	--- [1]	--- [2]	--- [2]	--- [2]
4	N/A	N/A	N/A	N/A	N/A	N/A
5	N/A	N/A	N/A	N/A	N/A	N/A
6	30	26	4	62	62	0
7	32	24	8	67	59	8
8	N/A	N/A	N/A	N/A	N/A	N/A
9	24	22	2	61	55	6
10	32	25	7	74	66	8
11	N/A	N/A	N/A	N/A	N/A	N/A
12	29	18	11	60	63	-3
13	31	32	-1	66	68	-2
14	N/A	N/A	N/A	N/A	N/A	N/A
15	30	25	5	64	61	3
16	N/A	N/A	N/A	N/A	N/A	N/A

[1] Ground-borne train noise was not discernable at Site 3.
[2] Vibration at Site 3 was dominated by non-train sources.
N/A = Not Applicable. Increase was not analyzed for outdoor sites.

8.4.2 Comparison of 1/3-Octave Band Spectra

Figure 26 through Figure 30 compare the average 1/3-octave band vibration spectra for the 7000 Series with each of the other series that were in operation at the time of the measurements. Each chart shows the respective vehicle comparison for all basement vibration locations at all sites. For example, Figure 26 presents the average passby data for the 7000 Series relative to the 6000 Series (7000 Series minus the 6000 Series) for each residential site. The charts show the relative vibration levels in VdB. Data above the 0 VdB line indicate that the 7000 Series vibration data is higher than the 6000 Series vibration. For all sites, the 7000 Series levels were higher than the 6000 Series levels by a significant amount, roughly 10 to 12 VdB, between 31.5 Hz and 500 Hz, inclusive, which are frequencies in the audible frequency range.

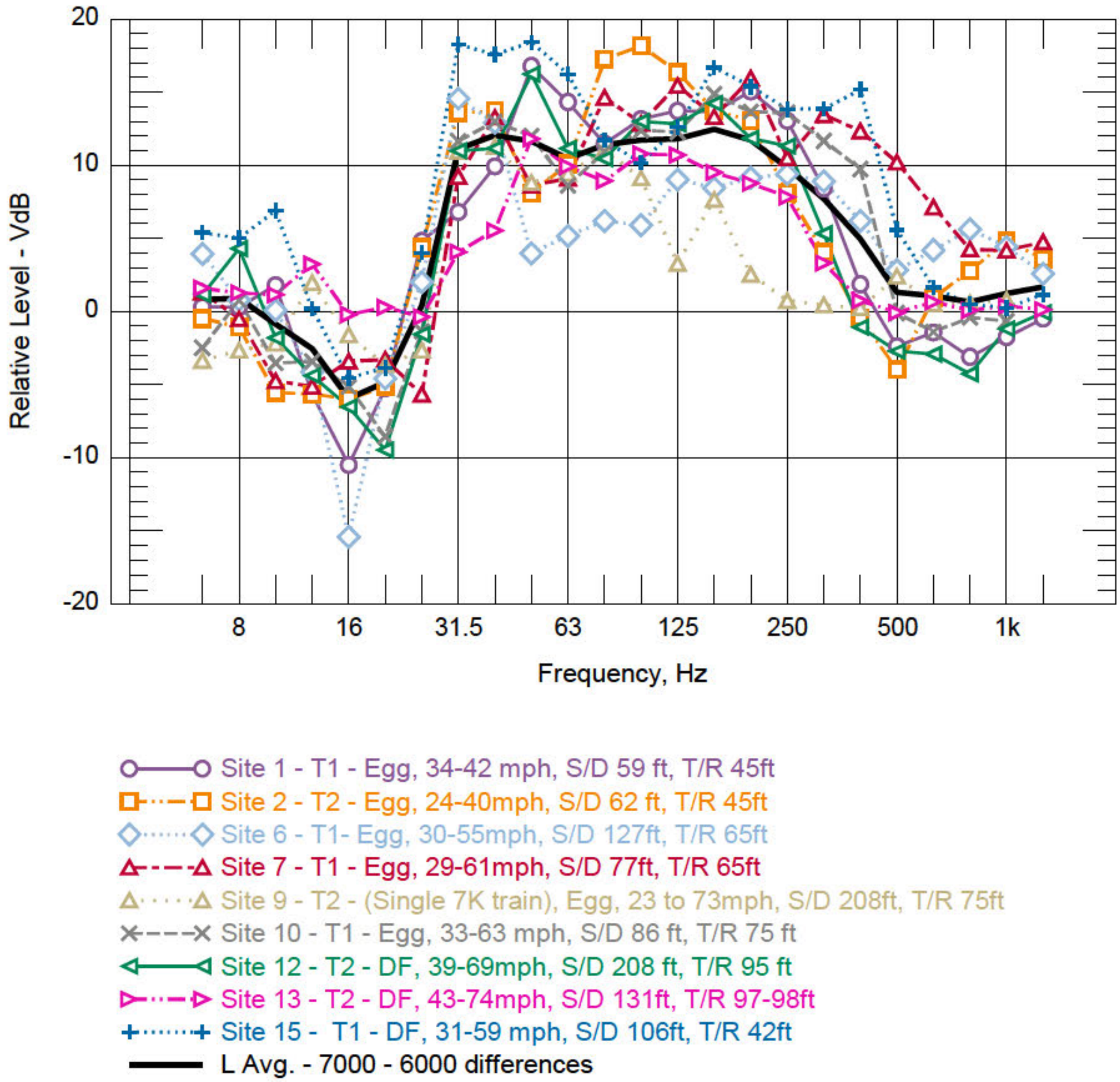


Figure 26: 7000 Series Minus 6000 Series - Basement Positions

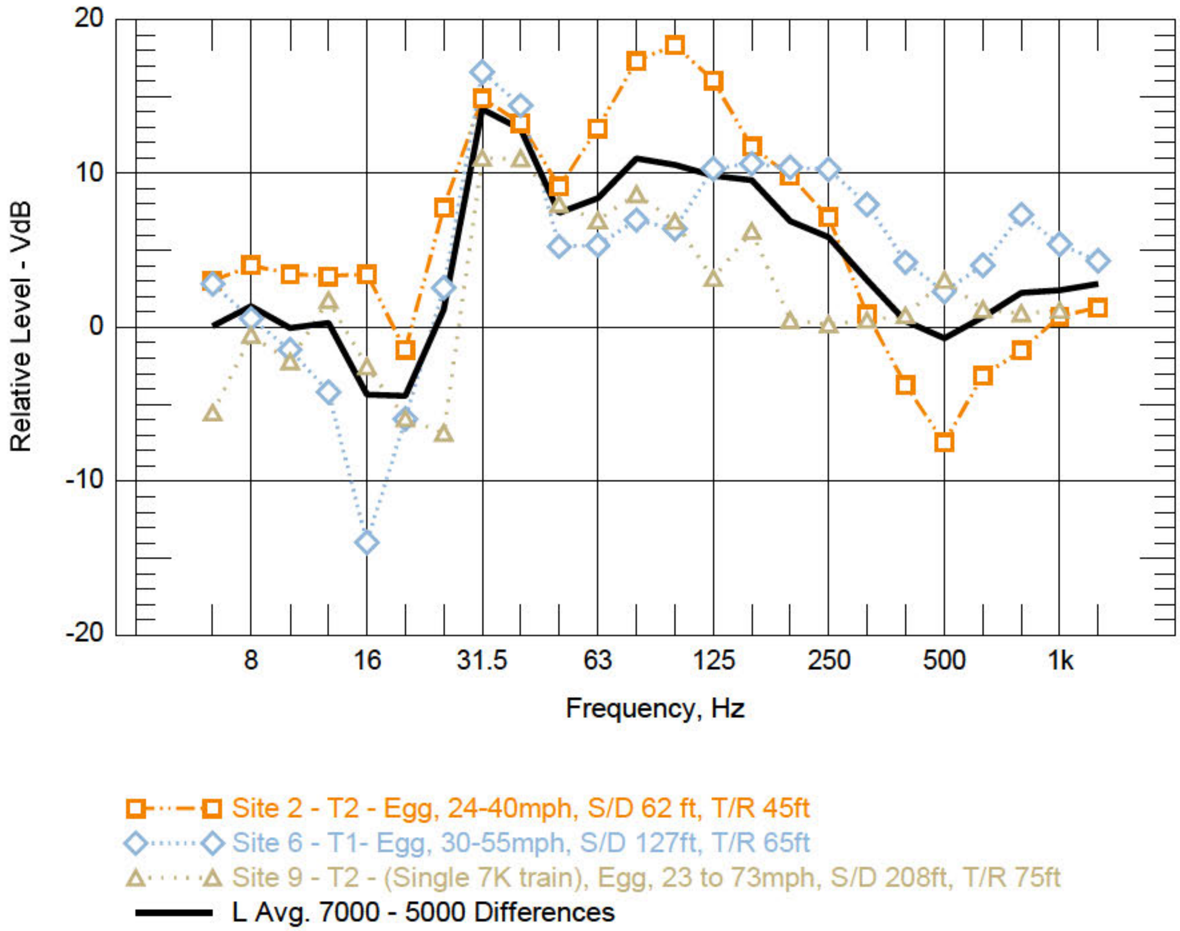


Figure 27: 7000 Series Minus 5000 Series- Basement Positions

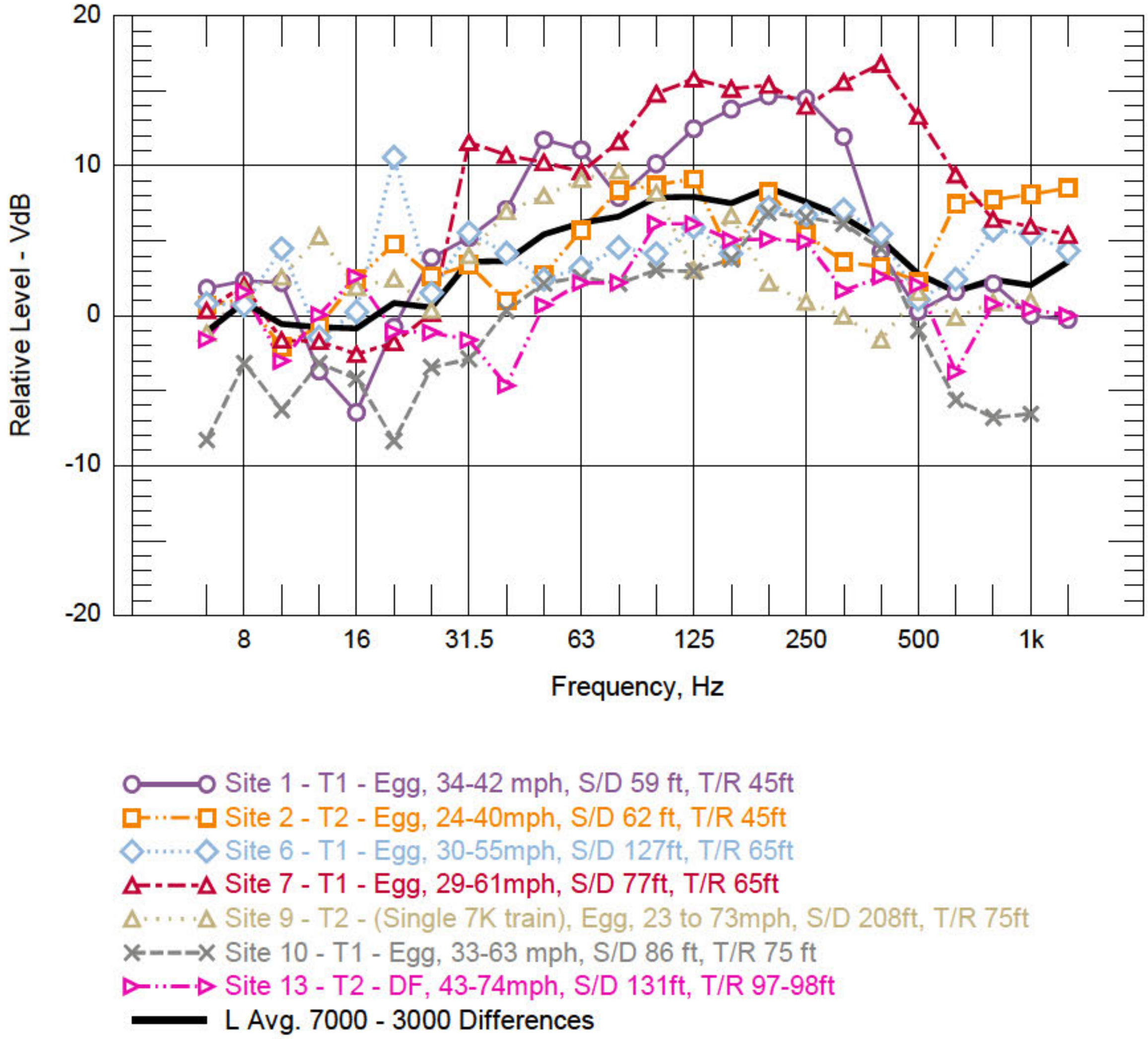


Figure 28: 7000 Series Minus 3000 Series - Basement Positions

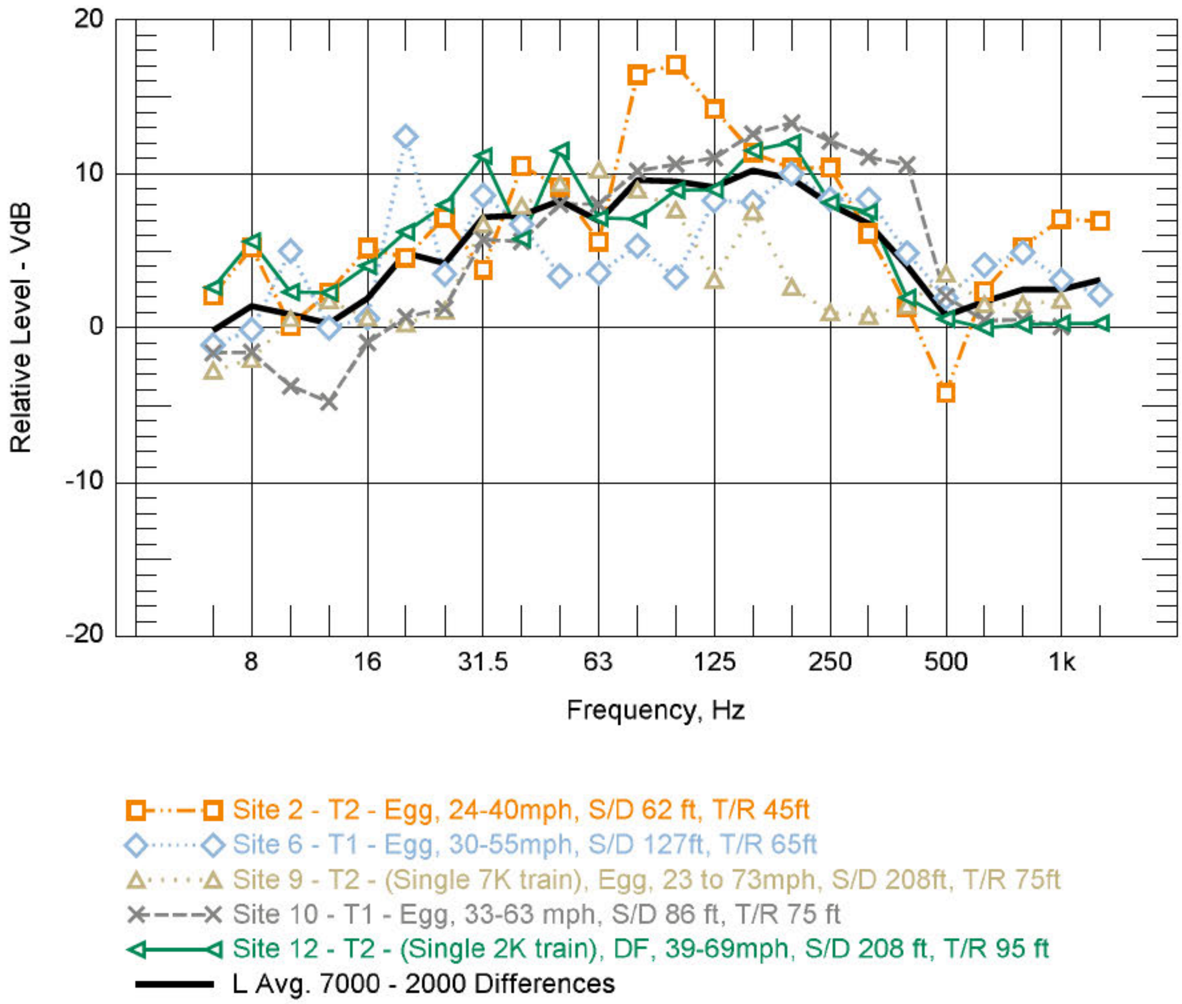


Figure 29: 7000 Series Minus 2000 Series - Basement Positions

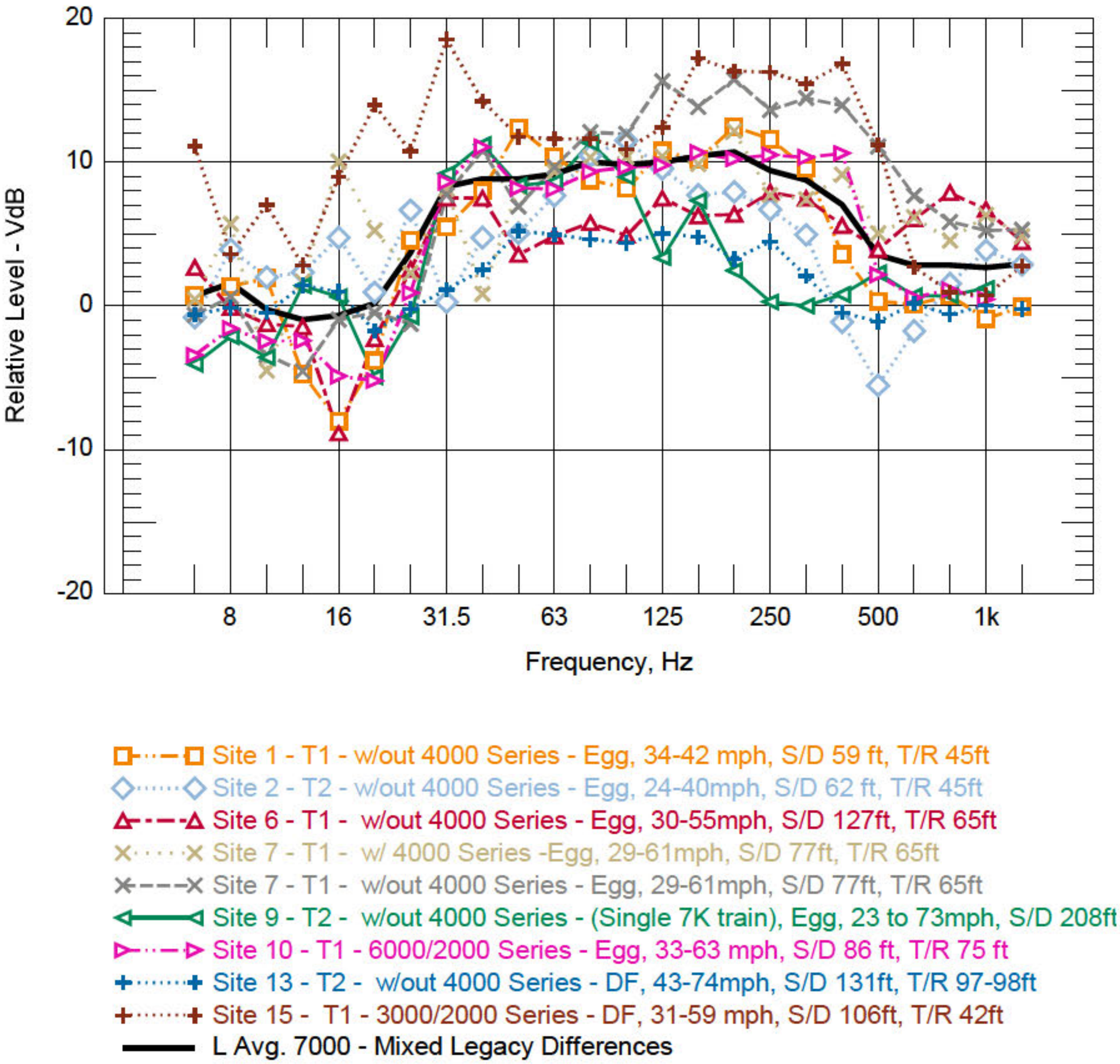


Figure 30: 7000 Series Minus Mixed Series - Basement Positions

9 Vehicle Characteristics

Table 16 summarizes the main design features of a vehicle that may affect ground vibration generation.[5] Overall, the main differences between the vehicles appear to be related to their primary suspension systems. The 7000 Series and earlier 2000/3000/4000 Series vehicles have elastomer chevron suspensions with nominal vertical stiffnesses ranging from 9,750 to 10,360 pounds per inch (lbs/in) for the 2000/3000/4000 Series vehicles, and 7,530 (AW0) to 8,083 (AW3) lbs/in for the 7000 Series vehicles. The primary suspensions of the original 1000 Series vehicles and the 5000/6000 Series vehicles are elastomer journal bushing suspensions with nominal stiffness of 60,000 and 74,300 lbs/in, respectively.

9.1 Primary Resonance Frequency

The primary resonance frequency of a vehicle is determined by the mass of the truck frame and other suspended components acting against the combined stiffness of the primary suspension and secondary suspension. The secondary suspension stiffnesses are very similar for all vehicle types. Thus, the major suspension component affecting differences between the primary resonance frequencies of various vehicle series is the primary suspension stiffness. The solid elastomer journal bushing of the 1000 Series vehicle may well be stiff enough to produce a resonance frequency above 20 Hz.[6] The primary resonance frequency of the chevron suspension trucks at transit systems are typically 6.3 to 10 Hz. (The static stiffnesses shown in Table 16 must be multiplied by a factor of at least 1.5 to obtain the dynamic stiffnesses when calculating resonance frequencies for elastomer springs.[7])

One may expect higher levels of ground vibration for elastomer journal bushing suspensions than for chevron suspensions for the 1/3-octave bands between 12.5 Hz and 31.5 Hz. This appears to be the case as shown in Figure 26 and Figure 27 for the 6000 and 5000 Series vehicles, respectfully.

The vibration produced by the 7000 Series vehicles would be expected to be greater than that produced by the 5000/6000 Series vehicles at about 8 Hz. This is not apparent in the data shown in Figure 26 and Figure 27, though this may be due to the background vibration dominating the ground vibration spectrum at these frequencies.

The ground vibration and ground-borne noise levels for the 7000 Series vehicles are consistently much higher than those produced by the 4000/5000/6000 Series, regardless of suspension type. The forgoing suggests that the cause is something other than differences between the primary suspension.

[5] Email correspondence from [redacted], 14 July 2017.

[6] Based on Wilson Ihrig experience with the Atchison Casting trucks of the Rohr vehicles used at BART and WMATA.

[7] The 1.5 factor is referred to as the "dynamic-to-static stiffness ratio". See, for example, Use of Rubber in Engineering, P. W. Allen, P. B. Lindley, and A. R. Payne editors, Maclaren & Sons, Ltd., London, 1967.

9.2 Un-Sprung Mass and Track Resonance (P2)

The principal features that affect ground vibration loading at frequencies in the 31.5 Hz and higher bands are the un-sprung masses of the wheel sets consisting of the wheels, axles, brake discs, bearings, and gear units, and to a lesser extent the motors. The un-sprung mass combined with the rail and rail support modulus[8] determine the track resonance frequency (P2 resonance), which may range from 50 Hz to well above 100 Hz, depending on rail support stiffness. The resonance frequency is usually best represented by the parallel impedance model of wheel/rail interaction.[9,10] Additional factors include the bending resonance of the axle, which should be about 100 Hz or higher for the hollow axle, but is reduced by the mass of the gear unit hanging on the axle. All of the vehicles apparently have gear units that are supported directly by the axles, without flexible coupling between the gear unit drive gear and axle. (This differs from many light rail vehicle configurations.) As listed in Table 16, the un-sprung weight of the 7000 Series vehicle is very similar to that of the 5000 and 6000 Series vehicles. All of the vehicles appear to have similar wheel set configurations, and thus should produce similar levels of ground-borne noise and vibration above 31.5 Hz.

[8] The rail support dynamic modulus is the direct fixation fastener stiffness (about 80,000 lbs/in for the high-compliance egg) divided by the fastener pitch (typically 30 in), and is about 2,700 lb/in/in.
[9] Transportation Cooperative Research Program (TCRP) Report 23.
[10] TCRP Report 155, Chapter 9.

Table 16: Vehicle Design Features

Feature	Unit of Measure	Car Series			
		1000	2000/3000/4000	5000/6000	7000
Manufacturer	---	Rohr	Breda	CAF/Alstom	Kawasaki
A-Car Weight	lbs	77,500	77,100 - 79,050	76,465 - 78,580	84,289
B-Car Weight	lbs	~80,000	77,650	77,335 - 79,340	84,289
Truck Manufacturer	---	Atchison	Breda	Bradken (Atchison)	Kawasaki
Truck Weight	lbs	12,838	13,773	12,838 - 13,231	13,961
Primary Suspension Type	---	Elastomer Journal Bushing	Chevron (Lord/Saga)	Elastomer Journal Bushing	Chevron (Tokai Rubber)
Primary Suspension Vertical Stiffness (Static)	lbs/in	60,000	9,750 - 10,360	74,300	7,530 - 8,083
Primary Lateral Stiffness (Static)	lbs/in	19,000	19,555	62,300	14,430
Primary Longitudinal	lbs/in	106,000	139,700	115,000	138,054
Wheel Diameter	in	28 – 25	28 – 25	28 - 25	28 - 25
Flange Angle	degrees	70	70	70	63
Axle	---	Hollow/Solid	Hollow	Hollow	Hollow
Wheels[1]	---	Solid	Solid	Solid	Solid
Wheelset Weight	lbs	No data	No data	2,077	2,259
Motor/Gear Unit Weight	lbs	No data	No data	1,452 (5000 Series) 2,234 (6000 Series)	1,102/661
Total Un-Sprung Weight	lbs	No data	No data	3,529 (5000 Series) 4,311 (6000 Series)	4,022

[1] Assumed

9.3 Wheel Condition

Table 11 shows that non-7000 Series vehicles generated vibration that exceeded the design criterion of 70 VdB in four of ten houses tested. In these houses, the number of passbys that exceeded the criterion ranged from 8% to 29%.[11] Table 11 also shows that 7000 Series vehicles exceeded the design criterion in three of ten houses and that 13% to 67% of the passbys did so. The particular trains that generated the highest vibration very likely had wheels with wheel flats.

Wheel surface condition degrades with wear, and infrequent truing may result in increased ground vibration loading. Rough wheels with flats that may or may not be visible may produce vibration levels that are 7 to 10 decibels greater than newly trued wheels. Wheel flats would manifest themselves in wayside noise as well as ground vibration.

Wilson Ihrig consultants aurally observed wayside and car interior noise produced by the 7000 Series vehicles and 6000 Series vehicles on the Green Line and on the Red Line. The 7000 Series produced greater rumbling noise than did the 6000 Series vehicles. This was observed at the Mt. Vernon Sq. Station, the West Hyattsville Station, Gallery Place, and Metro Center platforms. Low frequency rumbling noise is much more apparent inside the 7000 Series vehicle compared to the 6000 Series vehicles that were observed. Additionally, hunting of the 7000 Series vehicle was more apparent than with the 6000 Series vehicle. The nature of the noise is consistent with excessive wheel/rail roughness. Moreover, the rumbling noise appeared to subside on the curves, and also during braking. The pitch of the rumbling noise did not appear to change significantly with train speed, but remain focused at the track resonance frequency.[12]

If any of the vehicles have experienced emergency braking and or if the 7000 Series vehicles were subjected to braking tests as part of their acceptance, they may have wheel flats that may be a factor (possibly the only factor) in wayside ground-borne noise and vibration. However, the wheels of all trains and those of the 7000 Series vehicles have evidently been trued. Wilson Ihrig consultants listened carefully to analog data recorded in these homes but were unable to determine if any of the trains had wheel flats. This is not to say that the wheels did not have flats; they might be obscured by reverberation of vibration in the ground

As shown in Figure 26 through Figure 29, the ground vibration at frequencies above 30 Hz is much higher for the 7000 Series vehicles compared to the 2000/3000/5000/6000 Series vehicles. This suggests that other factors may be influencing the ground vibration loading from the 7000 Series besides wheel flats and roughness. Given that the truck and suspension characteristics of the 7000 Series are similar to the 2000/3000/4000 Series vehicles, the most likely difference is the wheel profile.

Wheel profiles may affect ground vibration, especially at curves. Ground vibration levels at curves may be three to five decibels higher than at tangent track. Most of the measurements in this report

[11] These percentages are based on the number of passbys, not the number of train consists. A given consist may have passed the measurement location more than once during the measurement period.
[12] Observations by the author, James Nelson, P.E., on 9 January 2018

were conducted at tangent track sections, so curving performance should not be a factor.[13] However, Table 16 indicates that the flange angle of the 7000 Series vehicles that have been delivered is 63-degrees, which differs from the 70-degree flange angle of the remaining fleet. The possibility exists that the taper near the throat may be greater with the 7000 Series vehicles than with the earlier vehicles, with the result that the contact between the wheel and rail is not entirely on the top running surface of the rail in tangent track, but may be shifted toward the gauge side of the rail head. Visual observation from the platform of the rail head at Metro Center and Gallery Place indicate wear and possibly incipient corrugation of the top of the rail between the wear band and gauge corner. The tracks in this area are tangent, so that wear in this area would not be expected unless there is a high degree of conformal contact across the rail head, possibly involving the throat.

Photographs shown in Figure 31 and Figure 32 of freshly ground rail suggest that the profile of the ground rail is not rounded across the rail head with a uniform ball radius, but includes a top running band and a band between the top running band and gauge corner. Wheels trued to the 63-degree profile and running on the top running band and on the area between the top running band may experience excess roughness at this dividing line. Lateral variation of the position of the dividing line between these surfaces will contribute to rail roughness, regardless of smoothness of the wheel and rail. A possibility exists that the wheels are running entirely on the rail head between the running band and gauge corner, leading to excessive hunting as well as roughness.

The 7000 Series vehicles up to Car Number 7464 were delivered with a 63-degree flange angle, and cars delivered after Car Number 7464 will be delivered with a 70-degree flange angle. Further, the flange angle wears to 68 to 69-degrees after a few months of service. In 2013, WMATA changed the flange angle from 63-degrees to 70-degrees to reduce the propensity of flange climb, reduce gauge corner stress, and increase life. When cars are brought in for wheel truing, the wheels are profiled to the new flange angle of 70-degrees. The majority of the WMATA 7000 Series cars have been trued at least once and now conform to 70-degrees.[14] At this point, the proportion of the 7000 Series vehicles that remain to be trued to the 70-degree profile has not been determined for this report. A possibility exists that the ground-borne noise and wayside rumbling noise of the 7000 Series vehicles will decrease to that produced by the 6000 Series vehicles after the 7000 Series vehicle wheels have been trued to the 70-degree profile.

The longitudinal stiffness of the 7000 Series chevron suspension is moderately higher than that of the 1000 Series and 5000/6000 Series vehicles. Self-steering of the wheel sets in curves may be less easily accommodated by the chevron suspensions of the 7000 Series than the journal bushing suspensions of the 5000/6000 Series vehicles, thus inducing greater wear rates in the 7000 Series vehicles. However, the higher vibration levels for the 7000 Series vehicles relative to those of the 2000/3000/4000 Series vehicles, also with chevron suspensions, suggests that this is not a factor.

13 Good curving performance involves minimal lateral slip, minimal hunting, and good ride quality. In curves, the vehicle wheels may steer around the curve with little or no contact between the wheel flanges and the rails. However, it may also be the case that contact occurs to varying degrees. This induces additional vibration.

14 Memorandum from [redacted], P.E. to Andrew Off, 5 January 2018

Figure 31 Photograph of left ground rail (guage corner at bottom) ([redacted] "WMATA Post-Grind Surface Roughness Report", Loram Maintenance of Way, December 2013, Figure 1 of Page 2)

Figure 32 Photograph of right ground rail (guage corner at bottom) ([redacted] "WMATA Post-Grind Surface Roughness Report", Loram Maintenance of Way, December 2013, Figure 2 of Page 2)

If wheel profiles, and wheel gauges of the 7000 Series vehicles and 6000 Series vehicles are all essentially identical, one may conclude that the 7000 Series vehicles are not steering properly on tangent track, and involve lateral slip. Such may produce high levels of ground vibration and rumbling noise. This is highly unlikely, but must be considered.

9.4 Areas for Exploration

Vehicles that Exceed the Vibration Design Criterion

- Review maintenance records for all vehicles identified as being part of a consist that generated vibration levels greater than the design criterion. If none have been trued, inspect the wheels of those vehicles for flats, spalls, and/or unusual wear patterns.
- Alternatively, arrange for more ground-borne noise and vibration measurements to be made with the intent of inspecting very quickly the wheels of trains that generate vibration levels that exceed the criterion. In addition to making measurements in the homes, measurements could be made in the tunnel either on the rails or nearby on the safety walk. These in-tunnel measurements would facilitate identifying which wheel(s) are contributing to the high vibration levels.
- Once vehicles that exceed the vibration criterion are identified, true the wheels of those vehicles and then re-test in the tunnel and, possibly, in the homes.

The 7000 Series

The measurement data indicate that a fundamental difference exists between the 7000 Series vehicles and the earlier series vehicles. Table 16 does not indicate any apparent design features that would contribute to higher vibration levels for the 7000 Series vehicles except perhaps differences in the flange angle. The acceptance test report indicates no significant difference between ground vibration produced by the 7000 Series vehicle and the baseline vehicle. The findings in this report indicate that the cause of higher levels of ground vibration produced by the 7000 Series vehicle relative to that produced by the earlier series vehicles is related to wheel/rail roughness with wavelengths of 100mm or longer, lack of truing, and tread profile. The following is suggested:

- Review the wheel and rail profiles and compare the profiles of the 7000 Series vehicles and 6000 Series vehicles with the rail grinding profiles currently used on the Green Line and Red Line.
- Review maintenance records for the 7000 Series vehicles and compare wheel tread profiles and wheel gauge with the 6000 Series and earlier vehicles. Other maintenance practices may have some relevance. This should include a visit to the maintenance shop.
- Identify differences in shop practices that may be relevant to ground vibration. These include truing intervals, type of truing machine (lathe or milling type), and profiles.
- Investigate differences in wheel profiles and wheel gauges of the 7000 Series vehicles relative to those of the earlier series vehicles.

- True the wheels of a test train and conduct a controlled survey of the test train with trued wheels and a test train with un-trued wheels at two of the outdoor-only ground surface measurement locations used in this study. If significant reductions are obtained with the trued wheels, consider repeating the measurements in one or two basements.
- Measure wayside noise for the trued and un-trued wheels to correlate wayside noise with ground vibration.
- Visually inspect unloaded trucks of 7000 Series vehicles and earlier design vehicles at the maintenance shops to possibly identify differences that may contribute to wayside ground vibration.
- Measure wheel surface roughness.

Finally, a test procedure has been developed for measuring the in-situ mechanical impedance of transit vehicles in track.[15] The test was conducted at BART on the Rohr vehicles, and at the Transportation Test Center in Pueblo, Colorado. The test involves instrumenting the rail with strain gauges and parking the vehicle on the instrumented section of rail. Dynamic excitation of the rail and simultaneously analyzing the response velocity of the wheel and reaction forces acting on the rail, as obtained with the strain gauges, yields the mechanical impedance of the vehicle as seen by the rail. A high mechanical impedance, possibly due to mechanical shorting of the primary suspension, would produce high ground vibration loading. This test is not yet recommended, but remains as a possible tool in the event that a cause is not found by other means.

[15] Department of Transportation/Transportation Systems Center (DOT/TSC) Ground-Borne Noise and Vibration Study Memorandum (1984).

Appendix A Instrumentation and Calibration Documentation

Appendix B Site-Specific Field Studies

Appendix A Instrumentation and Calibration Documentation

Table of Contents

A.1 Attended Vibration and Noise

All vibration was measured with high-sensitivity Endevco accelerometers. The accelerometers were adhered to the floor with wax. Where carpet was present, the accelerometers were mounted on a carpet spike, which is a heavy steel plate with three slender spikes to poke through to the floor underneath. Outdoor accelerometers were adhered to sidewalk or curb with wax. At one location, the accelerometer was mounted on a ground spike driven into the soil.

The analog acceleration signals were conditioned and amplified with Wilson Ihrig (WI) 112L preamplifiers. The outputs of the charge amplifiers were recorded on 4-channel Rion data recorders for subsequent data processing.

All noise measurements were made with Type 1 precision microphones and sound level meters output to a Sony PCM-D50 or Rion multi-channel data recorders for subsequent data processing. The sound level meter microphones were fitted with windscreens and mounted on tripods.

A complete list of all instrumentation used for the attended vibration and noise measurements, including model and serial number, are included in the following table.

Type/Model	Quantity	Serial Number(s)	Description
Endevco 7701A-1000	2	11013, 11035	Accelerometer, 1000 pC/g sensitivity
Endevco 7703A-1000	2	11219, 11220	Accelerometer, 1000 pC/g sensitivity
Endevco 7707-1000	4	AV22, BB64, BA11, BB92	Accelerometer, 1000 pC/g sensitivity
WI Type 112L	8	20, 21, 22, 26, 28, 36, 37, 39	Low-noise Charge Amplifier, 1V/1000 pC
Bruel & Kjaer Type 4155	1	1082896	Microphone, ½" diameter
Bruel & Kjaer Type 2230	1	1428412	Sound Level Meter
Norsonic N-1225	1	96046	Microphone, ½" diameter
Norsonic N-1209	1	12328	Preamplifier, goes with N-1225 mic
Norsonic Nor140	1	1403173	Sound Level Meter/Vibration Logger
Rion DA-21	1	00150211	Digital Recorder, 4-channel
Rion DA-20	1	34321679	Digital Recorder, 4-channel
Sony PCM-D50	1	1039262	Digital Recorder, 2-channel
Kistler 808K	1	849	Reference Accelerometer for Vibration Calibration
Bruel & Kjaer 4291	1	398328	Lab Vibration Shaker/Calibrator
PCB 394C06	1	3378	Field Vibration Shaker/Calibrator
Bruel & Kjaer Type 4220	1	159016	Reference Pistonphone for Acoustic Calibration
Bruel & Kjaer Type 4230	1	992709	Field Acoustic Calibrator

The vibration measuring systems are checked prior to field use and calibrated with Bruel & Kjaer Type 4291 and PCB 394C06 vibration calibrators, which are cross-calibrated with a reference accelerometer used solely for this purpose. The reference accelerometer is a Kistler Type 808K, SN# 849, which was calibrated by Odin Metrology on August 1, 2017. This calibration is traceable to NIST Test No. 6831283402-13 BK256.

Noise measuring systems were calibrated before and after testing with a Bruel & Kjaer Type 4230 acoustic calibrator, SN# 992709, which is cross-calibrated with a reference pistonphone traceable to NIST. The reference pistonphone was Bruel & Kjaer pistonphone type 4220 SN# 159016, last calibrated by Odin Metrology on August 2, 2017. The NIST Test No. is TN-683/286992-15.

A.2 Peak Particle Velocity

Instrumentation used for the peak particle velocity (PPV) monitoring is included in the following table.

Type/Model	Quantity	Serial Number(s)	Description
Instantel Geophone	1	SE12863	ISEE Triaxial Geophone
Instantel MiniMate Pro4	1	MP12883	Vibration Monitor/Logger

The geophone and monitor are sent to Instantel for annual calibration; both were last calibrated on April 12, 2017.

A.3 Overnight Vibration Logging

Overnight vibration was measured with the same high-sensitivity Endevco type accelerometers. The accelerometers were adhered to the floor with wax. The analog acceleration signals were conditioned and amplified with a Wilson Ihrig (WI) 112L preamplifier. The output of the charge amplifier was recorded using Norsonic Nor140 set to log 1/3 octave band root mean square (RMS) acceleration levels at 1-second intervals.

Type/Model	Quantity	Serial Number(s)	Description
Endevco 7707-1000	1	BA11	Accelerometer, 1000 pC/g sensitivity
WI Type 112L	1	21	Low-noise Charge Amplifier, 1V/1000 pC
Norsonic Nor140	2	1403200	Sound Level Meter/Vibration Logger

The overnight vibration measuring system was calibrated with the same calibration equipment and method as the attended vibration system.

A.4 Rail Roughness

Rail roughness was measured with a Corrugation Analysis Trolley (CAT). The instrumentation used is included in the following table.

Type/Model	Quantity	Serial Number(s)	Description
RailMeasurement CAT 3	1	641002	Corrugation Analysis Trolley

Appendix B Site-Specific Field Studies

Table of Contents

"Road Map" for Reviewing the Site-Specific Field Studies

The following provides a brief description about how the field studies are organized.

Residential Sites (1, 2, 3, 6, 7, 9, 10, 12, 13, 15)

Item (in order of presentation)	Description
Building and Tunnel Notes	Building type, track type, observations
Distance Table	List of sensor positions and distances to tunnels
Aerial map	Shows track centerlines, residential buildings, and exterior sensor position points on aerial map
Cross-section sketch	Sketch depicting multi-story sensor locations and proximity to tunnels
GBNV Assessment Table	Lists the vehicle types analyzed for each site and whether the average of multiple trains or highest individual train exceed ground-borne noise and vibration (GBNV) assessment thresholds
PPV Results Table	Presents the average and range of peak particle velocity to address whether there is potential for building vibration damage
Passby Vibration Spectra and Overall Levels	1/3 octave band velocity spectra plot with overall (OA) level along left-hand axis. Four plots for each sensor: 1. Average by Vehicle Type, Track 1 2. Average by Vehicle Type, Track 2 3. Highest Individual Train by Vehicle Type, Track 1 4. Highest Individual Train by Vehicle Type, Track
Passby Ground-borne Noise Spectra and A-weighted Levels	1/3 octave band noise plot with A-weighted (AW) level along right-hand axis. Four plots for each sensor: 1. Average by Vehicle Type, Track 1 2. Average by Vehicle Type, Track 2 3. Highest Individual Train by Vehicle Type, Track 1 4. Highest Individual Train by Vehicle Type, Track 2

Outdoor Only Sites (4, 5, 8, 11, 14, 16)

Item (in order of presentation)	Description
Tunnel Notes	Site location, track type, observations
Distance Table	List of sensor positions and distances to tunnels
Aerial map	Shows track centerlines and exterior sensor position points on aerial map
Overall Level vs Distance Plot	Average overall vibration levels for all sensor positions as a function of horizontal plan distance from track centerline. The data are sorted by 7000 Series and Non-7000 series vehicles on each track.

B.1 Site 1 – 1300 block of Park Road NW (Residence)

B.1.1 Building and Tunnel Notes

Location: Inbound track 2 side at 143+75

Building Notes: Residential townhouse, 4 floors comprised of partial underground basement plus 3 upper floors, exterior wall of brick construction

Tunnel Structure: Earth Tunnel

Track Type: transition from stiff DF to Egg Fasteners

T/R Depth: 73 to 74 feet (track 2) / 45 feet (track 1)

Train Speed: 34 to 42 mph

Measurement Period: Monday, 5 June 2017, 16:43 to 20:45

Field Observations: Homeowners present during the measurements, children playing inside the home on the first and second floors.

B.1.2 Measurement Positions

<table>
<tr><th></th><th></th><th colspan="3">INBOUND TRACK 2</th><th colspan="3">OUTBOUND TRACK 1</th></tr>
<tr><th>Sensor[a,b,c]</th><th>Location / Room Occupancy</th><th>Horizontal Distance[d] (feet)</th><th>T/R Depth[e] (feet)</th><th>Total Slant Distance to T/R[f] (feet)</th><th>Horizontal Distance (feet)</th><th>T/R Depth[e] (feet)</th><th>Total Slant Distance to T/R[f] (feet)</th></tr>
<tr><td>Triaxial Geo.</td><td rowspan="4">Basement Bedroom</td><td rowspan="6">31</td><td rowspan="6">74</td><td rowspan="6">80</td><td rowspan="6">38</td><td rowspan="6">45</td><td rowspan="6">59</td></tr>
<tr><td>V1</td></tr>
<tr><td>N1</td></tr>
<tr><td>N2</td></tr>
<tr><td>V2</td><td>1st Floor Livingroom</td></tr>
<tr><td>V3</td><td>2nd Floor Playroom</td></tr>
<tr><td>V4</td><td>Outside House</td><td>25</td><td>74</td><td>78</td><td>32</td><td>45</td><td>55</td></tr>
<tr><td>V5</td><td>Across Street</td><td>28</td><td>73</td><td>78</td><td>21</td><td>45</td><td>50</td></tr>
<tr><td>V6</td><td>Across Street</td><td>26</td><td>74</td><td>78</td><td>19</td><td>45</td><td>49</td></tr>
</table>

Notes:

a) Triaxial geophone mounted on floor, logging peak particle velocity
b) V# vibration locations with accelerometer mounted on floor in vertical direction
c) N# noise locations with microphone/sound level meter mounted on tripod 48 inches above floor
d) Horizontal distance from track to building façade for indoor locations, not accounting for tunnel depth.
e) T/R depth = top-of-rail depth
f) Total slant distance to T/R = total distance from building to track, accounting for tunnel depth

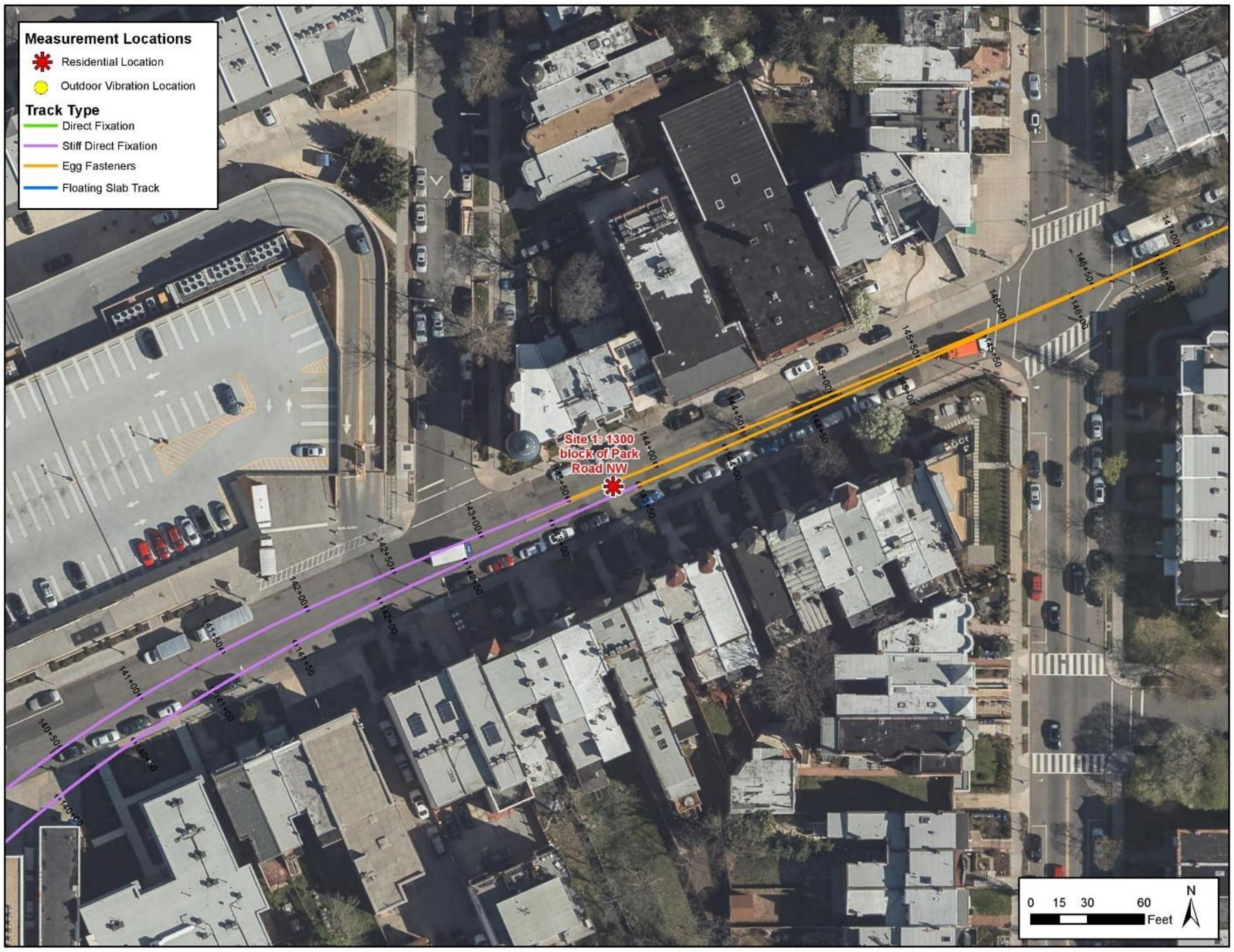


Figure 1: Aerial Map of 1300 block of Park Road Residence and Exterior Measurement Locations

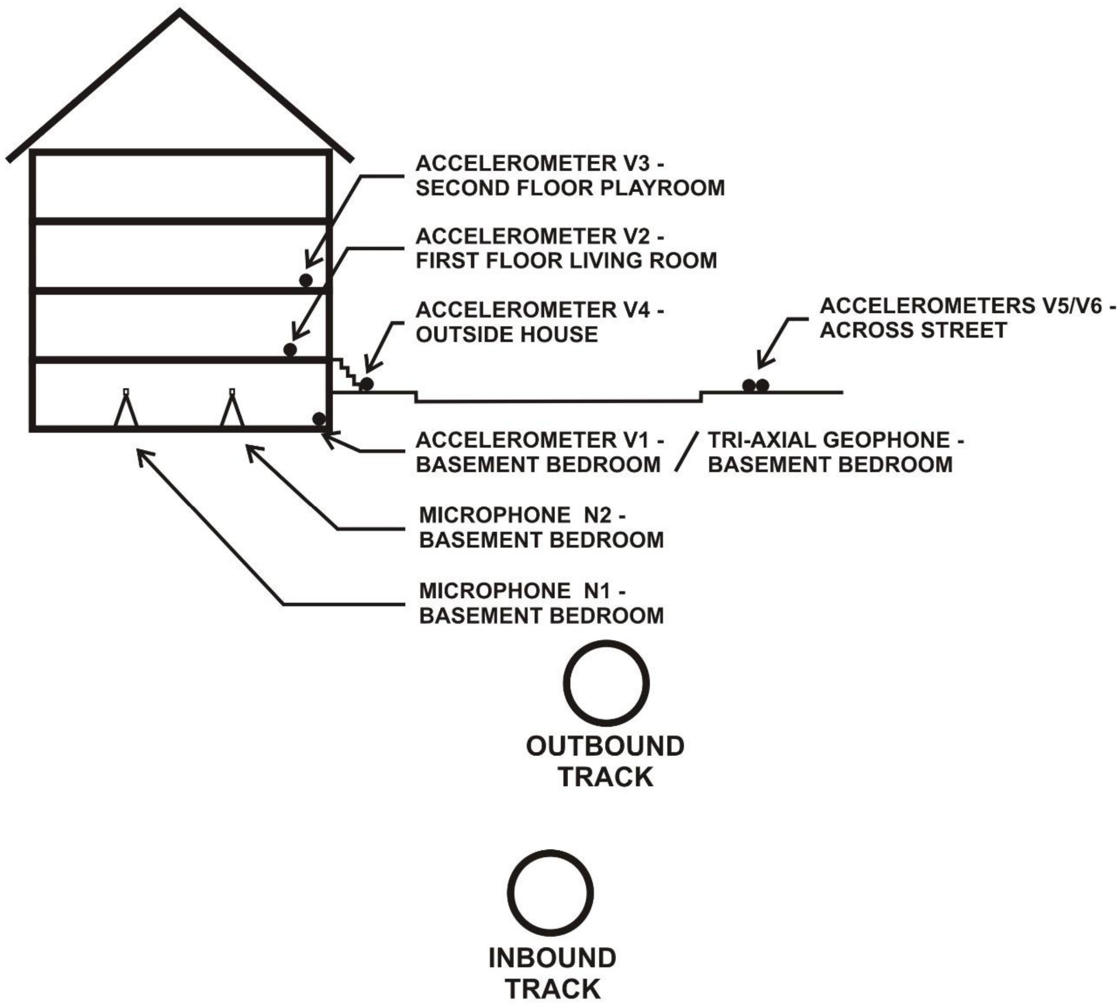


Figure 2: Cross-section Sketch (not to scale) of 1300 block of Park Road Indoor and Exterior Measurement Locations

B.1.3 GBNV Assessment Summary

SITE 1	1300 block of PARK ROAD NW – ATTENDED PASSBY MEASUREMENT GBNV ASSEMENT		
	Ground-borne Vibration (GBV)	**>70 VdB?**	**Notes**
	7000 Series - Average of Multiple Passbys	NO	
	6000 Series - Average of Multiple Passbys	NO	
	3000 Series - Average of Multiple Passbys	NO	
	Mixed Legacy with 4000 Series (Single Passby)	NO	
	Mixed Legacy without 4000 Series - Average of Multiple Passbys	NO	
	7000 Series - Individual Train with Highest Overall Vibration	NO	
	6000 Series - Individual Train with Highest Overall Vibration	NO	
	3000 Series - Individual Train with Highest Overall Vibration	NO	
	Mixed Legacy - Individual Train with Highest Overall Vibration	NO	
	Ground-borne Noise (GBN)	**>40 dBA?**	**Notes**
	7000 Series - Average of Multiple Passbys	NO	
	6000 Series - Average of Multiple Passbys	NO	
	3000 Series - Average of Multiple Passbys	NO	
	Mixed Legacy without 4000 Series (Average of Multiple Passbys)	NO	
	7000 Series - Individual Train with Highest A-weighting	NO	
	6000 Series - Individual Train with Highest A-weighting	NO	
	3000 Series - Individual Train with Highest A-weighting	NO	
	Mixed Legacy - Individual Train with Highest A-weighting	NO	

B.1.4 PPV Results

SITE 1	1300 block of PARK ROAD NW – POTENTIAL FOR BUILDING VIBRATION DAMAGE ASSESSMENT						
	>0.2 in/sec PPV in any direction?	Average PPV (in/s)			PPV Range (in/s)		
		Tran	Vert	Long	Tran	Vert	Long
	NO	0.0012	0.0008	0.0005	0 - 0.0236	0 - 0.0062	0 - 0.0801
Basement 5-Jun-17, 4:58:00 PM to 9:10:50 PM							

B.1.5 Passby Vibration Spectra and Overall Levels

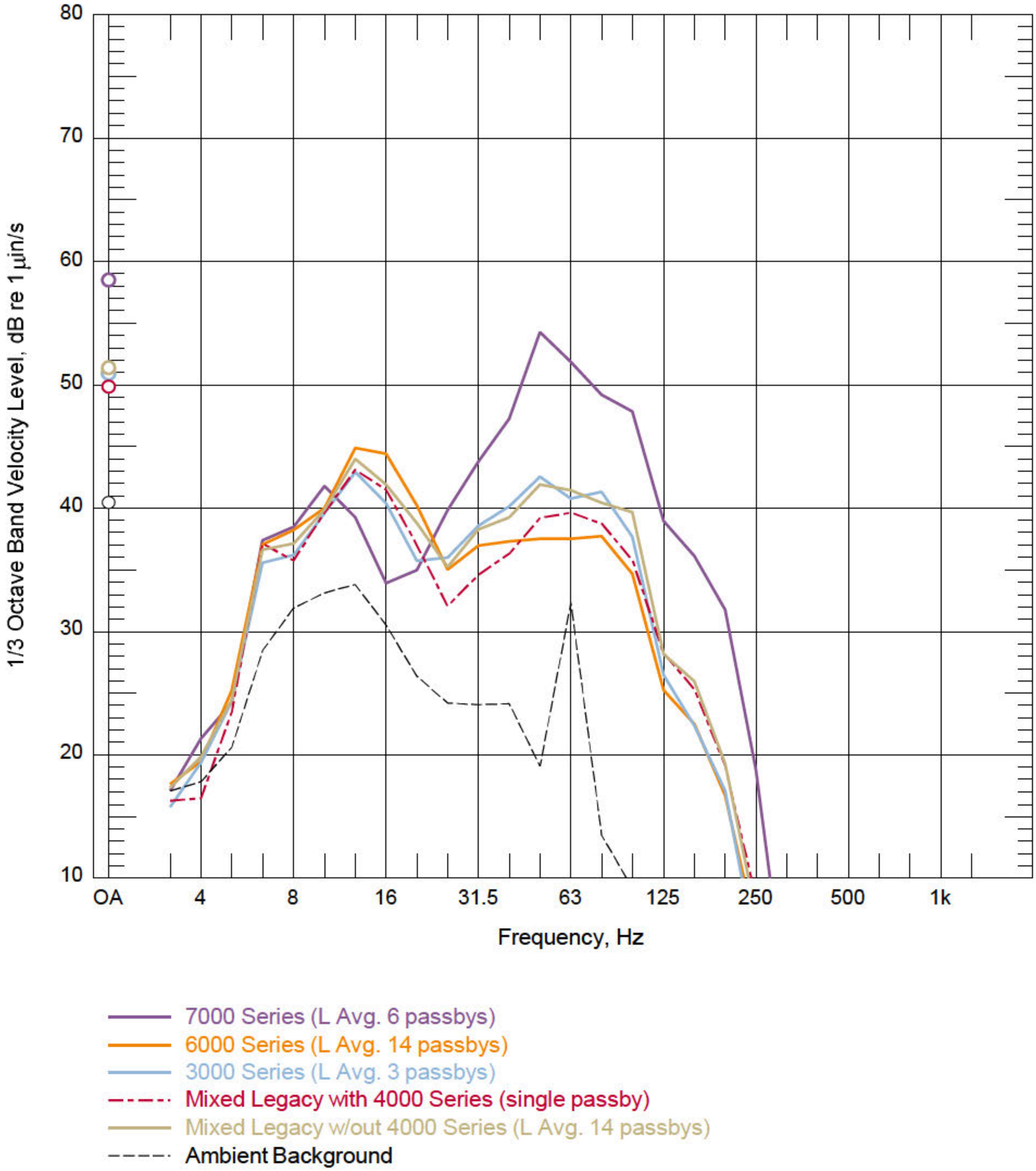


Figure 3: ***Site 1 at Location V1 Basement Bedroom***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

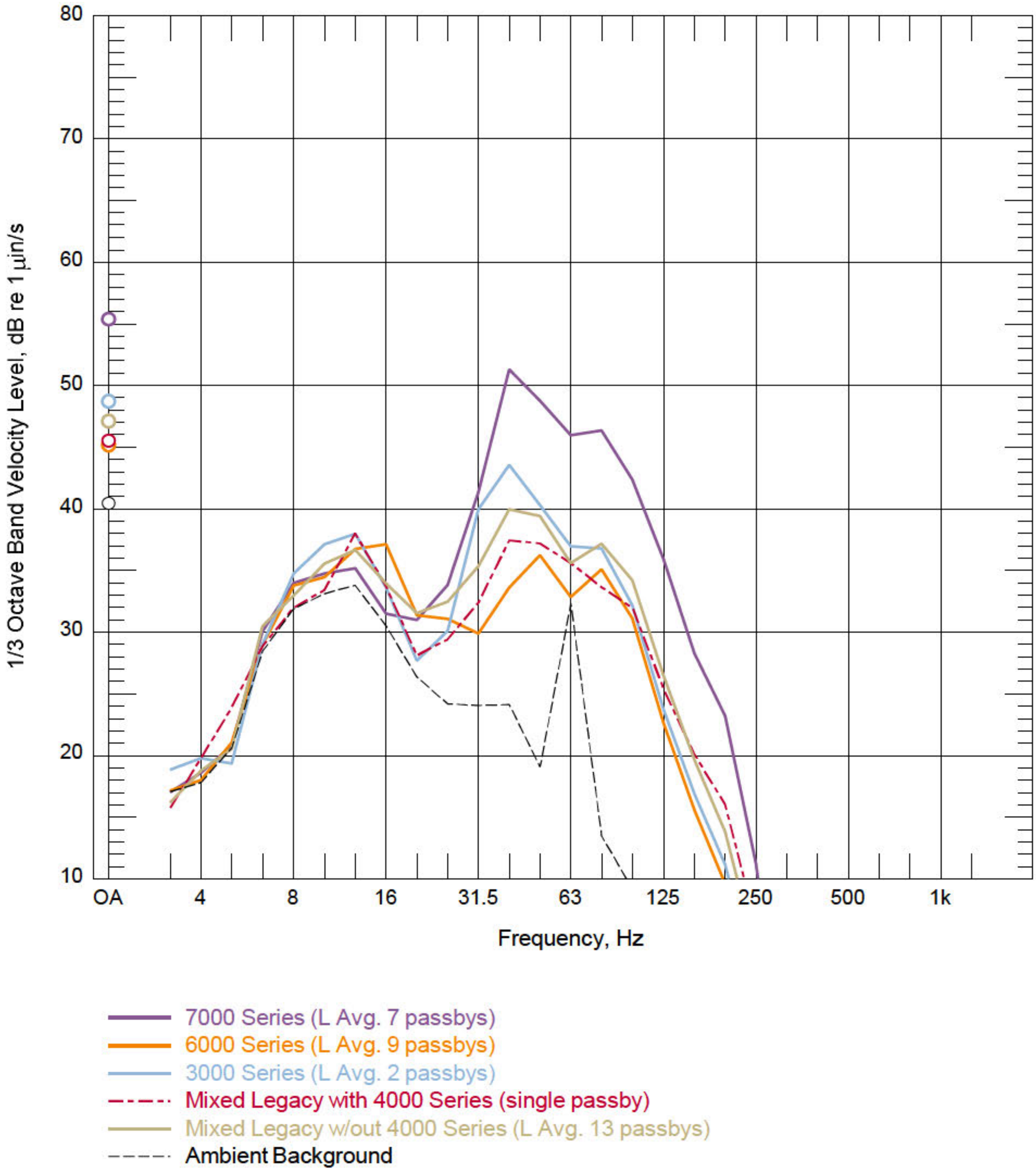


Figure 4: ***Site 1 at Location V1 Basement Bedroom***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

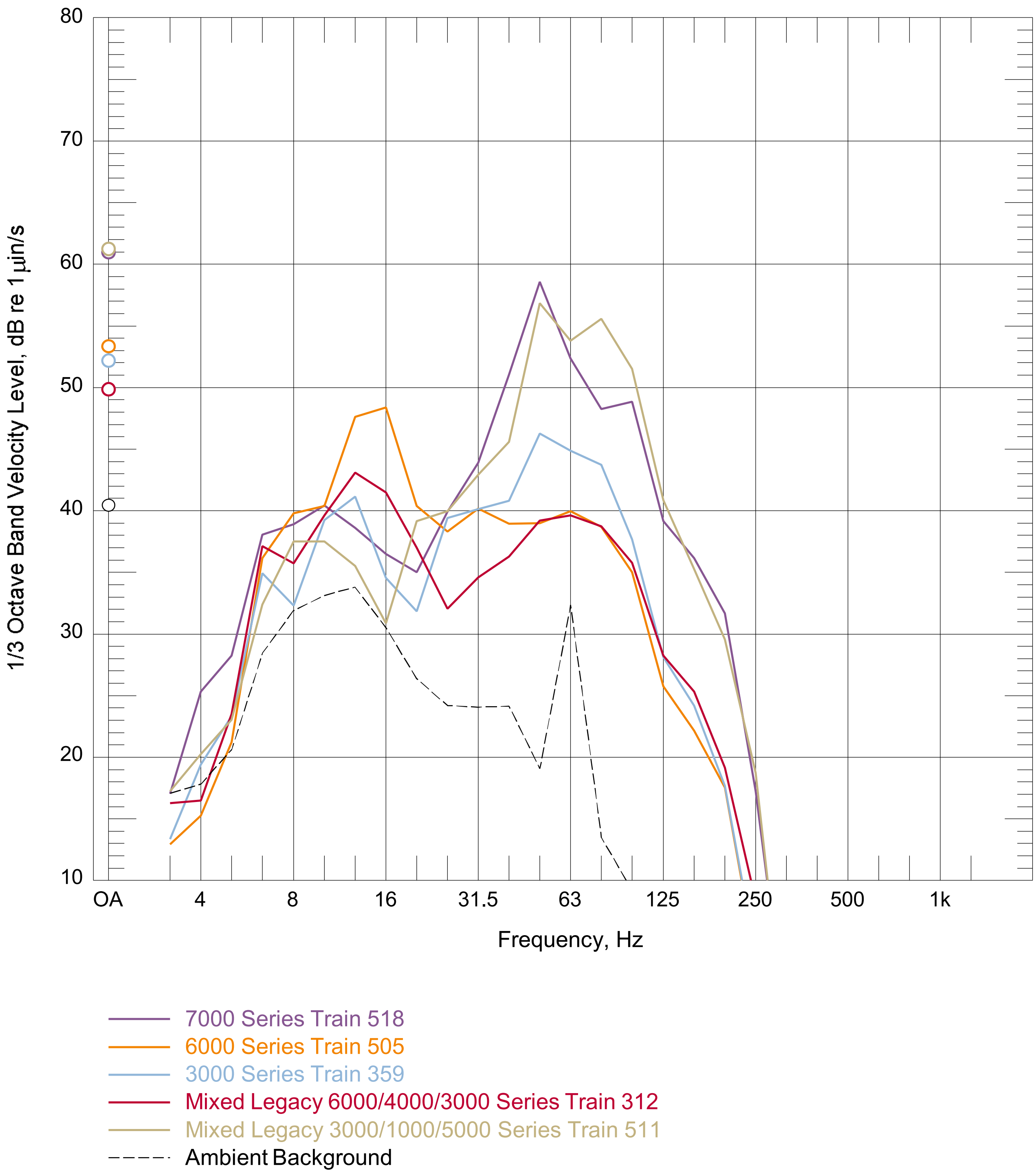


Figure 5: ***Site 1 at Location V1 Basement Bedroom***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

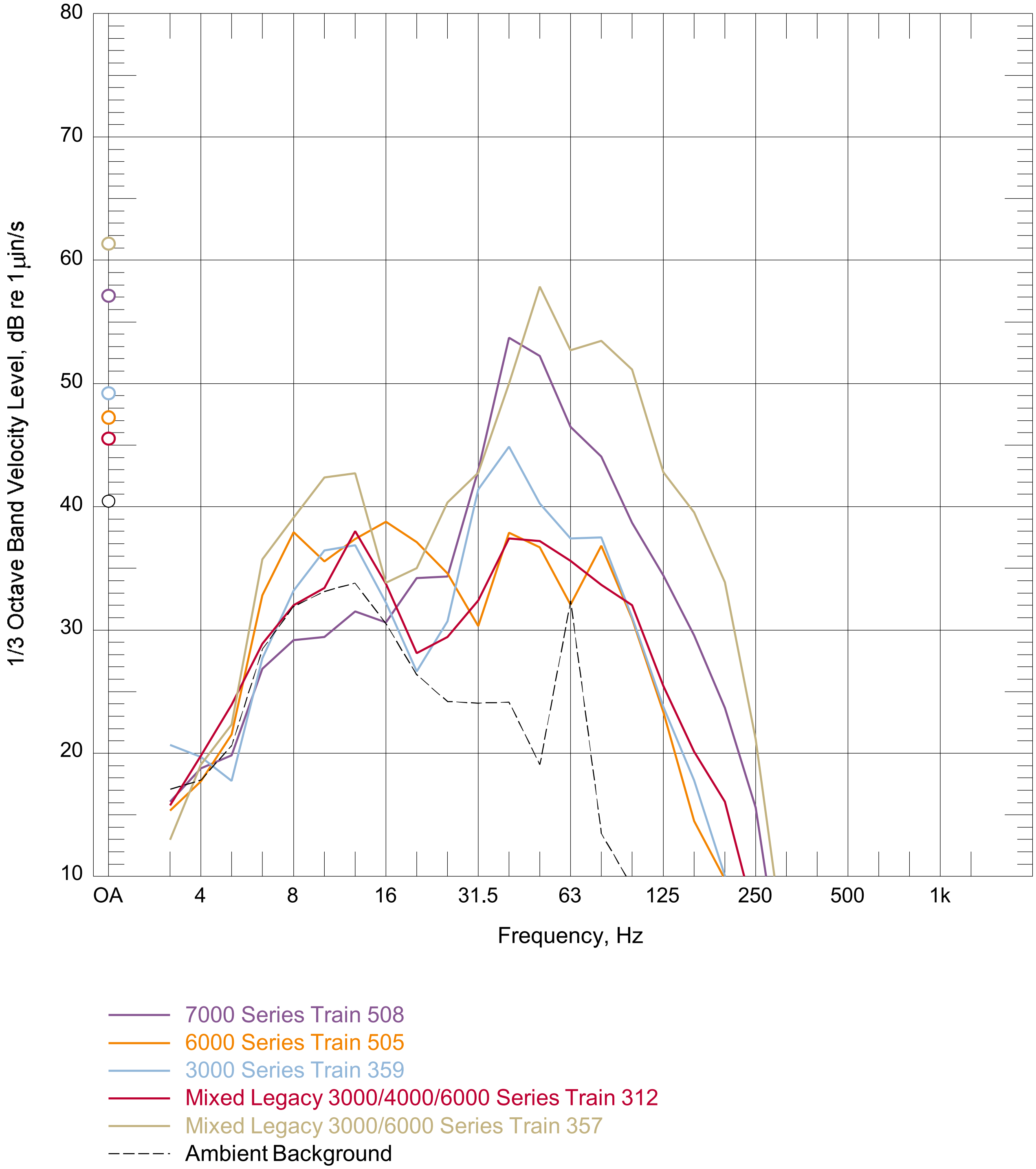


Figure 6: ***Site 1 at Location V1 Basement Bedroom***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

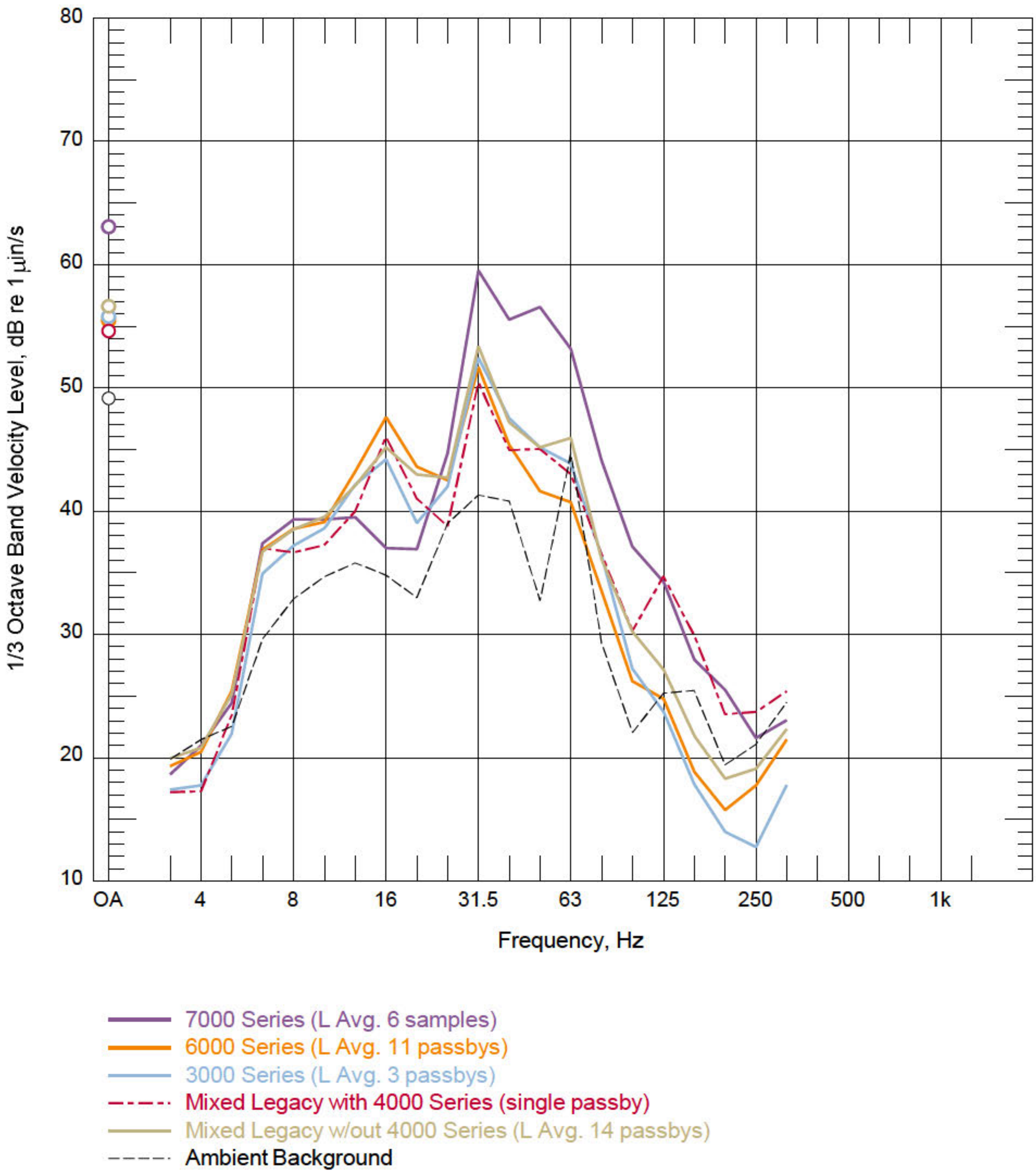


Figure 7: ***Site 1 at Location V2 1st Floor Living Room***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

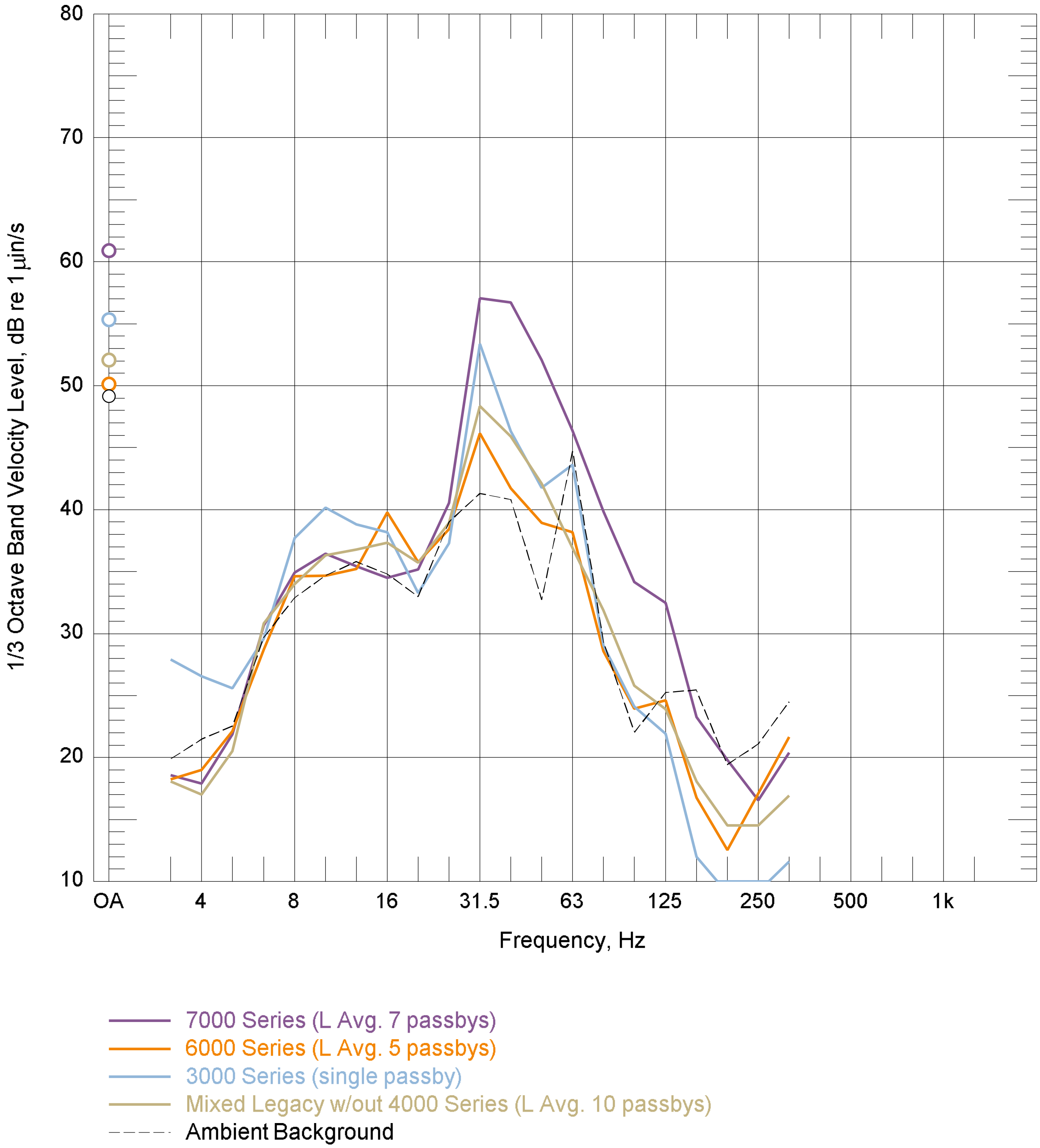


Figure 8: ***Site 1 at Location V2 1st Floor Living Room***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

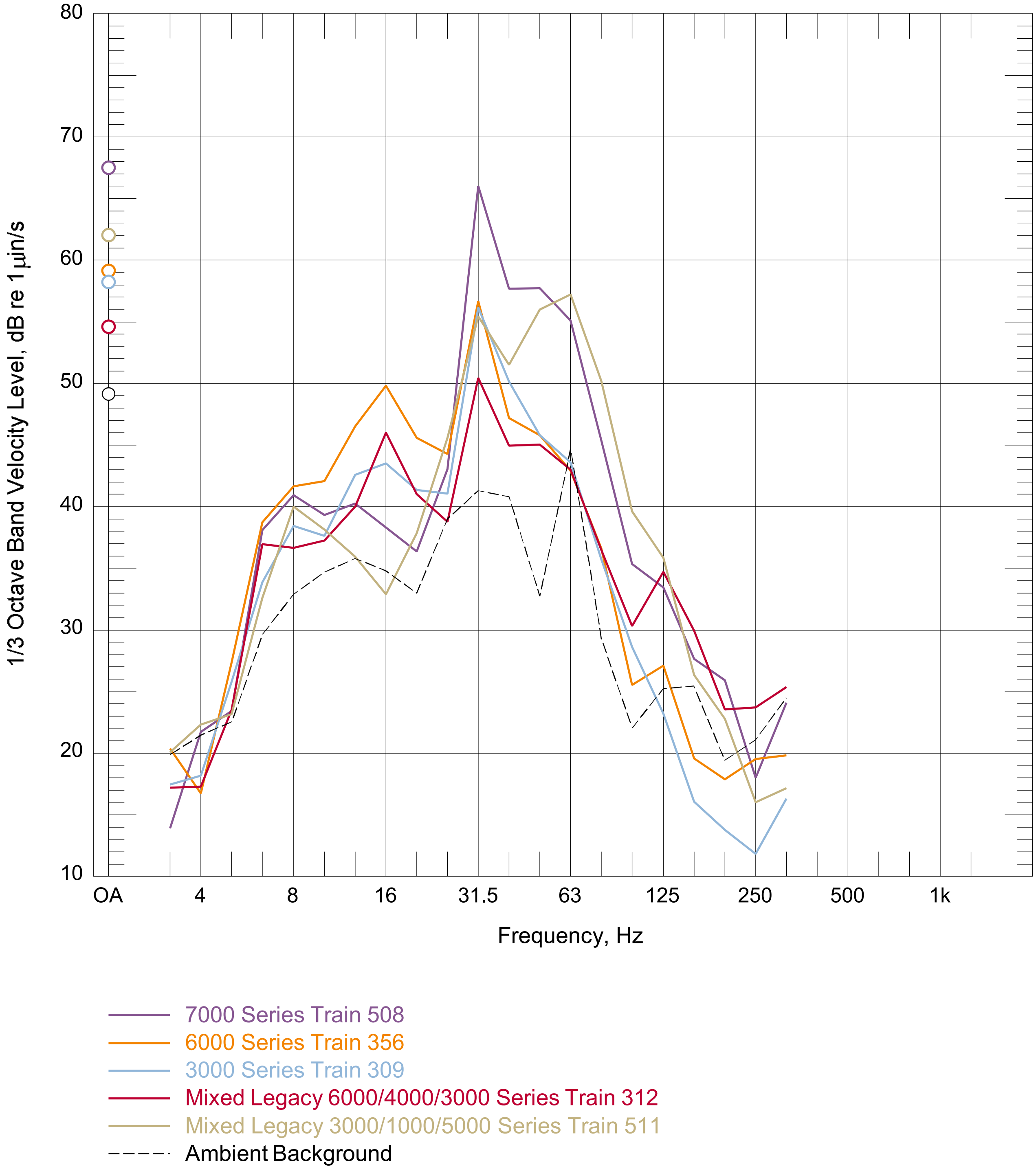


Figure 9: ***Site 1 at Location V2 1st Floor Living Room***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

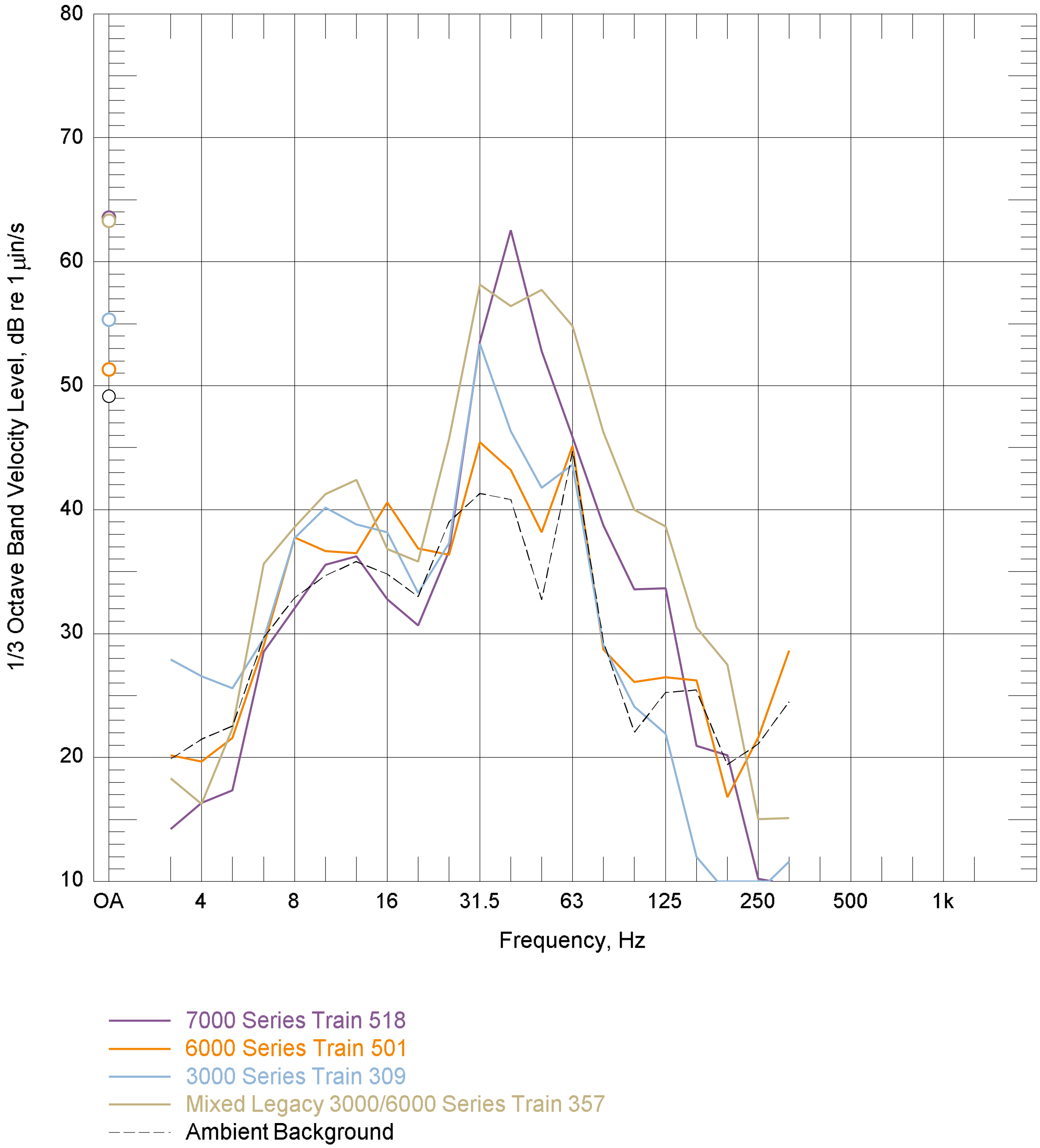


Figure 10: ***Site 1 at Location V2 1st Floor Living Room***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

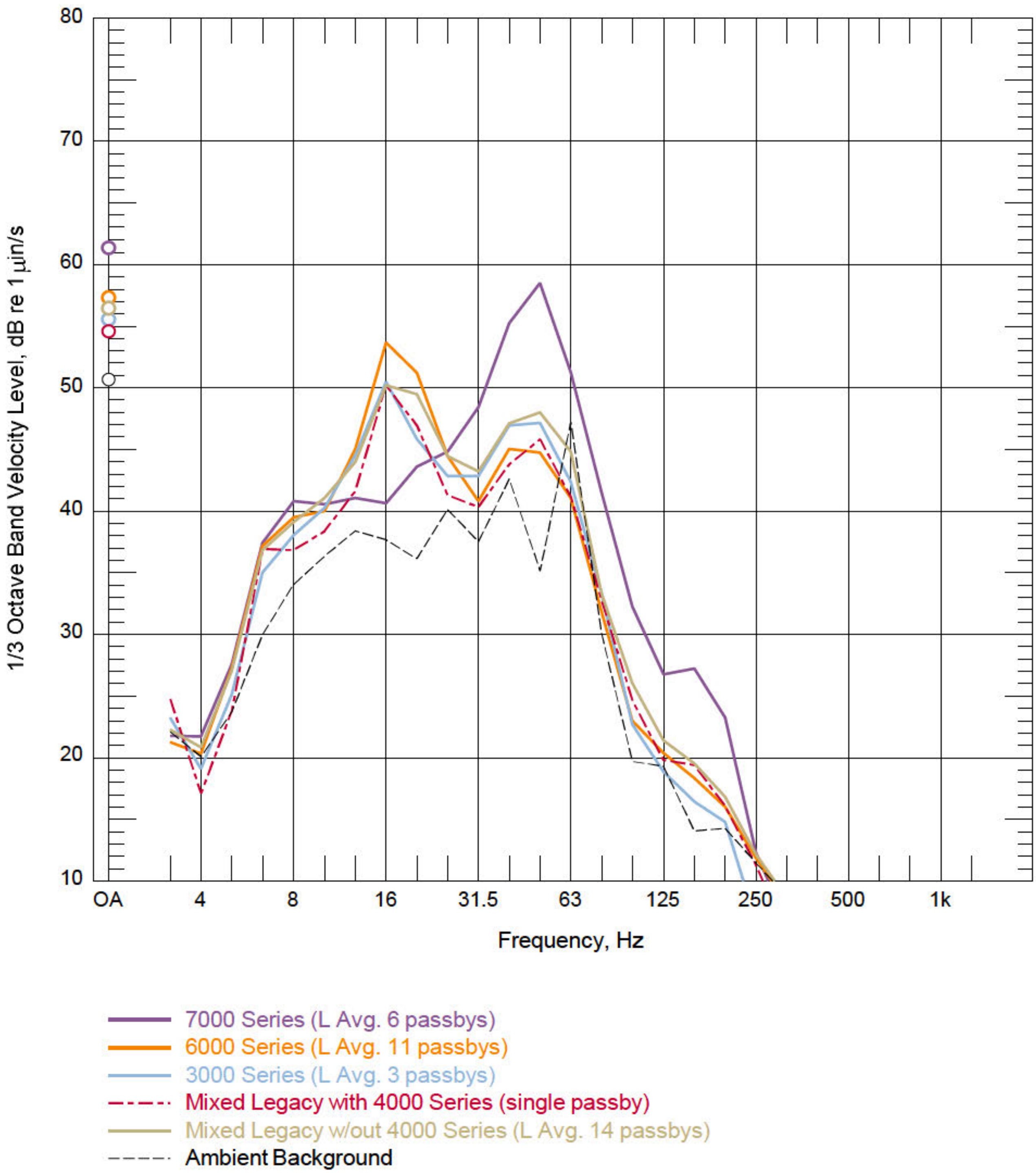


Figure 11: ***Site 1 at Location V3 2nd Floor Playroom***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

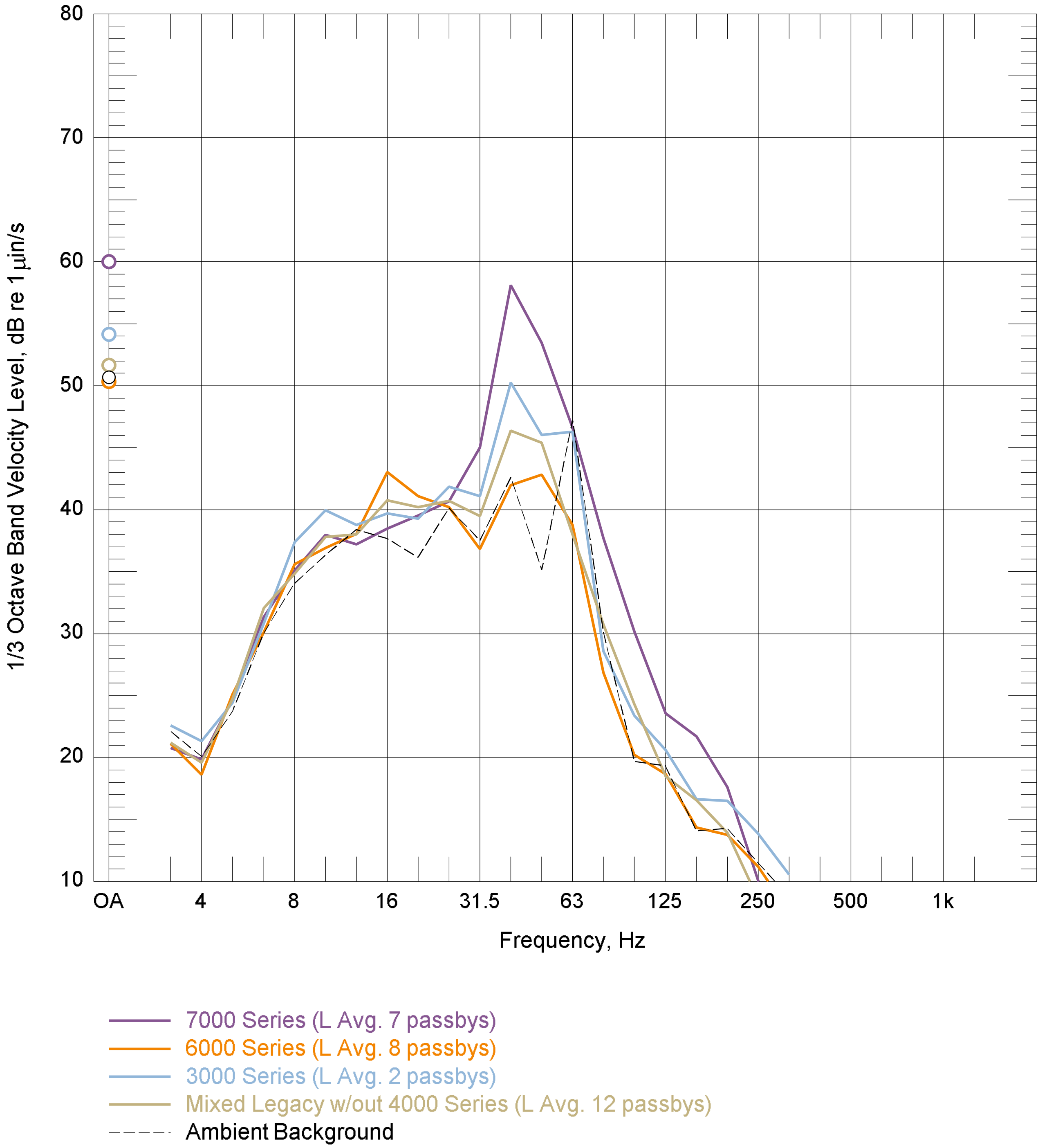


Figure 12: ***Site 1 at Location V3 2nd Floor Playroom***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

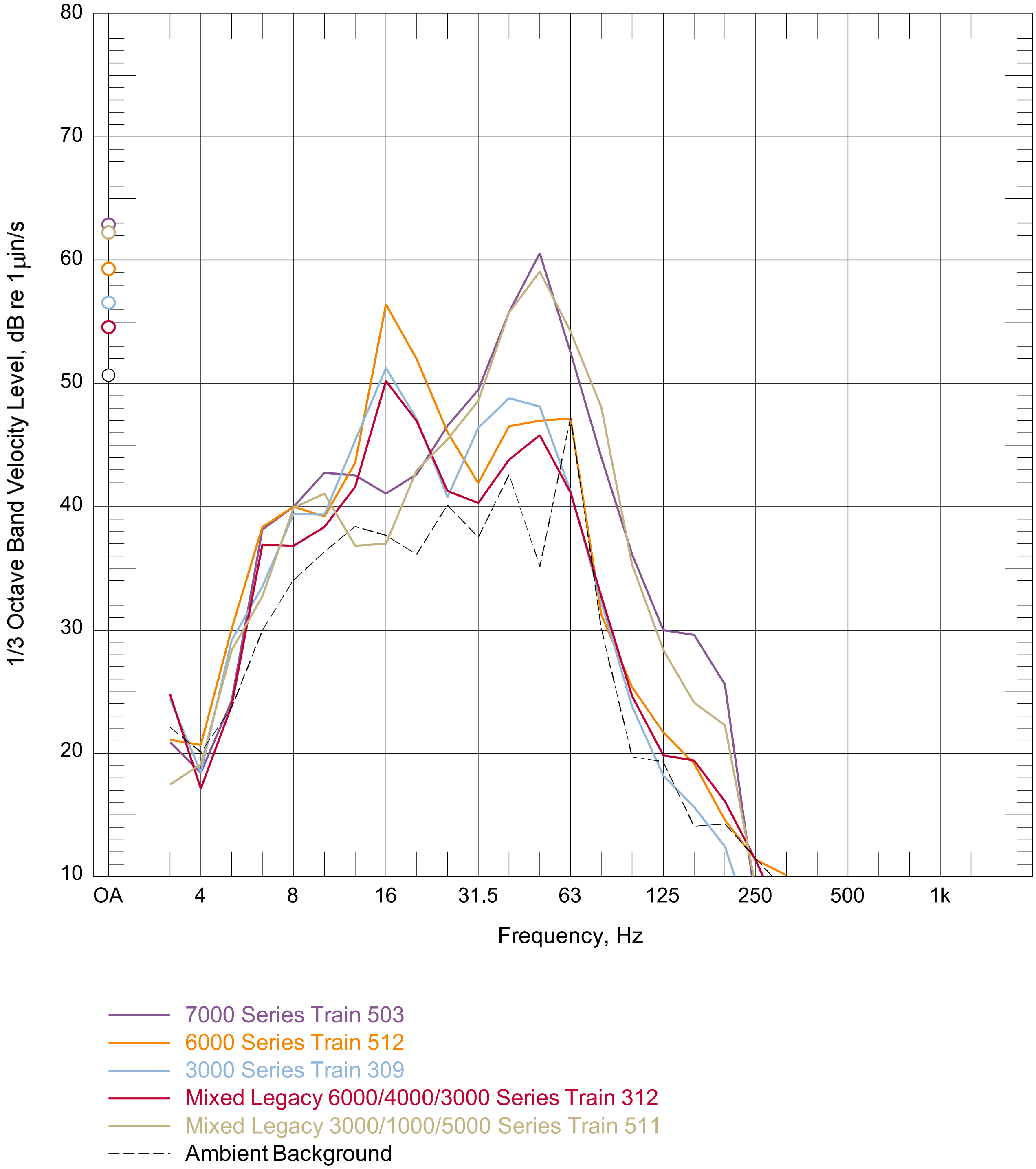


Figure 13: ***Site 1 at Location V3 2nd Floor Playroom***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

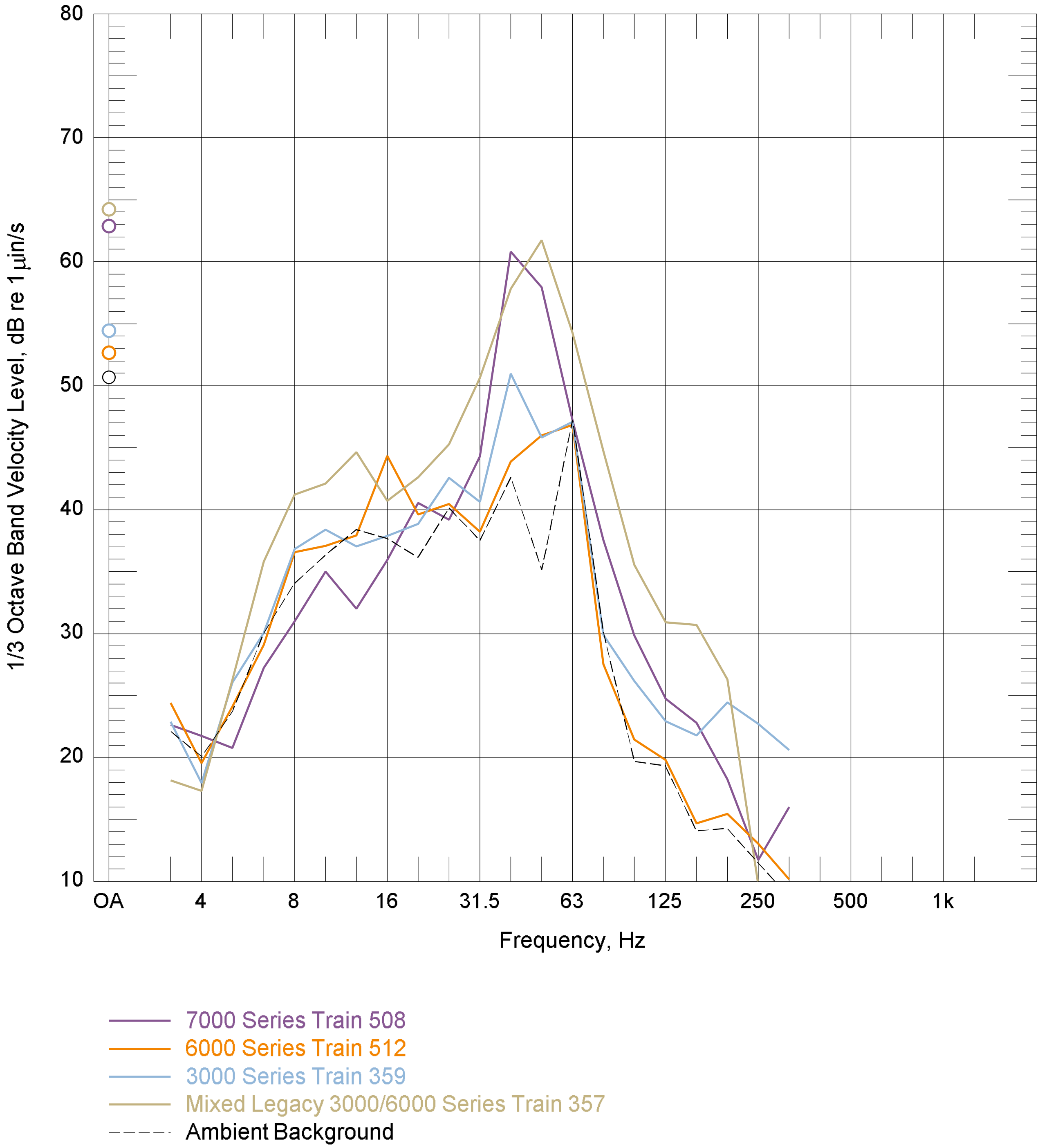


Figure 14: ***Site 1 at Location V3 2nd Floor Playroom***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

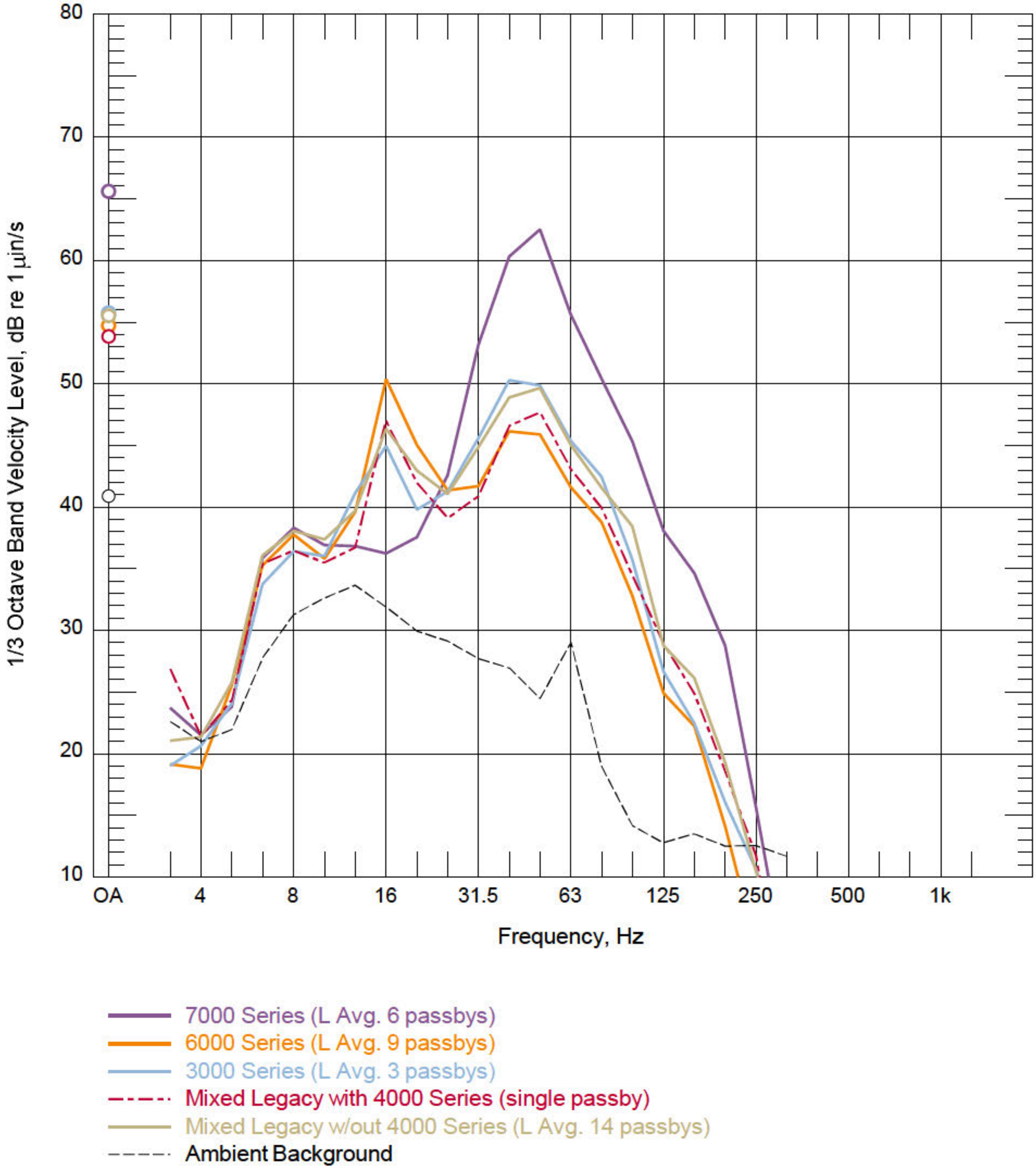


Figure 15: ***Site 1 at Location V4 Outside House***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

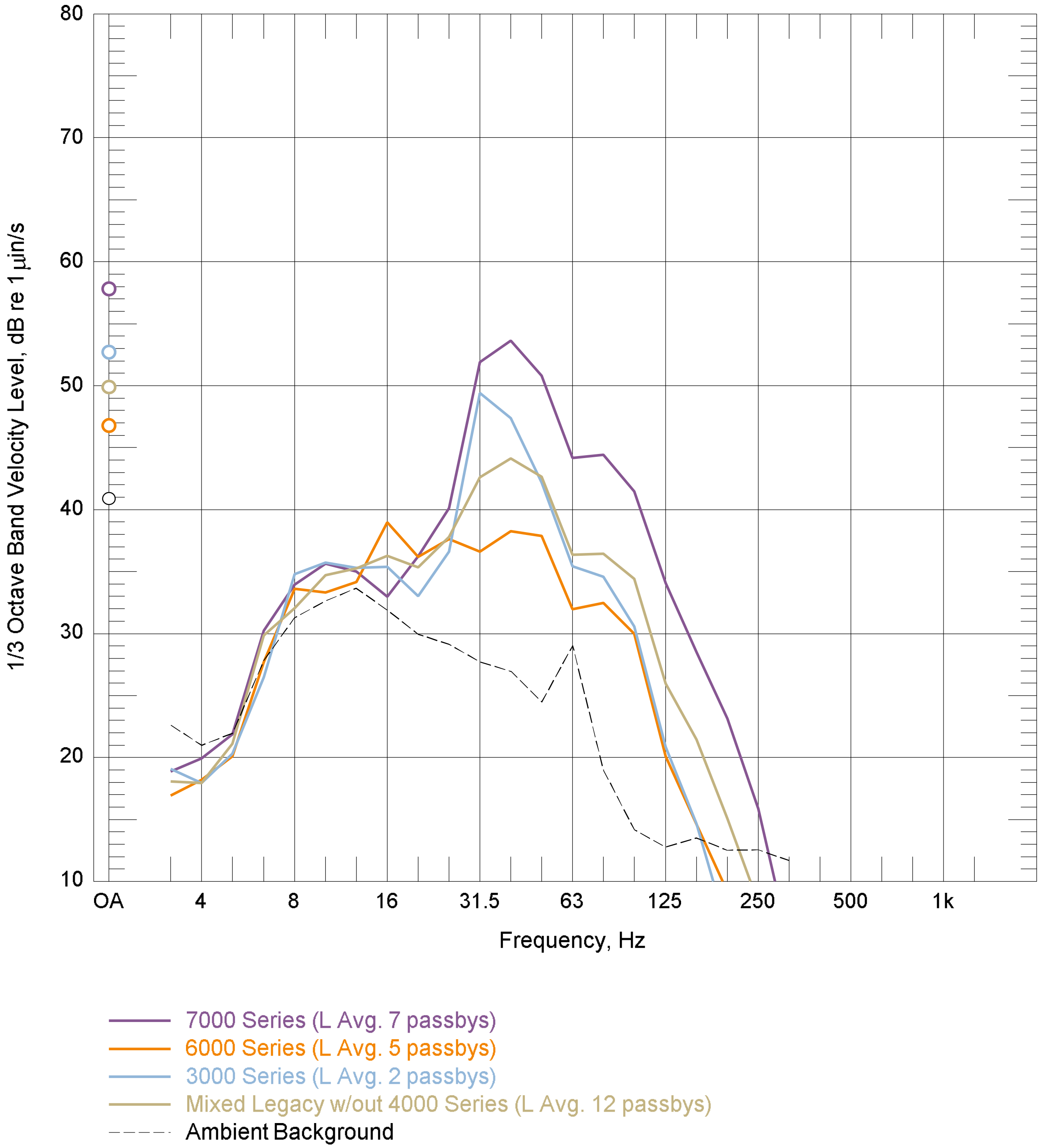


Figure 16: ***Site 1 at Location V4 Outside House***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

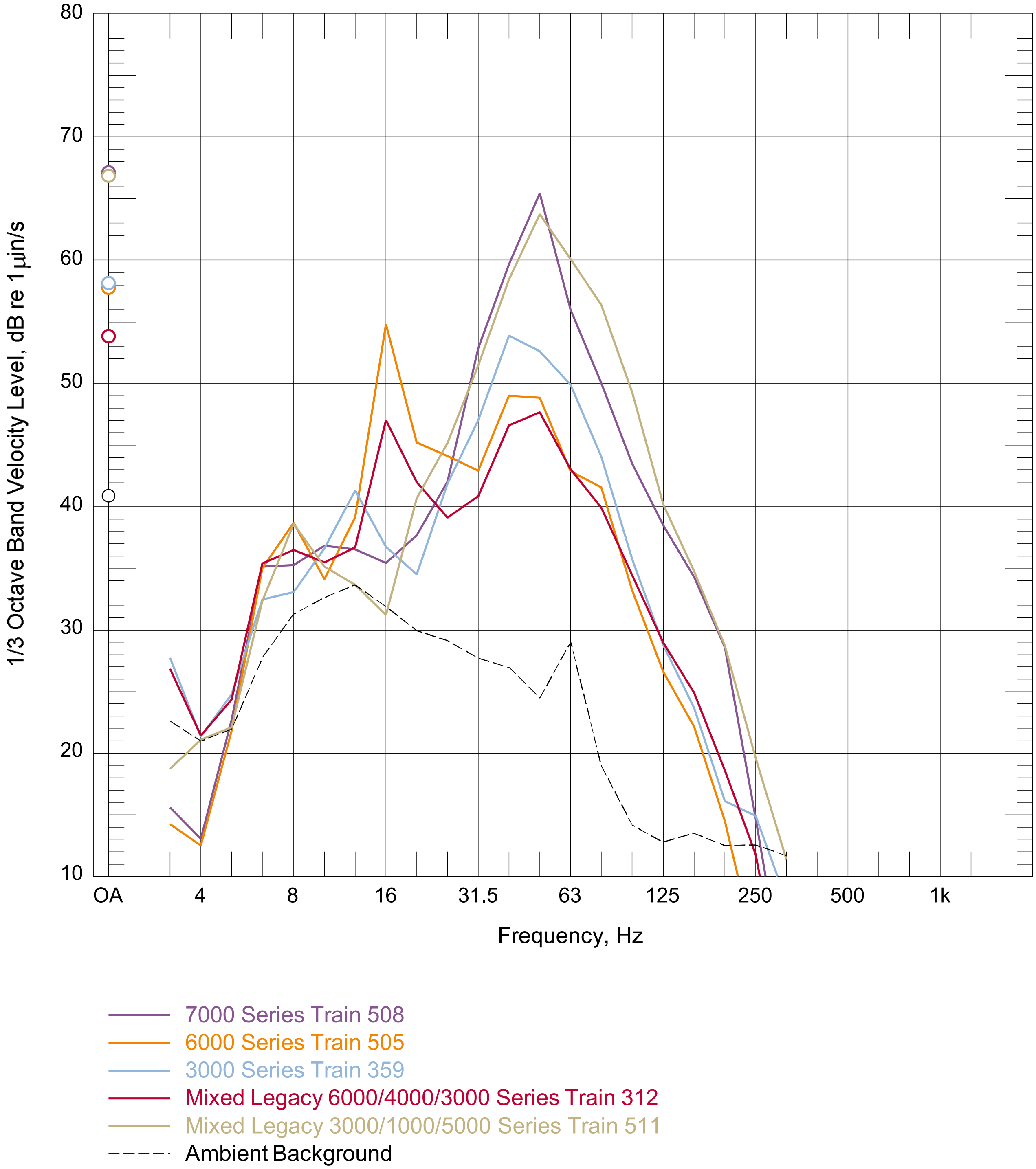


Figure 17: ***Site 1 at Location V4 Outside House***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

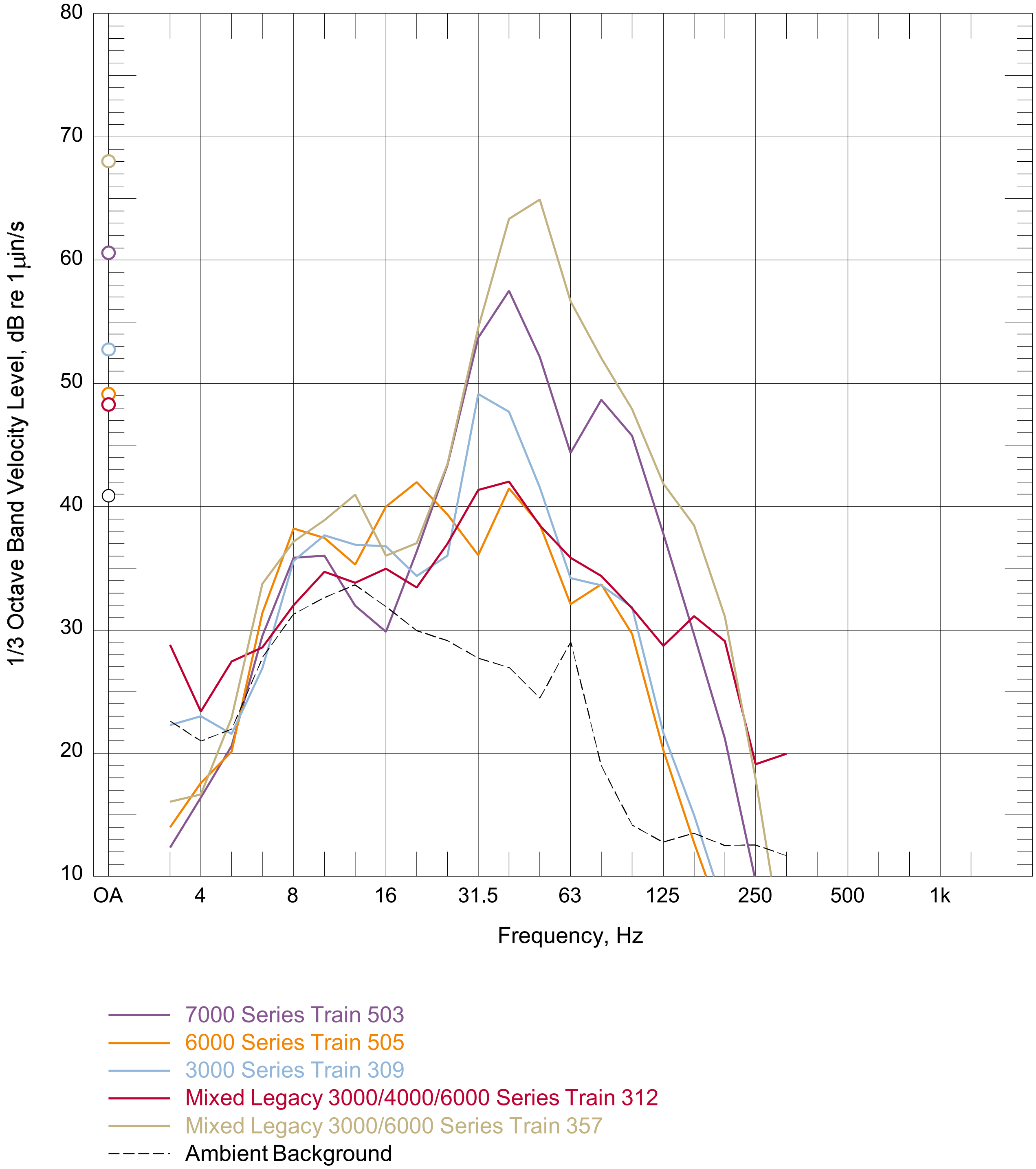


Figure 18: ***Site 1 at Location V4 Outside House***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

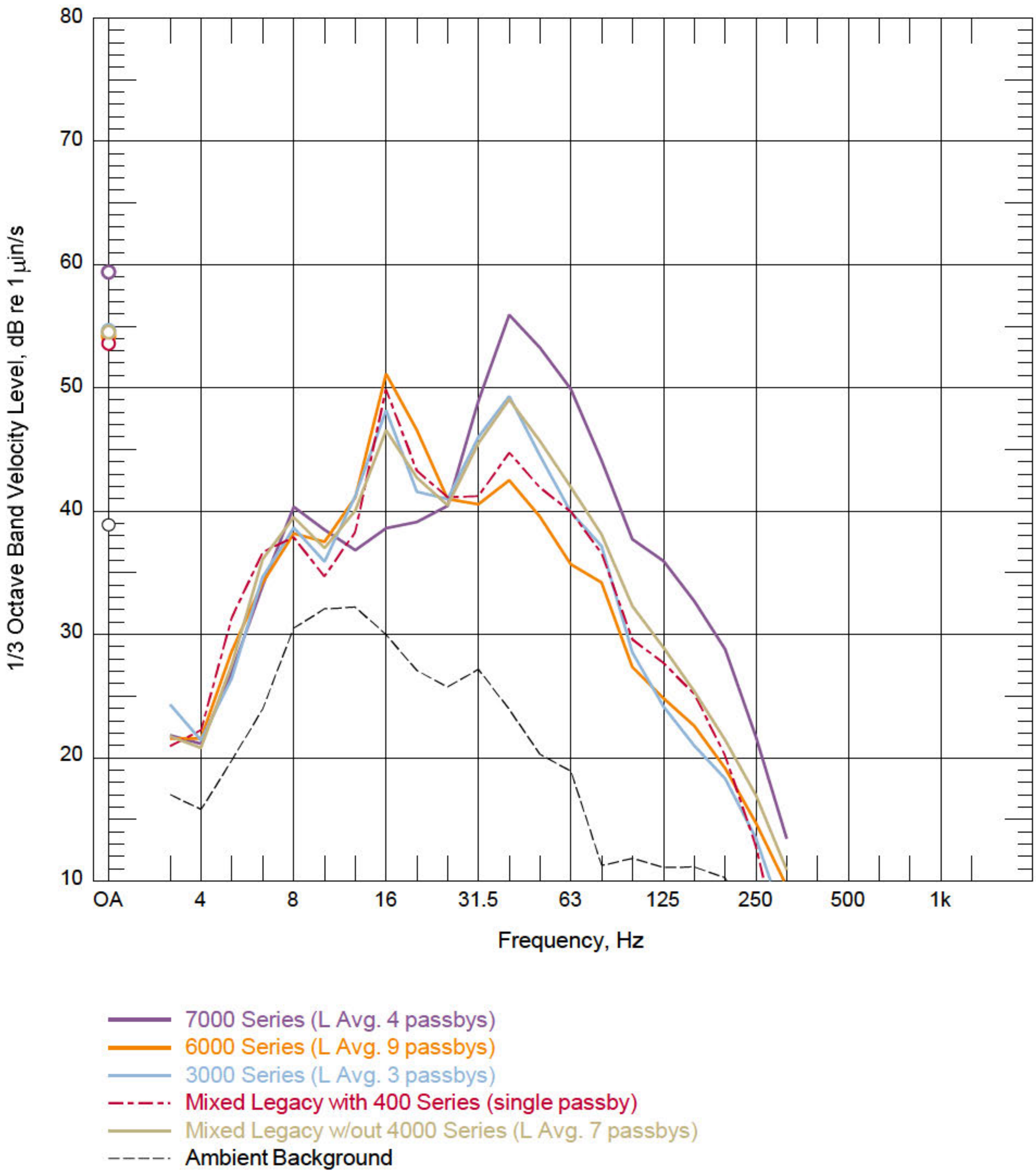


Figure 19: ***Site 1 at Location V5 Across Street***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

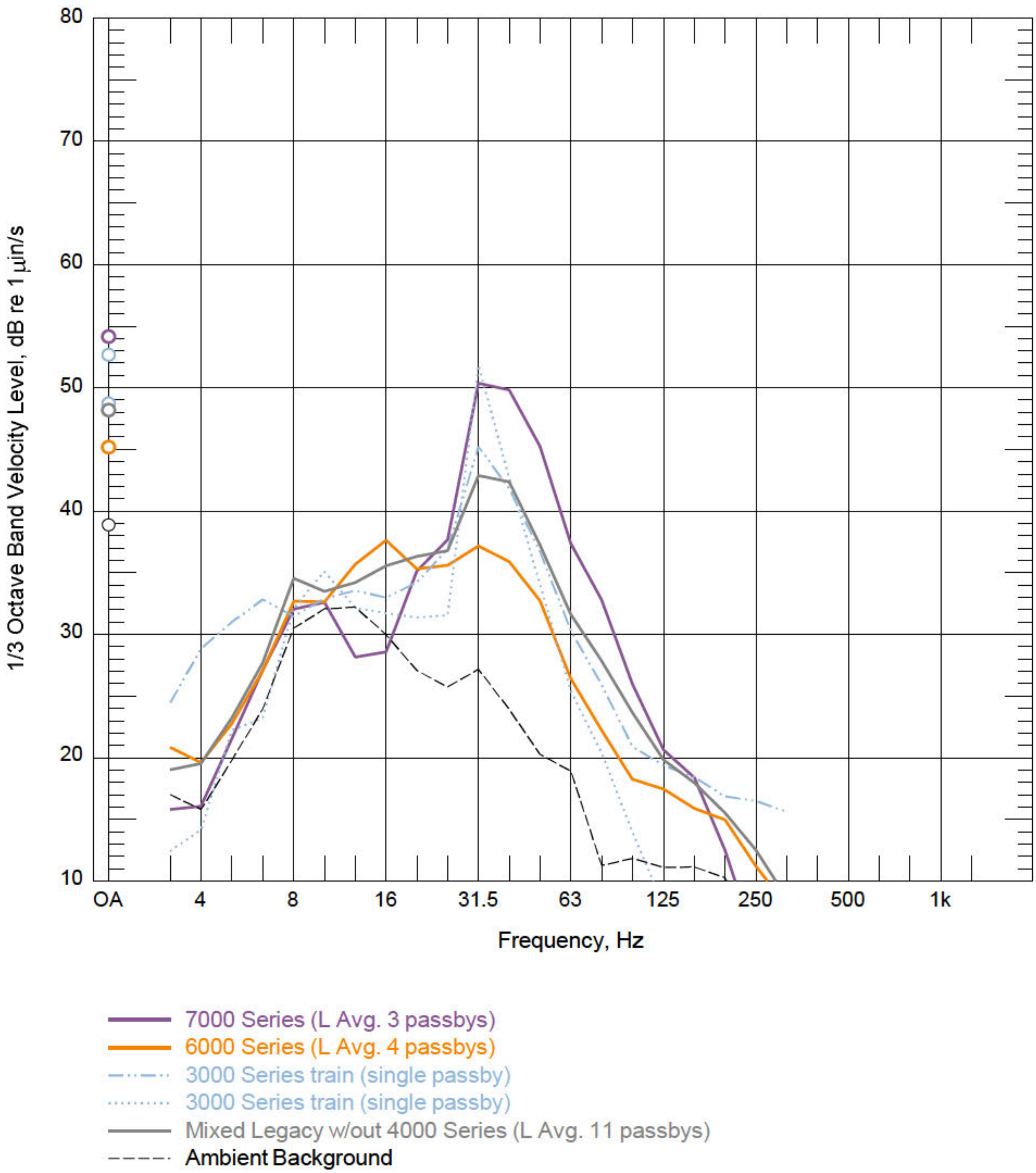


Figure 20: ***Site 1 at Location V5 Across Street***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

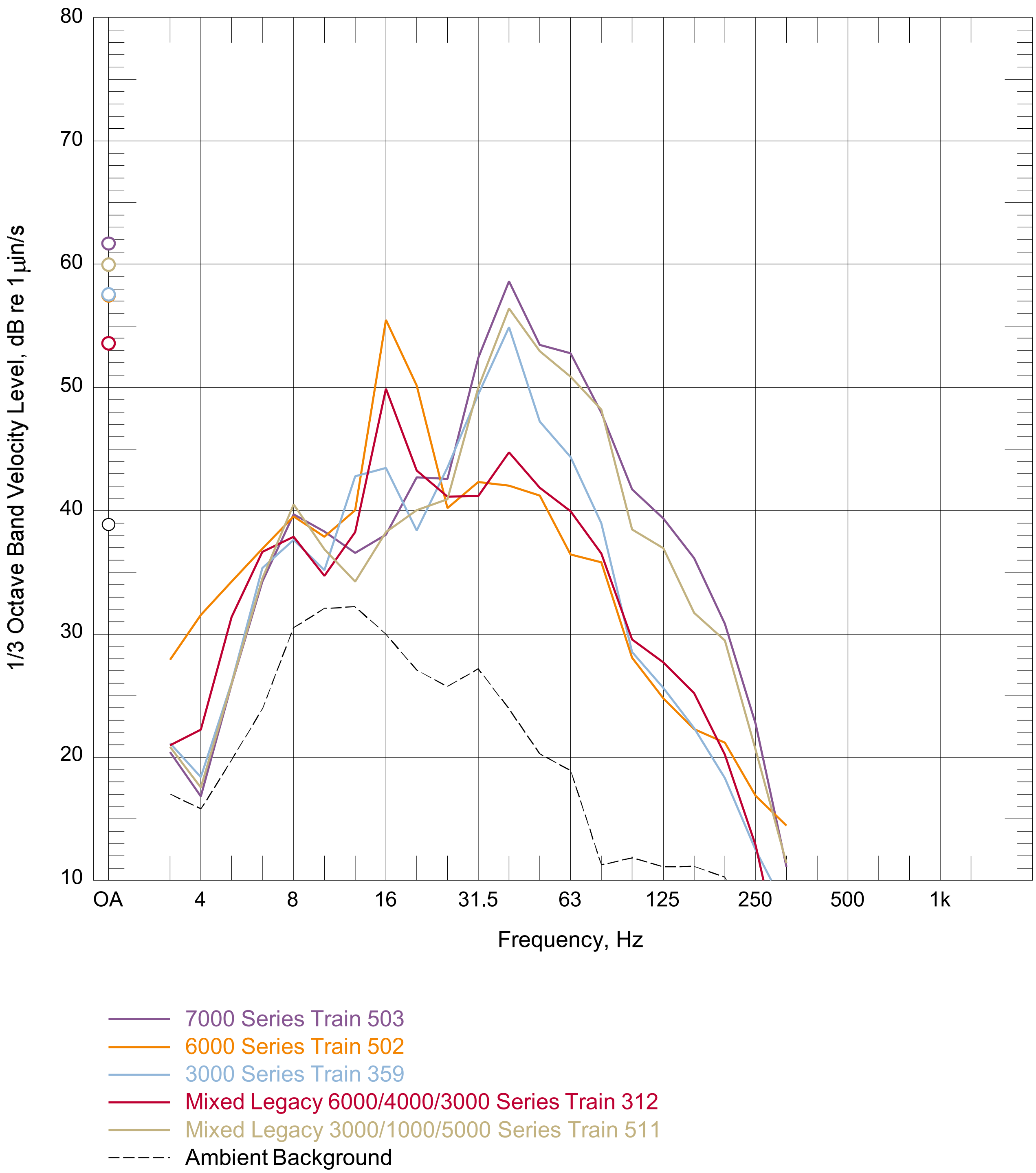


Figure 21: ***Site 1 at Location V5 Across Street***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

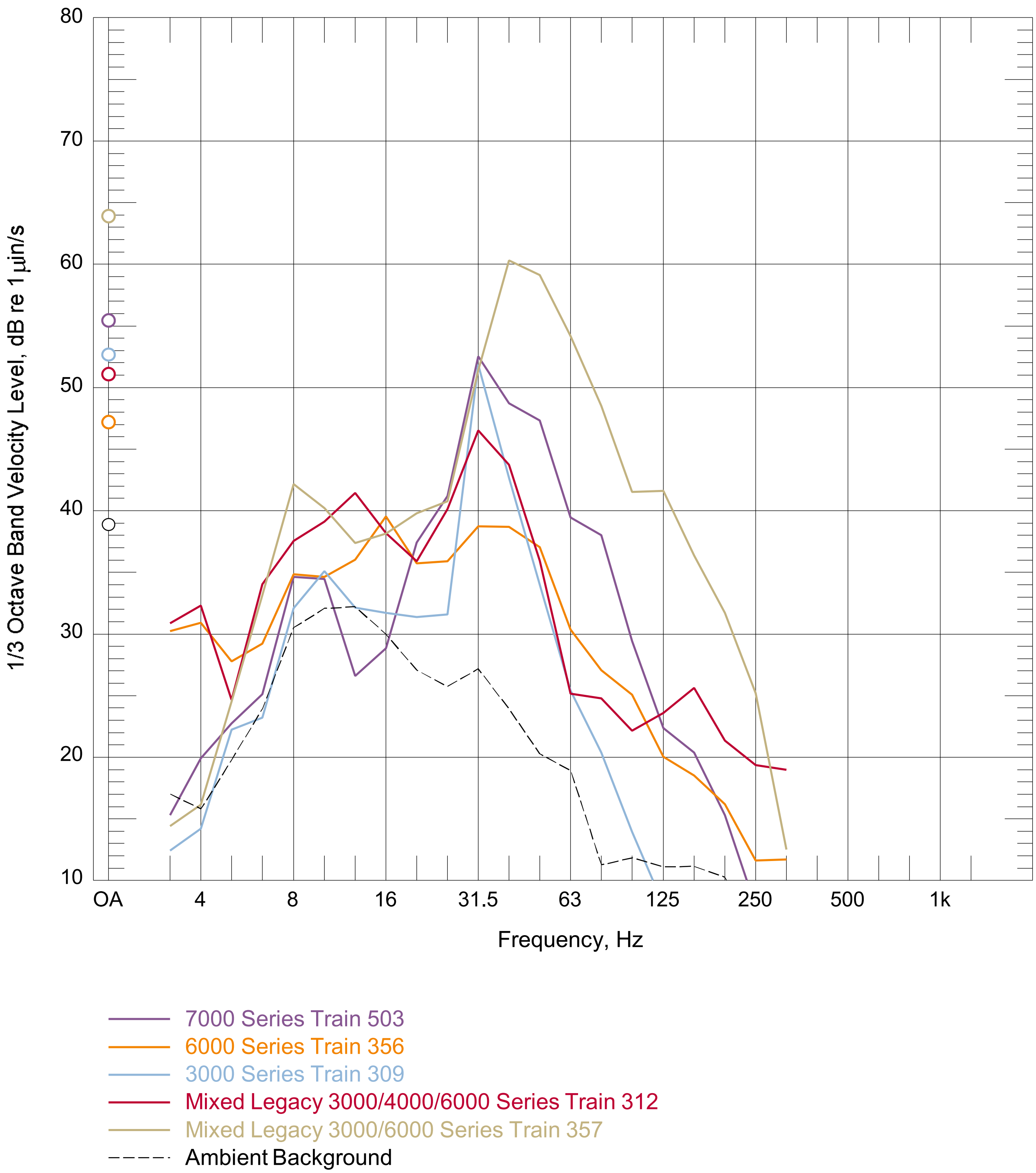


Figure 22: ***Site 1 at Location V5 Across Street***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

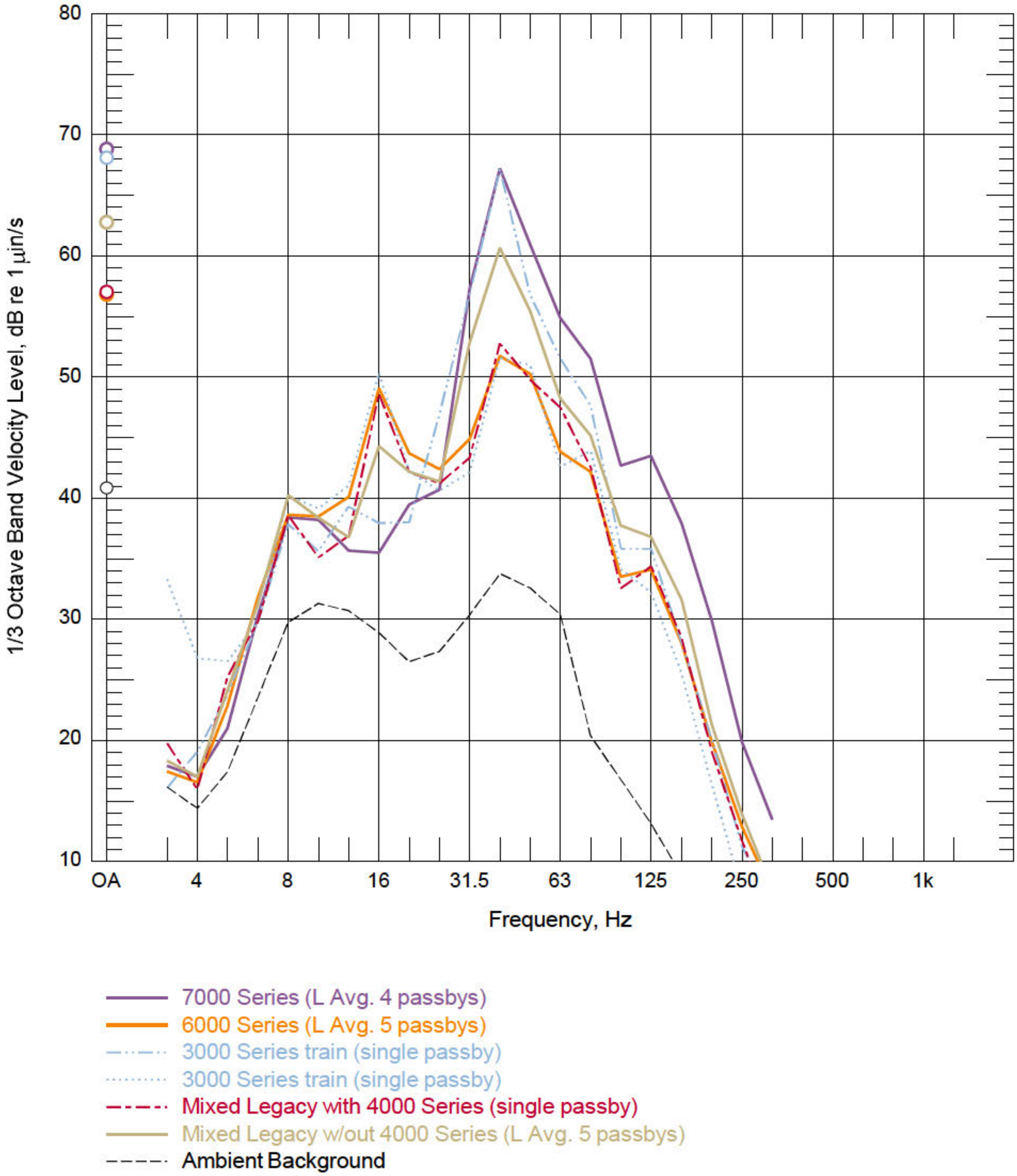


Figure 23: ***Site 1 at Location V6 Across Street***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

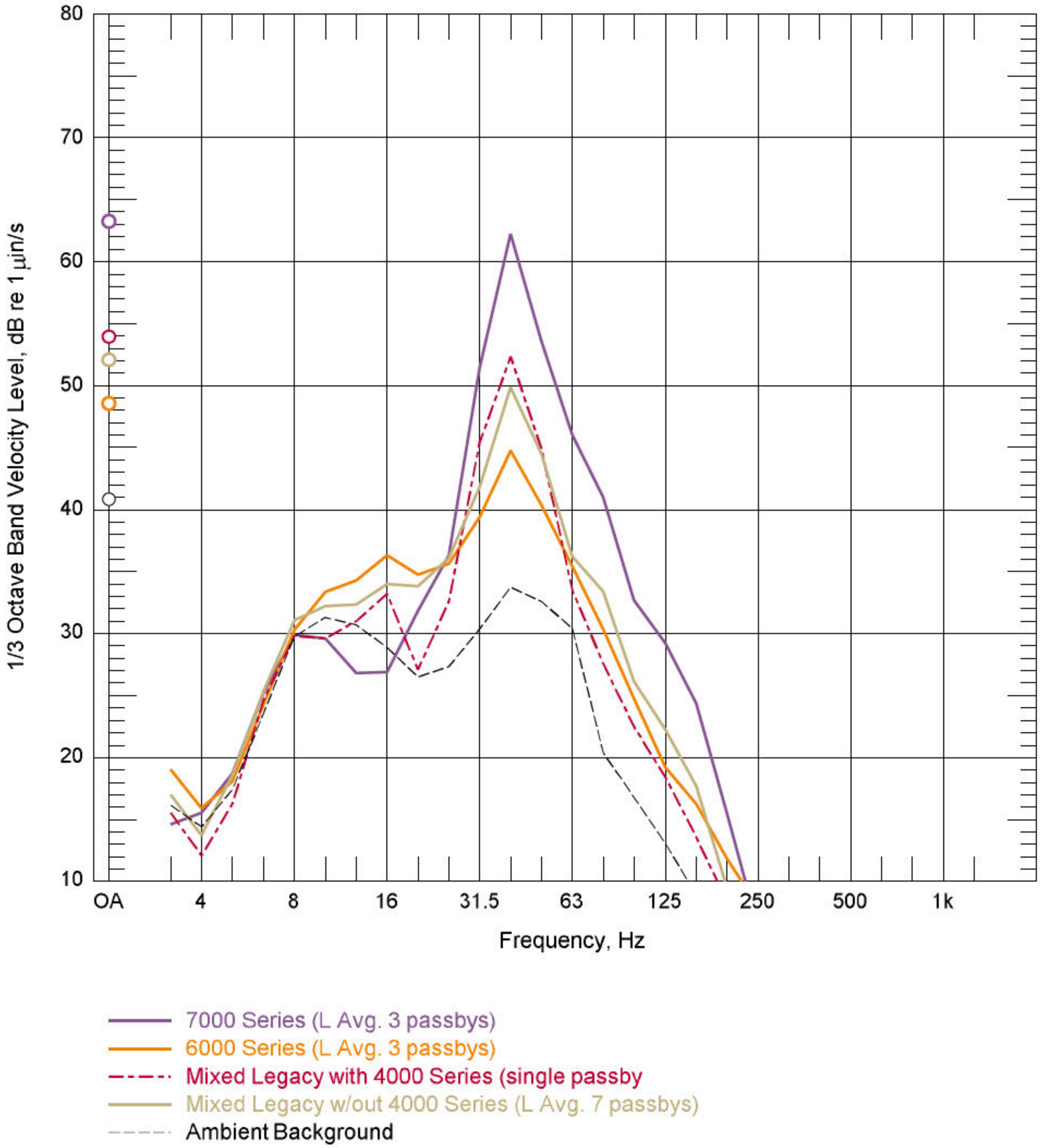


Figure 24: ***Site 1 at Location V6 Across Street***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

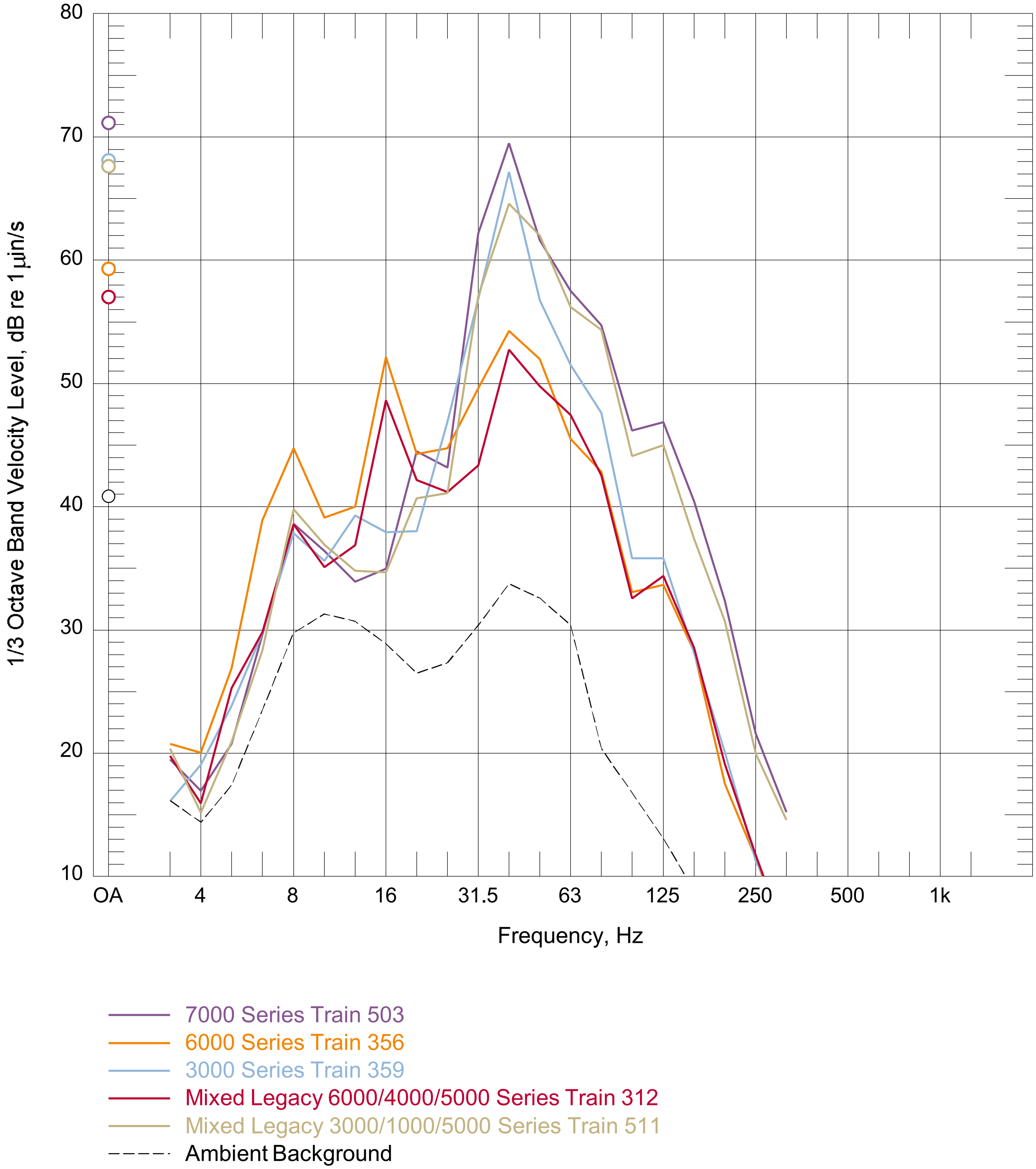


Figure 25: ***Site 1 at Location V6 Across Street***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

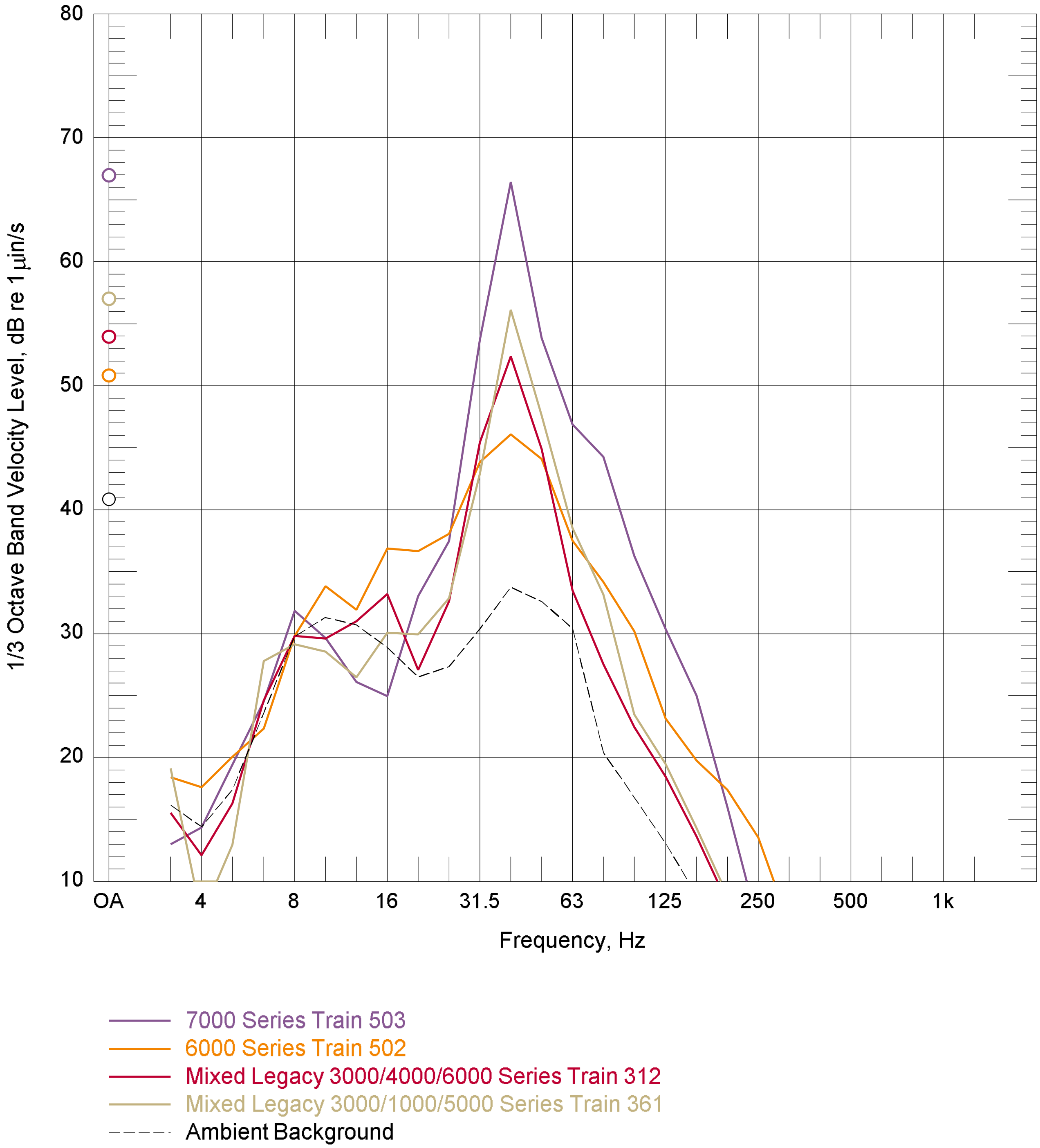


Figure 26: ***Site 1 at Location V6 Across Street***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

B.1.6 Passby Ground-borne Noise Spectra and A-weighted Levels

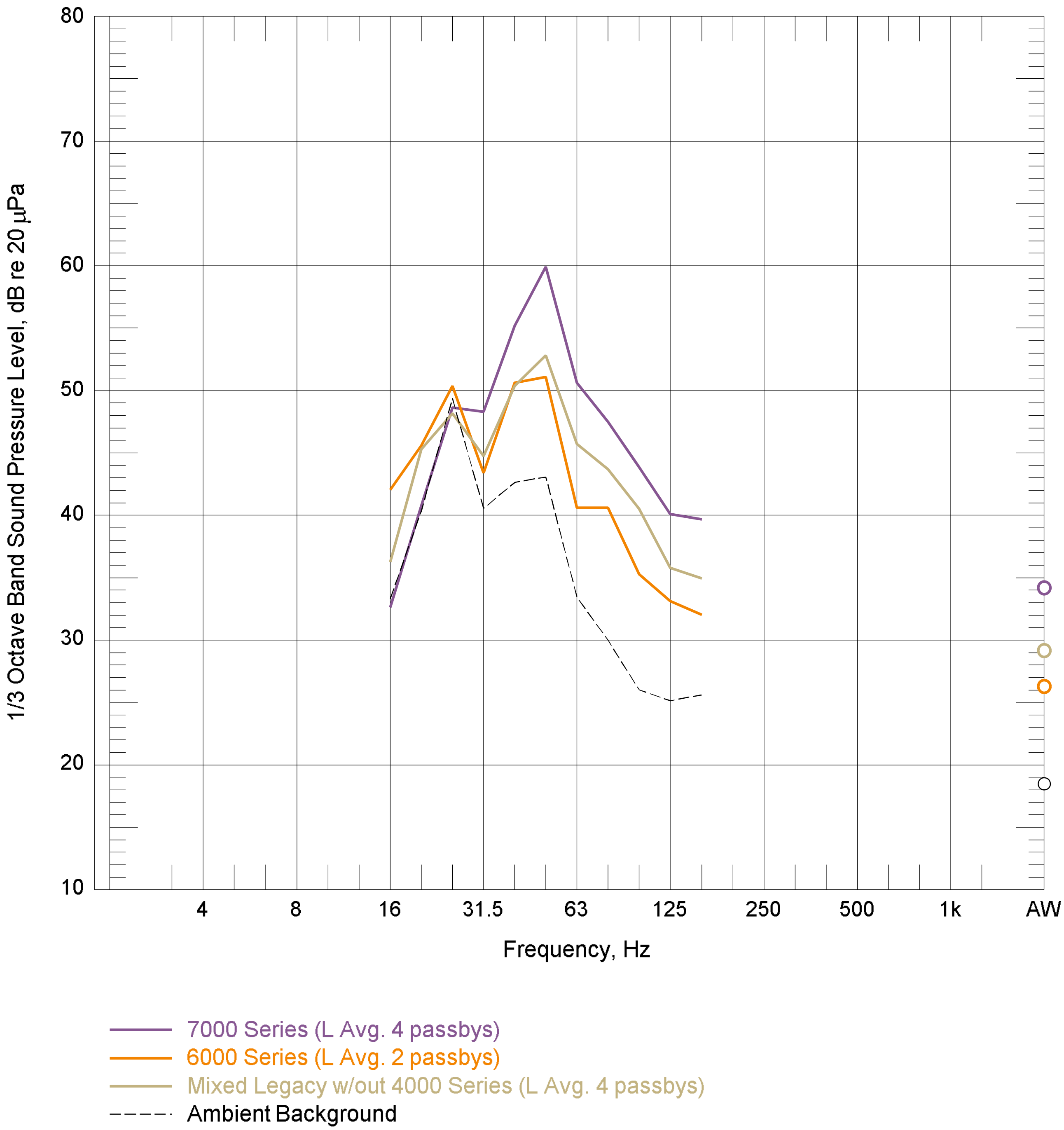


Figure 27: ***Site 1 at Microphone N1 in Basement Bedroom***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

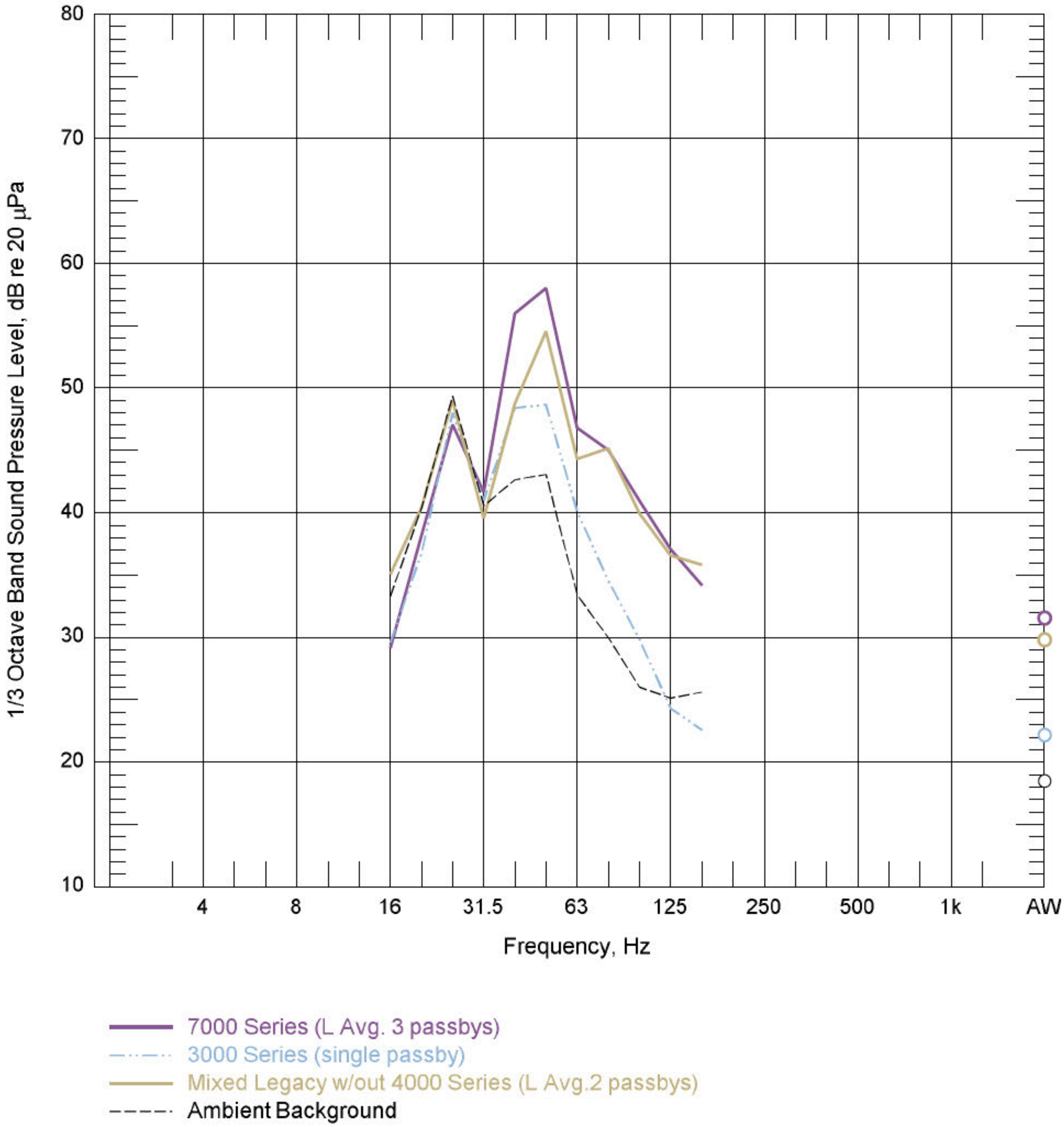


Figure 28: ***Site 1 at Microphone N1 in Basement Bedroom***
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

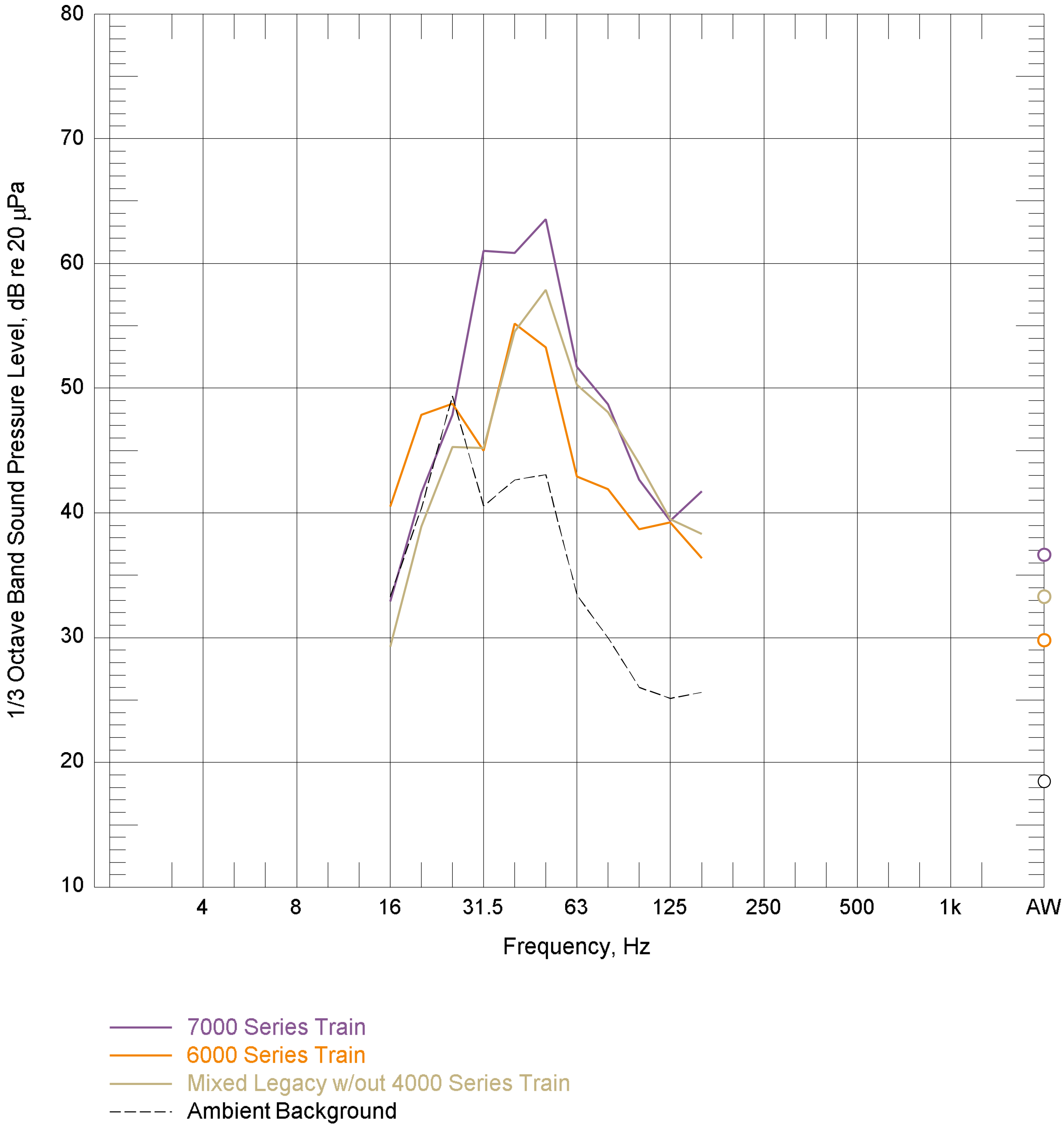


Figure 29: ***Site 1 at Microphone N1 in Basement Bedroom***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

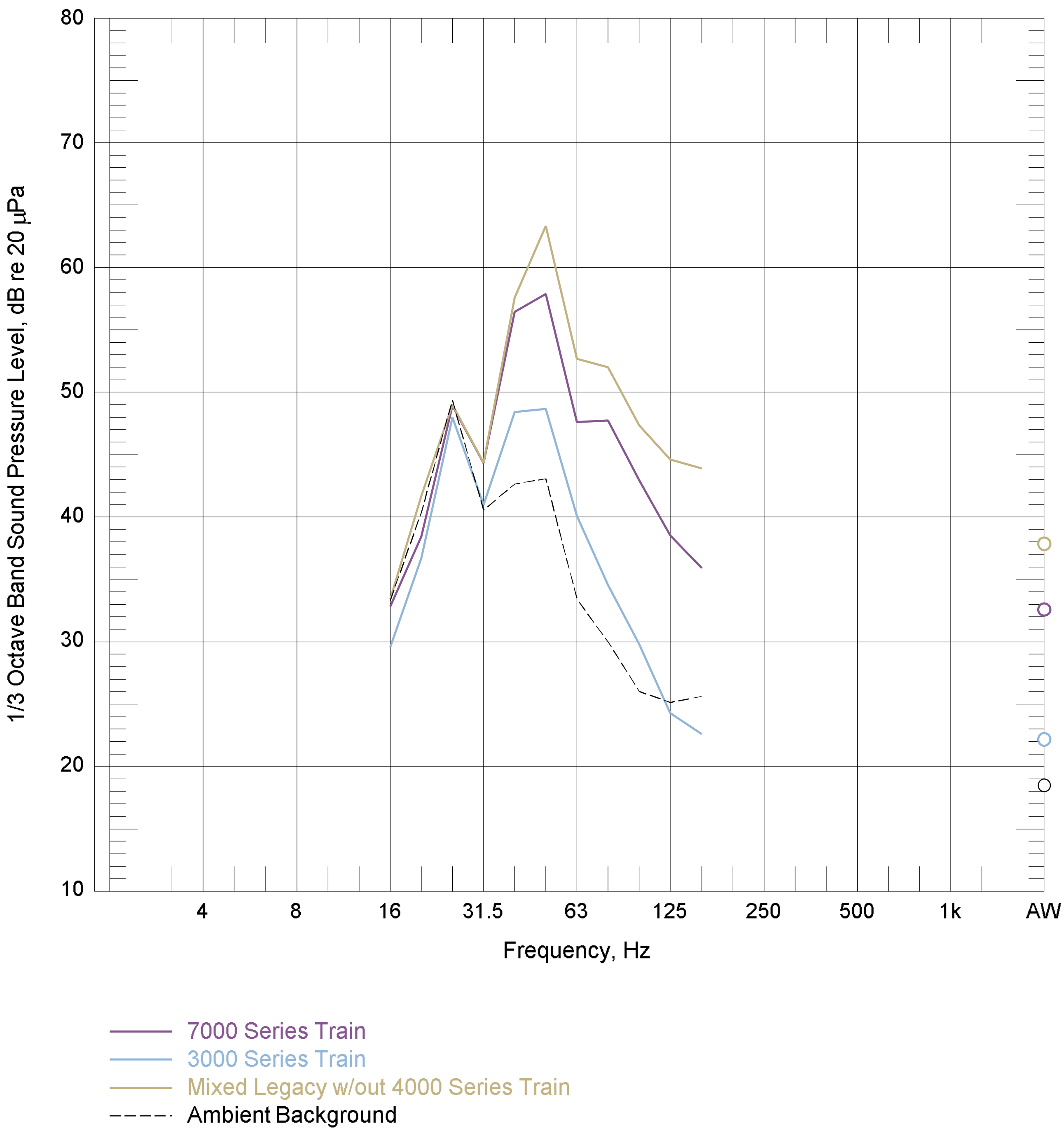


Figure 30: ***Site 1 at Microphone N1 in Basement Bedroom***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

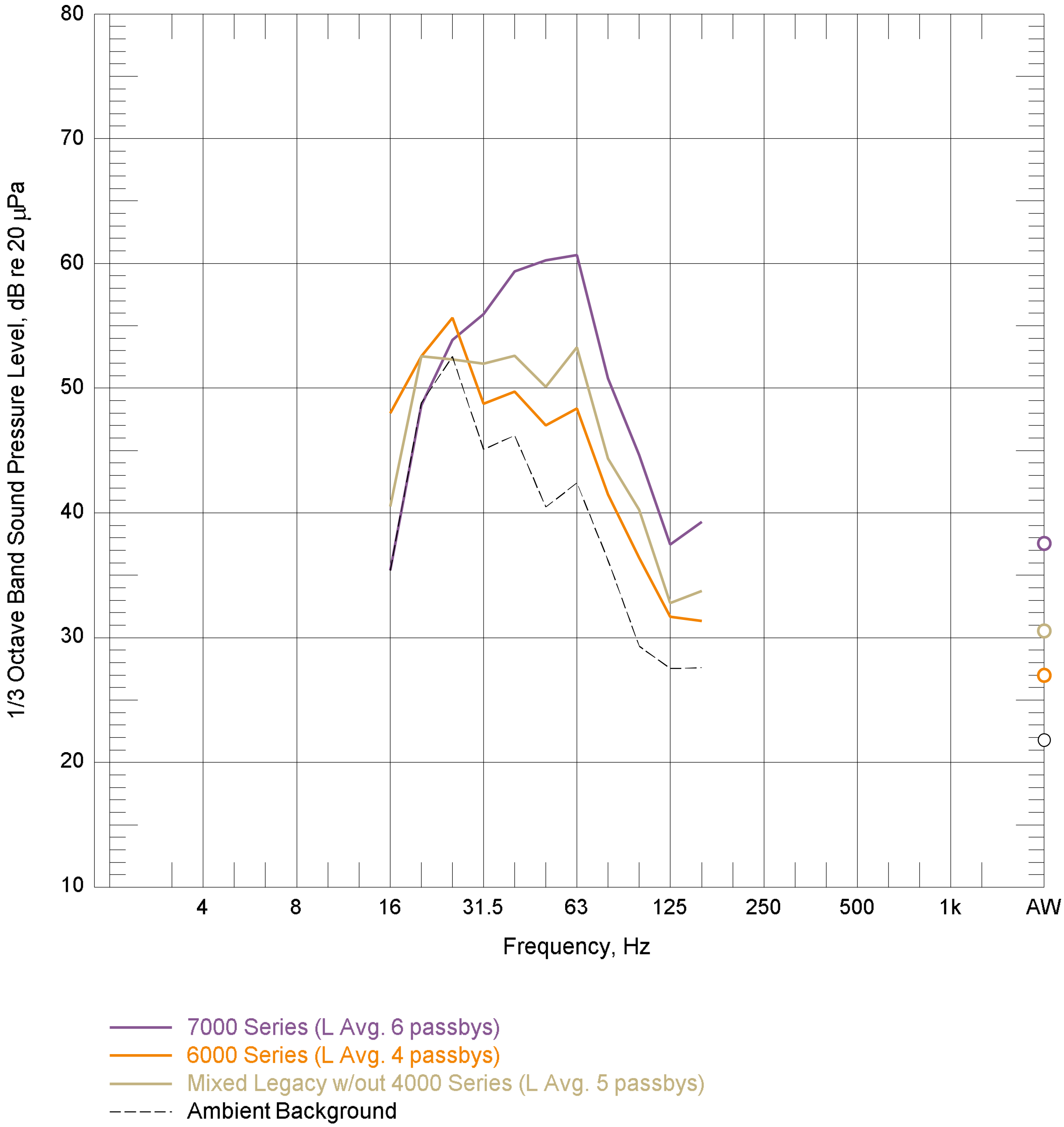


Figure 31: ***Site 1 at Microphone N2 in Basement Bedroom***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

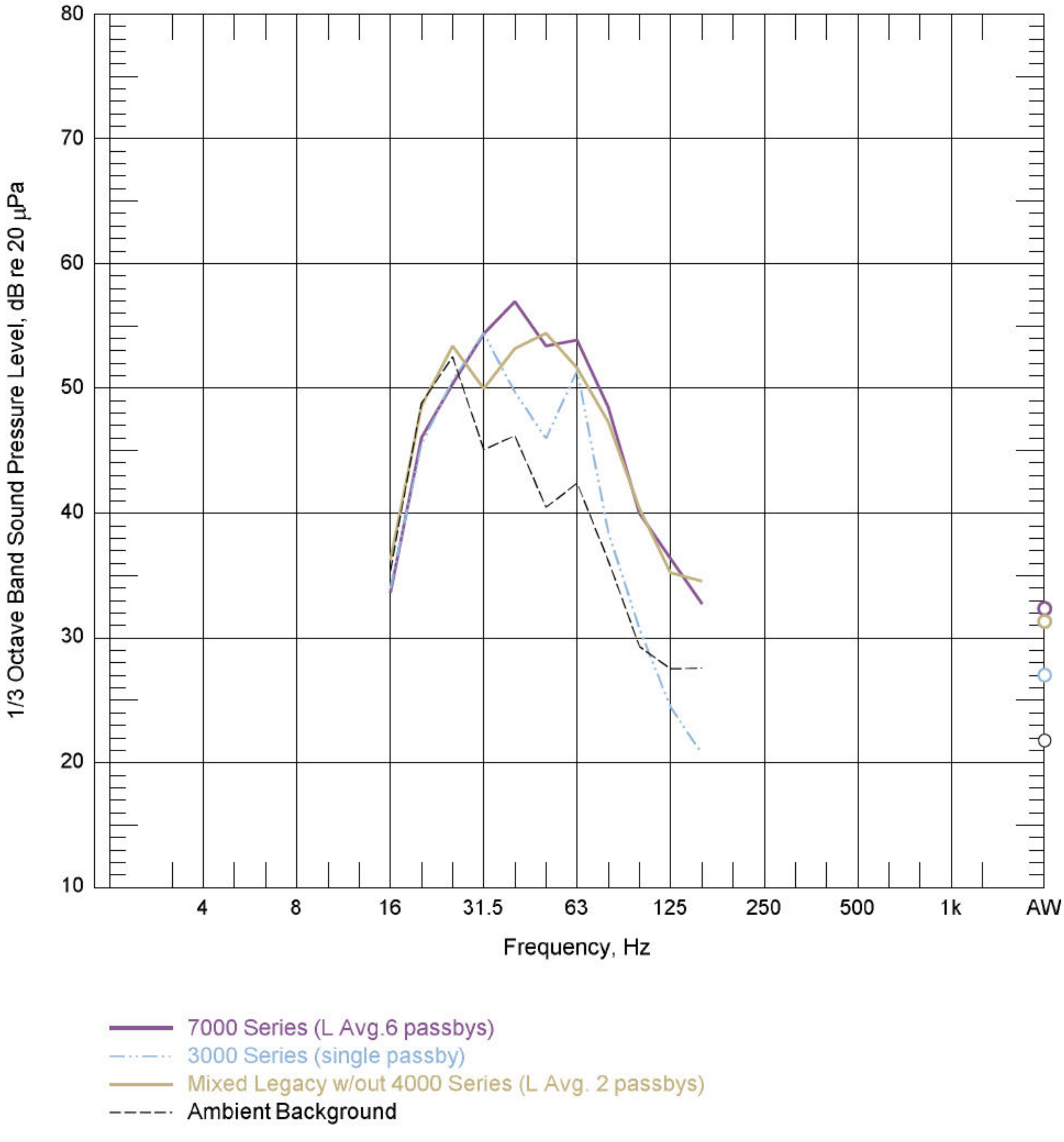


Figure 32: ***Site 1 at Microphone N2 in Basement Bedroom***
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

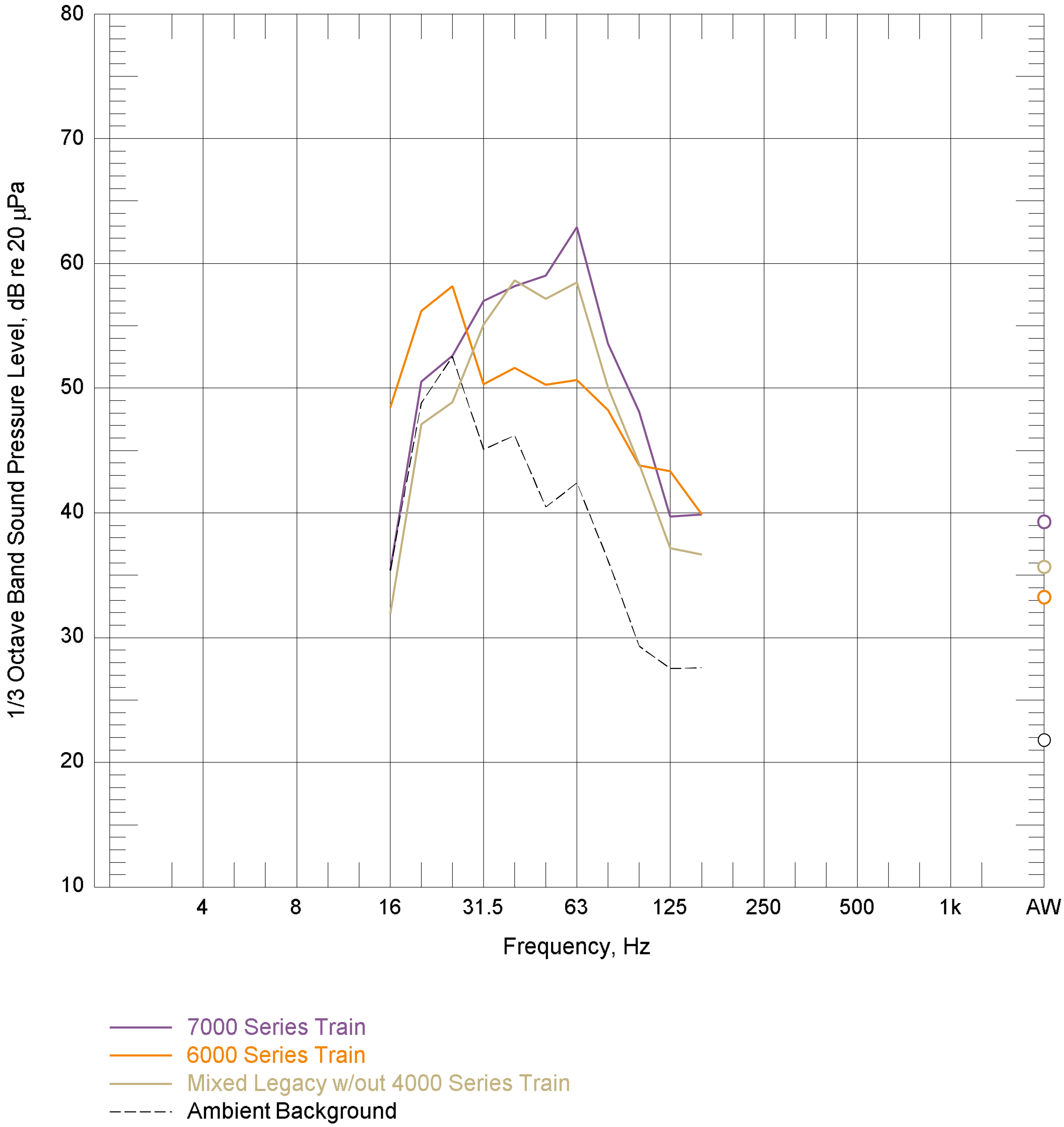


Figure 33: ***Site 1 at Microphone N2 in Basement Bedroom***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

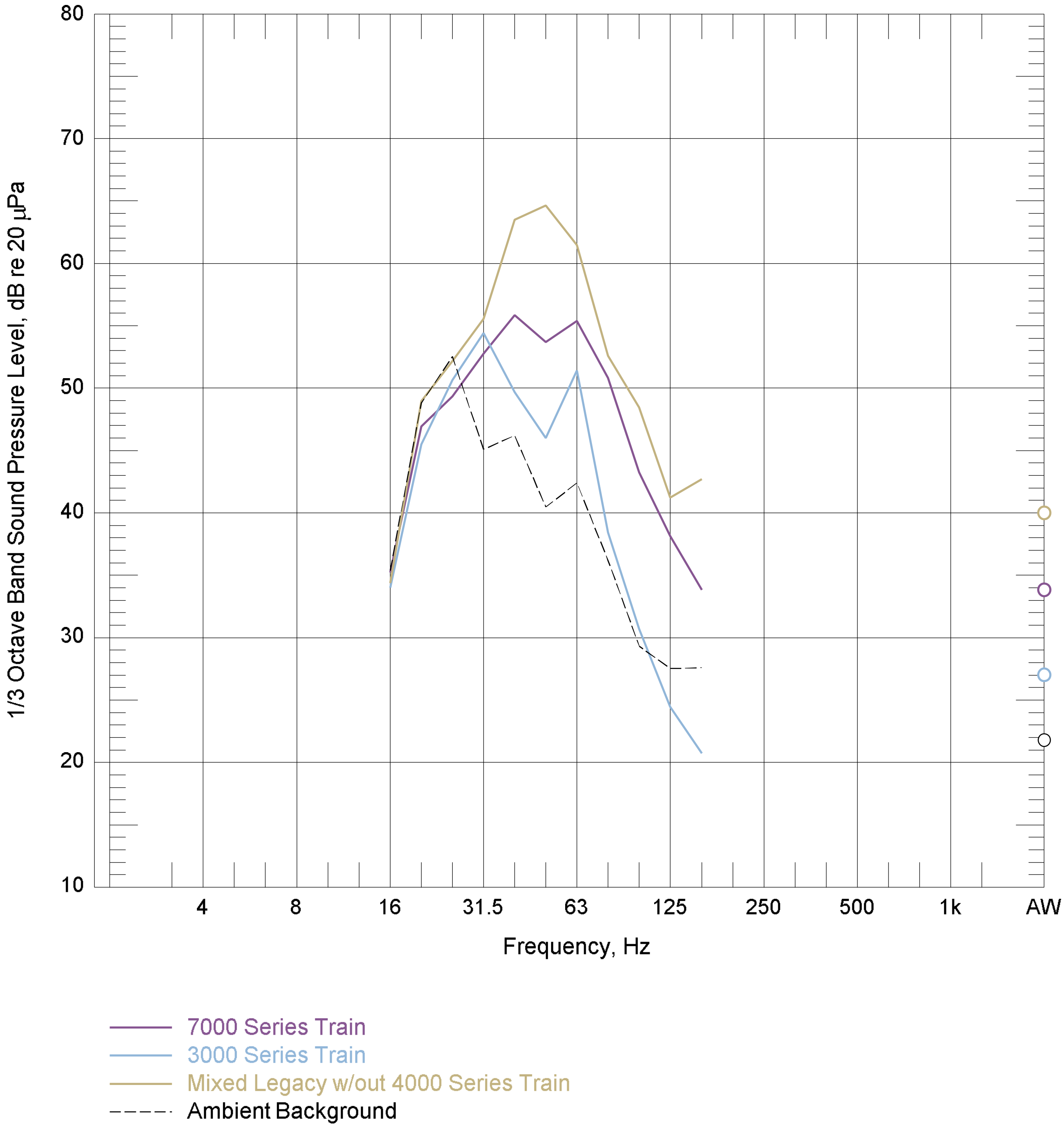


Figure 34: ***Site 1 at Microphone N2 in Basement Bedroom***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

B.2 Site 2 – 3600 block of New Hampshire Avenue NW (Residence)

B.2.1 Building and Tunnel Notes

Location:	Inbound track 2 side at 163+90
Building Notes:	Single-family residential townhouse, attached rowhouse, 3 floors comprised of partial underground basement plus 2 upper floors, exterior wall of brick construction, wood-joist floor, renovated
Tunnel Structure:	Tunnel
Track Type:	Egg Fasteners
T/R Depth:	43 to 45 feet
Train Speed:	24 to 40 mph
Measurement Period:	Wednesday, 16 August 2017, 9:05 to 12:56

B.2.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Sensor[a,b,c]	Location / Room Occupancy	Horizontal Distance[d] (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)	Horizontal Distance (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)
V1	Outside House	26	45	52	63	43	76
Triaxial Geo.	Basement Family Room	43	45	62	79	43	90
V2	Basement Family Room						
N1	Basement Family Room						
Triaxial Geo.	Basement Laundry Room (Position 1 on bare concrete)						
V3a	Basement Laundry Room (Position 1 on bare concrete)						
V3b	Basement Laundry Room (Position 2 on finished flooring)						
V4	First Floor Living Room						
V5	First Floor Dining Room						
N2	First Floor Dining Room						

Notes:

a) Triaxial geophone mounted on floor, logging peak particle velocity
b) V# vibration locations with accelerometer mounted on floor in vertical direction
c) N# noise locations with microphone/sound level meter mounted on tripod 48 inches feet above floor
d) Horizontal distance from track to building façade for indoor locations, not accounting for tunnel depth.
e) T/R depth = top-of-rail depth
f) Total slant distance to T/R = total distance from building to track, accounting for tunnel depth

Figure 35: Aerial Map of 3600 block of New Hampshire Residence and Exterior Measurement Location

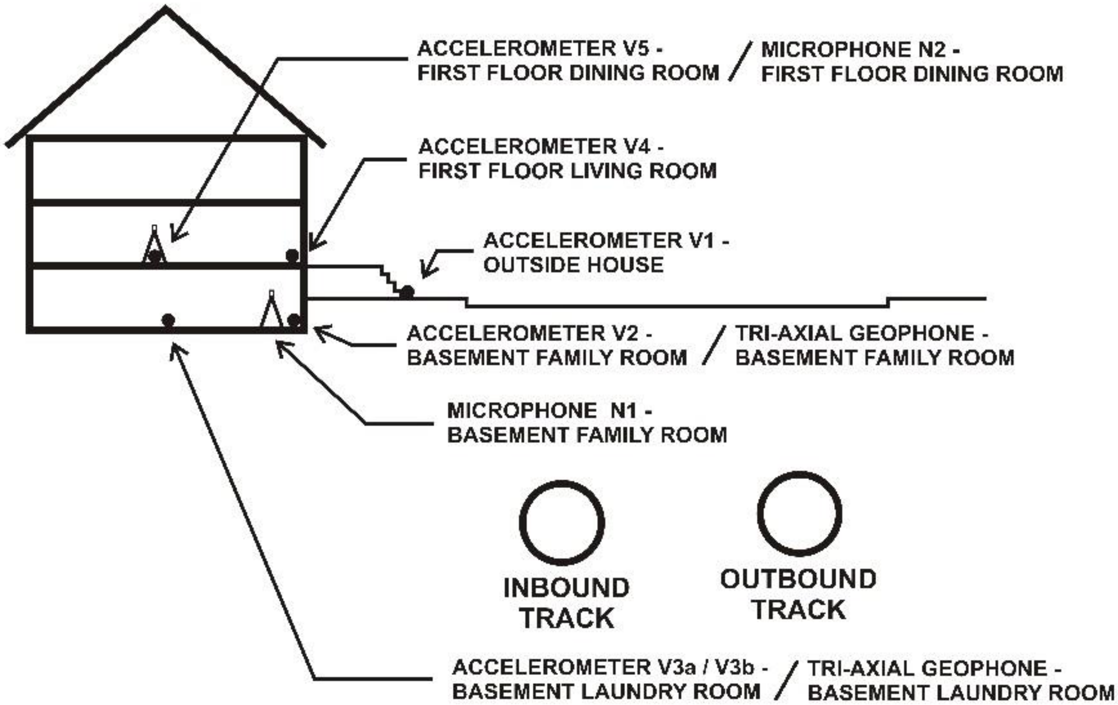


Figure 36: Cross-section Sketch (not to scale) of 3600 block of New Hampshire Avenue NW Indoor and Exterior Measurement Locations

B.2.3 GBNV Assessment Summary

SITE 2 3600 block of NEW HAMPSHIRE NW - ATTENDED PASSBY MEASUREMENT GBNV ASSESSMENT

Ground-borne Vibration (GBV)	>70 VdB?	Notes
7000 Series - Average of Multiple Passbys	NO	
6000 Series - Average of Multiple Passbys	NO	
5000 Series - Average of Multiple Passbys	NO	
3000 Series - Average of Multiple Passbys	NO	
2000 Series - Average of Multiple Passbys	NO	
Mixed Legacy 3000/2000 Series - Average of Multiple Passbys	NO	
7000 Series - Individual Train with Highest Overall Vibration	YES*	*pos. V5
6000 Series - Individual Train with Highest Overall Vibration	NO	
5000 Series - Individual Train with Highest Overall Vibration	NO	
3000 Series - Individual Train with Highest Overall Vibration	YES*	*pos. V5
2000 Series - Individual Train with Highest Overall Vibration	NO	
Mixed Legacy 3000/2000 Series - Individual Train with Highest Overall Vibration	YES*	*pos. V4 (1st floor living room) & V5

Ground-borne Noise (GBN)	>40 dBA?	Notes
7000 Series - Average of Multiple Passbys	NO	
6000 Series - Average of Multiple Passbys	NO	
5000 Series - Average of Multiple Passbys	NO	
3000 Series - Average of Multiple Passbys	NO	
2000 Series - Average of Multiple Passbys	NO	
Mixed Legacy 3000/2000 Series - Average of Multiple Passbys	NO	
7000 Series - Individual Train with Highest A-weighting	NO	
6000 Series - Individual Train with Highest A-weighting	NO	
5000 Series - Individual Train with Highest A-weighting	NO	
3000 Series - Individual Train with Highest A-weighting	NO	
2000 Series - Individual Train with Highest A-weighting	NO	
Mixed Legacy 3000/2000 Series - Individual Train with Highest A-weighting	NO	

B.2.4 PPV Results

SITE 2a	**3600 block of NEW HAMPSHIRE NW – POTENTIAL FOR BUILDING VIBRATION DAMAGE ASSESSMENT**						
	>0.2 in/sec PPV in any direction?	Average PPV (in/s)			PPV Range (in/s)		
		Tran	Vert	Long	Tran	Vert	Long
	NO	0.0036	0.0034	0.0020	0.003 - 0.008	0.002 - 0.013	0.002 - 0.004
Basement Laundry Room at V3a 16-Aug-17 9:02:50 AM to 11:11:10 AM							

SITE 2b	**3600 block of NEW HAMPSHIRE NW – POTENTIAL FOR BUILDING VIBRATION DAMAGE ASSESSMENT**						
	>0.2 in/sec PPV in any direction?	Average PPV (in/s)			PPV Range (in/s)		
		Tran	Vert	Long	Tran	Vert	Long
	NO	0.0033	0.0034	0.0021	0.003 - 0.034	0.003 - 0.025	0.002 - 0.012
Basement Family Room at V2 16-Aug-17 11:12:45 AM to 12:53:51 PM							

B.2.5 Passby Vibration Spectra and Overall Levels

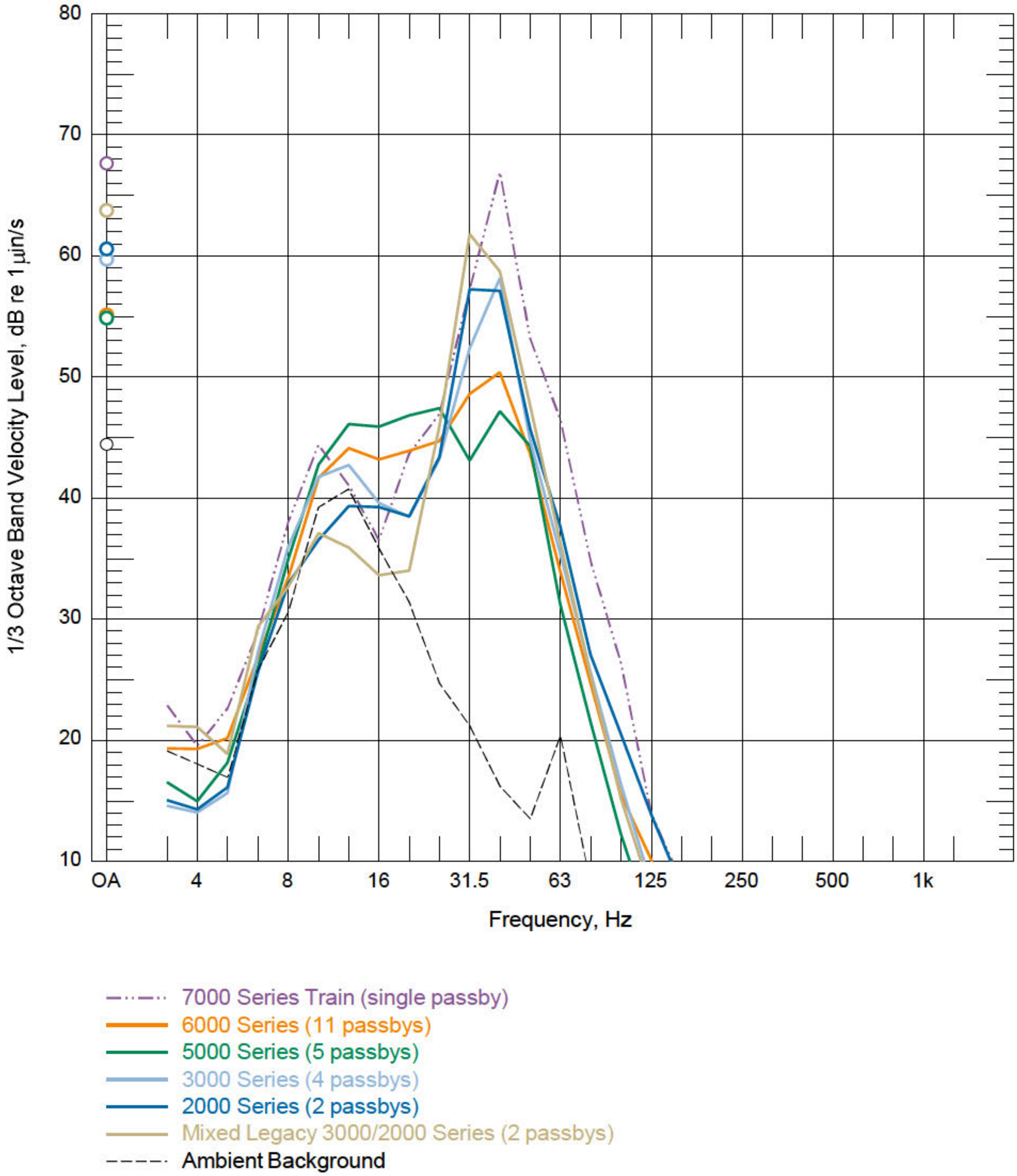


Figure 37: ***Site 2 at Location V1 Outside***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

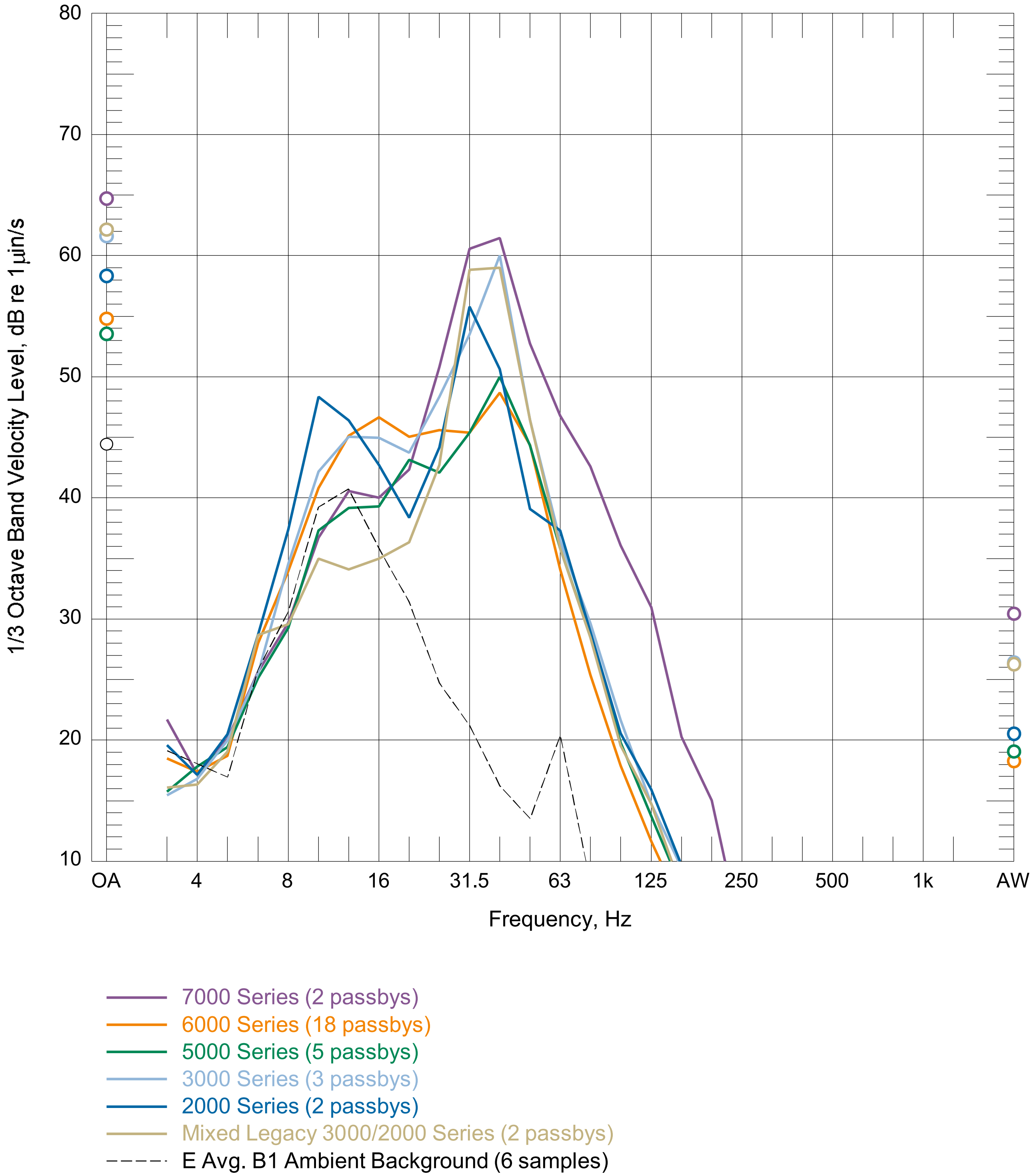


Figure 38: ***Site 2 at Location V1 Outside***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

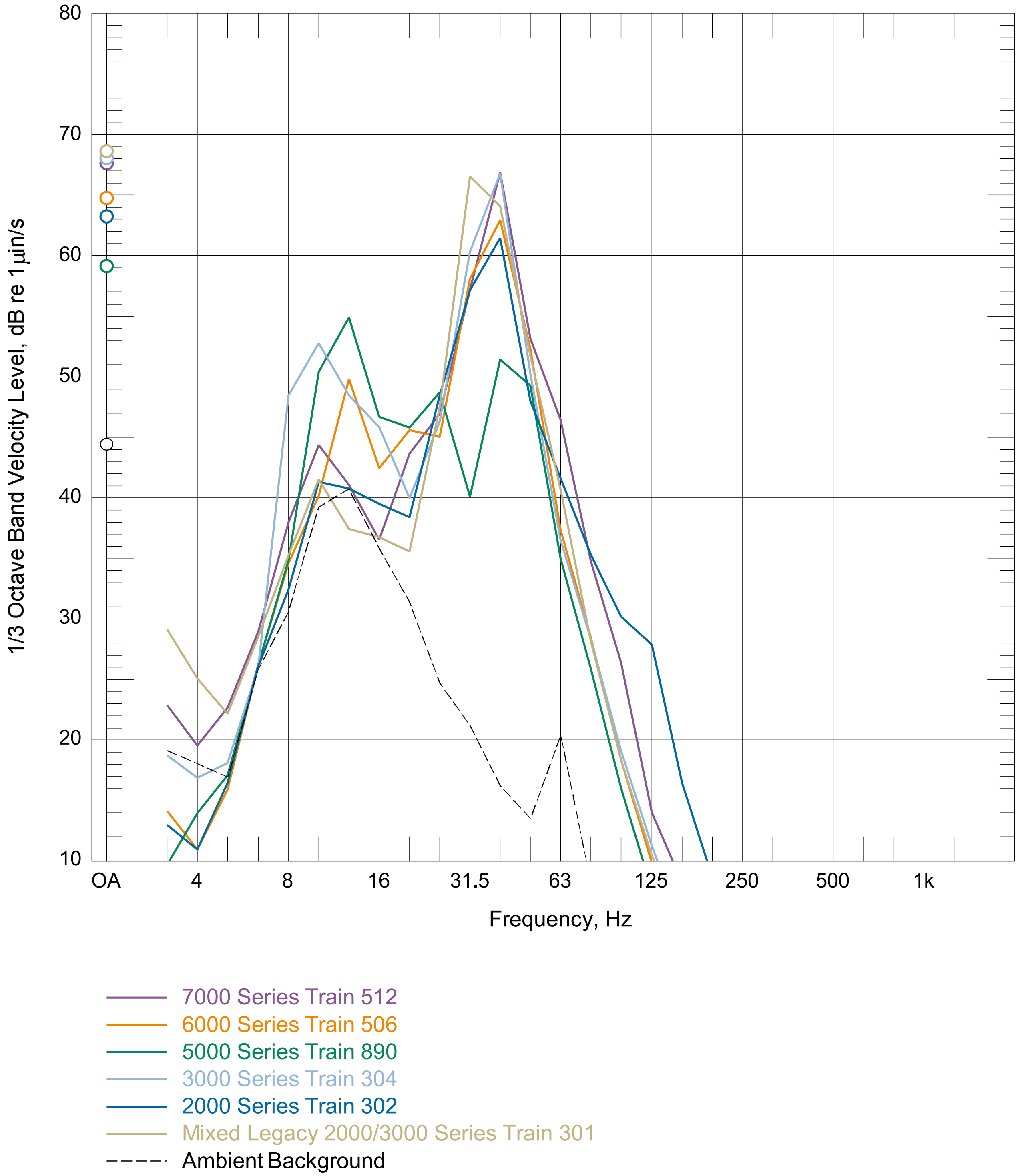


Figure 39: ***Site 2 at Location V1 Outside***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

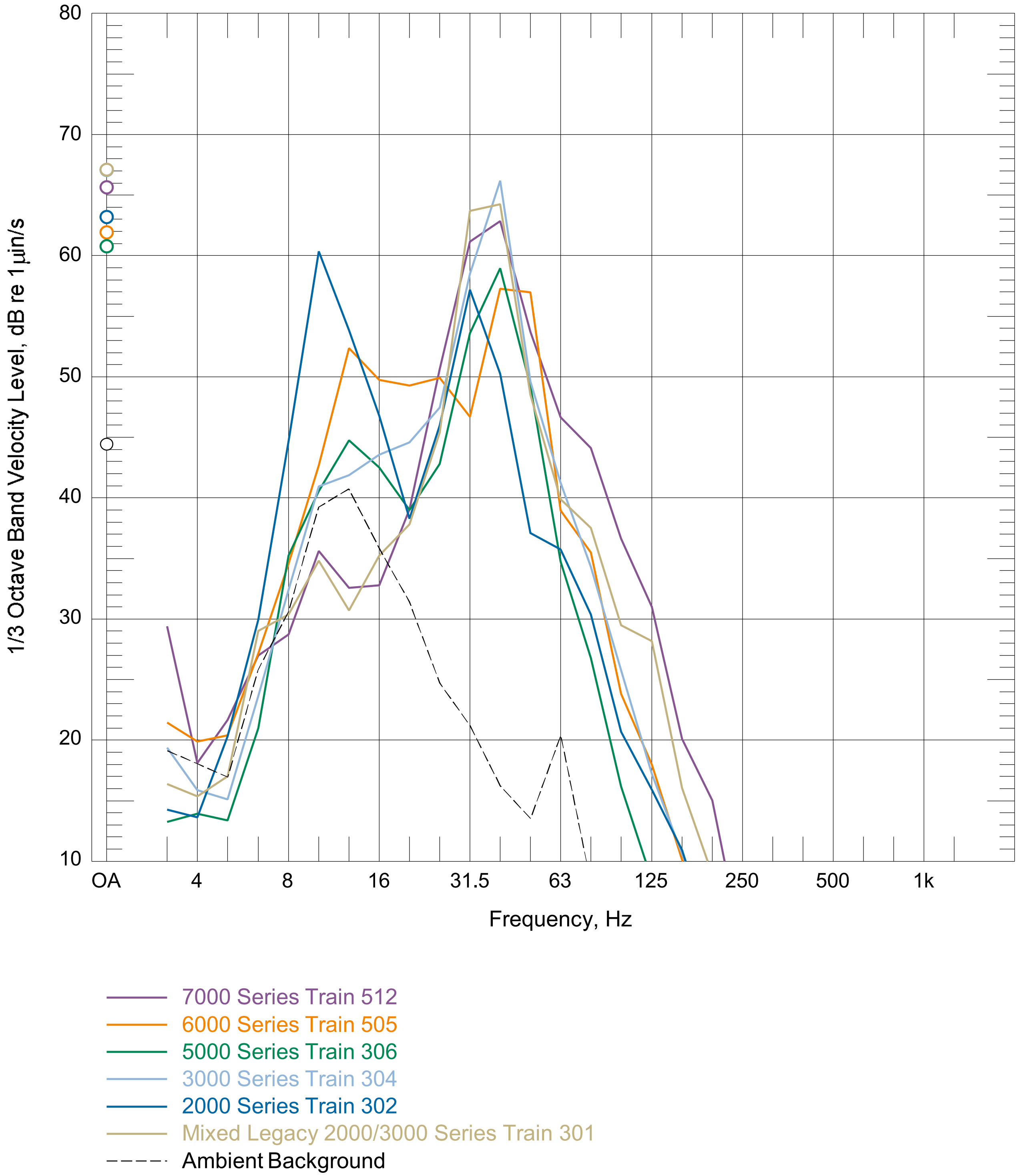


Figure 40: ***Site 2 at Location V1 Outside***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

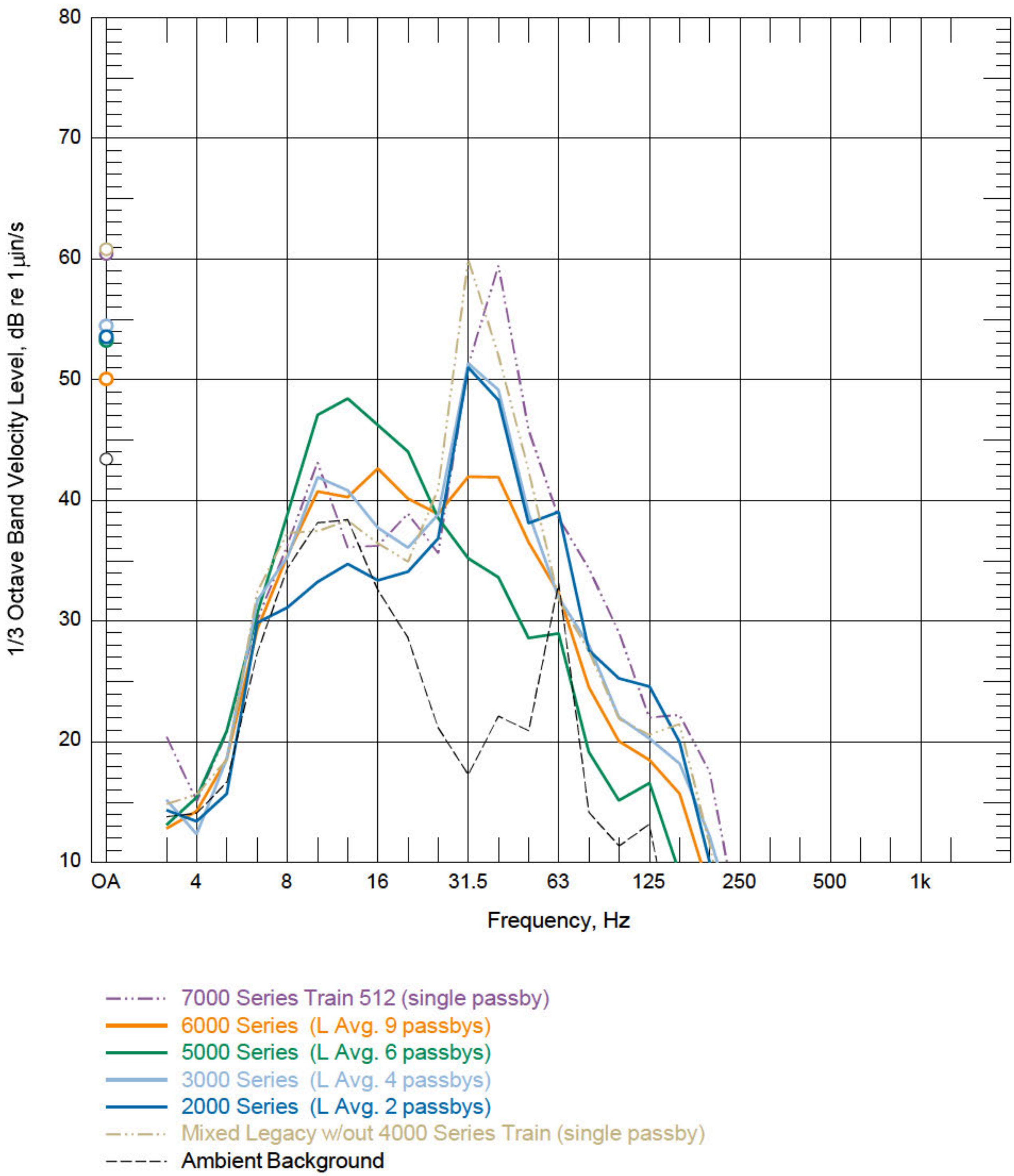


Figure 41: ***Site 2 at Location V2 Basement Family Room***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

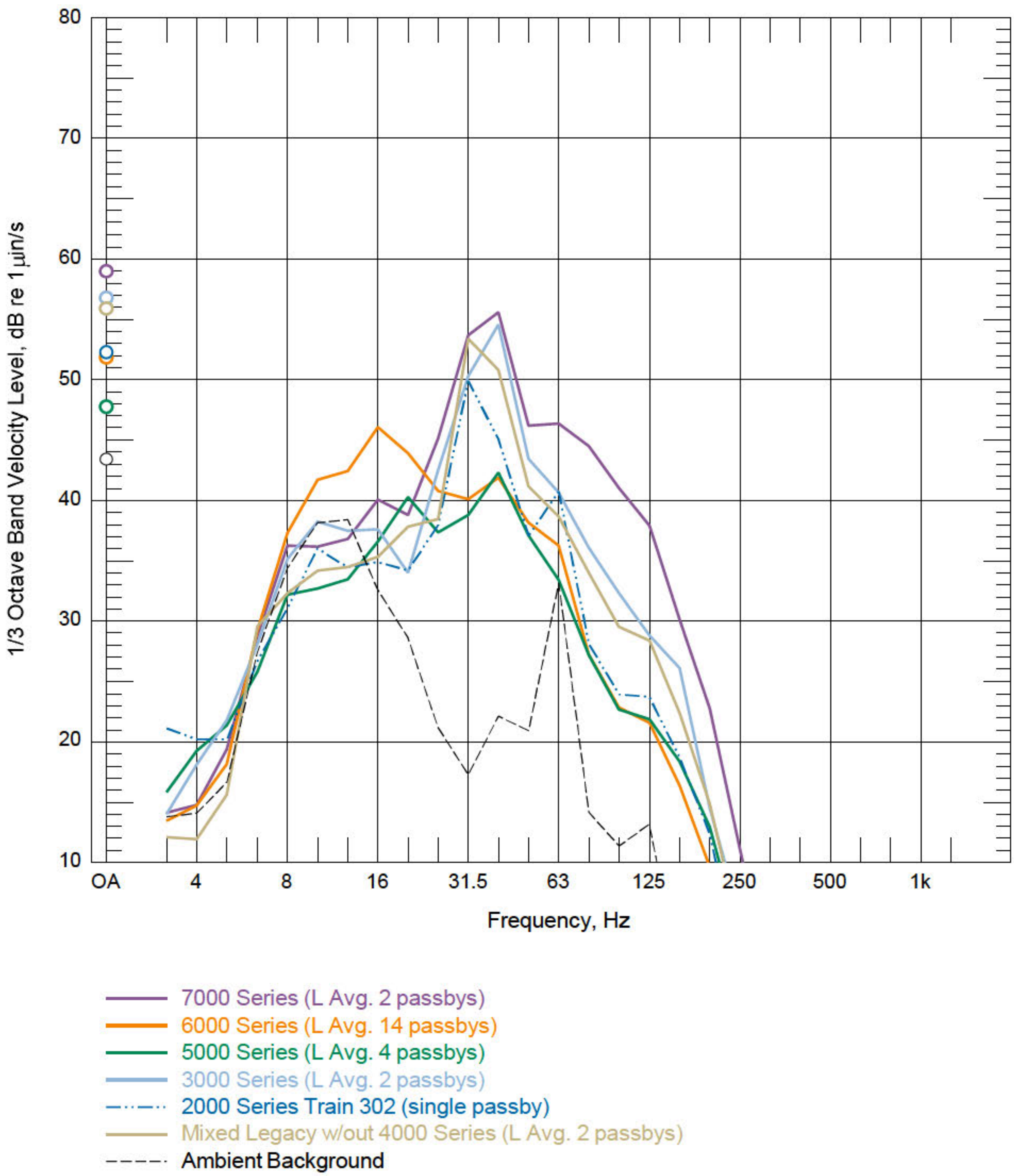


Figure 42: ***Site 2 at Location V2 Basement Family Room***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

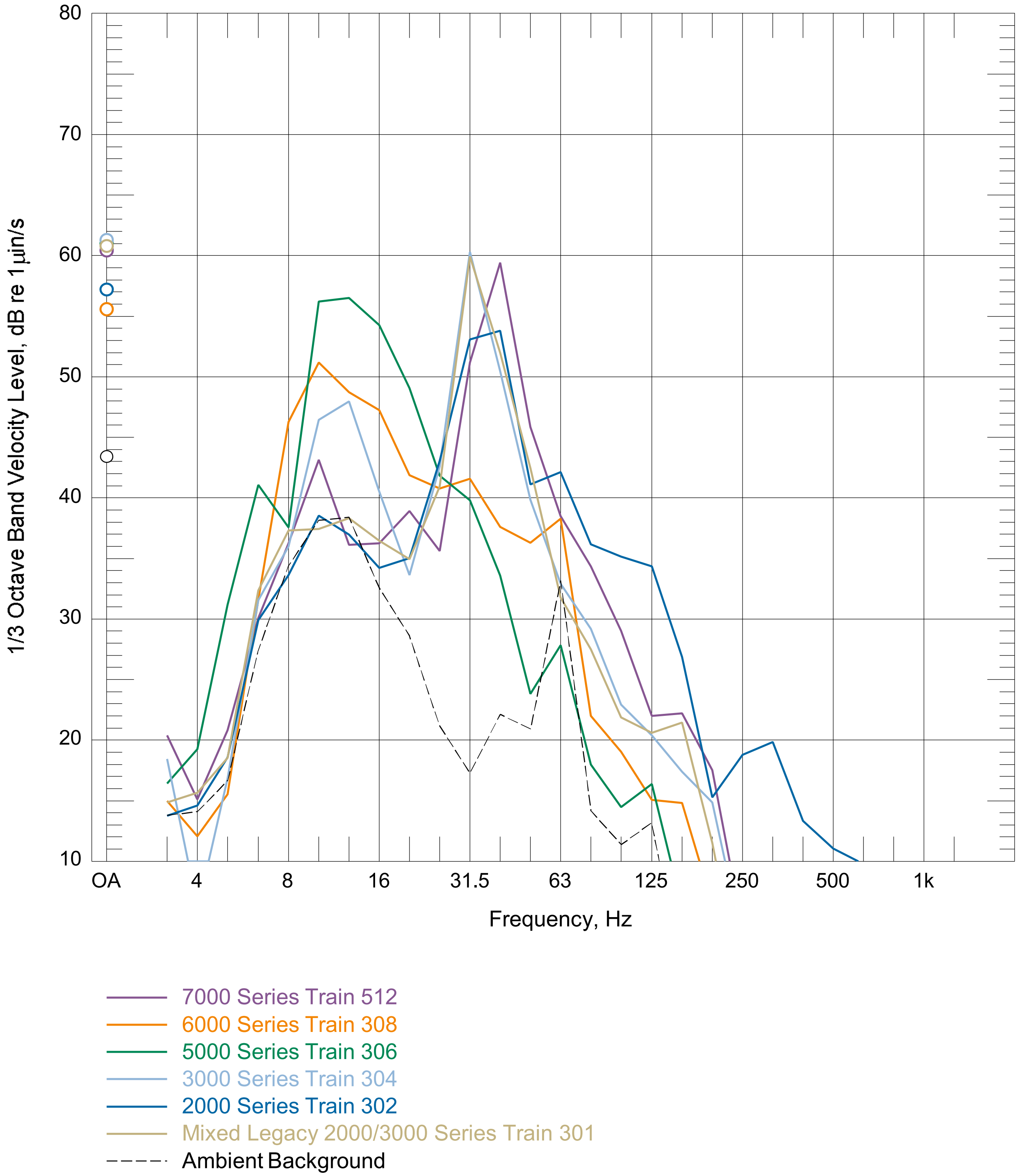


Figure 43: ***Site 2 at Location V2 Basement Family Room***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

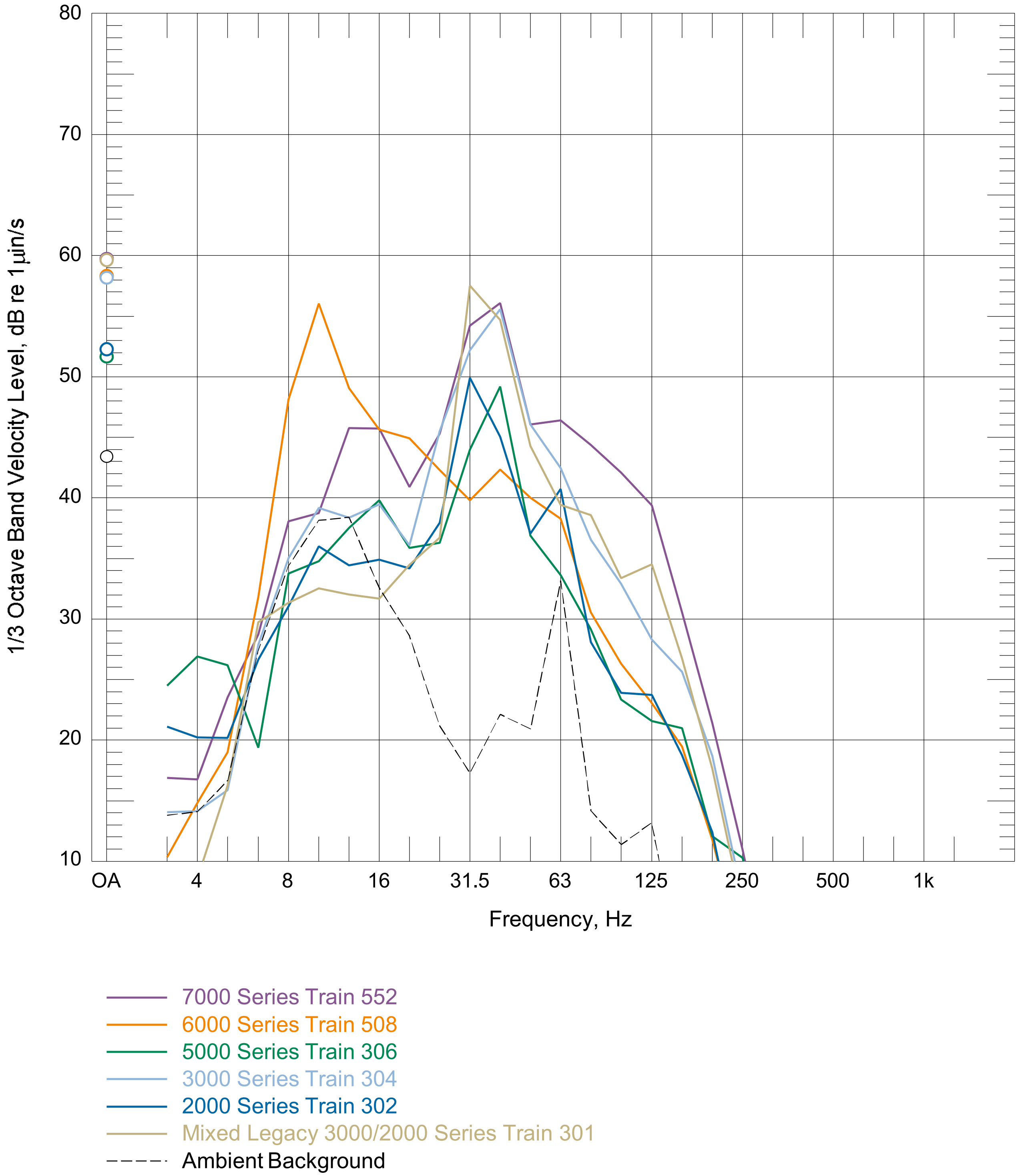


Figure 44: ***Site 2 at Location V2 Basement Family Room***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

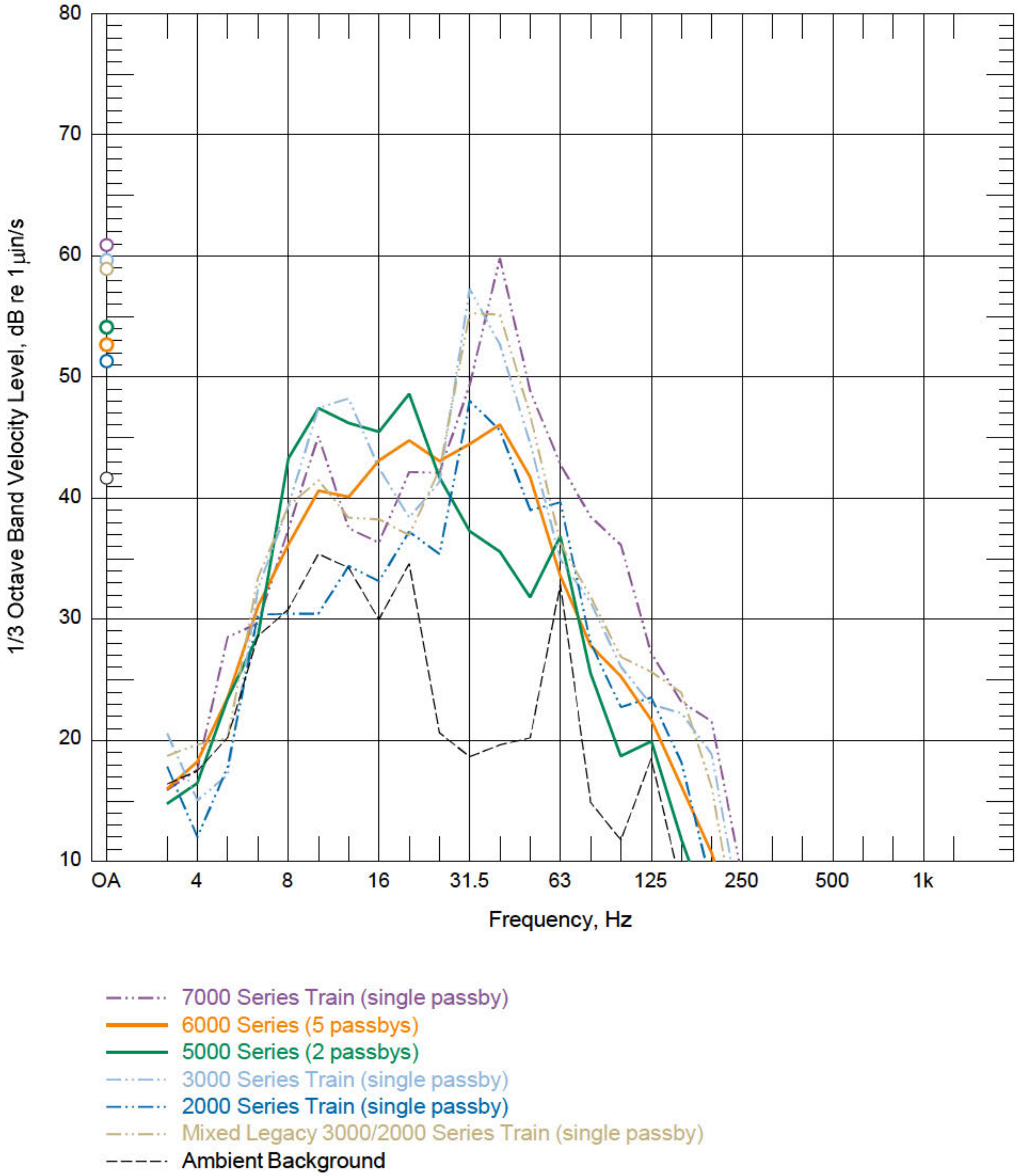


Figure 45: ***Site 2 at Location V3a Basement Laundry Room (bare concrete)***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

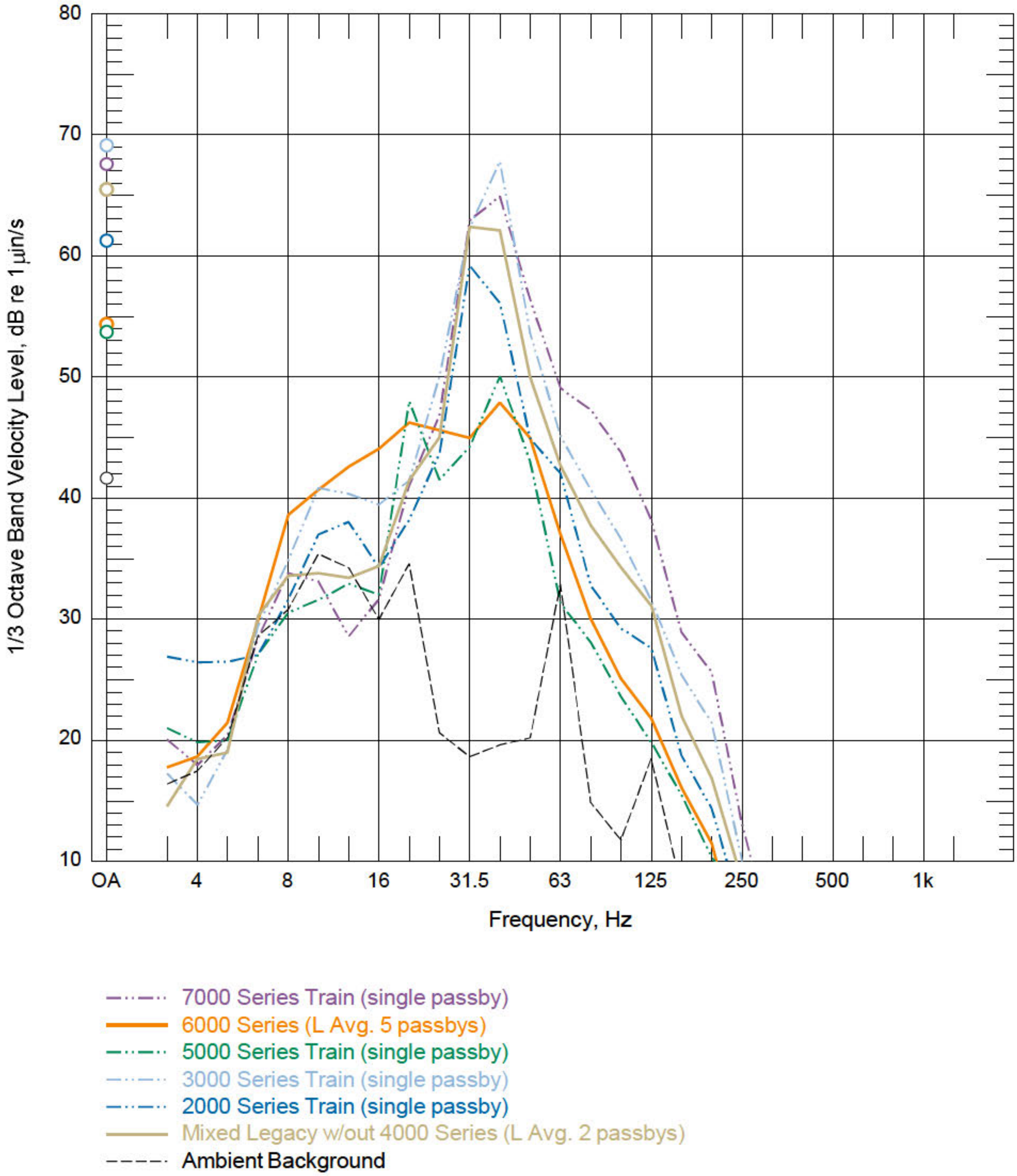


Figure 46: ***Site 2 at Location V3a Basement Laundry Room (bare concrete)***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

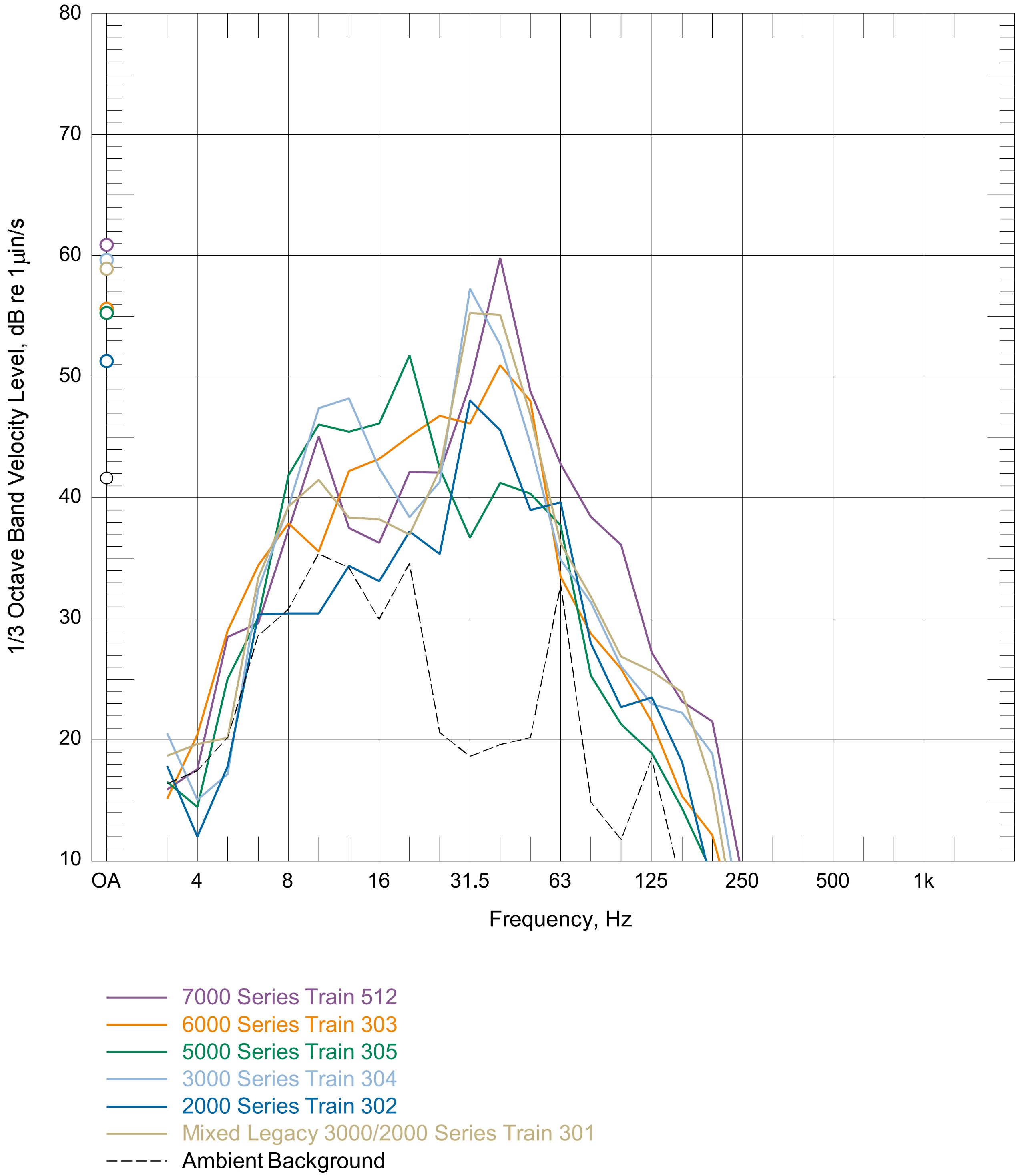


Figure 47: ***Site 2 at Location V3a Basement Laundry Room (bare concrete)***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

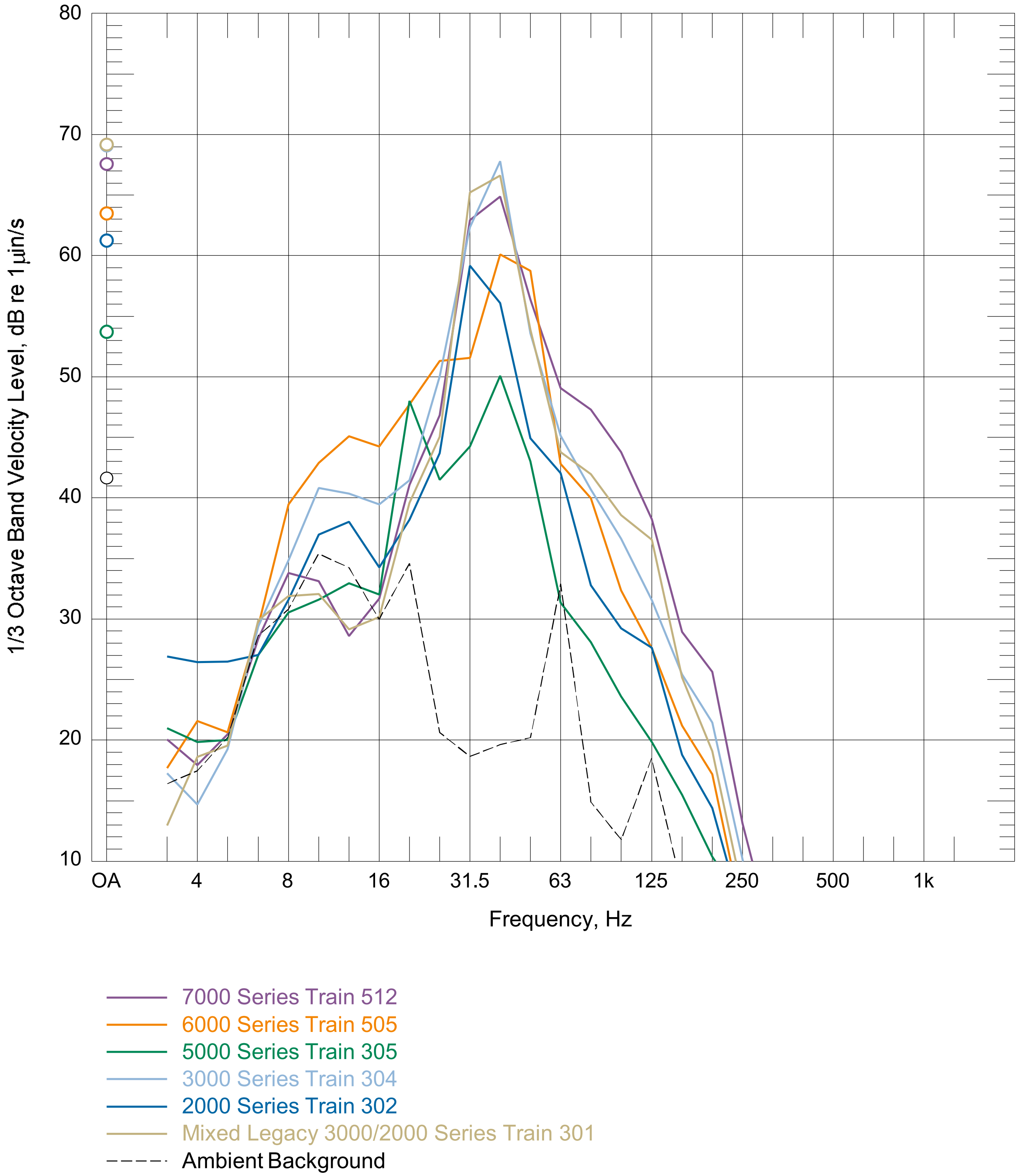


Figure 48: ***Site 2 at Location V3a Basement Laundry Room (bare concrete)***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

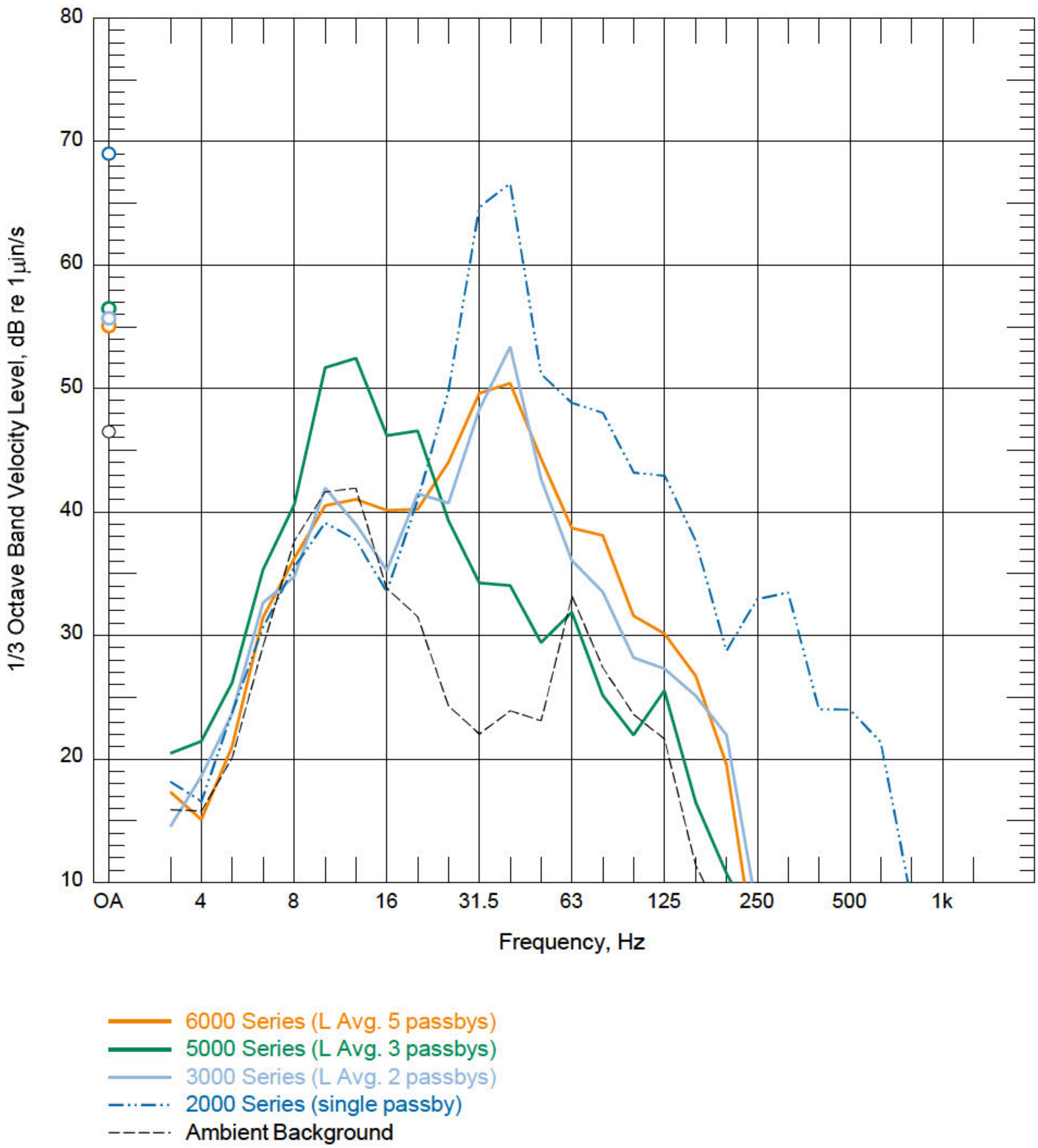


Figure 49: ***Site 2 at Location V3b Basement Laundry Room (finished flooring)***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

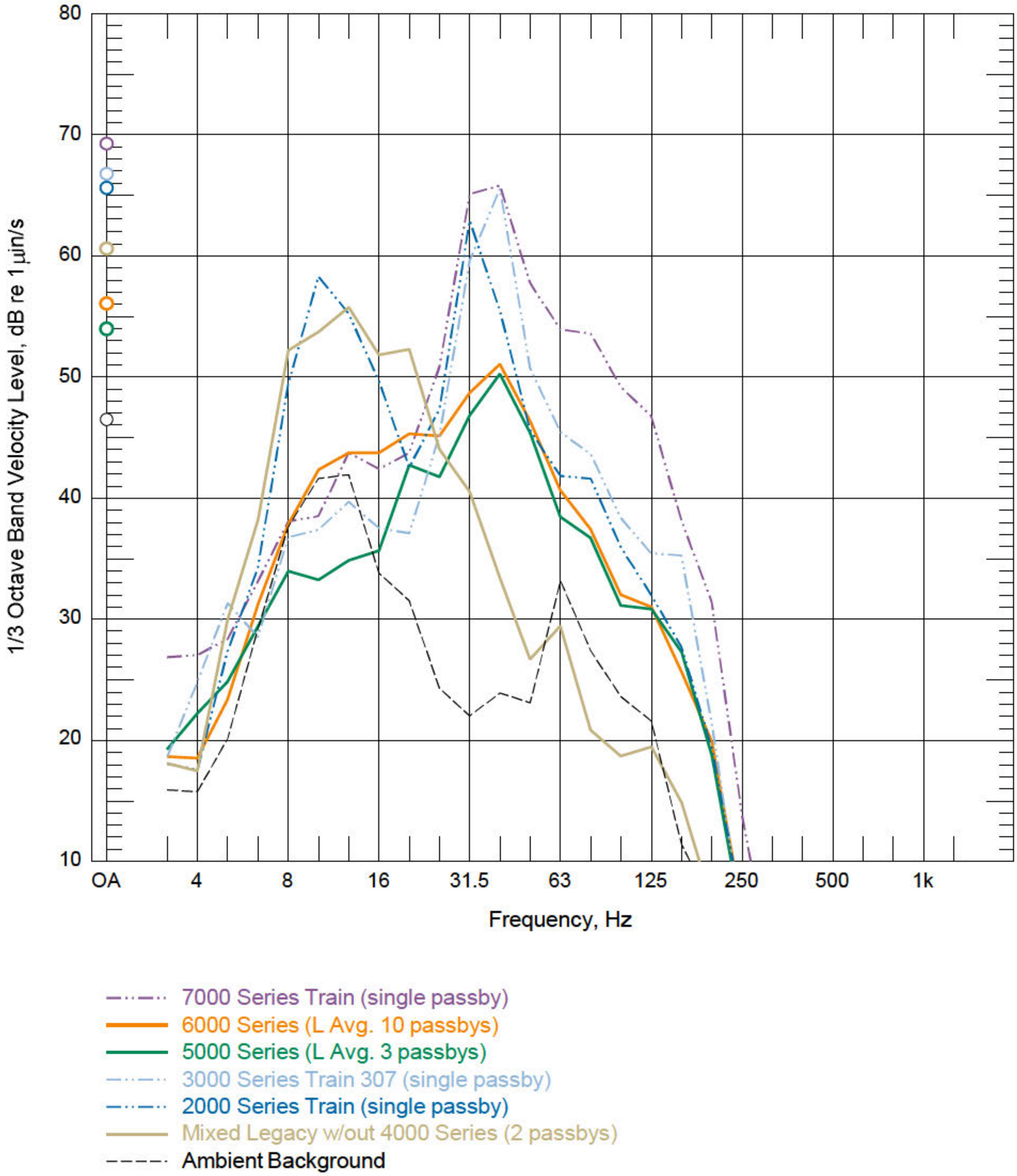


Figure 50: ***Site 2 at Location V3b Basement Laundry Room (finished flooring)***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

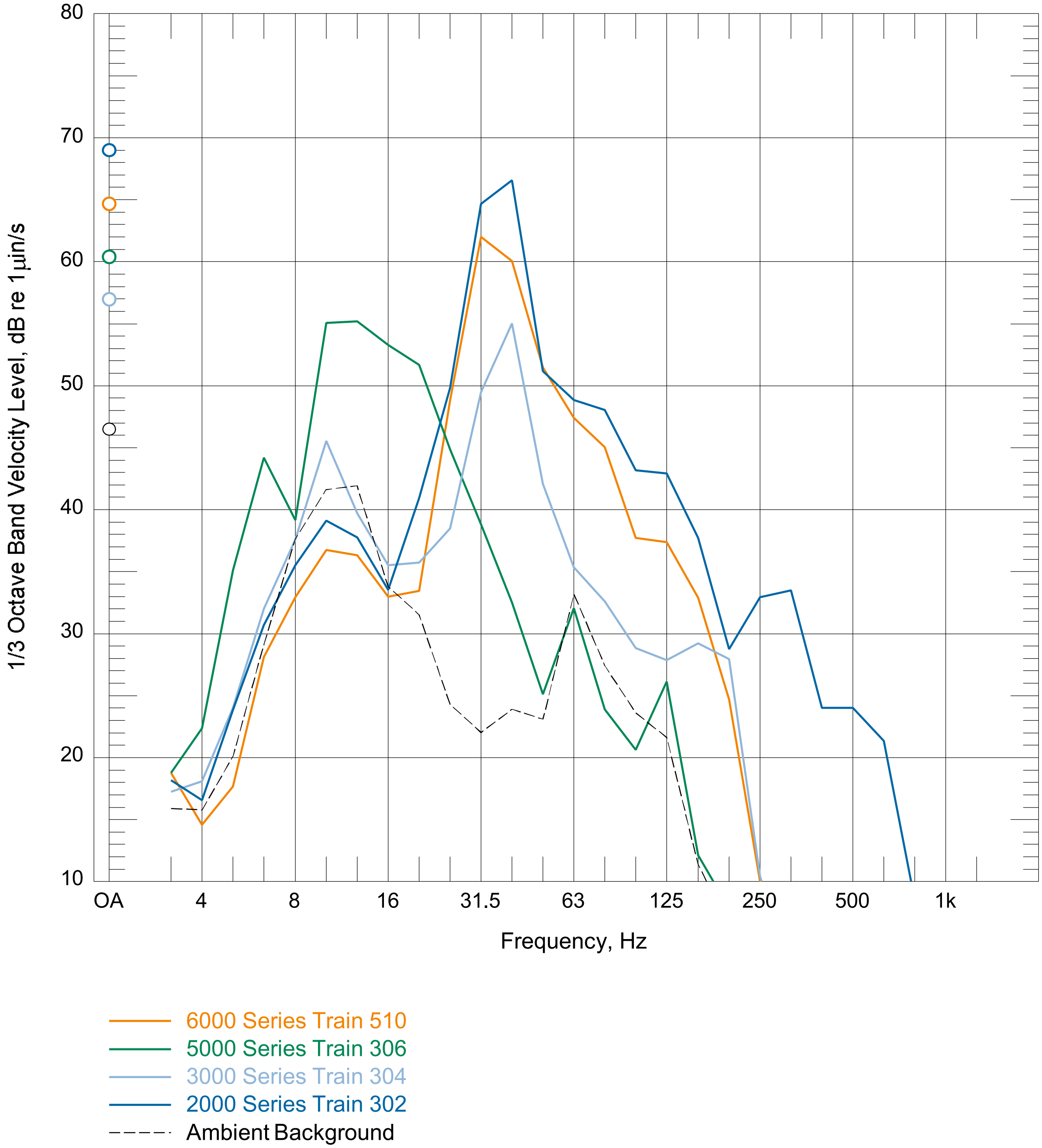


Figure 51: ***Site 2 at Location V3b Basement Laundry Room (finished flooring)***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

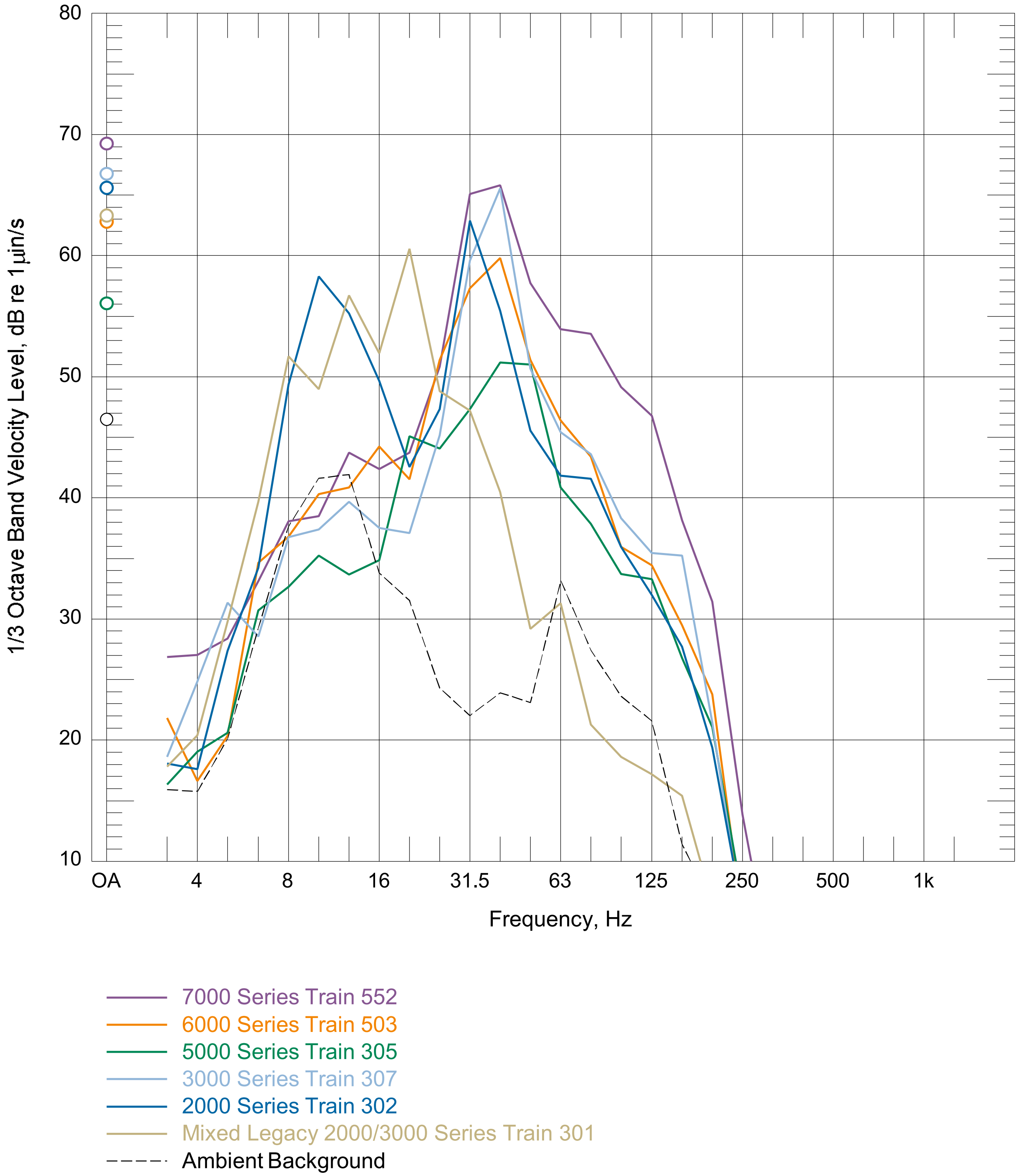


Figure 52: ***Site 2 at Location V3b Basement Laundry Room (finished flooring)***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

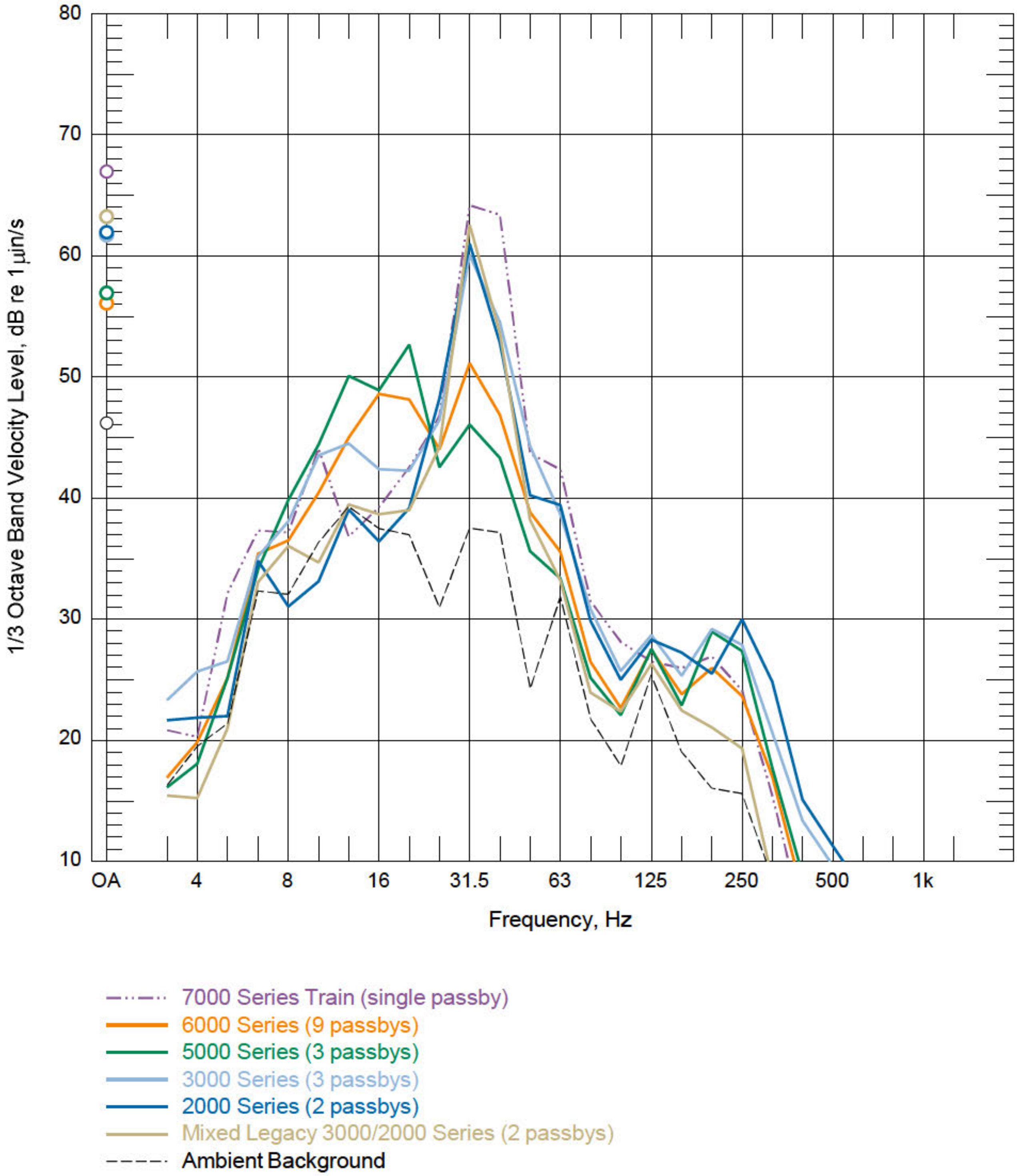


Figure 53: ***Site 2 at Location V4 First Floor Living Room***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

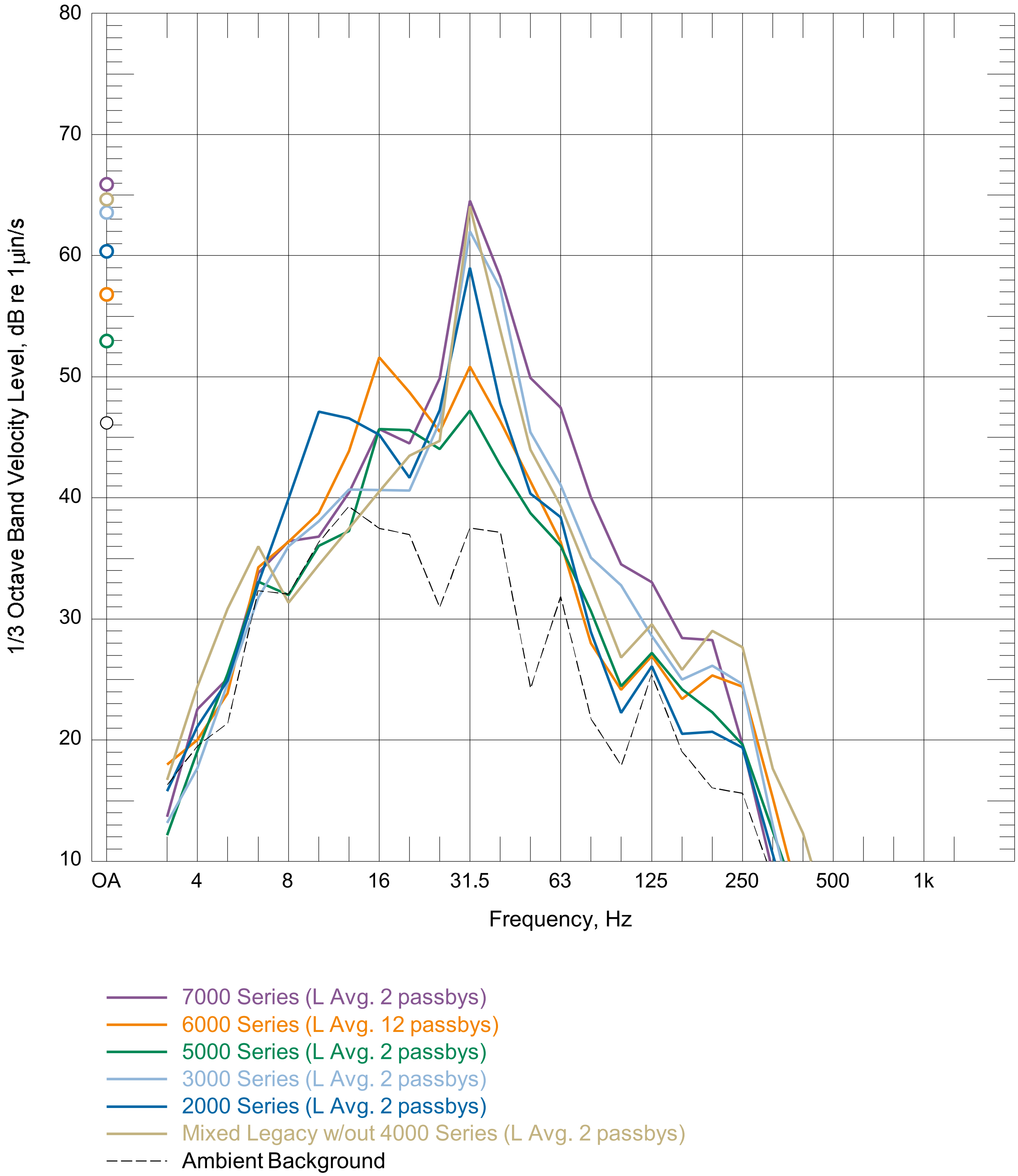


Figure 54: ***Site 2 at Location V4 First Floor Living Room***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

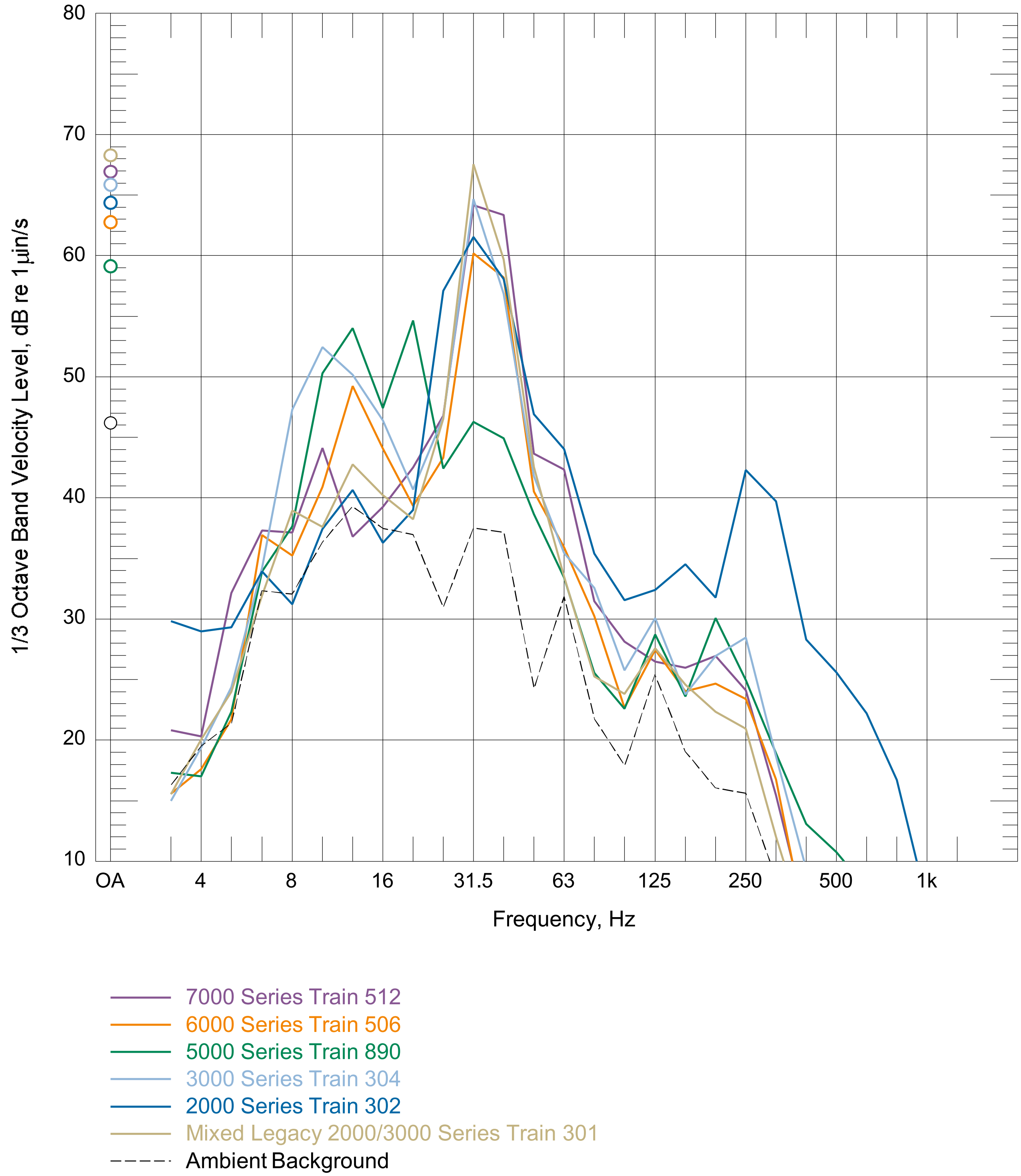


Figure 55: ***Site 2 at Location V4 First Floor Living Room***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

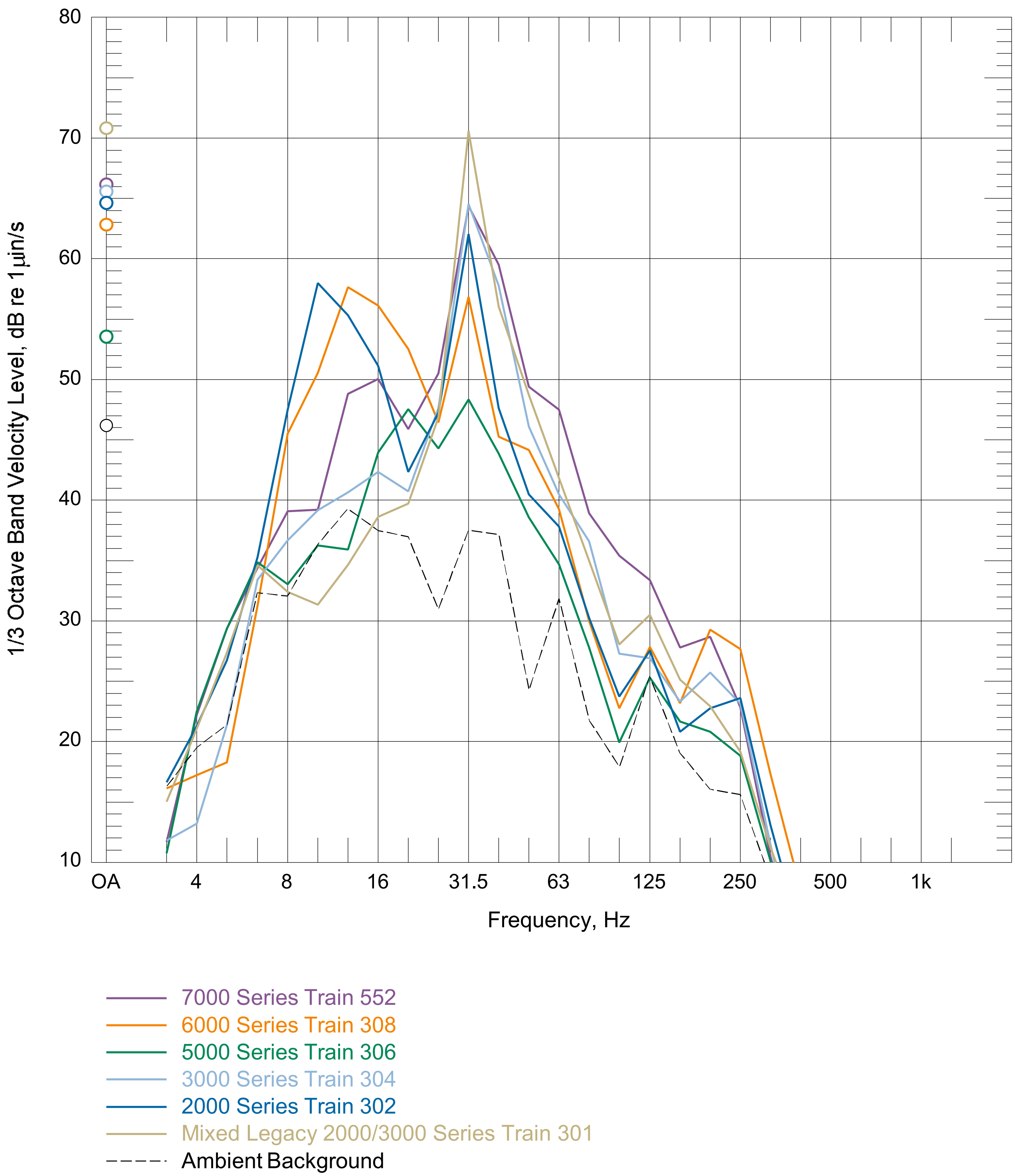


Figure 56: ***Site 2 at Location V4 First Floor Living Room***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

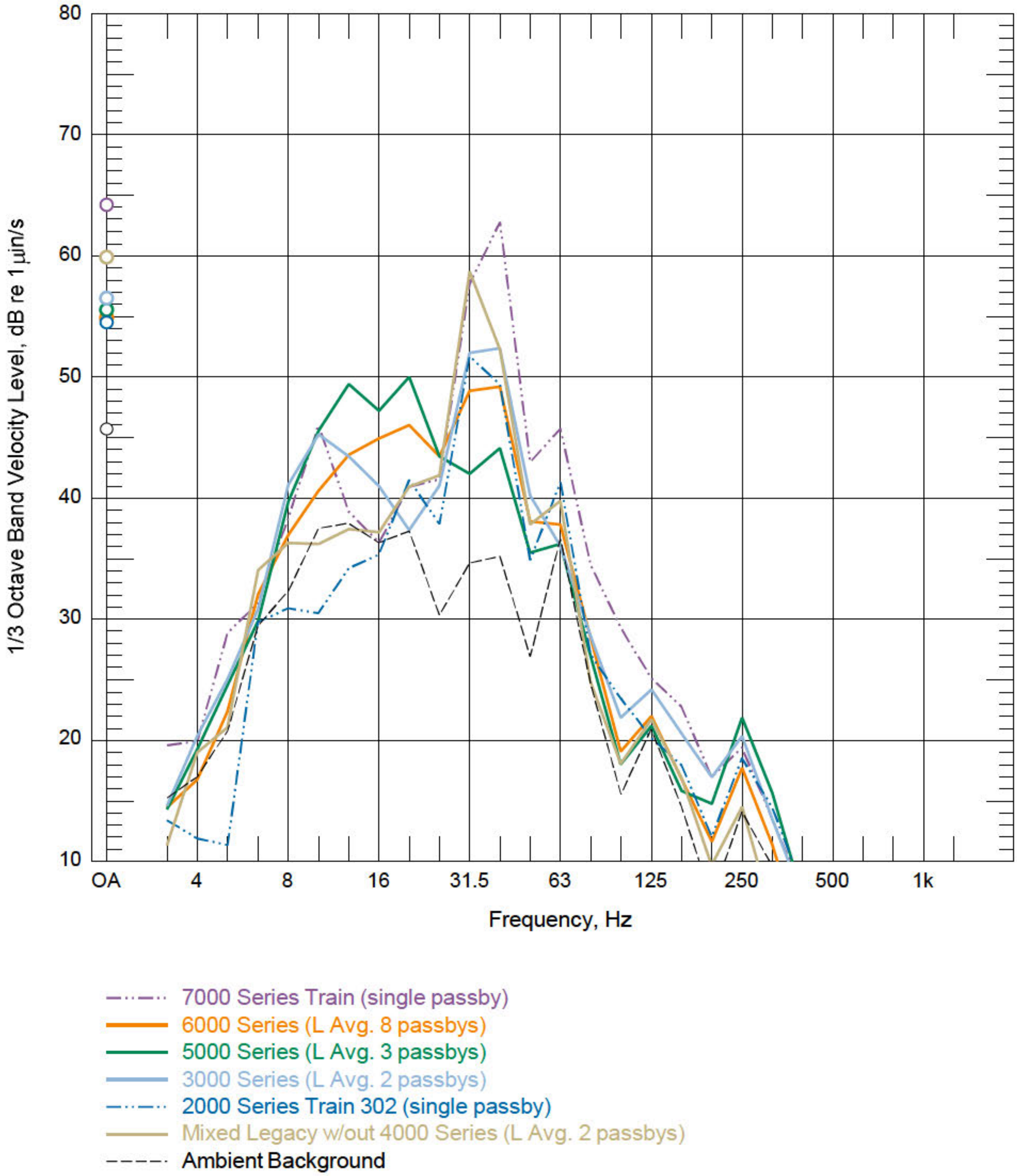


Figure 57: ***Site 2 at Location V5 First Floor Dining Room***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

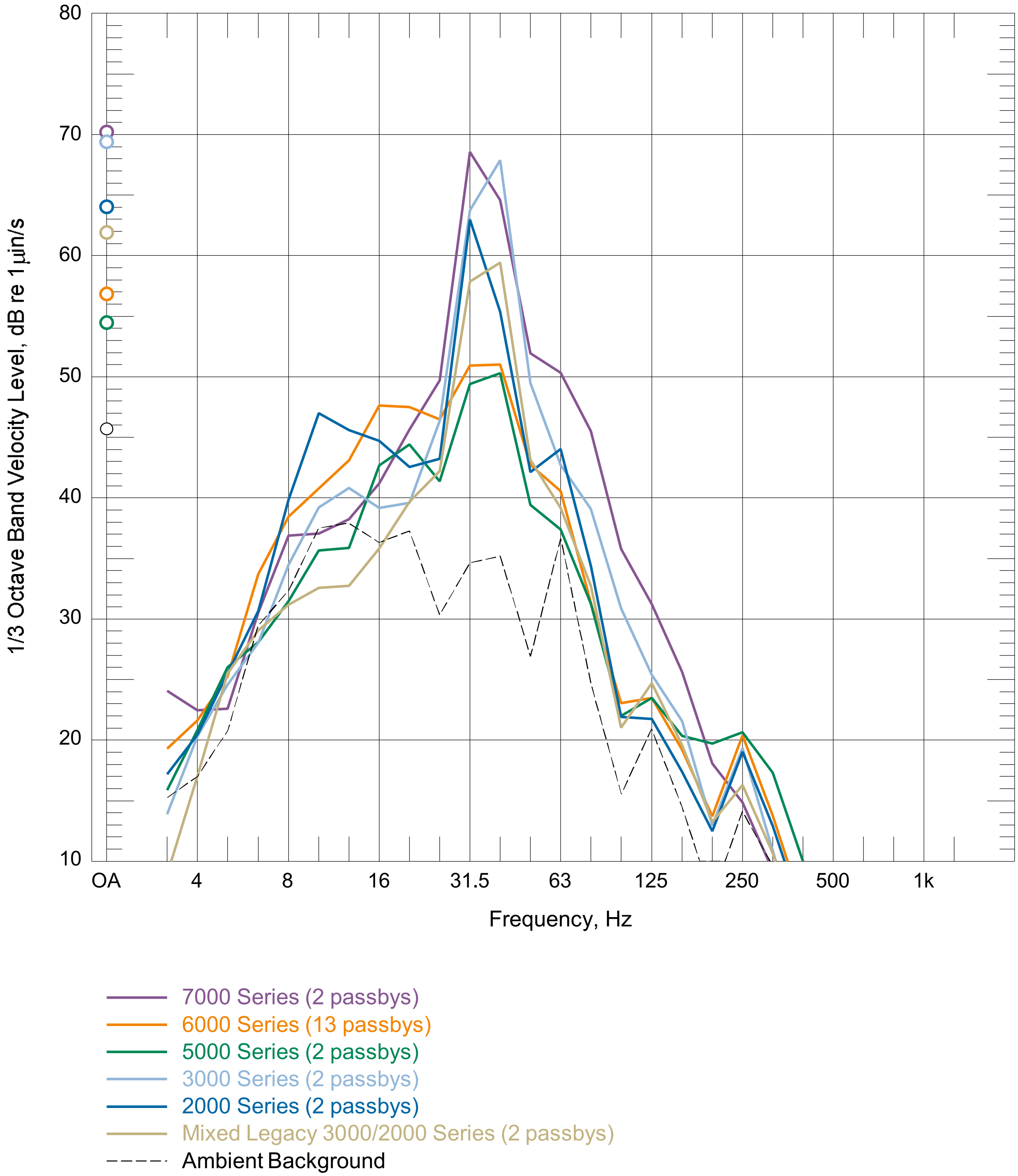


Figure 58: ***Site 2 at Location V5 First Floor Dining Room***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

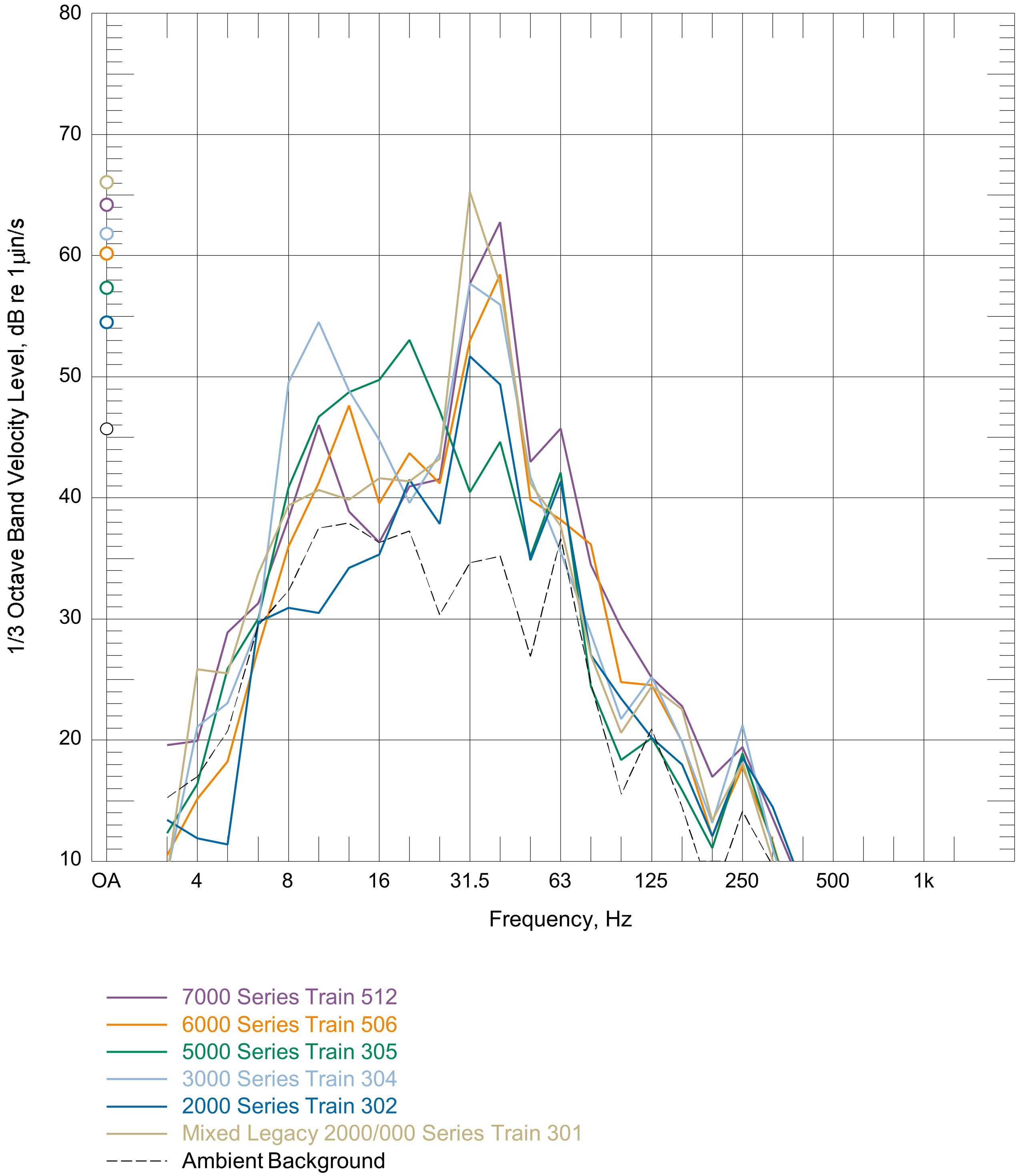


Figure 59: ***Site 2 at Location V5 First Floor Dining Room***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

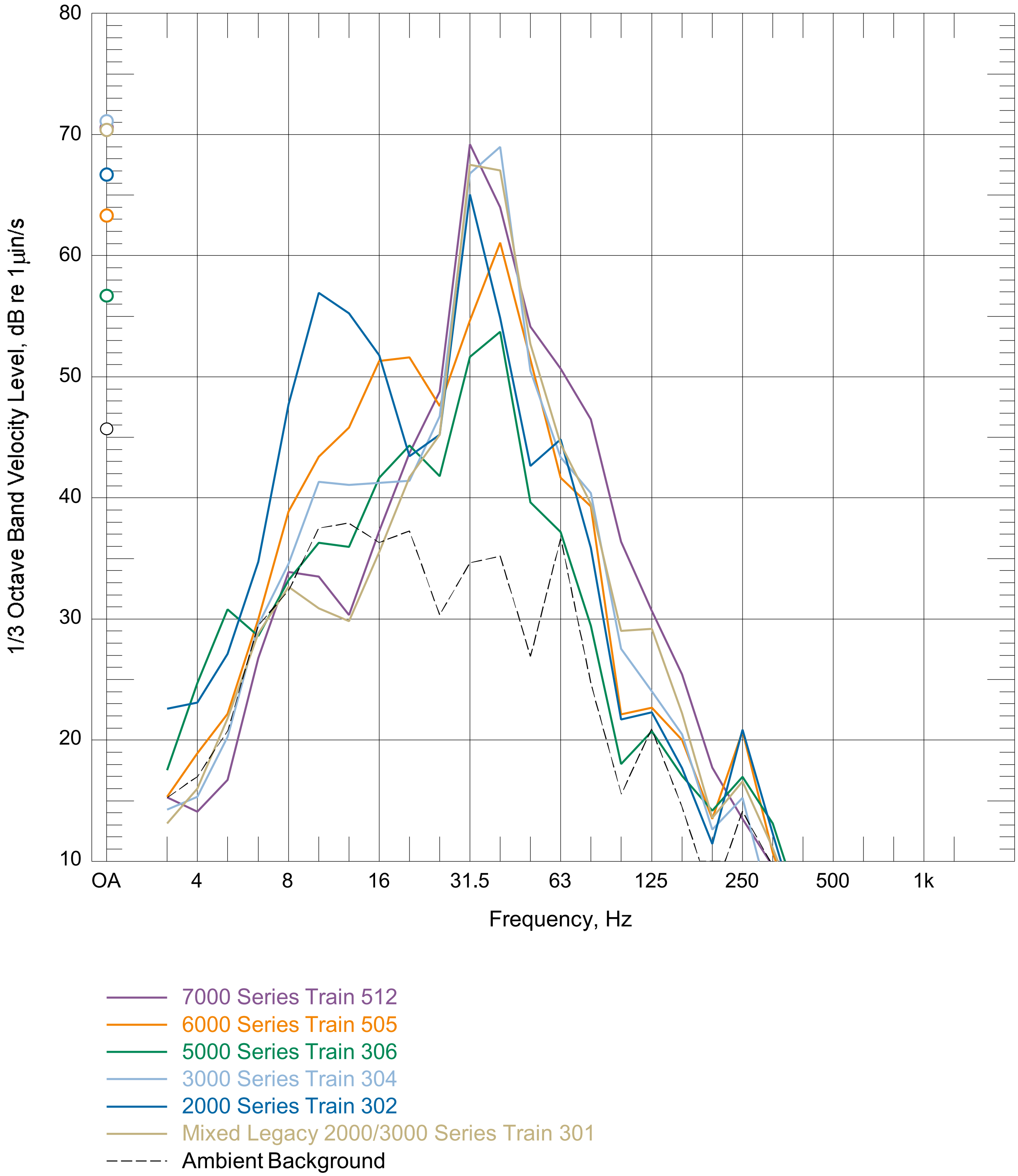


Figure 60: ***Site 2 at Location V5 First Floor Dining Room***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

B.2.6 Passby Ground-borne Noise Spectra and A-weighted Levels

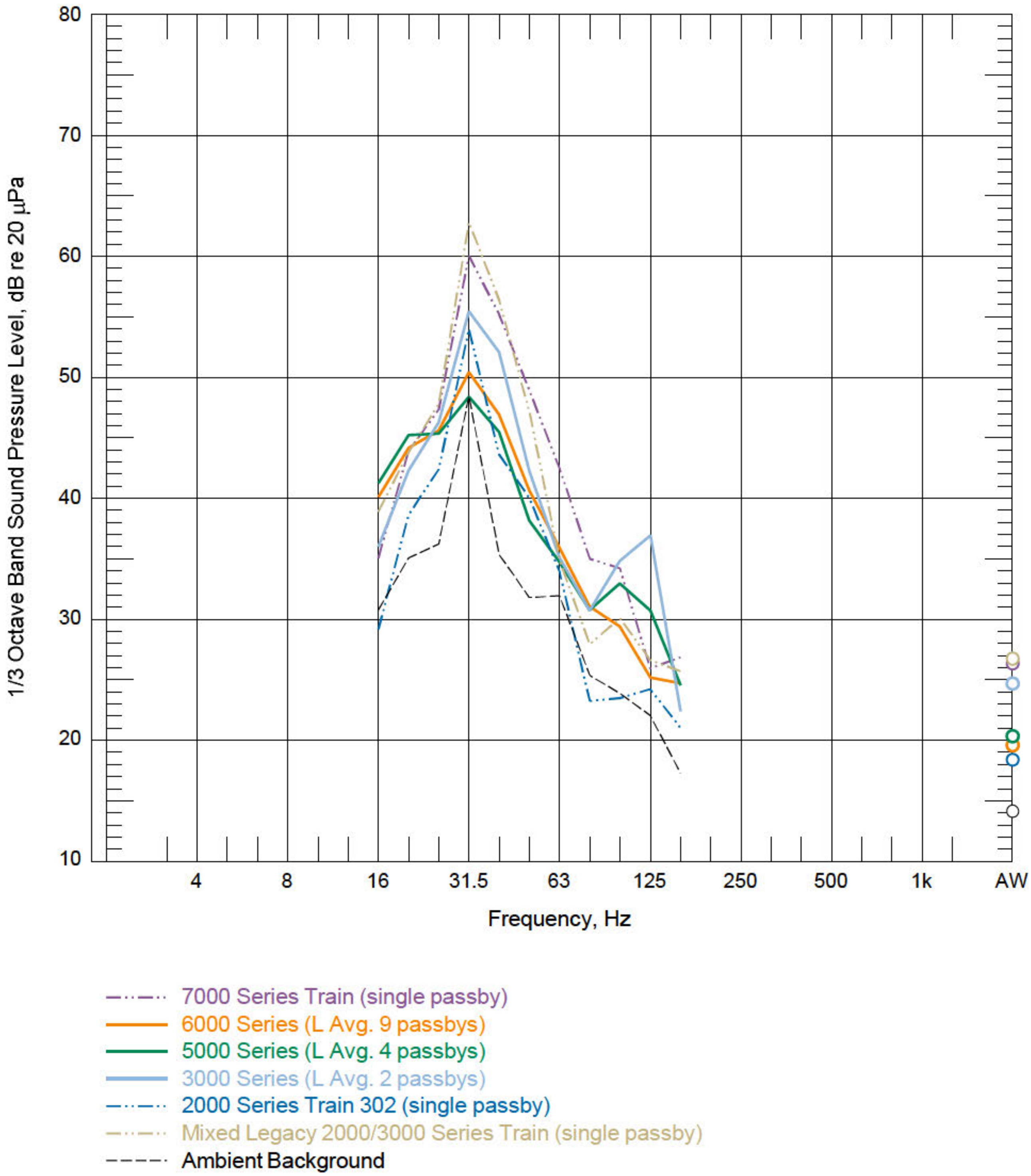


Figure 61: ***Site 2 at Location N1 Basement Family Room***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

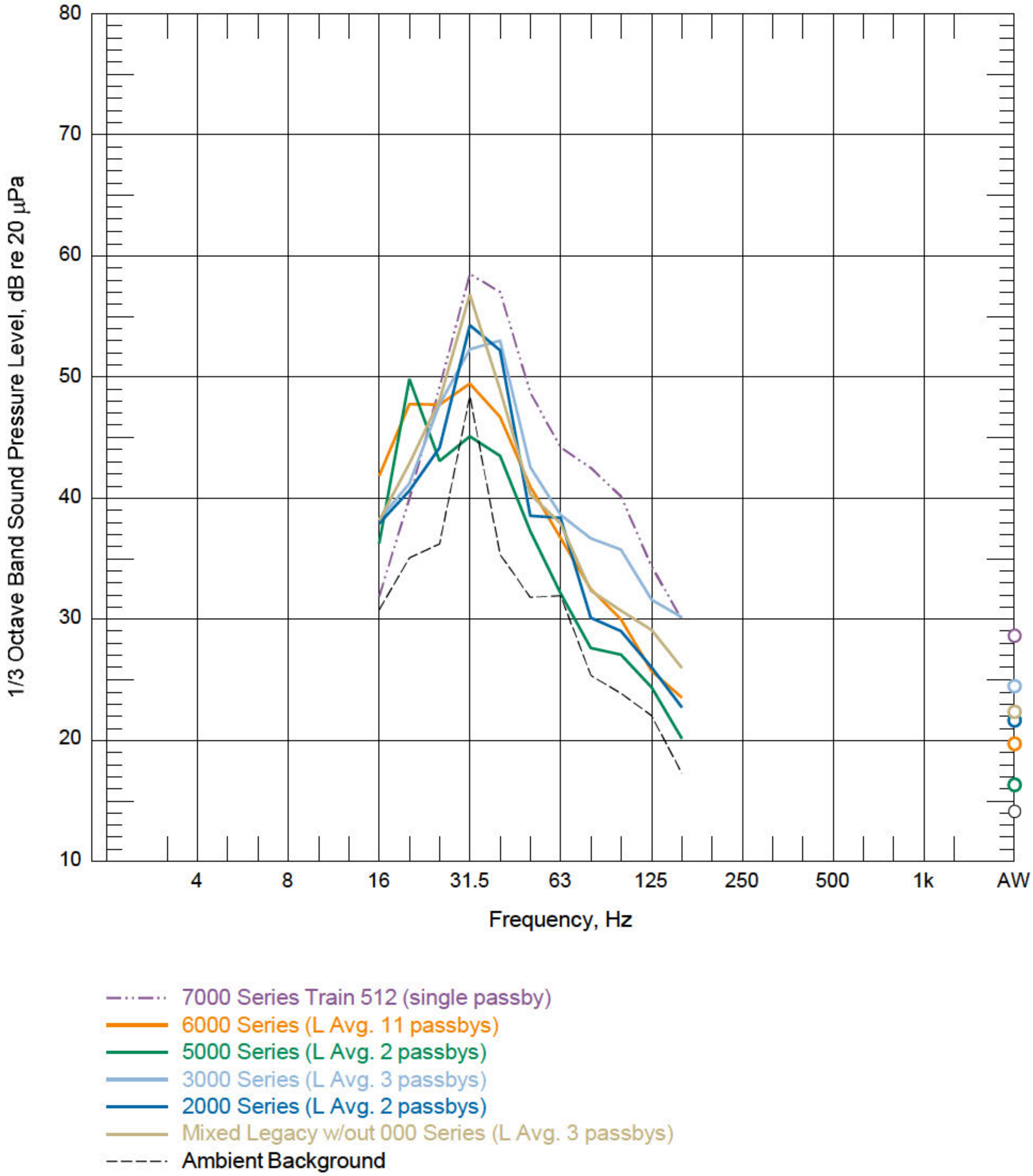


Figure 62: ***Site 2 at Location N1 Basement Family Room***
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

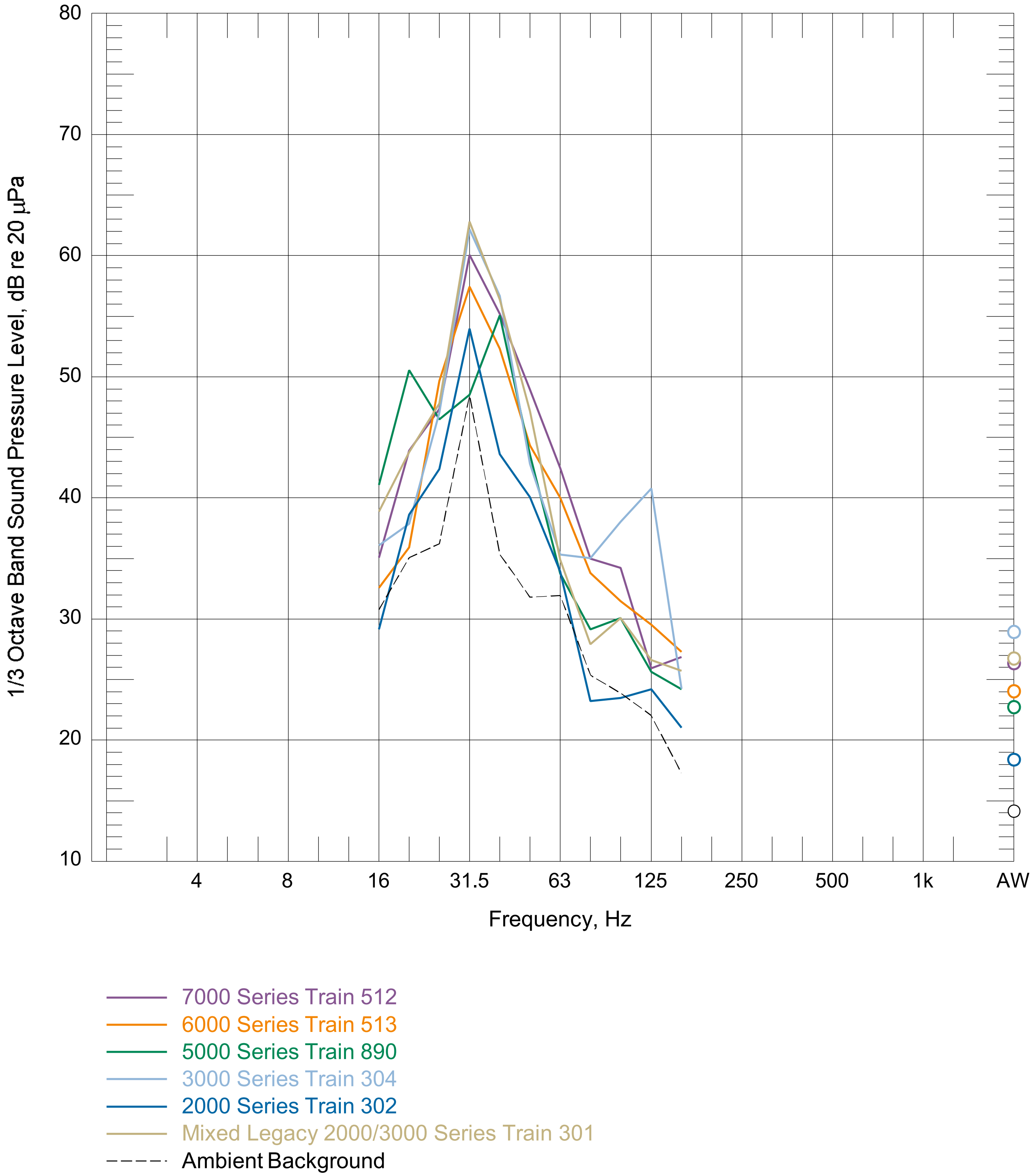


Figure 63: ***Site 2 at Location N1 Basement Family Room***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

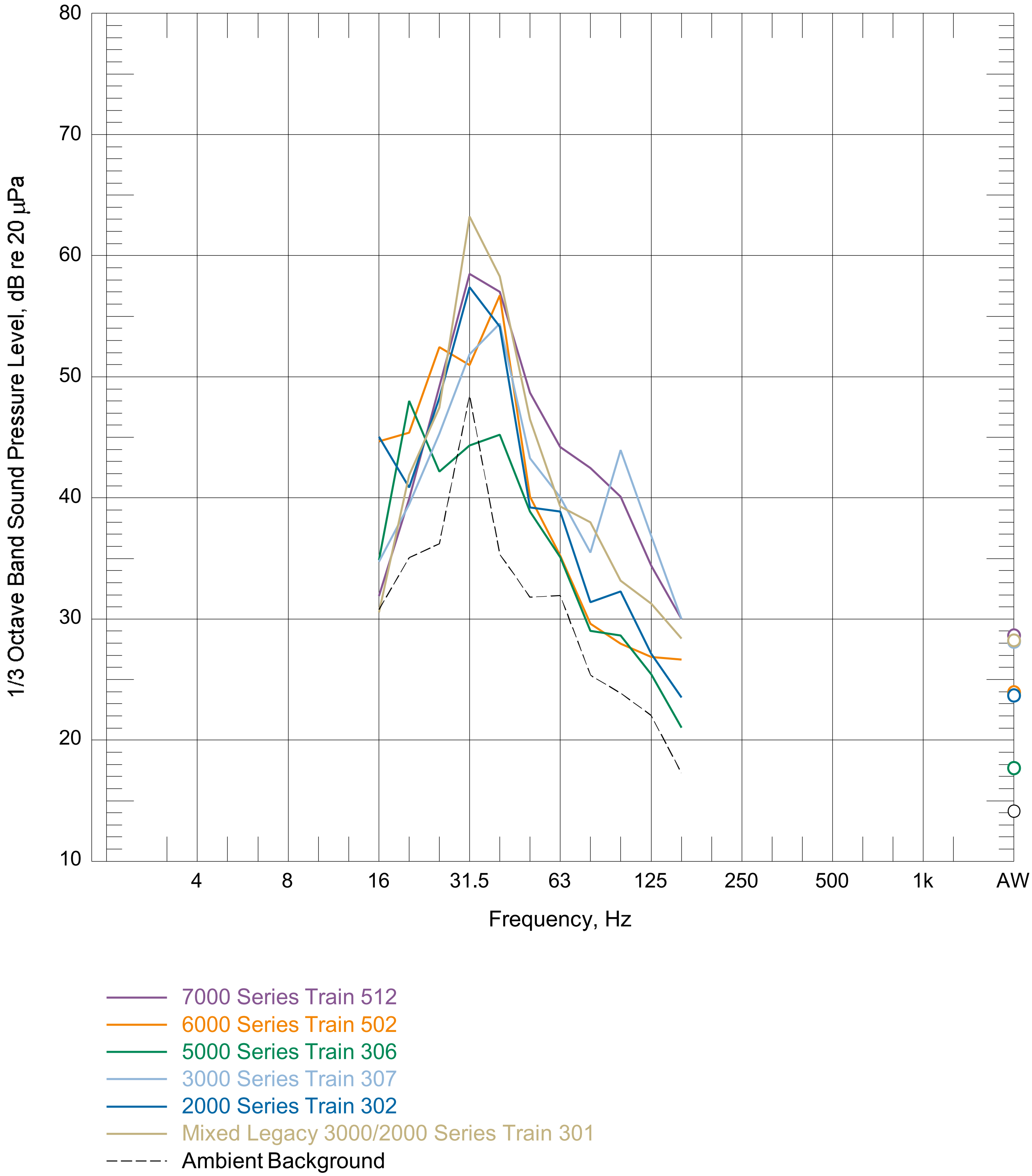


Figure 64: ***Site 2 at Location N1 Basement Family Room***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

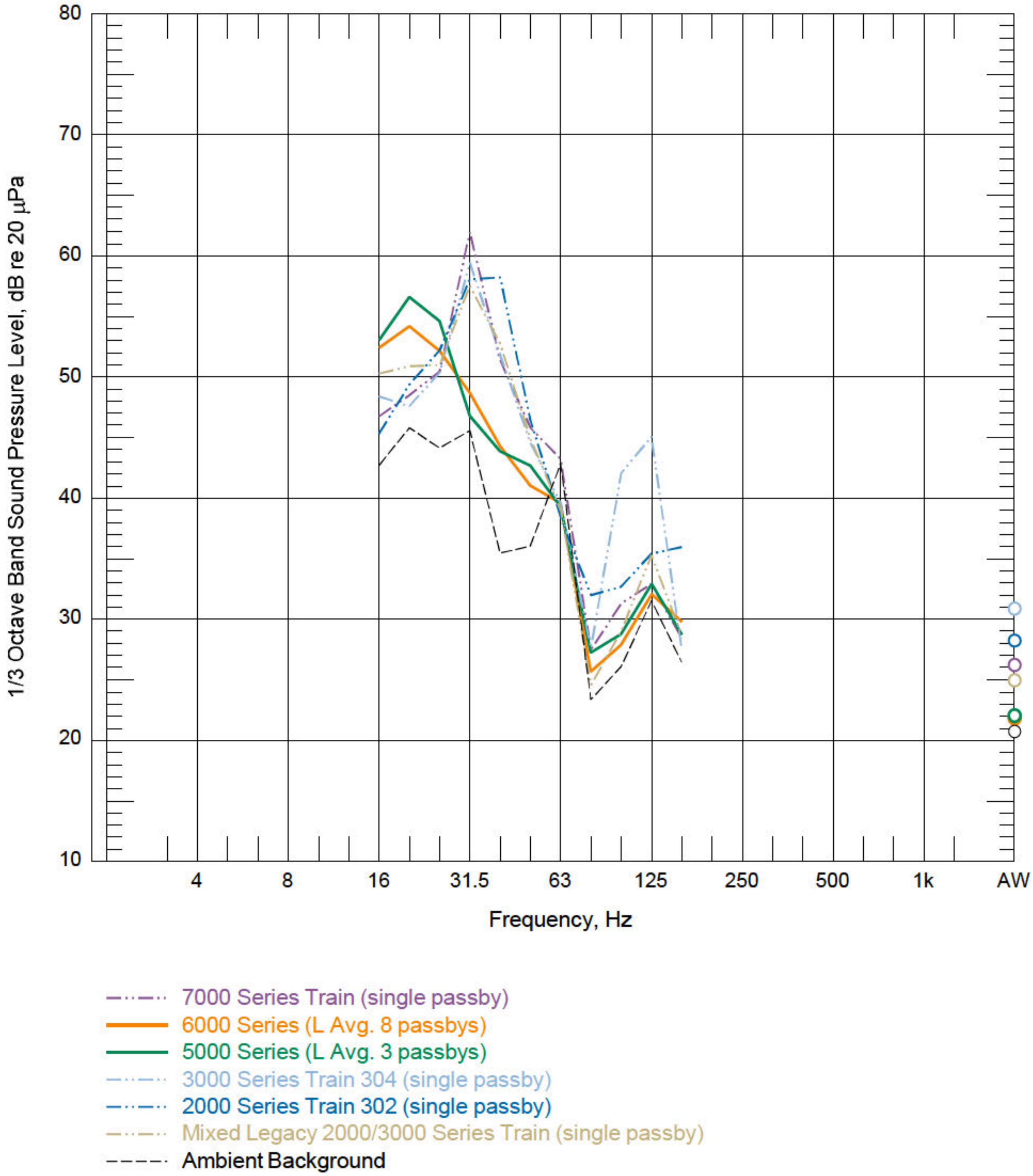


Figure 65: ***Site 2 at Location N2 First Floor Dining Room***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

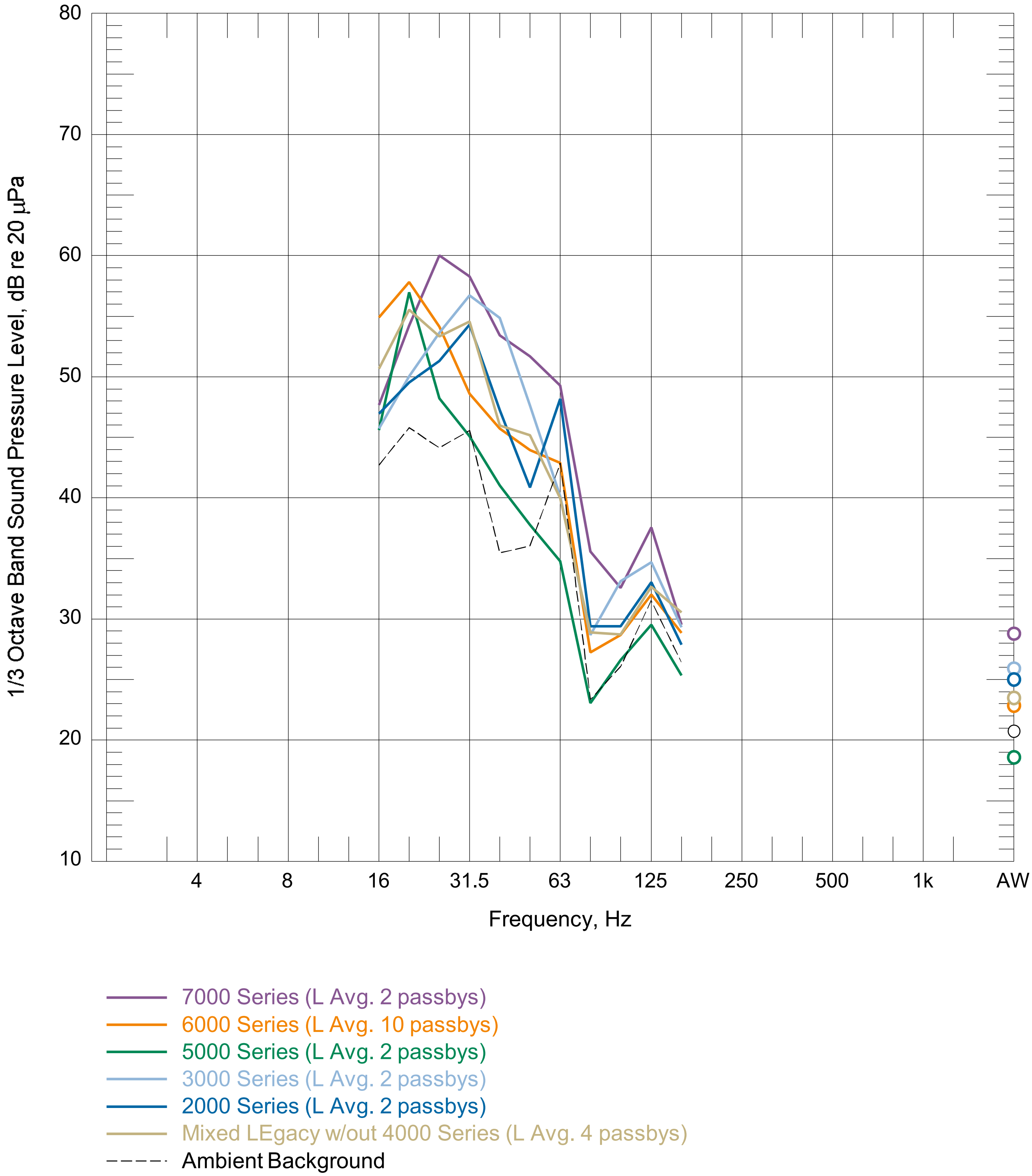


Figure 66: ***Site 2 at Location N2 First Floor Dining Room***
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

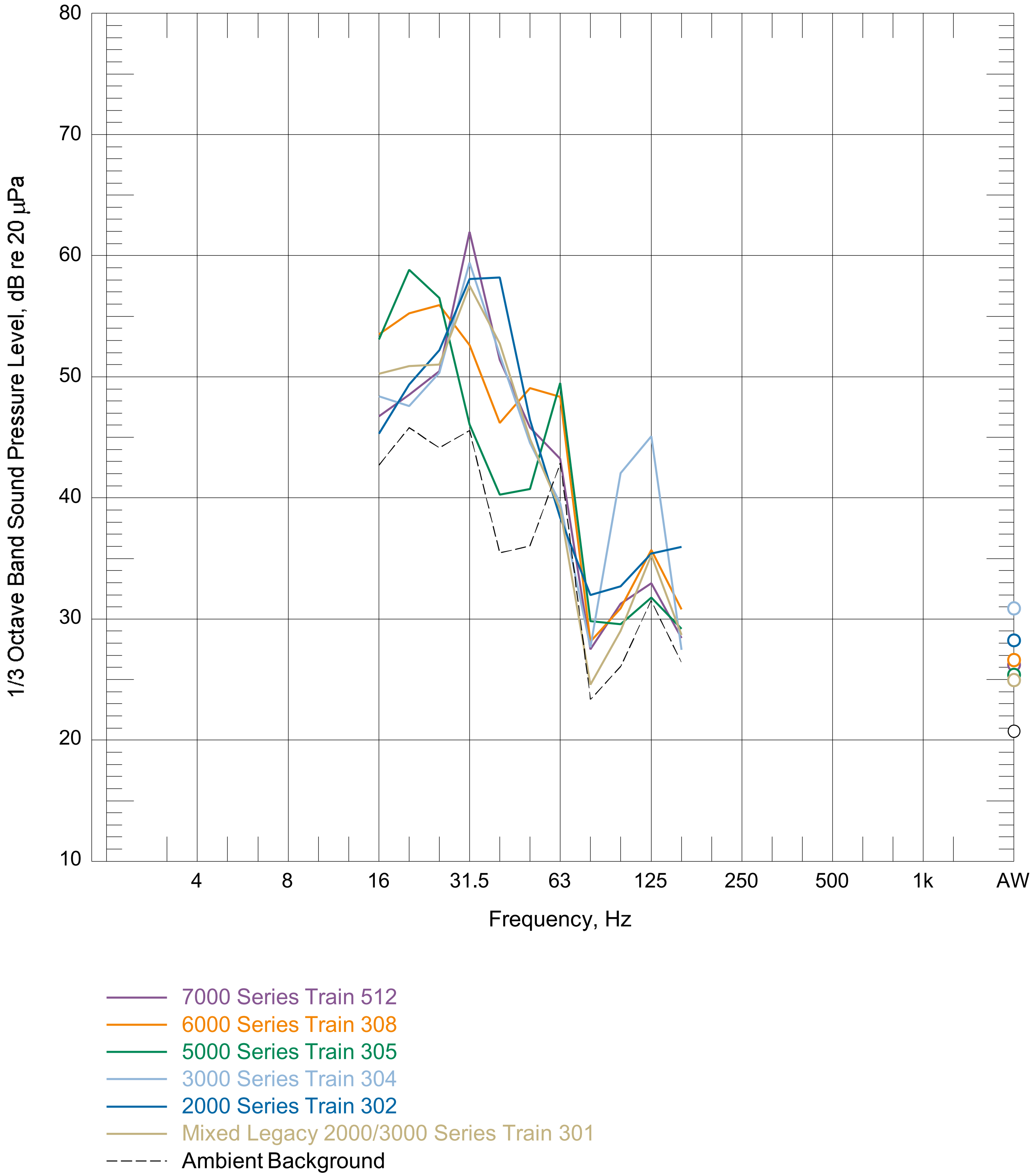


Figure 67: ***Site 2 at Location N2 First Floor Dining Room***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

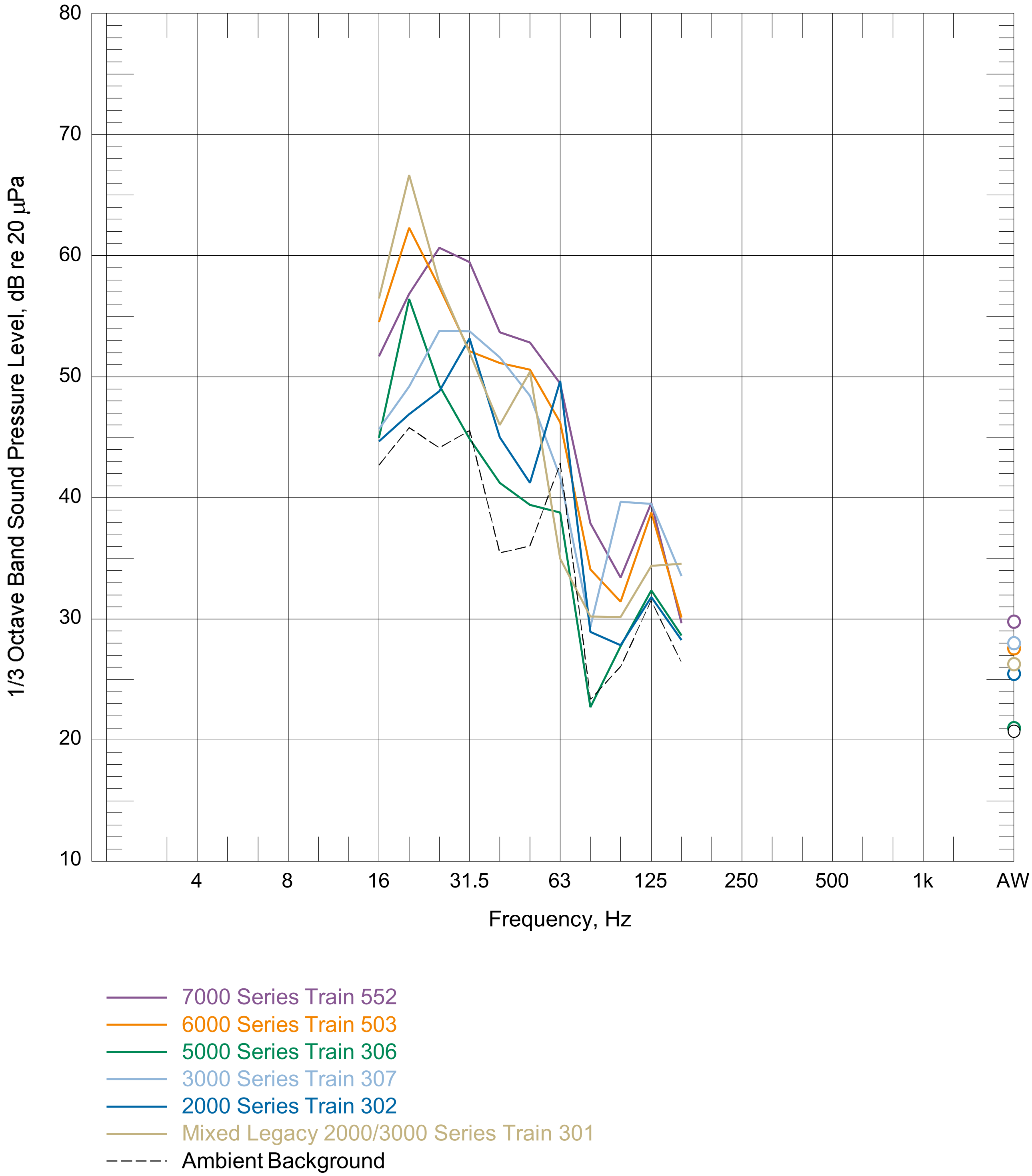


Figure 68: ***Site 2 at Location N2 First Floor Dining Room***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

B.3 Site 3 – 700 block of Princeton Place (Residence)

B.3.1 Building and Tunnel Notes

Location: Outbound track 1 side at 169+00

Building Notes: Single-family residential, attached rowhouse

Tunnel Structure: Cut and Cover

Track Type: Floating Slab Track

T/R Depth: 50 to 52 feet

Train Speed: 14 to 30 mph

Measurement Period: Tuesday, 6 June 2017, 15:50 to 19:15

B.3.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Sensor[a,b,c]	Location / Room Occupancy	Horizontal Distance[d] (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)	Horizontal Distance (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)
V1	Basement Laundry Room						
N1							
Triaxial Geo.	Basement Family Room						
V2		326	52	330	289	51	293
V3							
N2	1st Floor Living Room						
V4	1st Floor Dining Room						
V5	Outside House	330	52	334	293	51	297
V6	Back Alley	297	51	301	259	50	264
V7	Back Alley	268	52	273	230	51	236

Notes:

a) Triaxial geophone mounted on floor, logging peak particle velocity
b) V# vibration locations with accelerometer mounted on floor in vertical direction
c) N# noise locations with microphone/sound level meter mounted on tripod 48 inches feet above floor
d) Horizontal distance from track to building façade for indoor locations, not accounting for tunnel depth.
e) T/R depth = top-of-rail depth
f) Total slant distance to T/R = total distance from building to track, accounting for tunnel depth

Figure 69: Aerial Map of 700 block of Princeton Place NW Residence and Exterior Measurement Location

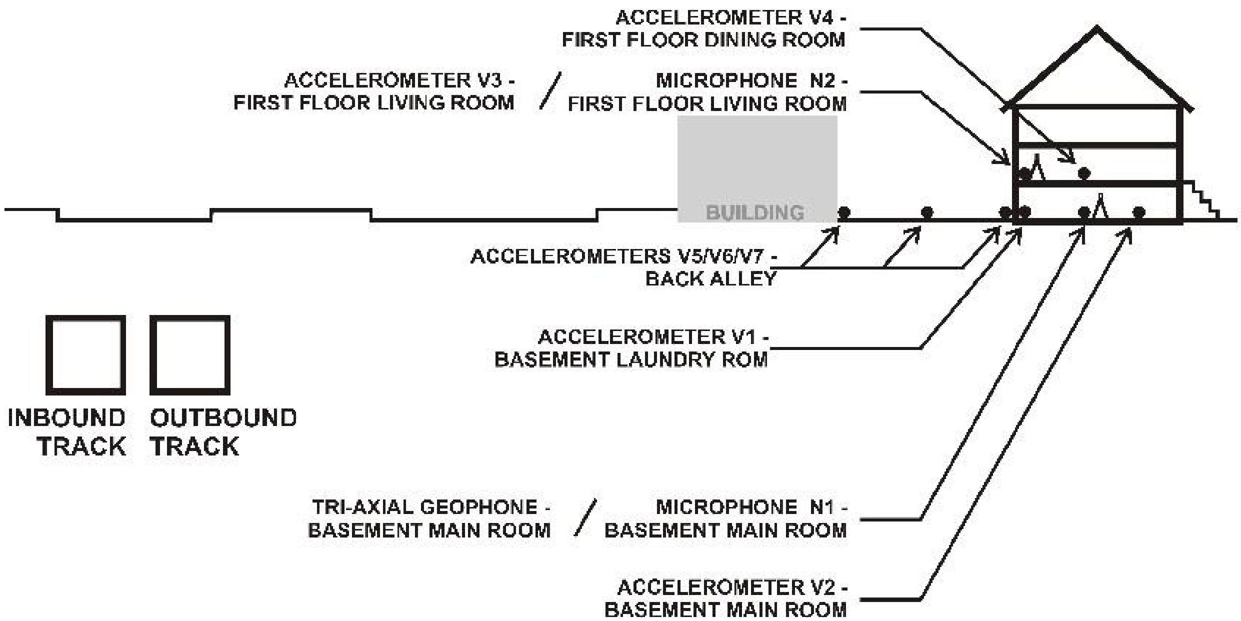


Figure 70: Cross-section Sketch (not to scale) of 700 block of Princeton Place Indoor and Exterior Measurement Locations

B.3.3 GBNV Assessment Summary

SITE 3	700 block of PRINCETON PLACE – ATTENDED PASSBY MEASUREMENT GBNV ASSESSMENT
	Train vibration detectable in 63Hz band but overall vibration levels dominated by non-train ambient sources. Train ground-borne noise not audible

B.3.4 PPV Results

SITE 3	700 block of PRINCETON PLACE – POTENTIAL FOR BUILDING VIBRATION DAMAGE ASSESSMENT						
	>0.2 in/sec PPV in any direction?	Average PPV (in/s)			PPV Range (in/s)		
		Tran	Vert	Long	Tran	Vert	Long
	NO	0.0012	0.0005	0.0004	0.0003 - 0.0016	0 - 0.0071	0 - 0.00155
Basement 6-Jun-17, 4:44:59 PM to 6:54:55 PM							

B.3.5 Statistical Vibration Spectra

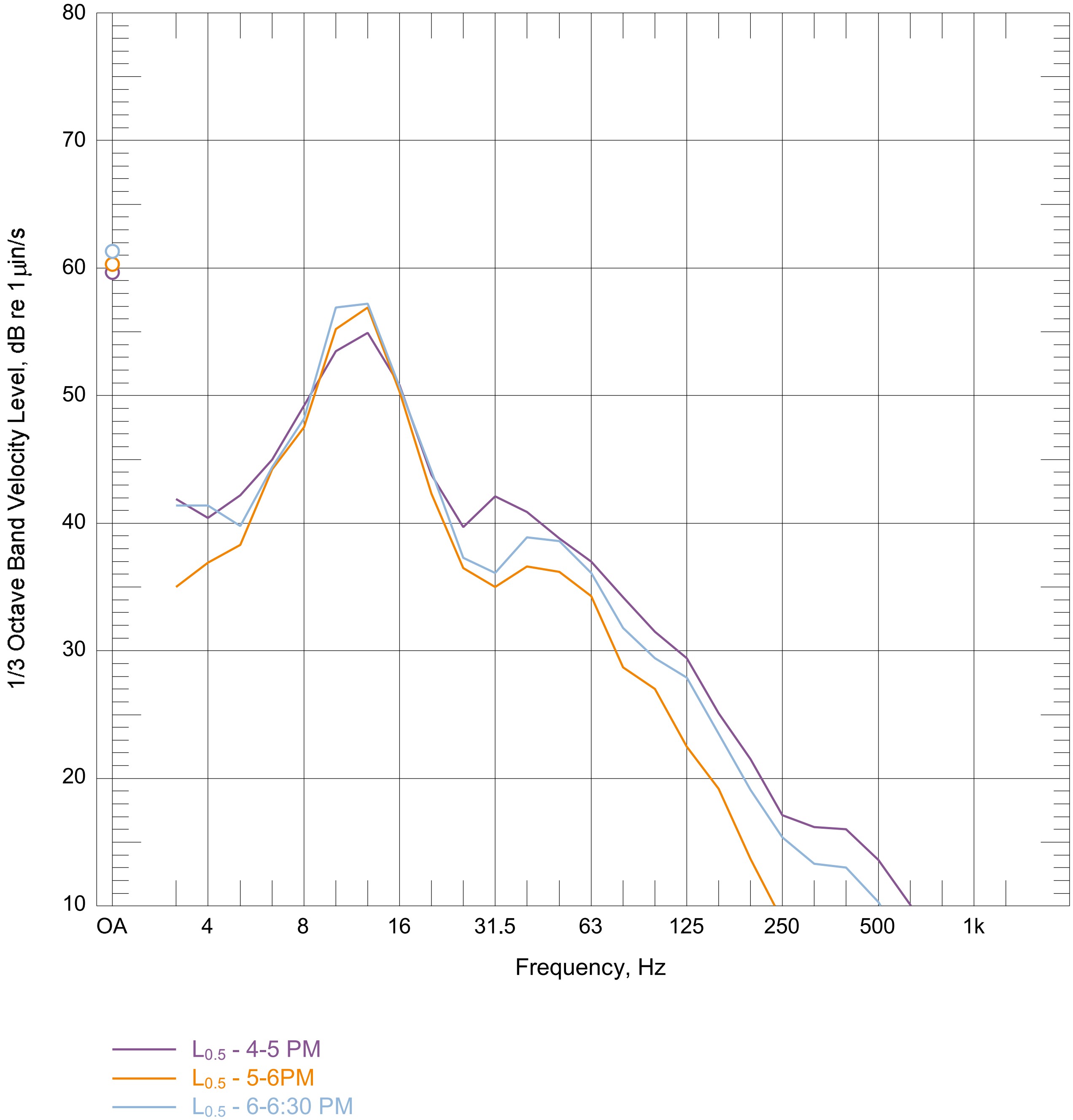


Figure 71: Site 3 at Location V1 Basement Laundry Room Hourly Percentile Vibration Levels

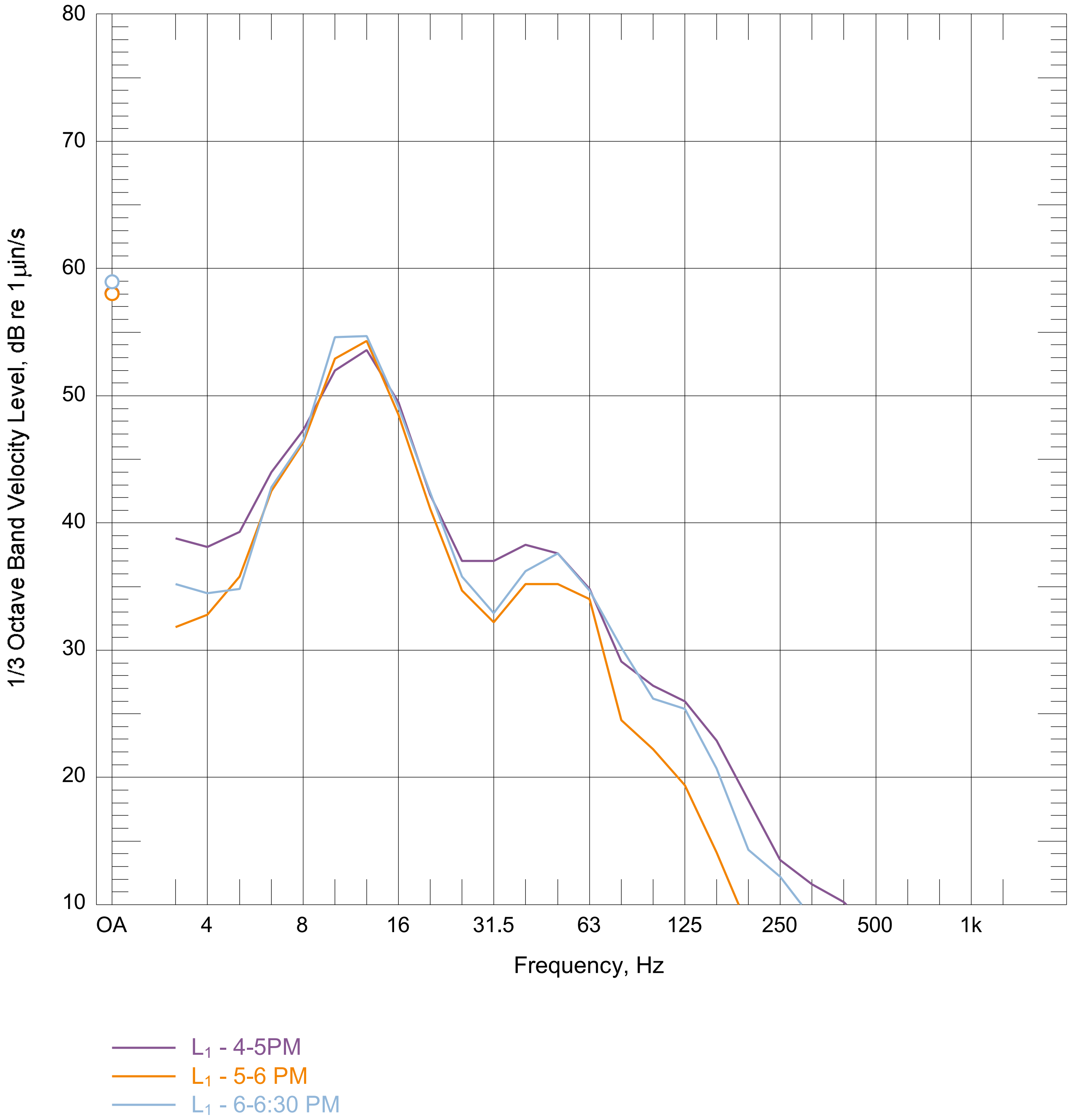


Figure 72: ***Site 3 at Location V1 Basement Laundry Room Hourly Percentile Vibration Levels***

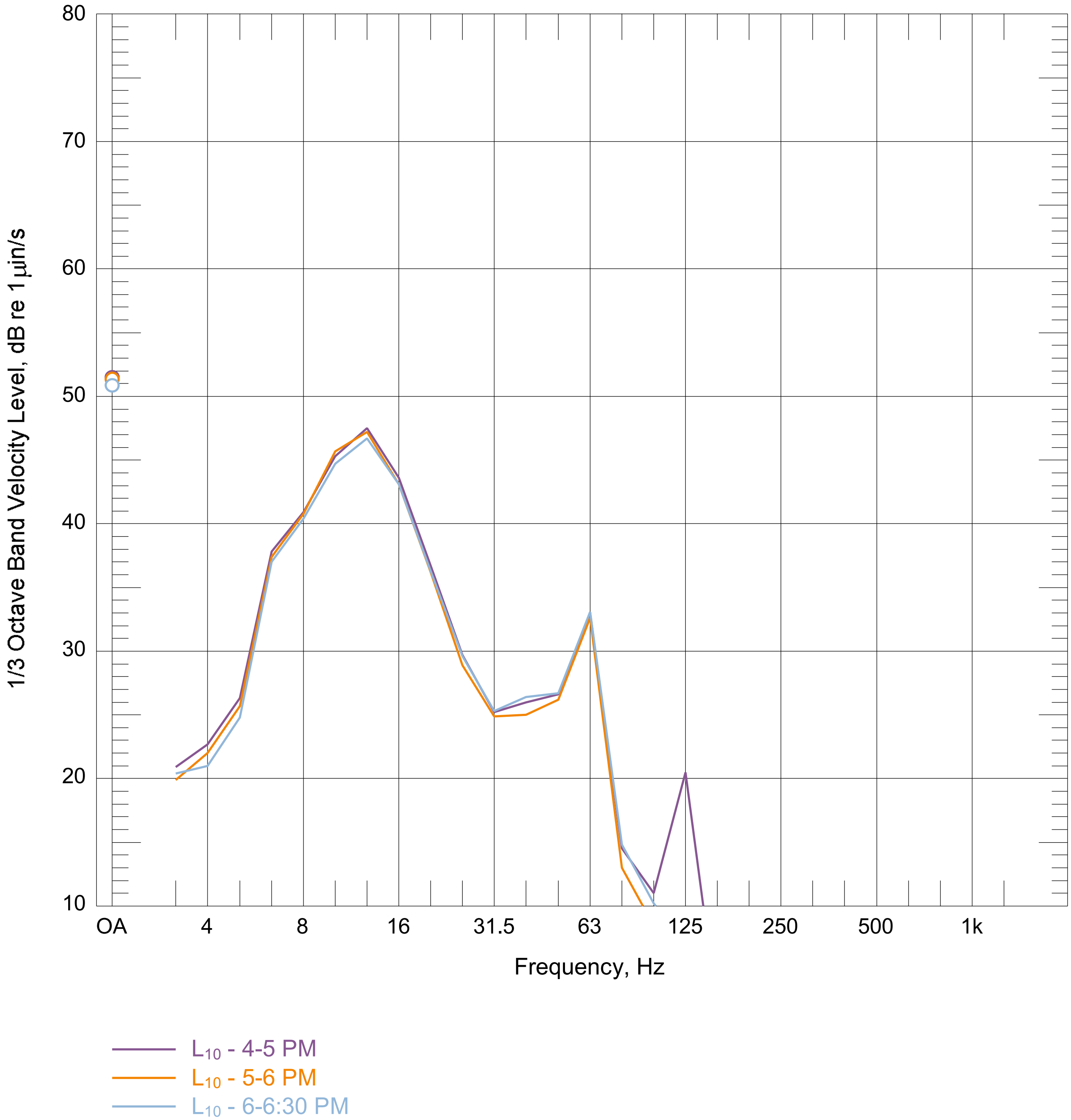


Figure 73: ***Site 3 at Location V1 Basement Laundry Room Hourly Percentile Vibration Levels***

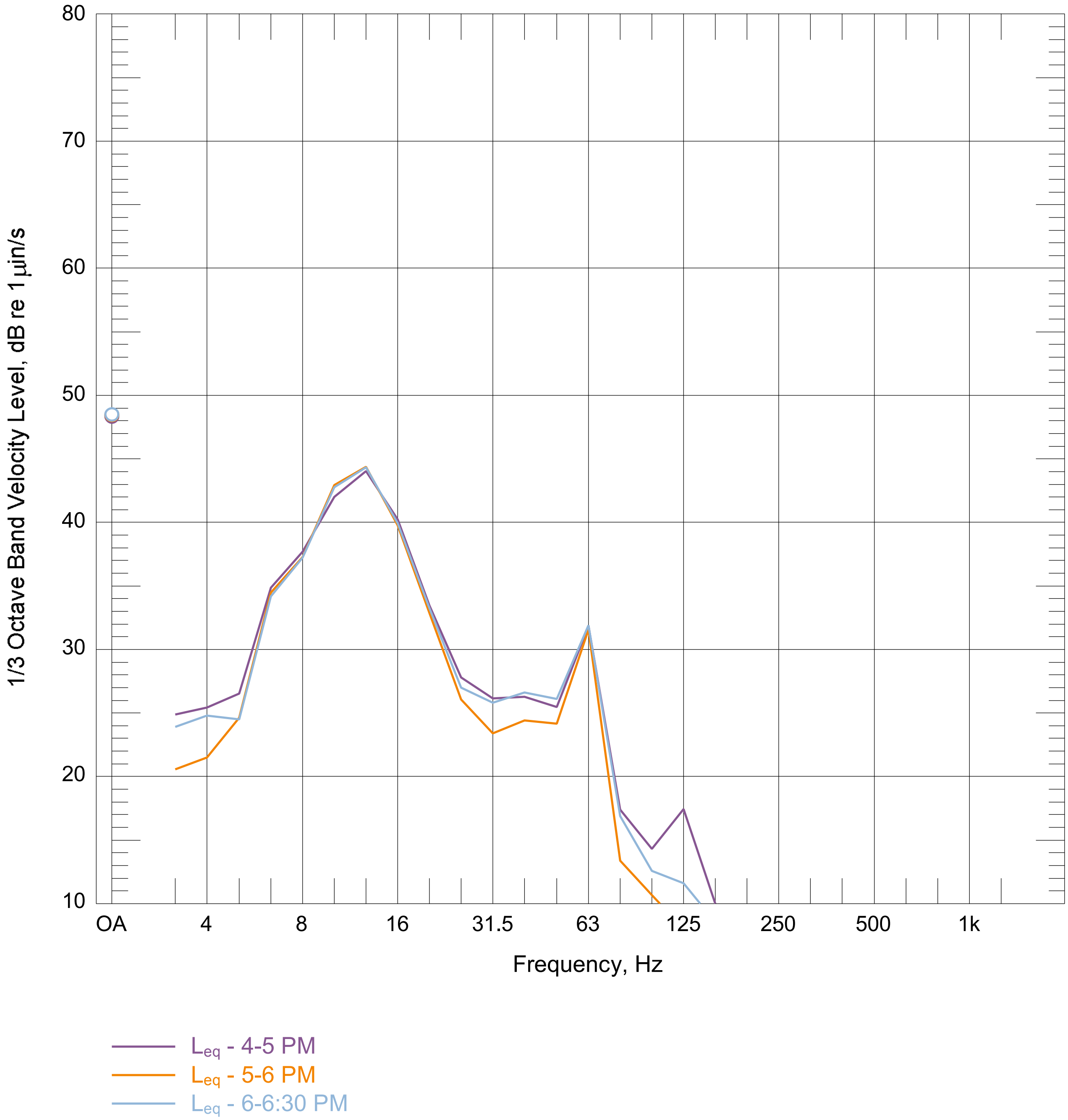


Figure 74: ***Site 3 at Location V1 Basement Laundry Room Hourly Percentile Vibration Levels***

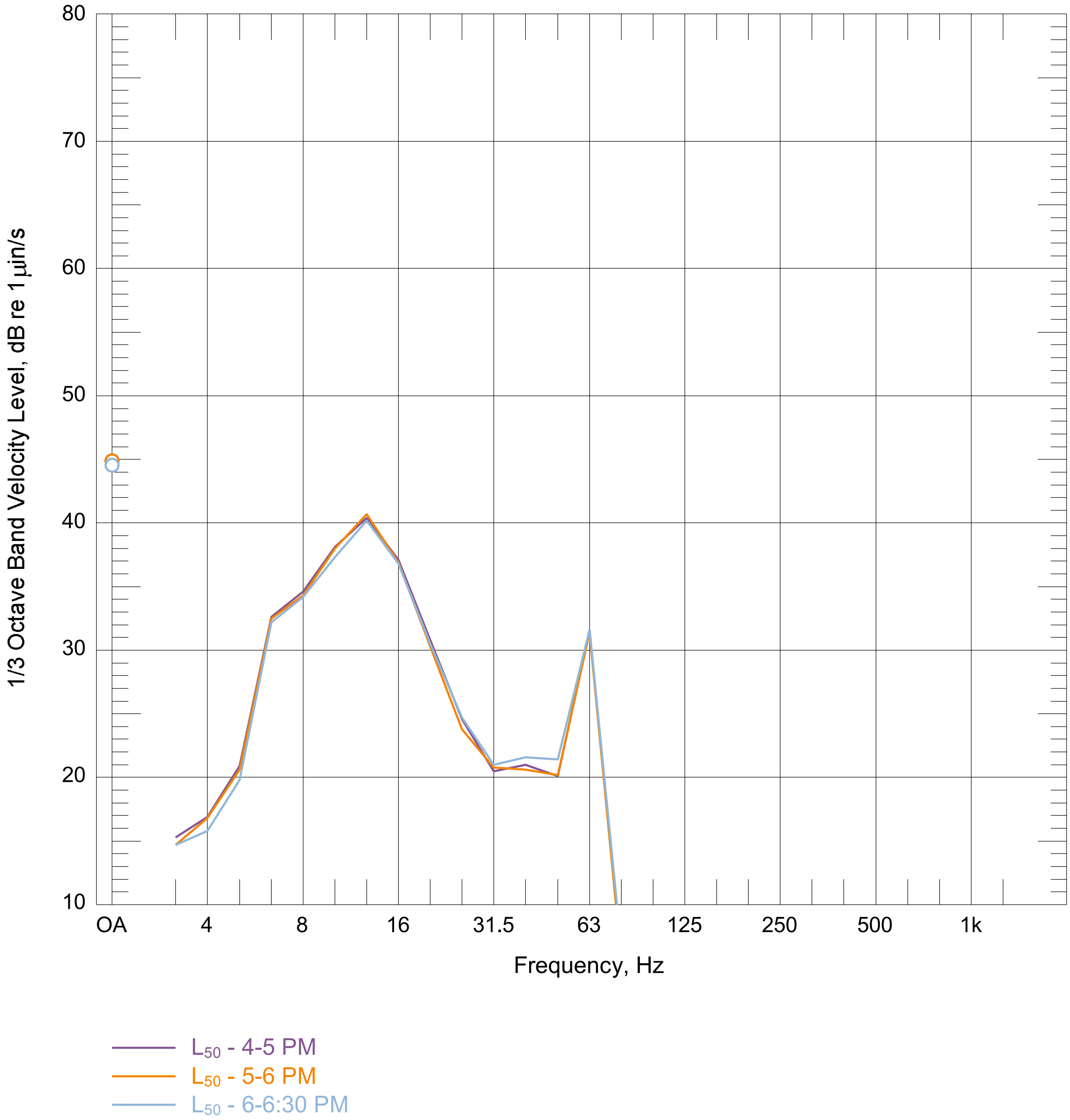


Figure 75: Site 3 at Location V1 Basement Laundry Room Hourly Percentile Vibration Levels

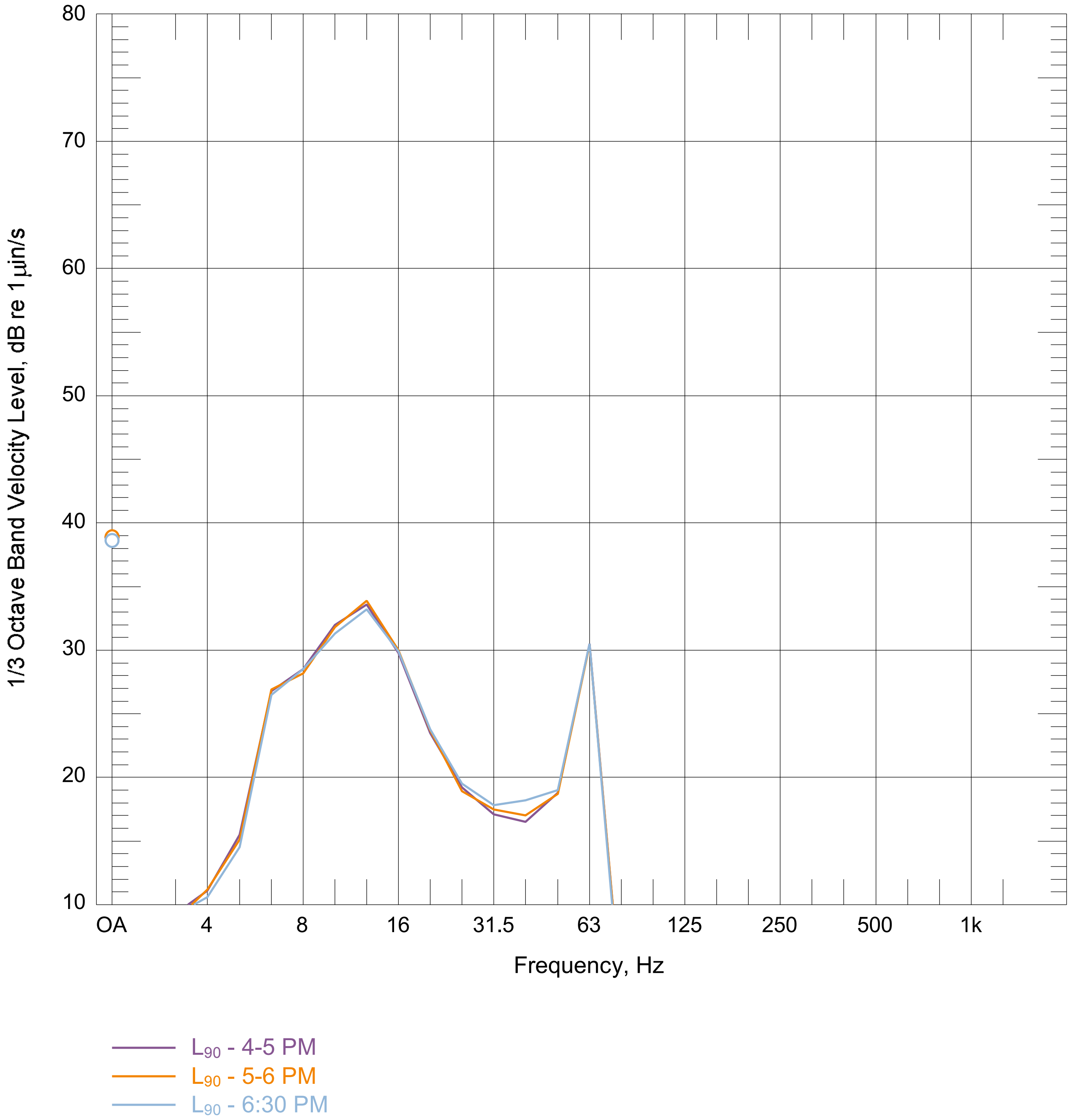


Figure 76: ***Site 3 at Location V1 Basement Laundry Room Hourly Percentile Vibration Levels***

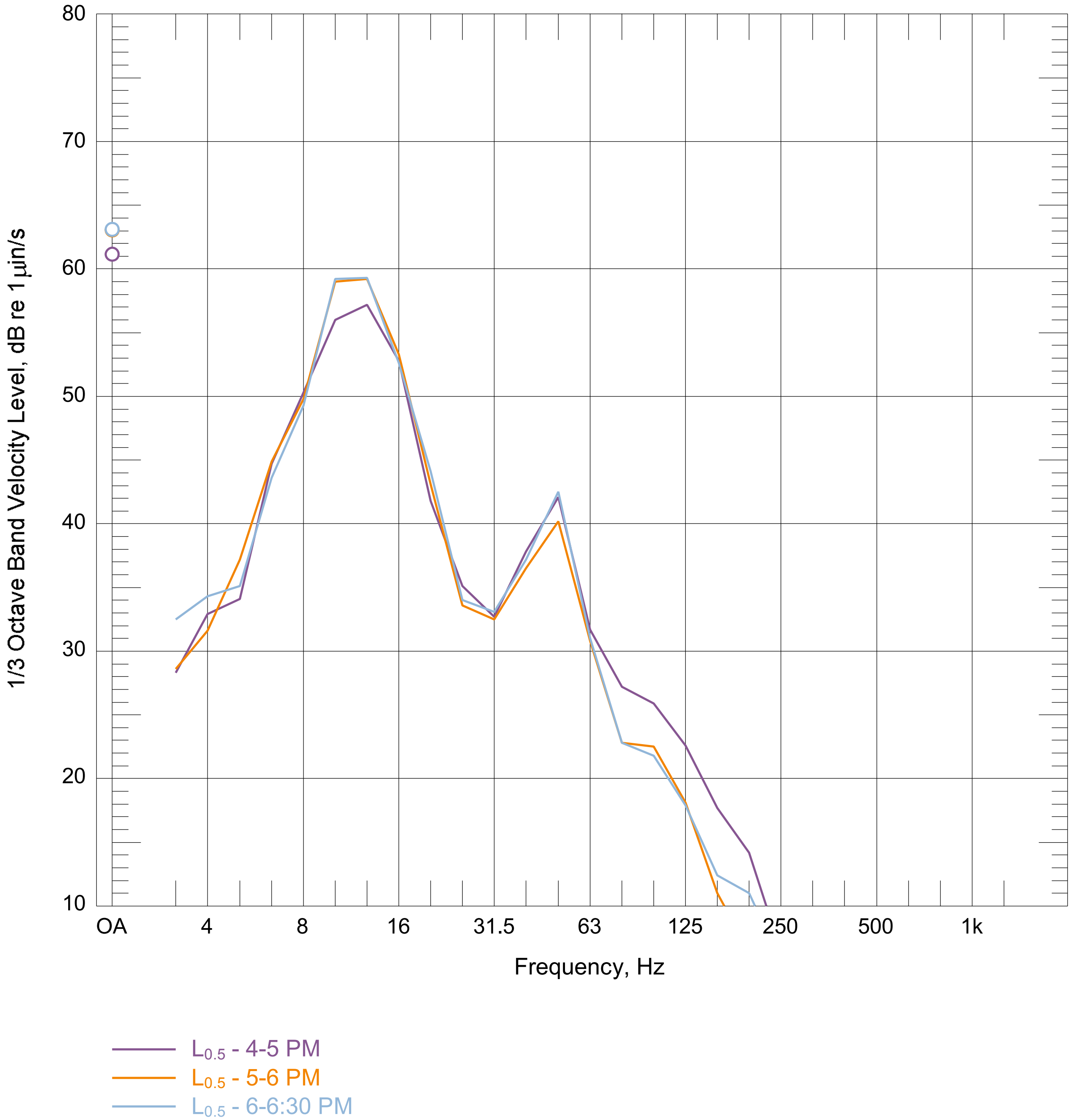


Figure 77: ***Site 3 at Location V2 Basement Family Room Hourly Percentile Vibration Levels***

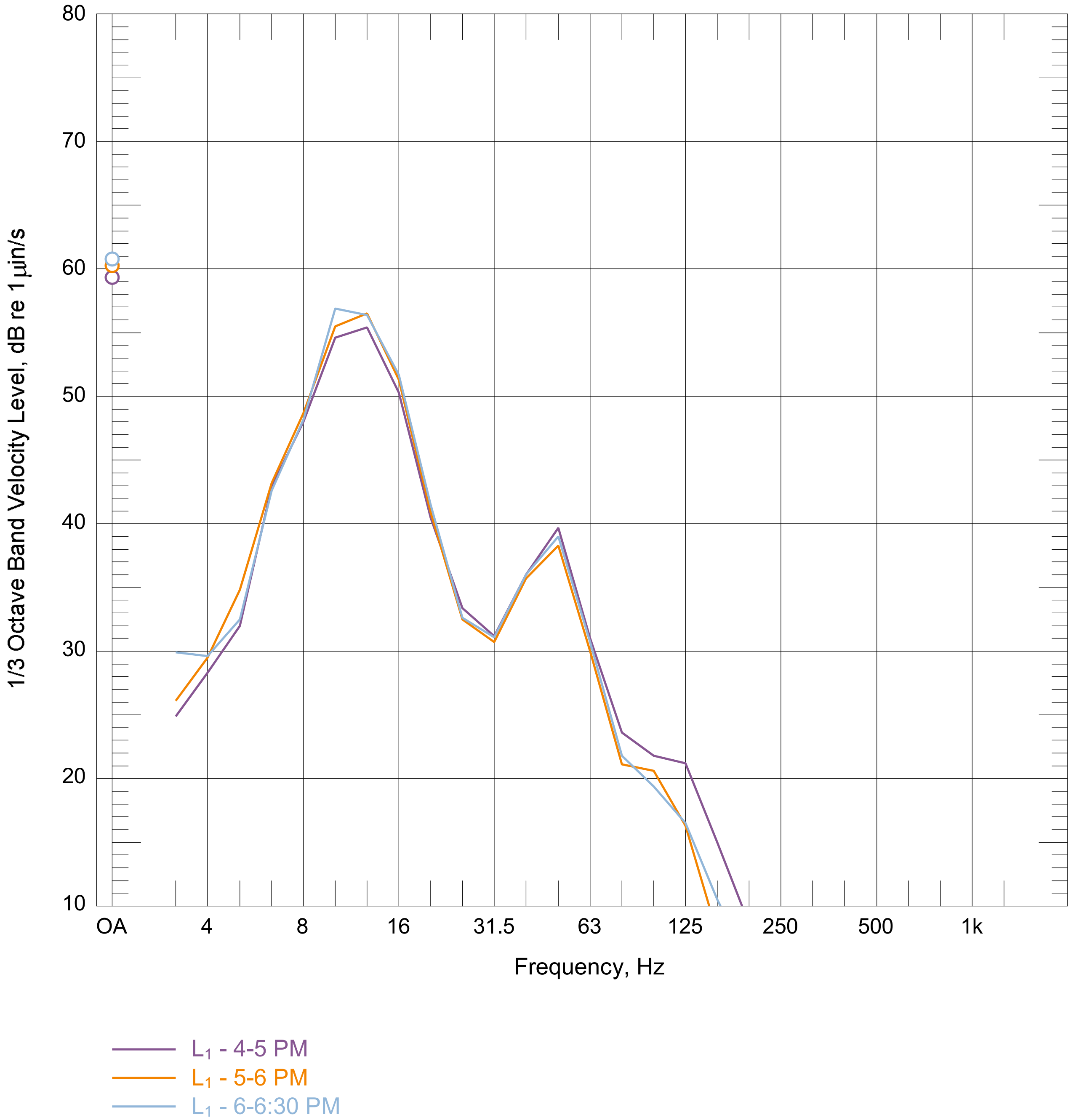


Figure 78: ***Site 3 at Location V2 Basement Family Room Hourly Percentile Vibration Levels***

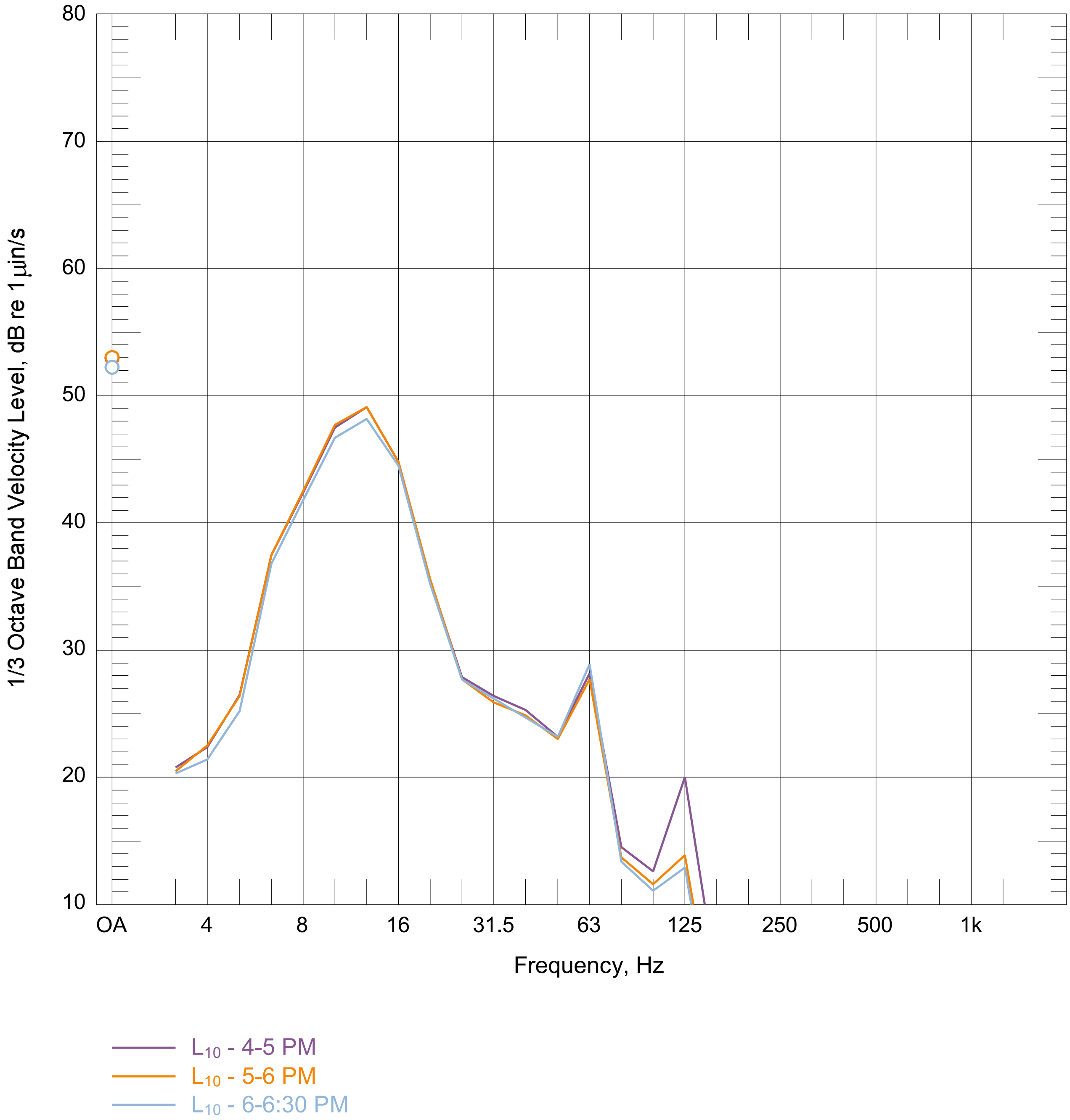


Figure 79: ***Site 3 at Location V2 Basement Family Room Hourly Percentile Vibration Levels***

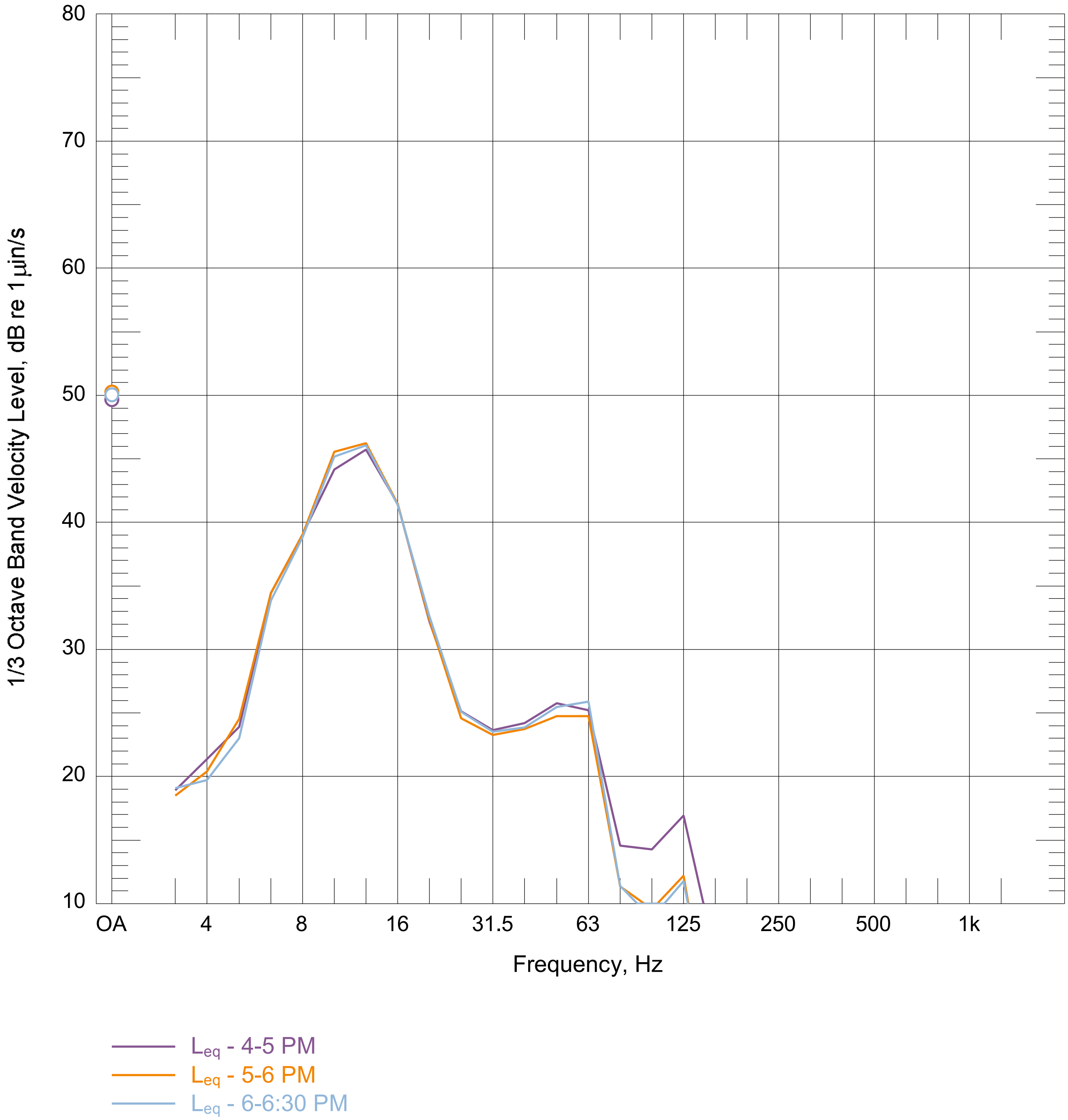


Figure 80: ***Site 3 at Location V2 Basement Family Room Hourly Percentile Vibration Levels***

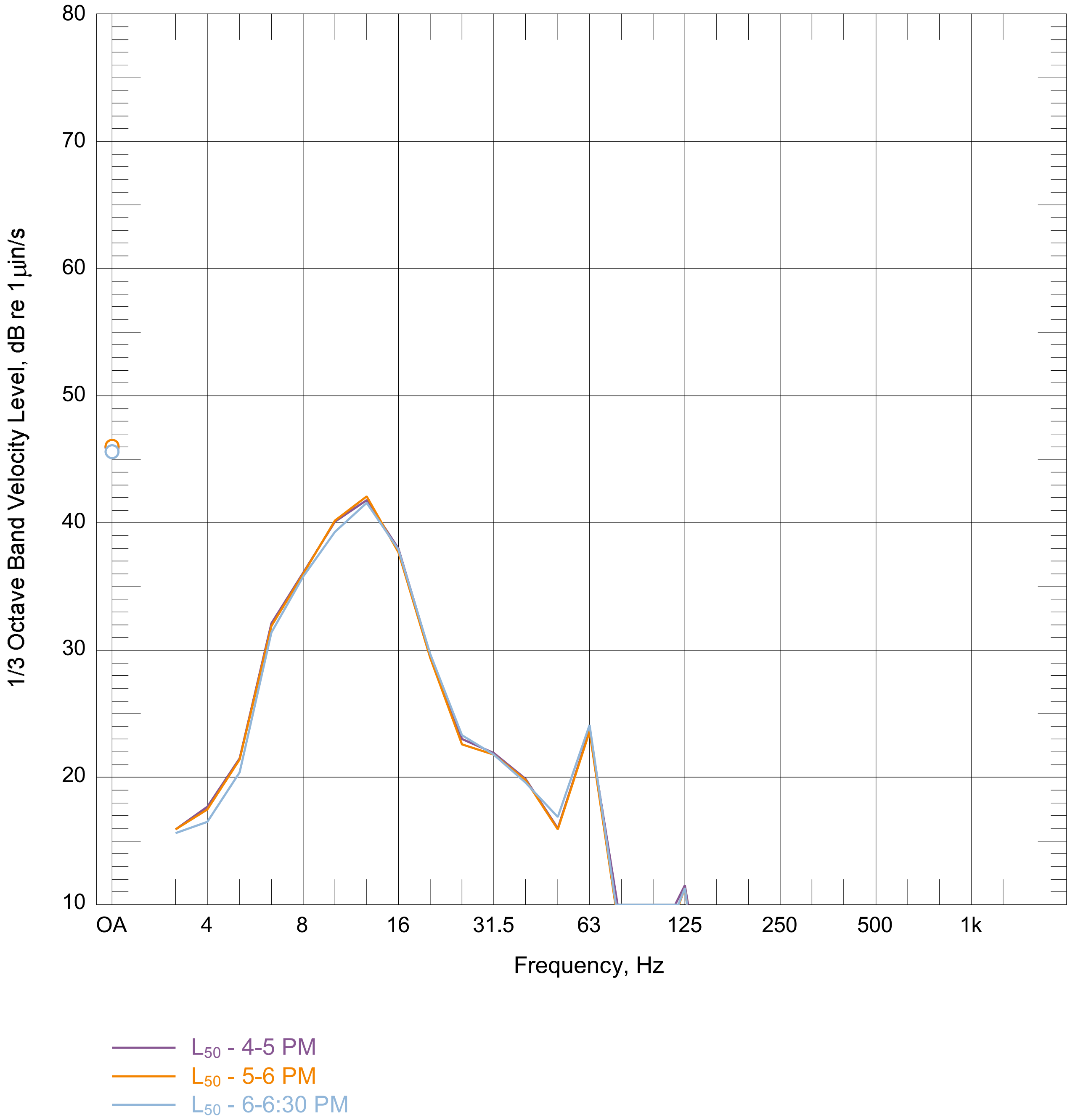


Figure 81: ***Site 3 at Location V2 Basement Family Room Hourly Percentile Vibration Levels***

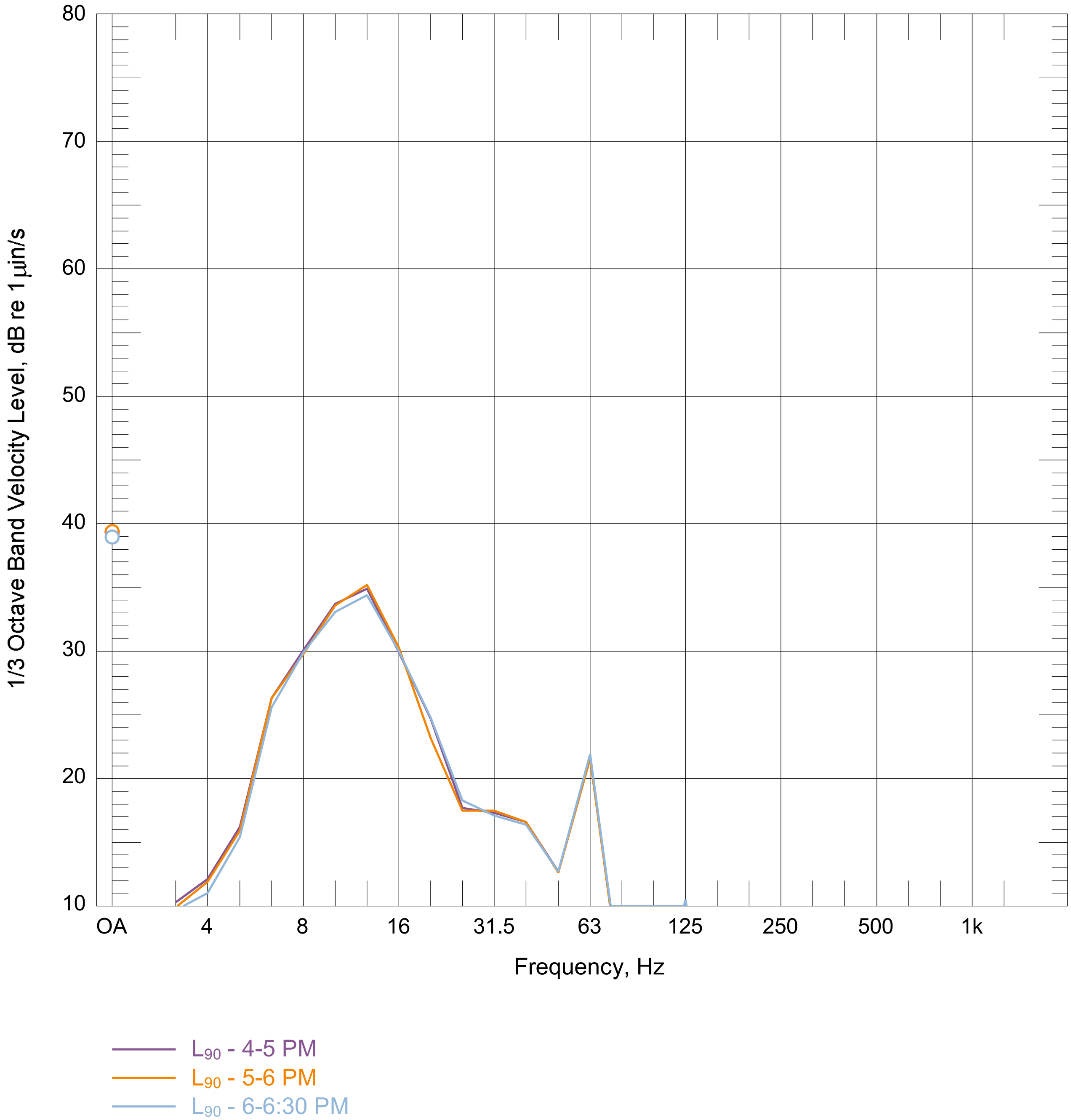


Figure 82: ***Site 3 at Location V2 Basement Family Room Hourly Percentile Vibration Levels***

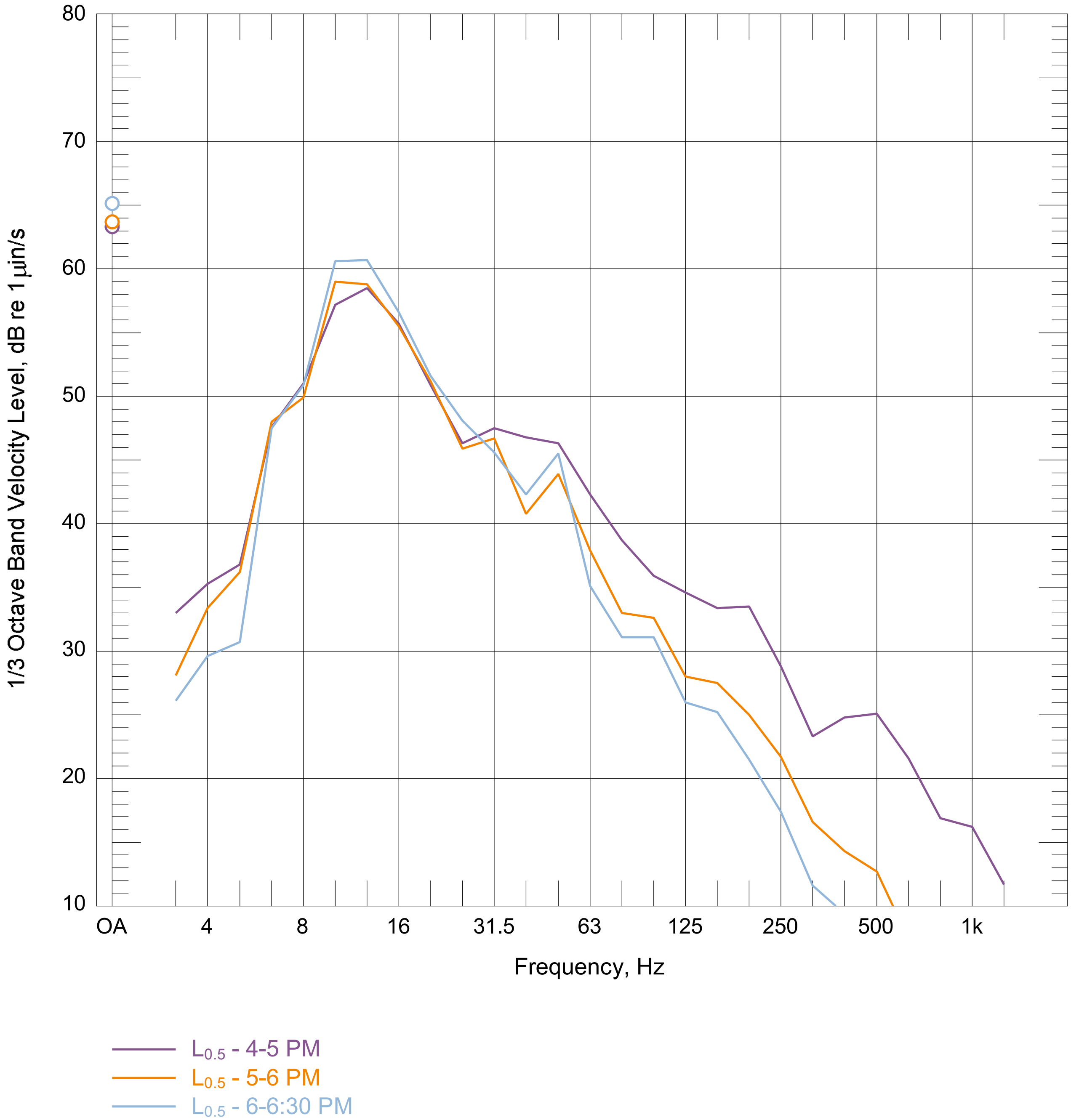


Figure 83: ***Site 3 at Location V3 First Floor Living Room Hourly Percentile Vibration Levels***

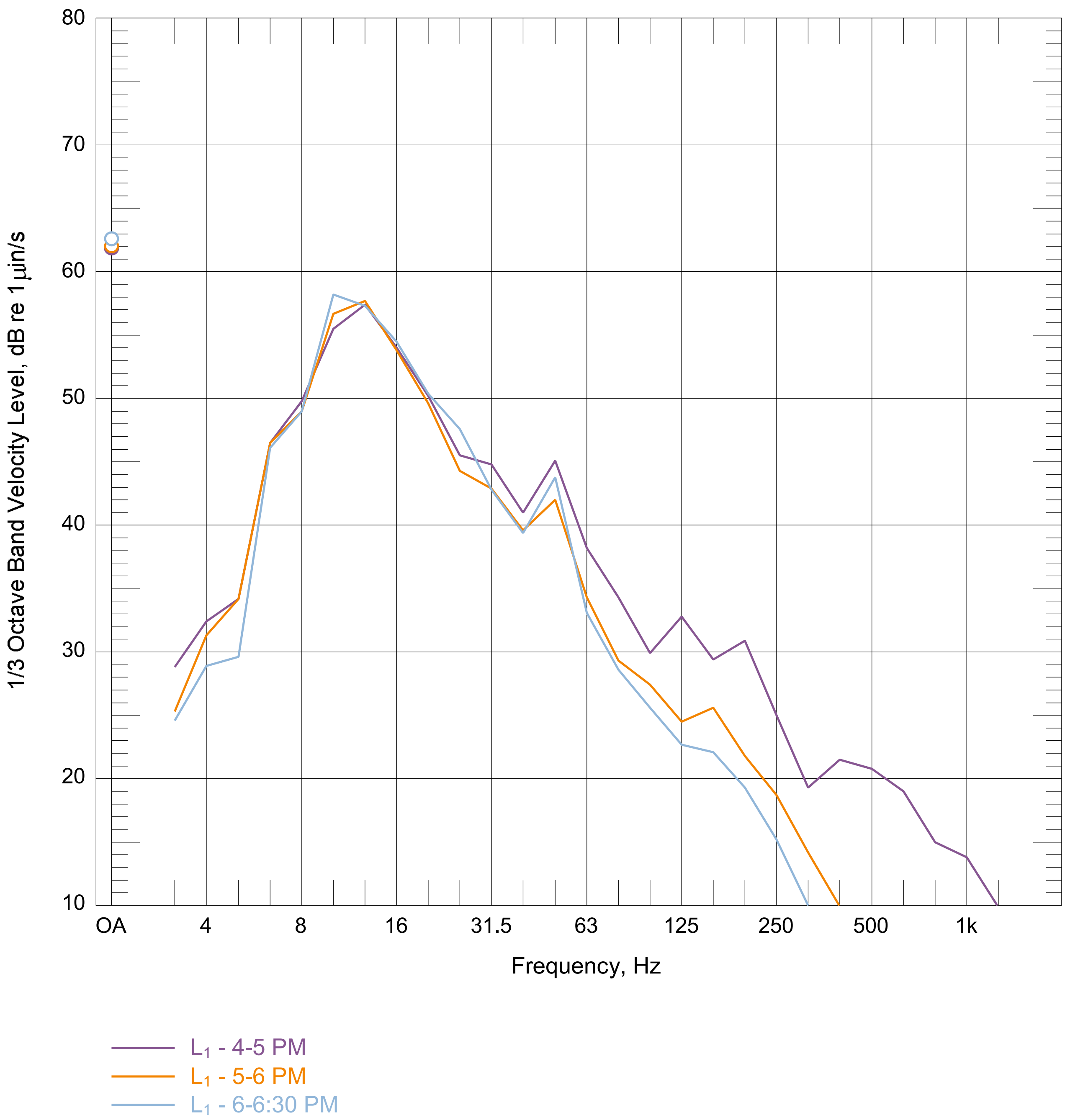


Figure 84: ***Site 3 at Location V3 First Floor Living Room Hourly Percentile Vibration Levels***

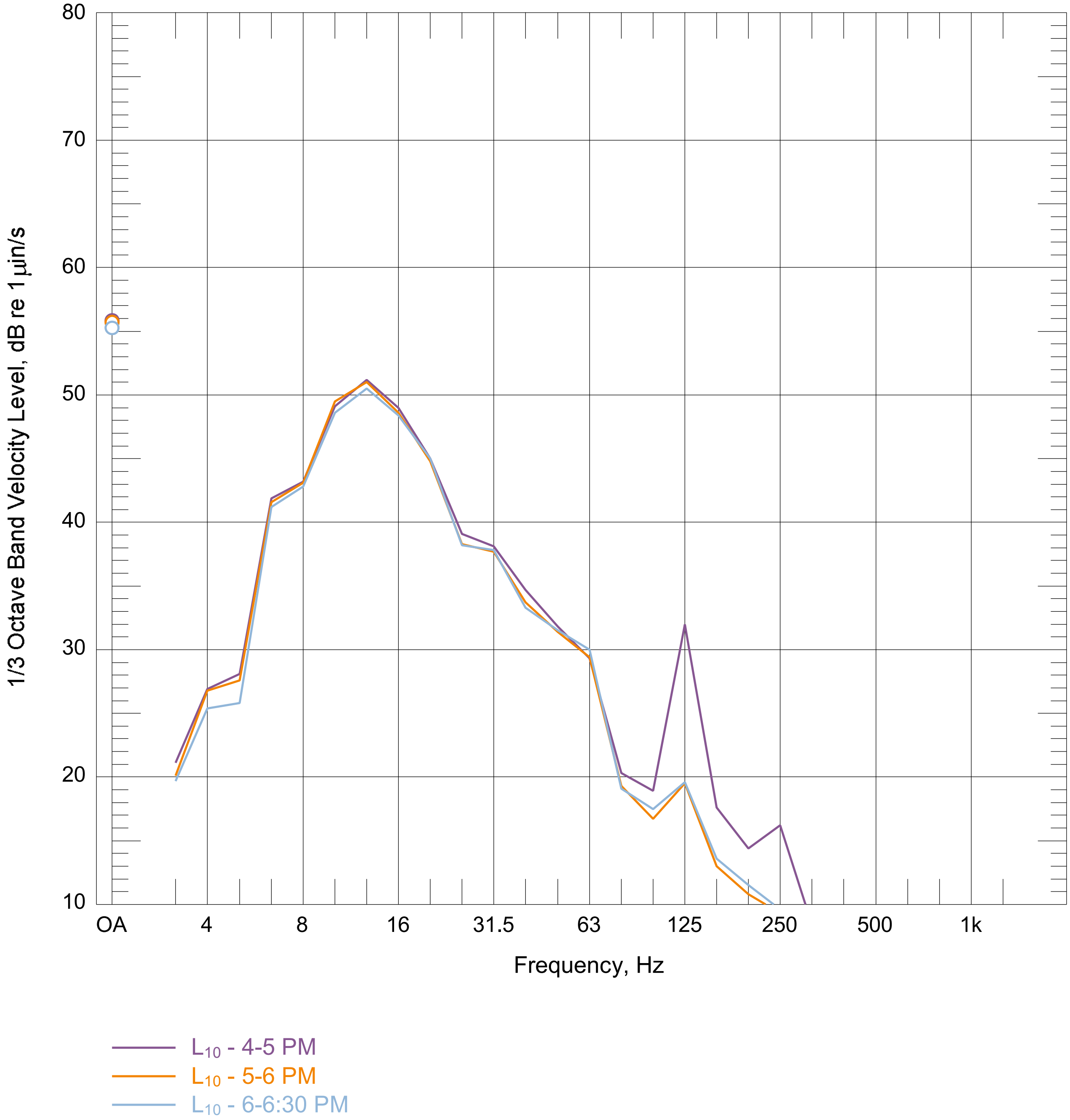


Figure 85: ***Site 3 at Location V3 First Floor Living Room Hourly Percentile Vibration Levels***

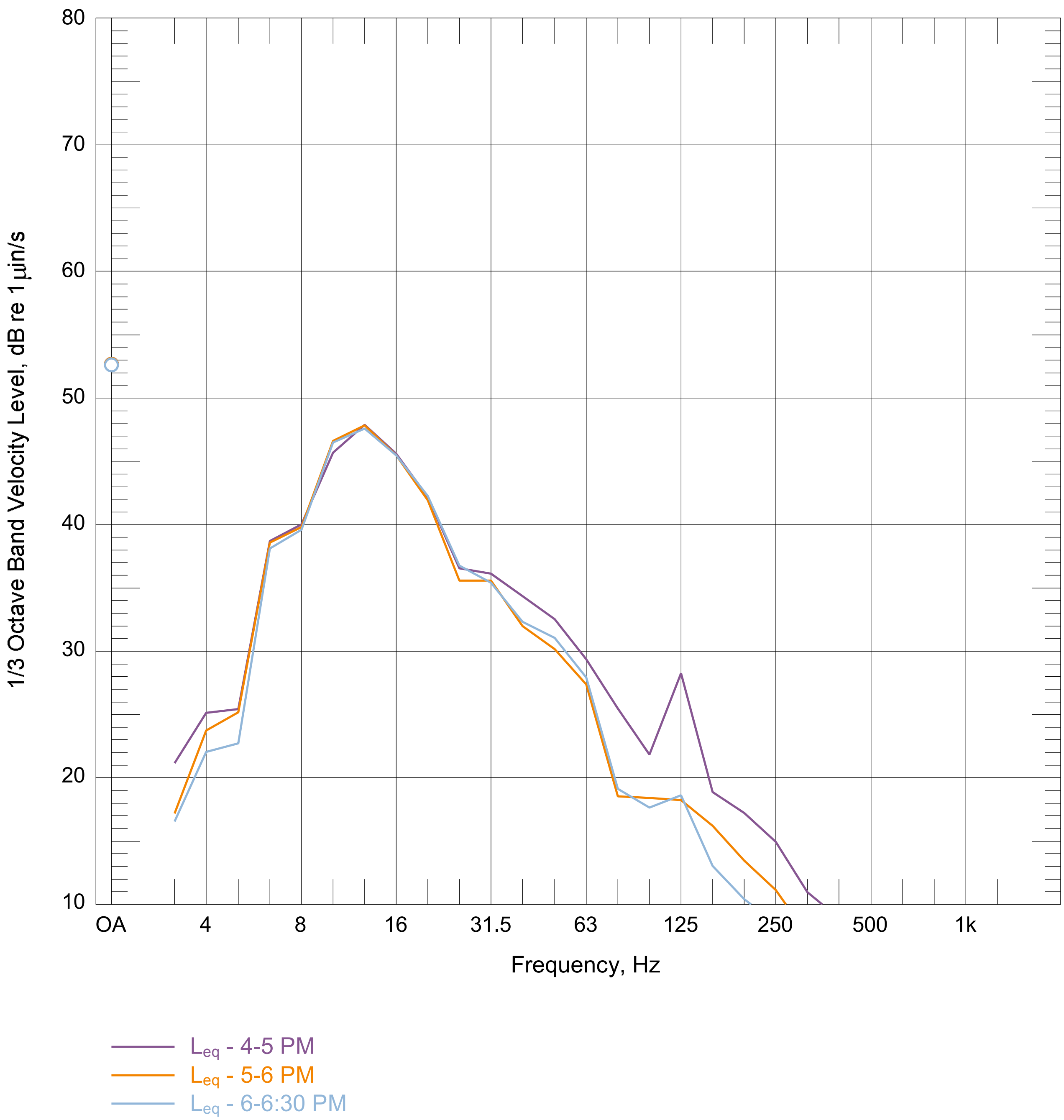


Figure 86: ***Site 3 at Location V3 First Floor Living Room Hourly Percentile Vibration Levels***

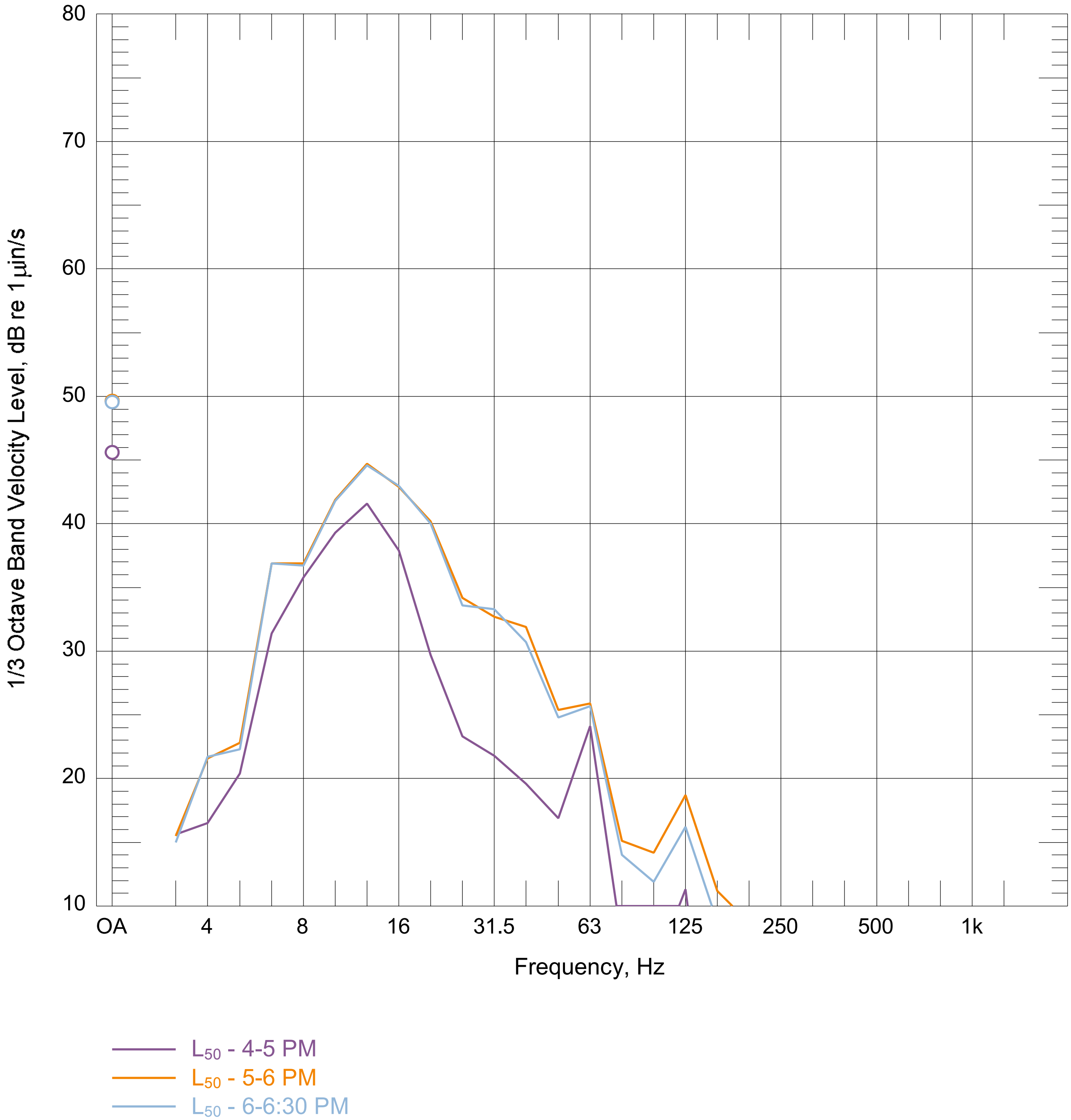


Figure 87: ***Site 3 at Location V3 First Floor Living Room Hourly Percentile Vibration Levels***

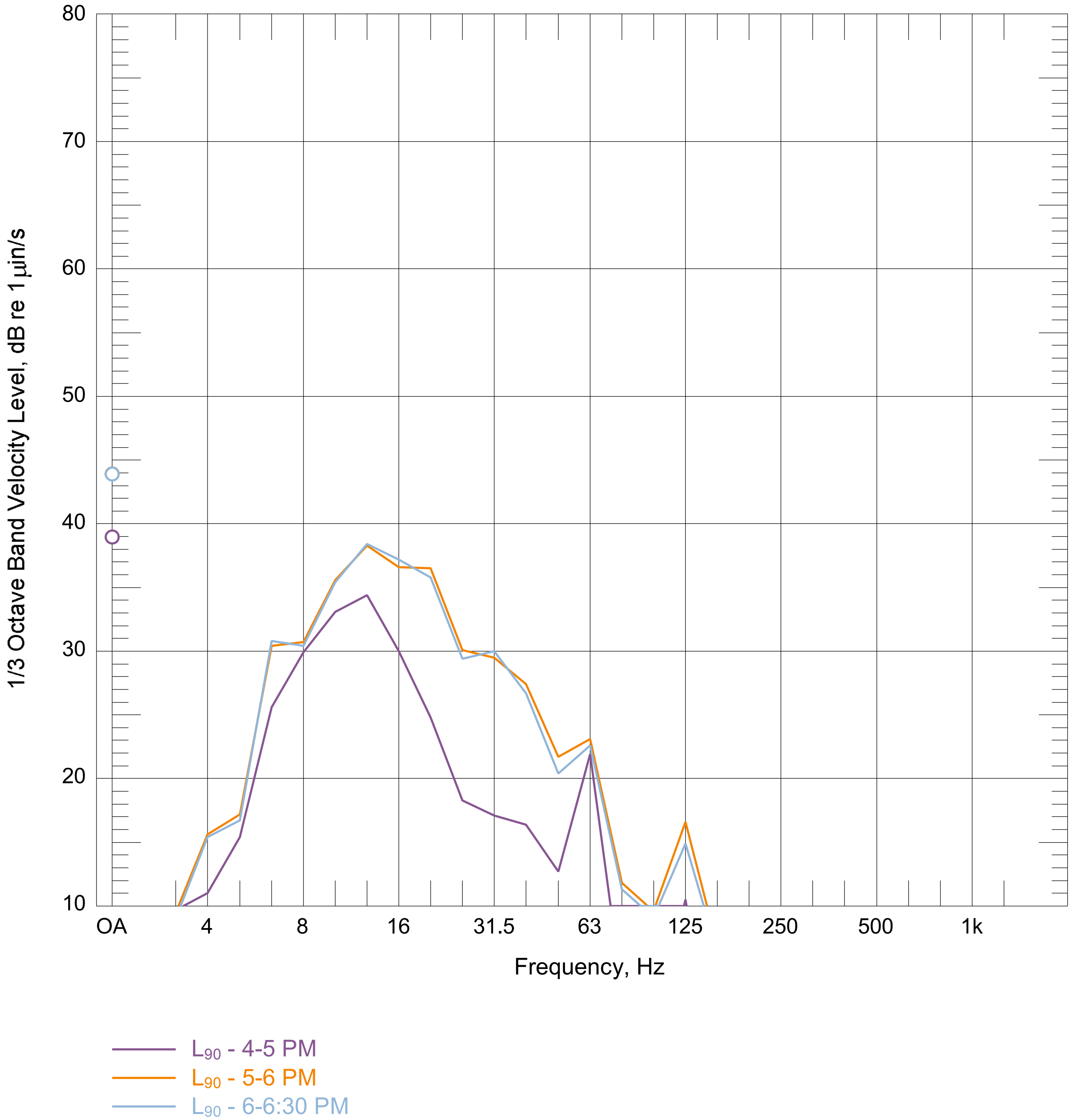


Figure 88: ***Site 3 at Location V3 First Floor Living Room Hourly Percentile Vibration Levels***

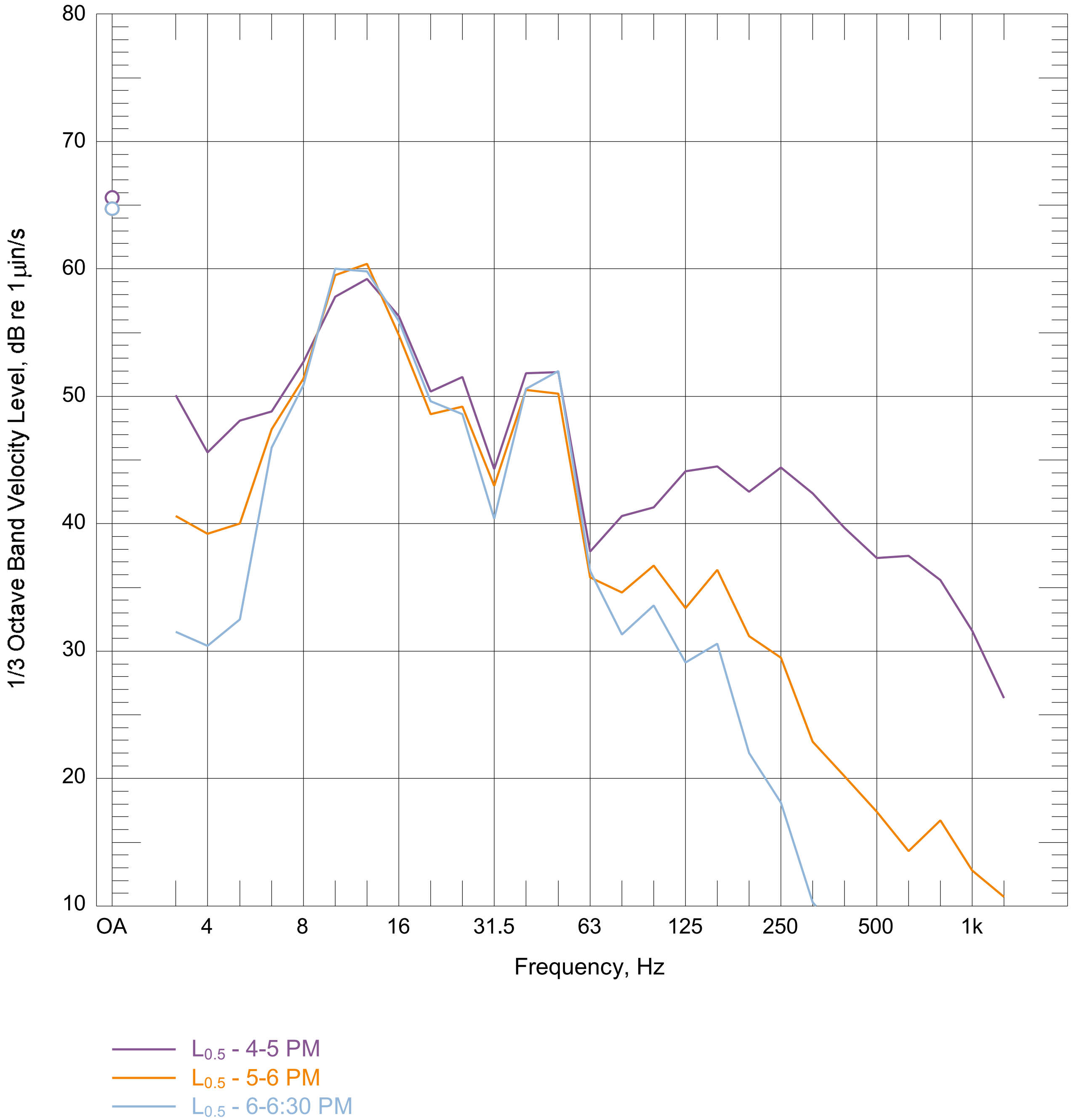


Figure 89: ***Site 3 at Location V4 First Floor Dining Room Hourly Percentile Vibration Levels***

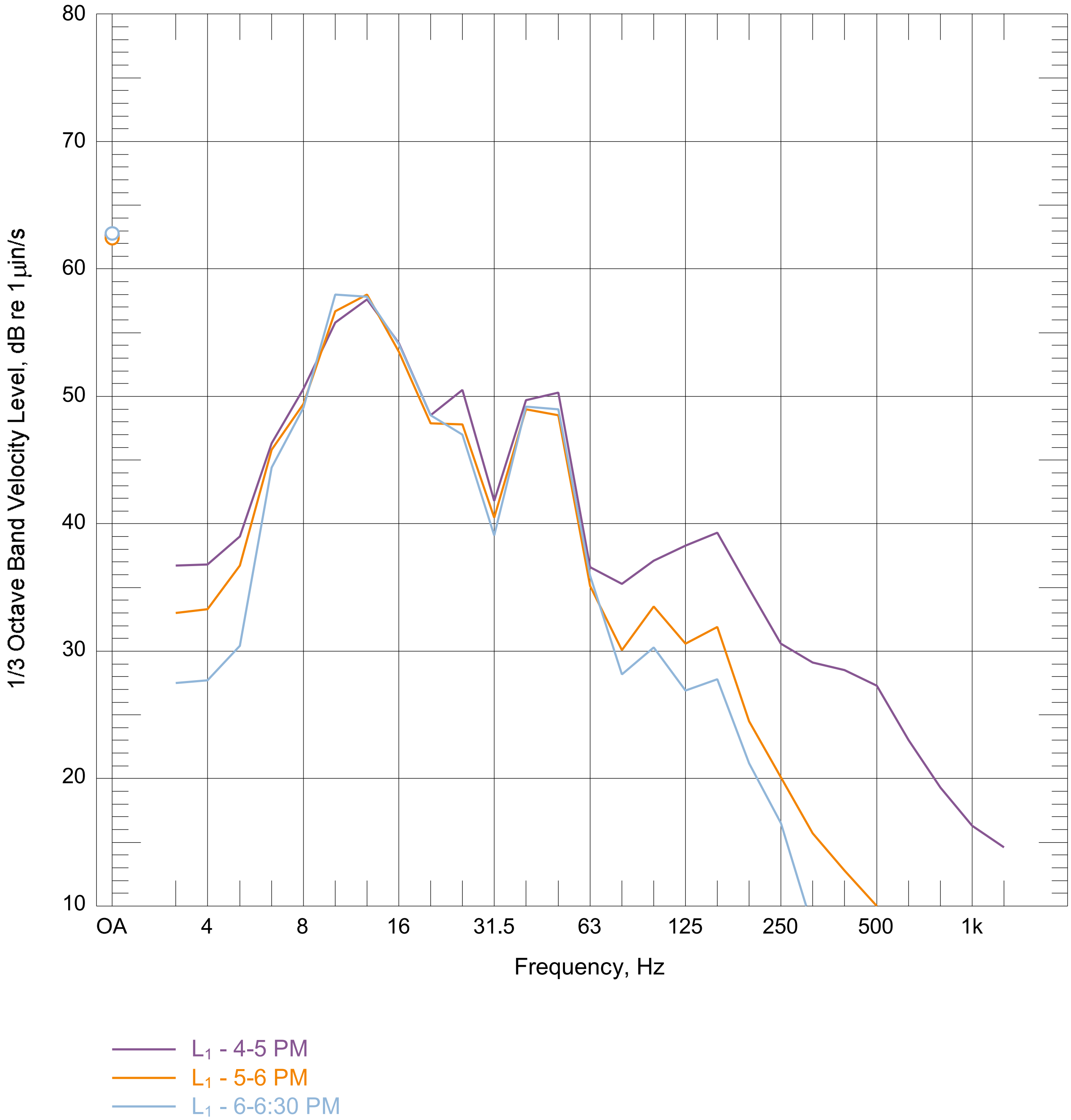


Figure 90: Site 3 at Location V4 First Floor Dining Room Hourly Percentile Vibration Levels

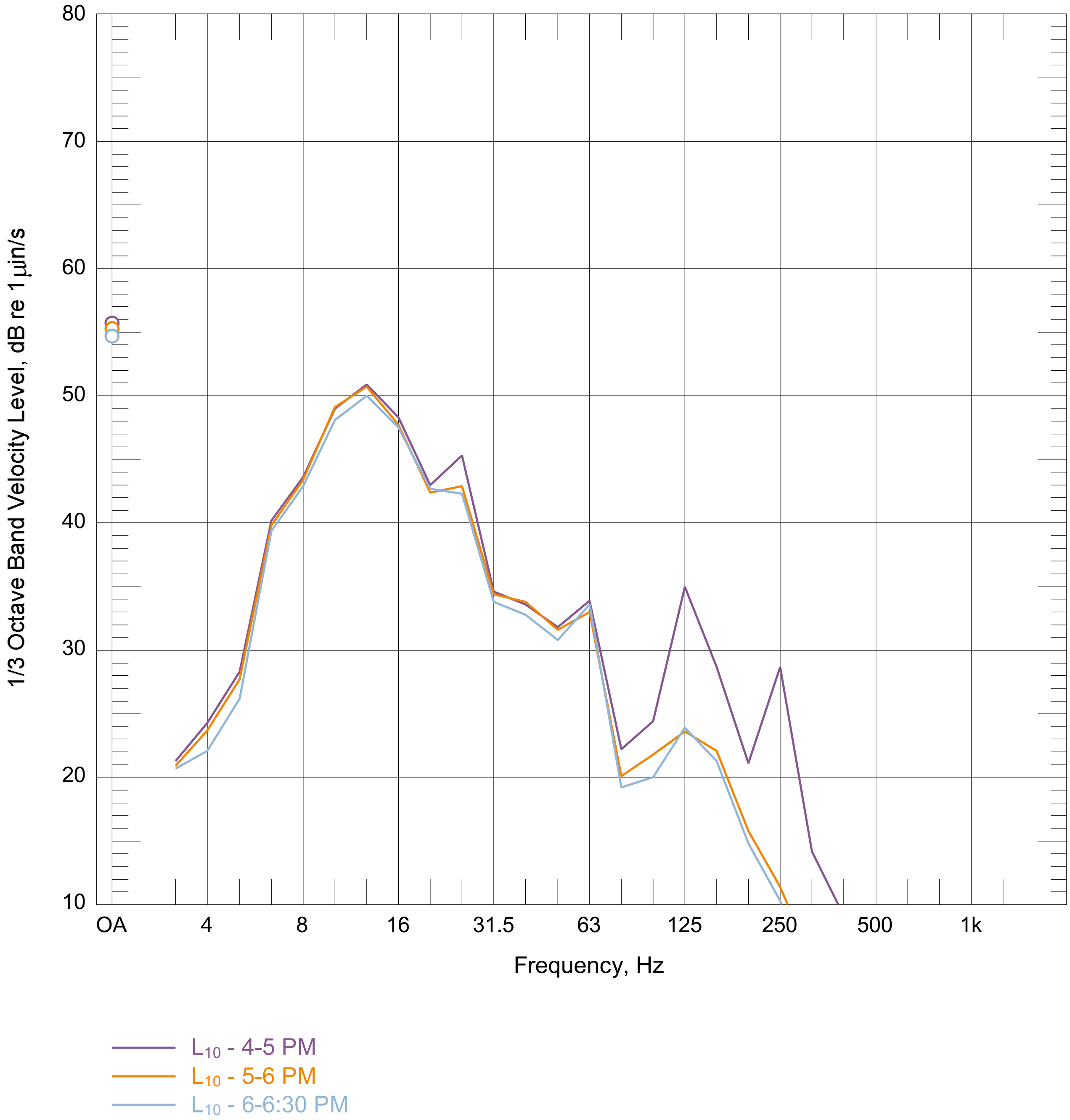


Figure 91: Site 3 at Location V4 First Floor Dining Room Hourly Percentile Vibration Levels

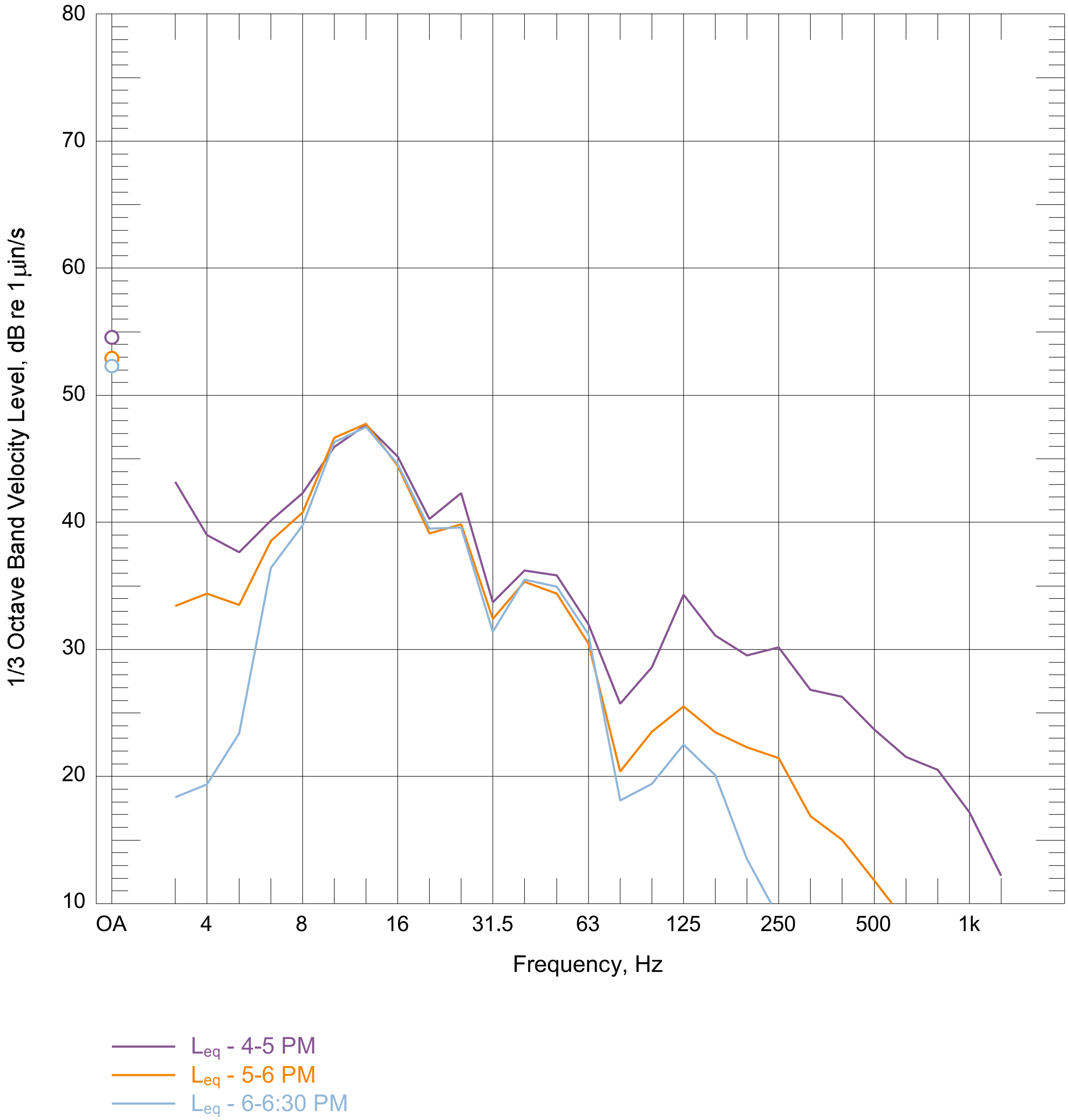


Figure 92: ***Site 3 at Location V4 First Floor Dining Room Hourly Percentile Vibration Levels***

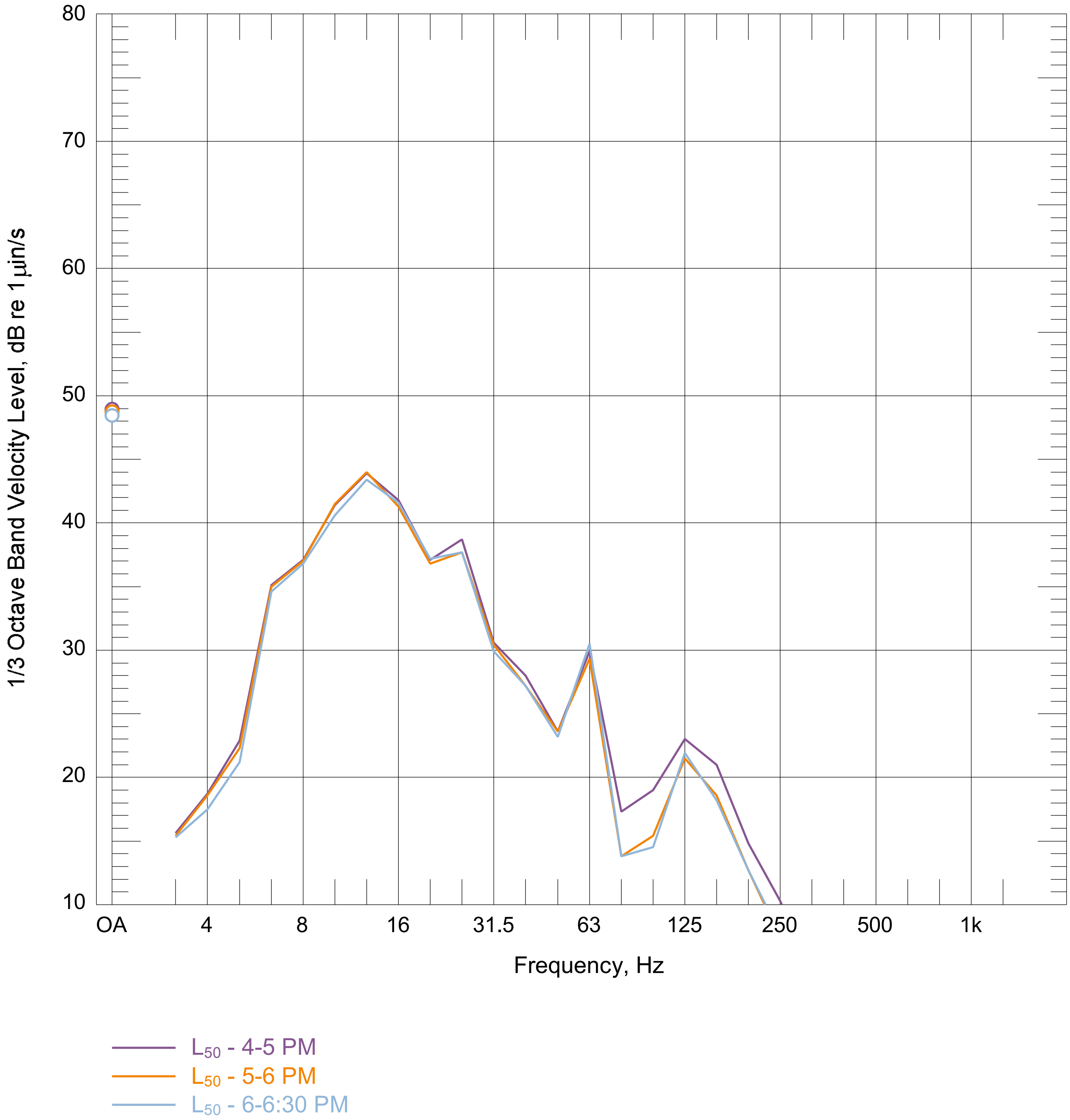


Figure 93: ***Site 3 at Location V4 First Floor Dining Room Hourly Percentile Vibration Levels***

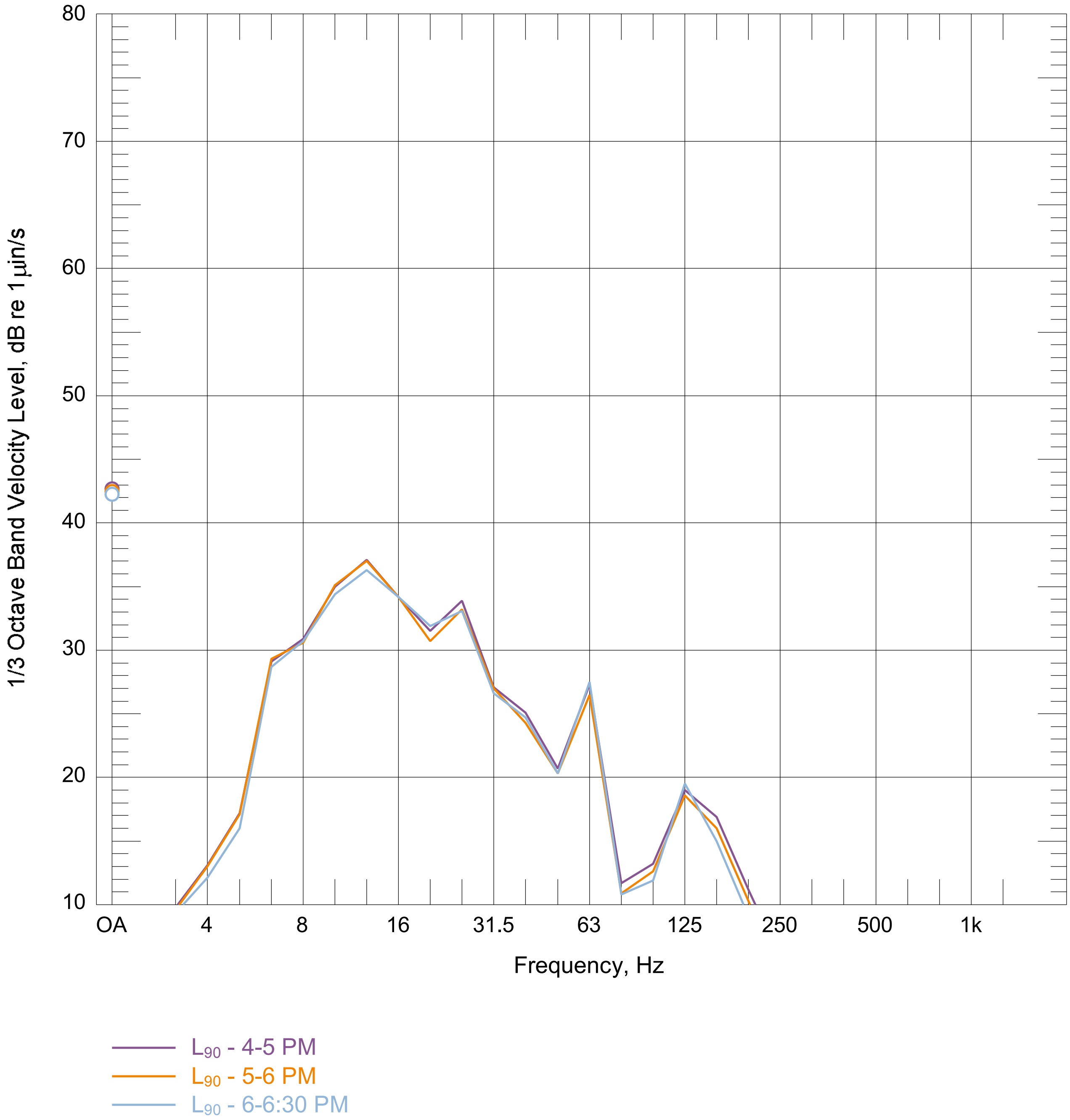


Figure 94: ***Site 3 at Location V4 First Floor Dining Room Hourly Percentile Vibration Levels***

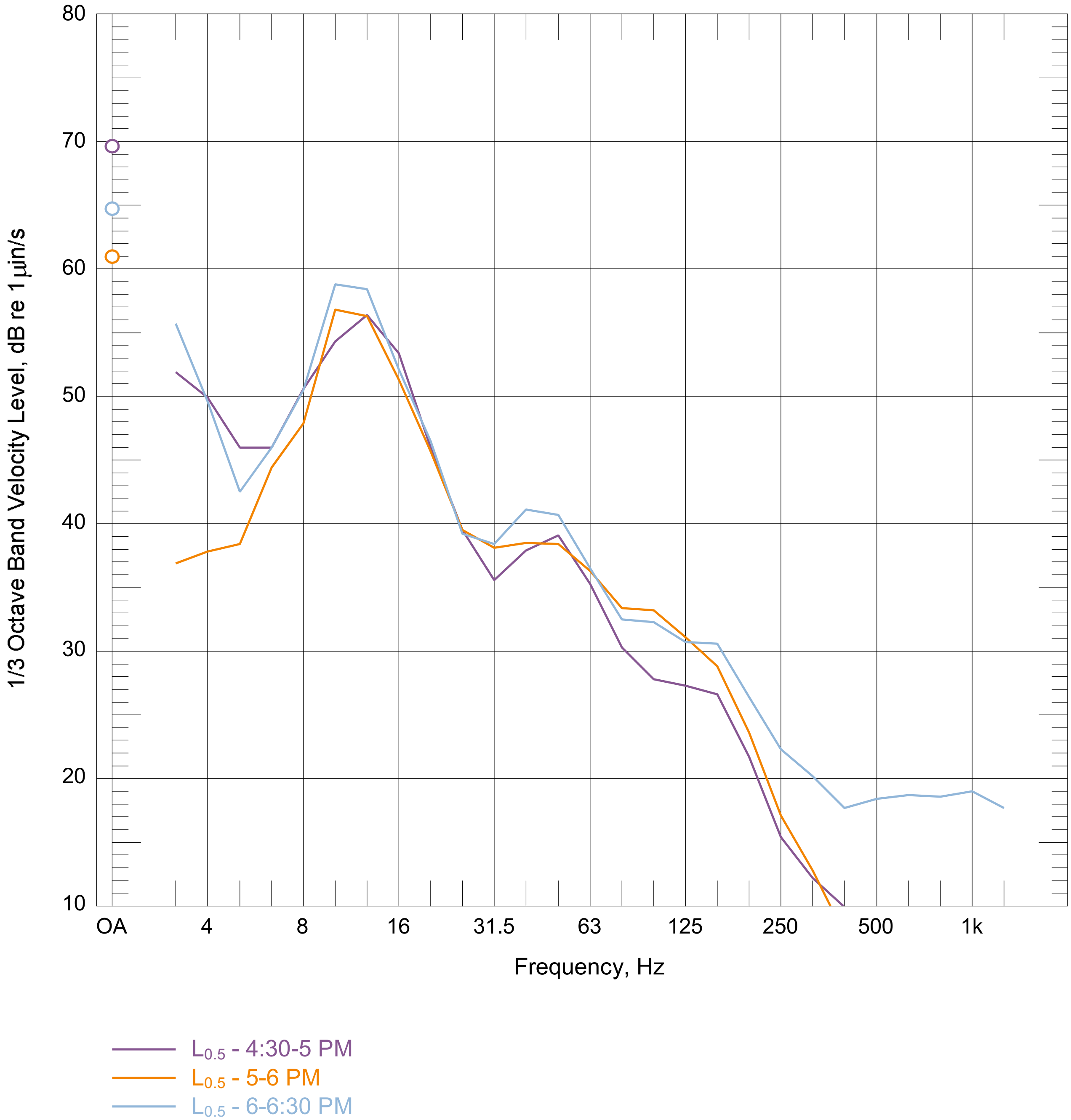


Figure 95: ***Site 3 at Location V5 Outside House Hourly Percentile Vibration Levels***

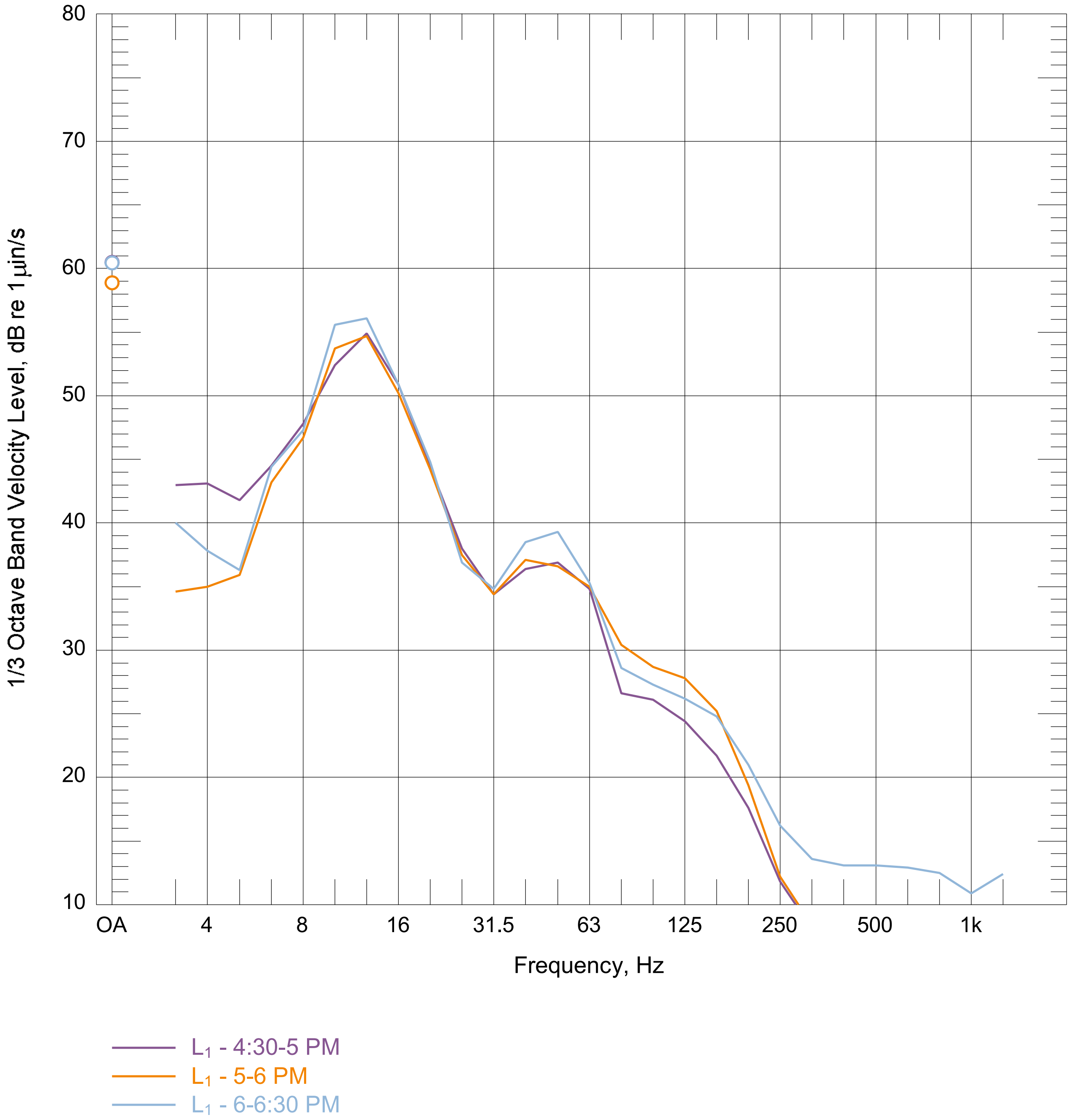


Figure 96: ***Site 3 at Location V5 Outside House Hourly Percentile Vibration Levels***

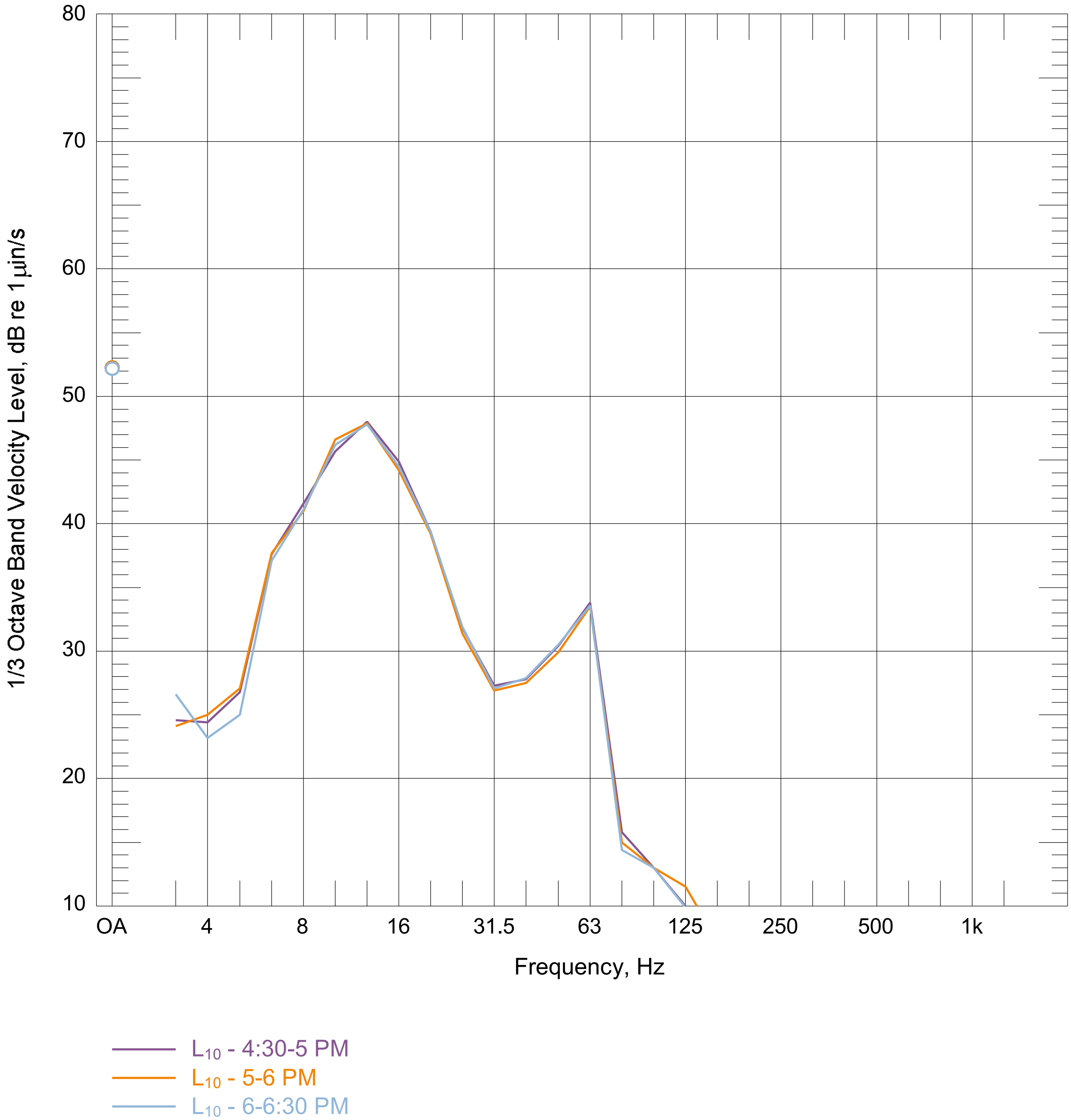


Figure 97: ***Site 3 at Location V5 Outside House Hourly Percentile Vibration Levels***

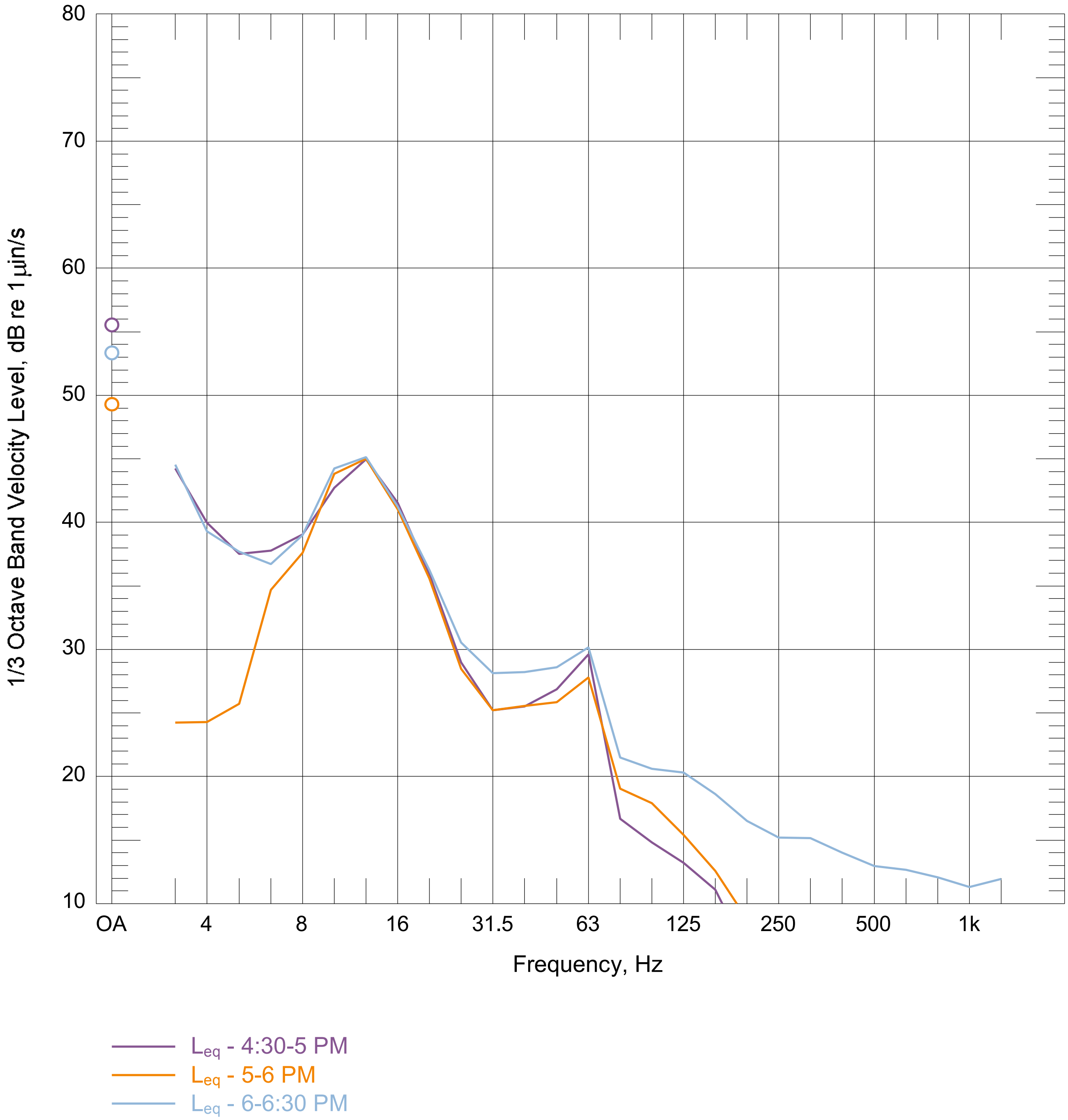


Figure 98: ***Site 3 at Location V5 Outside House Hourly Percentile Vibration Levels***

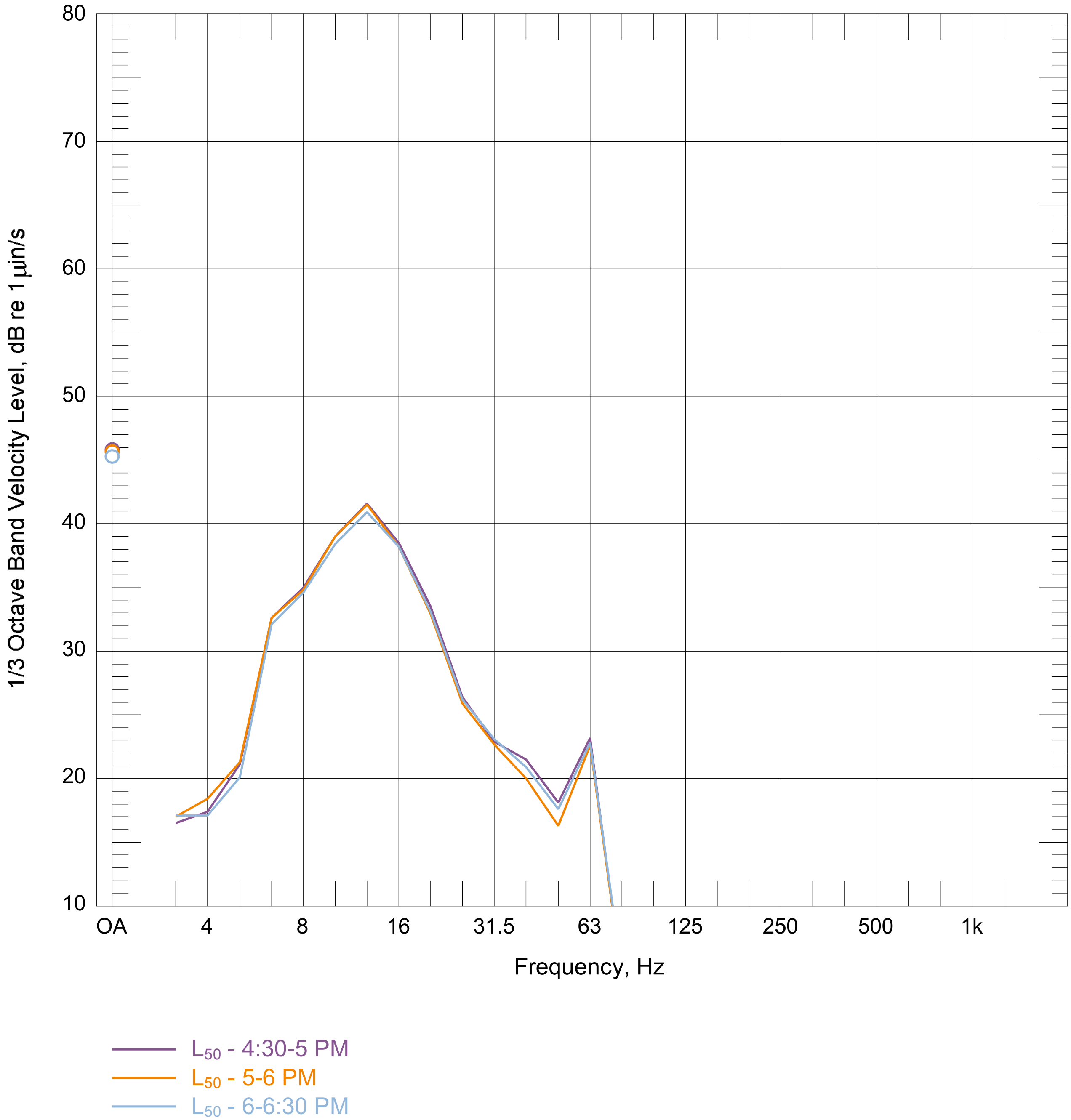


Figure 99: ***Site 3 at Location V5 Outside House Hourly Percentile Vibration Levels***

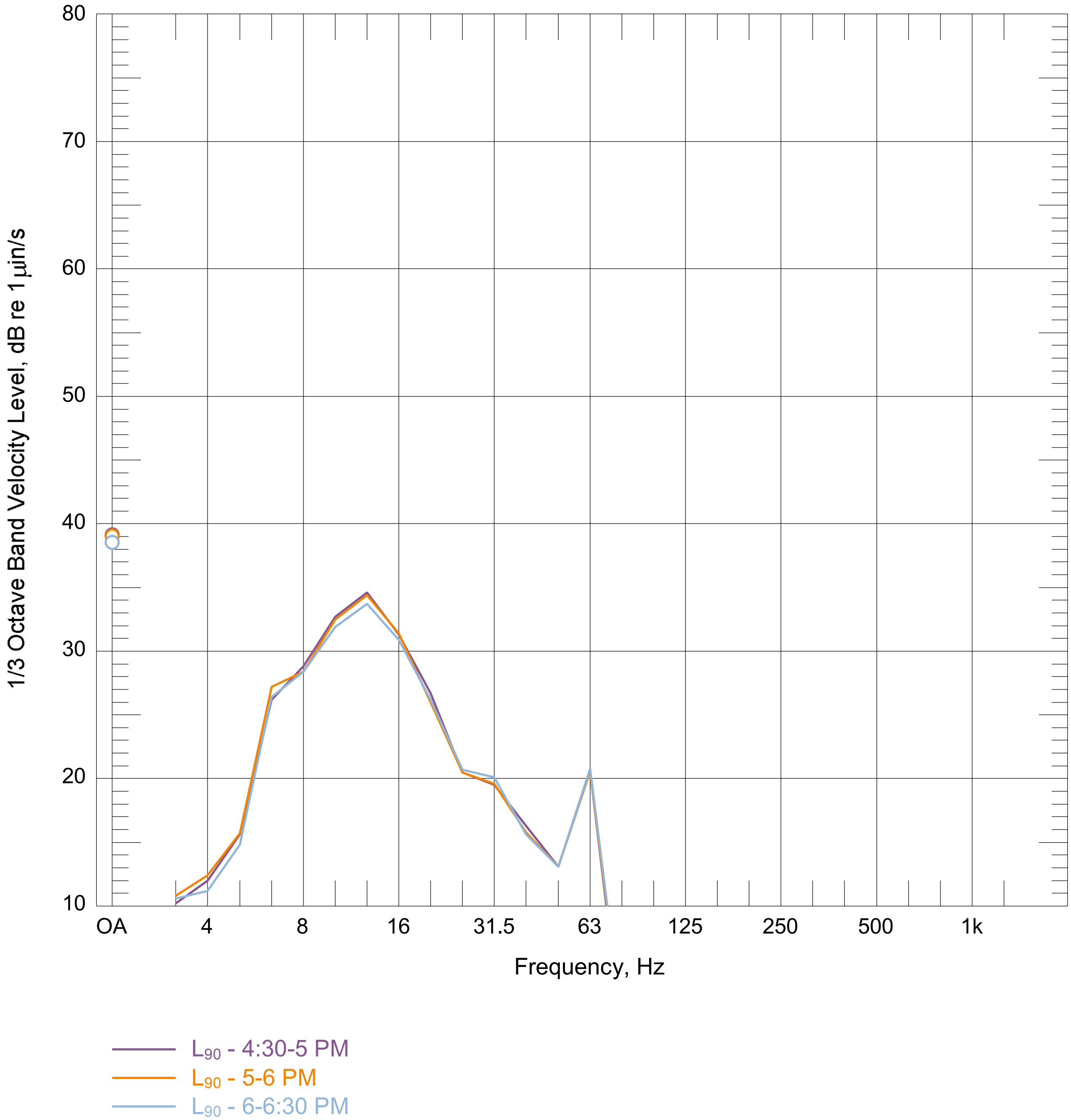


Figure 100: ***Site 3 at Location V5 Outside House Hourly Percentile Vibration Levels***

B.4 Site 4 – Rock Creek Church Road NW & 9th Street NW (Outdoor Only)

B.4.1 Tunnel Notes

Tunnel Structure: Cut and Cover

Track Type: Floating Slab Track, Crossover

T/R Depth: 50 to 52 feet

Measurement Period: Friday, 2 June 2017, 12:22 to 15:23

Field Observations: Busy intersection just south of Georgia Ave station. Most foot traffic of all outdoor locations. Metro buses along New Hampshire Ave NW. Trains are audible through vent shaft grates. Accelerometers mounted to curbs.

B.4.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Recorder Channel	Chainage (50 ft)	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)
A1	170+00	34	52	62	71	52	88
A2	170+00	41	52	66	78	52	94
A3	169+50	72	52	89	109	52	121
A4	169+00	101	52	114	138	52	147
B1	168+50	178	50	185	215	50	221
B2	169+00	206	52	212	243	52	249
B3	169+50	235	52	241	272	52	277

Perp. distance = perpendicular distance to track, not accounting for tunnel depth
T/R depth = top-of-rail depth
Total slant distance = total distance to track, accounting for tunnel depth

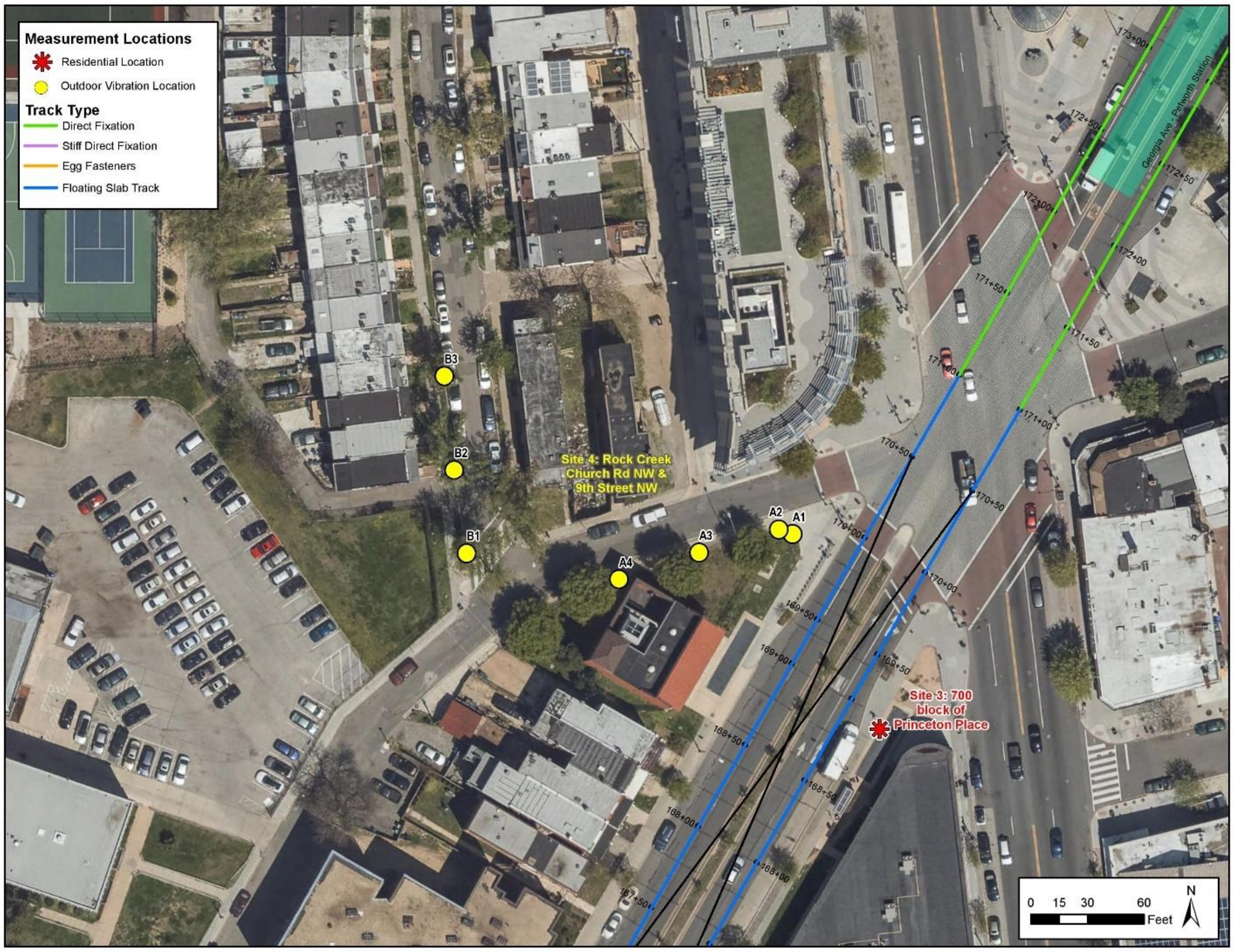


Figure 101: Aerial Map of Site 4 Measurement Positions

B.4.3 Overall Level vs Distance Plot

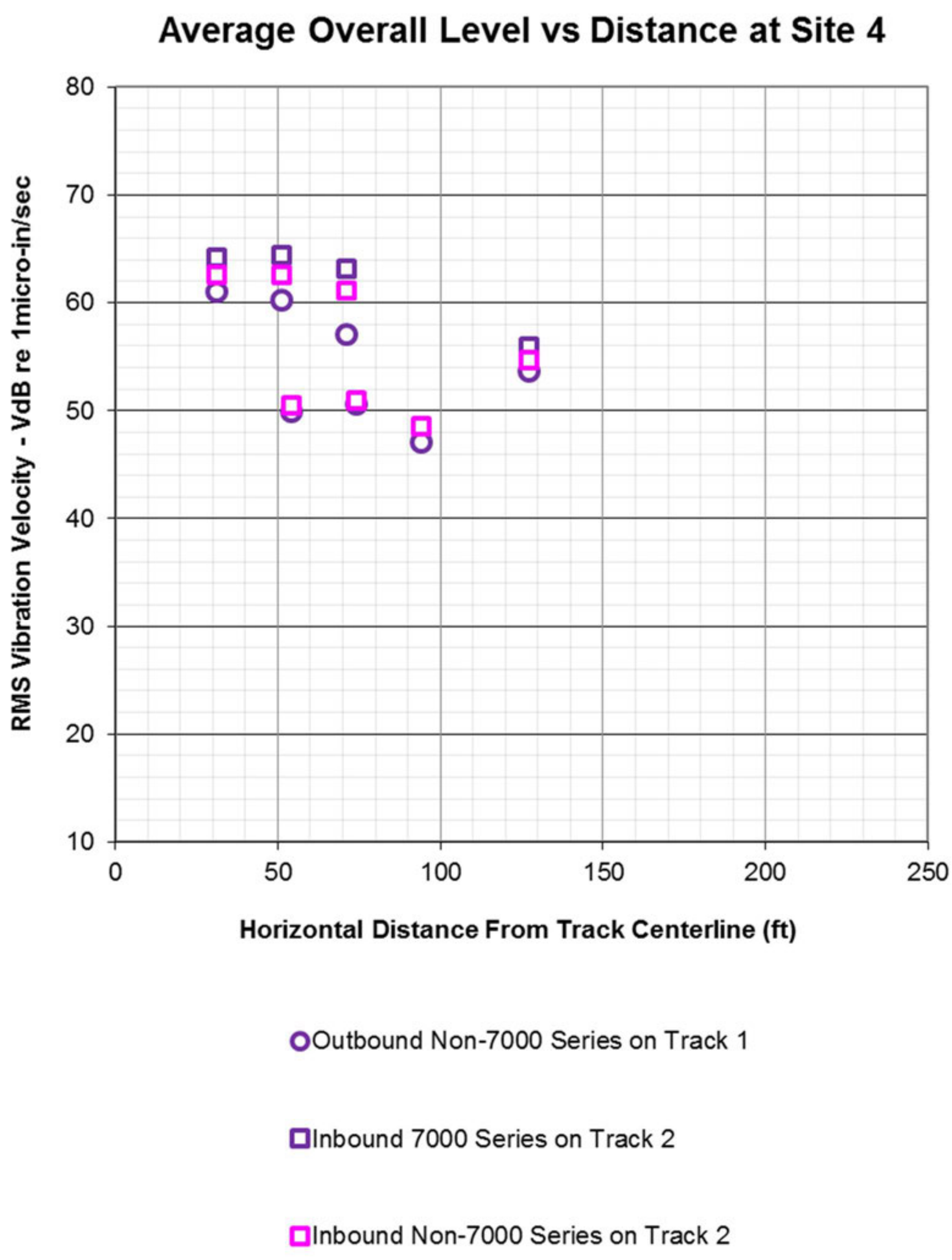


Figure 102: Site 4 Average Overall Level vs Distance

B.5 Site 5 – New Hampshire Avenue & Randolph Street NW (Outdoor Only)

B.5.1 Tunnel Notes

Tunnel Structure: Tunnel (just north of transition from cut and cover)

Track Type: Direct Fixation (DF)

T/R Depth: 76 to 86 feet

Measurement Period: Friday, 2 June 2017, 8:37 to 11:00

Field Observations: Just north of Georgia Ave station. Vehicles and Metro buses along New Hampshire Ave NW. A1-A3 accelerometers mounted to curb, all other accelerometers mounted to sidewalk.

B.5.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Recorder Channel	Chainage (50 ft)	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)
A1	181+50	83	85	119	46	85	97
A2	181+50	131	85	156	94	85	127
A3	182+00	183	83	201	147	83	169
A4	182+00	237	83	251	200	83	217
B1	183+00	323	81	333	286	81	297
B2	183+00	365	81	374	328	81	338
B3	183+50	463	79	470	426	79	433
B4	184+00	537	76	542	500	76	506

Perp. distance = perpendicular distance to track, not accounting for tunnel depth
T/R depth = top-of-rail depth
Total slant distance = total distance to track, accounting for tunnel depth

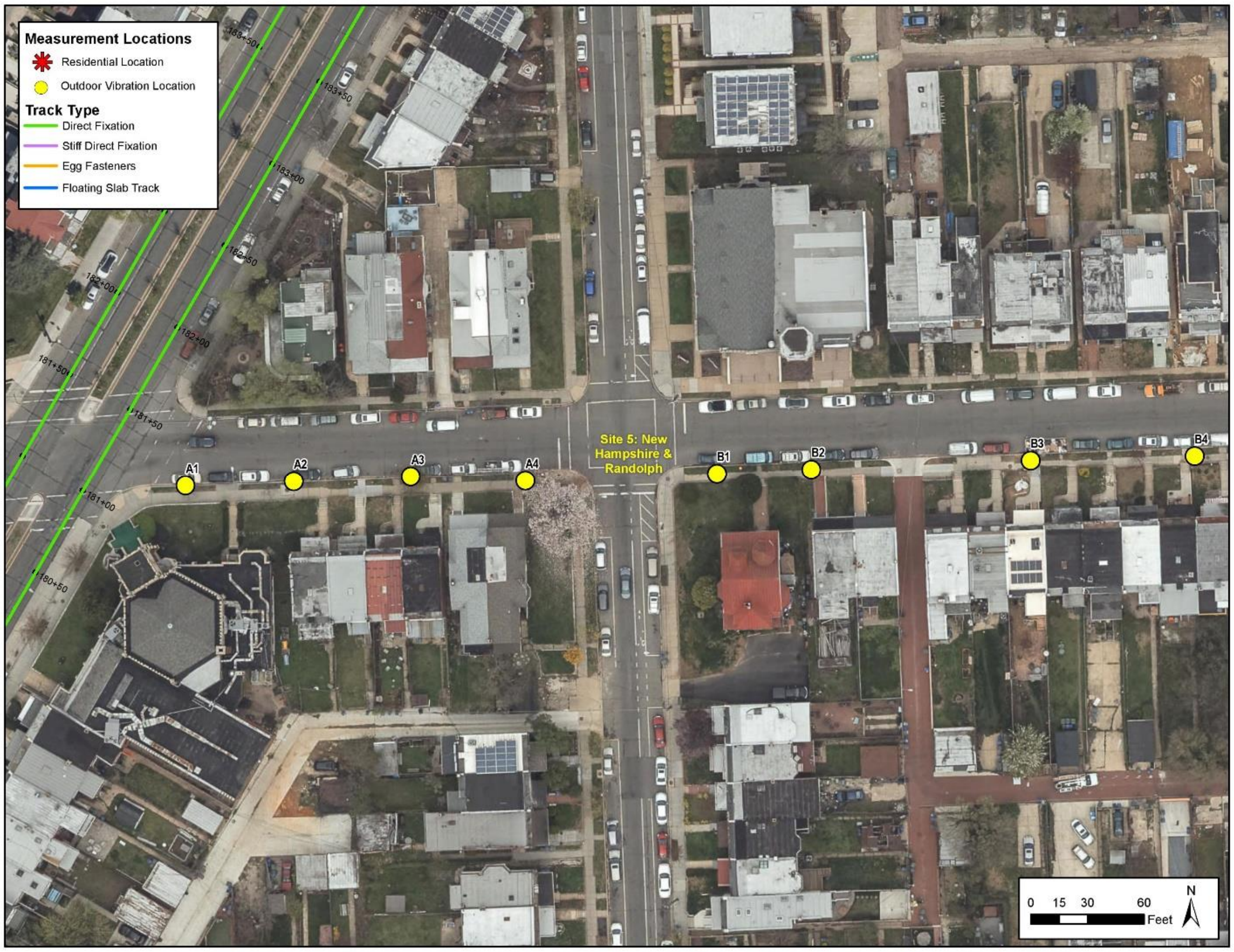


Figure 103: Aerial Map of Site 5 Measurement Positions

B.5.3 Overall Level vs Distance Plot

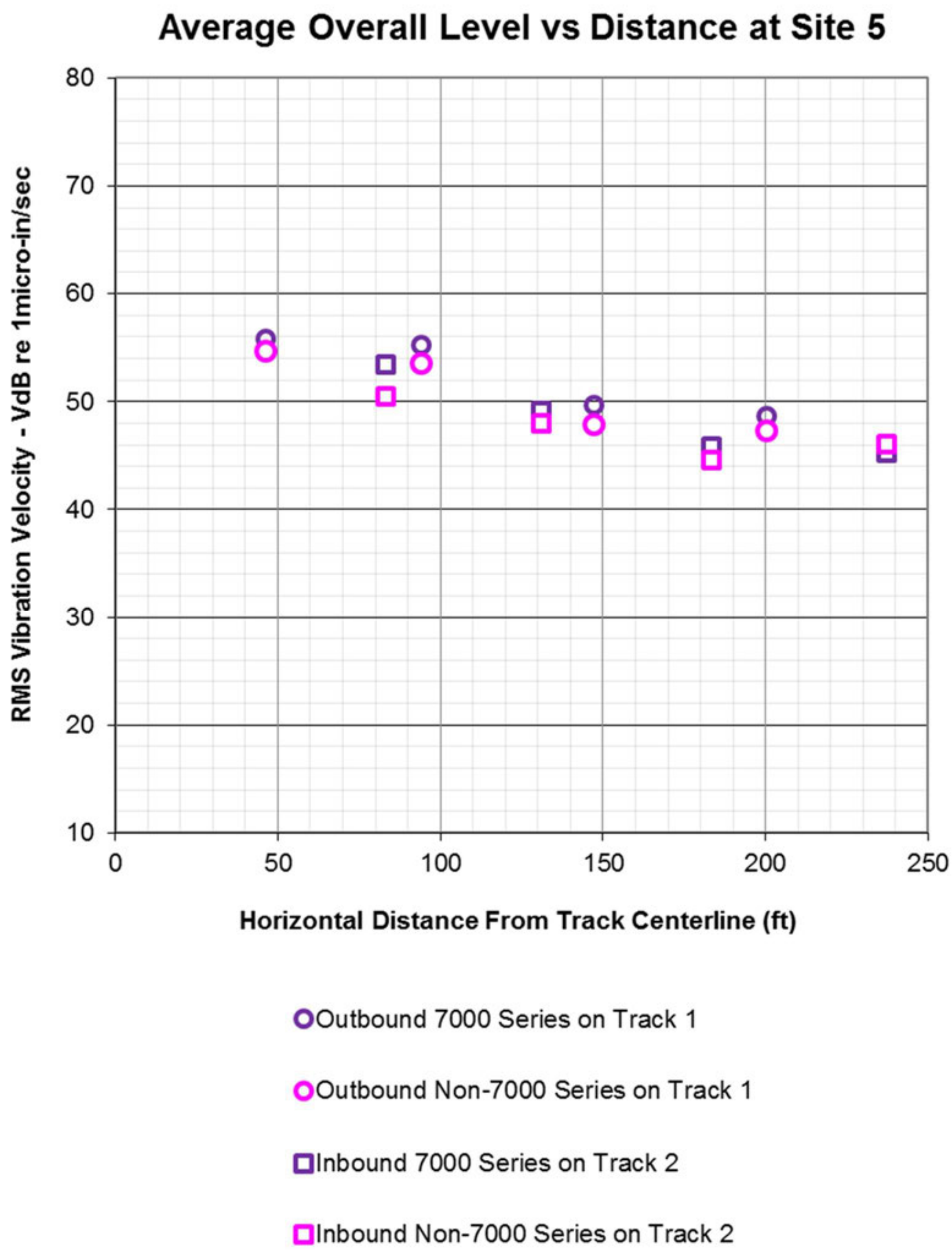


Figure 104: Site 5 Average Overall Level vs Distance

B.6 Site 6 – 4100 block of New Hampshire Avenue NW (Residence)

B.6.1 Building and Tunnel Notes

Location: Inbound track 2 side at 191+75

Building Notes: Residential attached rowhouse with 3 floors consisting of partial underground basement and 2 upper floors. Exterior walls of brick construction, foundation is below-grade slab. The residence is renovated and divided into 3 separate tenant condominiums. Bottom unit is the basement unit. Bottom unit renovated with Pergo flooring throughout.

Tunnel Structure: Tunnel

Track Type: Egg Fasteners

T/R Depth: 65 feet

Train Speed: 30 to 55 mph

Measurement Period: Tuesday, 15 August 2017, 9:01 to 13:02

Field Observations: Homeowners vacant during measurements, only Wilson Ihrig staff present. It was raining during the measurements, so the outdoor locations are affected to some degree.

B.6.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Sensor[a,b,c]	Location / Room Occupancy	Horizontal Distance[d] (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)	Horizontal Distance (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)
V1	Outdoor at Sidewalk	34	65	73	71	65	96
V2	Outdoor at [redacted] entrance	41	65	77	78	65	102
V3	Near Bedroom	72	65	97	109	65	127
N1	Near Bedroom	101	65	120	138	65	153
V4 / Triaxial Geophone	Closet (on bare concrete)	178	65	189	215	65	225
V5	Far Bedroom	206	65	216	243	65	252
N2	Far Bedroom	235	65	244	272	65	280

Notes:

a) Tri-axial geophone mounted on floor, logging peak particle velocity

b) V# vibration locations with accelerometer mounted on floor in vertical direction

c) N# noise locations with microphone/sound level meter mounted on tripod 48 inches feet above floor
d) Horizontal distance from track to building façade for indoor locations, not accounting for tunnel depth.
e) T/R depth = top-of-rail depth
f) Total slant distance to T/R = total distance from building to track, accounting for tunnel depth

Figure 105: Aerial Map of 4100 block of New Hampshire Ave NW Residence and Exterior Measurement Locations

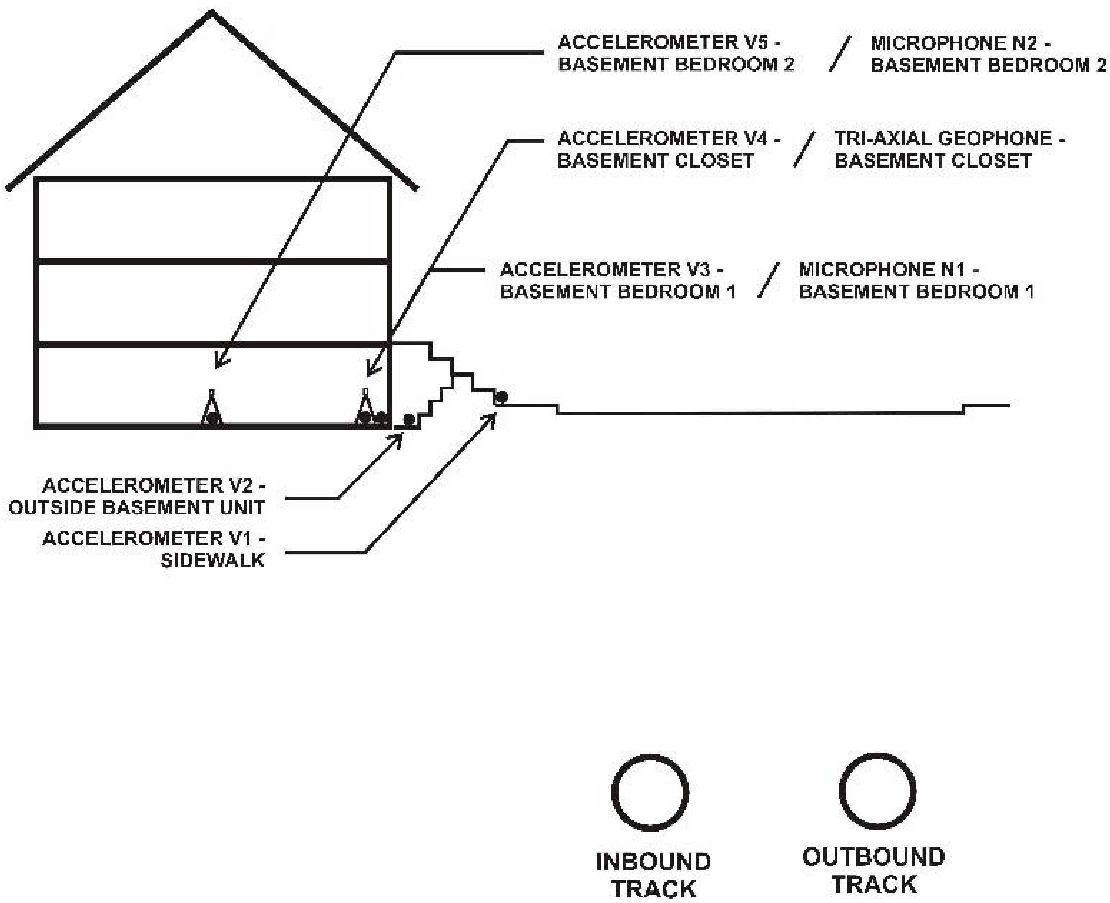


Figure 106: Cross-section Sketch (not to scale) of 4100 block of New Hampshire Ave NW Residence Measurement Locations

B.6.3 GBNV Assessment Summary

SITE 6	4100 block of NEW HAMPSHIRE NW – ATTENDED PASSBY MEASUREMENT GBNV ASSESSMENT		
	Ground-borne Vibration (GBV)	**>70 VdB?**	**Notes**
	7000 Series - Average of Multiple Passbys	NO	
	6000 Series - Average of Multiple Passbys	NO	
	5000 Series - Average of Multiple Passbys	NO	
	3000 Series - Average of Multiple Passbys	NO	
	2000 Series - Average of Multiple Passbys	NO	
	Mixed Legacy without 4000 Series - Average of Multiple Passbys	NO	
	7000 Series - Individual Train with Highest Overall Vibration	NO	
	6000 Series - Individual Train with Highest Overall Vibration	NO	
	5000 Series - Individual Train with Highest Overall Vibration	NO	
	3000 Series - Individual Train with Highest Overall Vibration	NO	
	2000 Series - Individual Train with Highest Overall Vibration	NO	
	Mixed Legacy without 4000 Series - Individual Train with Highest Overall Vibration	NO	
	Ground-borne Noise (GBN)	**>40 dBA?**	**Notes**
	7000 Series - Average of Multiple Passbys	NO	
	6000 Series - Average of Multiple Passbys	NO	
	5000 Series - Average of Multiple Passbys	NO	
	3000 Series - Average of Multiple Passbys	NO	
	2000 Series - Average of Multiple Passbys	NO	
	Mixed Legacy without 4000 Series - Average of Multiple Passbys	NO	
	7000 Series - Individual Train with Highest A-weighting	NO	
	6000 Series - Individual Train with Highest A-weighting	NO	
	5000 Series - Individual Train with Highest A-weighting	NO	
	3000 Series - Individual Train with Highest A-weighting	NO	
	2000 Series - Individual Train with Highest A-weighting	NO	
	Mixed Legacy without 4000 Series - Individual Train with Highest A-weighting	NO	

B.6.4 PPV Results

SITE 6	4100 block of NEW HAMPSHIRE NW – POTENTIAL FOR BUILDING VIBRATION DAMAGE ASSESSMENT						
	>0.2 in/sec PPV in any direction?	Average PPV (in/s)			PPV Range (in/s)		
		Tran	Vert	Long	Tran	Vert	Long
	NO	0.0031	0.0032	0.0021	0.003 - 0.005	0.002 - 0.013	0.002 - 0.007
Basement 15-Aug-17, 9:08:51 AM to 1:04:40 PM							

B.6.5 Passby Vibration Spectra and Overall Levels

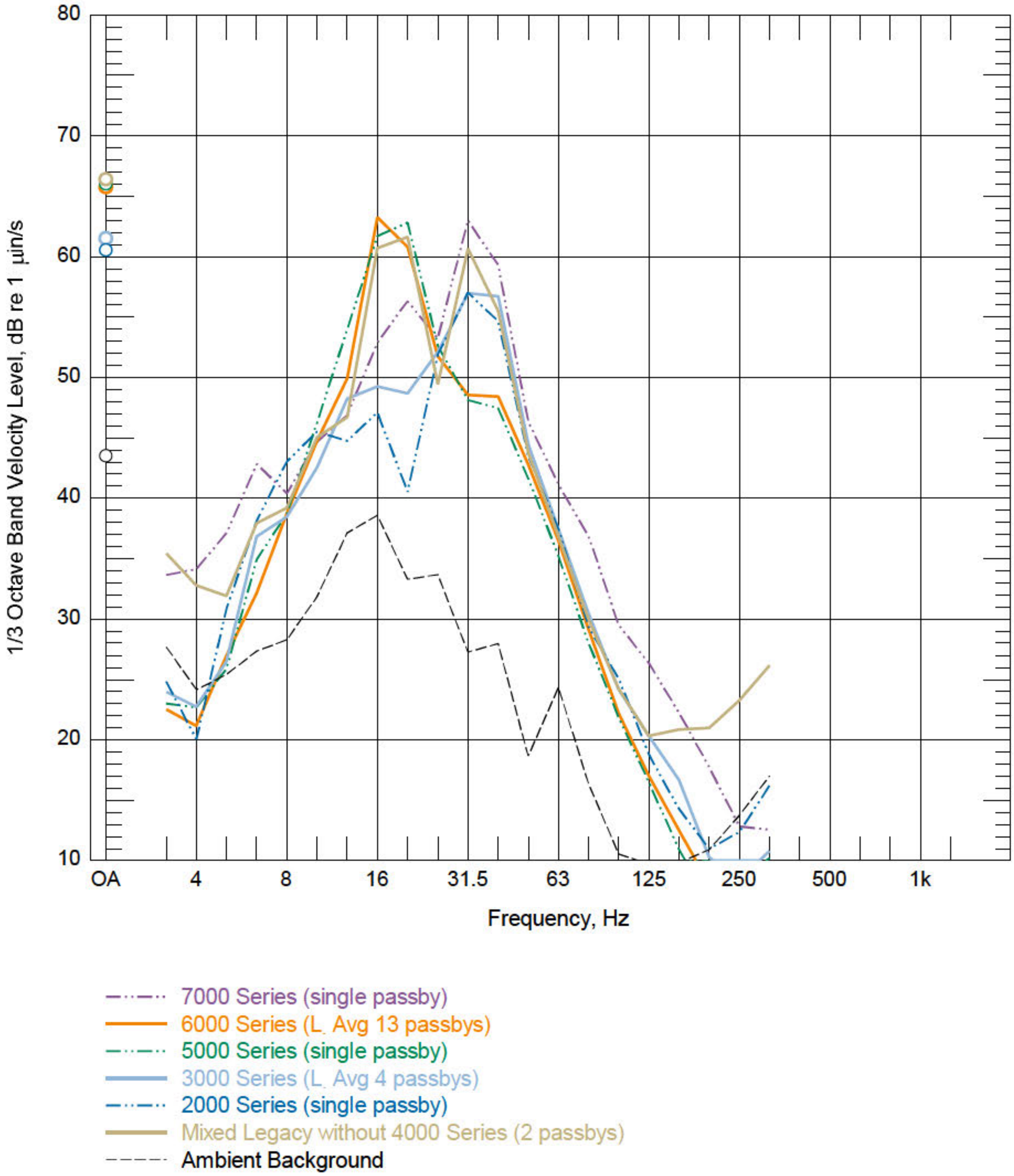


Figure 107: ***Site 6 at Location V1 Outdoor Sidewalk***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

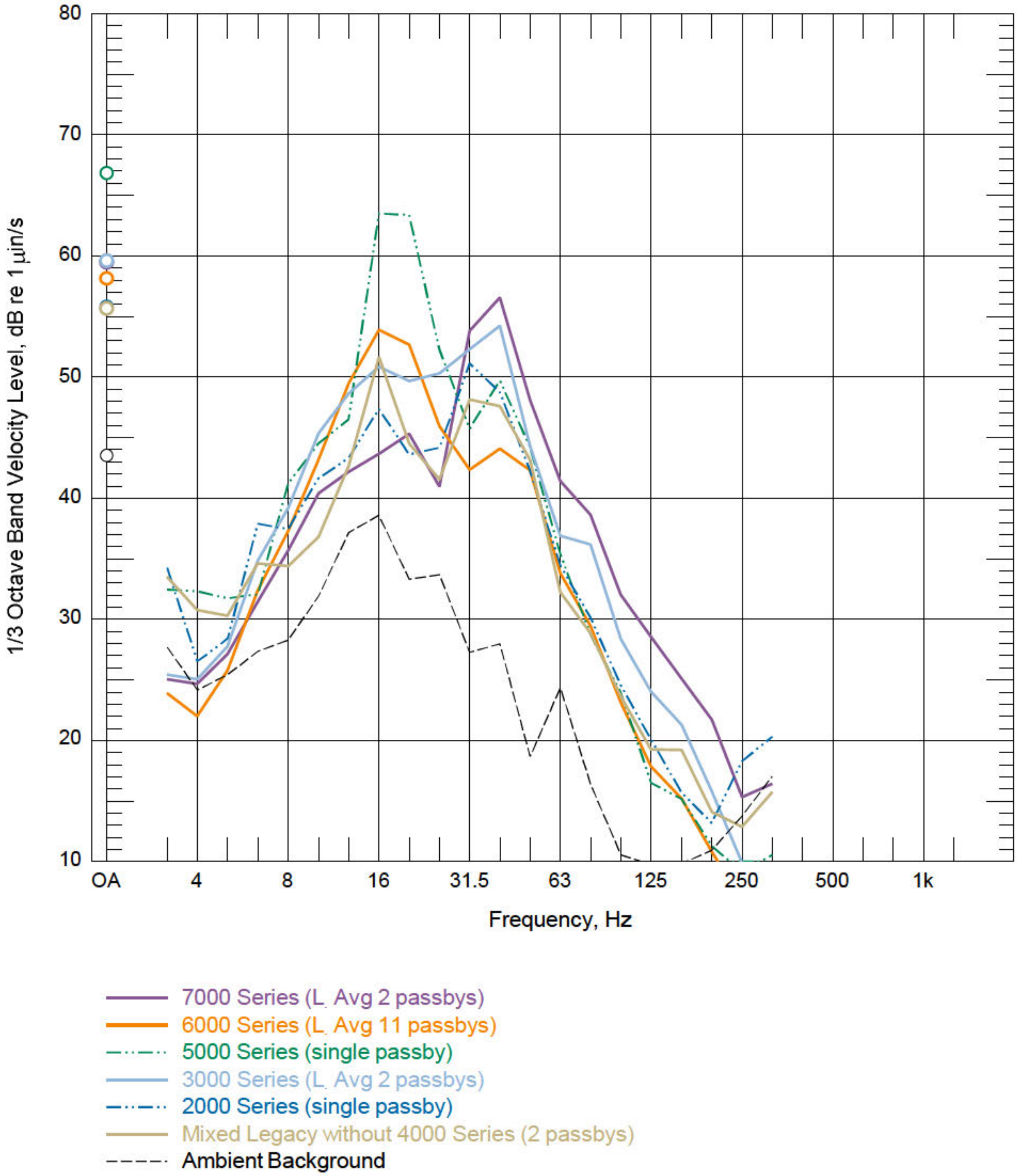


Figure 108: ***Site 6 at Location V1 Outdoor Sidewalk***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

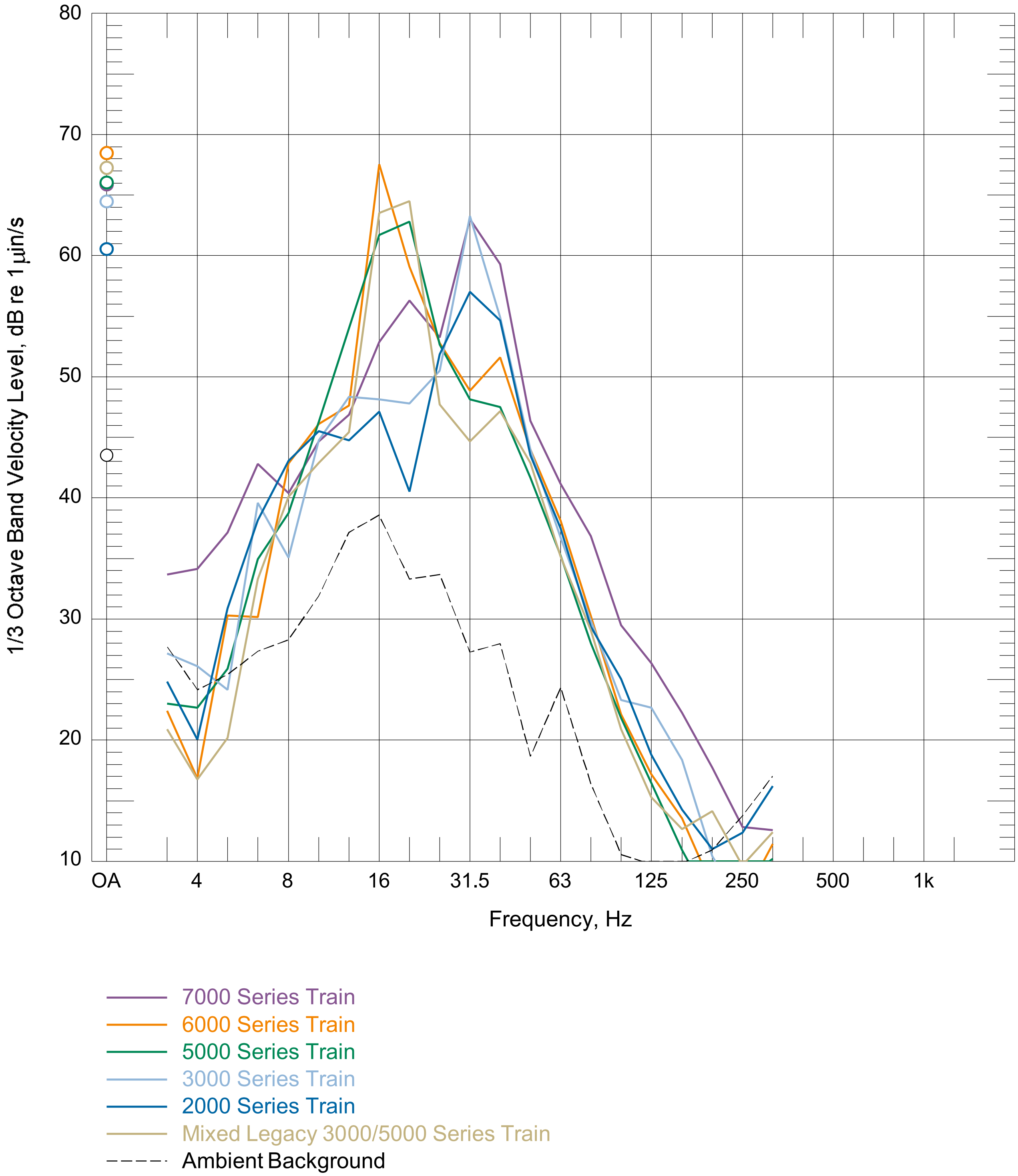


Figure 109: ***Site 6 at Location V1 Outdoor Sidewalk***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

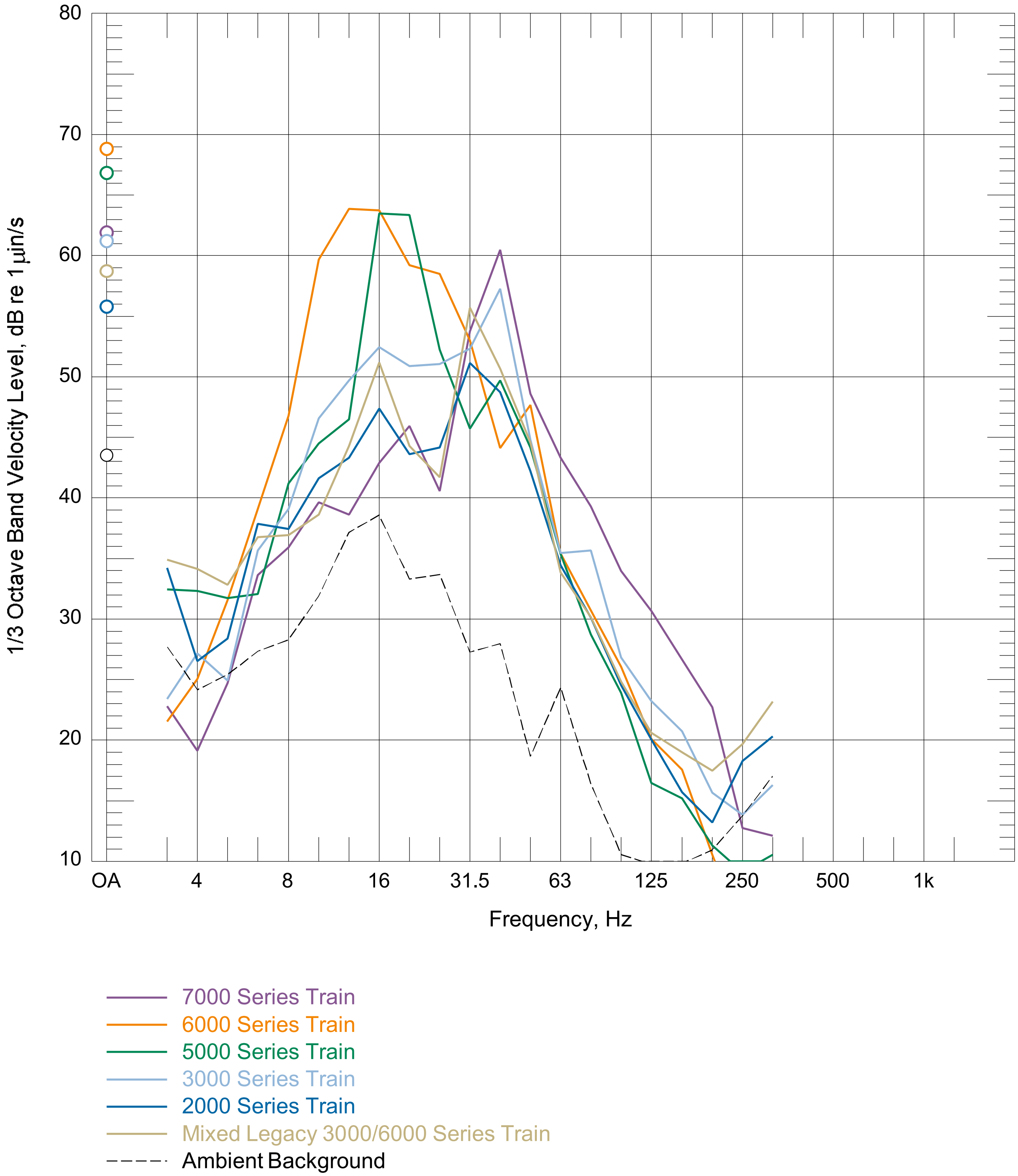


Figure 110: ***Site 6 at Location V1 Outdoor Sidewalk***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

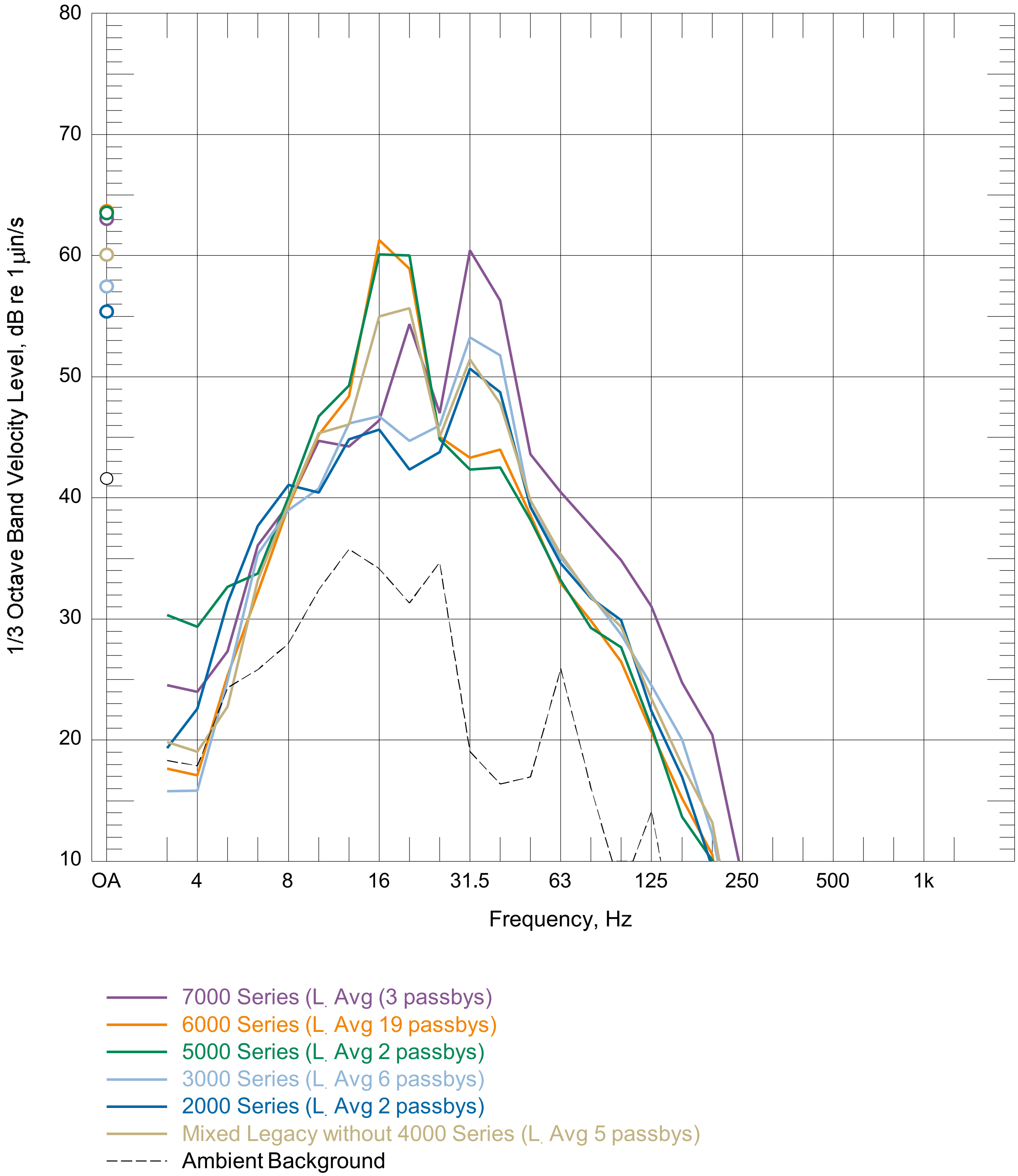


Figure 111: ***Site 6 at Location V2 Outdoor at Entrance***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

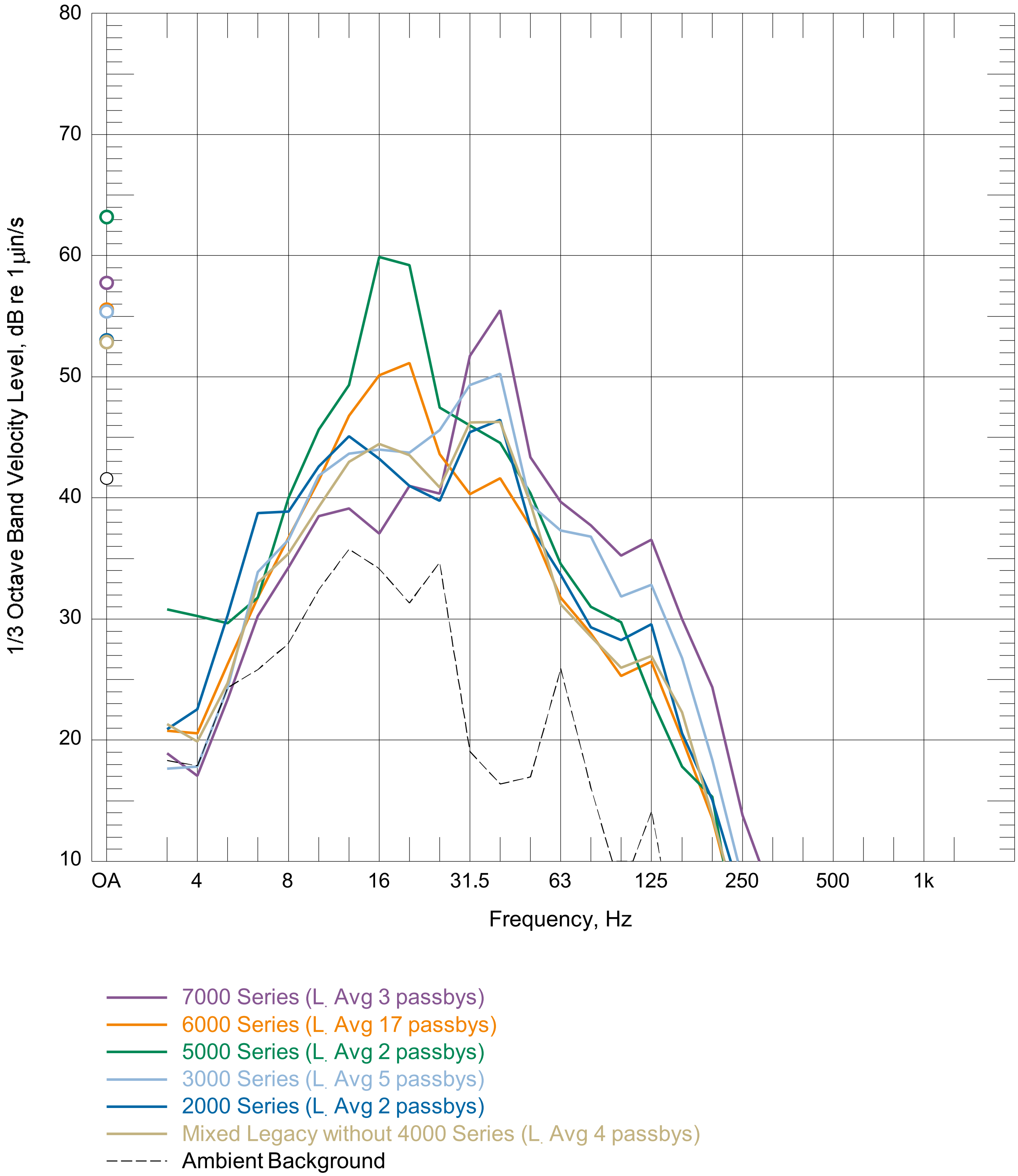


Figure 112: ***Site 6 at Location V2 Outdoor at Entrance***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

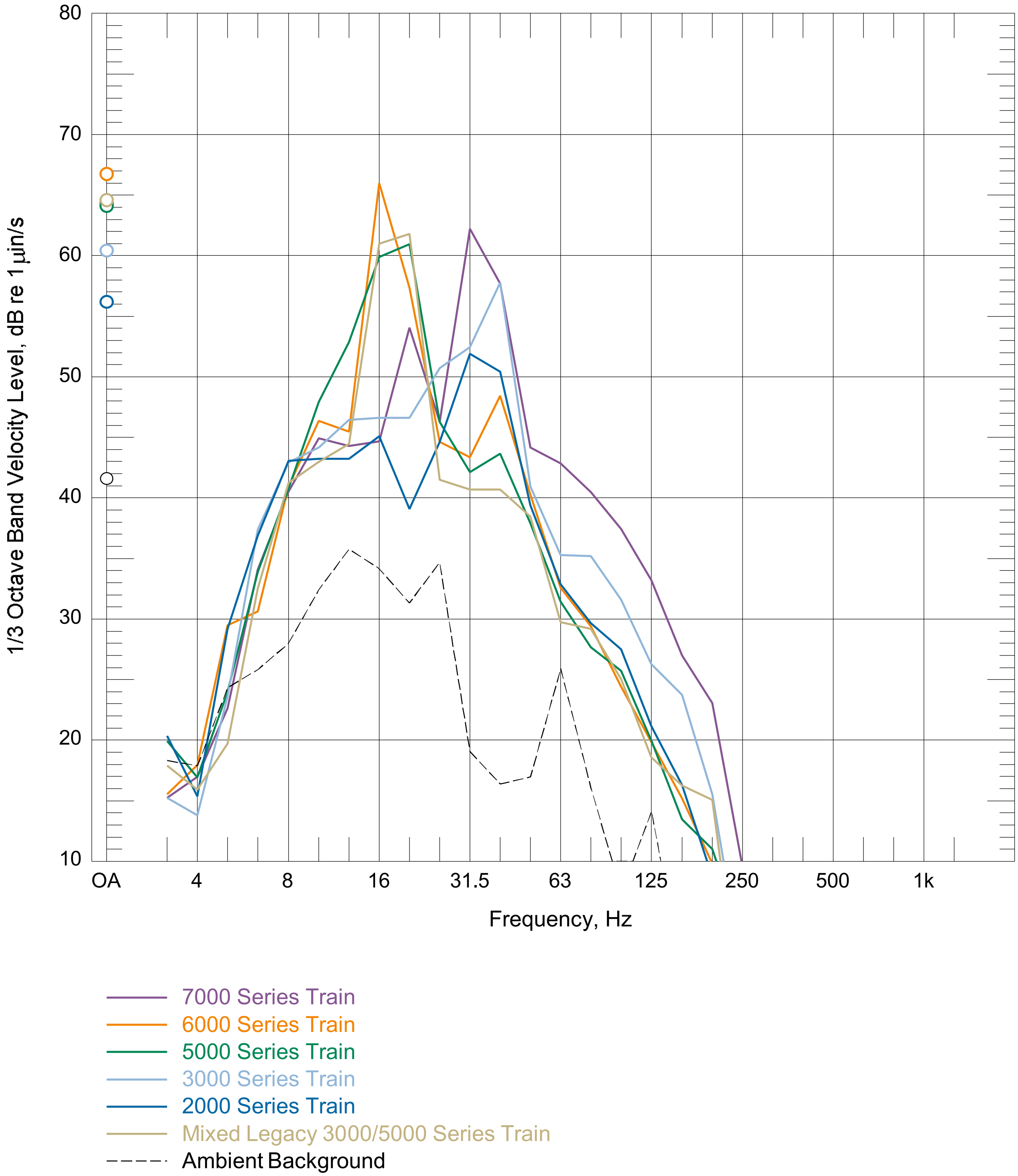


Figure 113: ***Site 6 at Location V2 Outdoor at Entrance***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

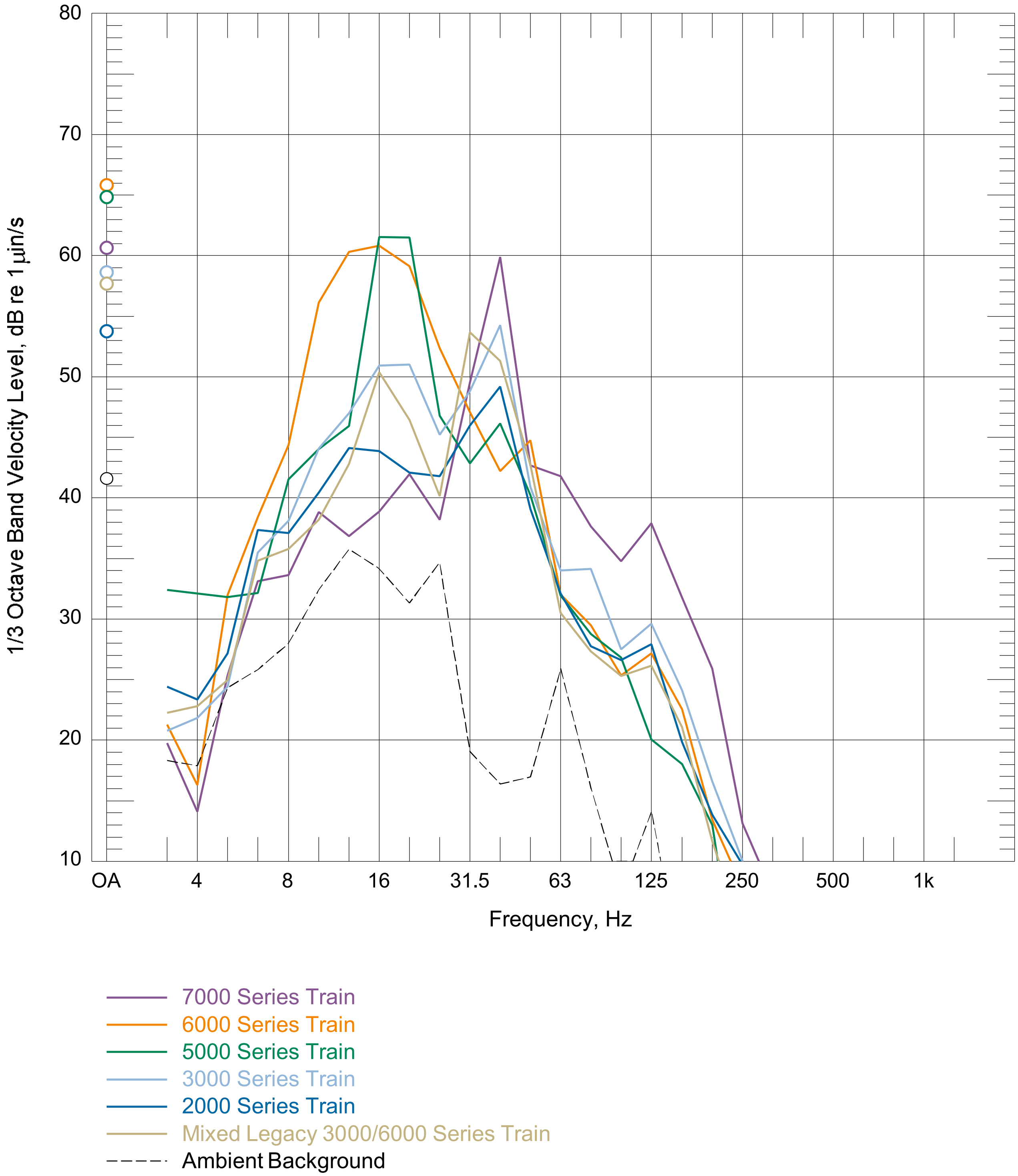


Figure 114: ***Site 6 at Location V2 Outdoor at Entrance***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

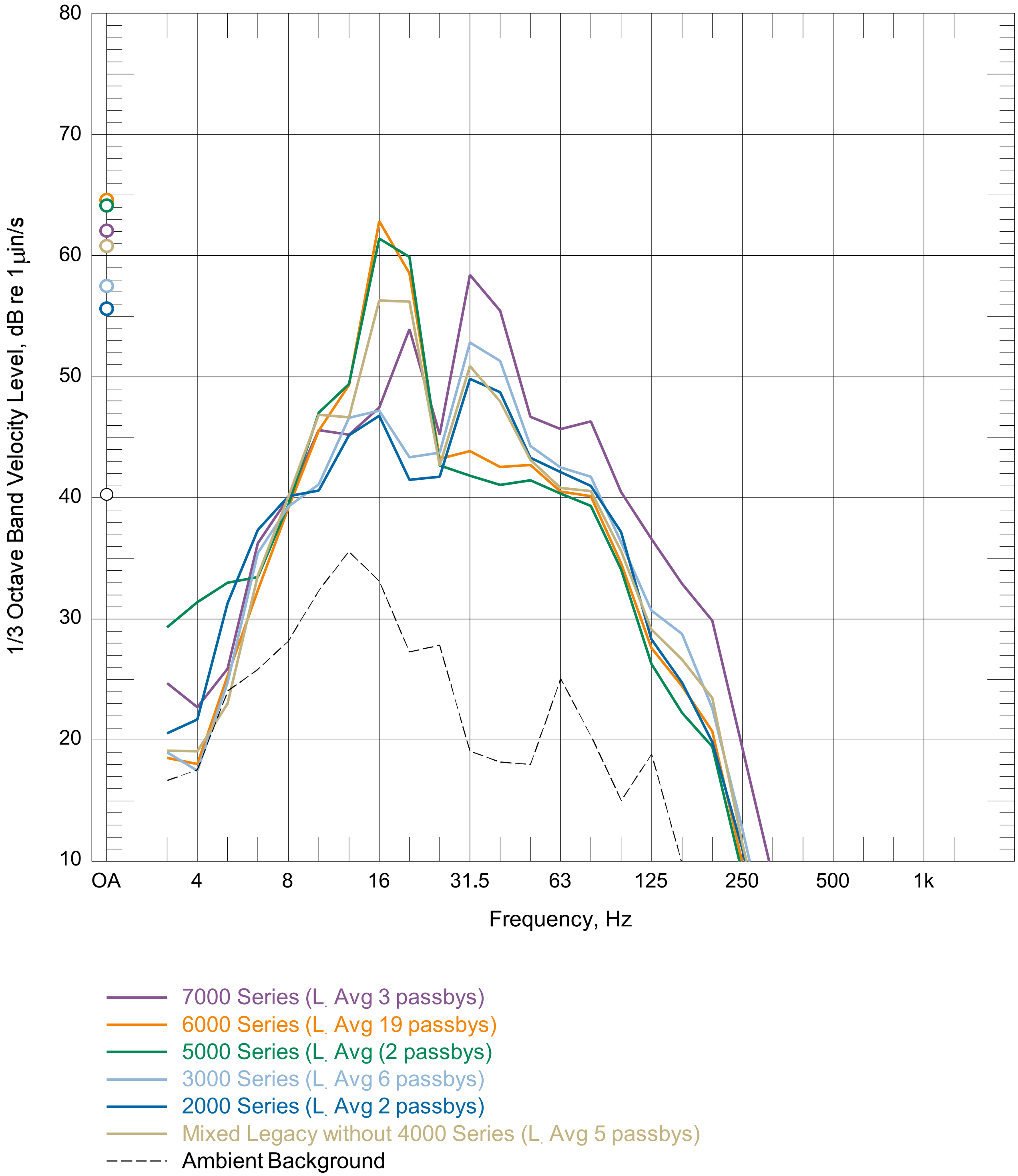


Figure 115: ***Site 6 at Location V3 Near Bedroom***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

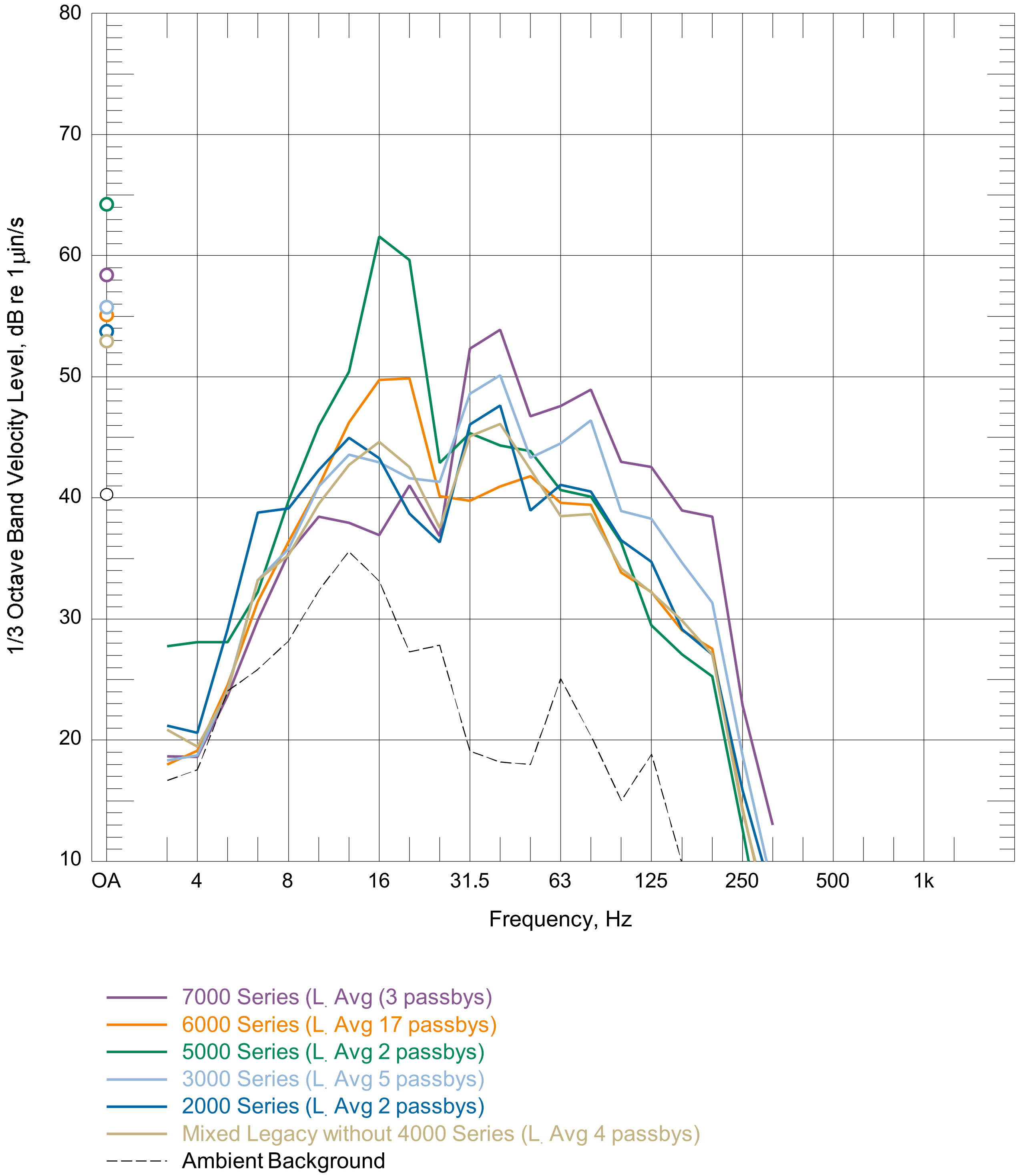


Figure 116: ***Site 6 at Location V3 Near Bedroom***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

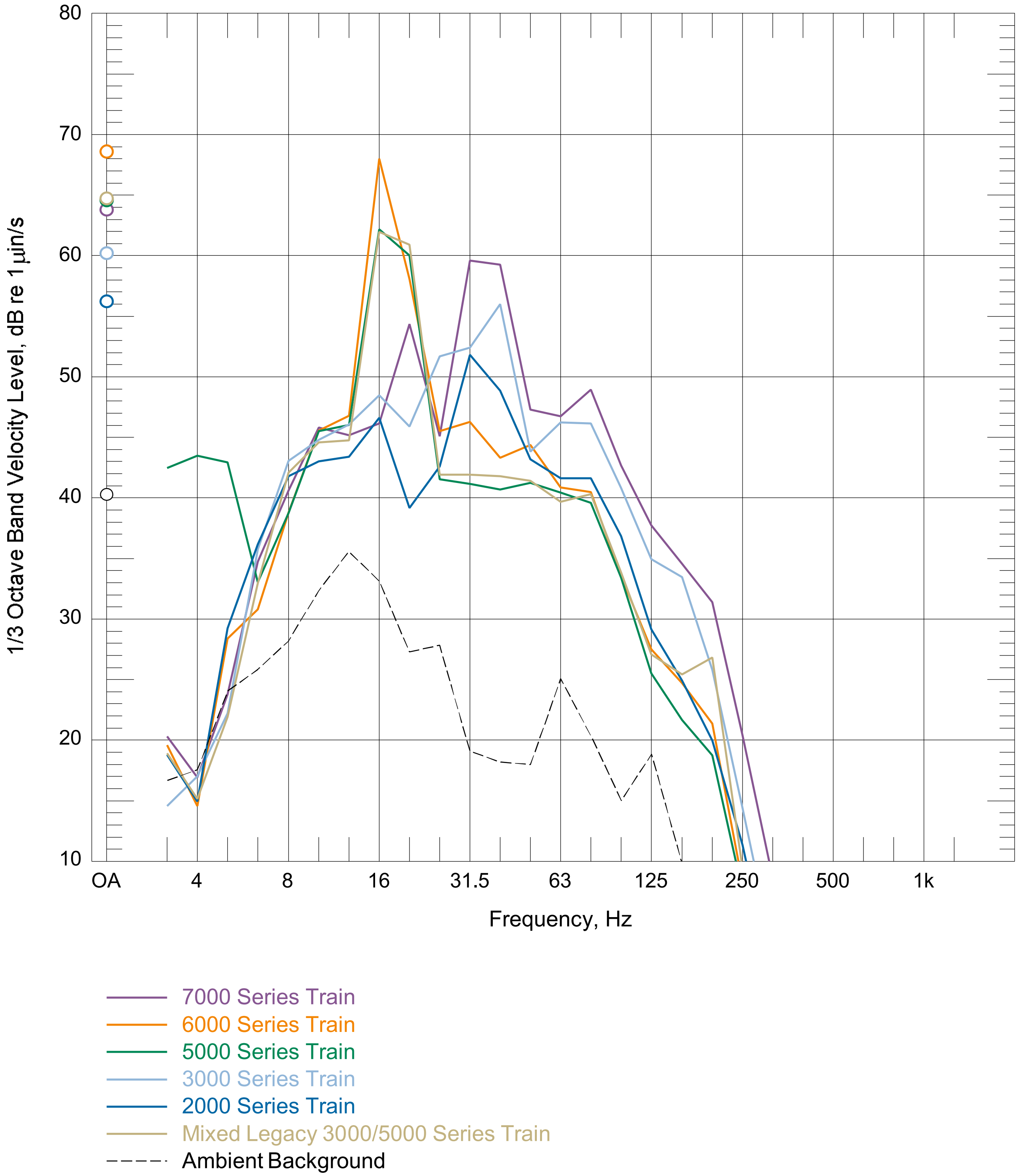


Figure 117: ***Site 6 at Location V3 Near Bedroom***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

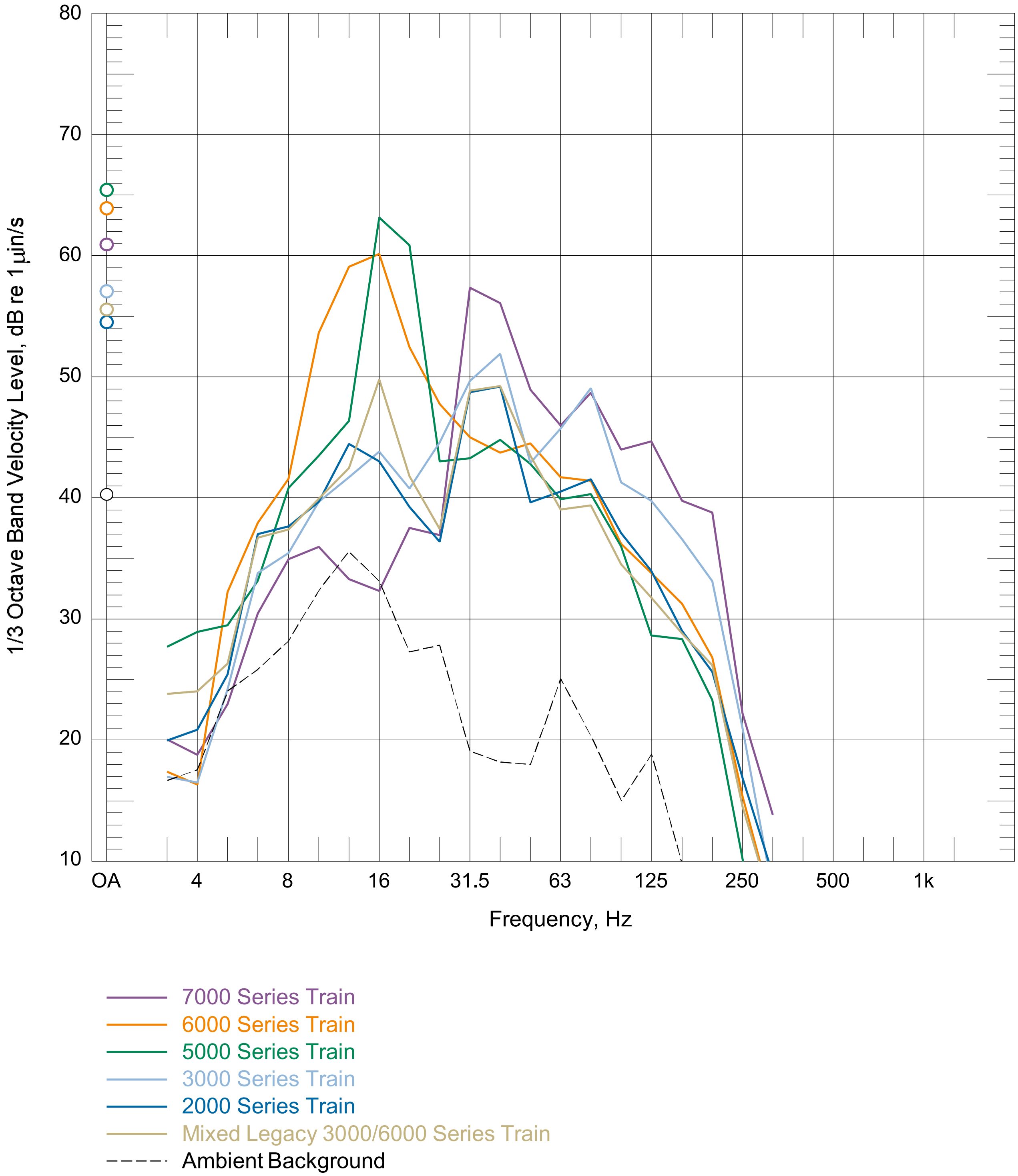


Figure 118: ***Site 6 at Location V3 Near Bedroom***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

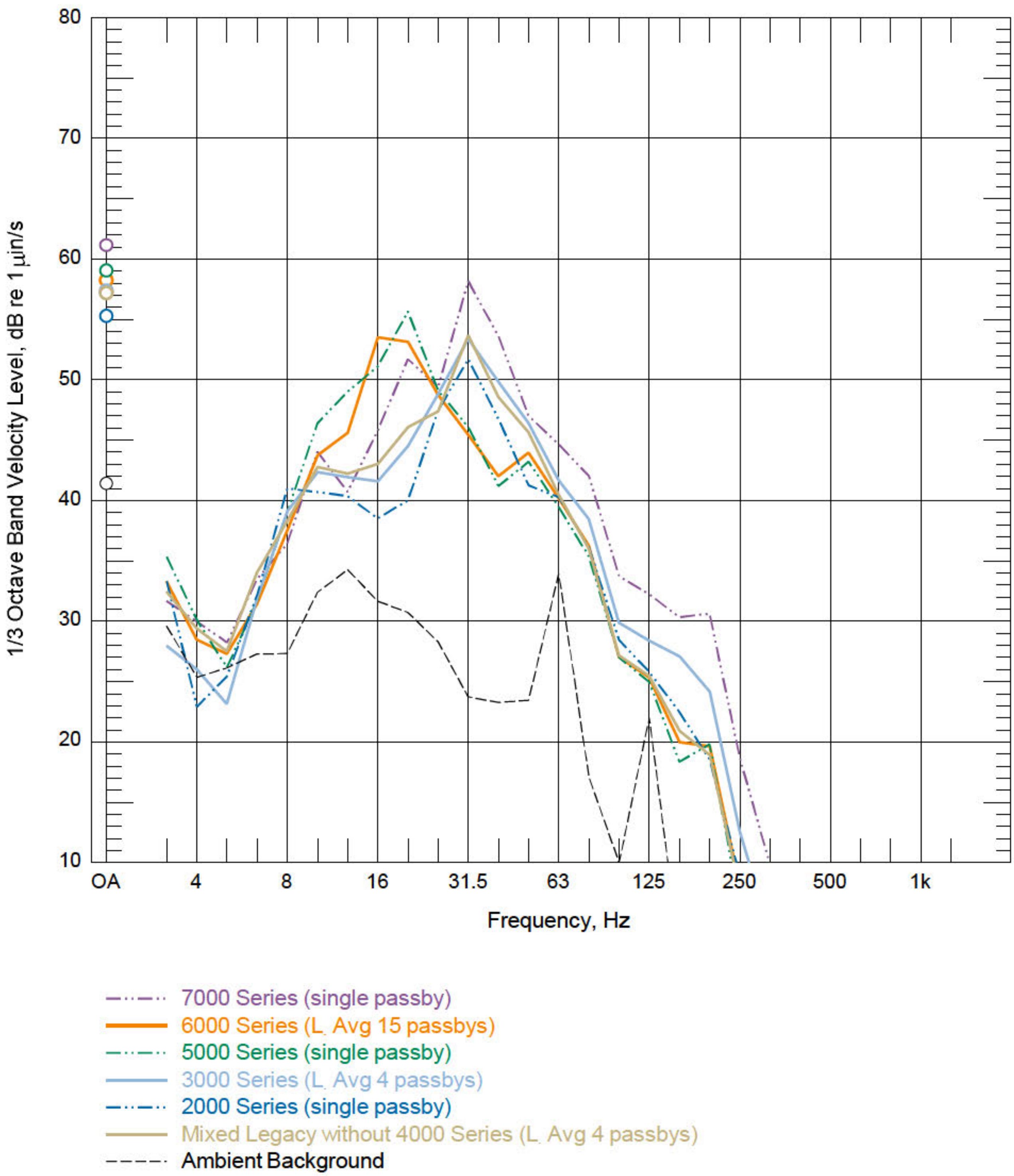


Figure 119: ***Site 6 at Location V5 Far Bedroom***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

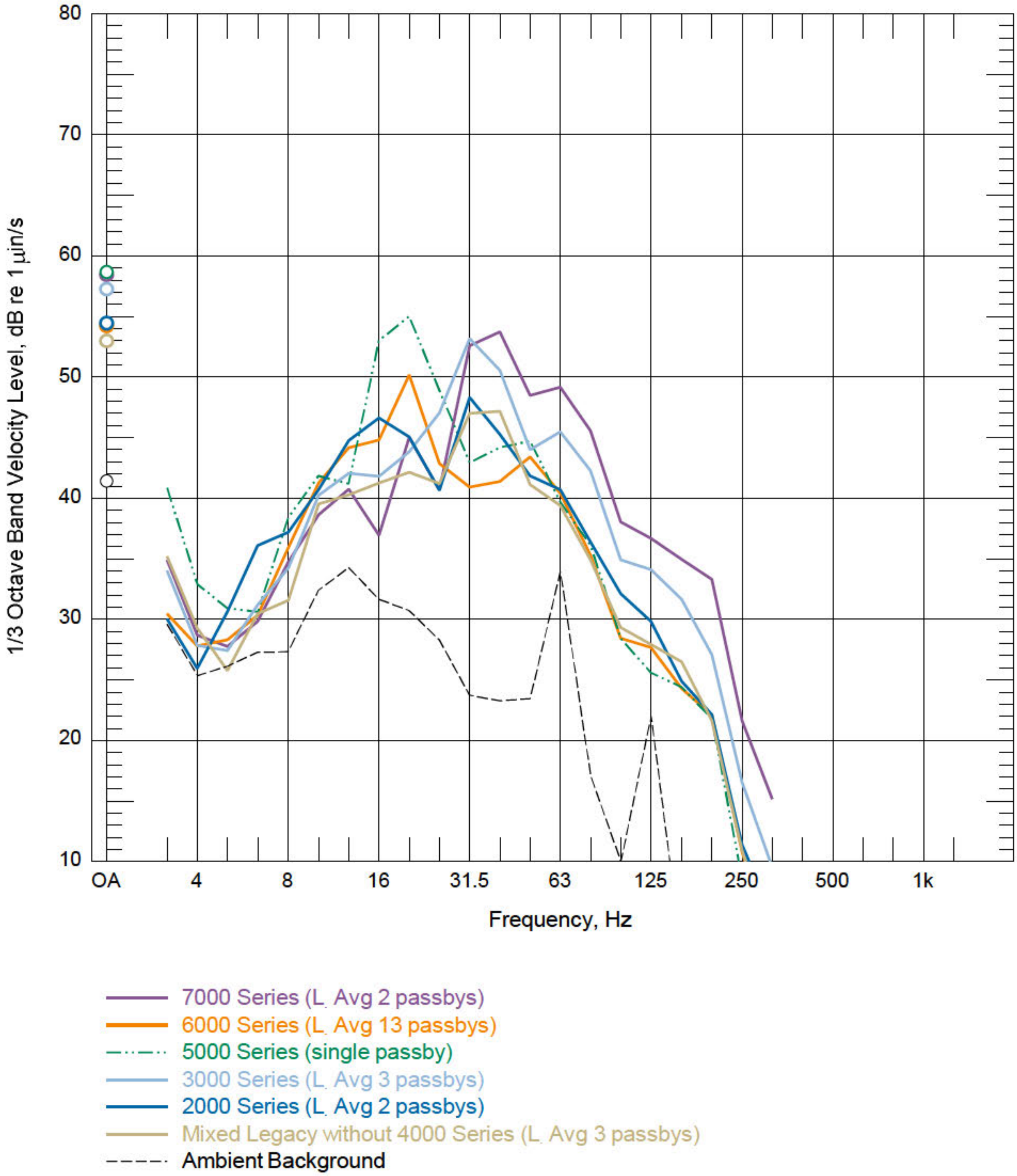


Figure 120: ***Site 6 at Location V5 Far Bedroom***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

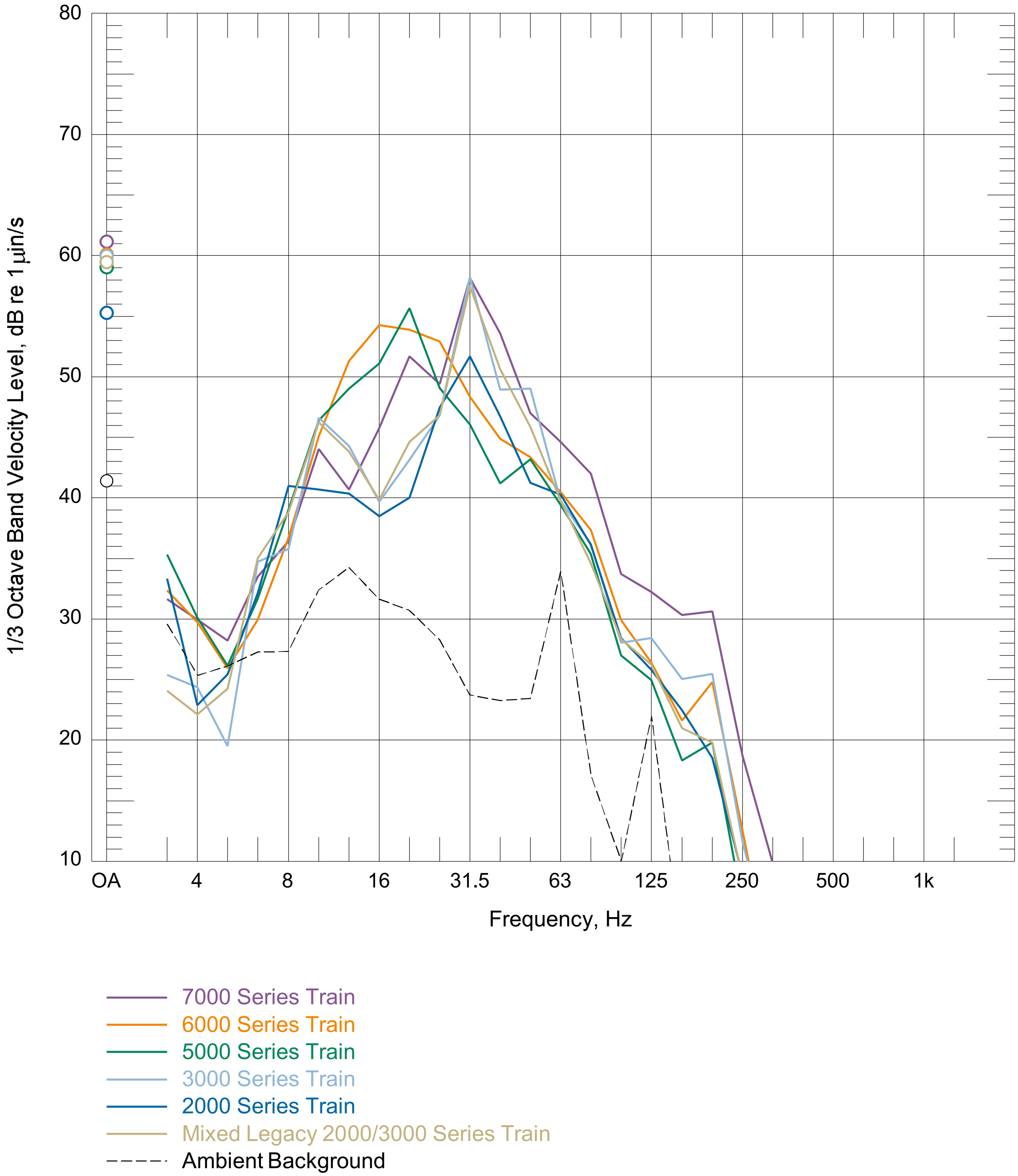


Figure 121: ***Site 6 at Location V5 Far Bedroom***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

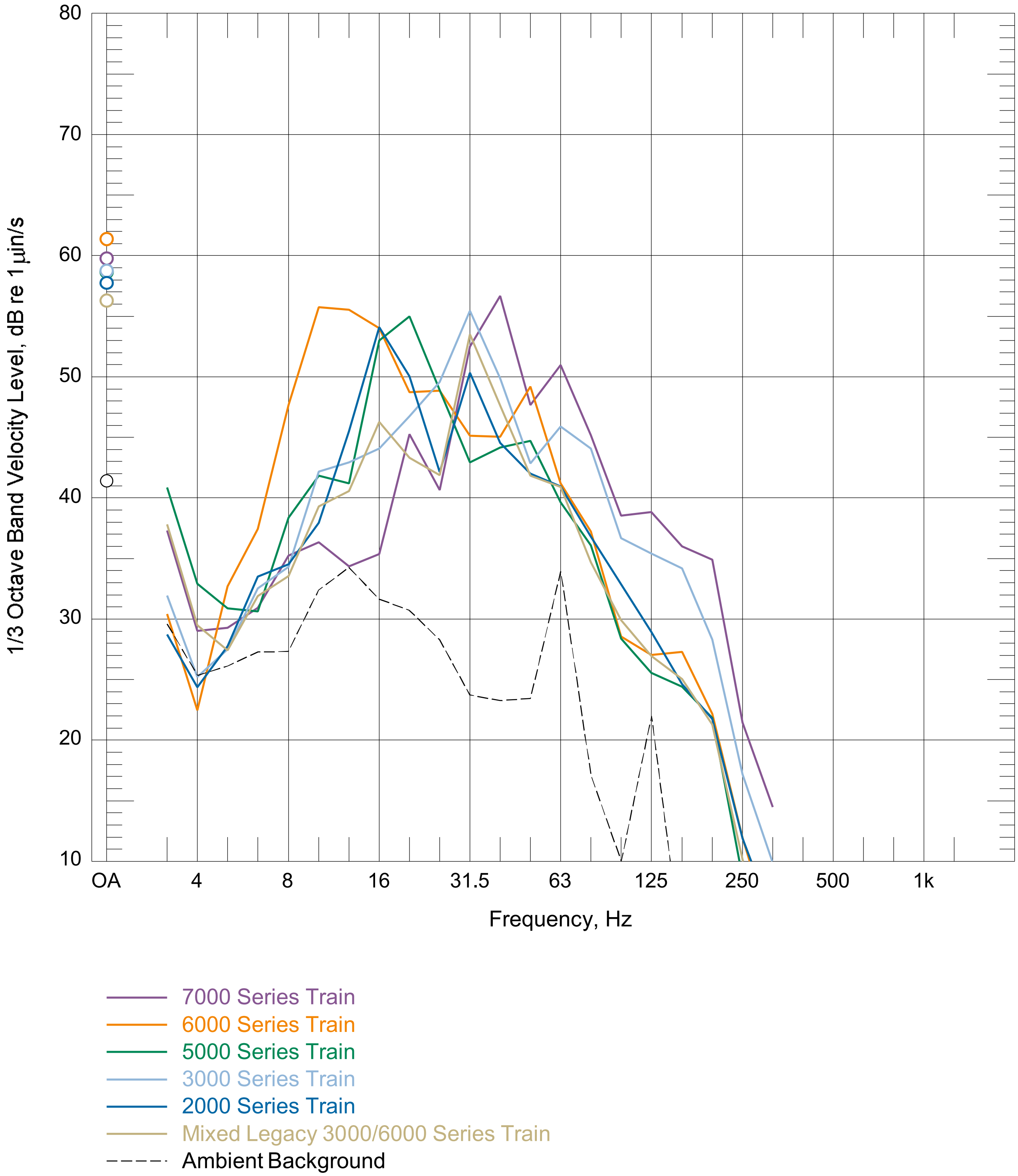


Figure 122: ***Site 6 at Location V5 Far Bedroom***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

B.6.6 Passby Ground-borne Noise Spectra and A-weighted Levels

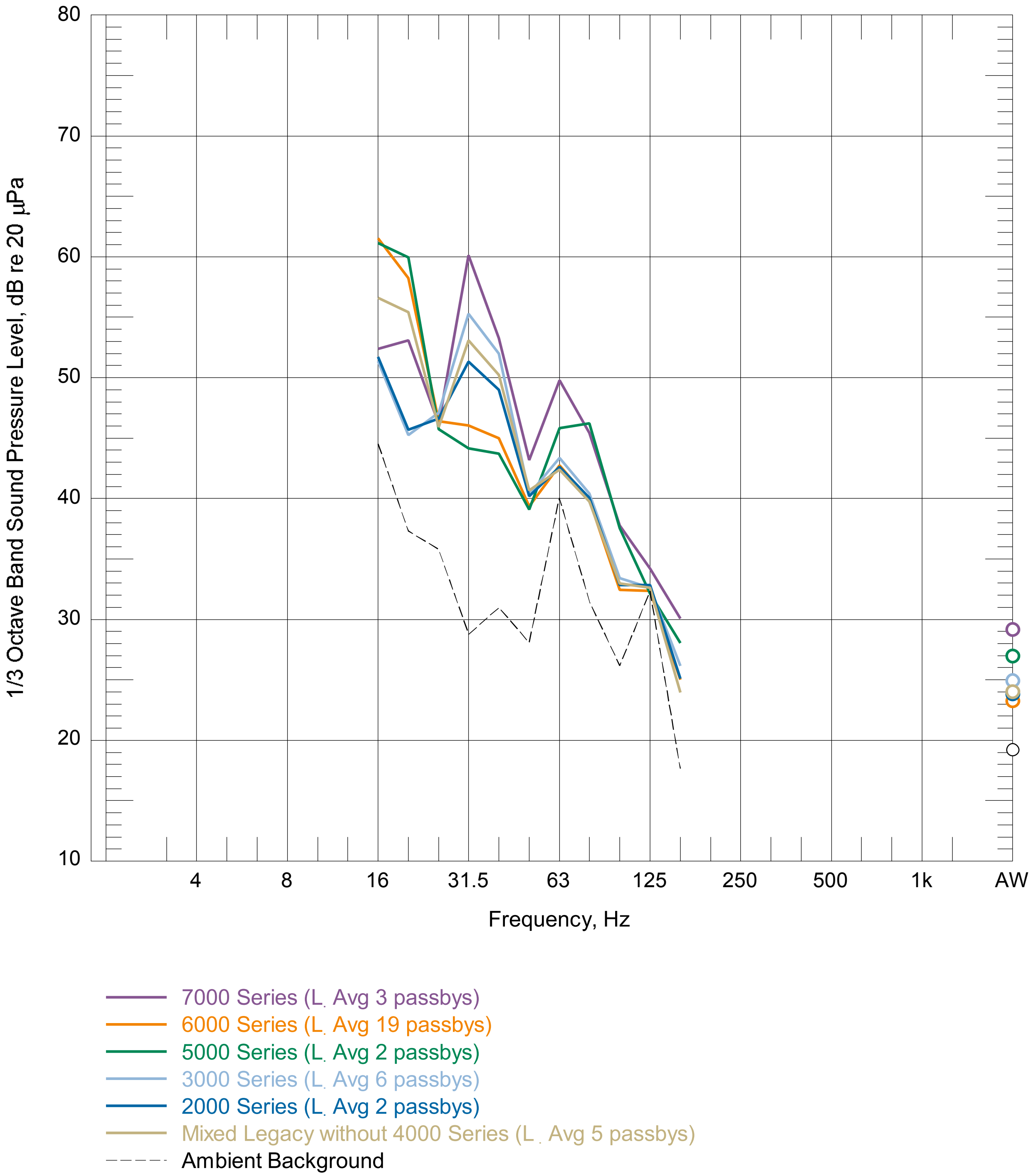


Figure 123: ***Site 6 at Location N1 Near Bedroom***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

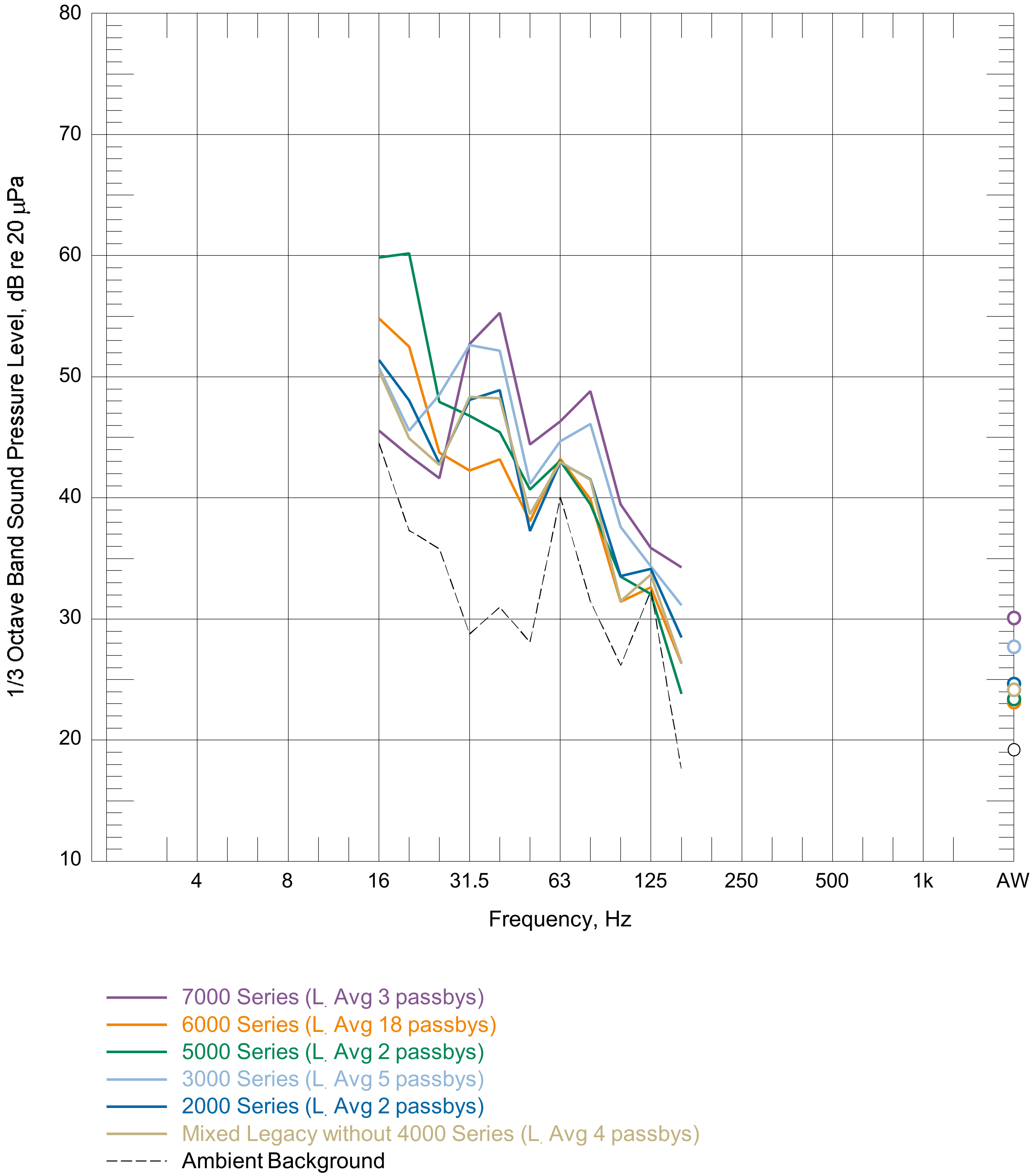


Figure 124: ***Site 6 at Location N1 Near Bedroom***
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

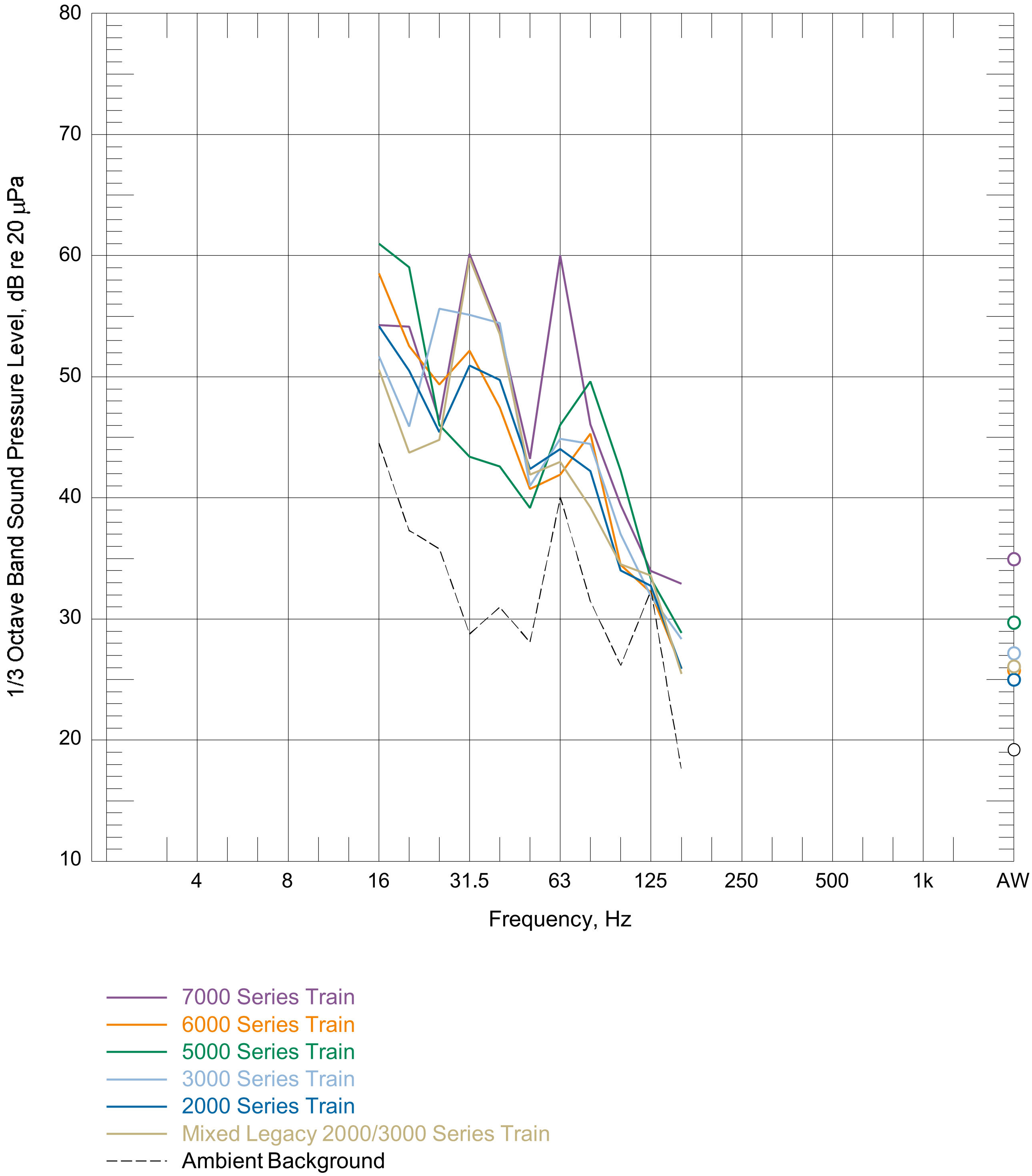


Figure 125: ***Site 6 at Location N1 Near Bedroom***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

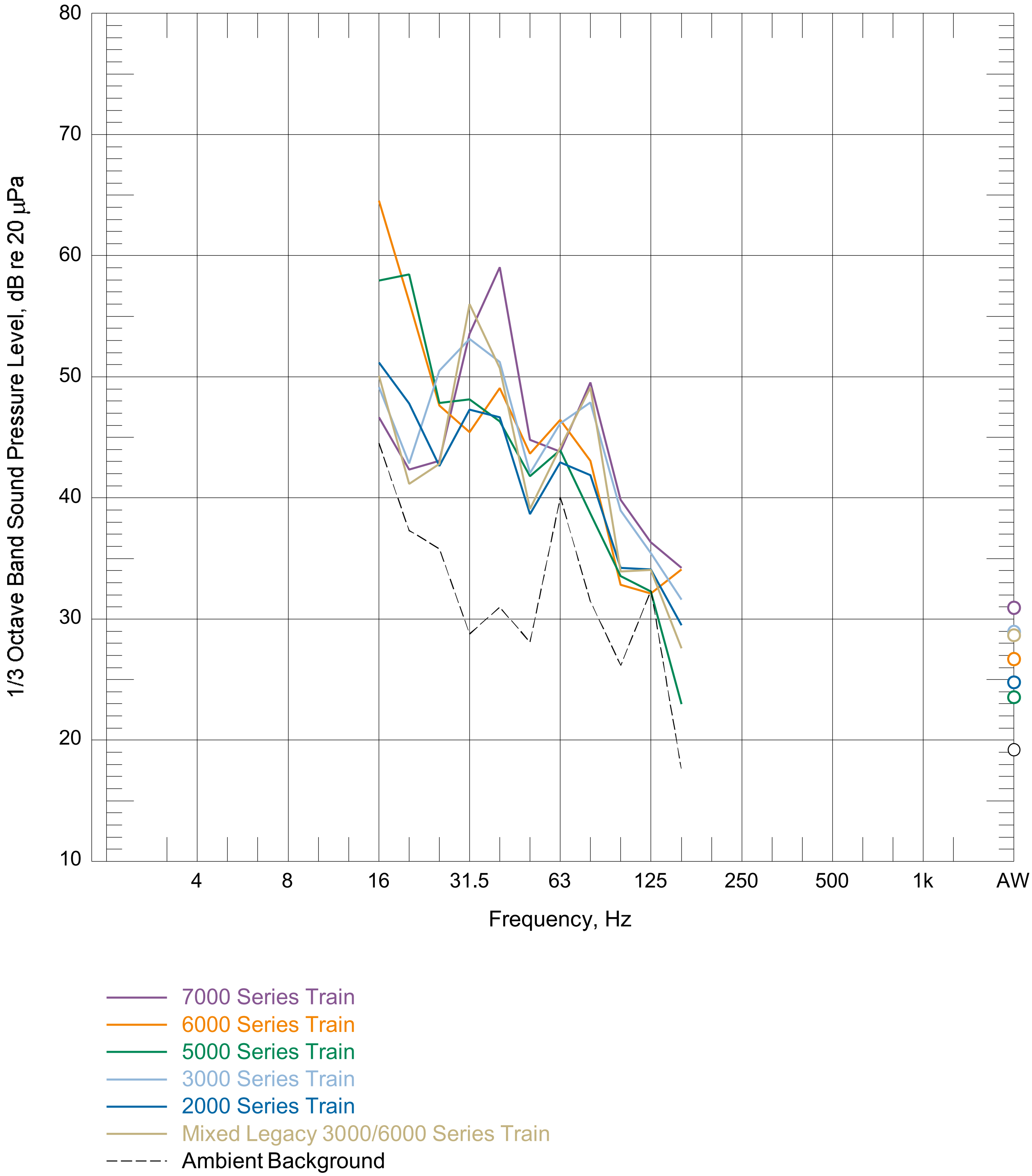


Figure 126: ***Site 6 at Location N1 Near Bedroom***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

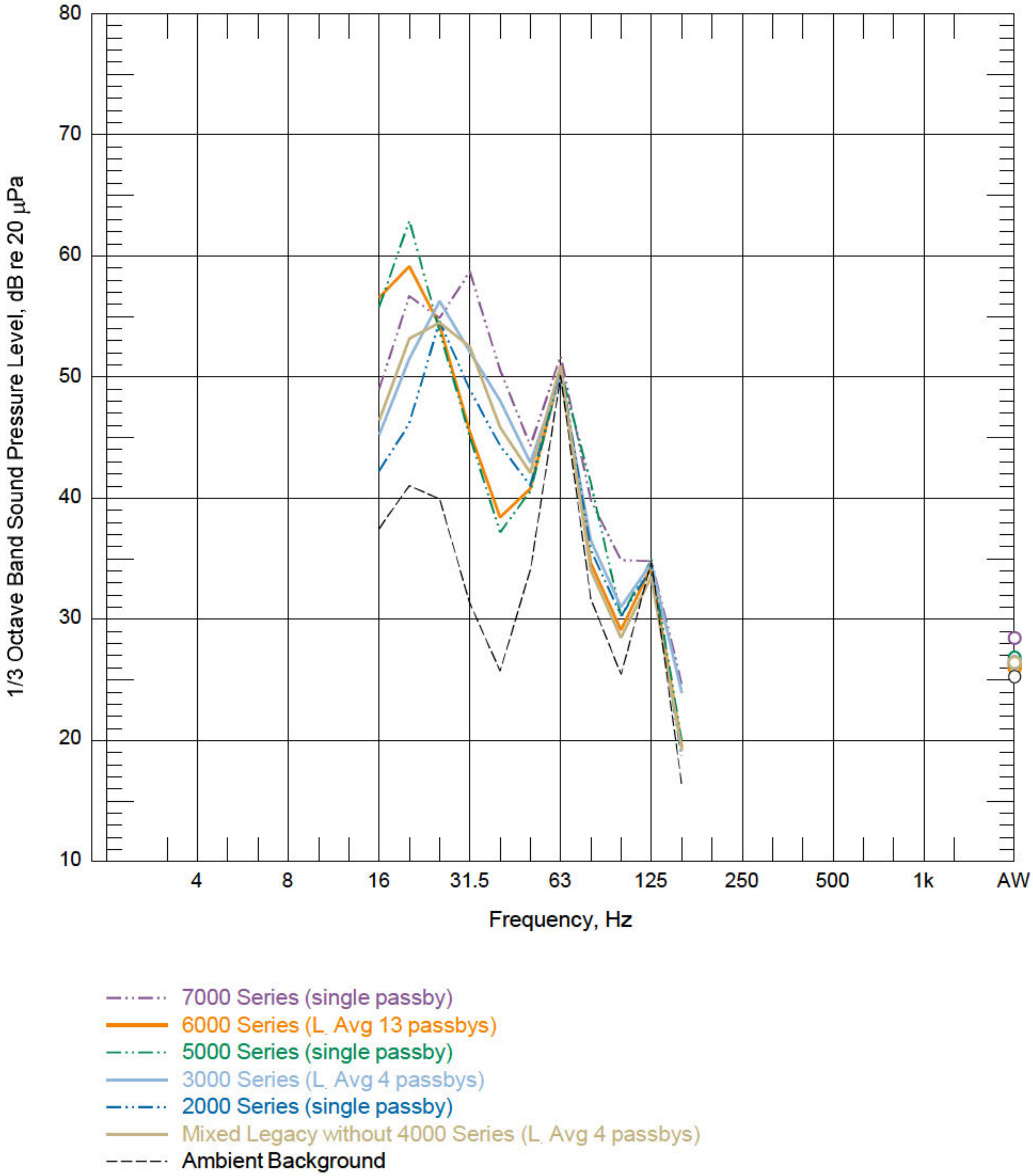


Figure 127: ***Site 6 at Location N2 Far Bedroom***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

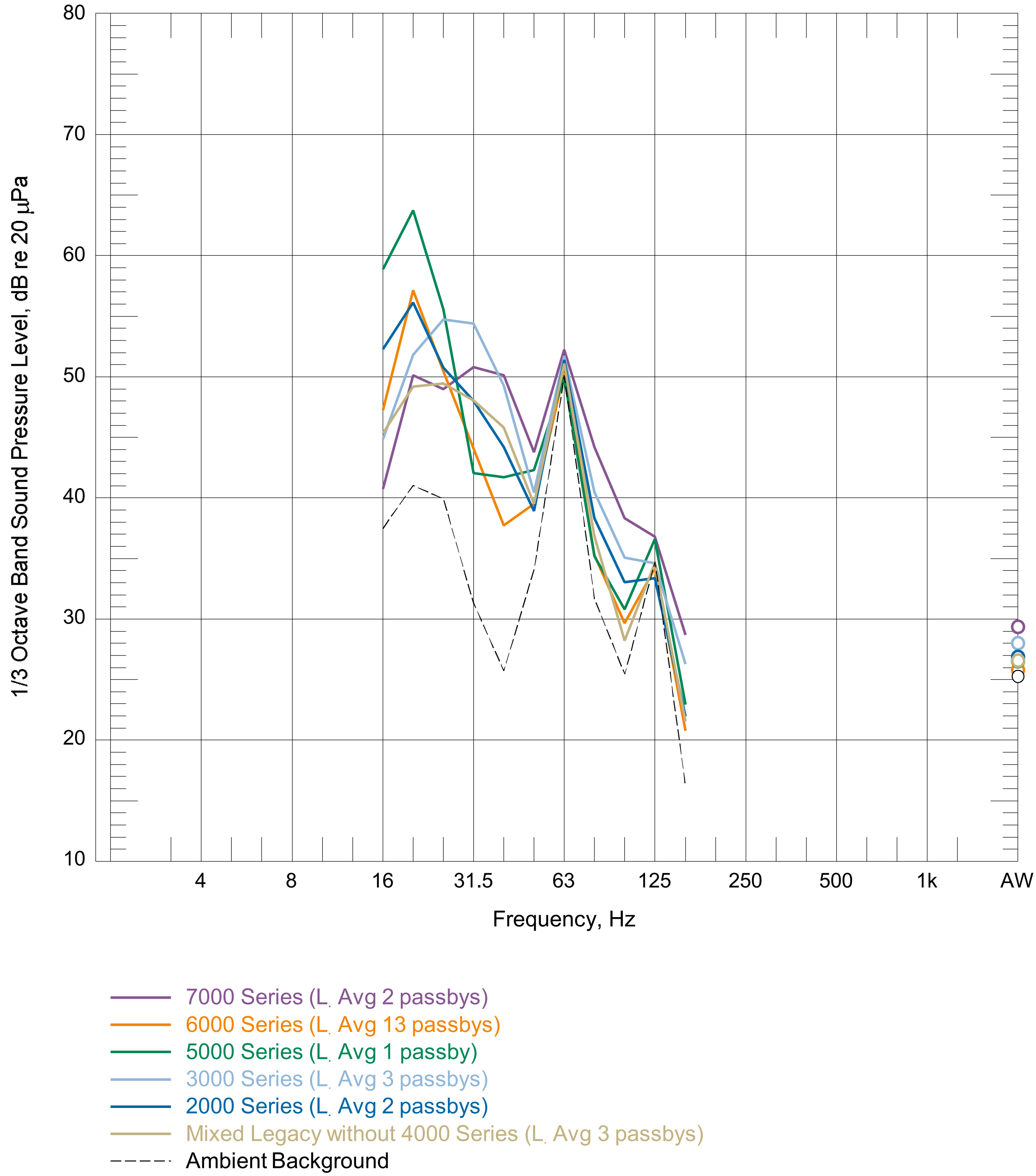


Figure 128: ***Site 6 at Location N2 Far Bedroom***
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

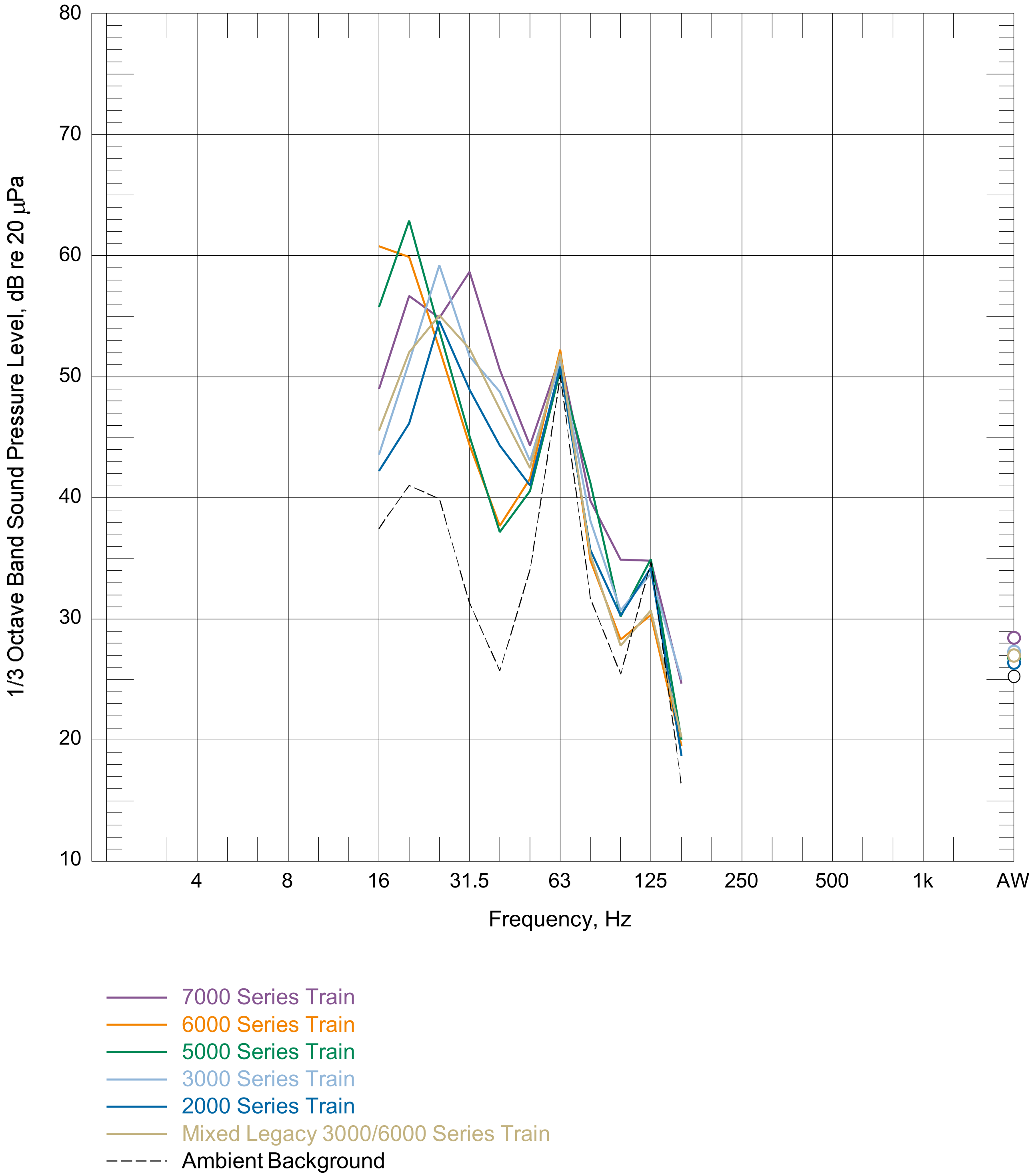


Figure 129: ***Site 6 at Location N2 Far Bedroom***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

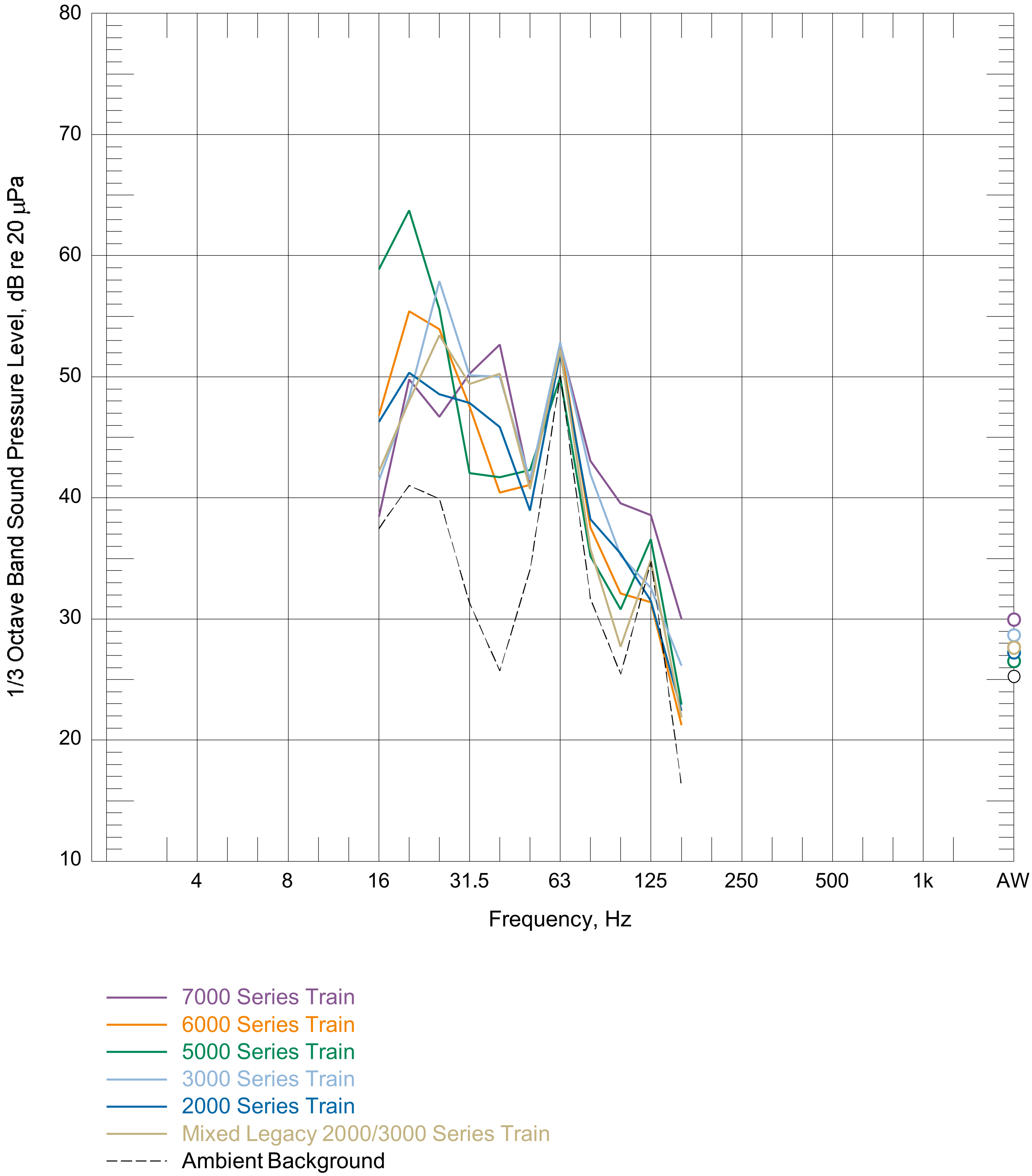


Figure 130: ***Site 6 at Location N2 Far Bedroom***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

B.7 Site 7 – 4300 block New Hampshire Avenue NW (Residence)

B.7.1 Building and Tunnel Notes

Location: Outbound Track 1 side at 203+50

Building Notes: multi-family residential townhouse, 3 floors comprised of partially-underground basement plus 2 upper floors, exterior wall of brick construction, wood frame construction?

Tunnel Structure: Earth Tunnel

Track Type: Egg Fasteners

T/R Depth: 65 feet

Train Speed: 29 to 61 mph

Measurement Period: Wednesday, 7 June 2017, 8:30 to 12:40

Field Observations: construction outside on street during measurements, which made some of the measured data unusable for train passby analysis

B.7.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Sensor[a,b,c]	Location / Room Occupancy	Horizontal Distance[d] (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)	Horizontal Distance (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)
Triaxial Geophone	Basement Bedroom No 1	79	65	102	42	65	77
V1	Basement Bedroom No 1						
N1	Basement Bedroom No 1						
V2	Basement Bedroom No 2						
N2	Basement Bedroom No 2						
V3	1st Floor Living Room						
V4	Outside House	55	65	85	19	65	68

Notes:

a) Tri-axial geophone mounted on floor, logging peak particle velocity
b) V# vibration locations with accelerometer mounted on floor in vertical direction
c) N# noise locations with microphone/sound level meter mounted on tripod 48 inches feet above floor
d) Horizontal distance from track to building façade for indoor locations, not accounting for tunnel depth.
e) T/R depth = top-of-rail depth
f) Total slant distance to T/R = total distance from building to track, accounting for tunnel depth

Figure 131: Aerial Map of 4300 block of New Hampshire Residence and Exterior Measurement Location at Site 7 (nearby Sites 8, 9, and 10 also shown for reference)

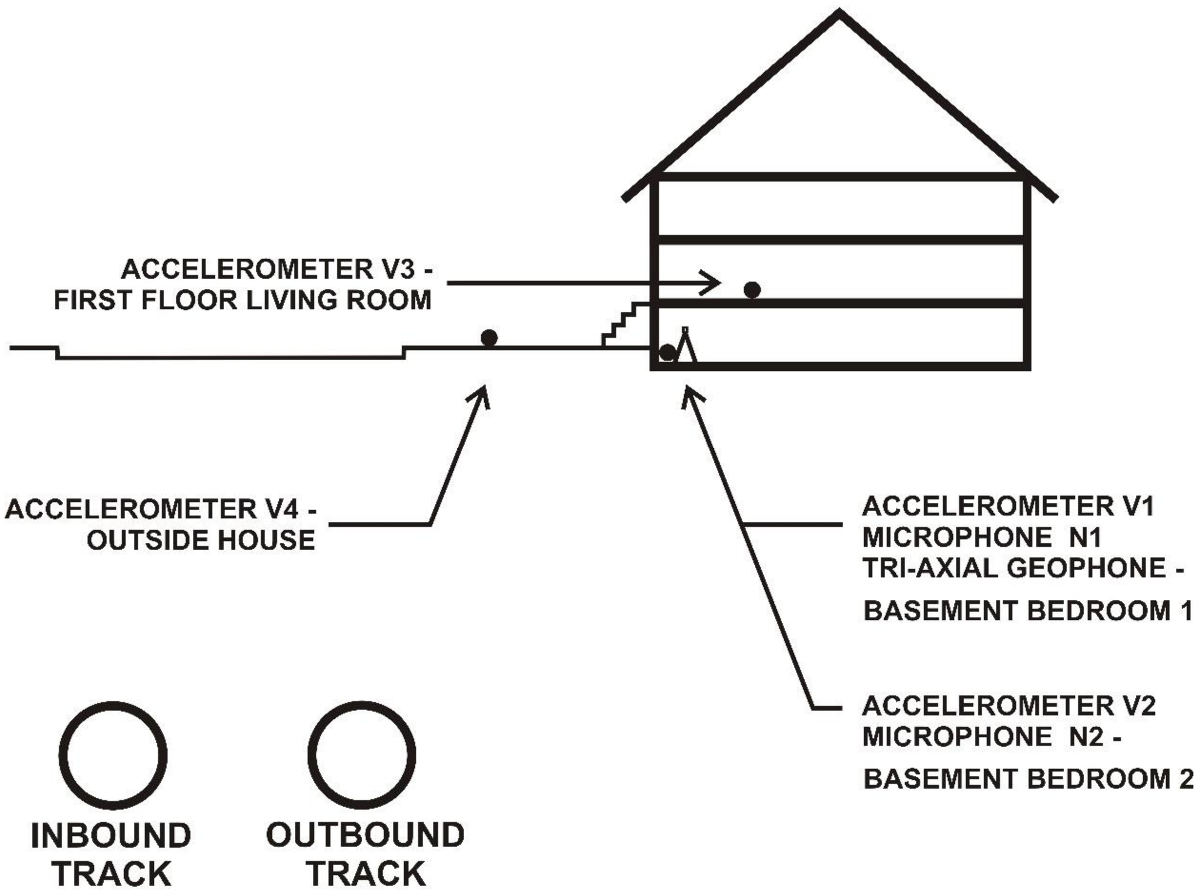


Figure 132: Cross-section Sketch (not to scale) of 4300 block of New Hampshire Indoor and Exterior Measurement Locations

B.7.3 GBNV Assessment Summary

SITE 7	4300 block of NEW HAMPSHIRE NW – ATTENDED PASSBY MEASUREMENT GBNV ASSESSMENT		
	Ground-borne Vibration (GBV)	**>70 VdB?**	**Notes**
	7000 Series - Average of Multiple Passbys	NO	
	6000 Series - Average of Multiple Passbys	NO	
	3000 Series - Average of Multiple Passbys	NO	
	Mixed Legacy with 4000 Series - Single Passby	NO	
	Mixed Legacy without 4000 Series - Average of Multiple Passbys	NO	
	7000 Series - Individual Train with Highest Overall Vibration	NO	
	6000 Series - Individual Train with Highest Overall Vibration	NO	
	3000 Series - Individual Train with Highest Overall Vibration	NO	
	Mixed Legacy - Individual Train with Highest Overall Vibration	NO	
	Ground-borne Noise (GBN)	**>40 dBA?**	**Notes**
	7000 Series - Average of Multiple Passbys	NO	
	6000 Series - Average of Multiple Passbys	NO	
	3000 Series - Average of Multiple Passbys	NO	
	Mixed Legacy without 4000 Series (Average of Multiple Passbys)	NO	
	7000 Series - Individual Train with Highest A-weighting	NO	
	6000 Series - Individual Train with Highest A-weighting	NO	
	3000 Series - Individual Train with Highest A-weighting	NO	
	Mixed Legacy - Individual Train with Highest A-weighting	NO	

B.7.4 PPV Results

SITE 7	4300 block of NEW HAMPSHIRE NW – POTENTIAL FOR BUILDING VIBRATION DAMAGE ASSESSMENT						
	>0.2 in/sec PPV in any direction?	Average PPV (in/s)			PPV Range (in/s)		
		Tran	Vert	Long	Tran	Vert	Long
	NO	0.0006	0.0005	0.0003	0 - 0.0012	0 - 0.0118	0 - 0.0016
Basement 7-Jun-17, 8:38:58 AM to 12:41:10 PM							

B.7.5 Passby Vibration Spectra and Overall Levels

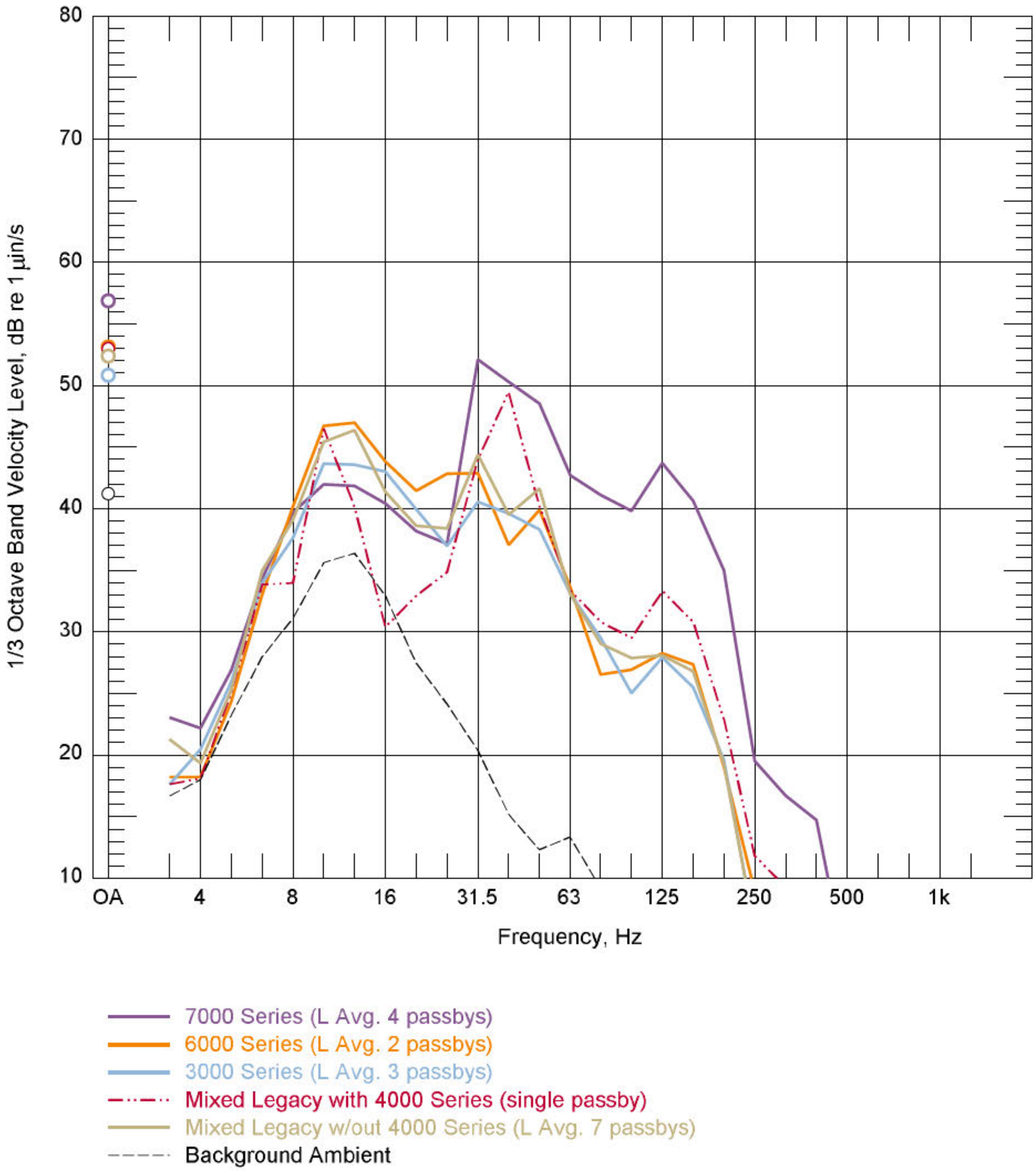


Figure 133: ***Site 7 at Location V1 Basement Bedroom #1***
Outbound Trains on Track 1 (near track)
Average Vibration Levels by Vehicle Type

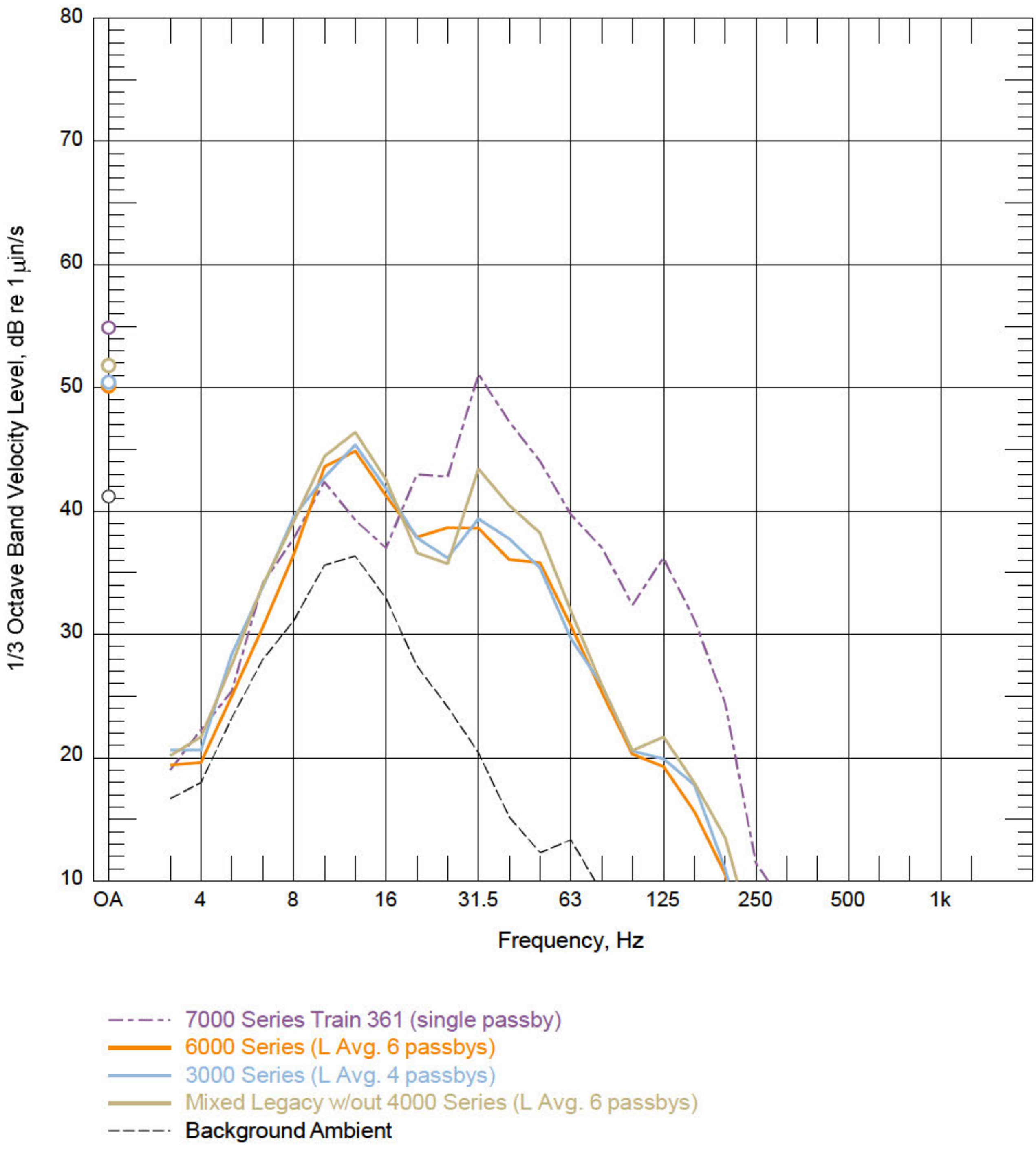


Figure 134: ***Site 7 at Location V1 Basement Bedroom #1***
Inbound Trains on Track 2 (far track)
Average Vibration Levels by Vehicle Type

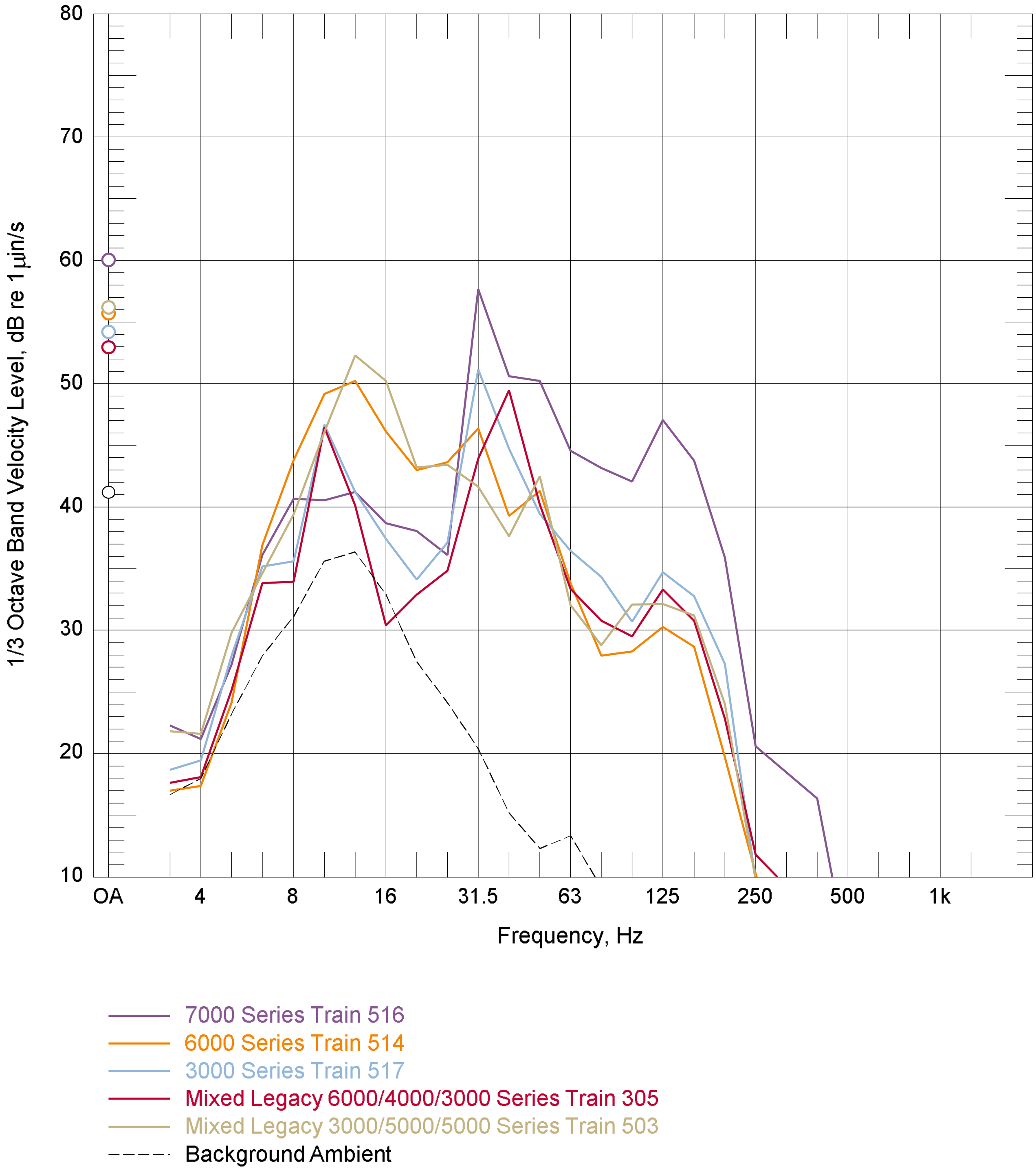


Figure 135: ***Site 7 at Location V1 Basement Bedroom #1***
Outbound Trains on Track 1 (near track)
Individual Train with Highest Overall Vibration

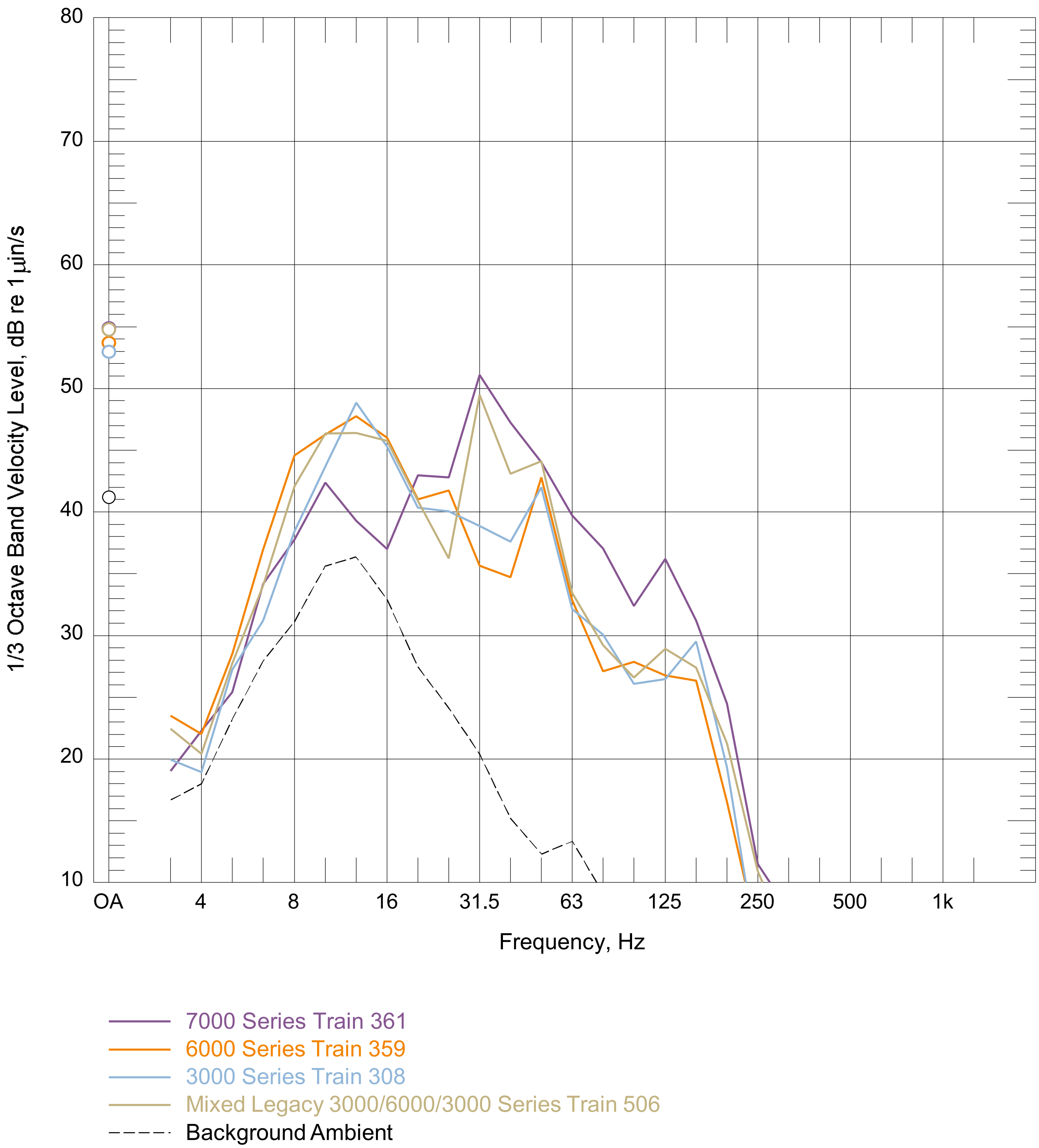


Figure 136: ***Site 7 at Location V1 Basement Bedroom #1***
Inbound Trains on Track 2 (far track)
Average Vibration Levels by Vehicle Type

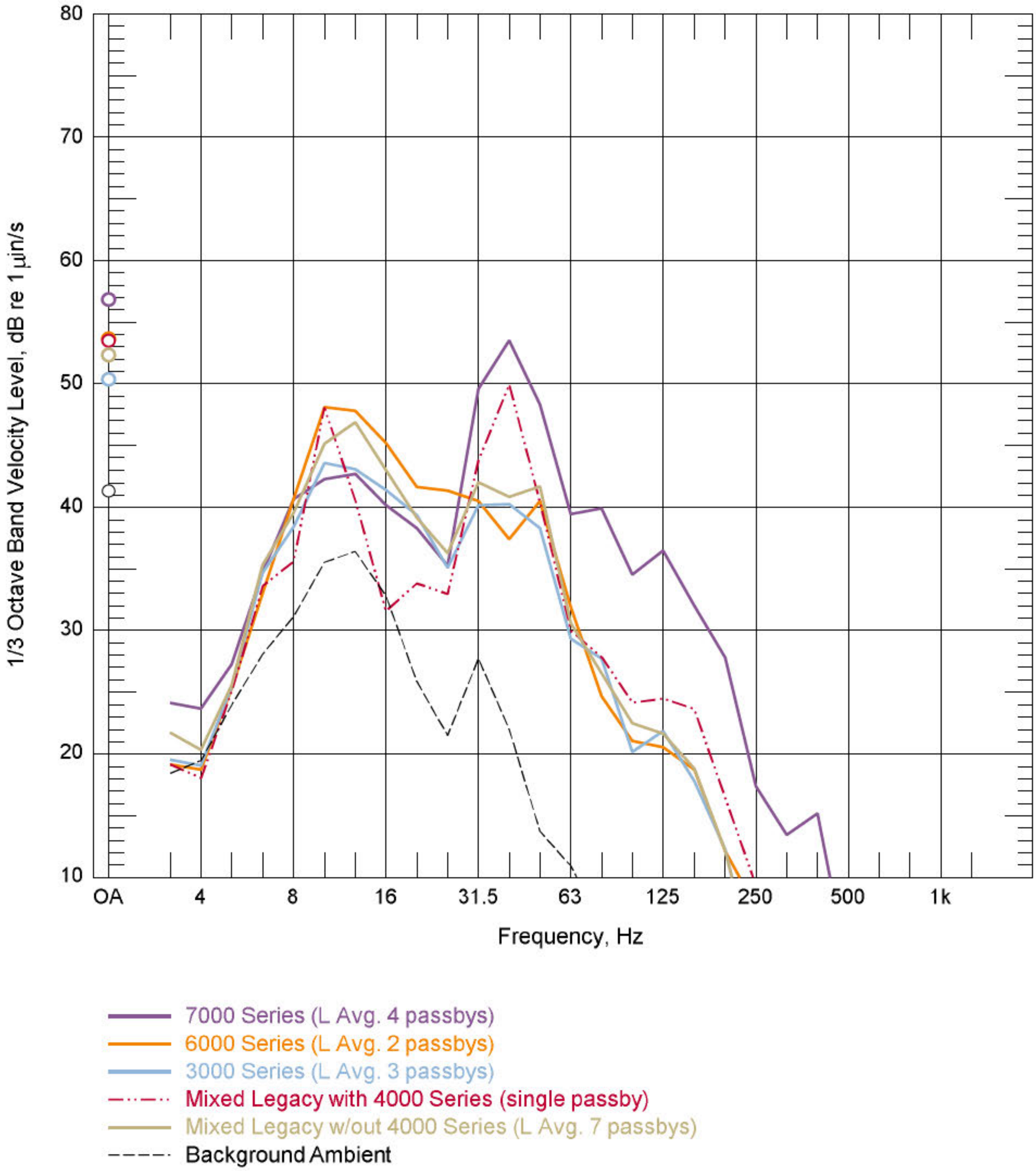


Figure 137: ***Site 7 at Location V2 Basement Bedroom #2***
Outbound Trains on Track 1 (near track)
Average Vibration Levels by Vehicle Type

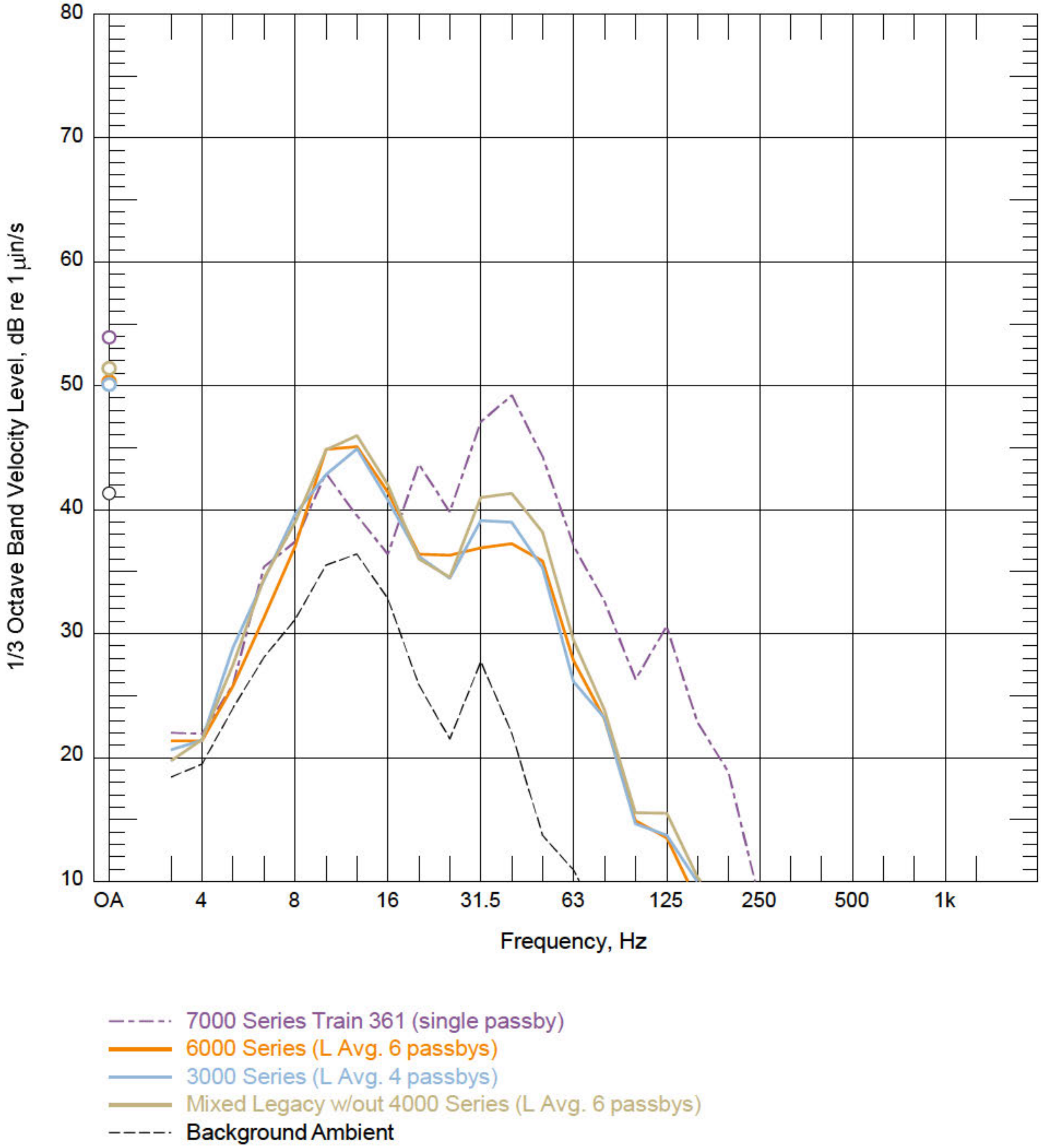


Figure 138: ***Site 7 at Location V2 Basement Bedroom #2***
Inbound Trains on Track 2 (far track)
Average Vibration Levels by Vehicle Type

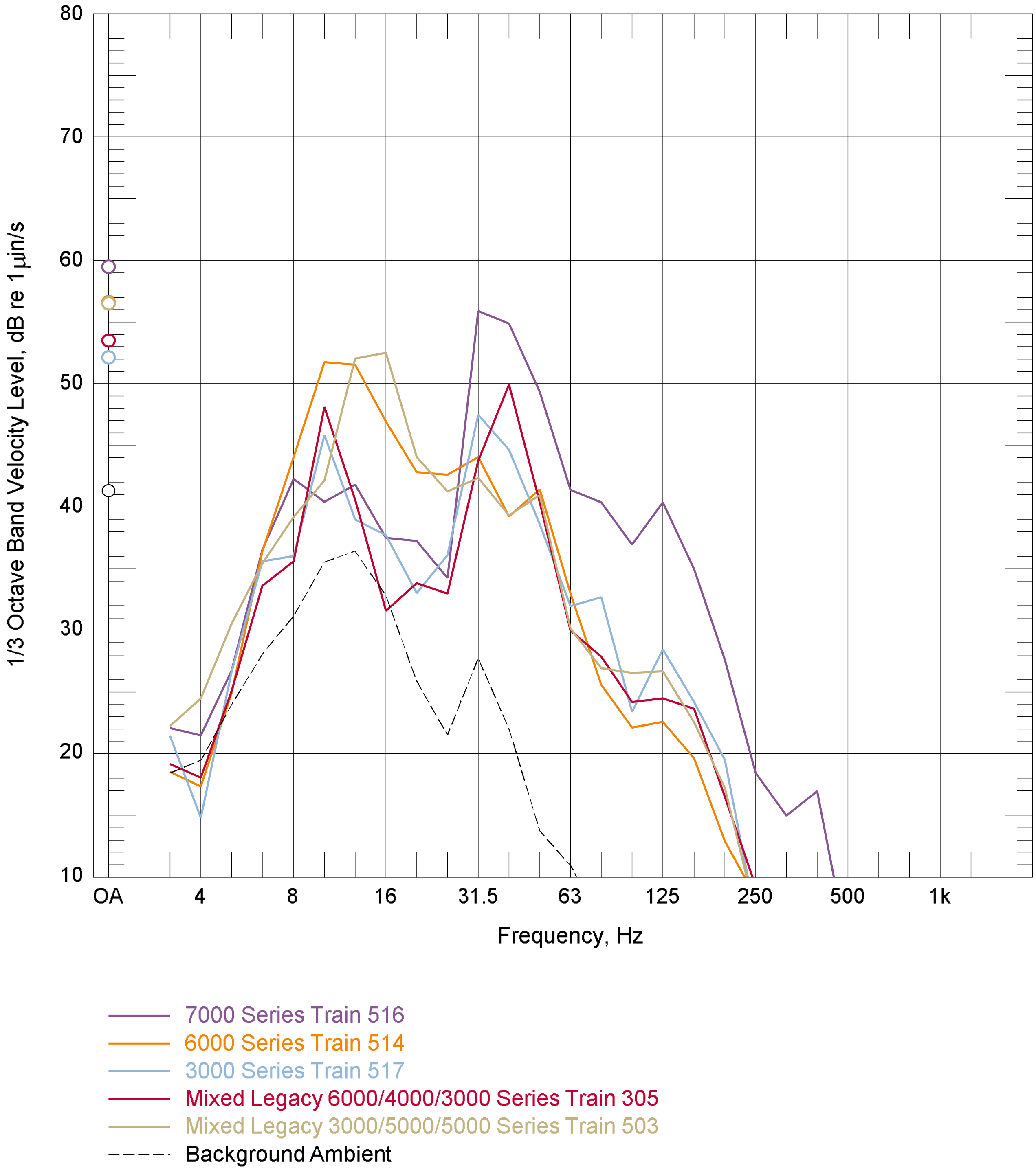


Figure 139: ***Site 7 at Location V2 Basement Bedroom #2***
Outbound Trains on Track 1 (near track)
Individual Train with Highest Overall Vibration

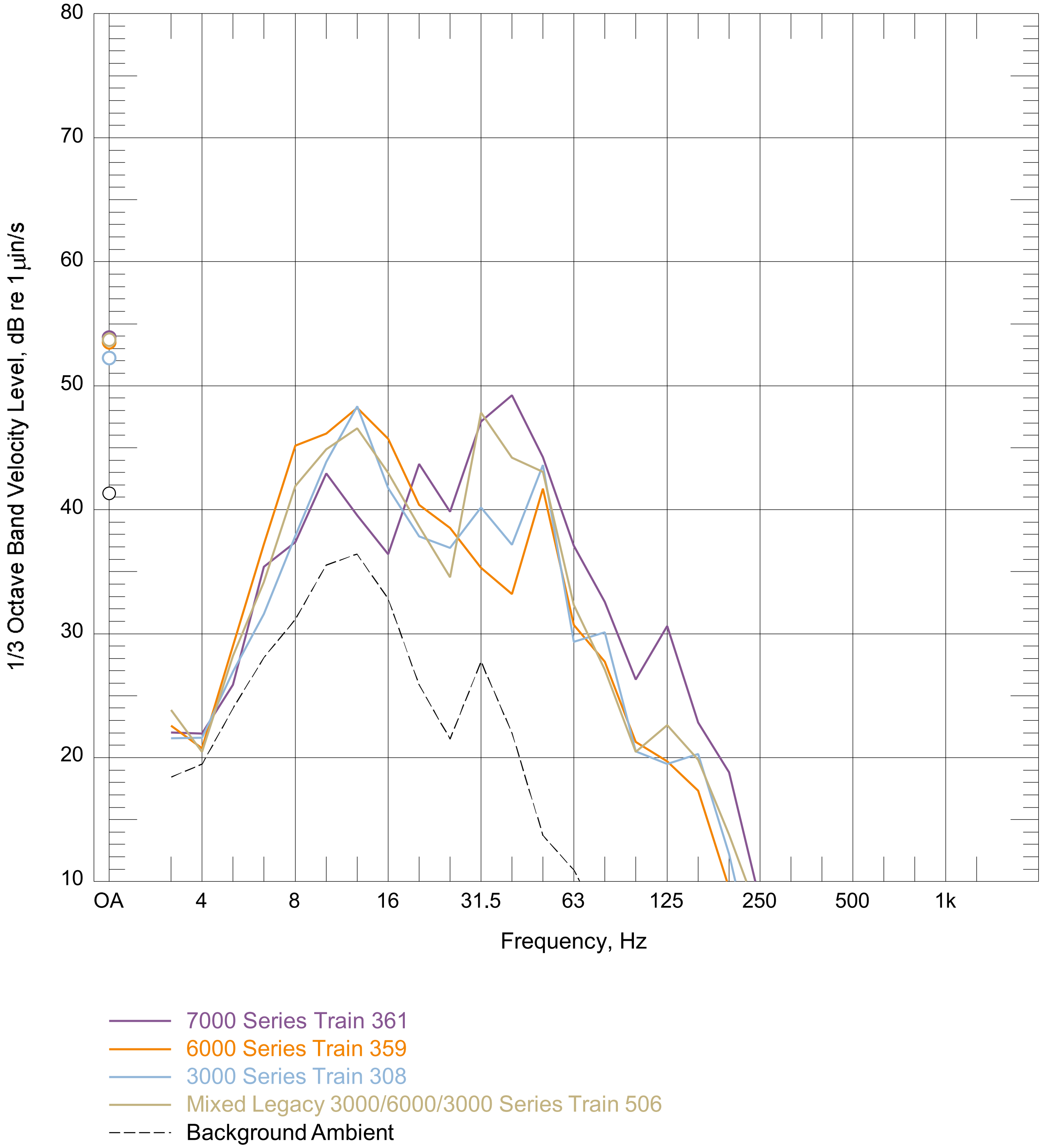


Figure 140: ***Site 7 at Location V2 Basement Bedroom #2***
Inbound Trains on Track 2 (far track)
Individual Train with Highest Overall Vibration

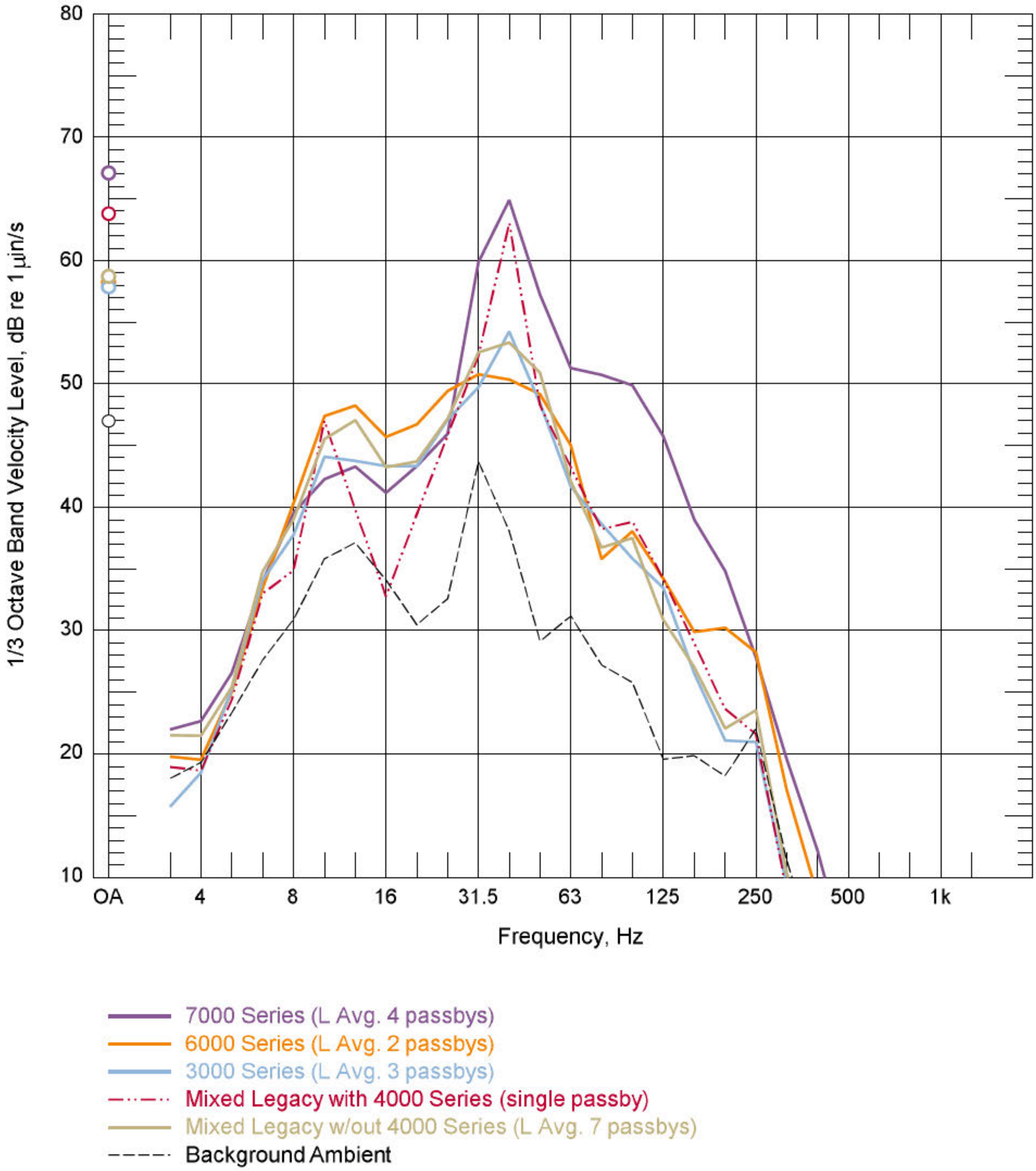


Figure 141: ***Site 7 at Location V3 First Floor Living Room***
Outbound Trains on Track 1 (near track)
Average Vibration Levels by Vehicle Type

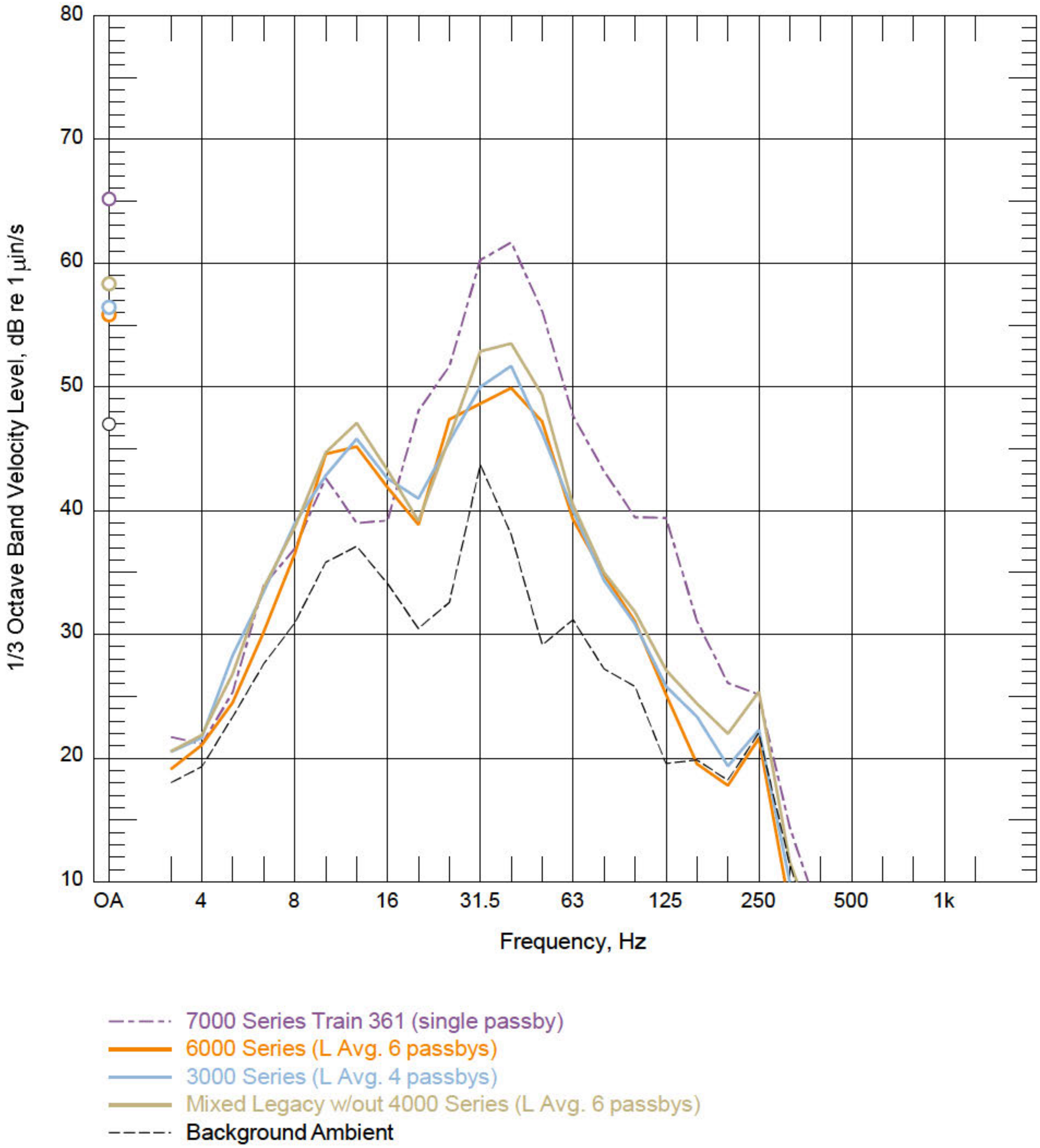


Figure 142: ***Site 7 at Location V3 First Floor Living Room***
Inbound Trains on Track 2 (far track)
Average Vibration Levels by Vehicle Type

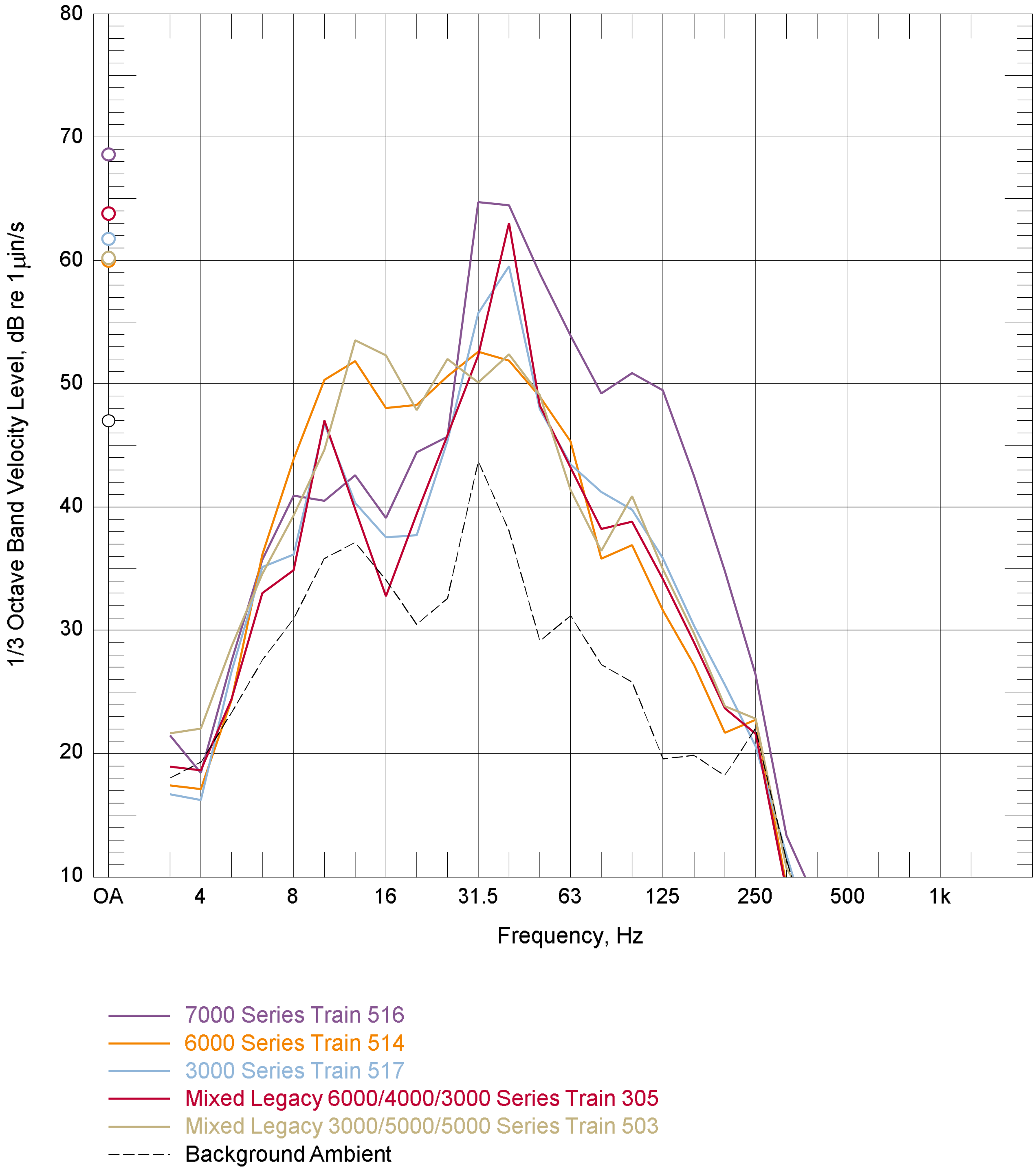


Figure 143: ***Site 7 at Location V3 First Floor Living Room***
Outbound Trains on Track 1 (near track)
Individual Train with Highest Overall Vibration

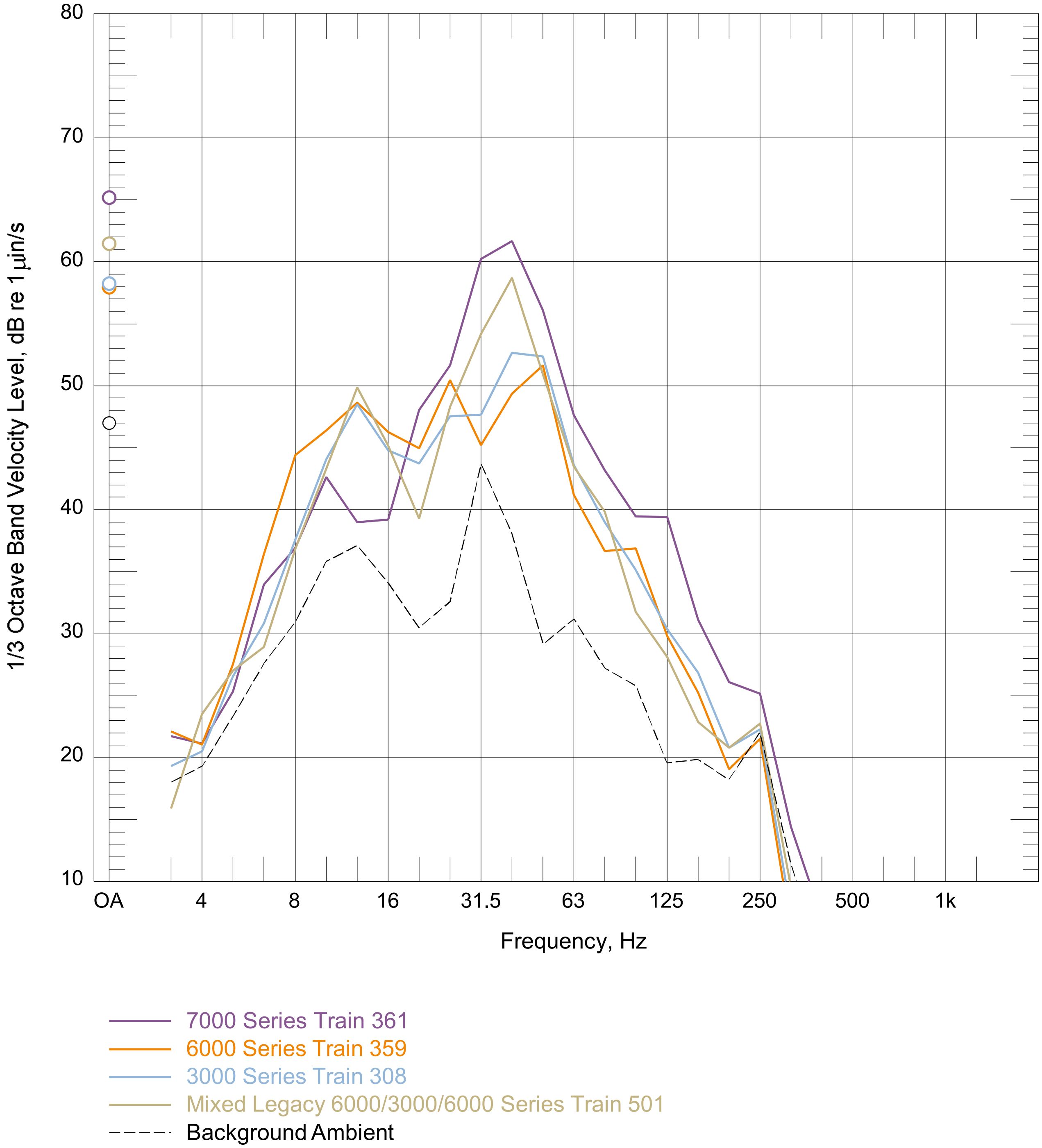


Figure 144: ***Site 7 at Location V3 First Floor Living Room***
Inbound Trains on Track 2 (far track)
Individual Train with Highest Overall Vibration

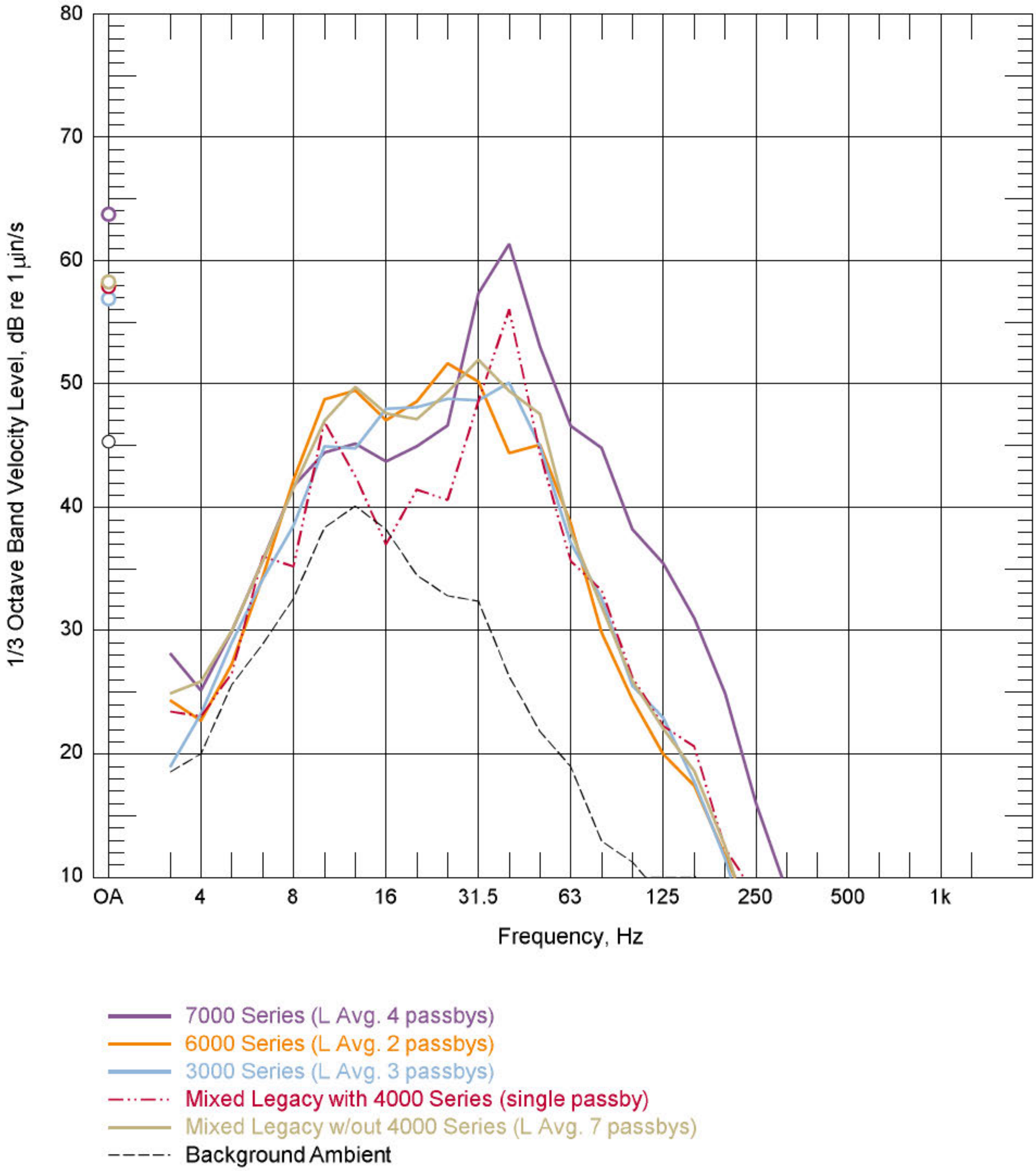


Figure 145: ***Site 7 at Location V4 Outside House***
Outbound Trains on Track 1 (near track)
Average Vibration Levels by Vehicle Type

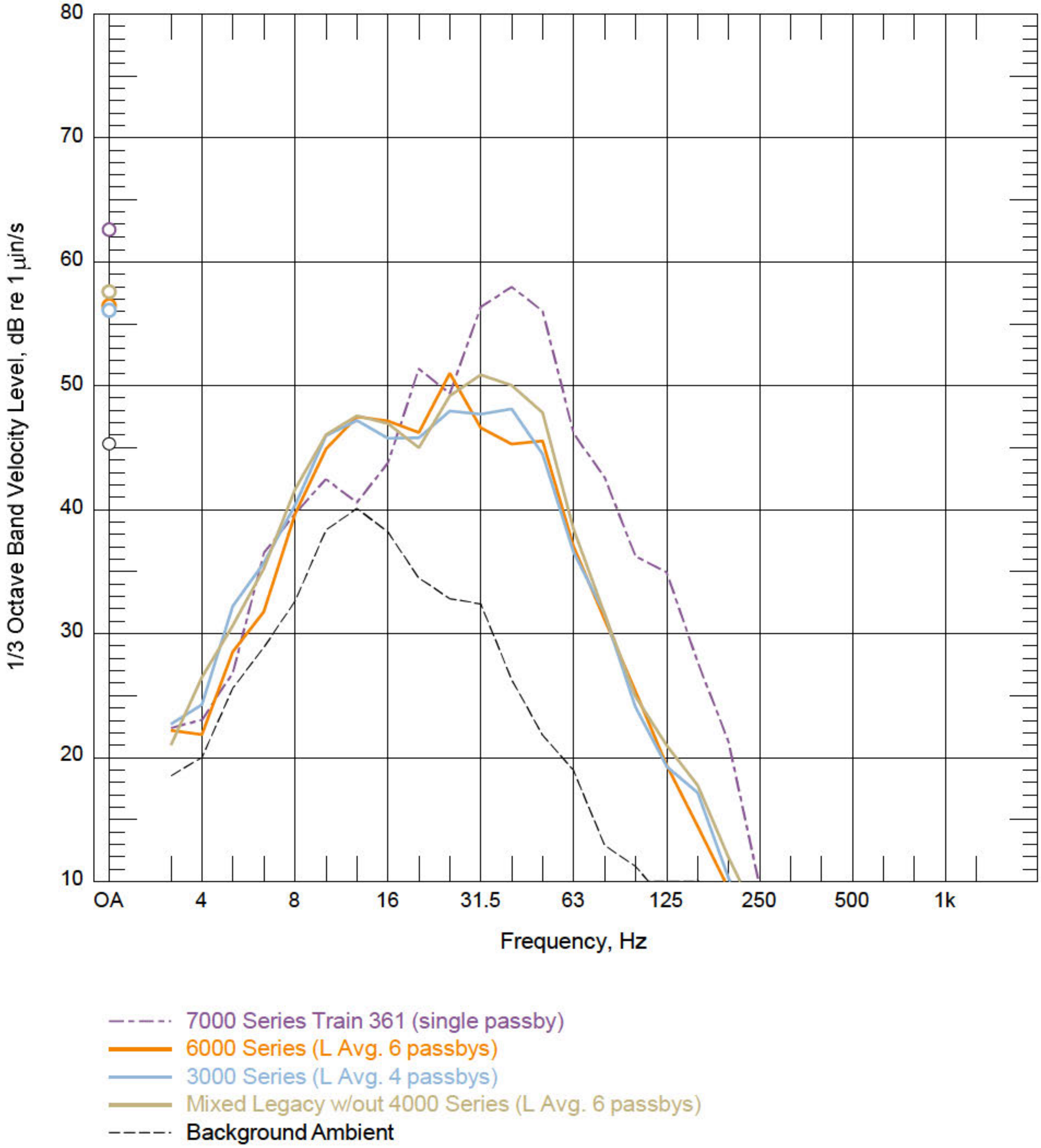


Figure 146: ***Site 7 at Location V4 Outside House***
Inbound Trains on Track 2 (far track)
Average Vibration Levels by Vehicle Type

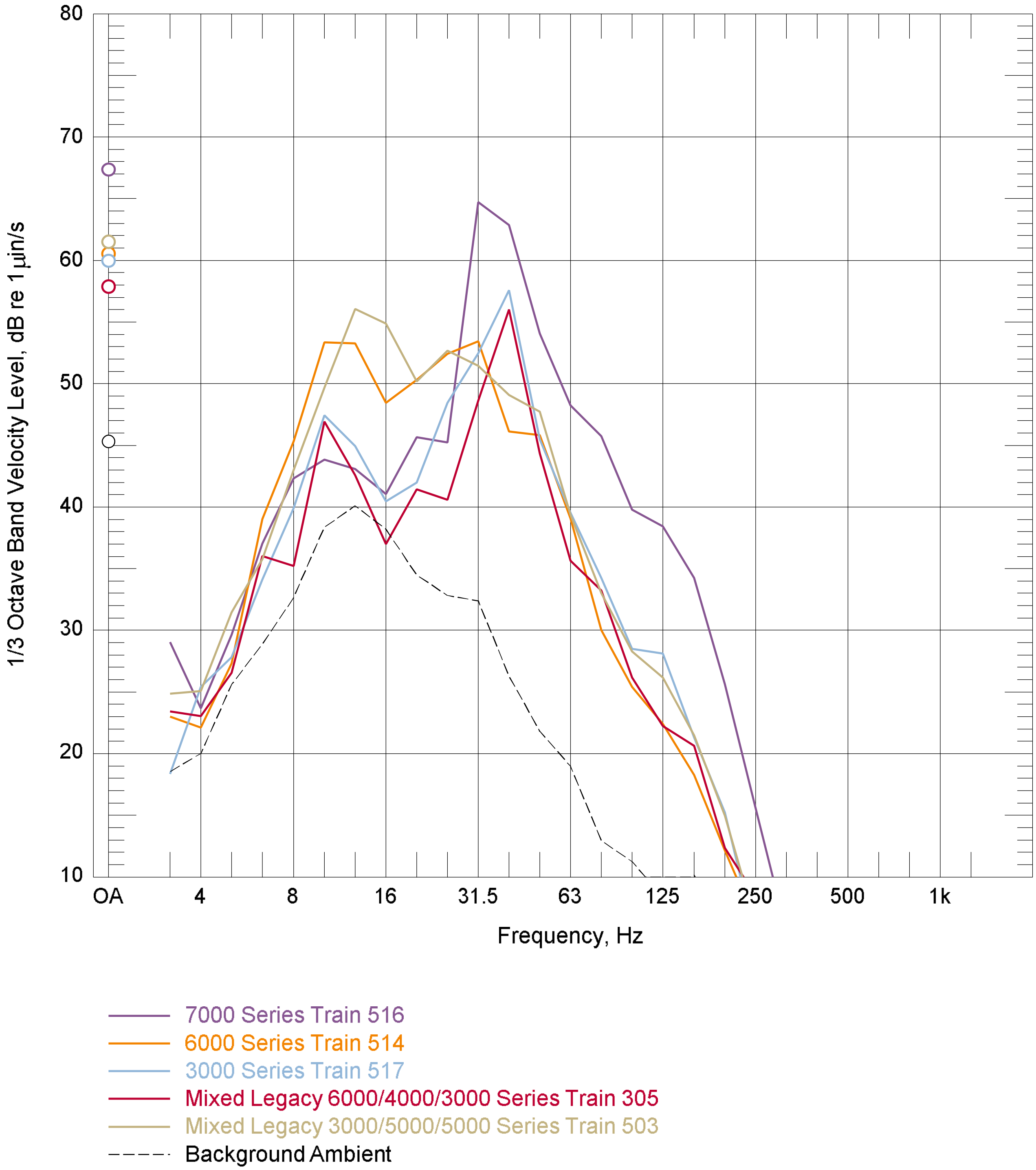


Figure 147: ***Site 7 at Location V4 Outside House***
Outbound Trains on Track 1 (near track)
Individual Train with Highest Overall Vibration

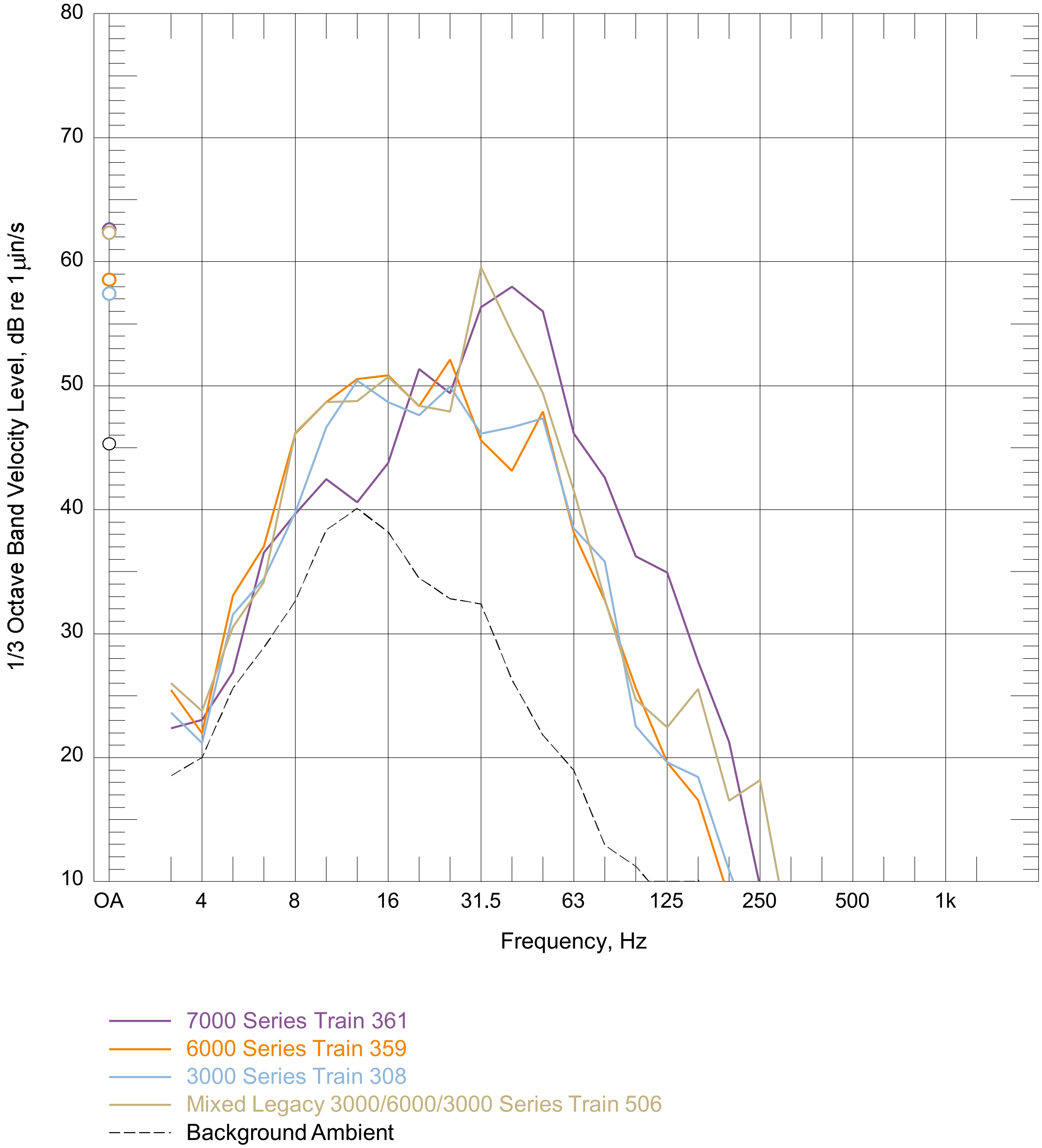


Figure 148: ***Site 7 at Location V4 Outside House***
Inbound Trains on Track 2 (far track)
Individual Train with Highest Overall Vibration

B.7.6 Passby Ground-borne Noise Spectra and A-weighted Levels

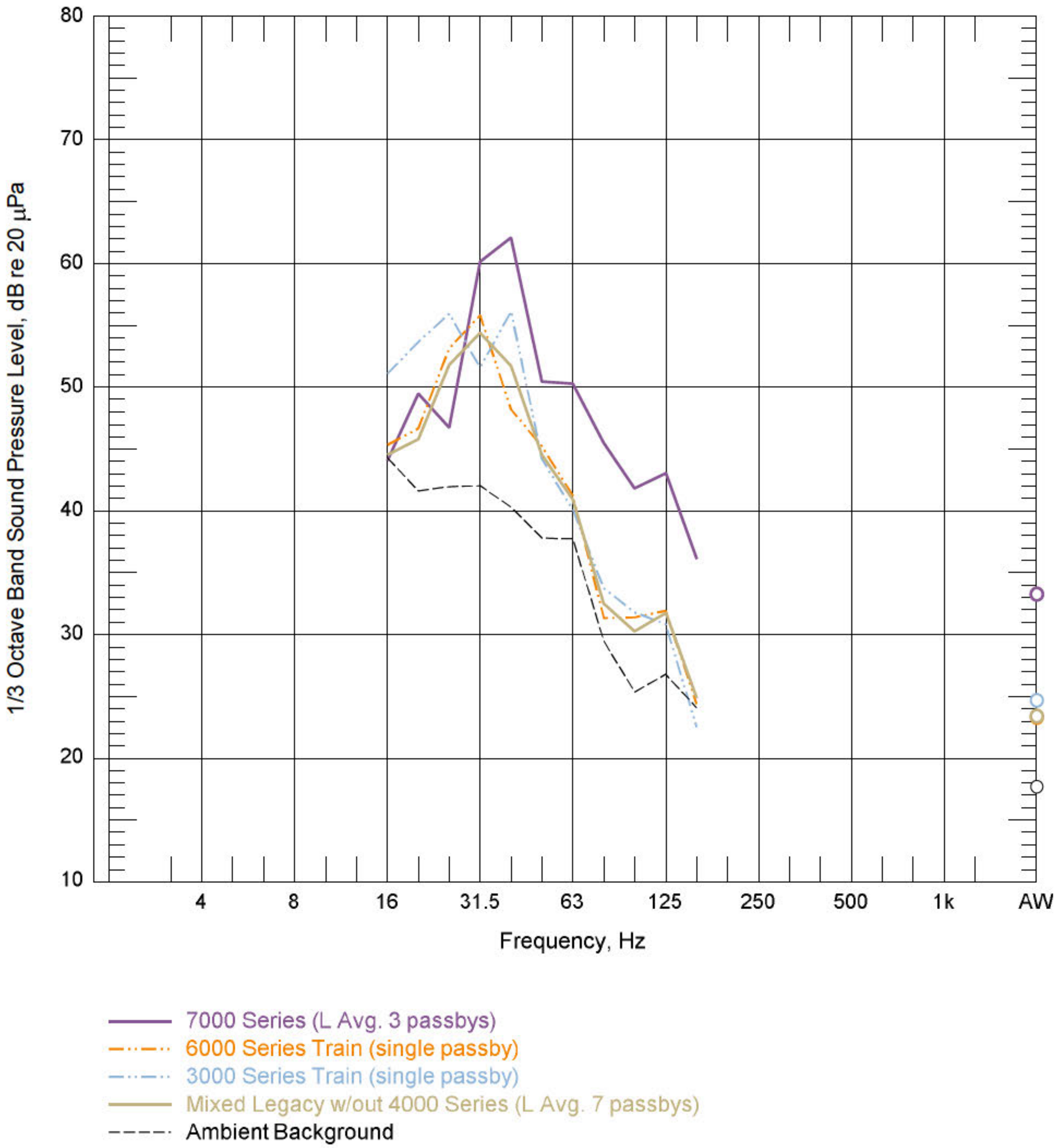


Figure 149: ***Site 7 at Location N1 Basement Bedroom #1***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

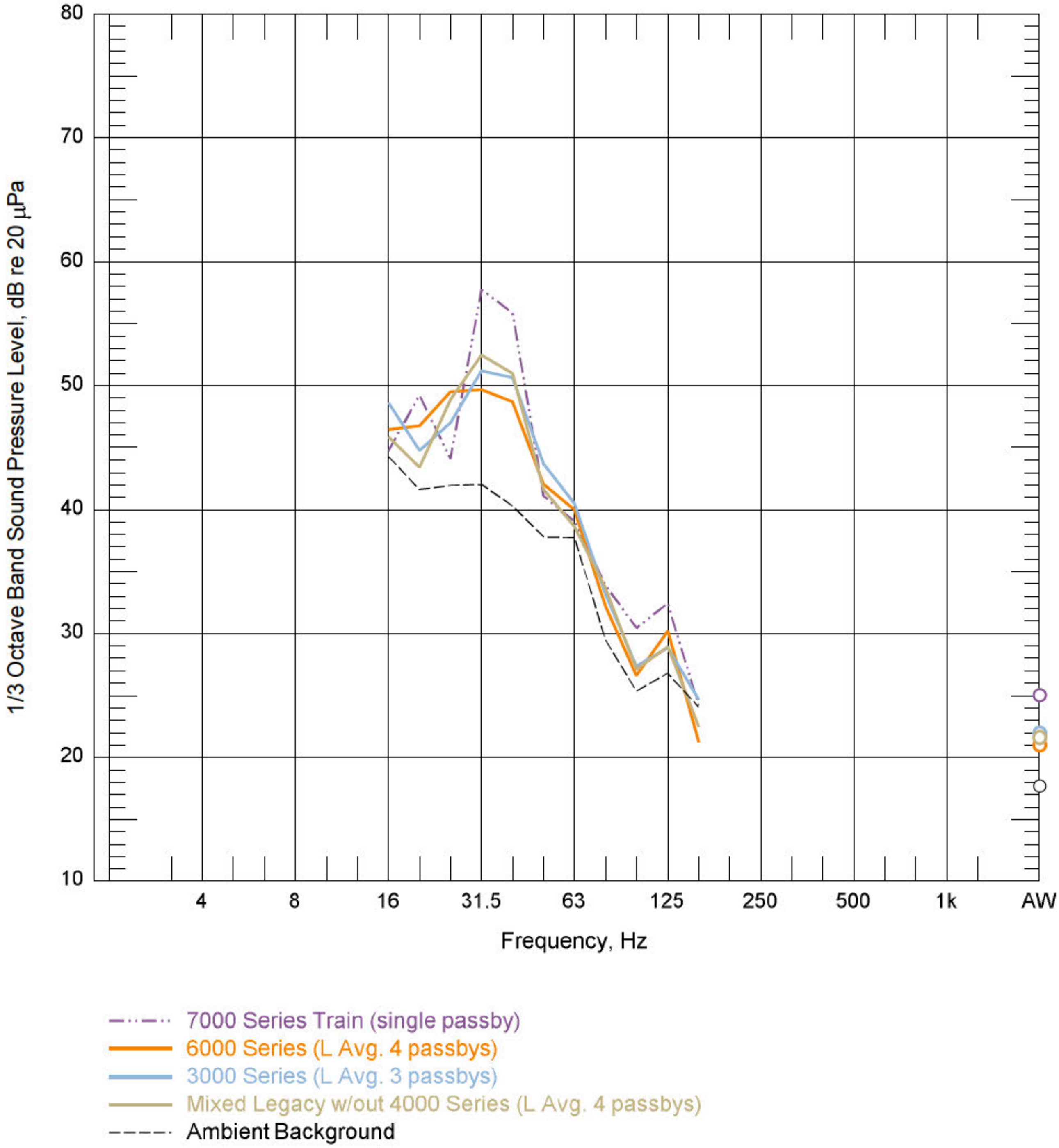


Figure 150: ***Site 7 at Location N1 Basement Bedroom #1***
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

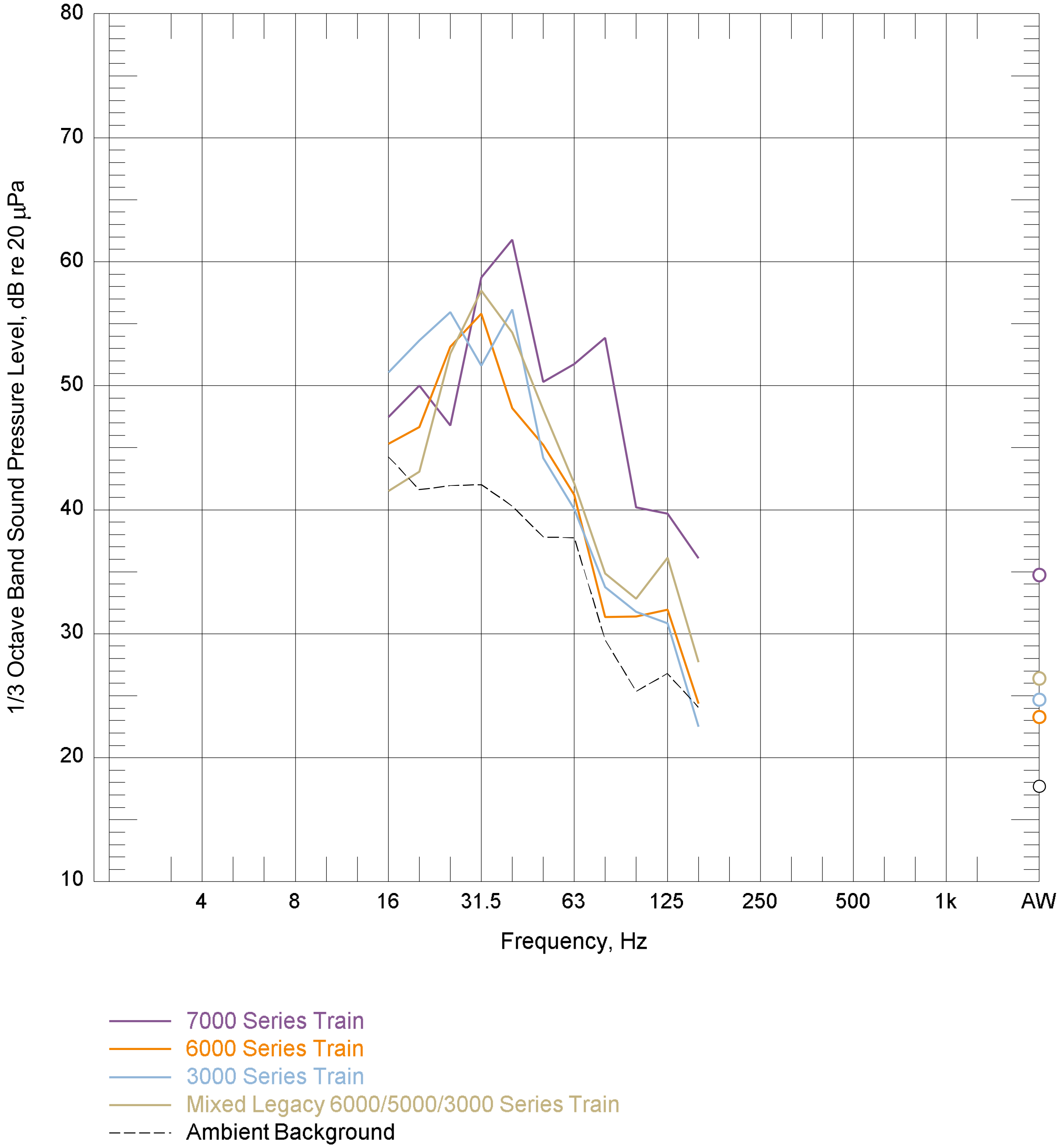


Figure 151: ***Site 7 at Location N1 Basement Bedroom #1***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

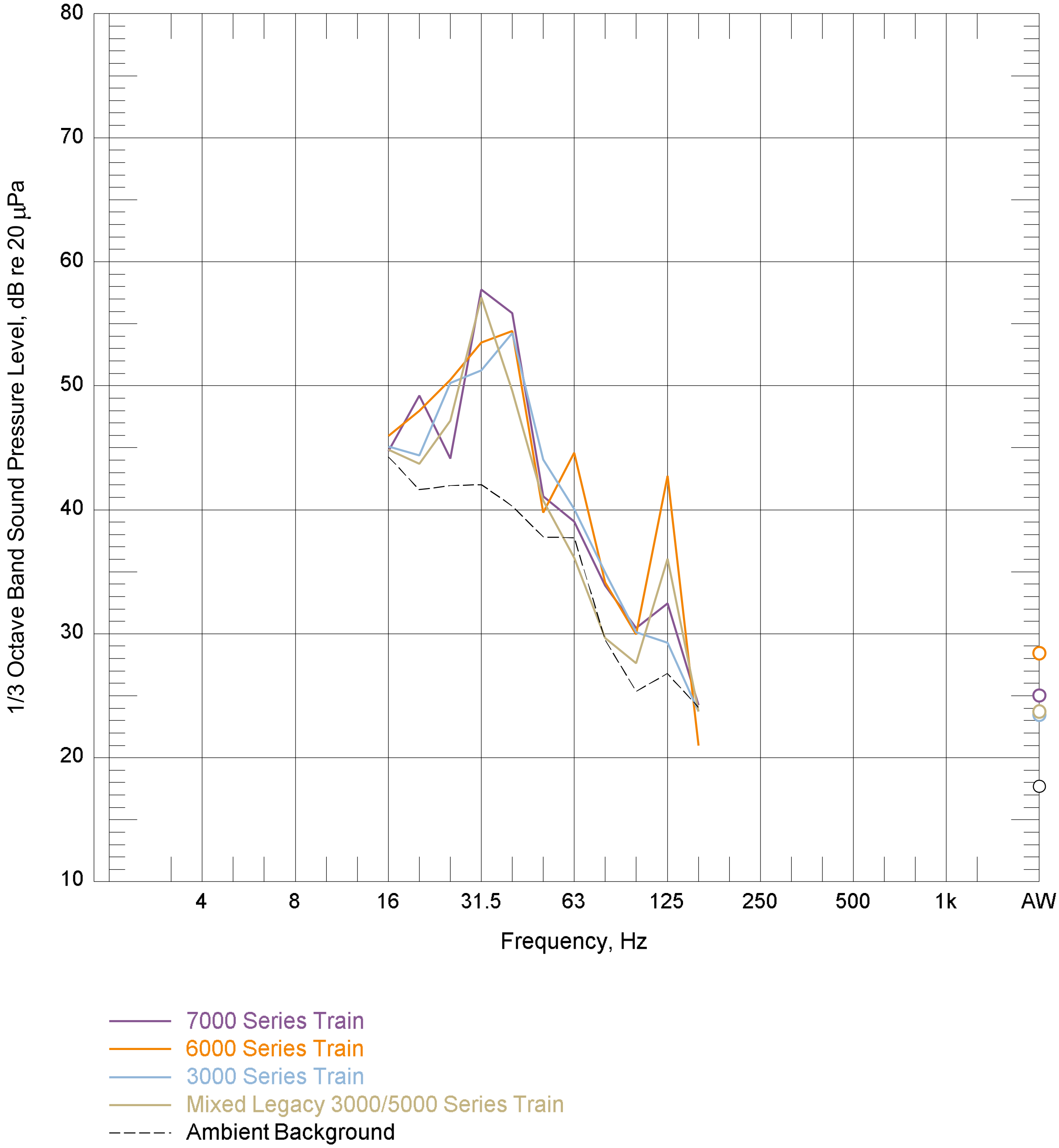


Figure 152: ***Site 7 at Location N1 Basement Bedroom #1***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

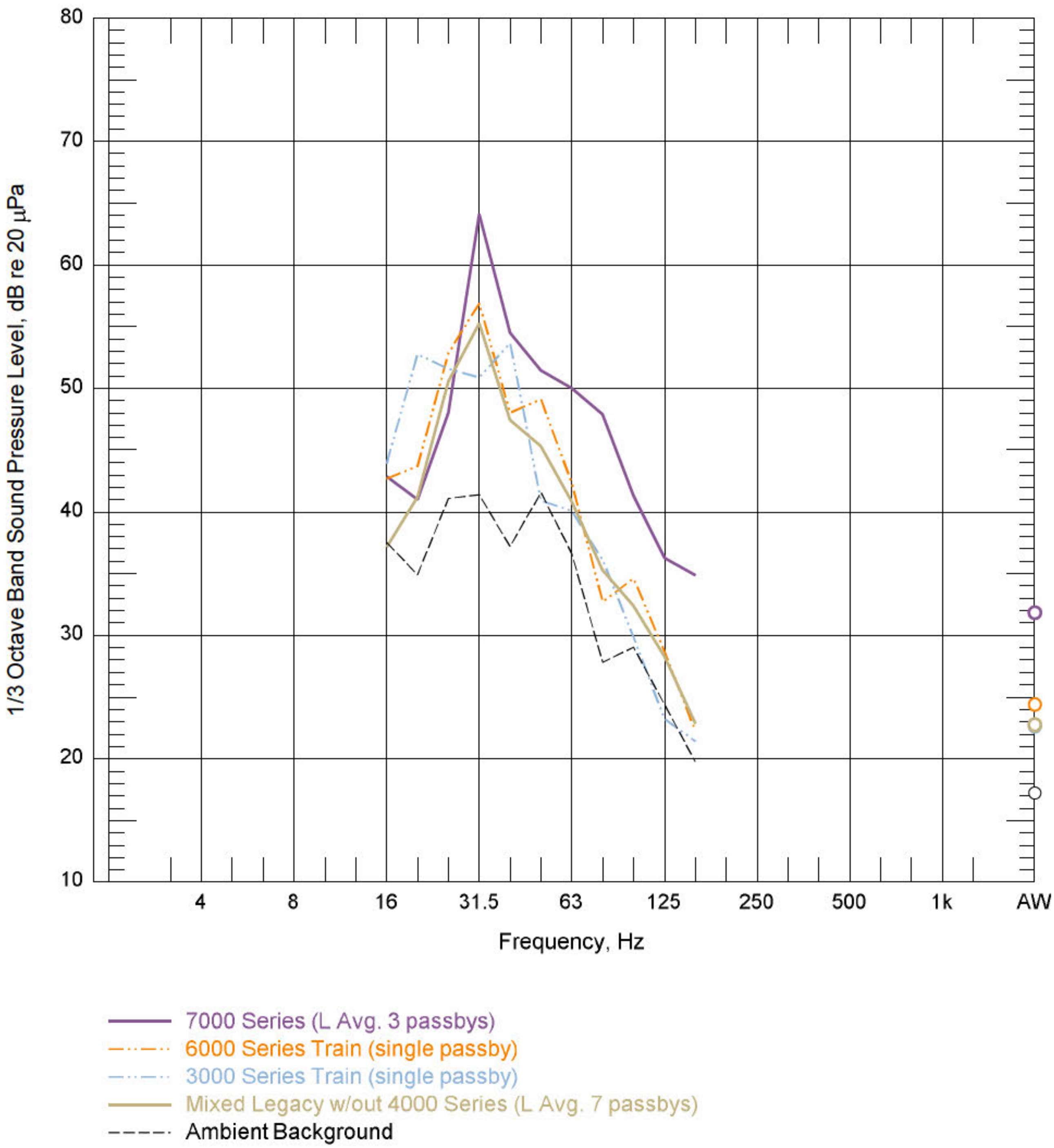


Figure 153: ***Site 7 at Location N2 Basement Bedroom #2***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

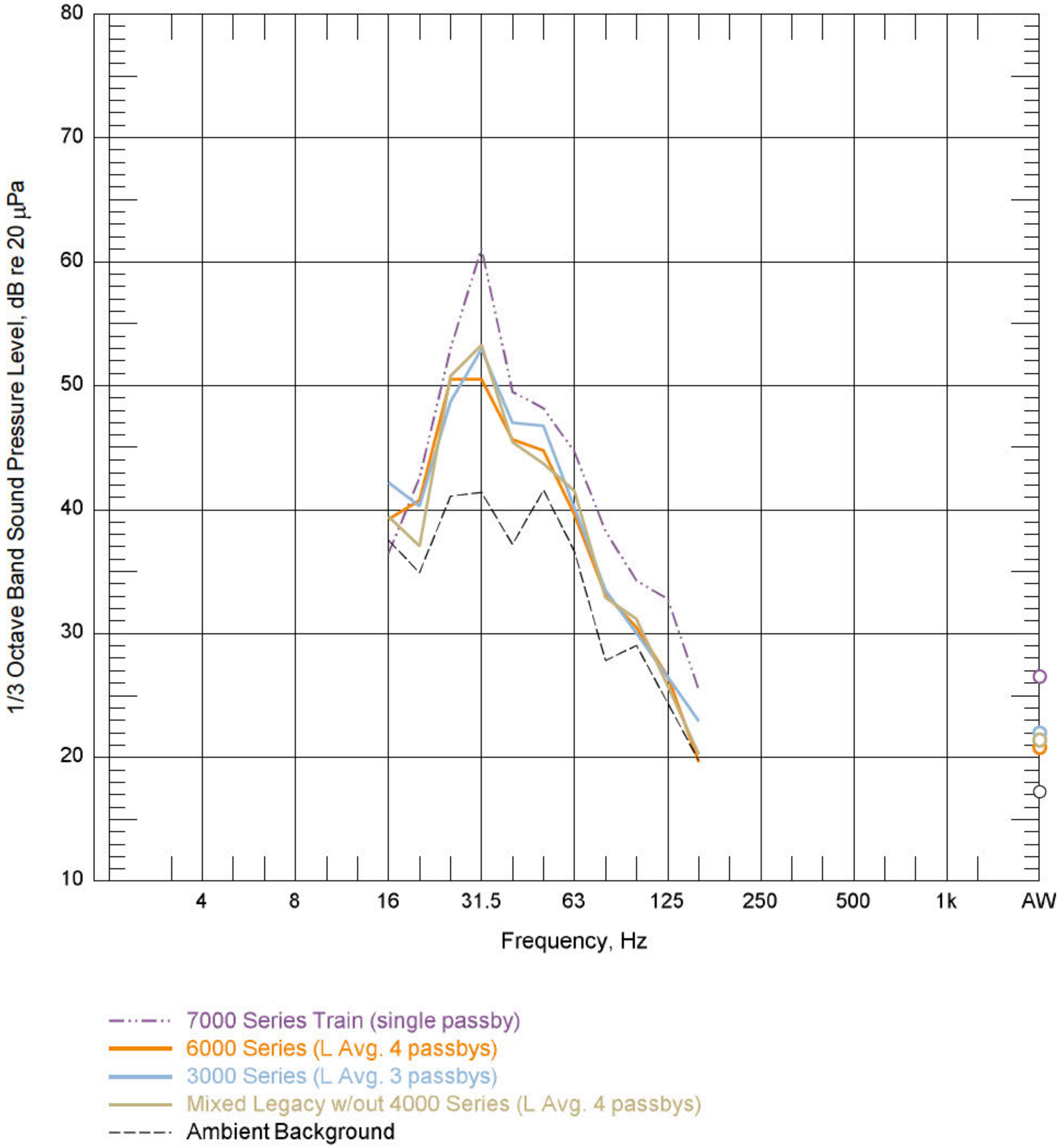


Figure 154: Site 7 at Location N2 Basement Bedroom #2
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

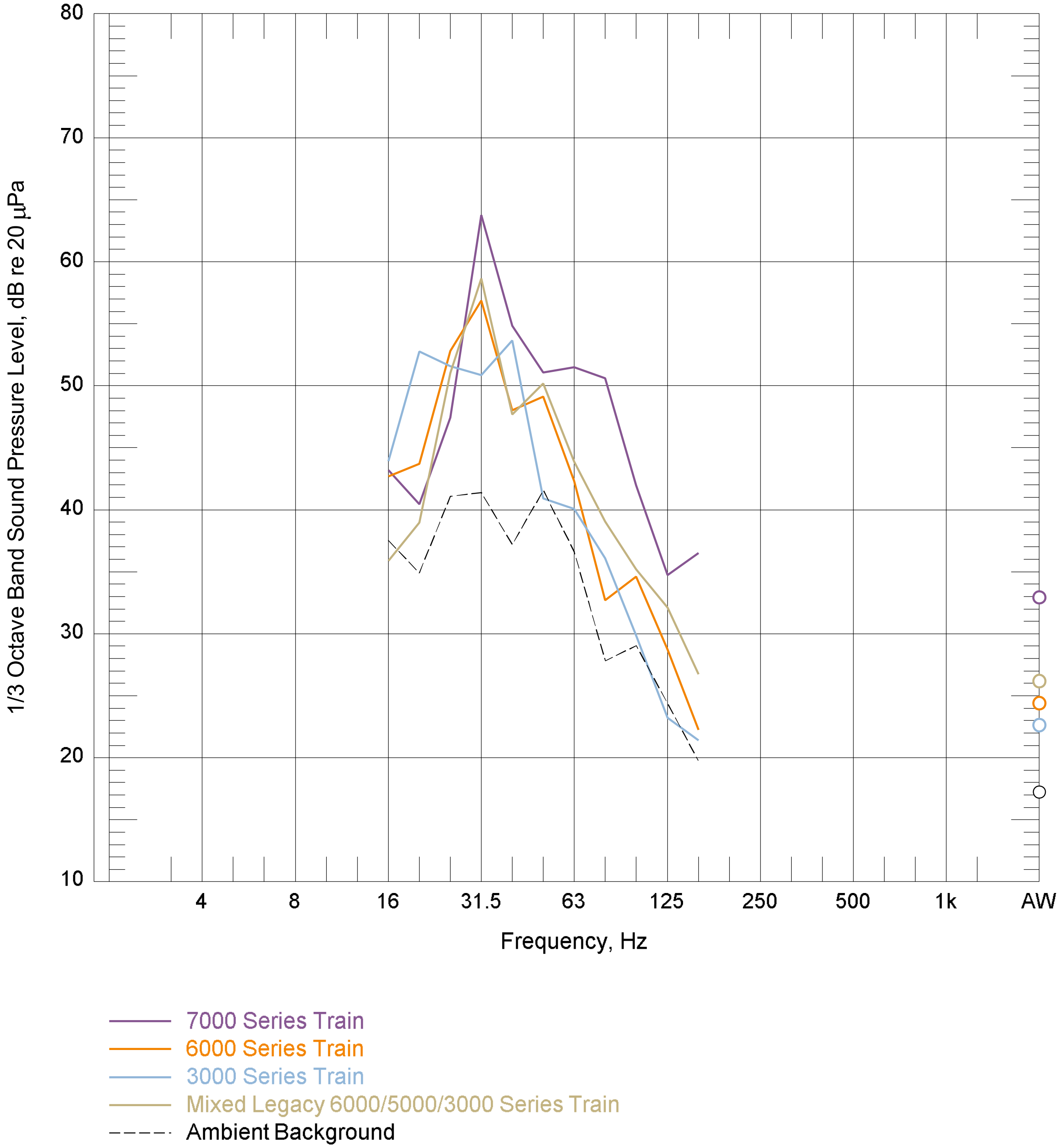


Figure 155: Site 7 at Location N2 Basement Bedroom #2
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

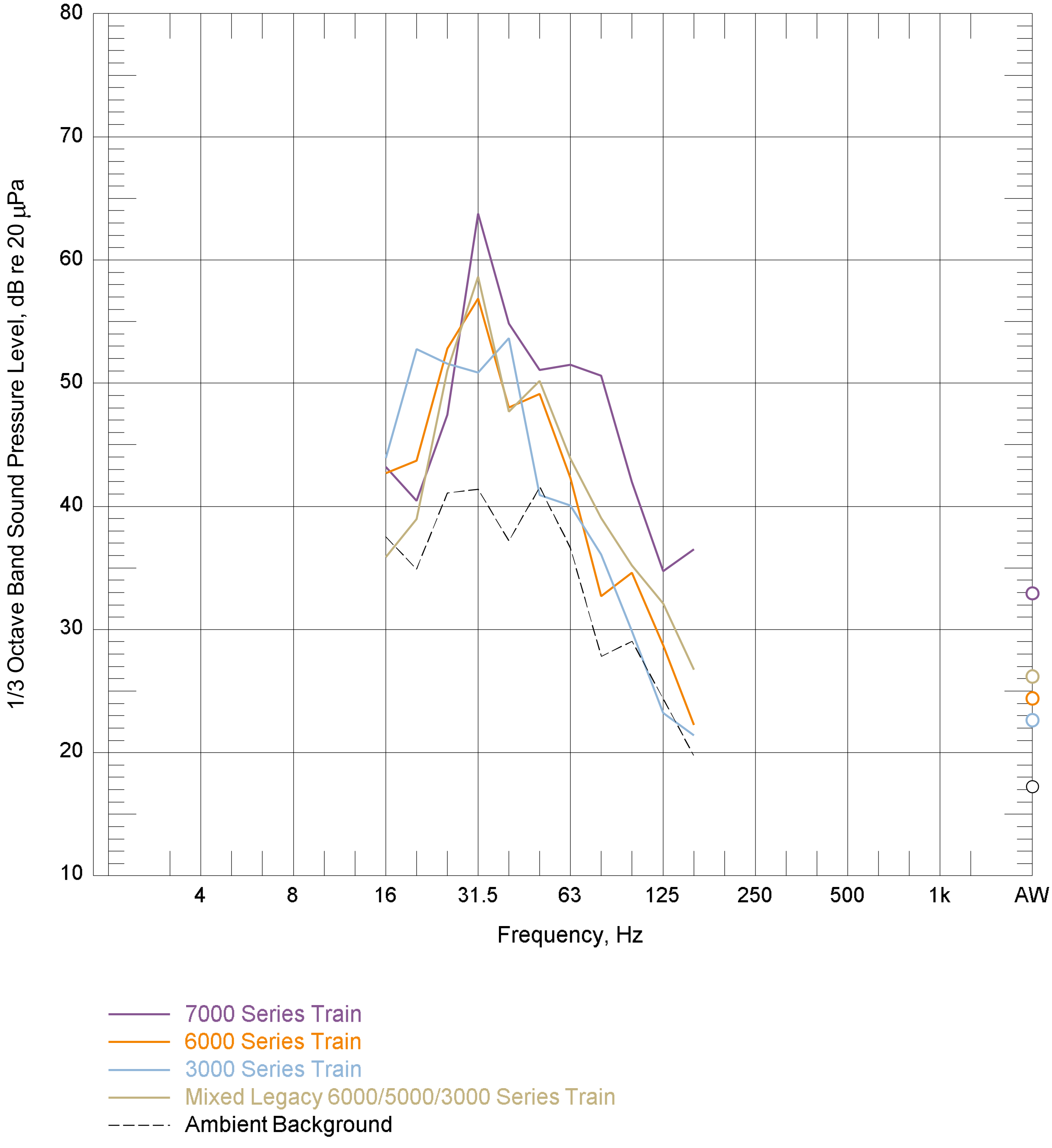


Figure 156: ***Site 7 at Location N2 Basement Bedroom #2***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

B.8 Site 8 – New Hampshire Avenue NW & Webster Street NW (Outdoor Only)

B.8.1 Tunnel Notes

Tunnel Structure: Earth Tunnel

Track Type: Egg Fasteners

T/R Depth: 65 to 70 feet

Measurement Period: Thursday, 1 June 2017, 9:12 to 11:40

B.8.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Recorder Channel	Chainage (50 ft)	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)
A1	205+00	80	67	104	43	67	80
A2	205+00	130	67	146	94	67	115
A3	205+50	189	69	201	153	69	168
A4	206+00	244	70	254	208	70	219
B1	204+00	45	65	79	81	65	104
B2	203+50	96	66	116	133	66	148
B3	203+50	124	66	140	161	66	174
B4	203+50	156	66	169	192	66	203

Perp. distance = perpendicular distance to track, not accounting for tunnel depth
T/R depth = top-of-rail depth
Total slant distance = total distance to track, accounting for tunnel depth

Figure 157: Aerial Map of Site 8 Measurement Positions (nearby Sites 7, 9, and 10 also shown for reference)

B.8.3 Overall Level vs Distance Plot

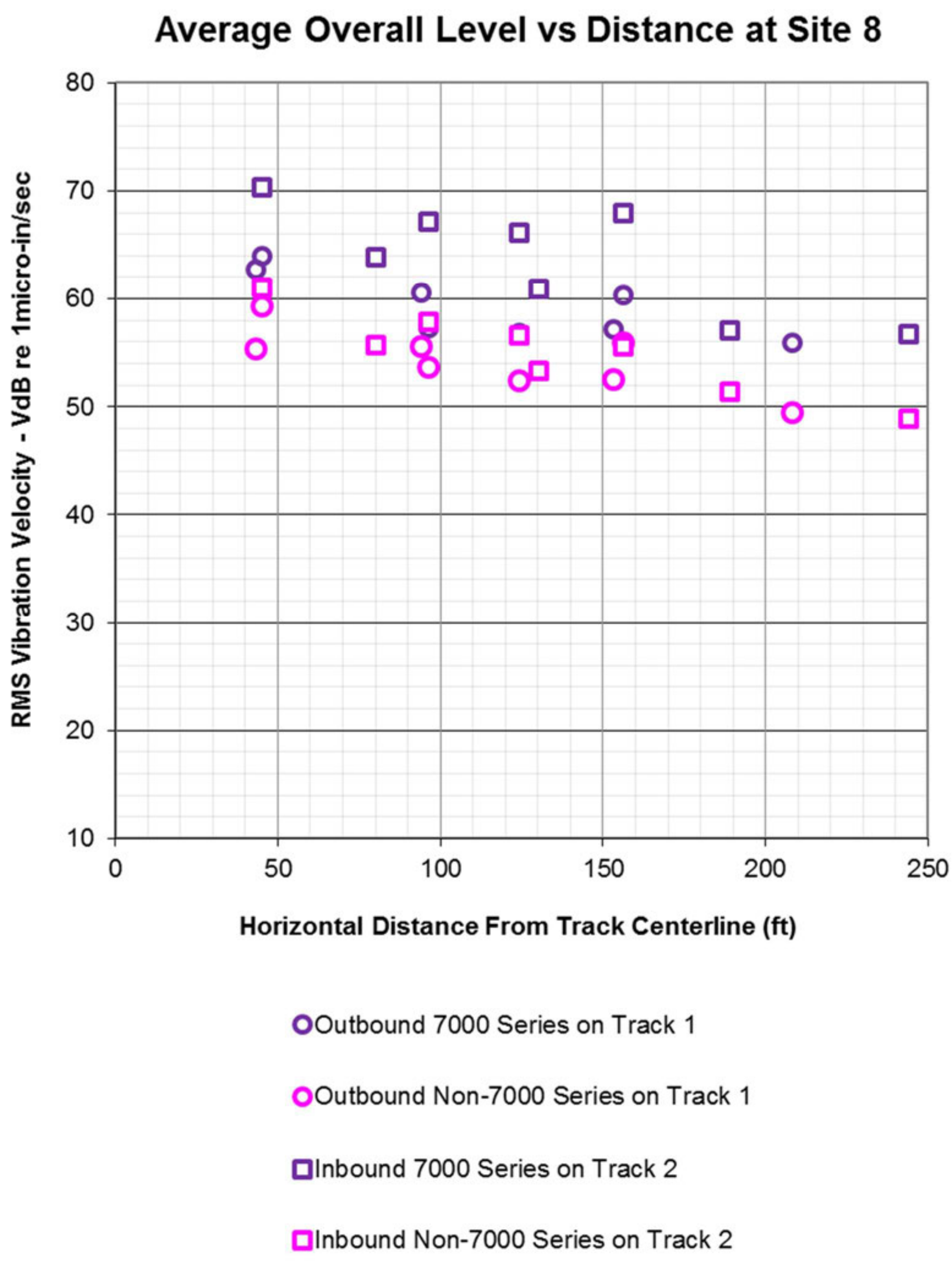


Figure 158: Site 8 Average Overall Level vs Distance

B.9 Site 9 – 4400 block of 5th Street NW (Residence)

B.9.1 Building and Tunnel Notes

Location: Inbound track 2 side at 204+50

Building Notes: single-family residential attached rowhouse, 3 floors comprised of partial underground basement plus 2 upper floors, foundation is below grade slab with exterior walls of brick construction, renovated

Tunnel Structure: Tunnel

Track Type: Egg Fasteners

T/R Depth: 73 to 74 feet (track 2) / 45 feet (track 1)

Train Speed: 23 to 73 mph

Measurement Period: Wednesday, 9 August 2017, 10:07 to 14:00

Field Observations:

B.9.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Sensor[a,b,c]	Location / Room Occupancy	Horizontal Distance[d] (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)	Horizontal Distance (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)
V1	Outside (far) on Driveway	174	73	189	211	45	216
V2	Outside (near) on Steps	197	73	210	234	45	238
Tri-axial geophone	Basement Laundry Room	195	73	208	232	45	236
V3							
N1							
V4	Basement Bedroom						
N2							
V5	First Floor Kitchen						
V6	First Floor Dining Room						

Notes:

a) Tri-axial geophone mounted on floor, logging peak particle velocity
b) V# vibration locations with accelerometer mounted on floor in vertical direction
c) N# noise locations with microphone/sound level meter mounted on tripod 48 inches feet above floor
d) Horizontal distance from track to building façade for indoor locations, not accounting for tunnel depth.
e) T/R depth = top-of-rail depth
f) Total slant distance to T/R = total distance from building to track, accounting for tunnel depth

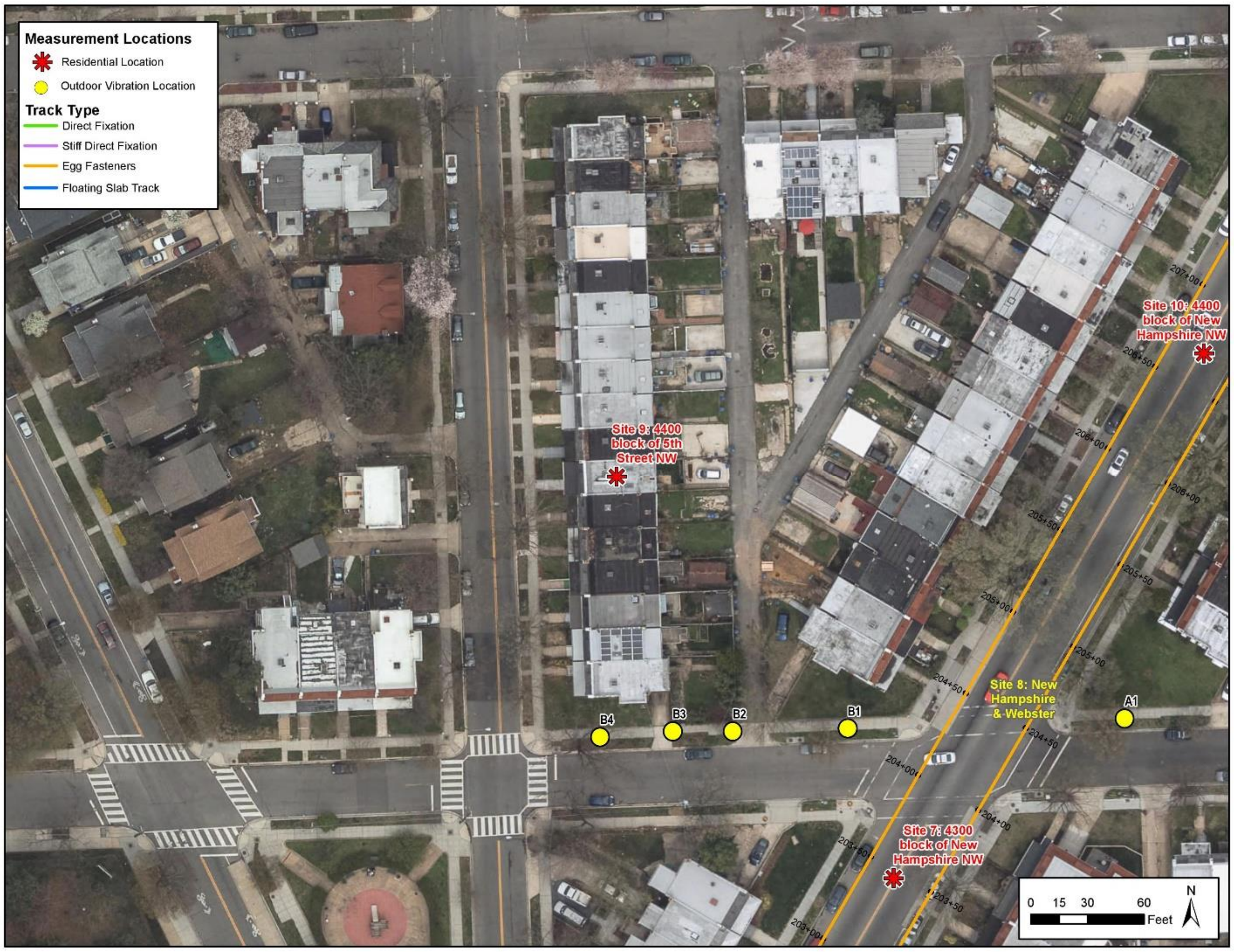


Figure 159: Aerial Map of 4400 block of 5th Street NW Residence and Exterior Measurement Locations at Site 9 (nearby Sites 8 and 10 shown for reference)

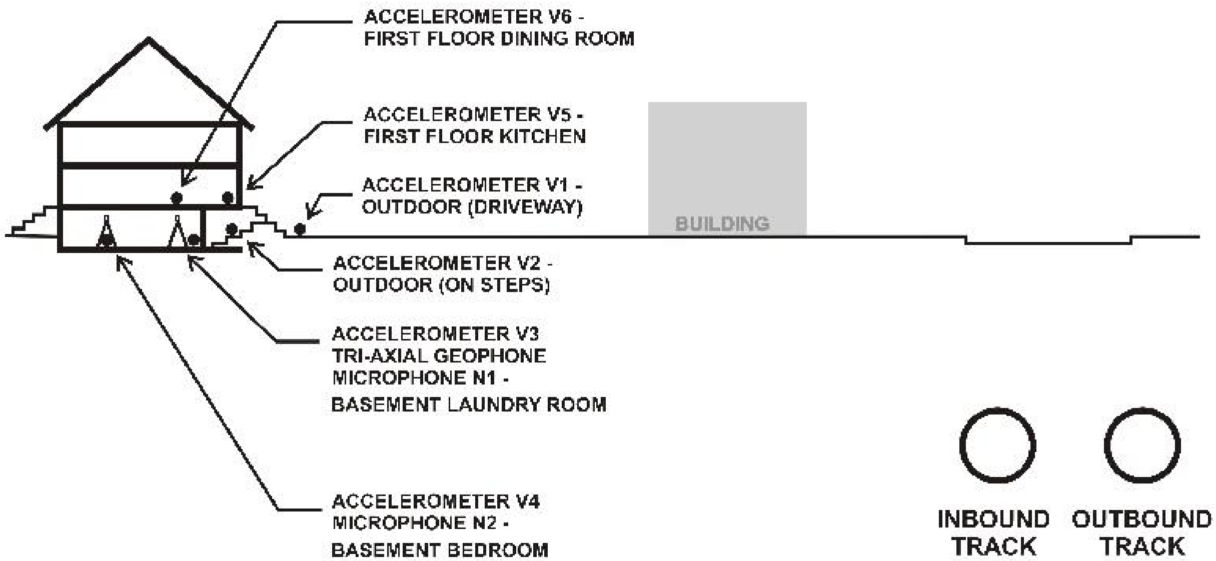


Figure 160: Cross-section Sketch (not to scale) of 4400 block of 5th Street NW Residence and Exterior Measurement Locations

B.9.3 GBNV Assessment Summary

SITE 9	4400 block of 5th STREET NW – ATTENDED PASSBY MEASUREMENT GBNV ASSESSMENT		
	Ground-borne Vibration (GBV)	**>70 VdB?**	**Notes**
	7000 Series - Single Passby	NO	
	6000 Series - Average of Multiple Passbys	NO	
	5000 Series - Average of Multiple Passbys	NO	
	3000 Series - Average of Multiple Passbys	NO	
	2000 Series - Average of Multiple Passbys	NO	
	Mixed Legacy without 4000 Series - Average of Multiple Passbys	NO	
	7000 Series - Individual Train with Highest Overall Vibration	NO	
	6000 Series - Individual Train with Highest Overall Vibration	NO	
	5000 Series - Individual Train with Highest Overall Vibration	NO	
	3000 Series - Individual Train with Highest Overall Vibration	NO	
	2000 Series - Individual Train with Highest Overall Vibration	NO	
	Mixed Legacy without 4000 Series - Individual Train with Highest Overall Vibration	NO	
	Ground-borne Noise (GBN)	**>40 dBA?**	**Notes**
	7000 Series - Single Passby	NO	
	6000 Series - Average of Multiple Passbys	NO	
	5000 Series - Average of Multiple Passbys	NO	
	3000 Series - Average of Multiple Passbys	NO	
	2000 Series - Average of Multiple Passbys	NO	
	Mixed Legacy without 4000 Series - Average of Multiple Passbys	NO	
	7000 Series - Individual Train with Highest A-weighting	NO	
	6000 Series - Individual Train with Highest A-weighting	NO	
	5000 Series - Individual Train with Highest A-weighting	NO	
	3000 Series - Individual Train with Highest A-weighting	NO	
	2000 Series - Individual Train with Highest A-weighting	NO	
	Mixed Legacy without 4000 Series - Individual Train with Highest A-weighting	NO	

B.9.4 PPV Results

SITE 9	4400 block of 5th STREET NW – POTENTIAL FOR BUILDING VIBRATION DAMAGE ASSESSMENT						
	>0.2 in/sec PPV in any direction?	Average PPV (in/s)			PPV Range (in/s)		
		Tran	Vert	Long	Tran	Vert	Long
	NO	0.0029	0.0029	0.002	0.002 - 0.003	0.002 - 0.007	0.002 - 0.004
Basement 9-Aug-17, 10:18:15 AM to 2:10:14 PM							

B.9.5 Passby Vibration Spectra and Overall Levels

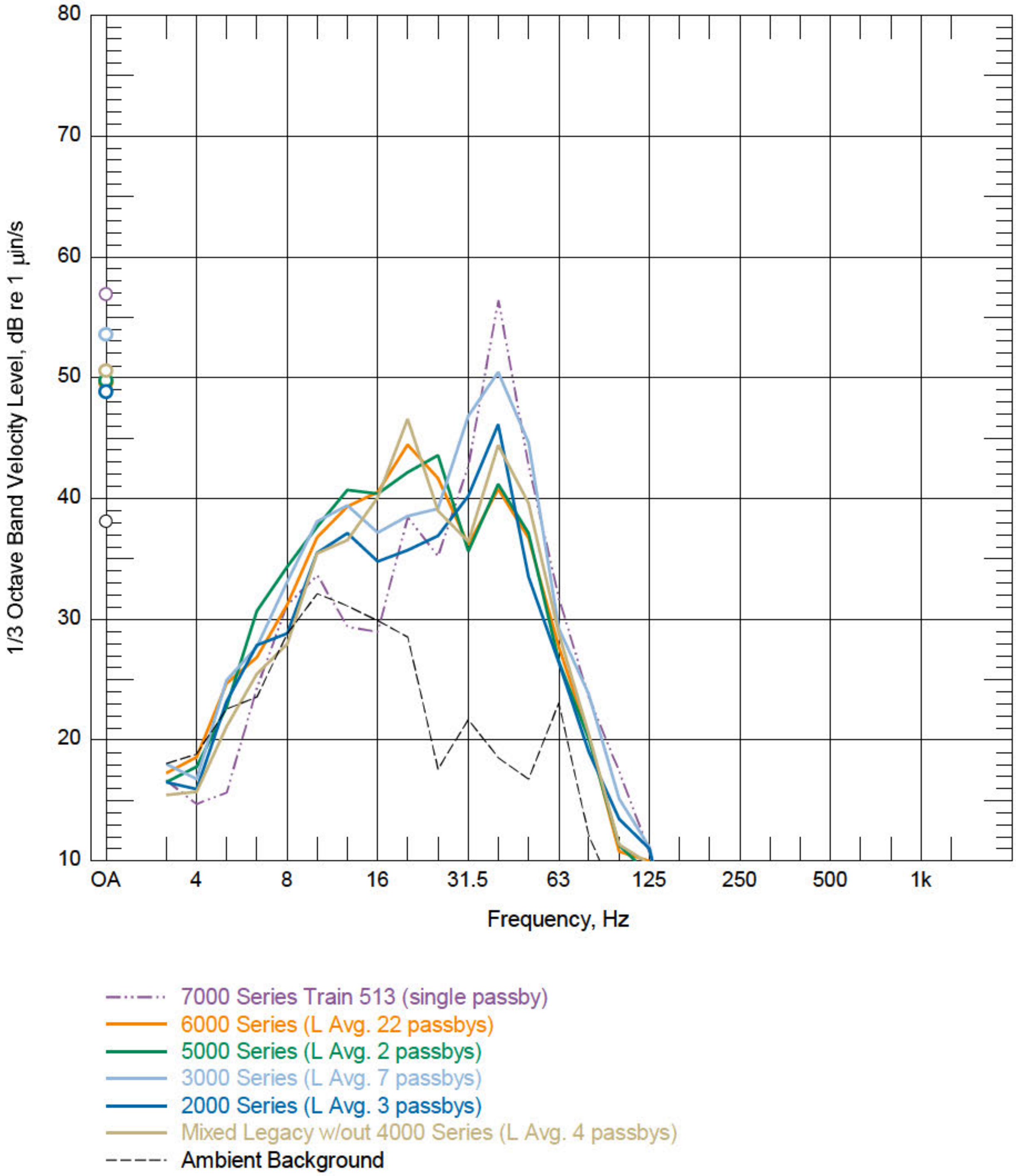


Figure 161: ***Site 9 at Location V1 Outside Far***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

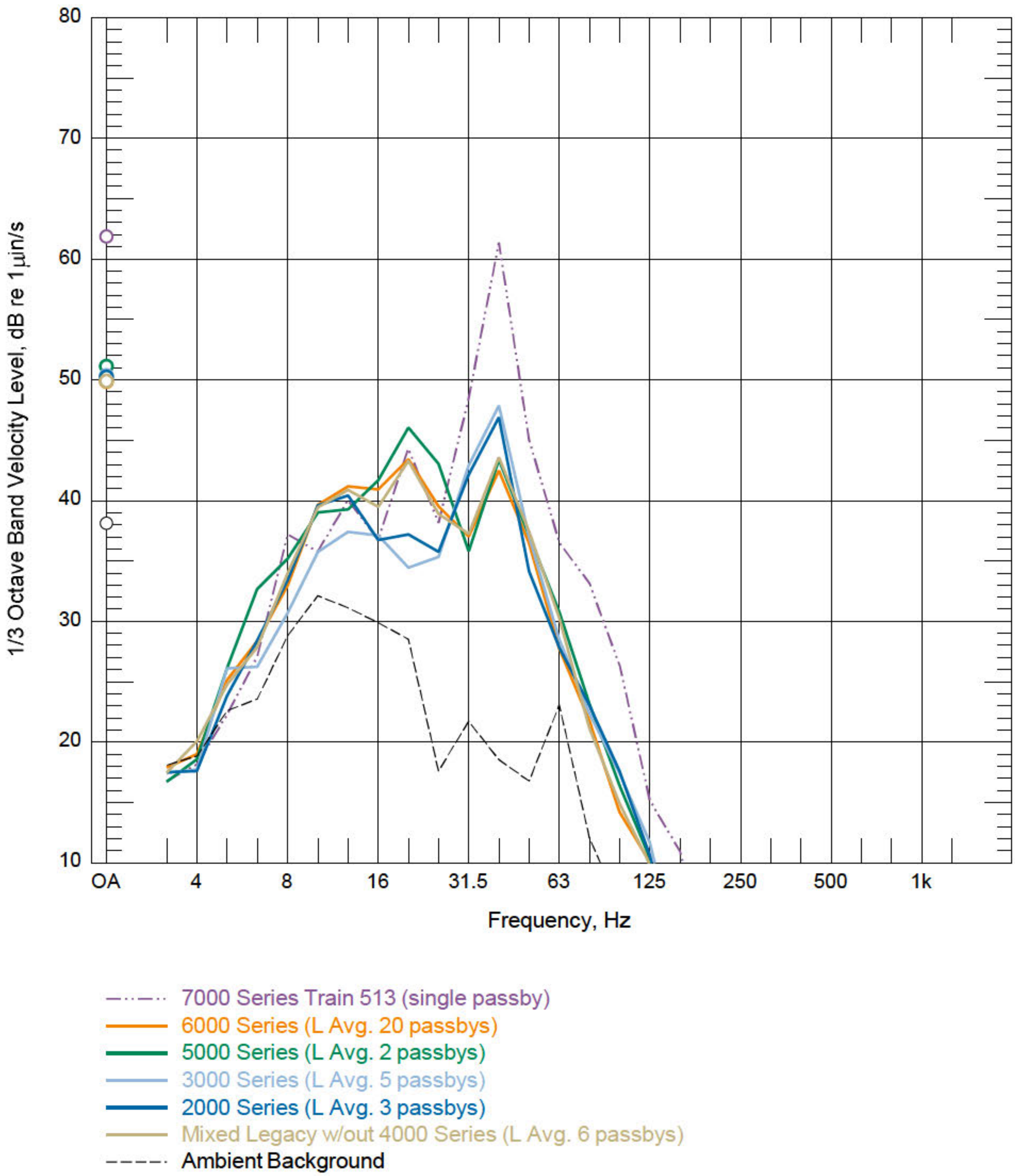


Figure 162: ***Site 9 at Location V1 Outside Far***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

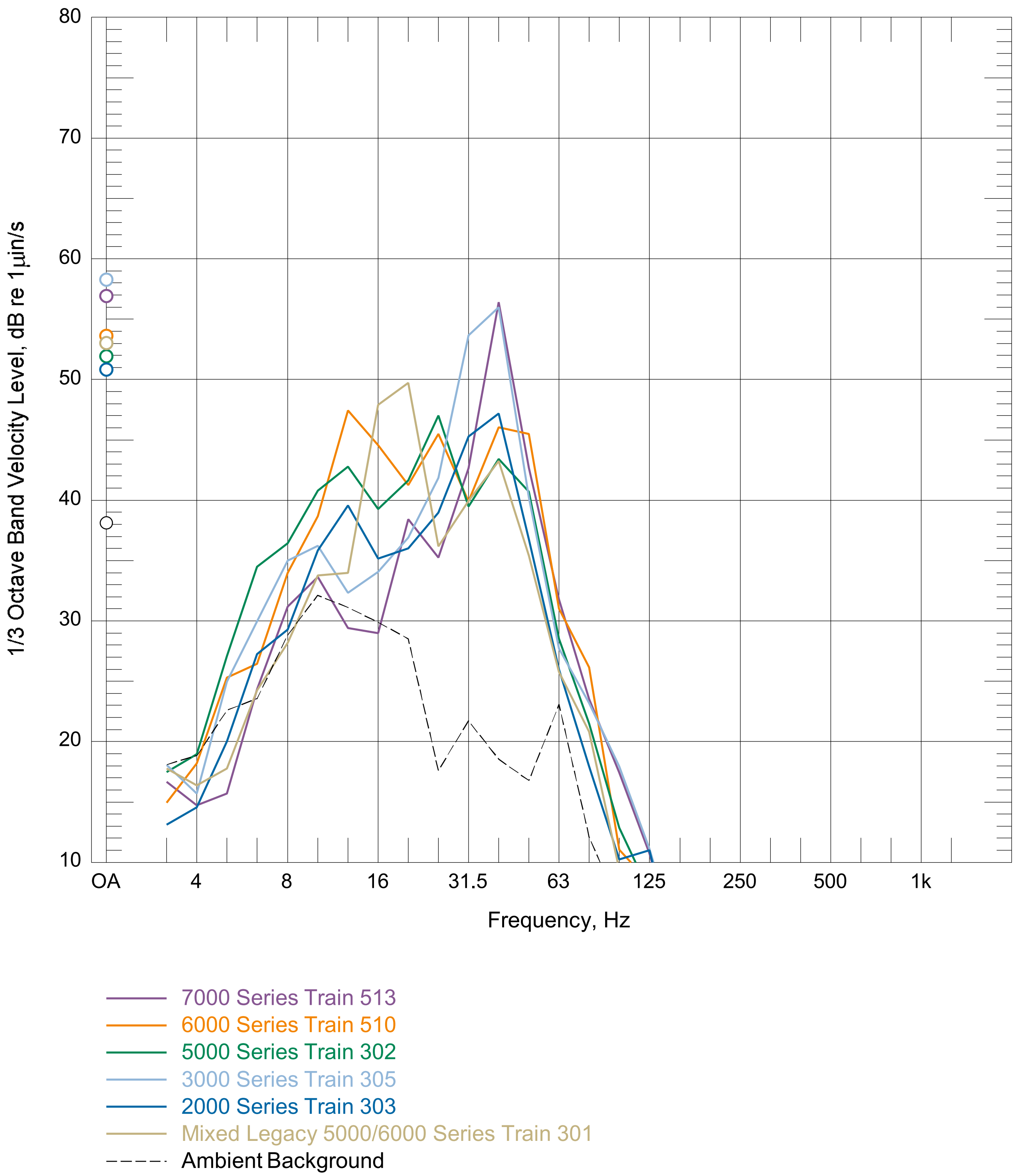


Figure 163: ***Site 9 at Location V1 Outside Far***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

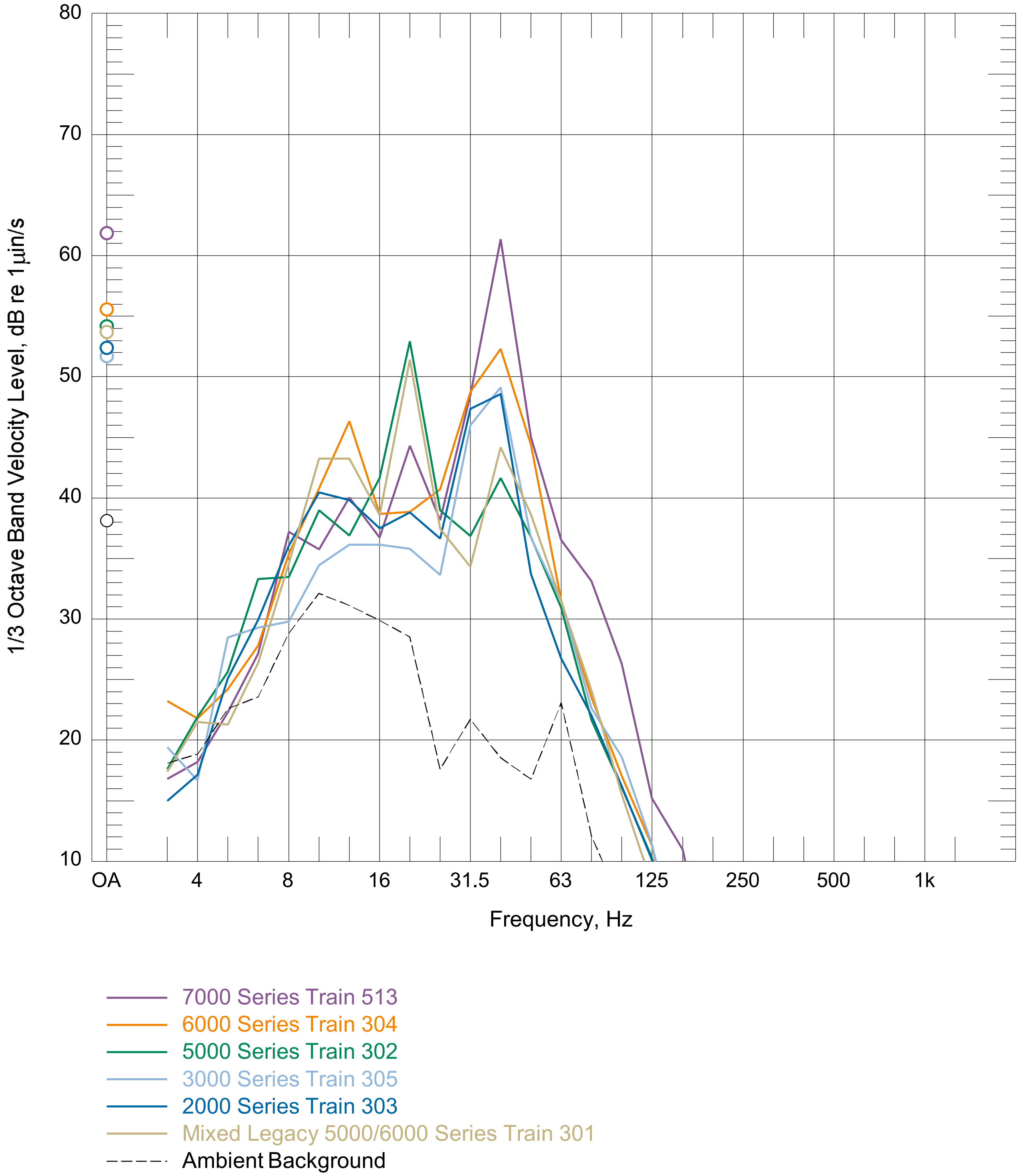


Figure 164: Site 9 at Location V1 Outside Far
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

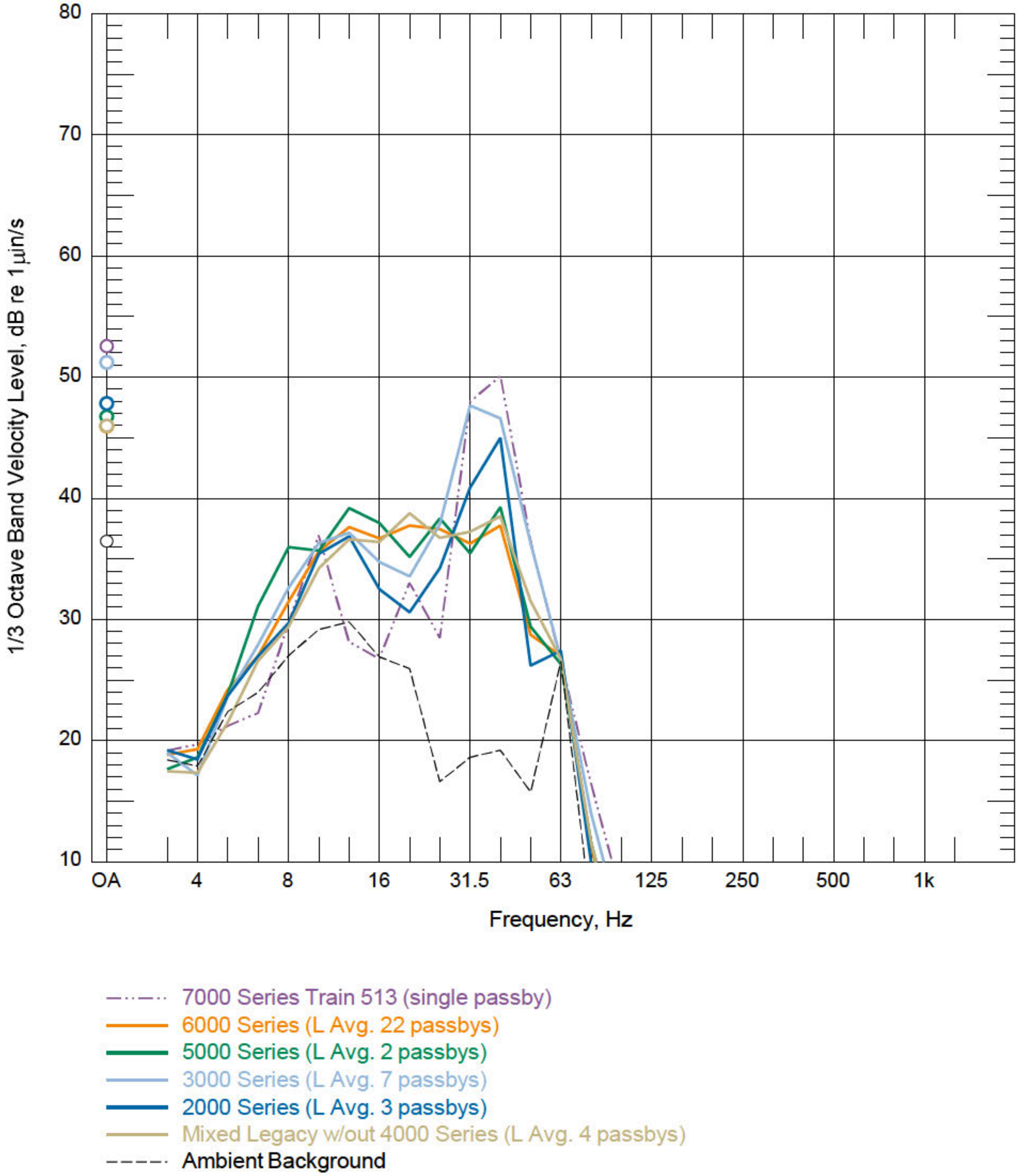


Figure 165: ***Site 9 at Location V2 Outside Near Outbound Trains on Track 1***
Average Vibration Levels by Vehicle Type

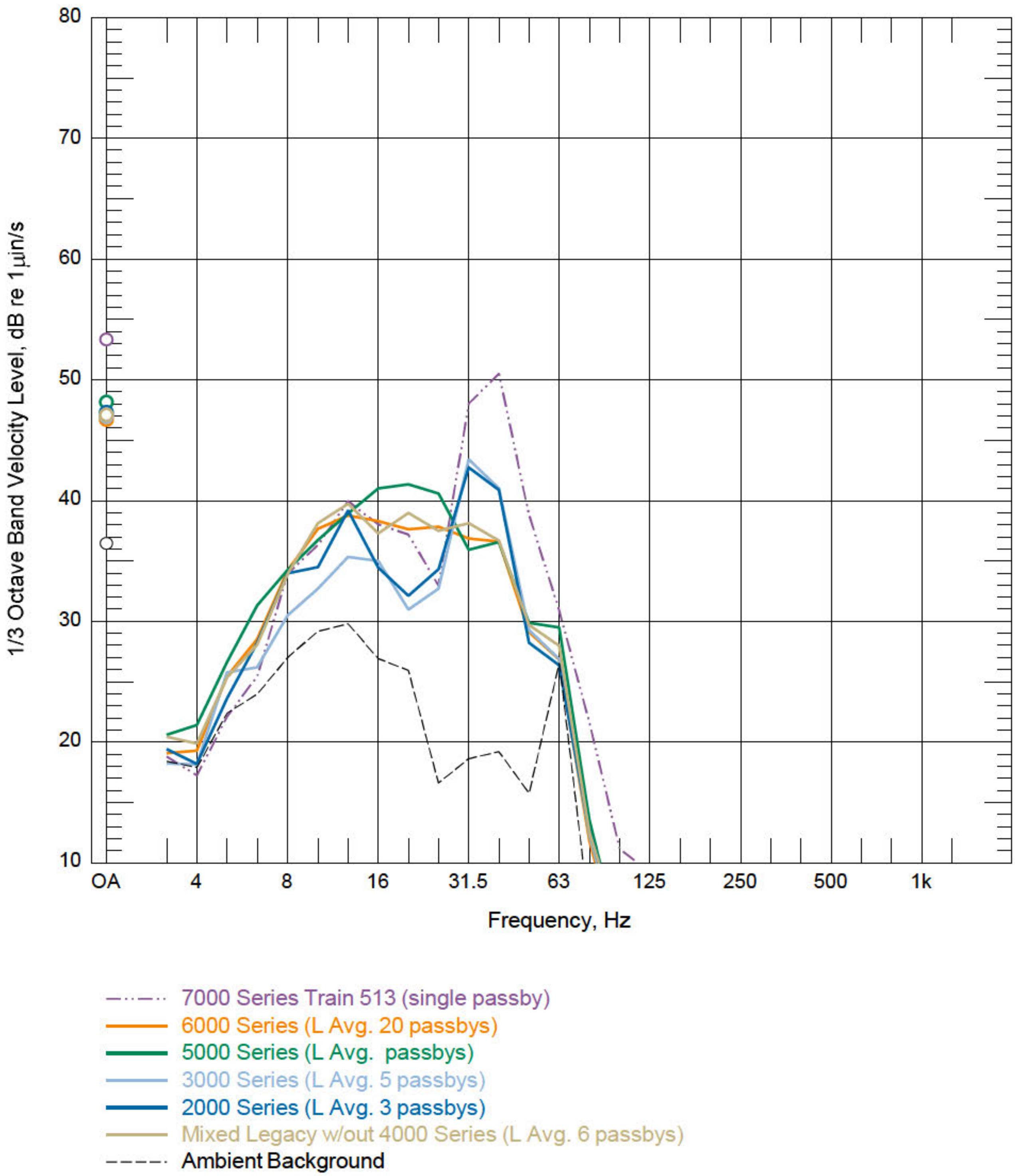


Figure 166: ***Site 9 at Location V2 Outside Near Inbound Trains on Track 2***
Average Vibration Levels by Vehicle Type

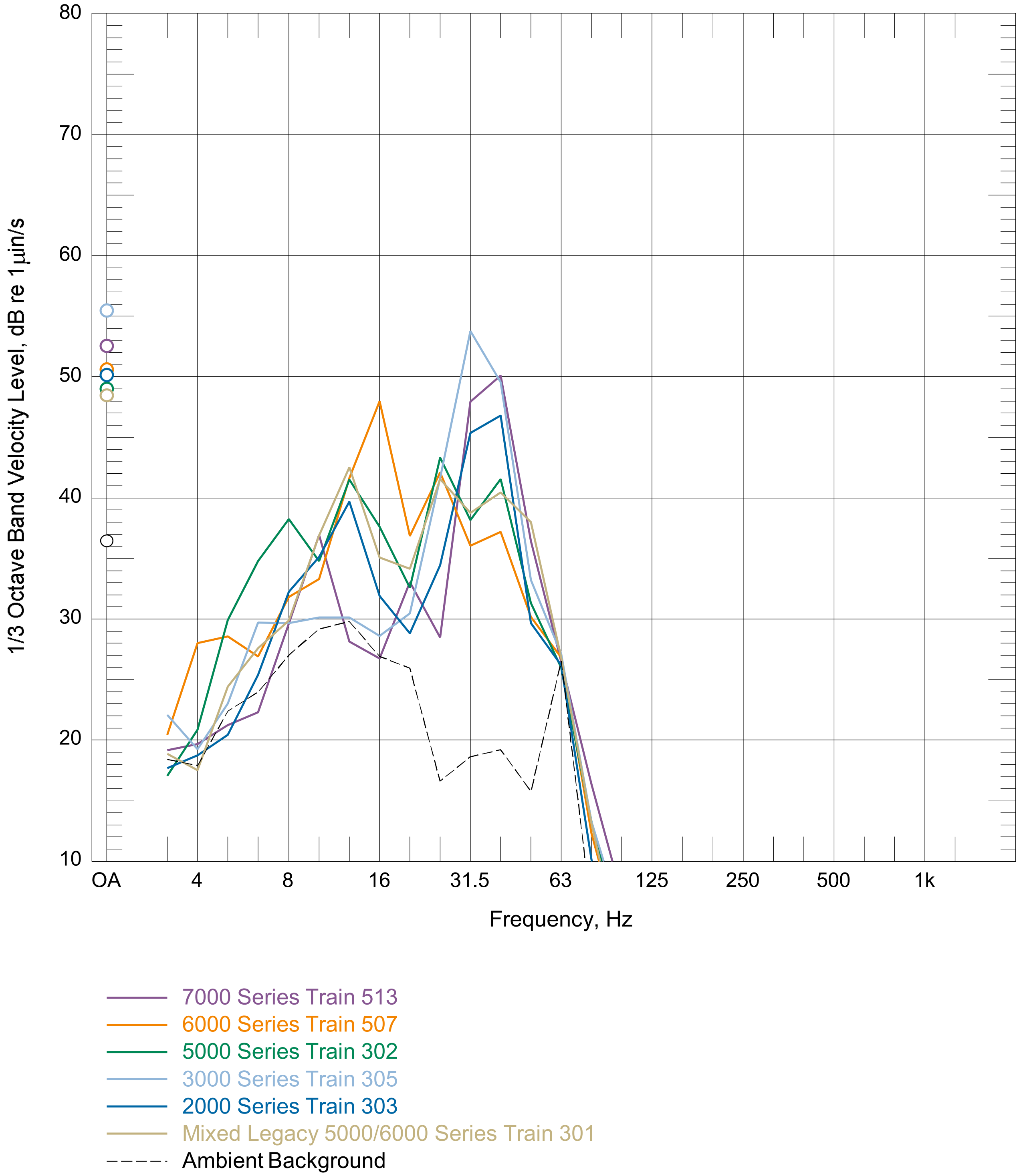


Figure 167: ***Site 9 at Location V2 Outside Near Outbound Trains on Track 1***
Individual Train with Highest Overall Vibration

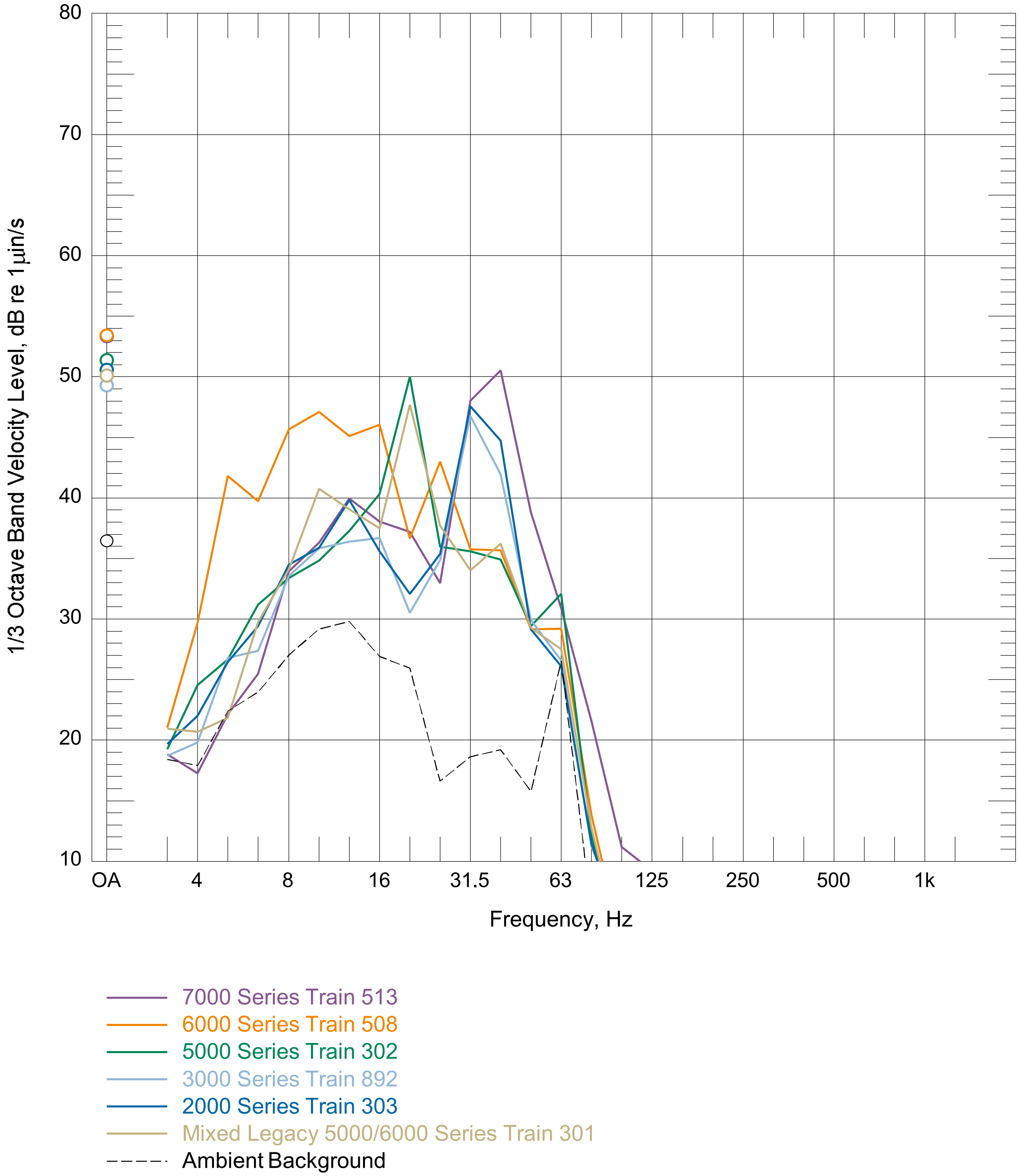


Figure 168: ***Site 9 at Location V2 Outside Near***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

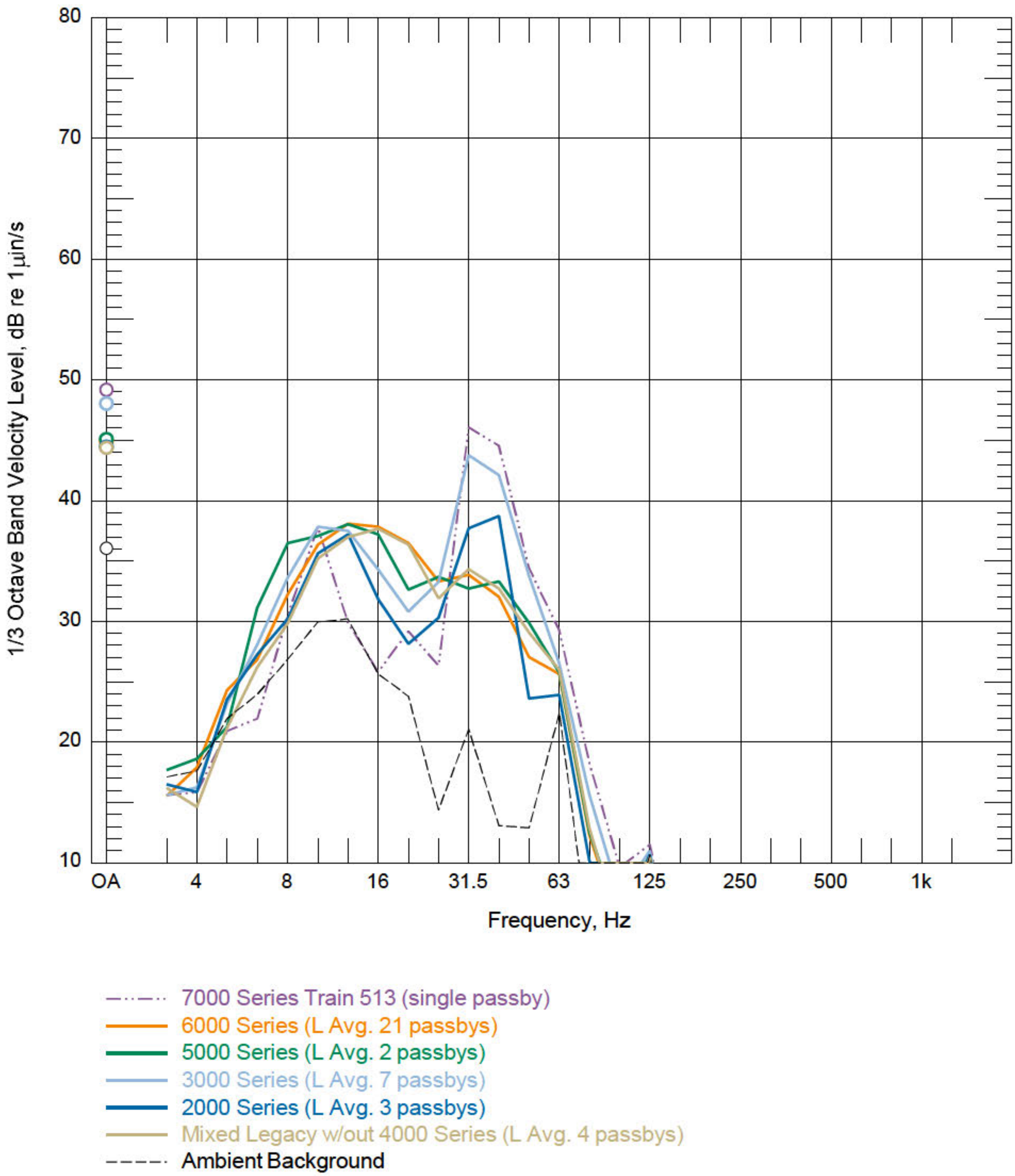


Figure 169: ***Site 9 at Location V3 Basement Laundry Room***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

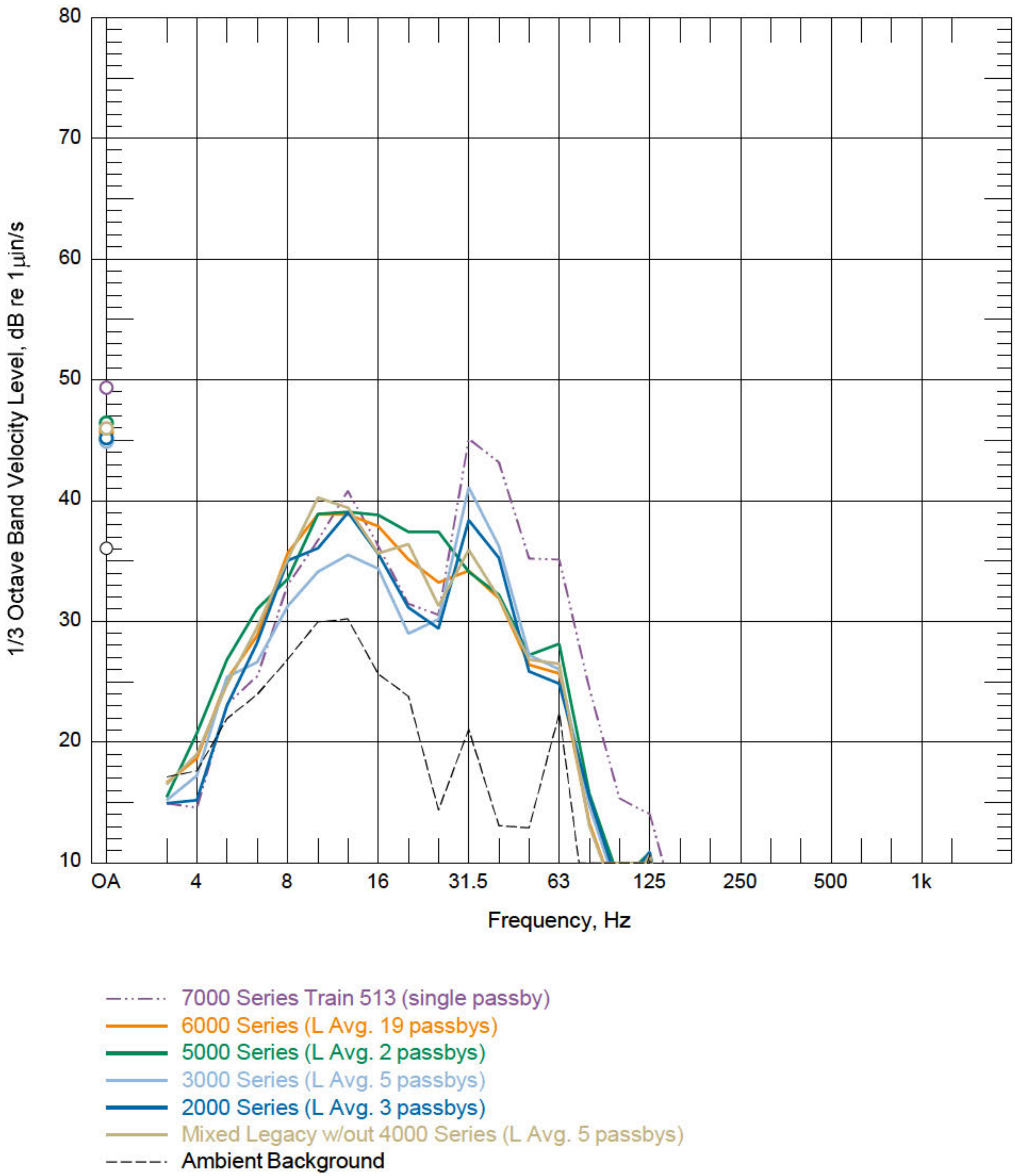


Figure 170: ***Site 9 at Location V3 Basement Laundry Room***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

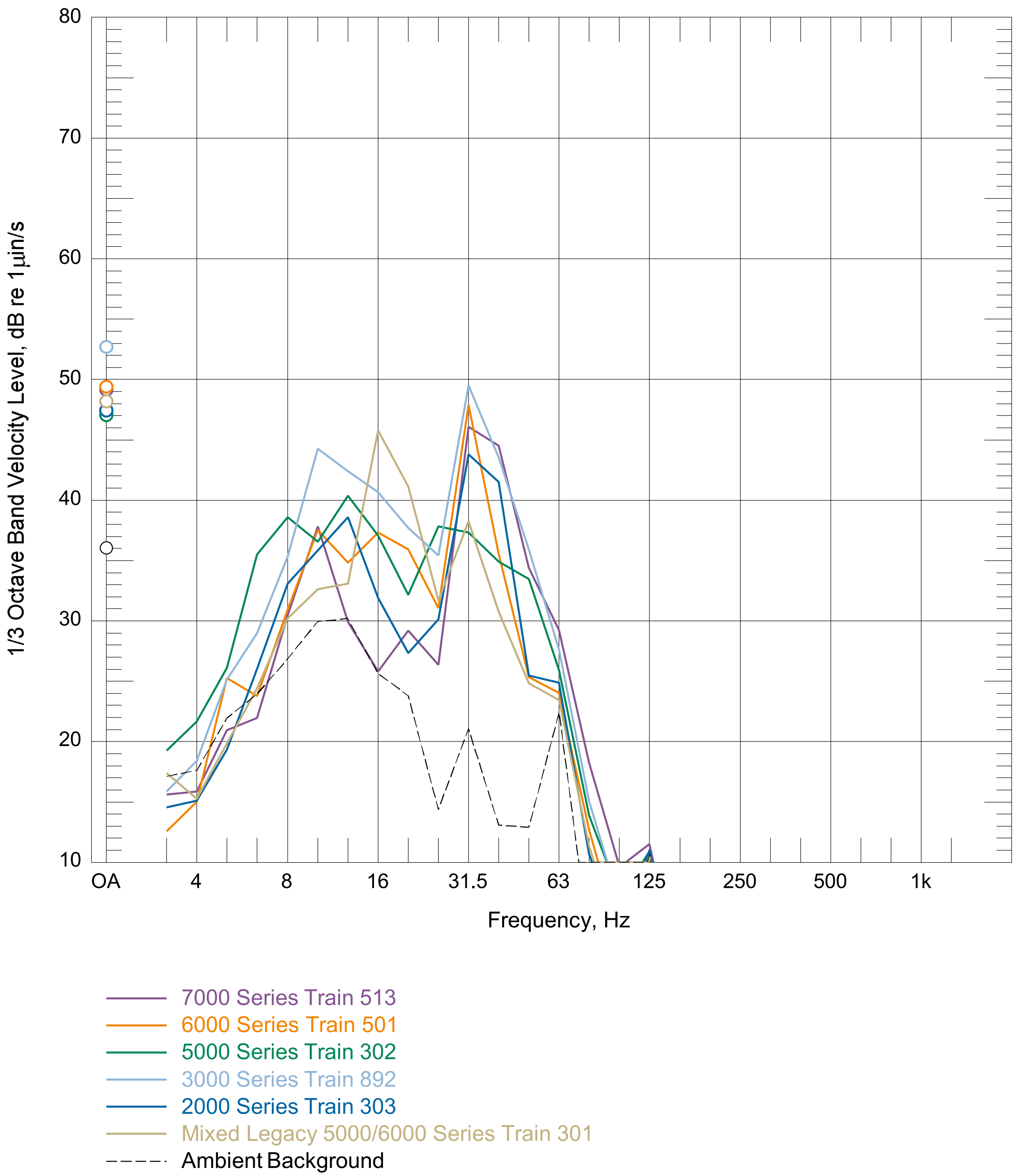


Figure 171: ***Site 9 at Location V3 Basement Laundry Room***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

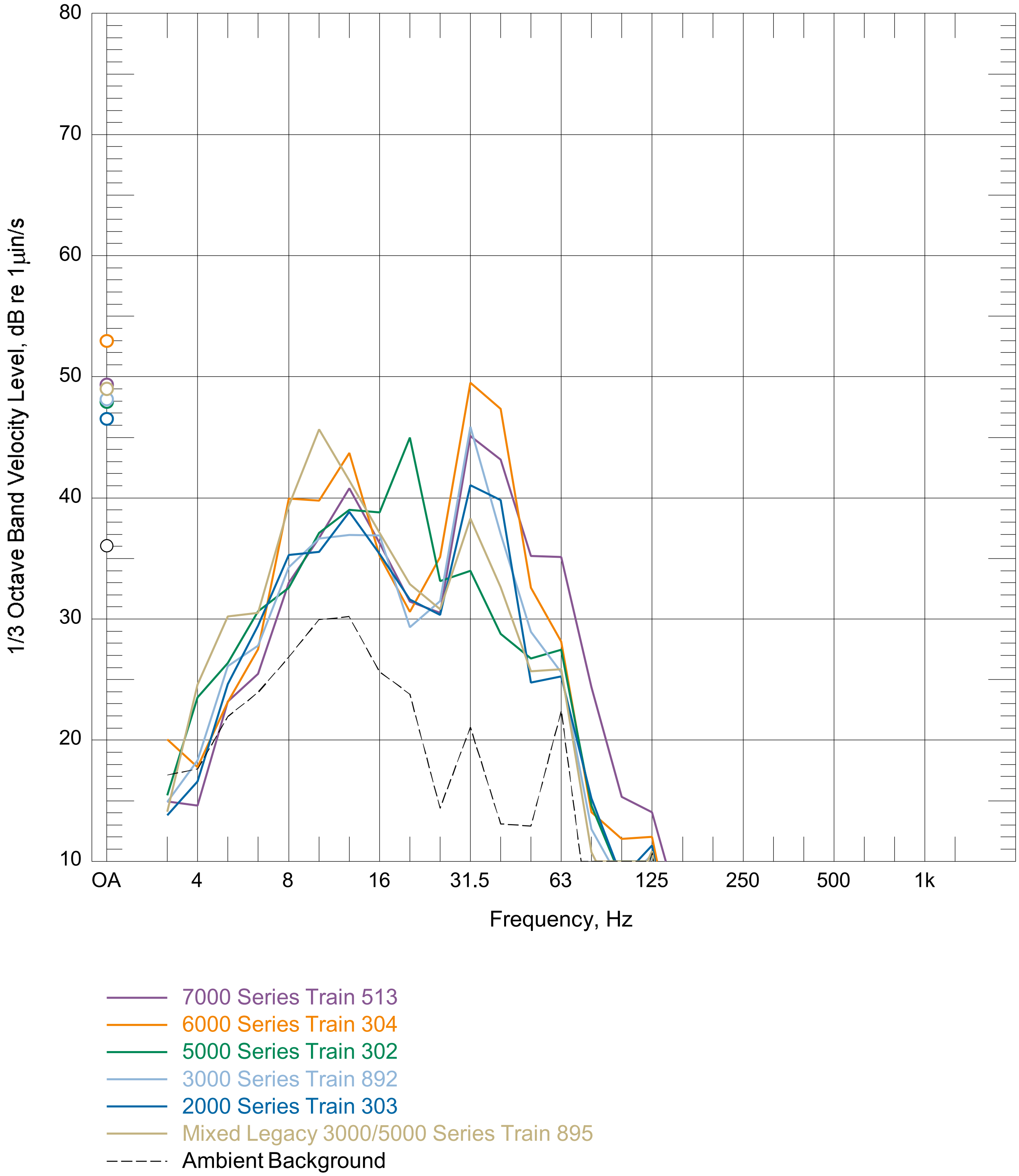


Figure 172: ***Site 9 at Location V3 Basement Laundry Room***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

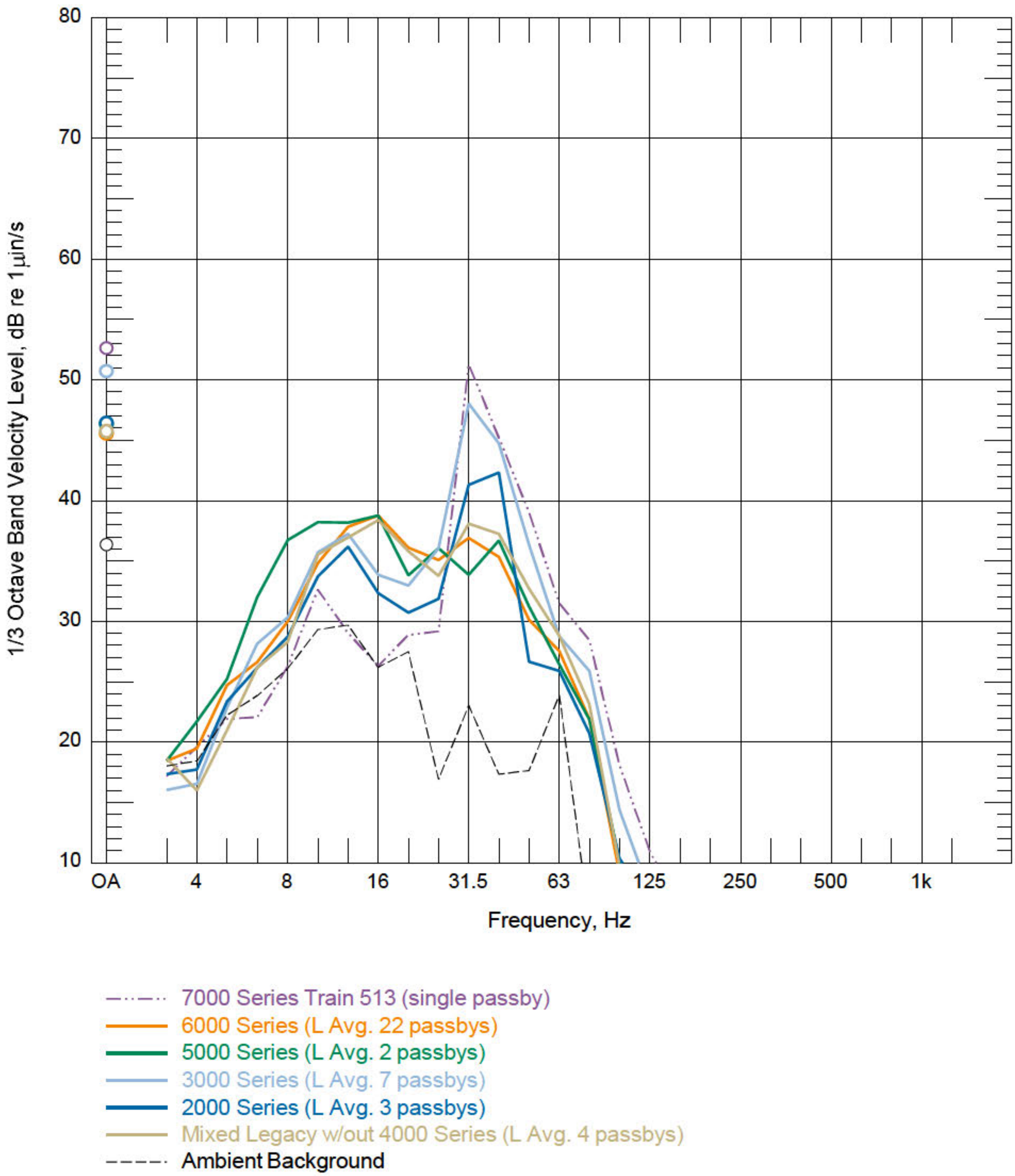


Figure 173: ***Site 9 at Location V4 Basement Bedroom***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

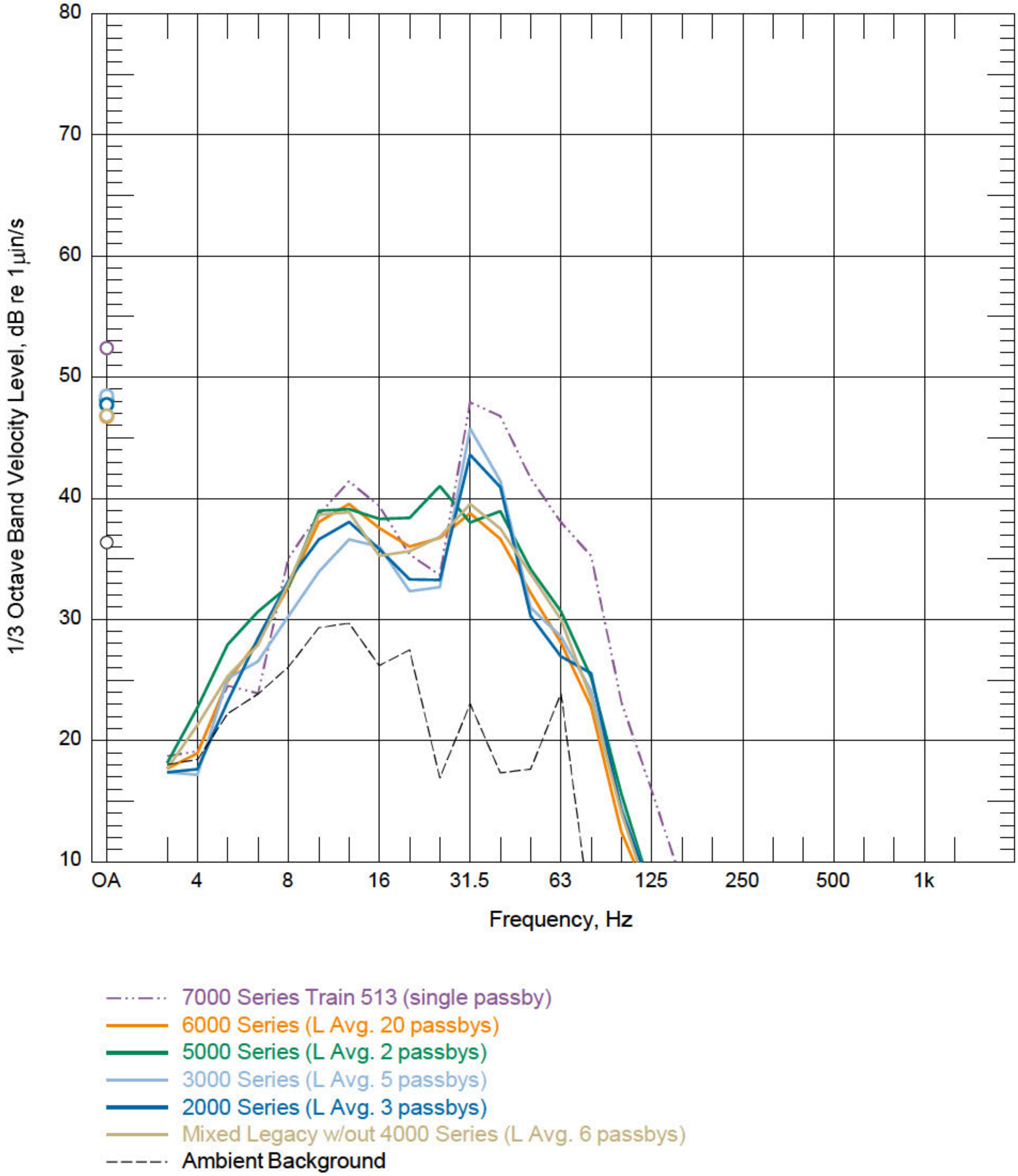


Figure 174: ***Site 9 at Location V4 Basement Bedroom***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

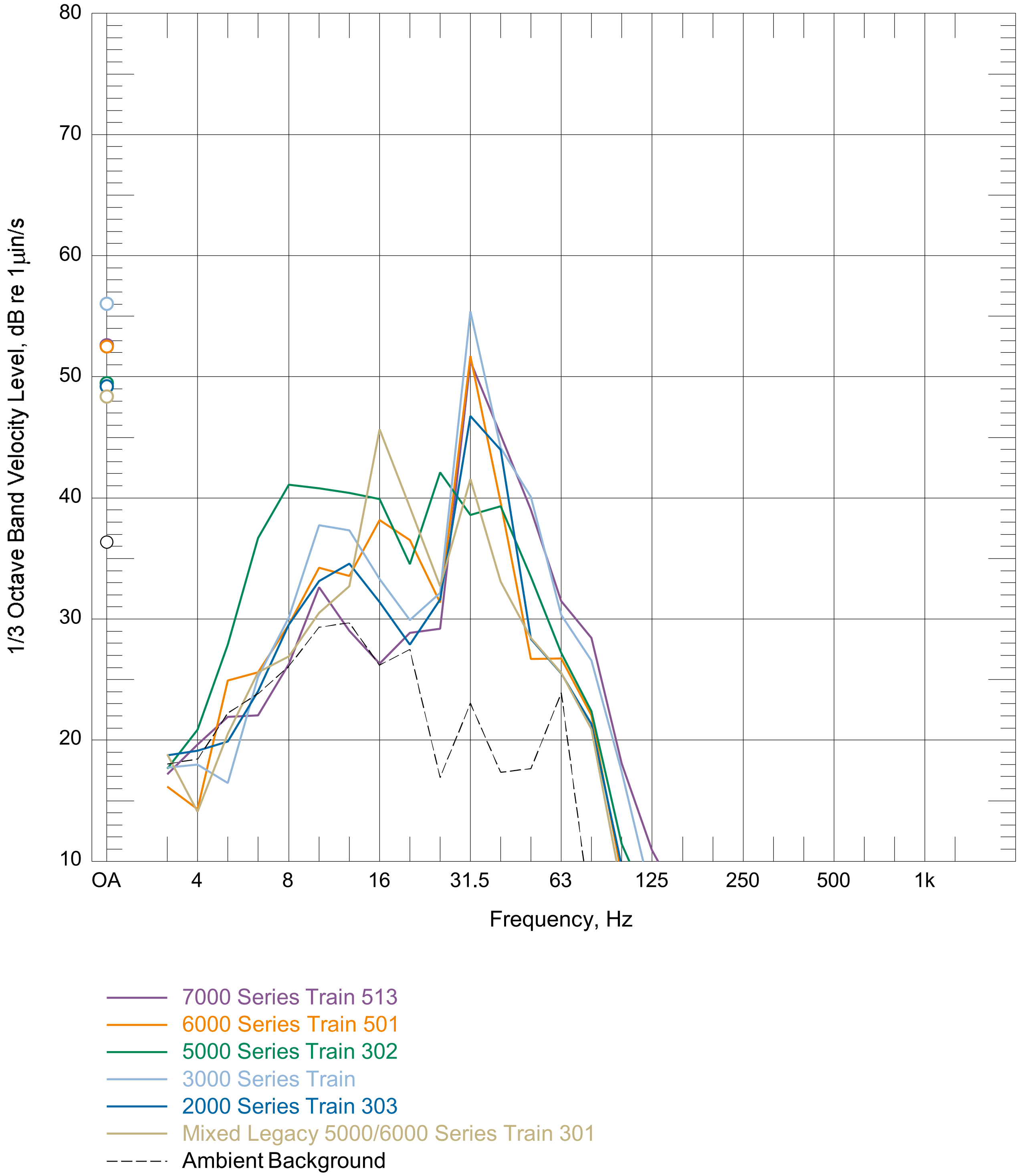


Figure 175: ***Site 9 at Location V4 Basement Bedroom***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

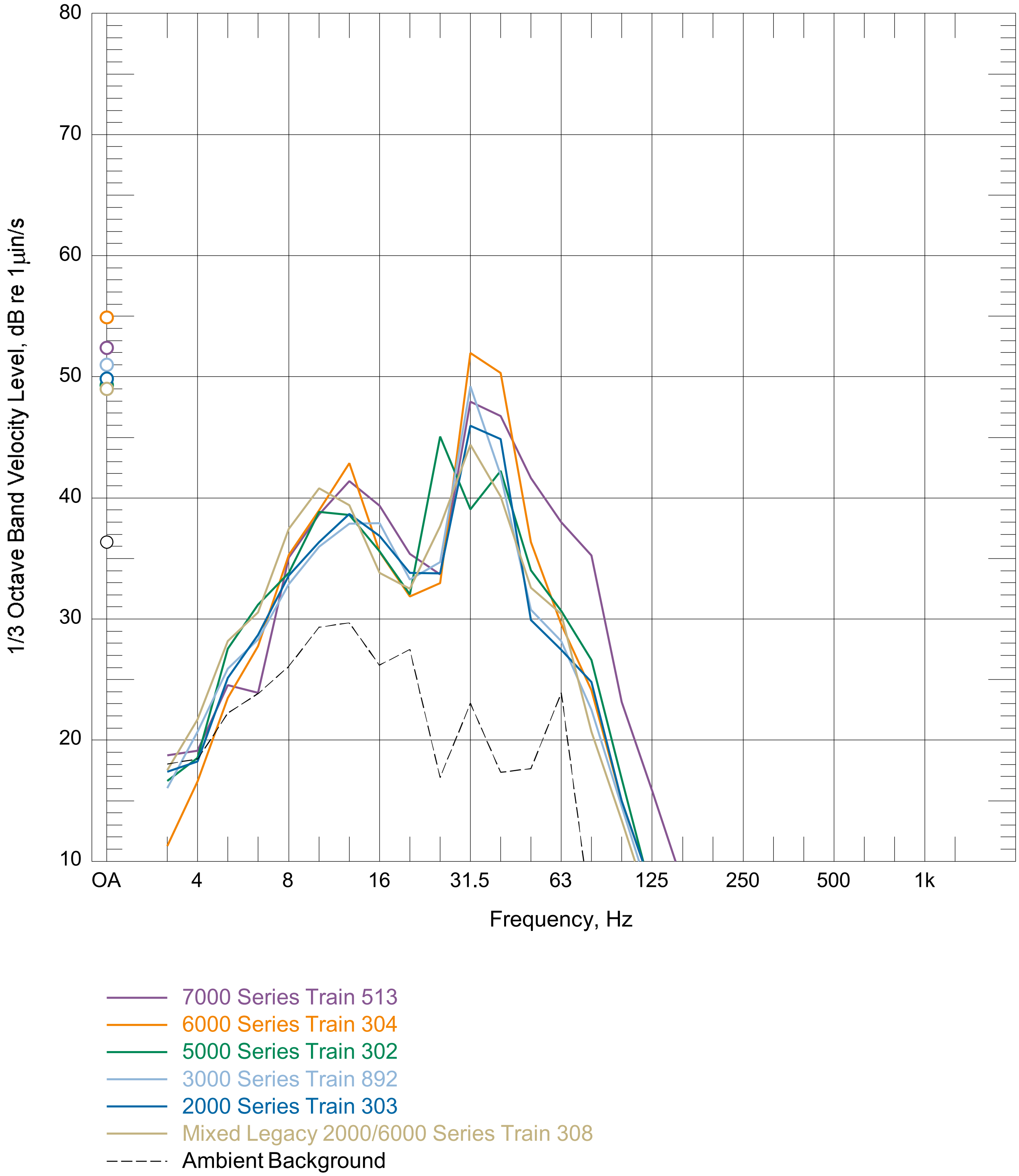


Figure 176: ***Site 9 at Location V4 Basement Bedroom***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

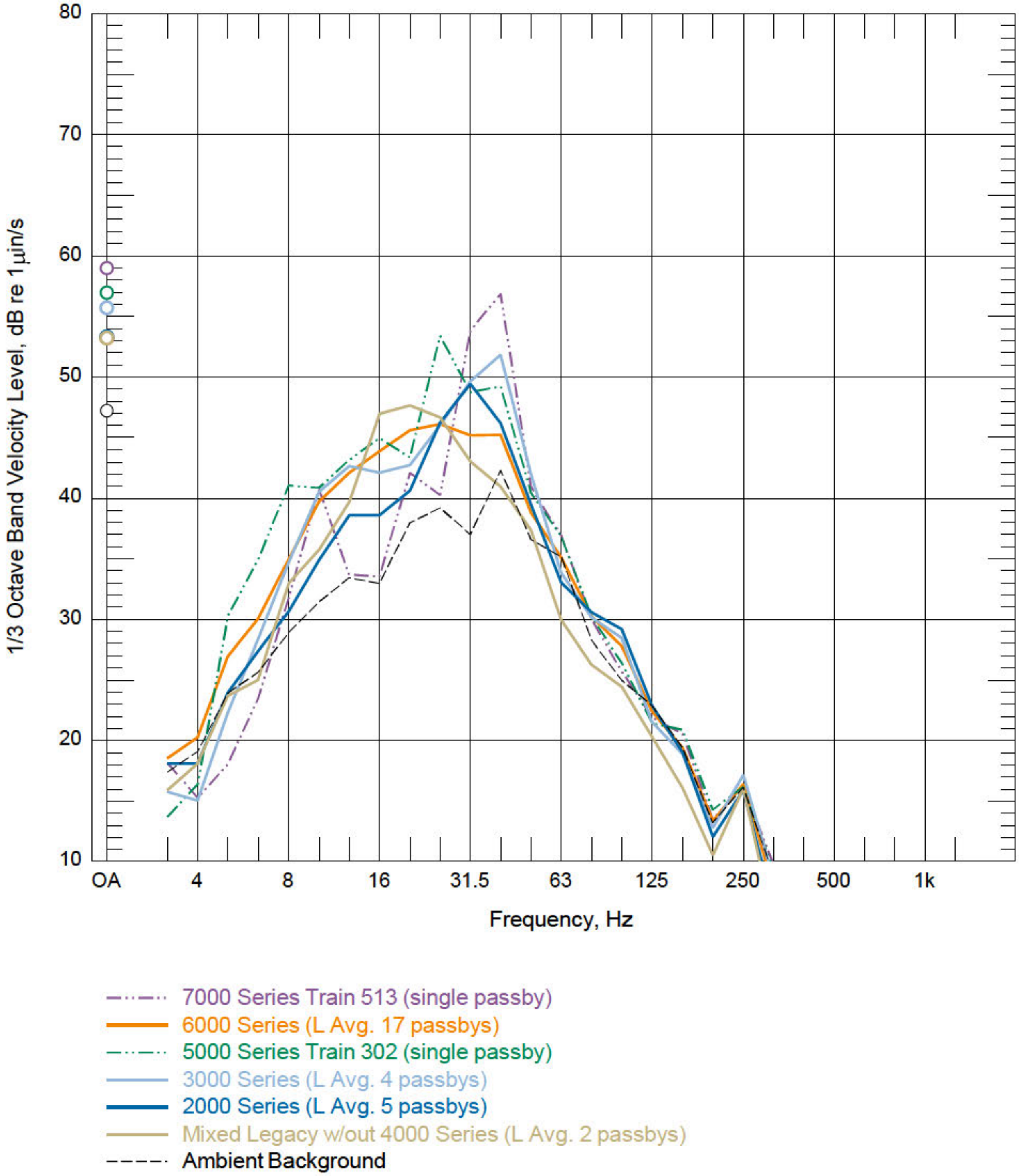


Figure 177: ***Site 9 at Location V5 First Floor Kitchen***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

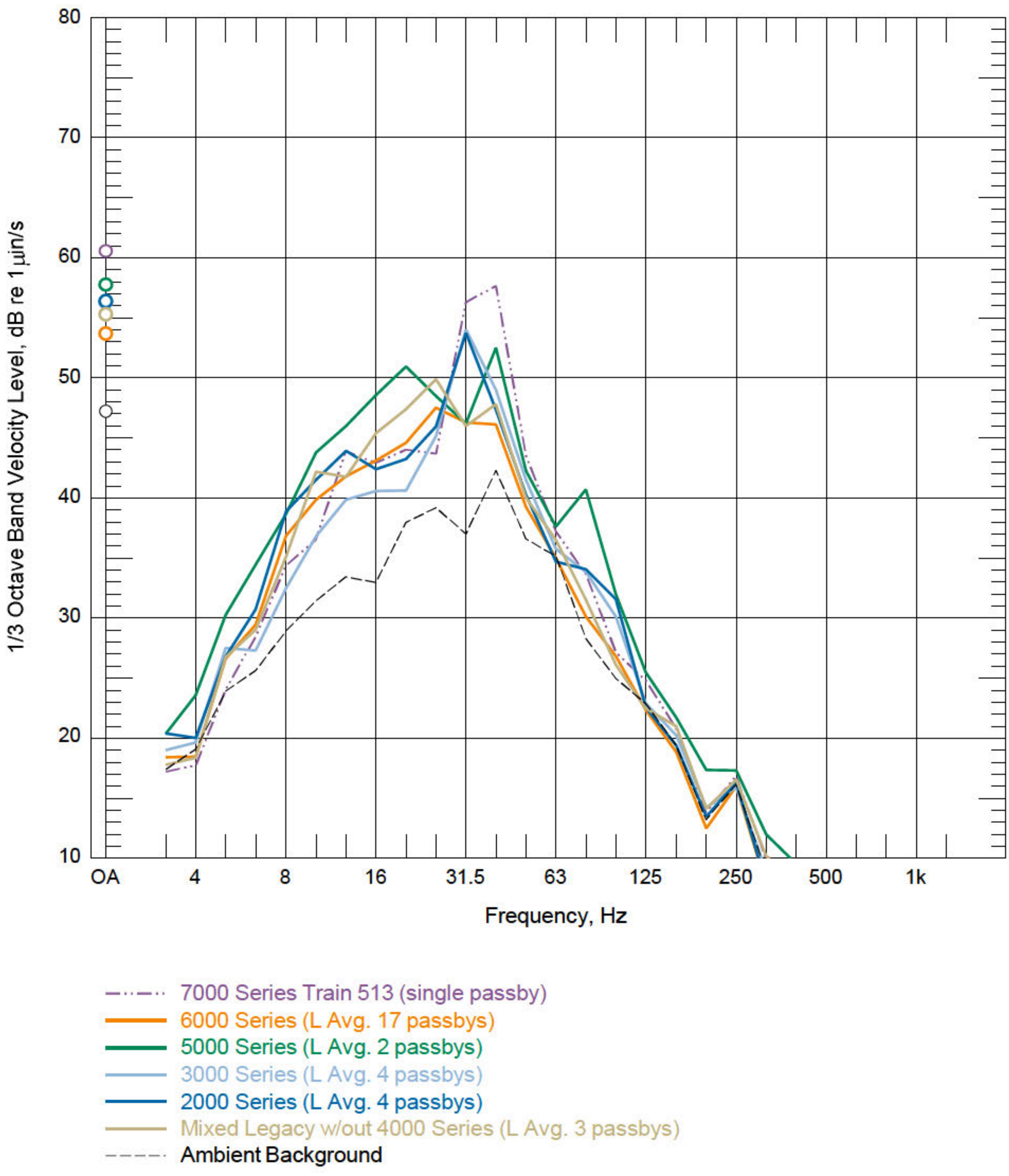


Figure 178: ***Site 9 at Location V5 First Floor Kitchen***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

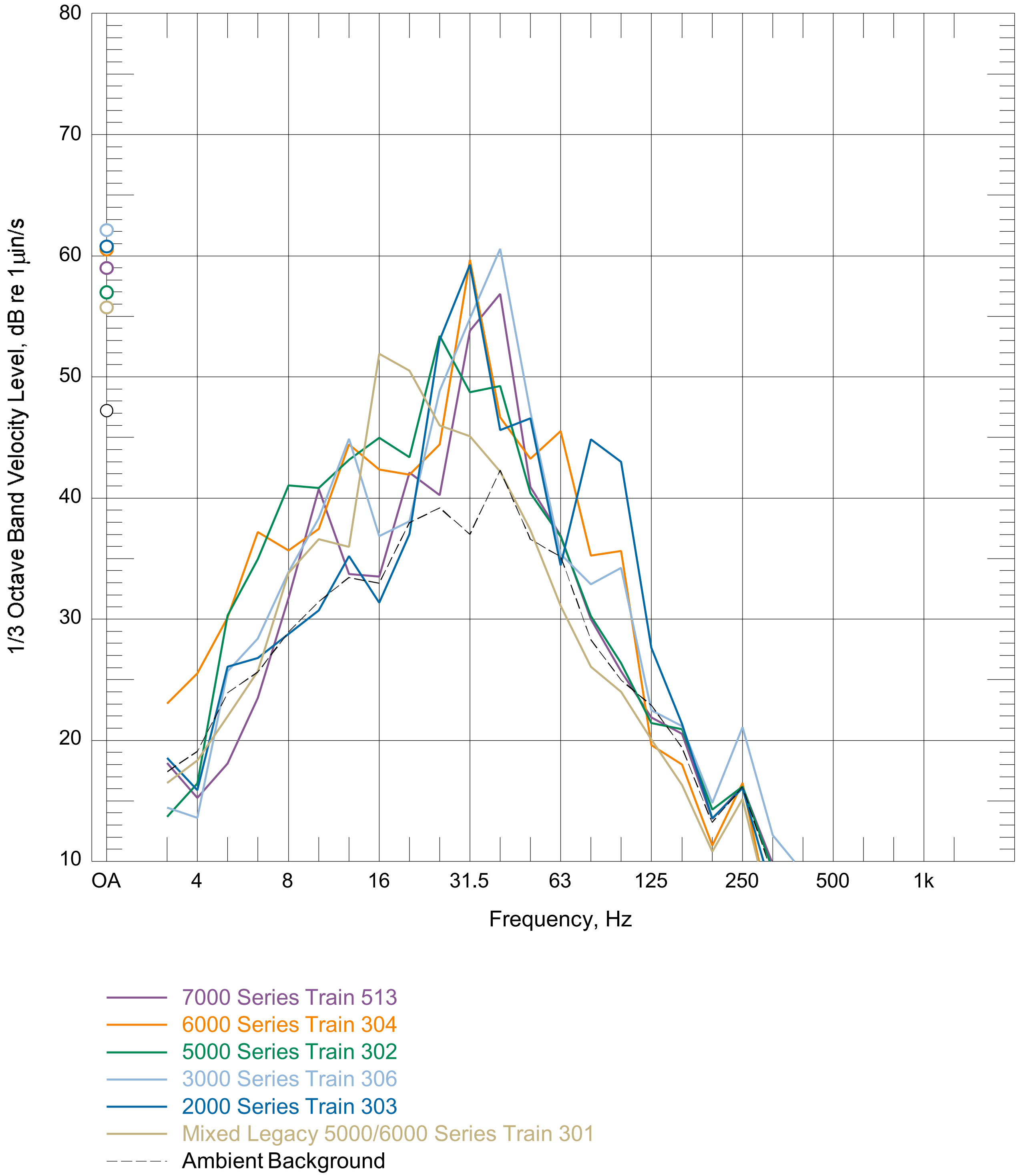


Figure 179: ***Site 9 at Location V5 First Floor Kitchen***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

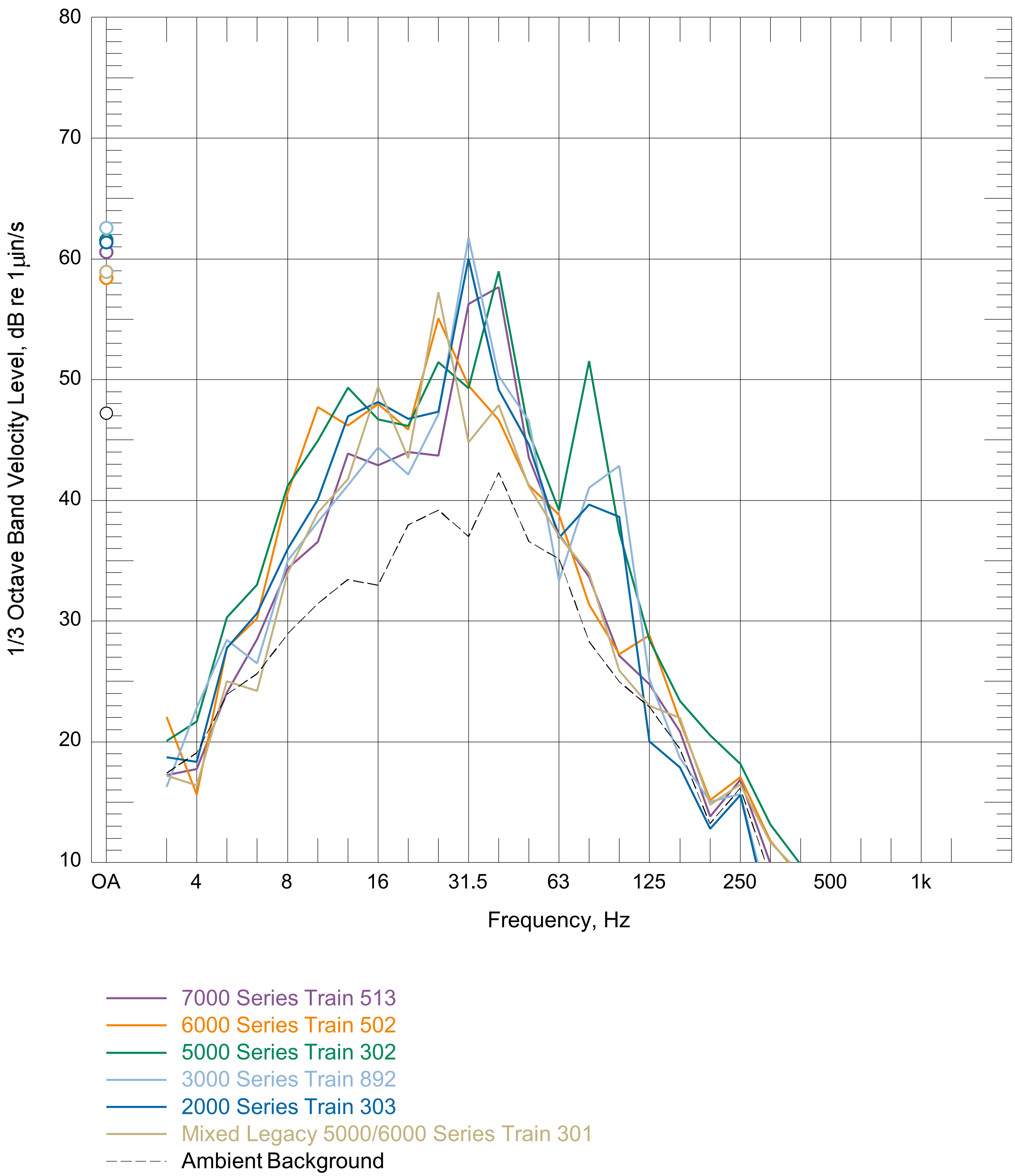


Figure 180: ***Site 9 at Location V5 First Floor Kitchen***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

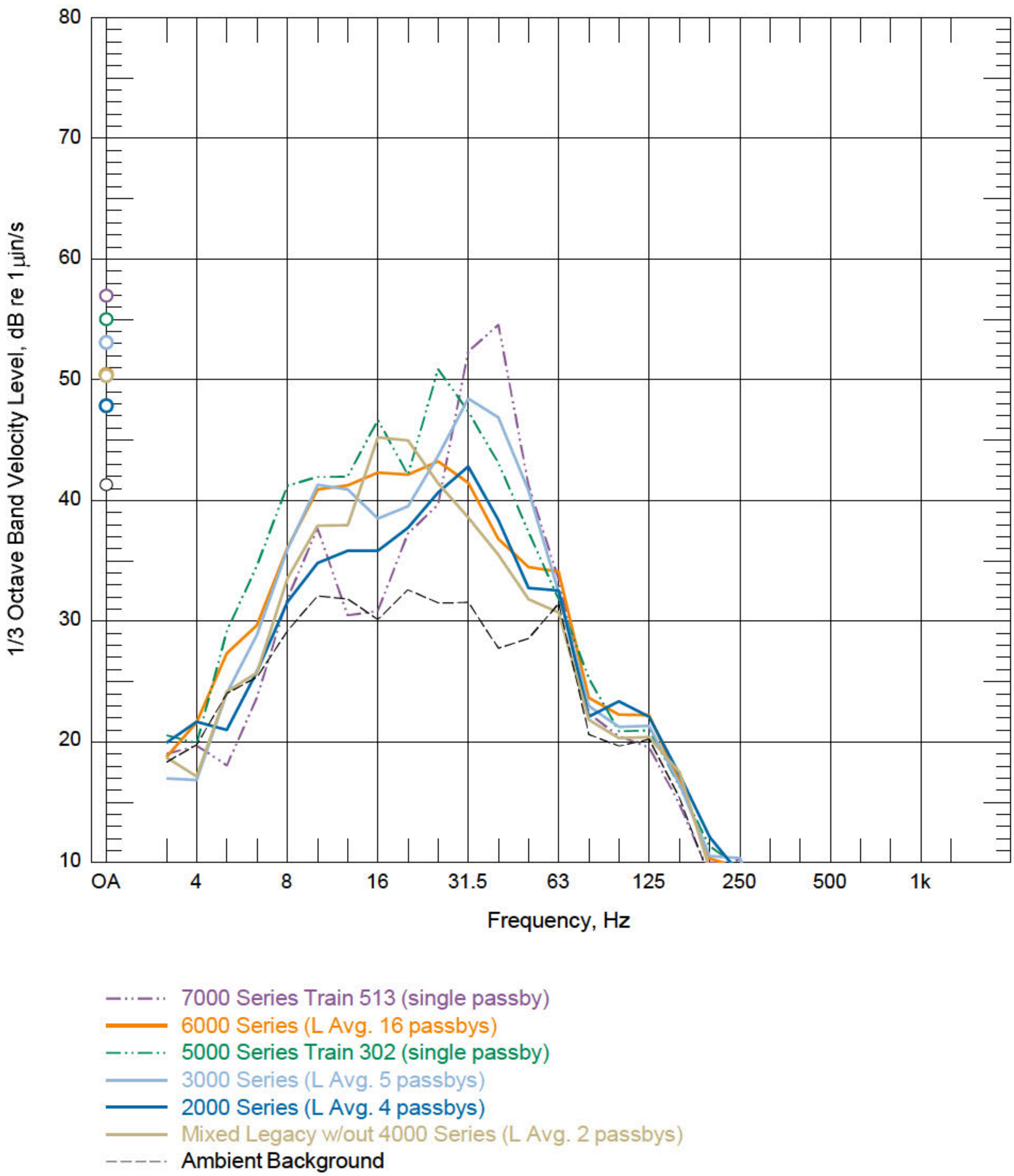


Figure 181: ***Site 9 at Location V6 First Floor Dining Room***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

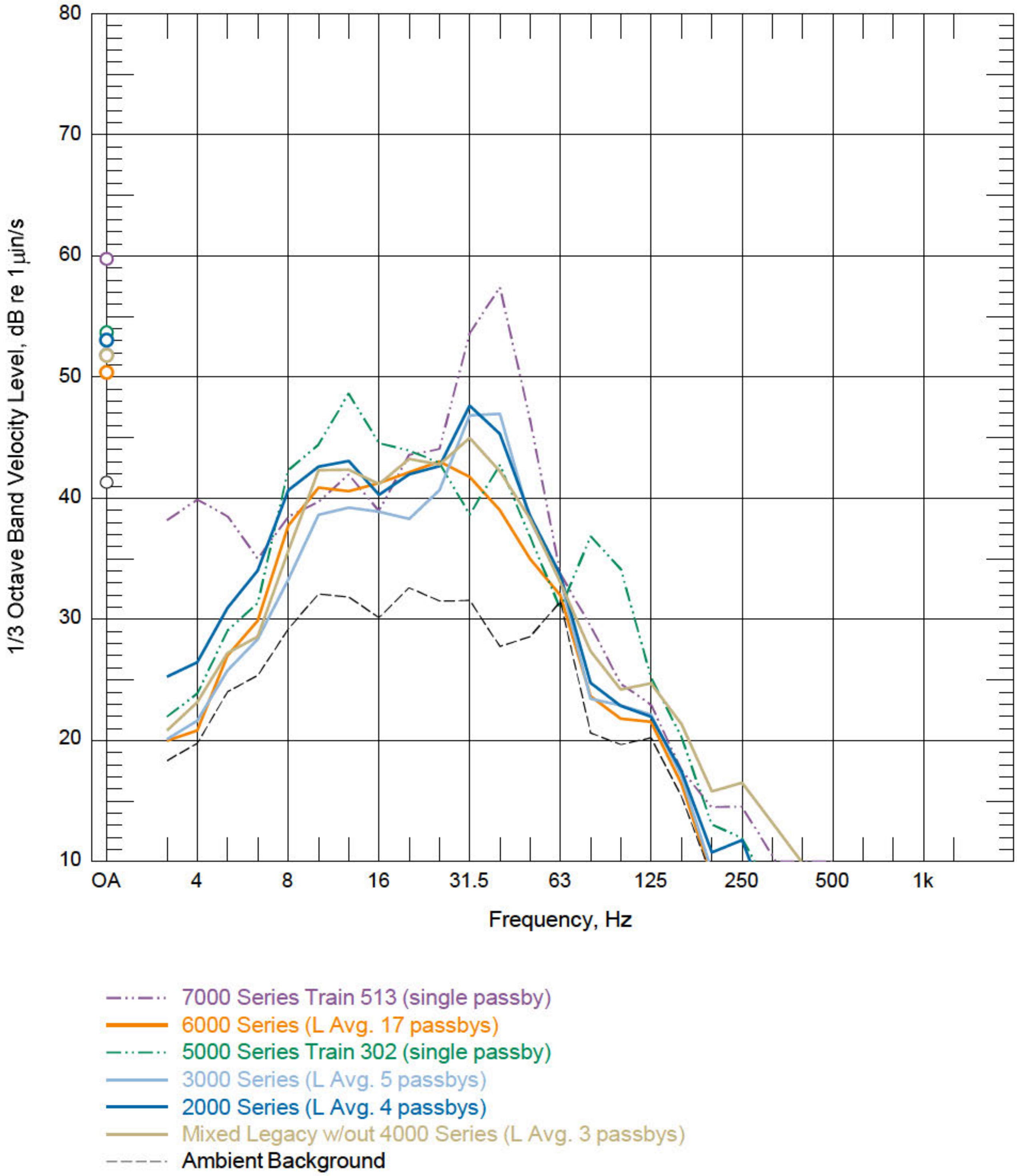


Figure 182: ***Site 9 at Location V6 First Floor Dining Room***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

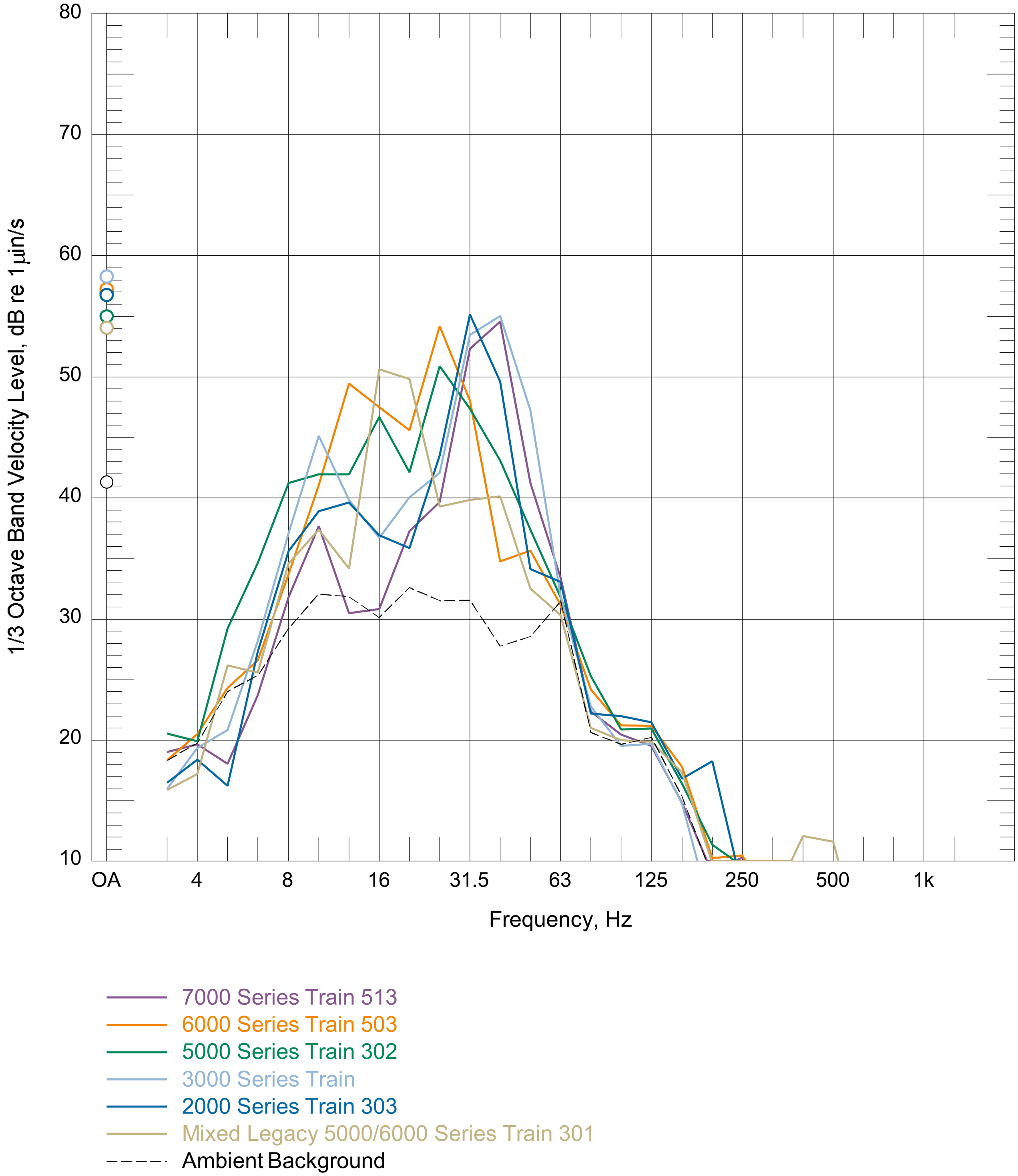


Figure 183: ***Site 9 at Location V6 First Floor Dining Room***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

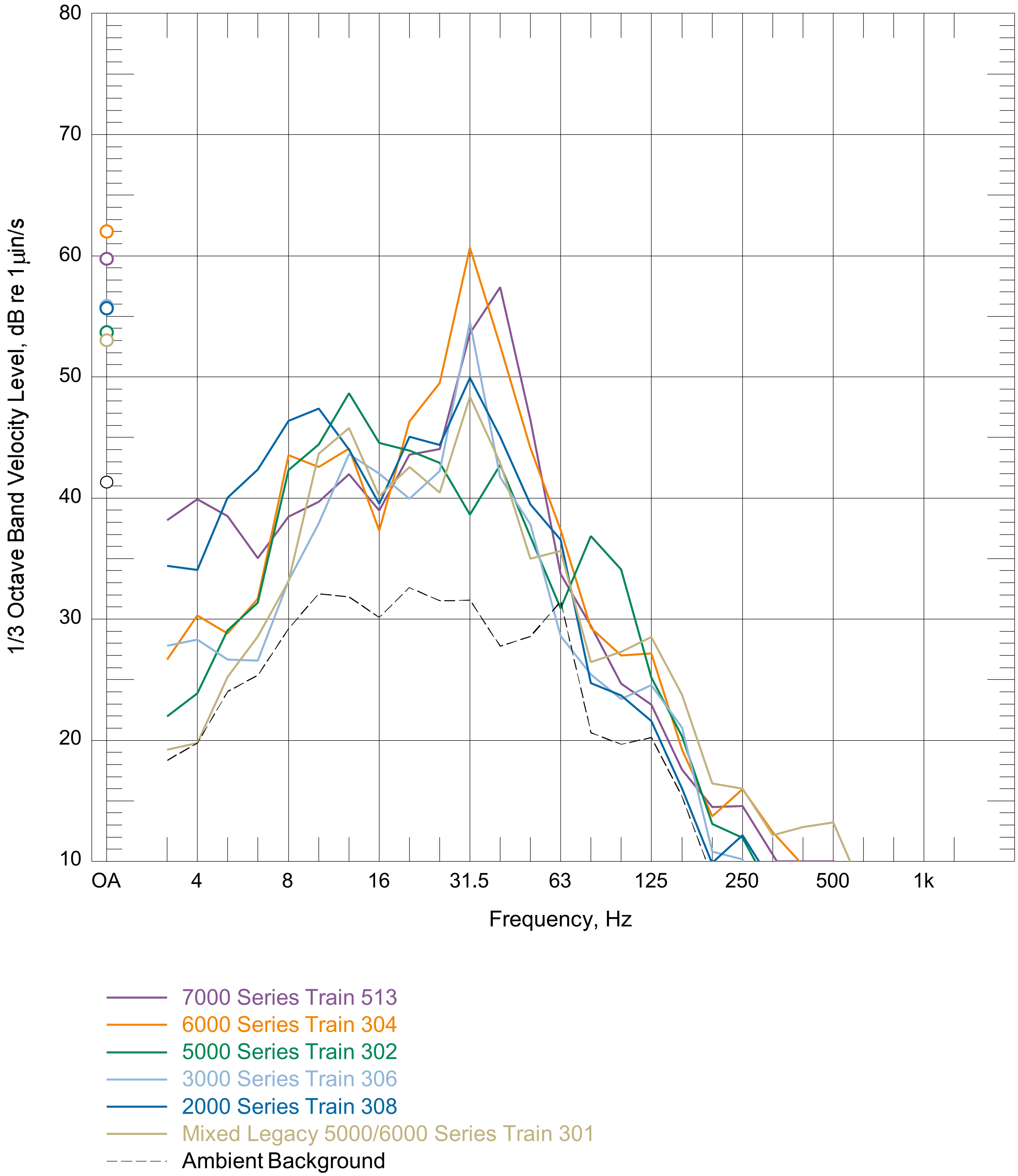


Figure 184: ***Site 9 at Location V6 First Floor Dining Room***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

B.9.6 Passby Ground-borne Noise Spectra and A-weighted Levels

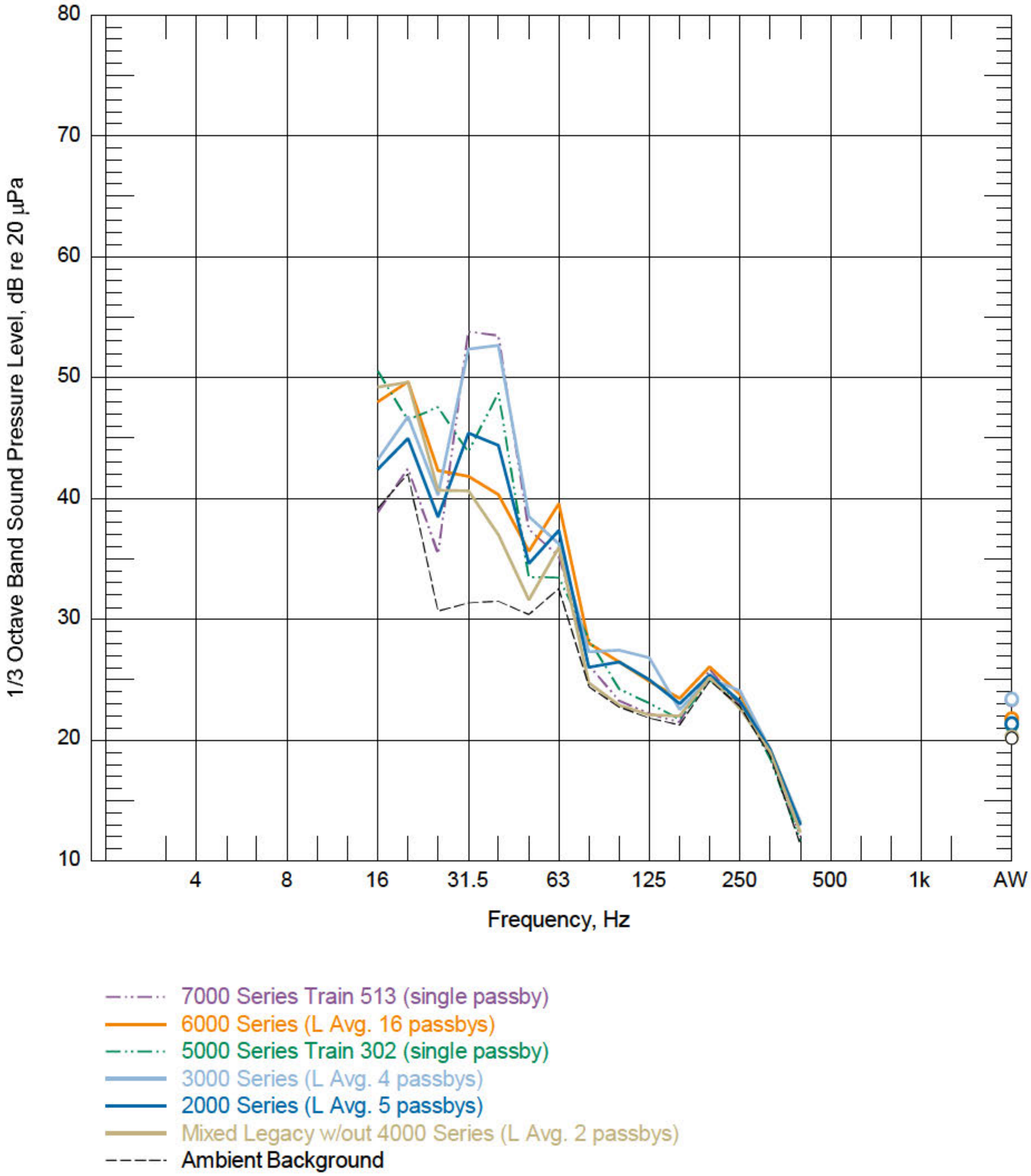


Figure 185: ***Site 9 at Location N1 Basement Laundry Room***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

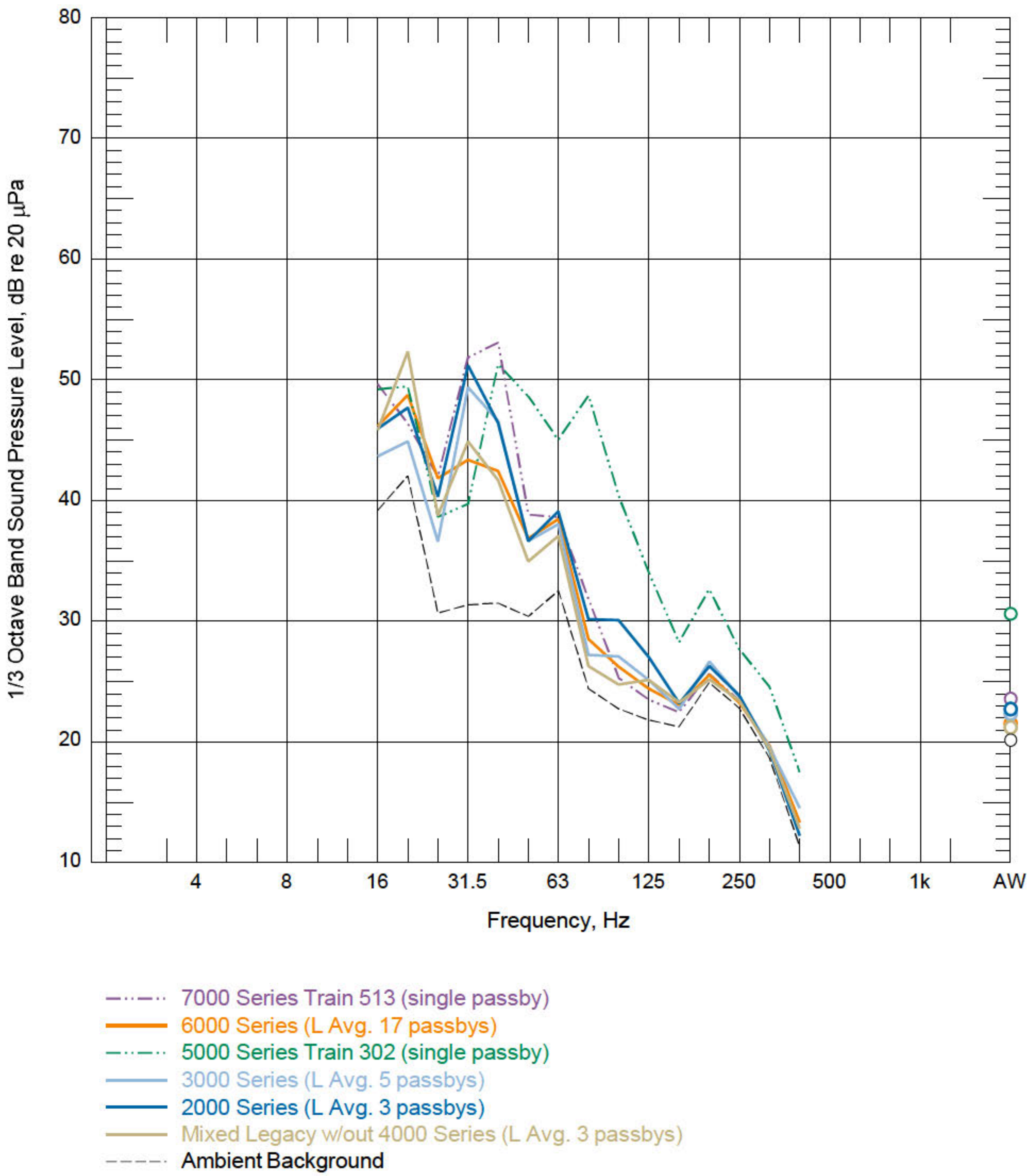


Figure 186: ***Site 9 at Location N1 Basement Laundry Room***
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

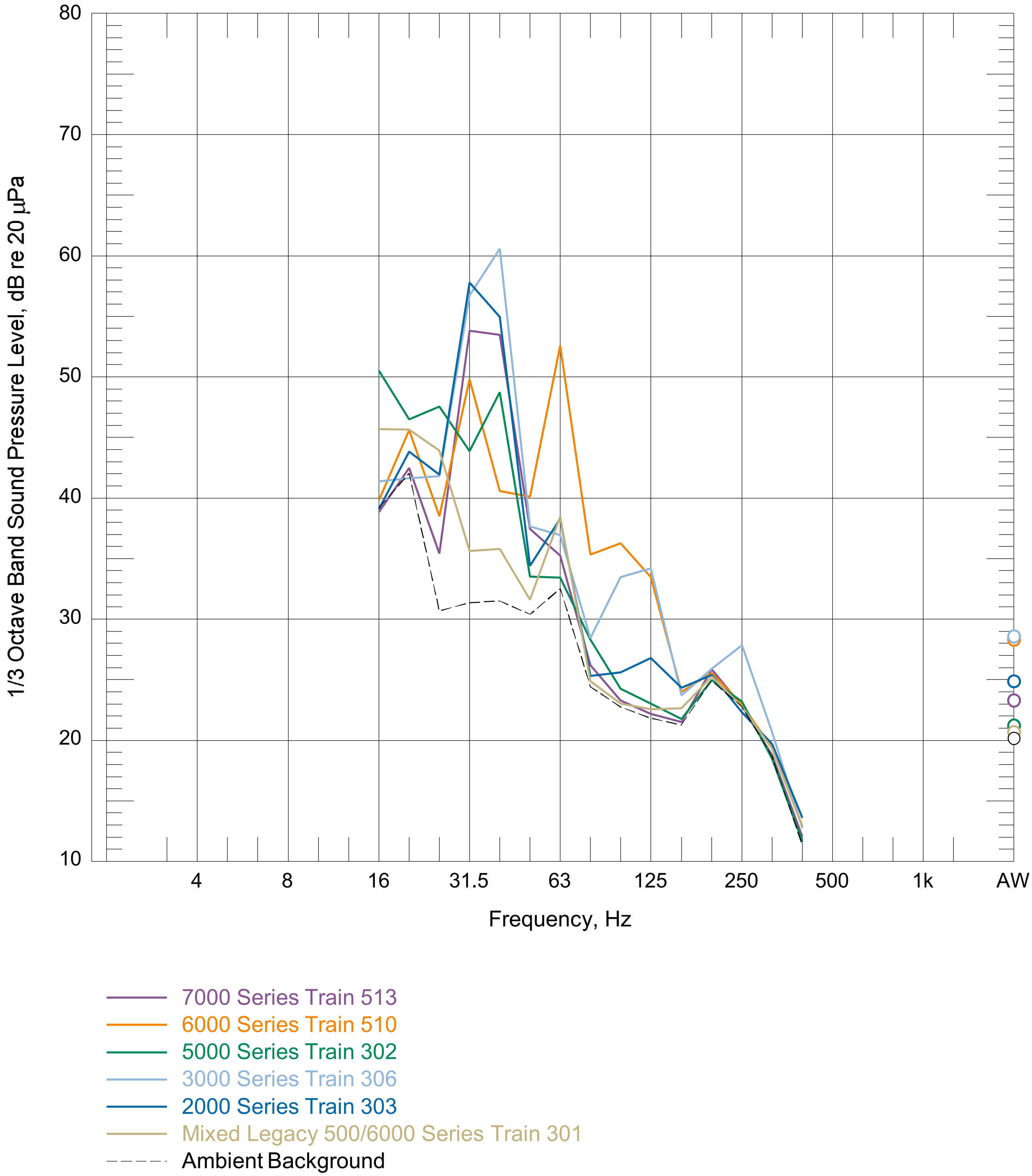


Figure 187: ***Site 9 at Location N1 Basement Laundry Room***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

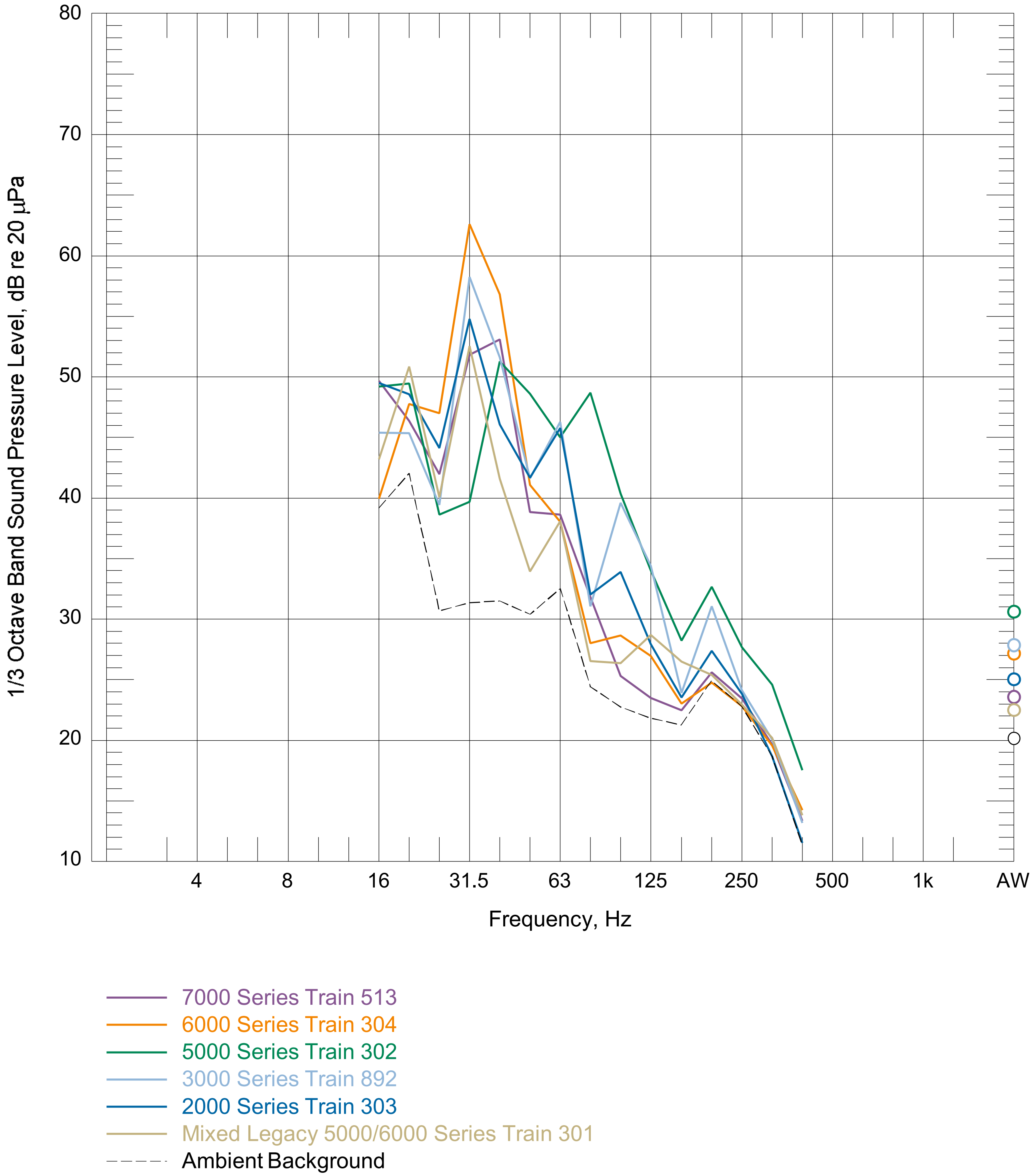


Figure 188: ***Site 9 at Location N1 Basement Laundry Room***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

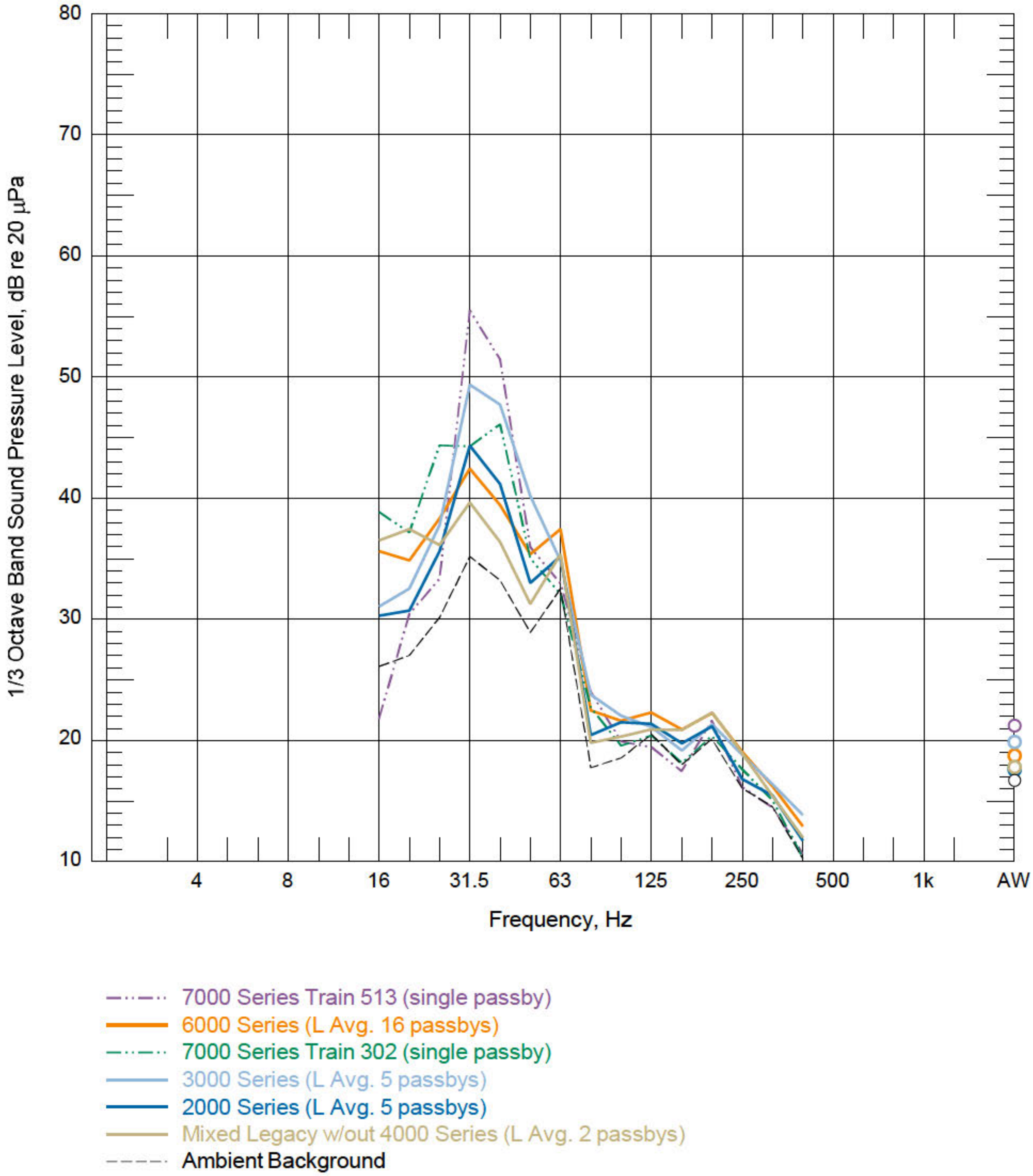


Figure 189: ***Site 9 at Location N2 Basement Bedroom***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

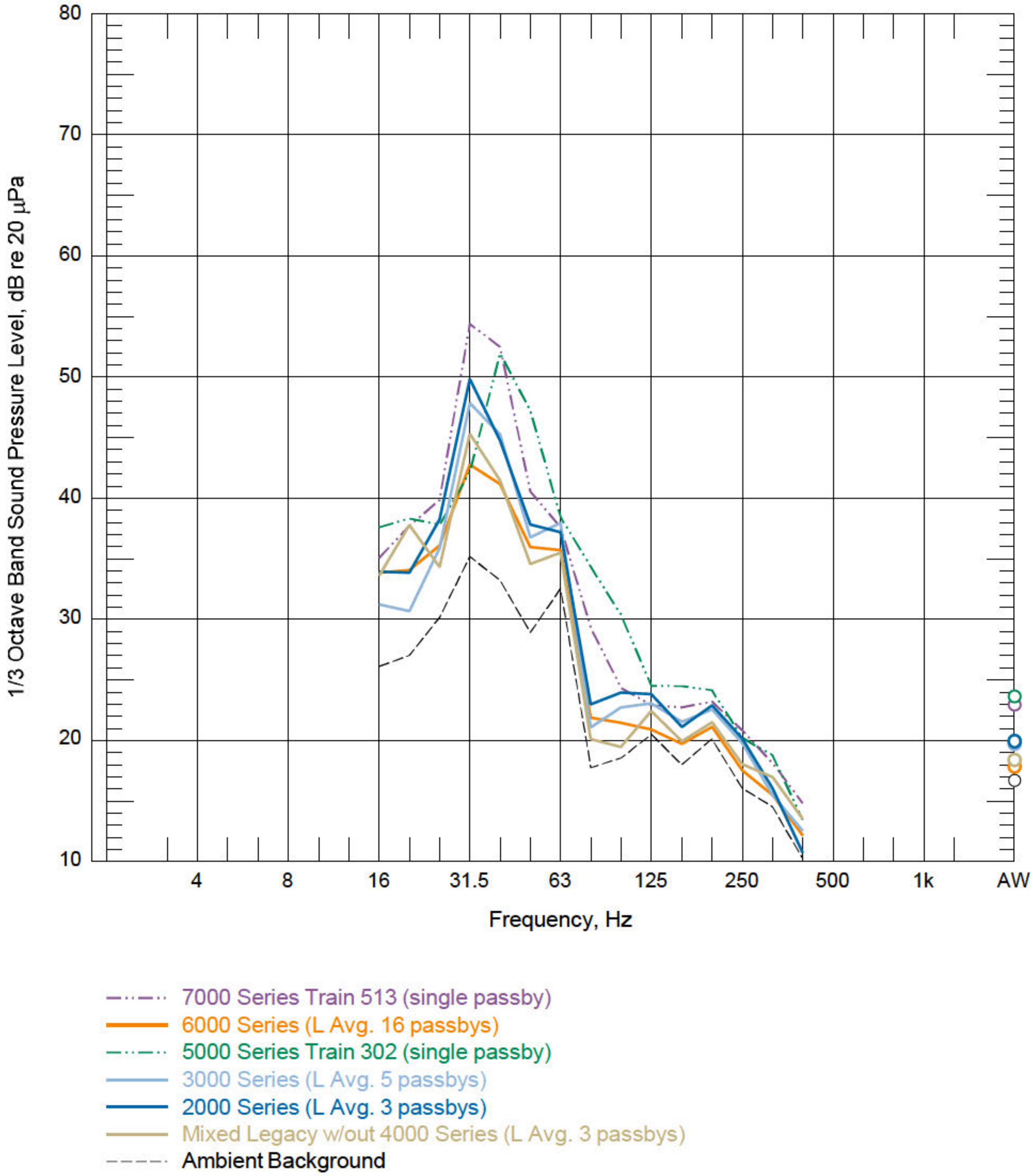


Figure 190: ***Site 9 at Location N2 Basement Bedroom***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

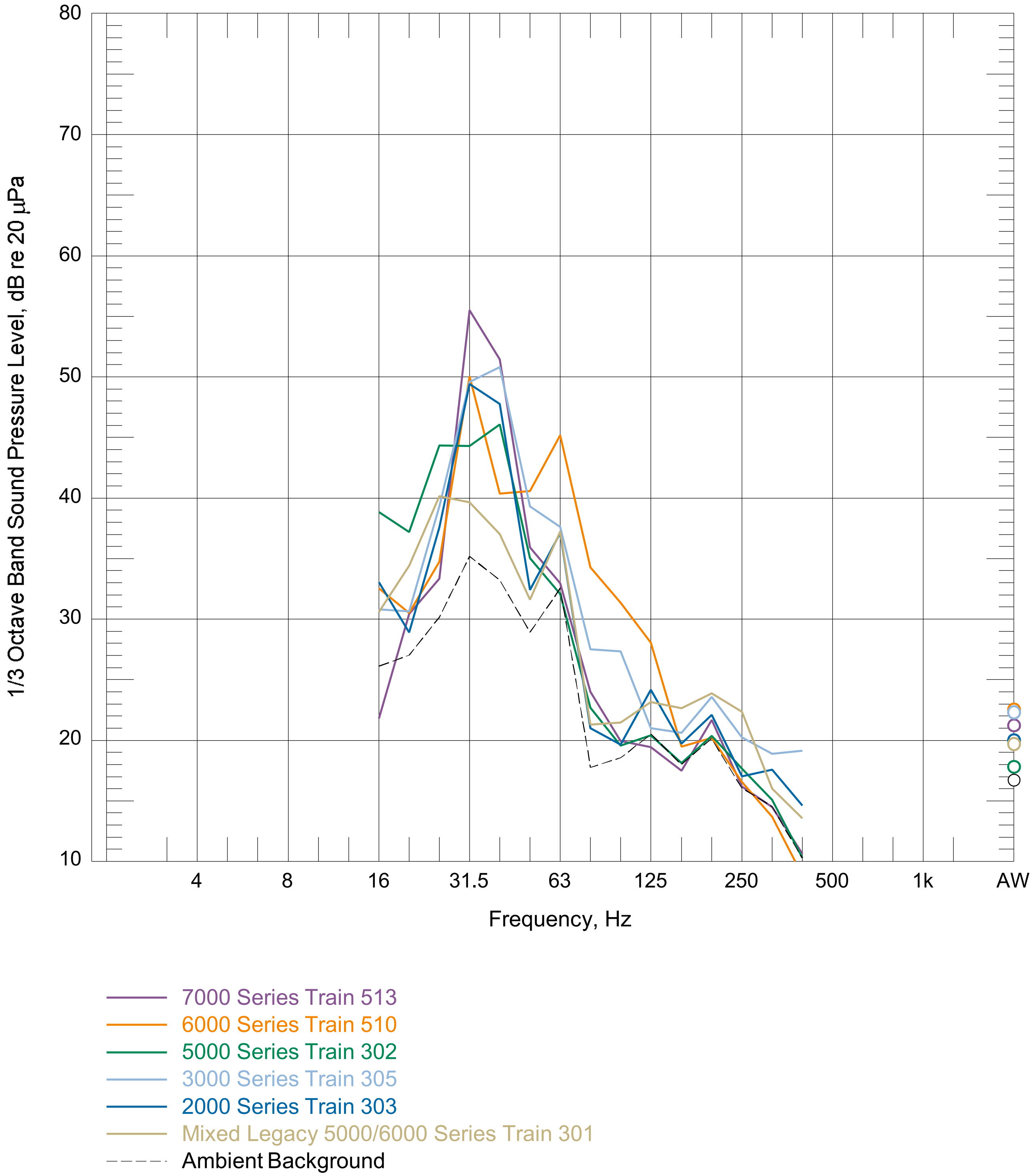


Figure 191: ***Site 9 at Location N2 Basement Bedroom***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

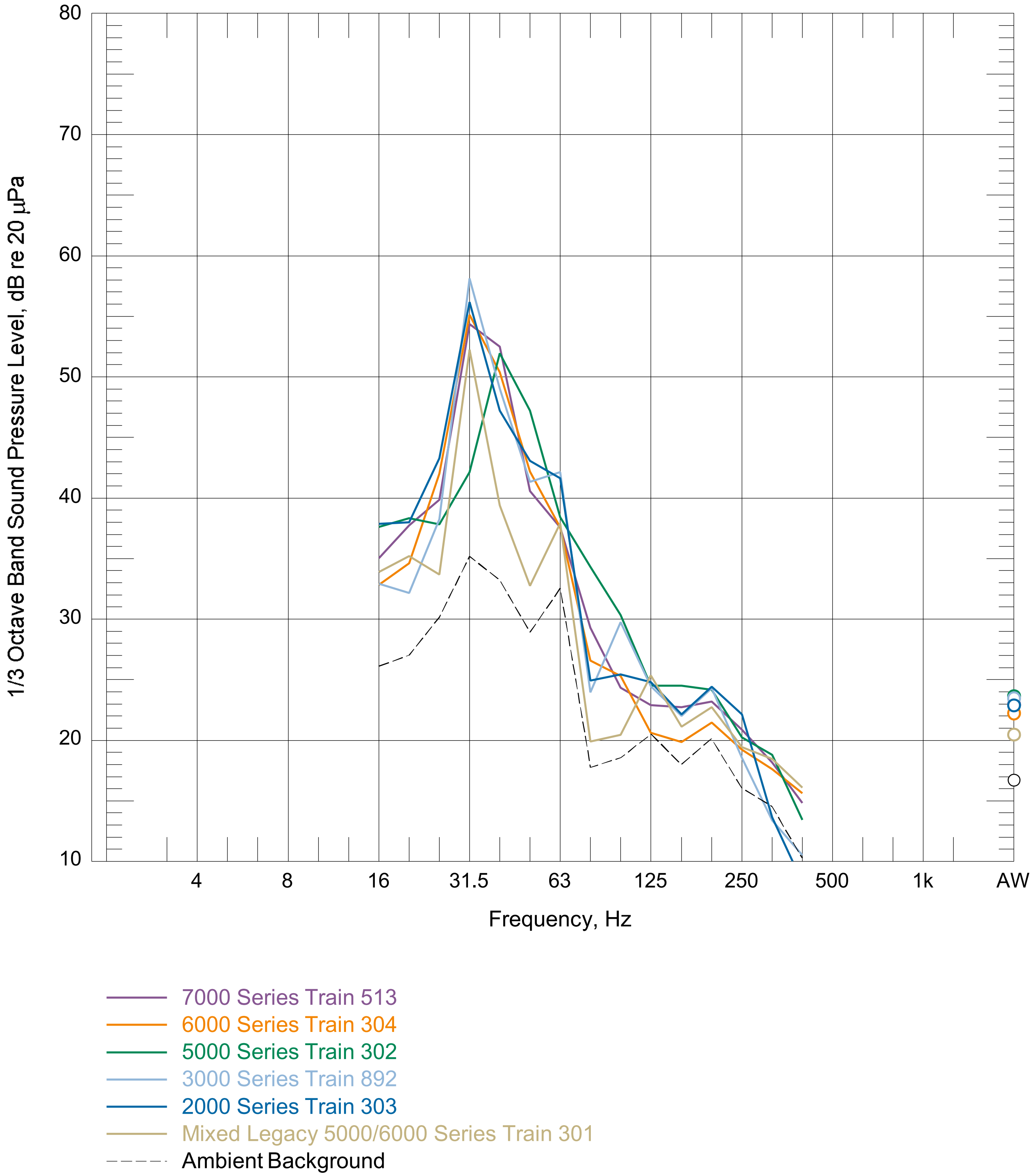


Figure 192: ***Site 9 at Location N2 Basement Bedroom***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

B.10 Site 10 – 4400 block of New Hampshire Avenue NW (Residence)

B.10.1 Building and Tunnel Notes

Location:	Outbound Track 1 side at 206+75
Building Notes:	Residential attached rowhouse with 3 floors consisting of partial underground basement and 2 upper floors. Exterior walls of brick construction, foundation is below-grade slab. One family/tenant for whole house.
Tunnel Structure:	Tunnel
Track Type:	Egg Fasteners
T/R Depth:	75 feet
Train Speed:	33 to 63 mph
Measurement Period:	Tuesday, 8 August 2017, 10:03 to 13:59

B.10.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Sensor[a,b,c]	Location / Room Occupancy	Horizontal Distance[d] (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)	Horizontal Distance (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)
Triaxial Geophone	Basement	79	75	109	42	75	86
V1							
N1	Basement 1/3 from walls						
N2	Basement corner						
V2	First Floor Living Room						
V3	First Floor Dining Room						
V4	Outside	54	75	92	17	75	77

Notes:

a) Tri-axial geophone mounted on floor, logging peak particle velocity
b) V# vibration locations with accelerometer mounted on floor in vertical direction
c) N# noise locations with microphone/sound level meter mounted on tripod 48 inches feet above floor
d) Horizontal distance from track to building façade for indoor locations, not accounting for tunnel depth.
e) T/R depth = top-of-rail depth
f) Total slant distance to T/R = total distance from building to track, accounting for tunnel depth

Figure 193: Aerial Map of 4400 block of New Hampshire Residence and Exterior Measurement Location (nearby Site 8 also shown for reference)

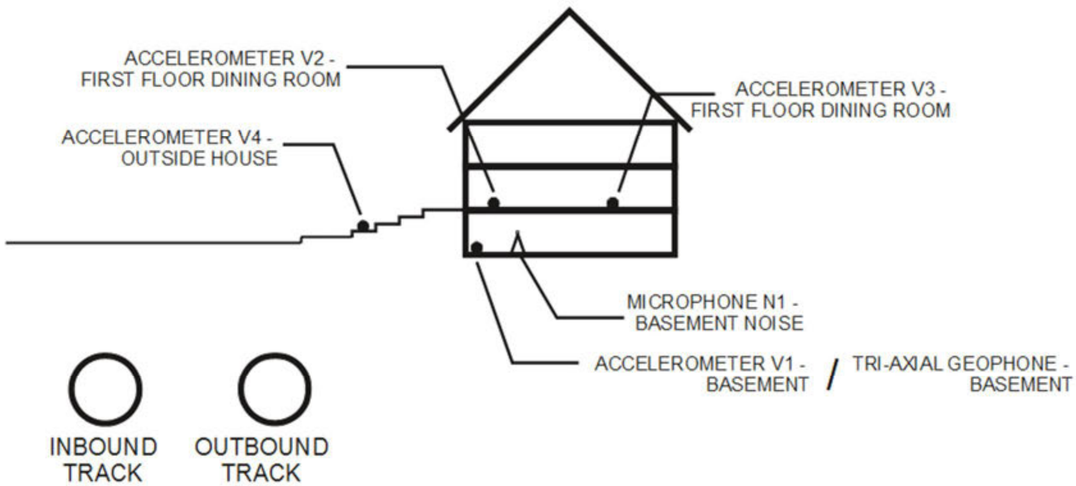


Figure 194: Cross-section Sketch (not to scale) of 4400 block of New Hampshire NW Residence Measurement Locations

B.10.3 GBNV Assessment Summary

SITE 10	4400 block of NEW HAMPSHIRE AVENUE NW – ATTENDED PASSBY MEASUREMENT GBNV ASSESSMENT		
	Ground-borne Vibration (GBV)	**>70 VdB?**	**Notes**
	7000 Series - Average of Multiple Passbys	YES*	*pos. V2 and V3
	6000 Series - Average of Multiple Passbys	NO	
	3000 Series - Average of Multiple Passbys	YES*	*pos. V2 and V3
	2000 Series - Average of Multiple Passbys	NO	
	Mixed Legacy without 4000 Series - Average of Multiple Passbys	NO	
	7000 Series - Individual Train with Highest Overall Vibration	YES*	*pos. V2 and V3
	6000 Series - Individual Train with Highest Overall Vibration	YES*	*pos. V2
	3000 Series - Individual Train with Highest Overall Vibration	YES*	*pos. V2 and V3
	2000 Series - Individual Train with Highest Overall Vibration	YES*	*pos. V2 and V3
	Mixed Legacy without 4000 Series - Individual Train with Highest Overall Vibration	YES*	*pos. V2 and V3
	Ground-borne Noise (GBN)	**>40 dBA?**	**Notes**
	7000 Series - Average of Multiple Passbys	NO	
	6000 Series - Average of Multiple Passbys	NO	
	3000 Series - Average of Multiple Passbys	NO	
	2000 Series - Average of Multiple Passbys	NO	
	Mixed Legacy without 4000 Series - Average of Multiple Passbys	NO	
	7000 Series - Individual Train with Highest A-weighting	NO	
	6000 Series - Individual Train with Highest A-weighting	NO	
	3000 Series - Individual Train with Highest A-weighting	NO	
	2000 Series - Individual Train with Highest A-weighting	NO	
	Mixed Legacy without 4000 Series - Individual Train with Highest A-weighting	NO	

B.10.4 PPV Results

SITE 10	4400 block of NEW HAMPSHIRE AVENUE NW – POTENTIAL FOR BUILDING VIBRATION DAMAGE ASSESSMENT						
	>0.2 in/sec PPV in any direction?	Average PPV (in/s)			PPV Range (in/s)		
		Tran	Vert	Long	Tran	Vert	Long
	NO	0.0031	0.0032	0.0027	0.003 - 0.011	0.002 - 0.023	0.002 - 0.017
Basement 8-Aug-17, 10:09:29 AM to 2:03:43 PM							

B.10.5 Passby Vibration Spectra and Overall Levels

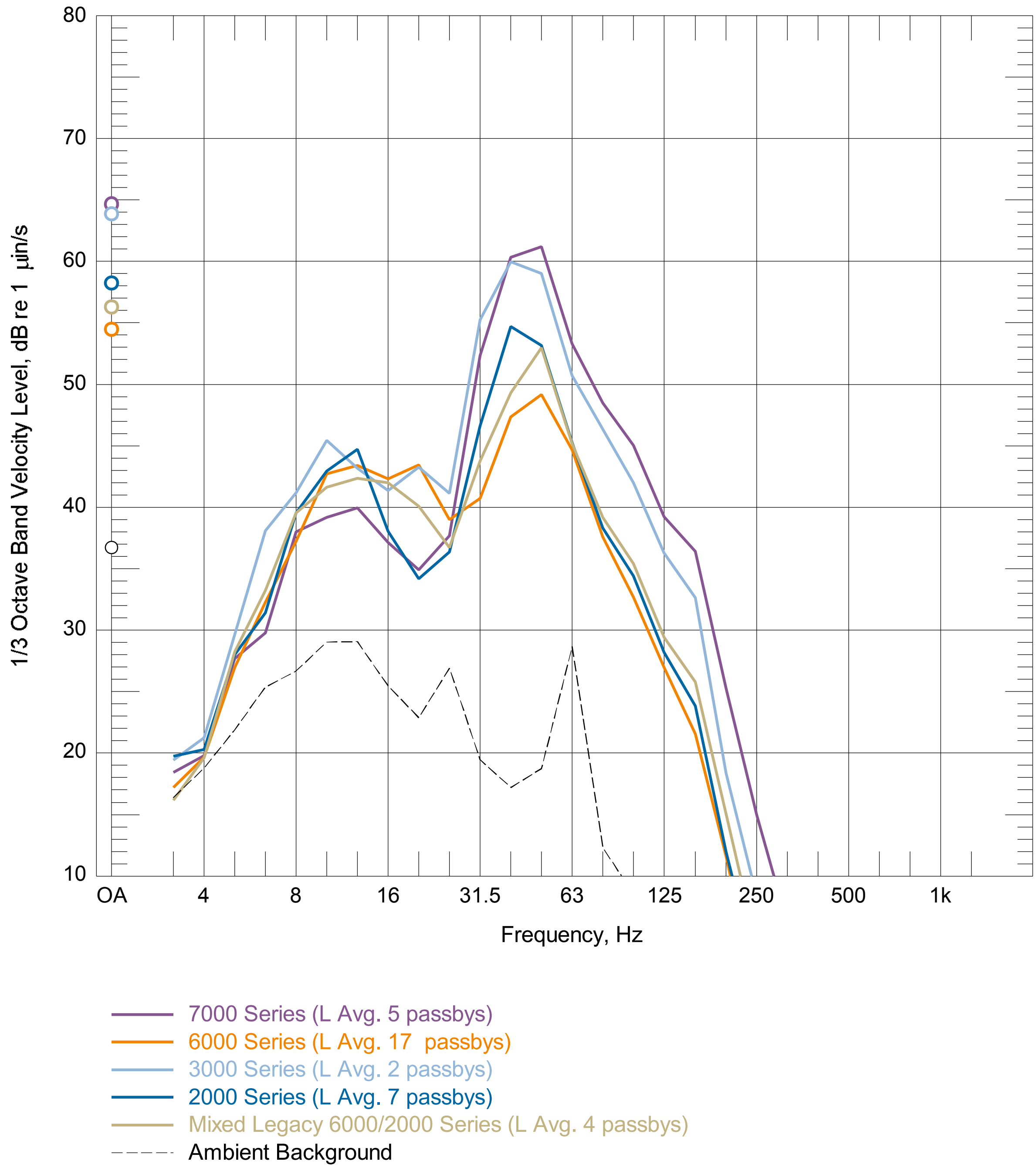


Figure 195: ***Site 10 at Location V1 Basement***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

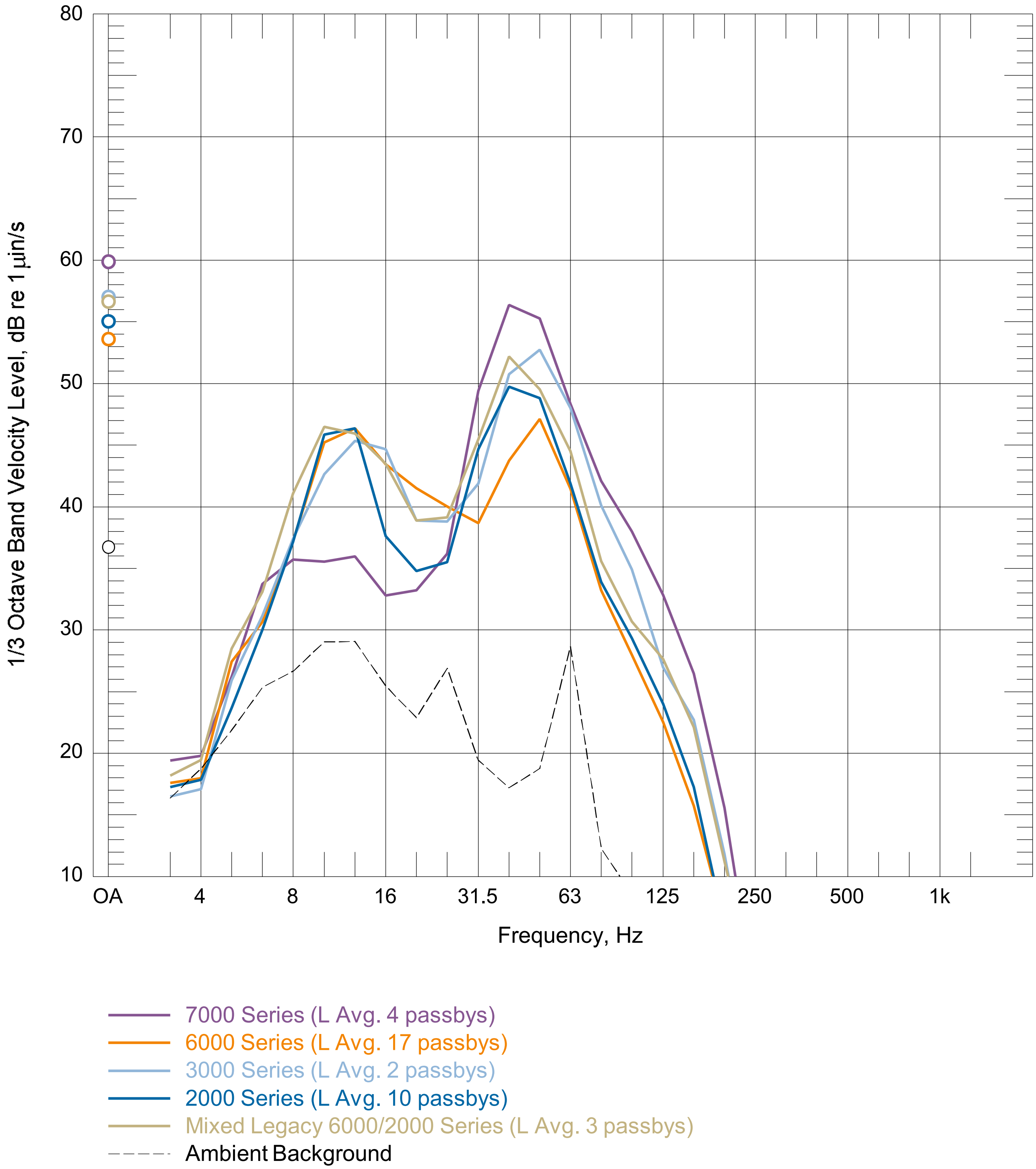


Figure 196: ***Site 10 at Location V1 Basement***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

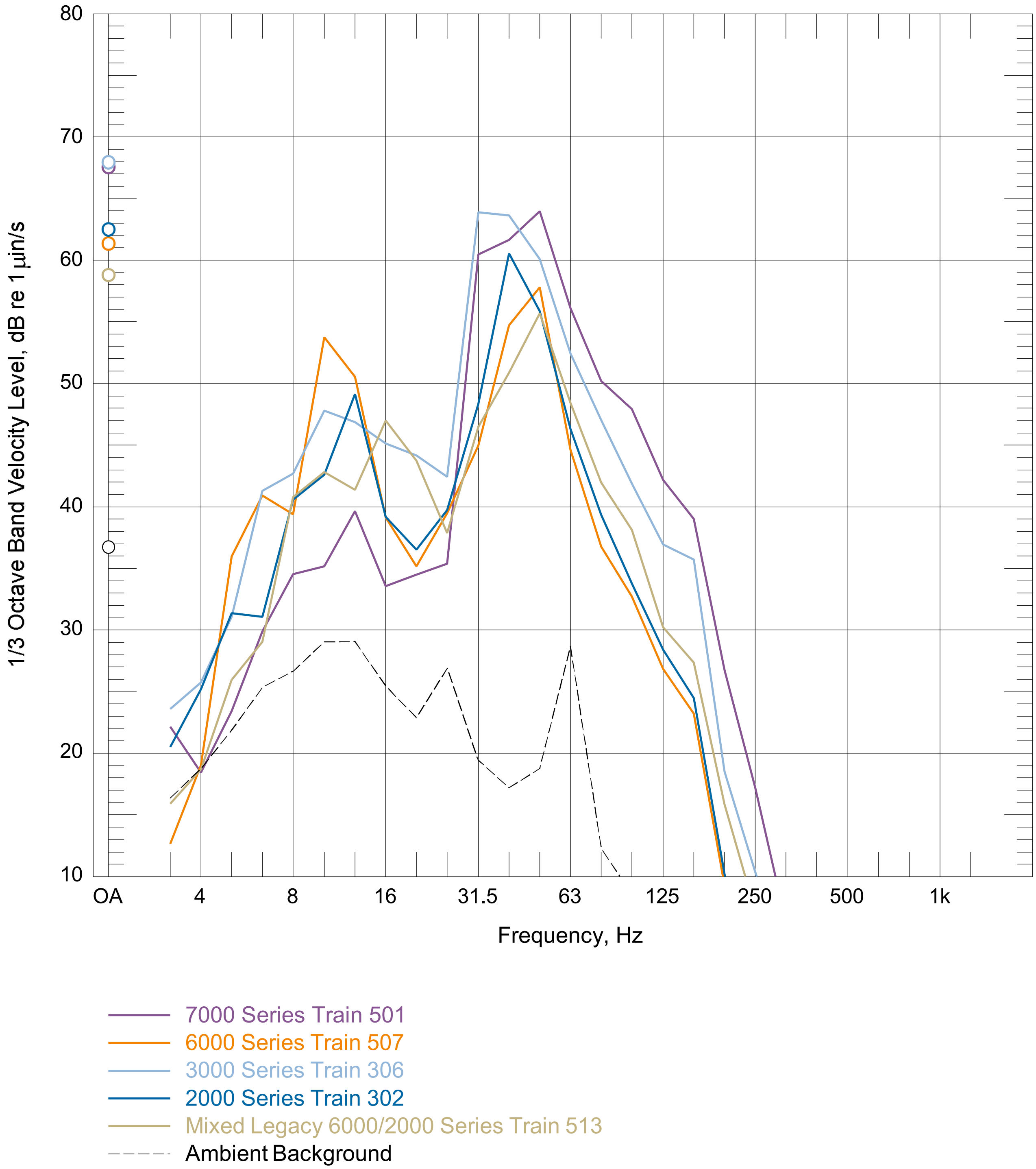


Figure 197: ***Site 10 at Location V1 Basement***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

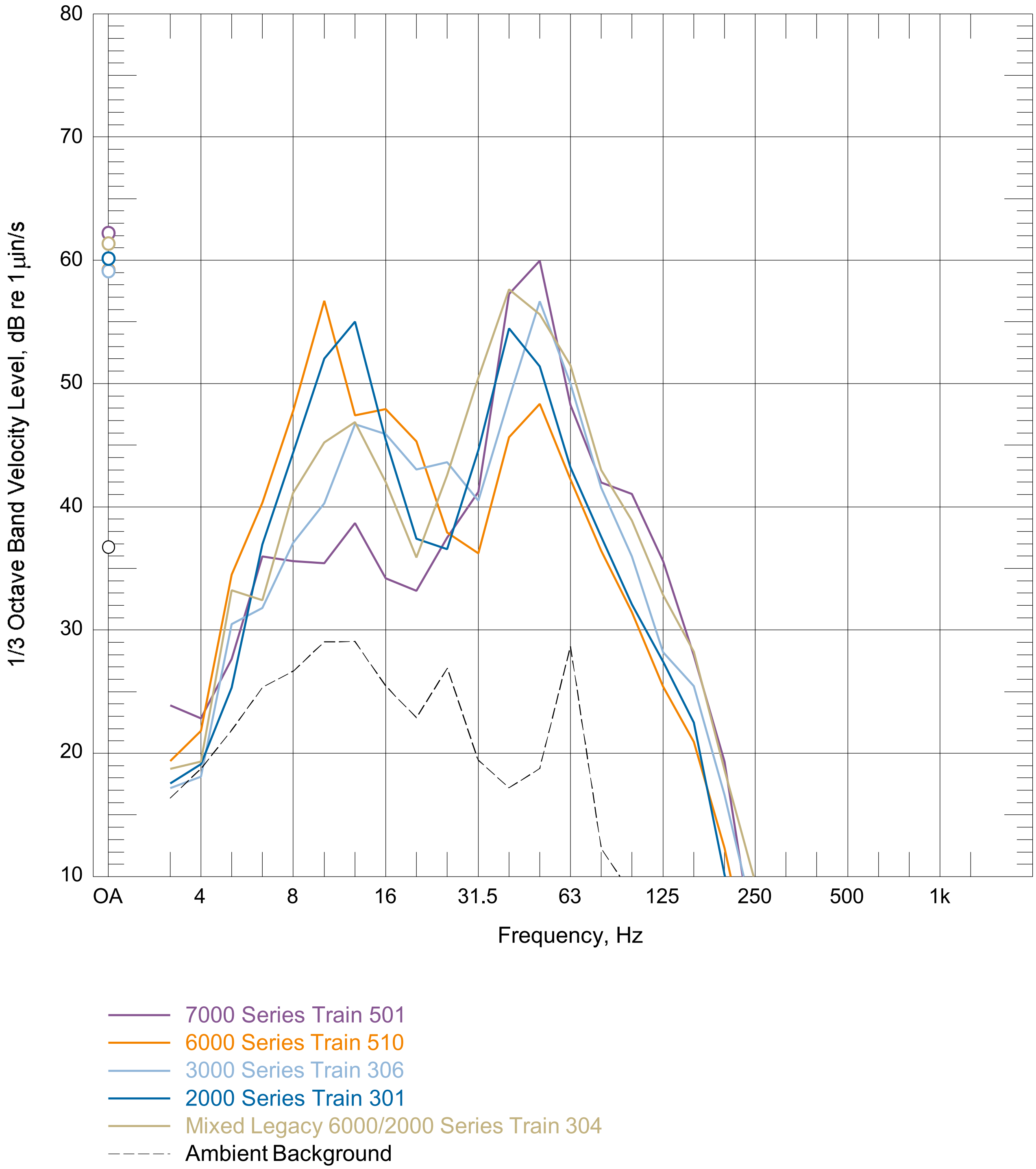


Figure 198: ***Site 10 at Location V1 Basement***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

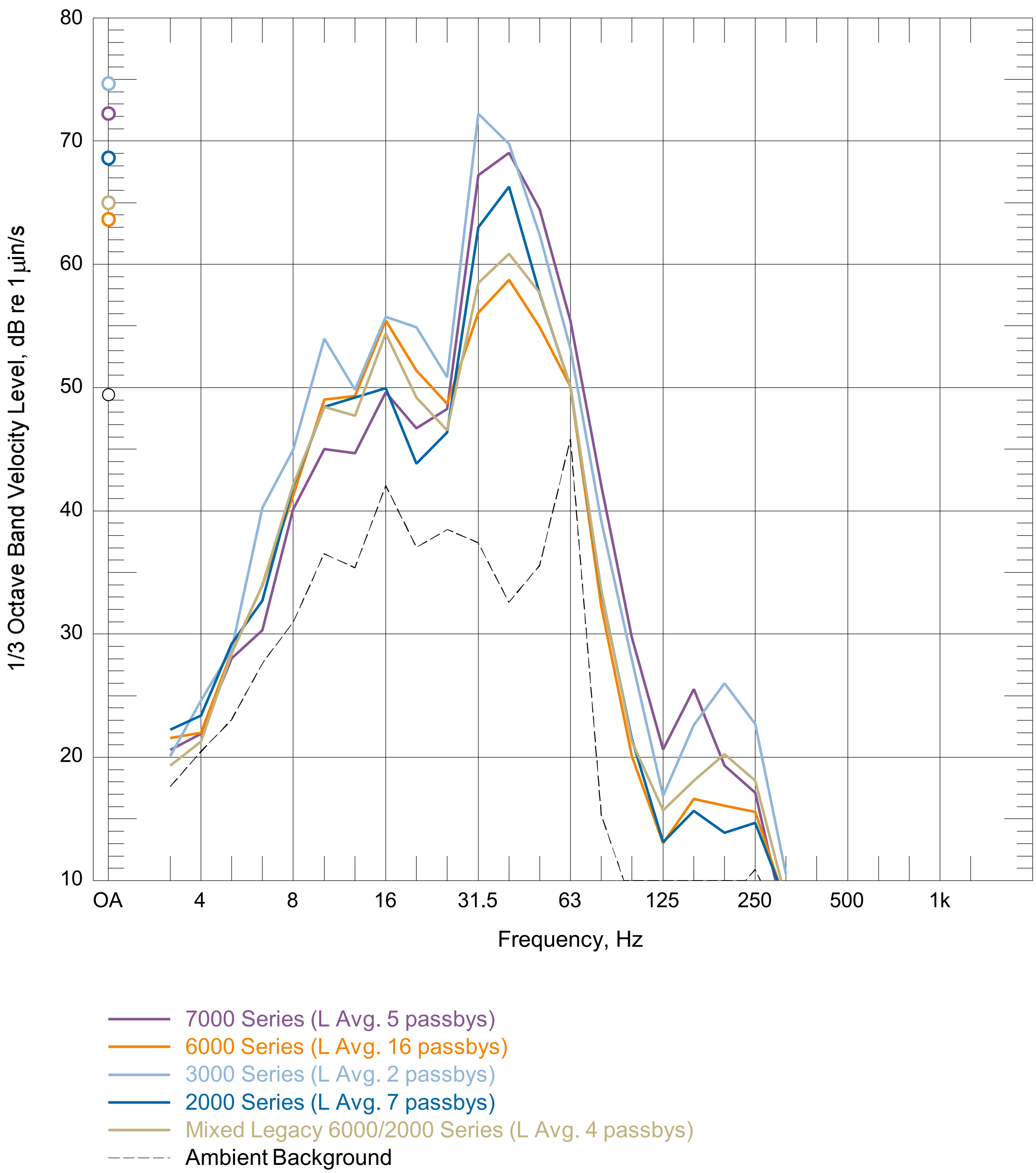


Figure 199: ***Site 10 at Location V2 First Floor Living Room***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

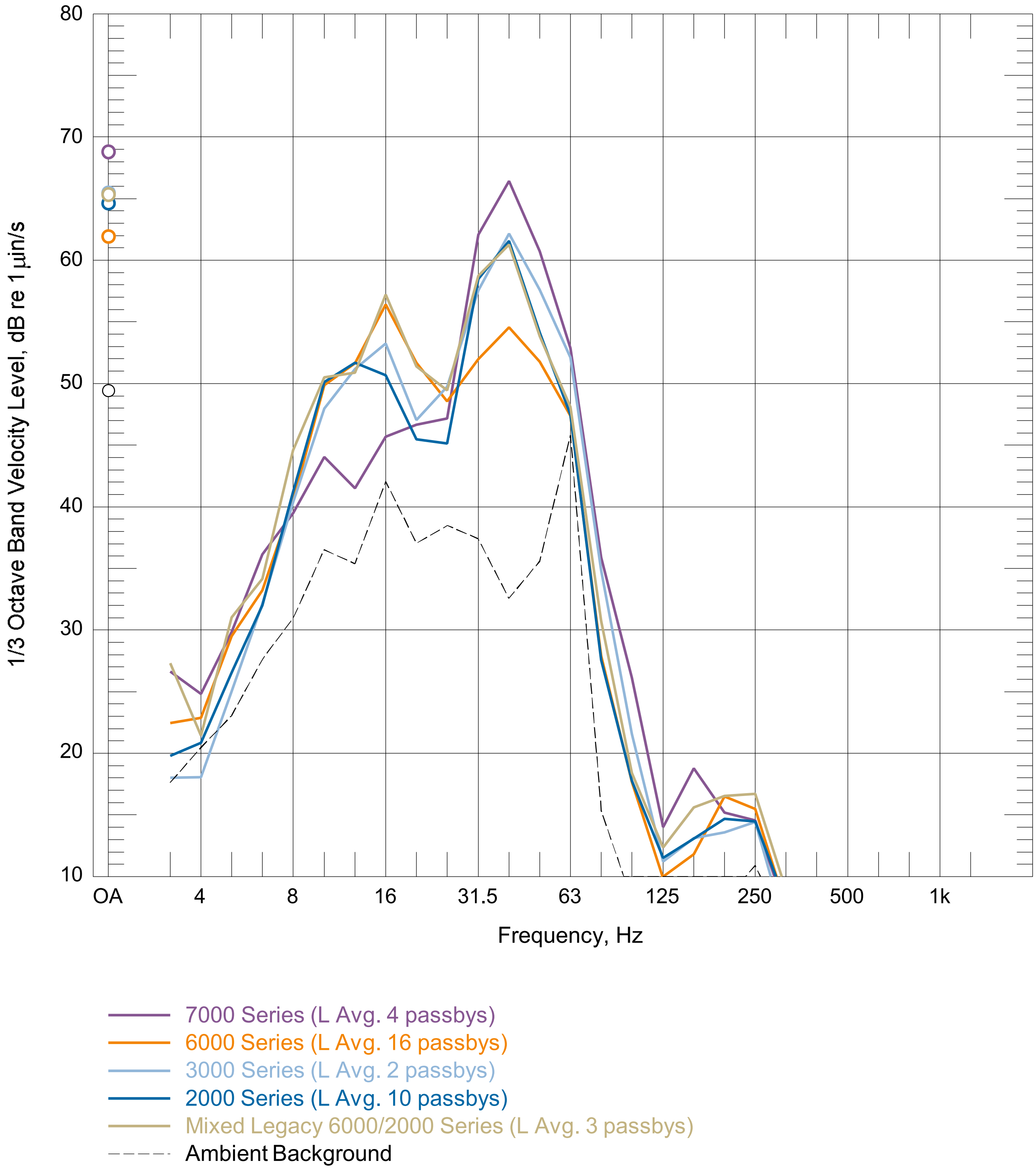


Figure 200: ***Site 10 at Location V2 First Floor Living Room***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

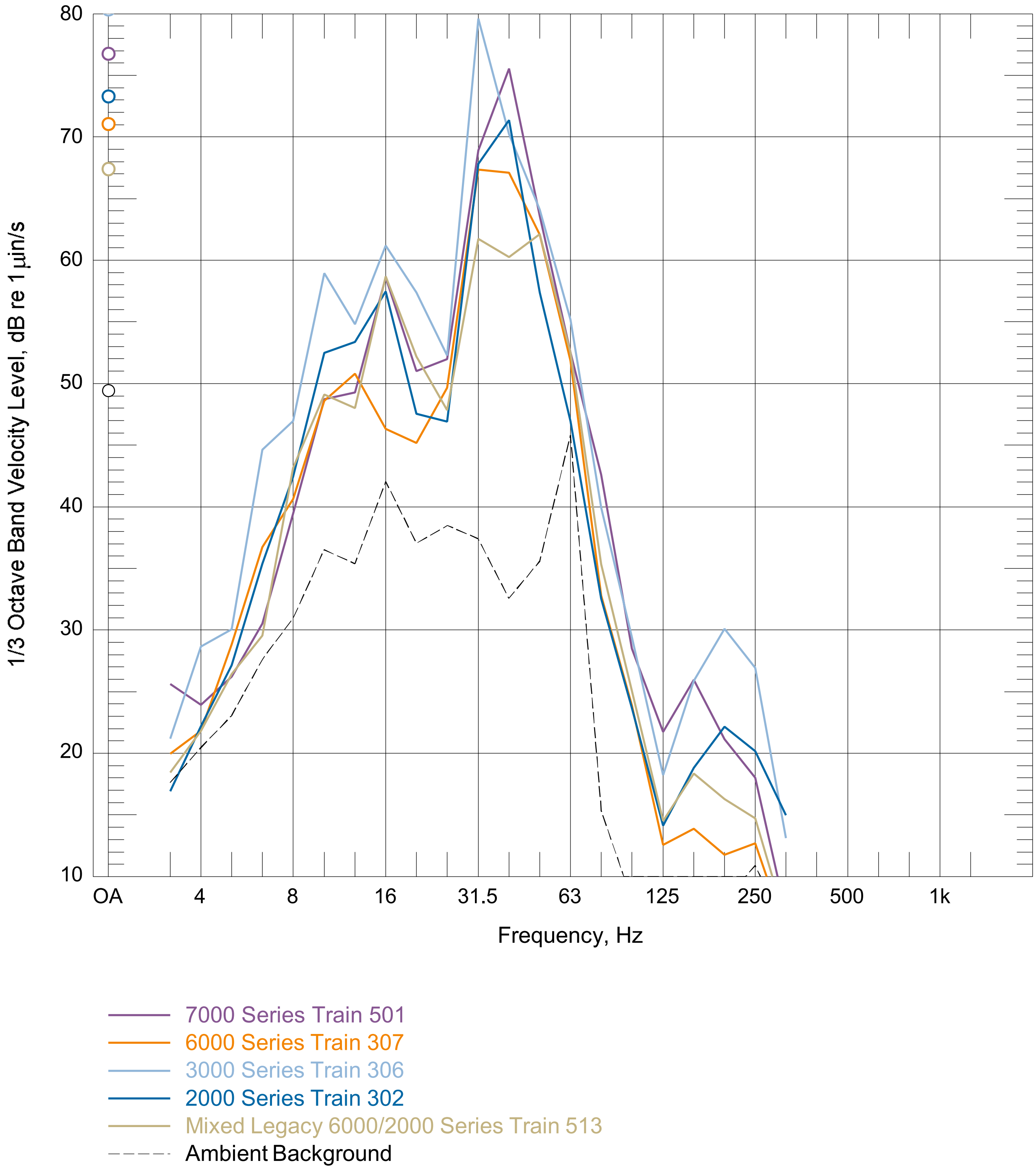


Figure 201: ***Site 10 at Location V2 First Floor Living Room***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

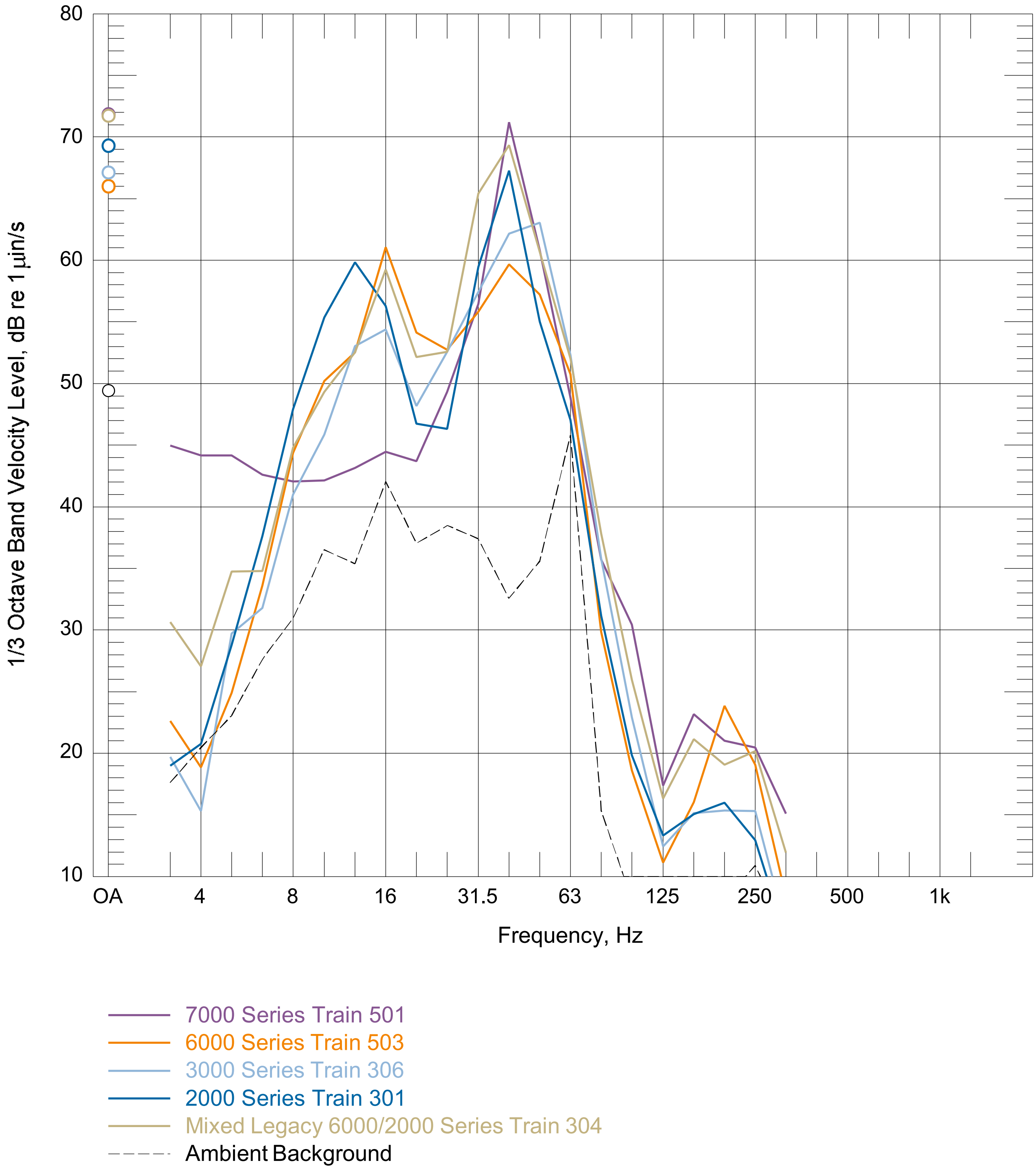


Figure 202: ***Site 10 at Location V2 First Floor Living Room***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

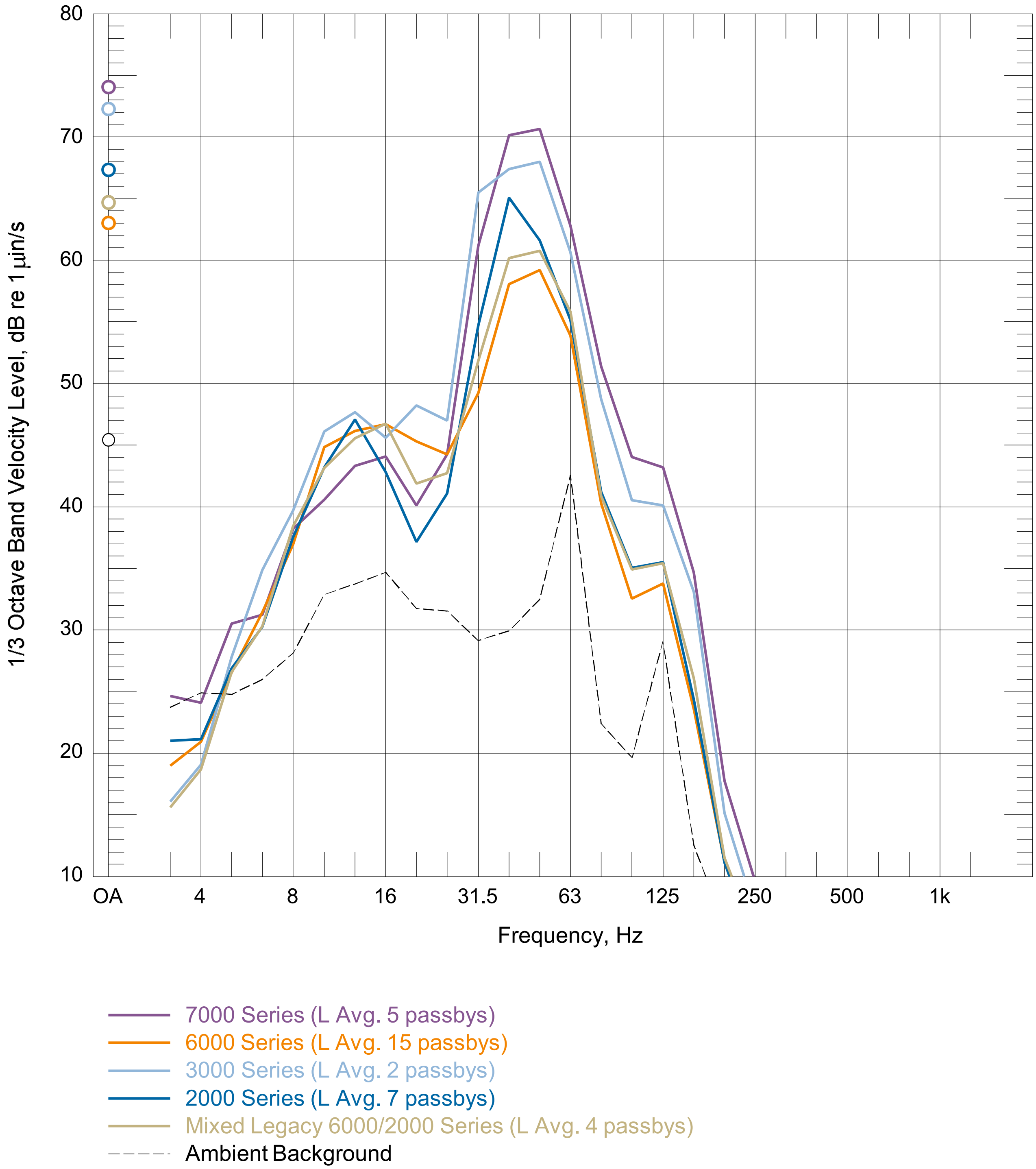


Figure 203: Site 10 at Location V3 First Floor Dining Room
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

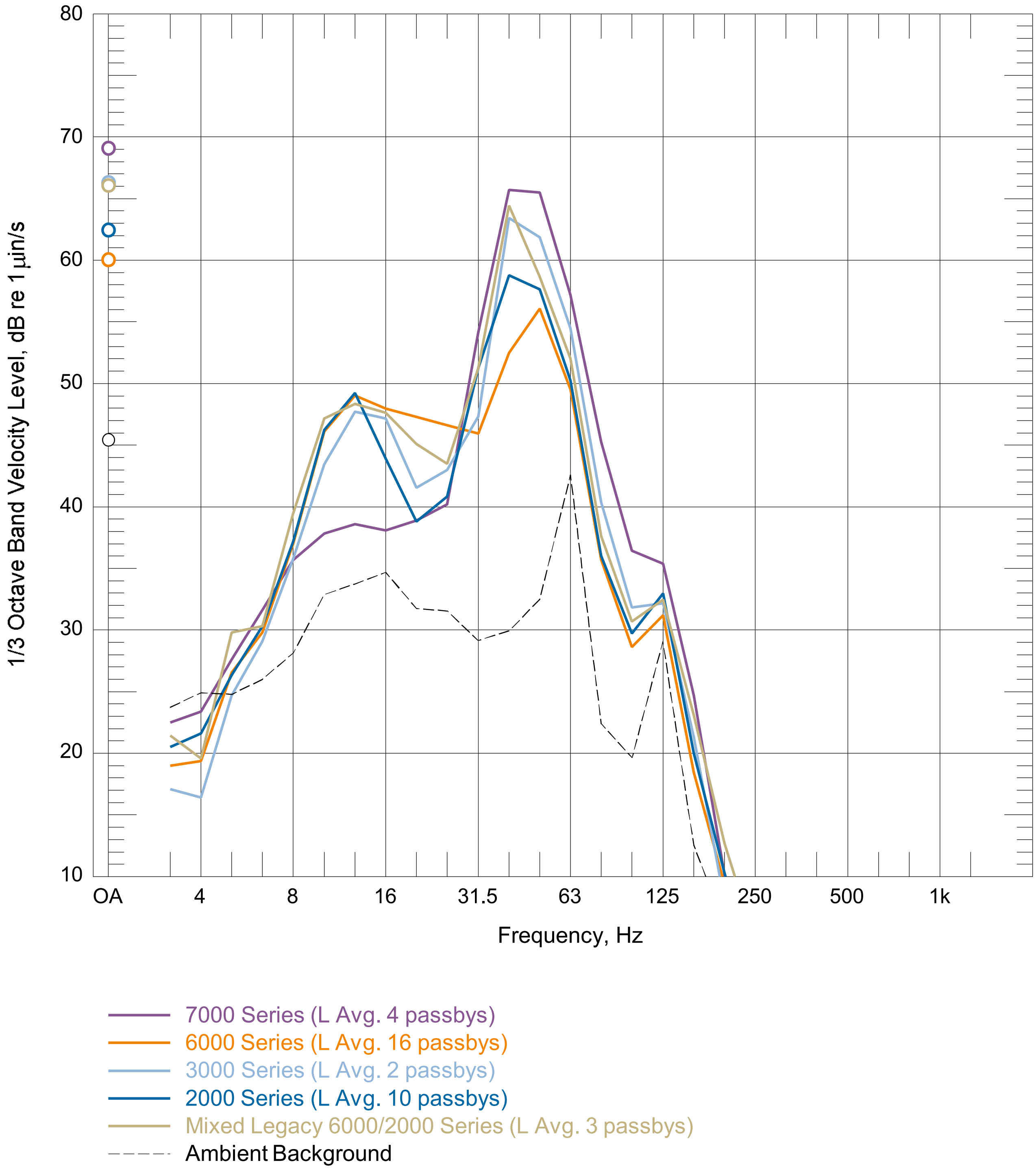


Figure 204: ***Site 10 at Location V3 First Floor Dining Room***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

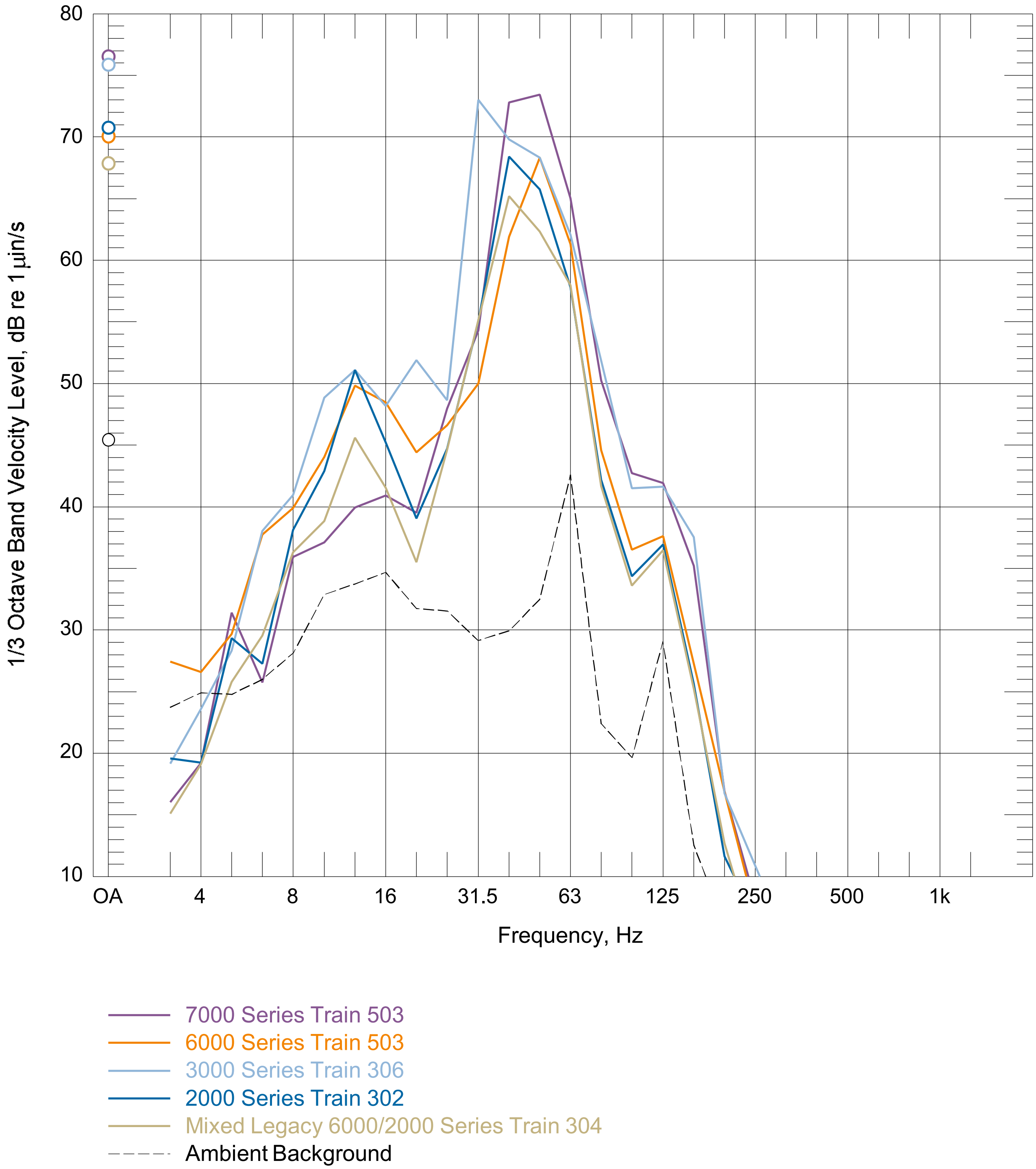


Figure 205: ***Site 10 at Location V3 First Floor Dining Room***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

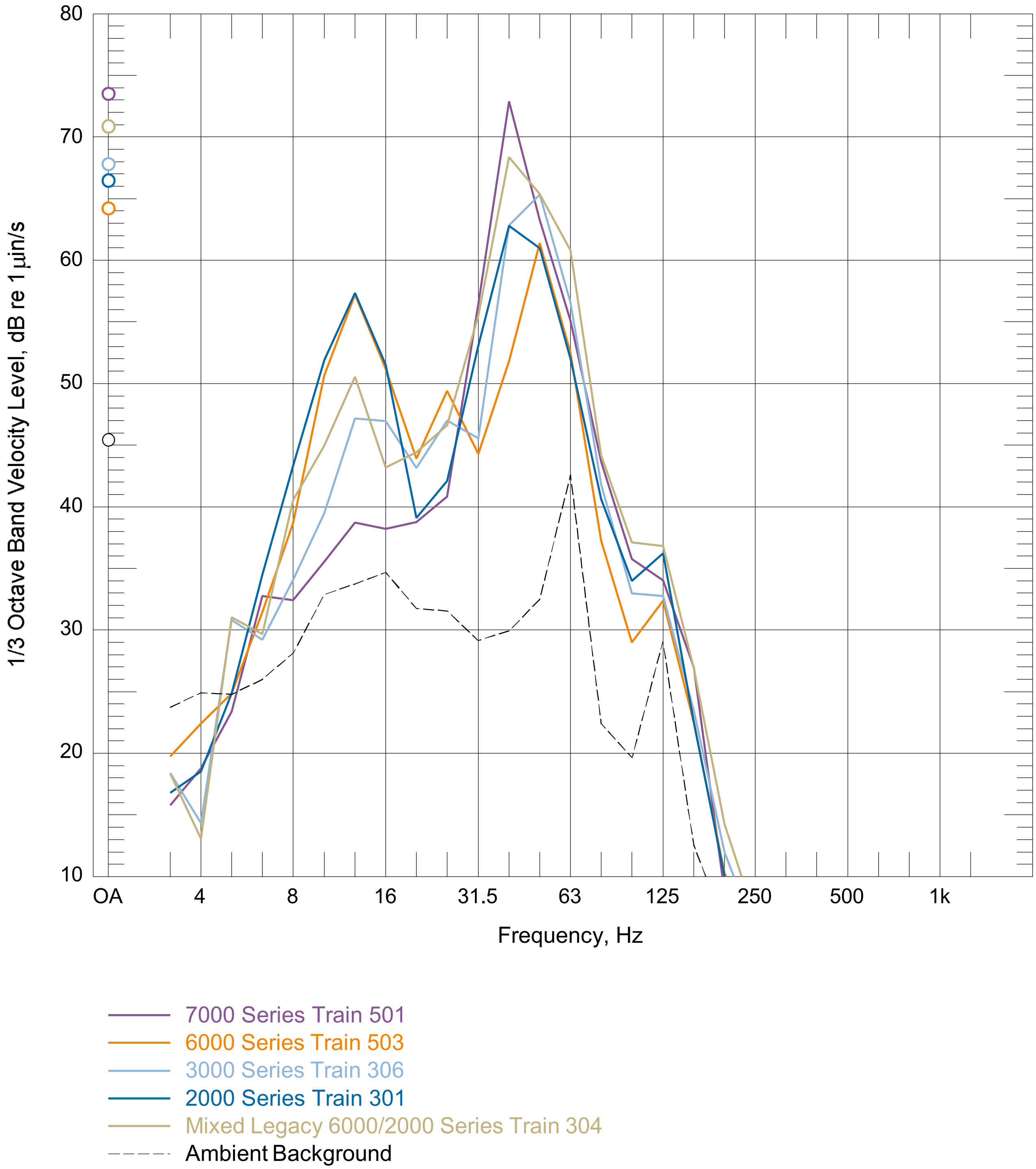


Figure 206: ***Site 10 at Location V3 First Floor Dining Room***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

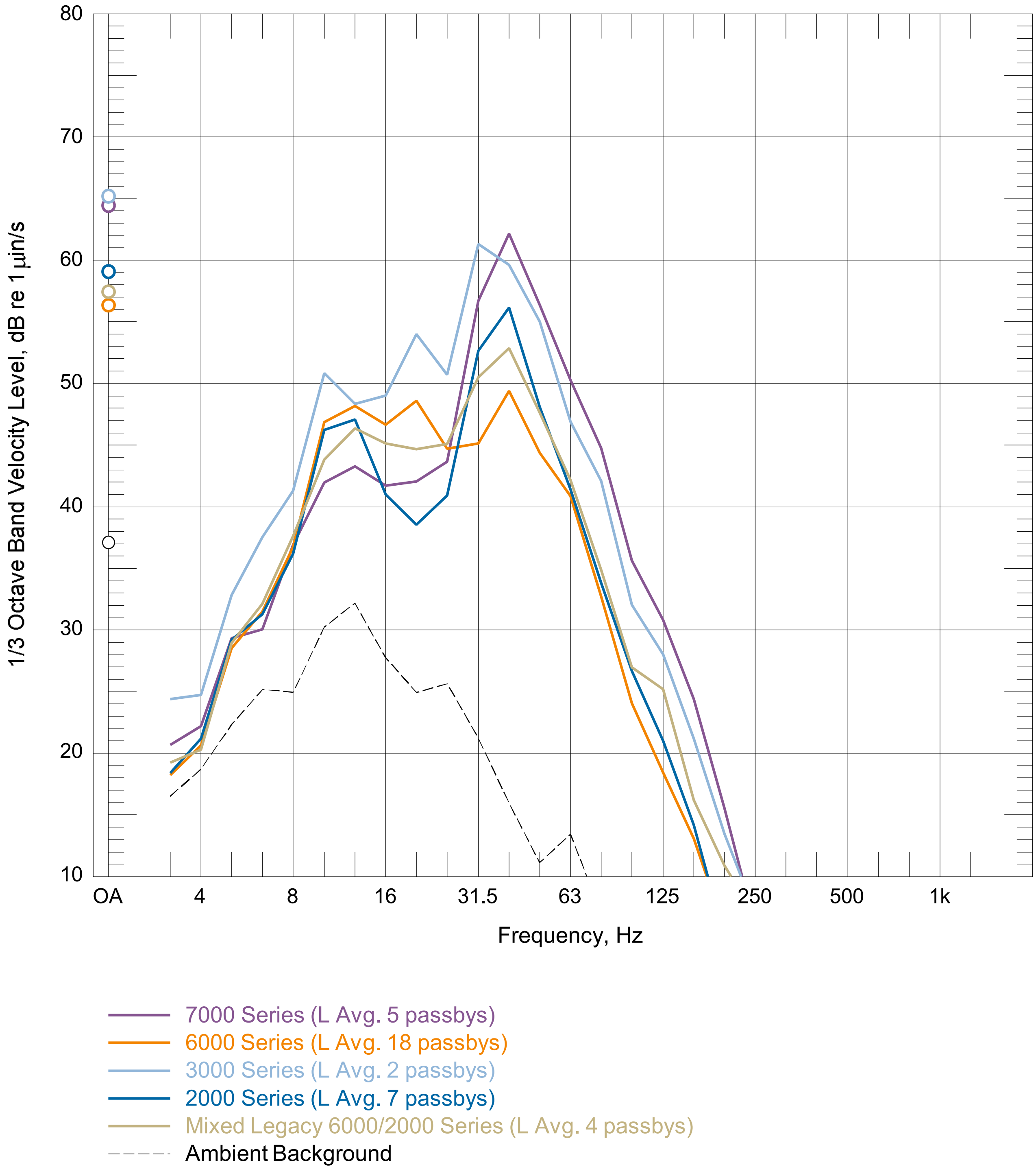


Figure 207: ***Site 10 at Location V4 Outside***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

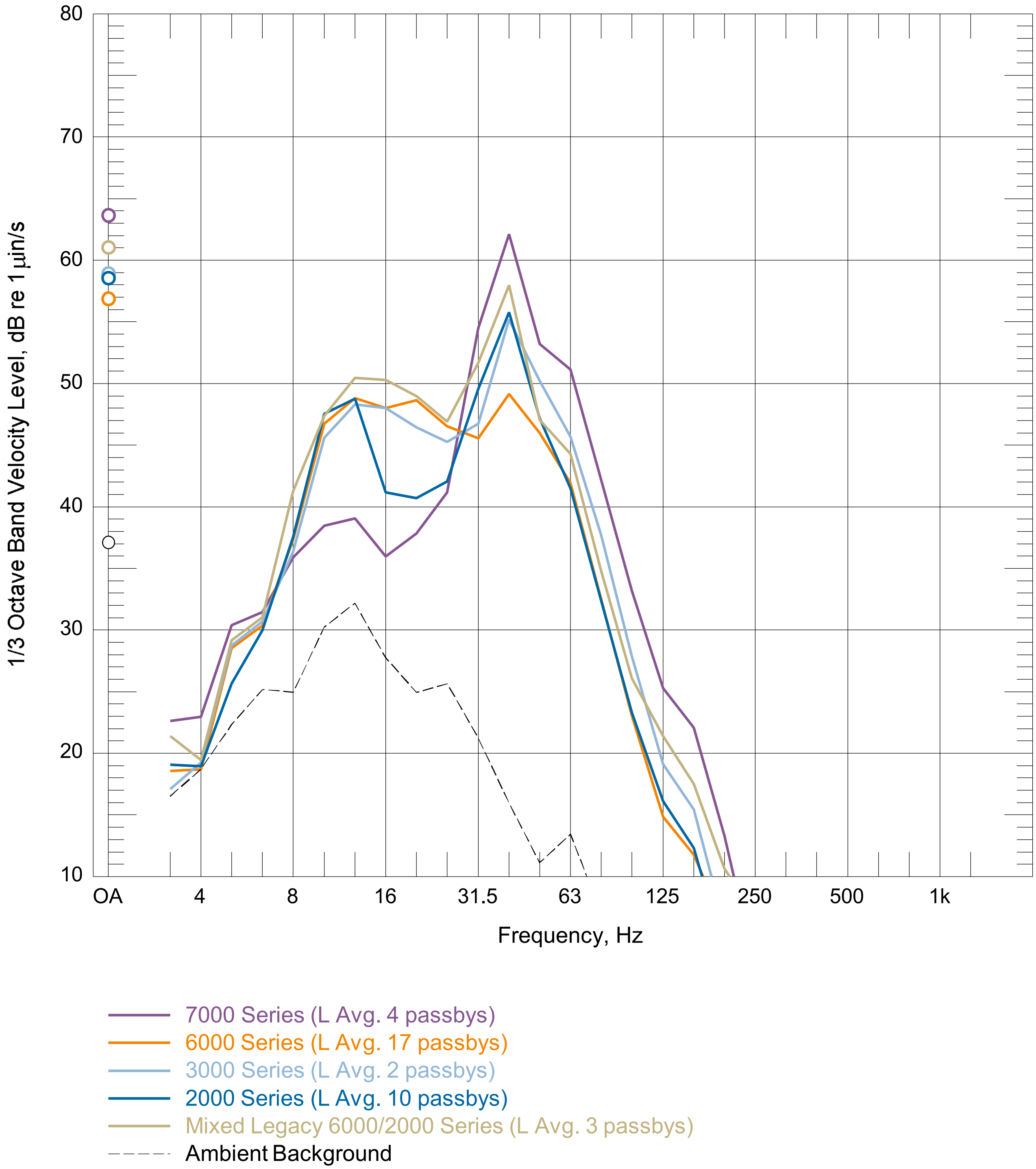


Figure 208: ***Site 10 at Location V4 Outside***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

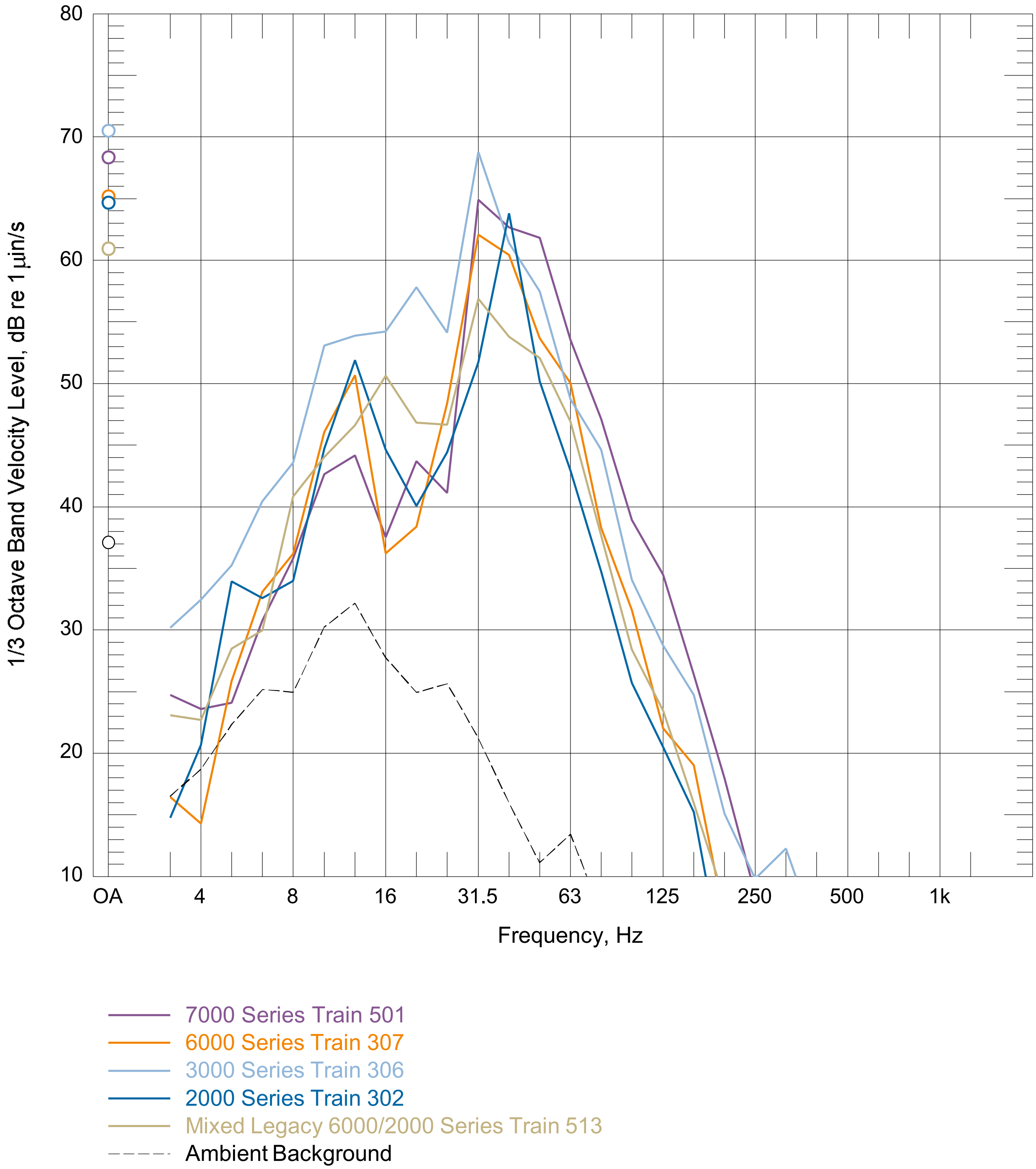


Figure 209: ***Site 10 at Location V4 Outside***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

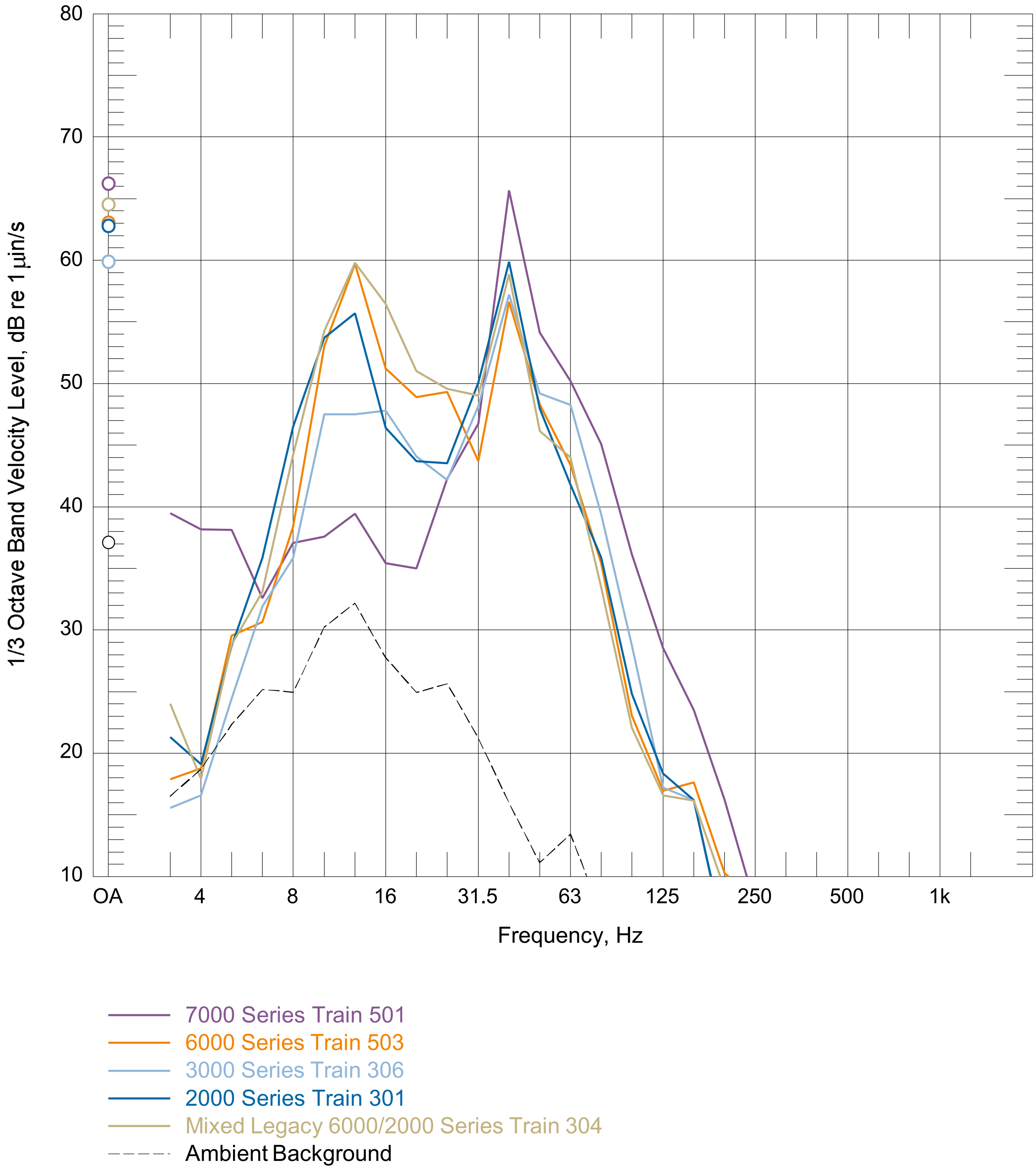


Figure 210: ***Site 10 at Location V4 Outside***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

B.10.6 Passby Ground-borne Noise Spectra and A-weighted Levels

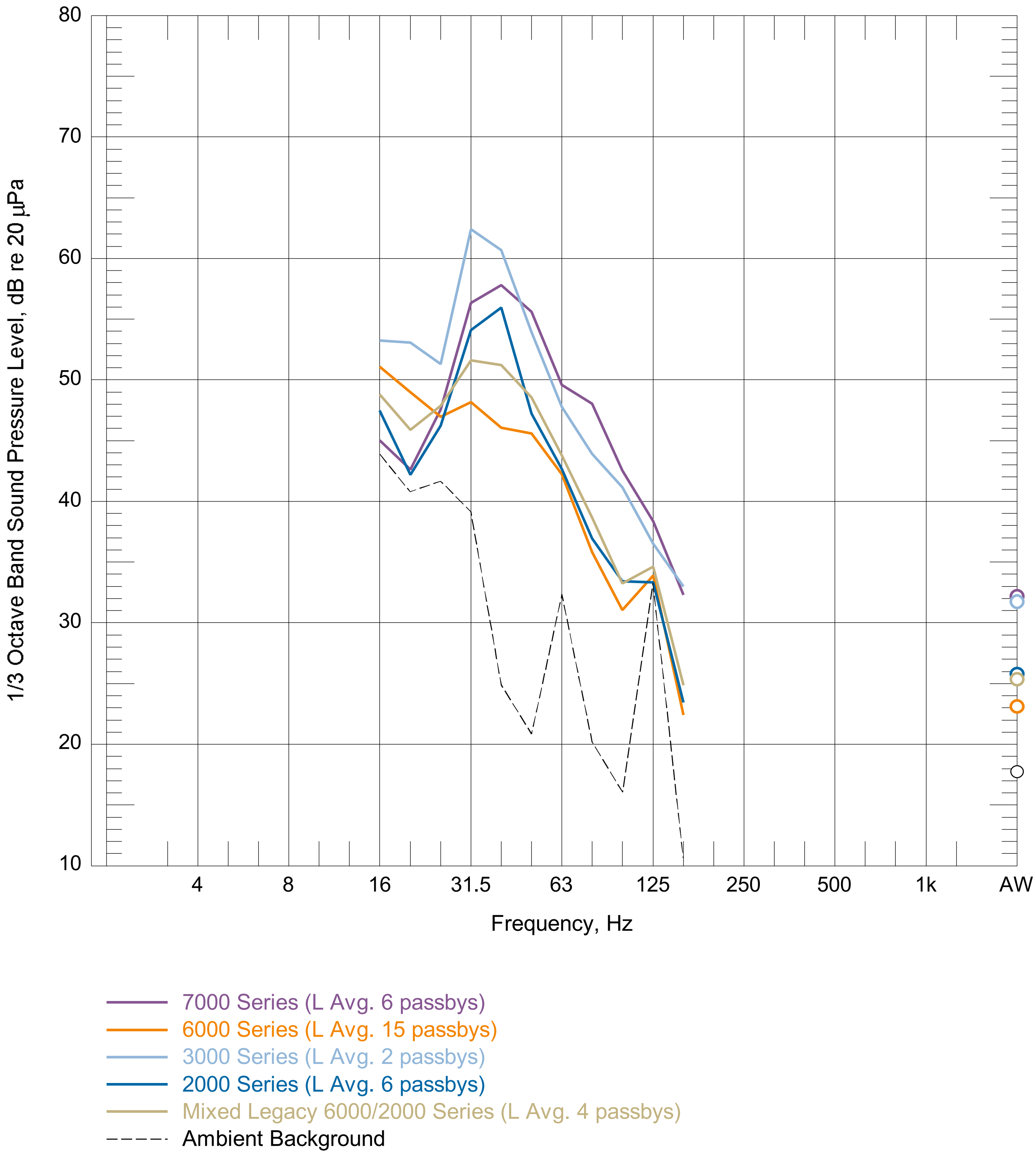


Figure 211: ***Site 10 at Location N1 Basement***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

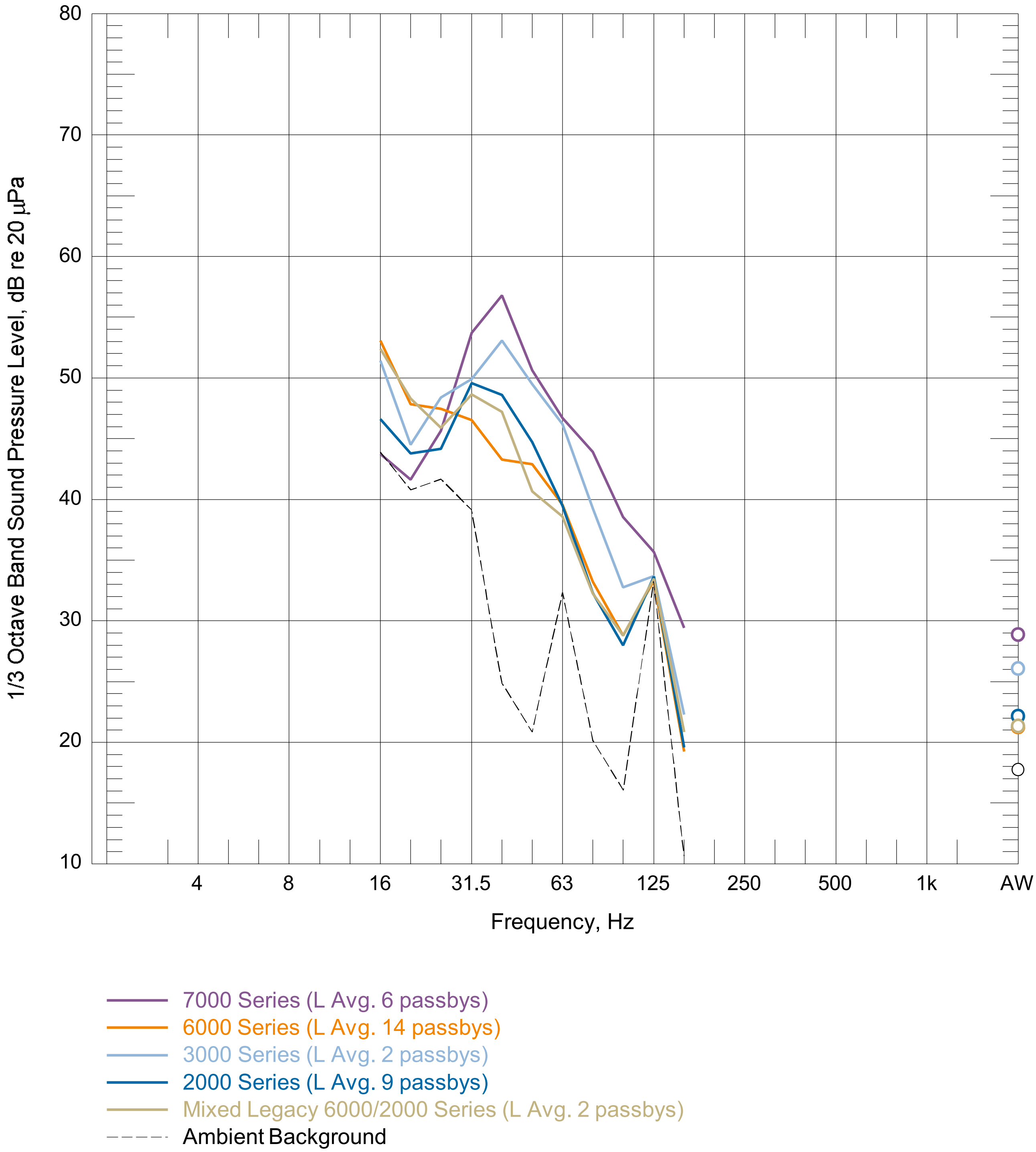


Figure 212: ***Site 10 at Location N1 Basement***
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

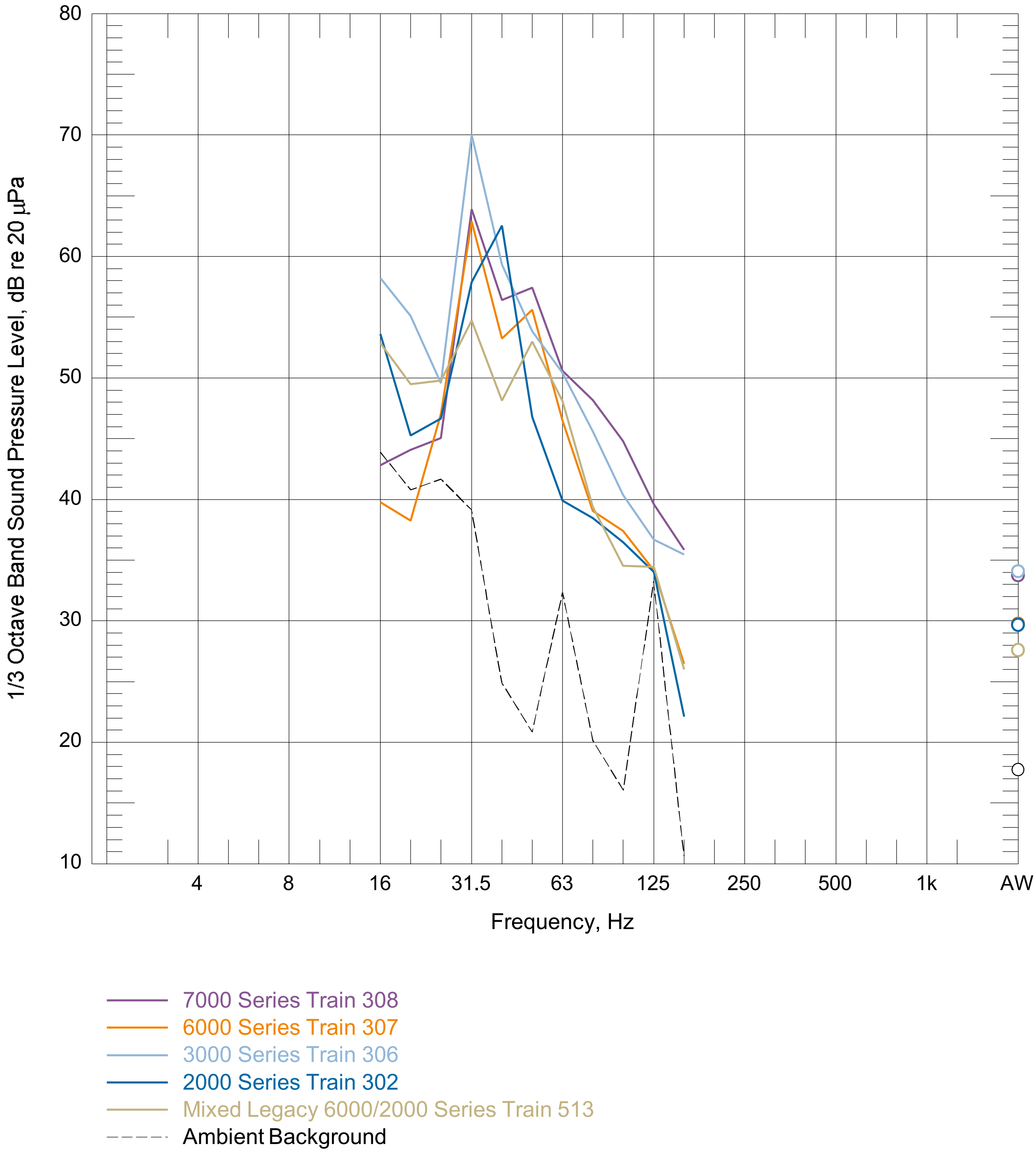


Figure 213: ***Site 10 at Location N1 Basement***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

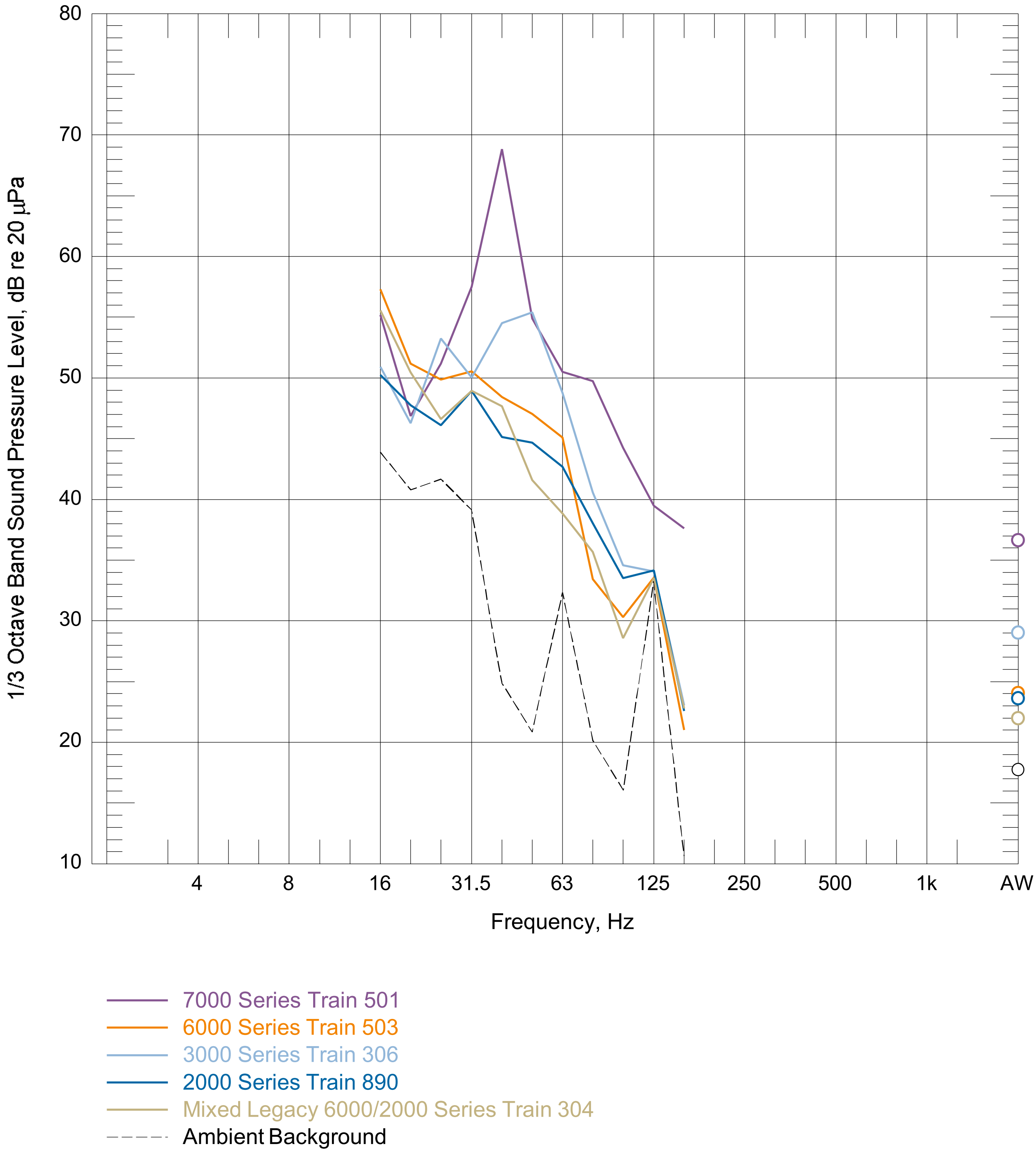


Figure 214: ***Site 10 at Location N1 Basement***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

B.11 Site 11 – New Hampshire Avenue NW & Buchanan Street NW (Outdoor Only)

B.11.1 Tunnel Notes

Tunnel Structure: Earth Tunnel

Track Type: Standard DF

T/R Depth: 90 to 95 feet

Measurement Period: Thursday, 1 June 2017, 13:10 to 15:21

Field Observations: Minimal road traffic on Buchanan, some Metro buses along New Hampshire. Trains are audible through vent shaft grate. Accelerometers mounted to curbs. Construction activity across 4th street on Buchanan.

B.11.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Recorder Channel	Chainage (50 ft)	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)
A1	214+00	68	92	114	31	92	97
A2	214+00	88	92	127	51	92	105
A3	214+50	108	93	143	71	93	117
A4	215+00	163	95	189	127	95	159
B1	213+00	54	90	105	90	90	127
B2	213+00	74	90	117	111	90	143
B3	213+00	94	90	130	131	90	159

Perp. distance = perpendicular distance to track, not accounting for tunnel depth
T/R depth = top-of-rail depth
Total slant distance = total distance to track, accounting for tunnel depth

Figure 215: Aerial Map of 4600 block of New Hampshire Residence and Exterior Measurement Location at Site 11 (with nearby Sites 12 and 13 shown for reference)

B.11.3 Overall Level vs Distance Plot

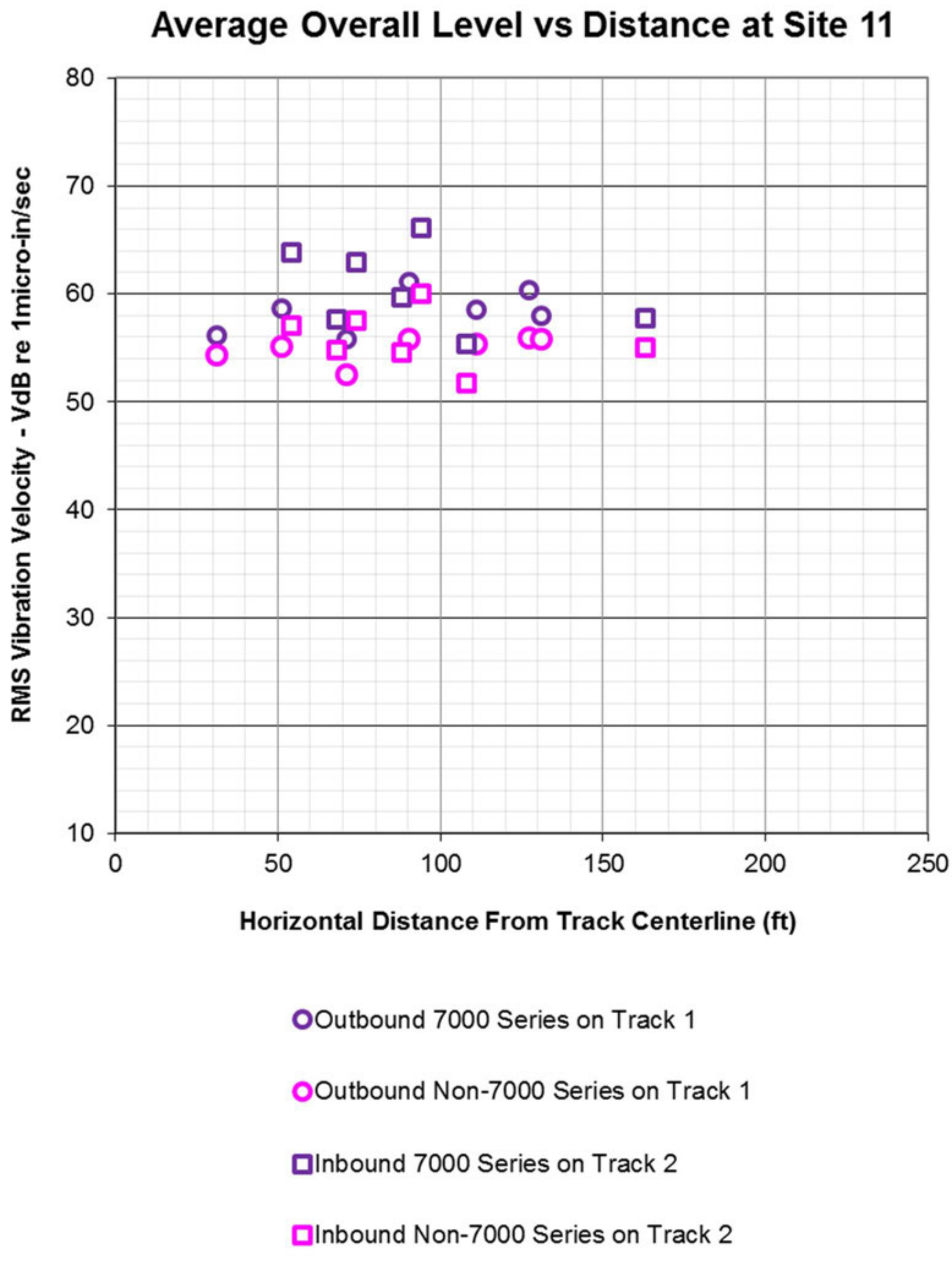


Figure 216: Site 11 Average Overall Level vs Distance

B.12 Site 12 – 4600 block of 4th Street NW (Residence)

B.12.1 Building and Tunnel Notes

Location:	Inbound Track 2 side at 214+75
Building Notes:	Residential attached rowhouse with 3 floors consisting of partial underground basement and 2 upper floors. Exterior walls of brick construction, foundation is below-grade slab. House is at end of row.
Tunnel Structure:	Tunnel
Track Type:	DF
T/R Depth:	95 feet
Train Speed:	39 to 69 mph
Measurement Period:	Monday, 14 August 2017, 14:35 to 18:36

B.12.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Sensor[a,b,c]	Location / Room Occupancy	Horizontal Distance[d] (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)	Horizontal Distance (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)
V1	Outside Far	176	85	200	212	95	232
V2	Outside Near	183	95	206	220	95	240
Triaxial Geophone	Basement Bedroom	185	95	208	222	95	241
V3							
N1							
V4	First Floor Dining Room						
V5	First Floor Living Room						

Notes:

a) Tri-axial geophone mounted on floor, logging peak particle velocity
b) V# vibration locations with accelerometer mounted on floor in vertical direction
c) N# noise locations with microphone/sound level meter mounted on tripod 48 inches feet above floor
d) Horizontal distance from track to building façade for indoor locations, not accounting for tunnel depth.
e) T/R depth = top-of-rail depth
f) Total slant distance to T/R = total distance from building to track, accounting for tunnel depth

Figure 217: Aerial Map of 4600 block of 4th Street NW Residence and Exterior Measurement Location (with nearby Sites 11 and 13 shown for reference)

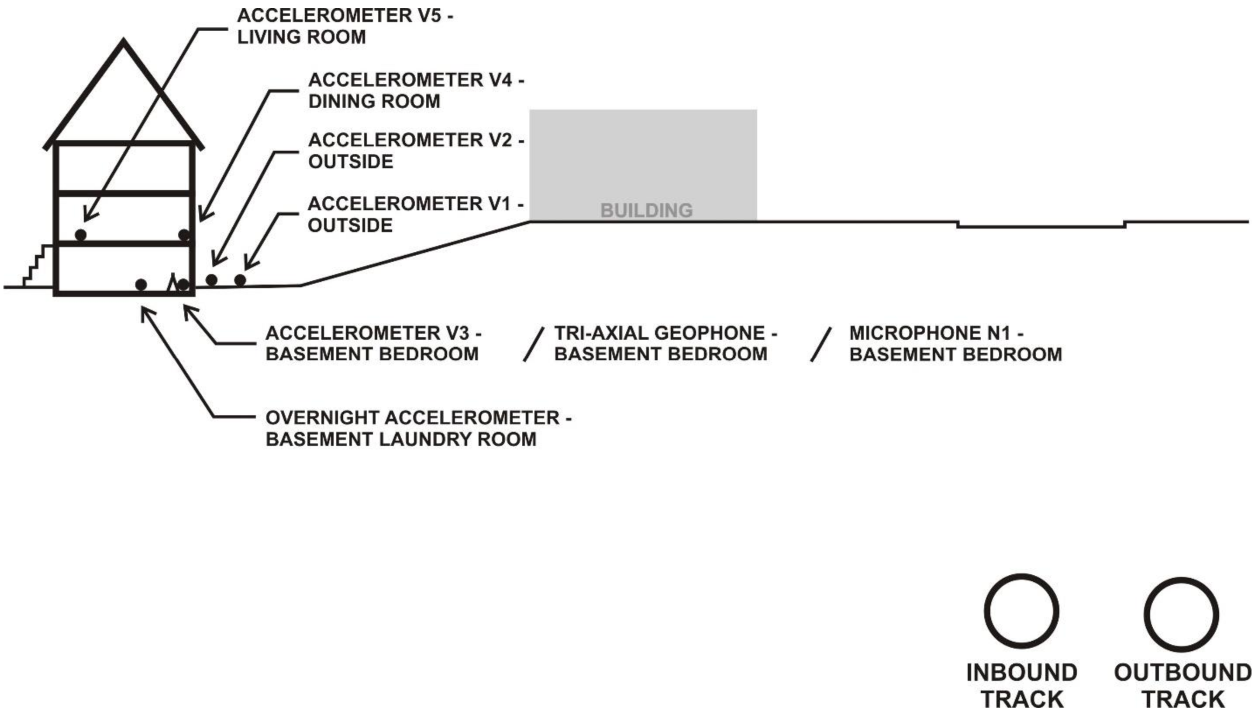


Figure 218: Cross-section Sketch (not to scale) of 4600 block of 4th Street NW Residence Measurement Locations

B.12.3 GBNV Assessment Summary

SITE 12	4600 block of 4TH STREET NW – ATTENDED PASSBY MEASUREMENT GBNV ASSESSMENT		
	Ground-borne Vibration (GBV)	**>70 VdB?**	**Notes**
	7000 Series - Average of Multiple Passbys	NO	
	6000 Series - Average of Multiple Passbys	NO	
	2000 Series - Average of Multiple Passbys	NO	
	7000 Series - Individual Train with Highest Overall Vibration	NO	
	6000 Series - Individual Train with Highest Overall Vibration	YES	V4
	2000 Series - Individual Train with Highest Overall Vibration	NO	
	Ground-borne Noise (GBN)	**>40 dBA?**	**Notes**
	7000 Series - Average of Multiple Passbys	NO	
	6000 Series - Average of Multiple Passbys	NO	
	2000 Series - Average of Multiple Passbys	NO	
	7000 Series - Individual Train with Highest A-weighting	NO	
	6000 Series - Individual Train with Highest A-weighting	NO	
	2000 Series - Individual Train with Highest A-weighting	NO	

B.12.4 PPV Results

SITE 12	4600 block of 4TH STREET NW – POTENTIAL FOR BUILDING VIBRATION DAMAGE ASSESSMENT						
	>0.2 in/sec PPV in any direction?	Average PPV (in/s)			PPV Range (in/s)		
		Tran	Vert	Long	Tran	Vert	Long
	NO	0.0032	0.003	0.0021	0.003 - 0.018	0.002 - 0.008	0.002 - 0.027
Basement 14-Aug-17, 2:36:21 PM to 6:34:08 PM							

B.12.5 Passby Vibration Spectra and Overall Levels

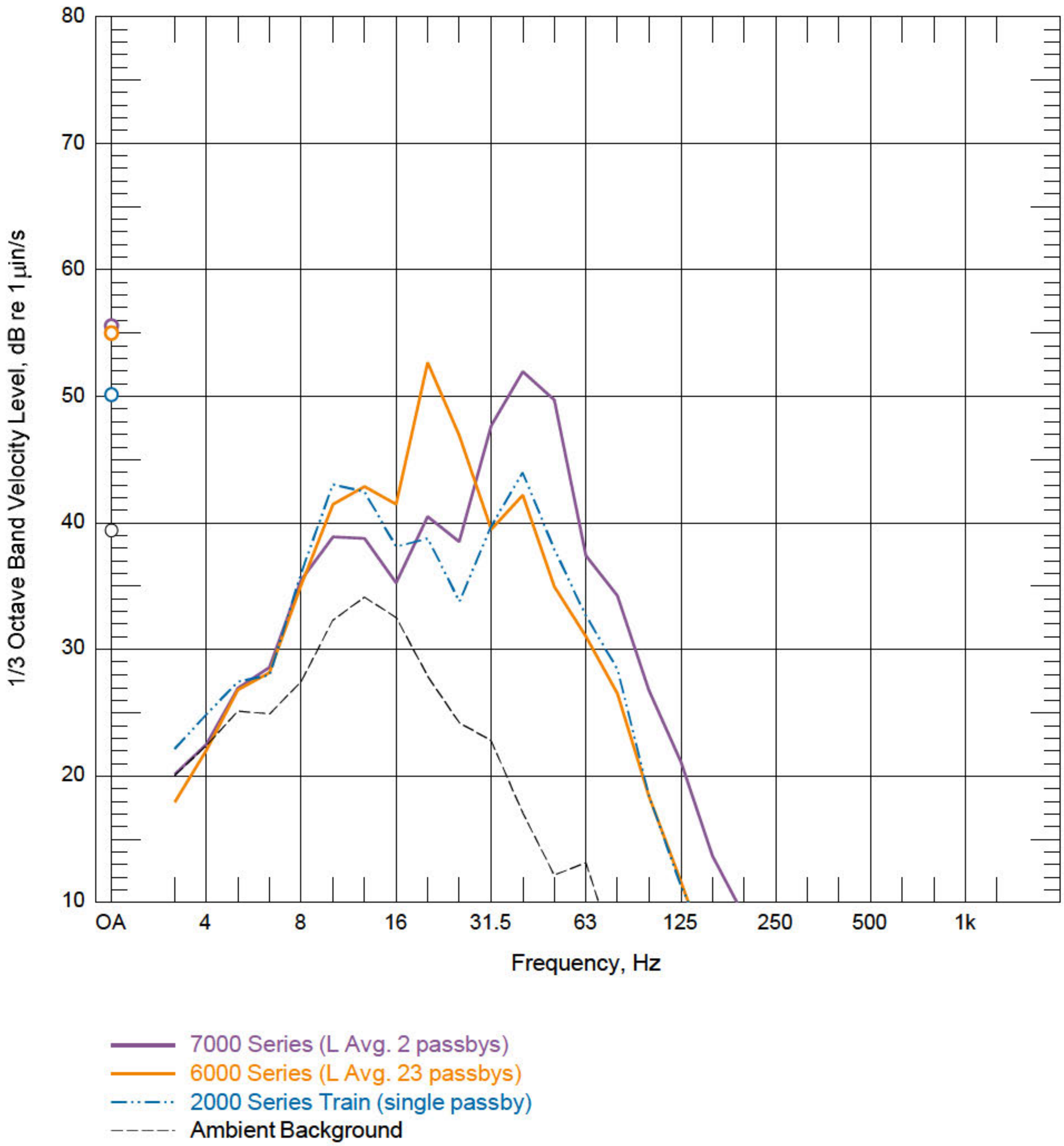


Figure 219: ***Site 12 at Location V1 Outside Far Outbound Trains on Track 1***
Average Vibration Levels by Vehicle Type

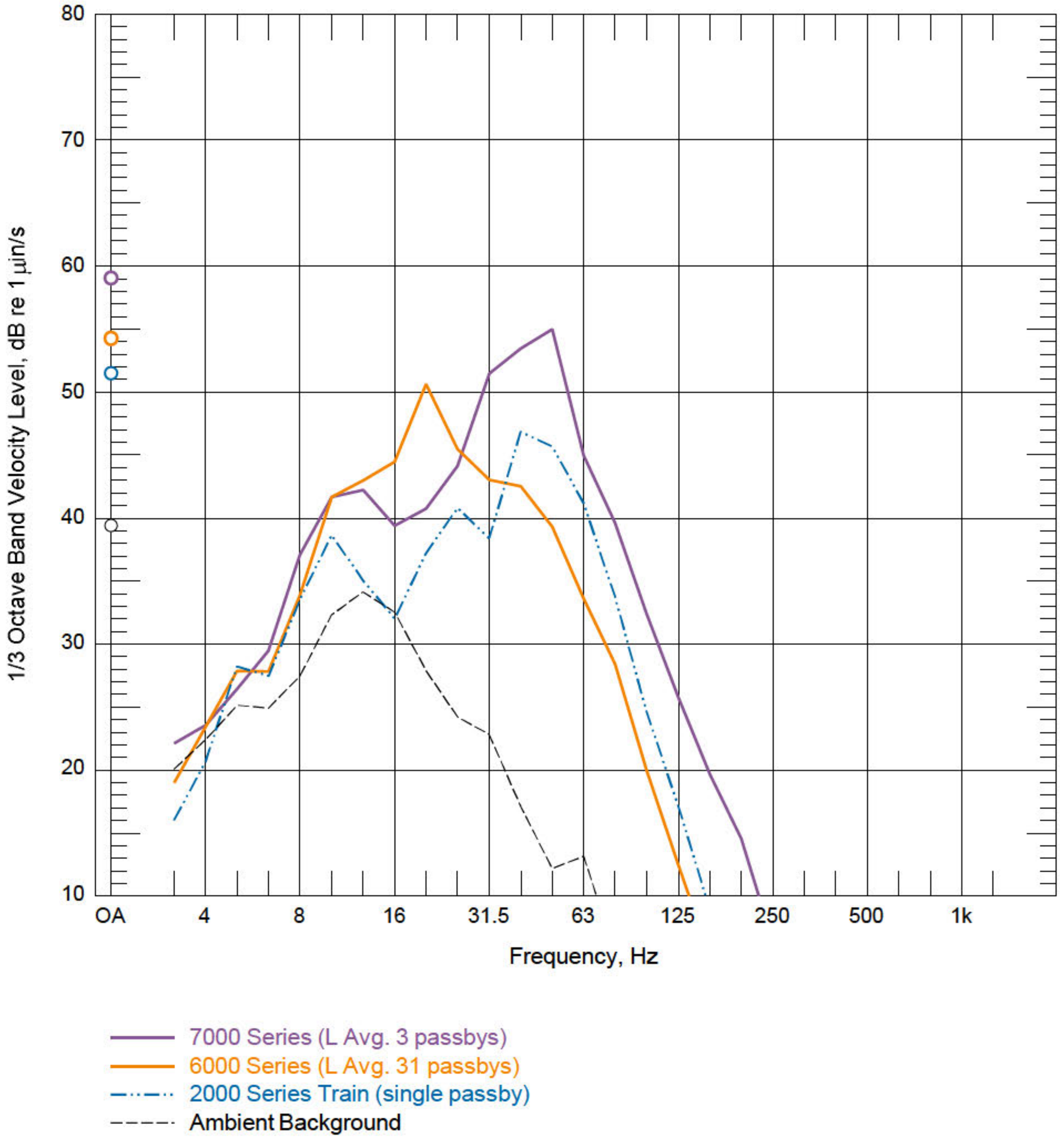


Figure 220: ***Site 12 at Location V1 Outside Far***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

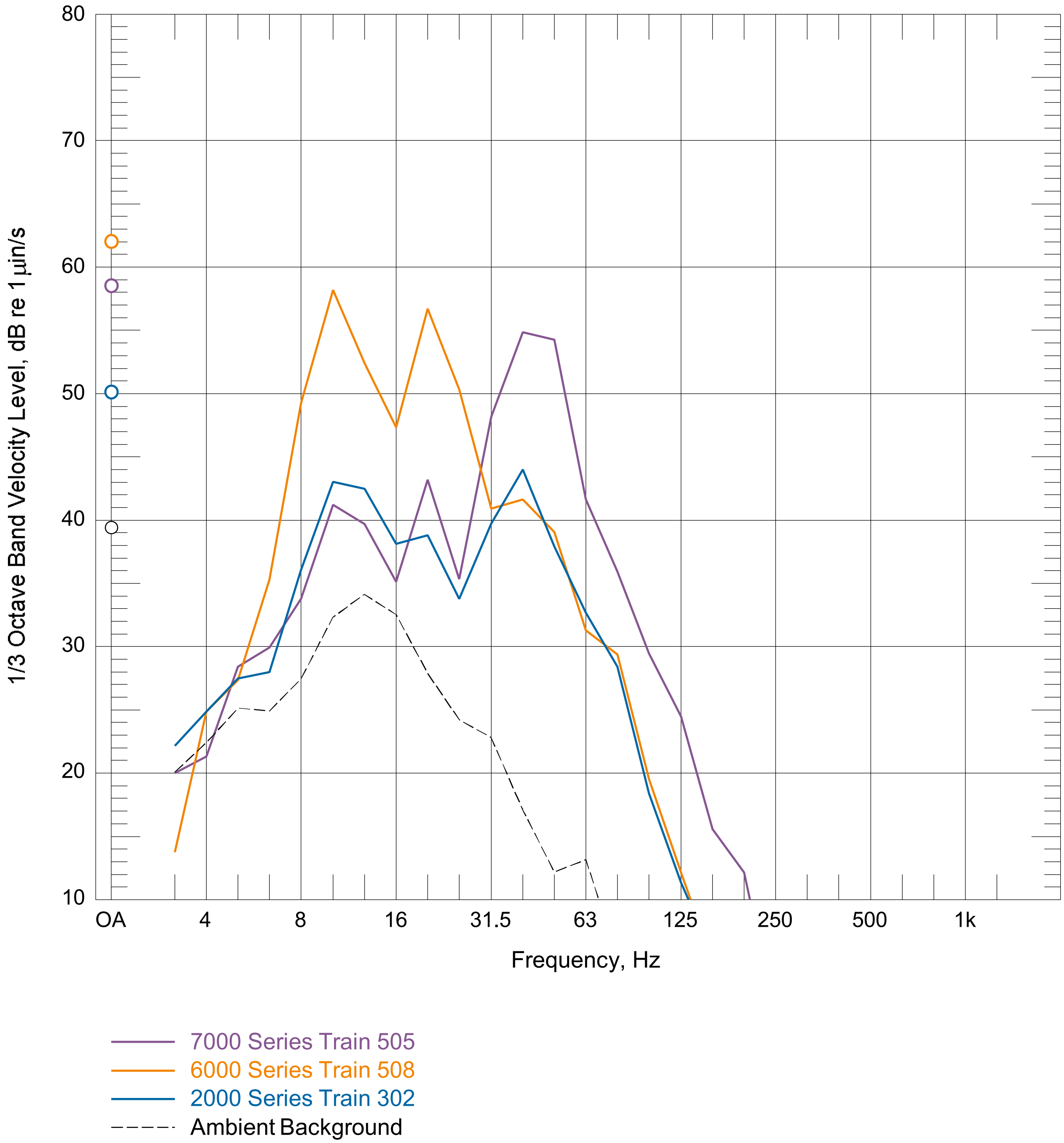


Figure 221: ***Site 12 at Location V1 Outside Far***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

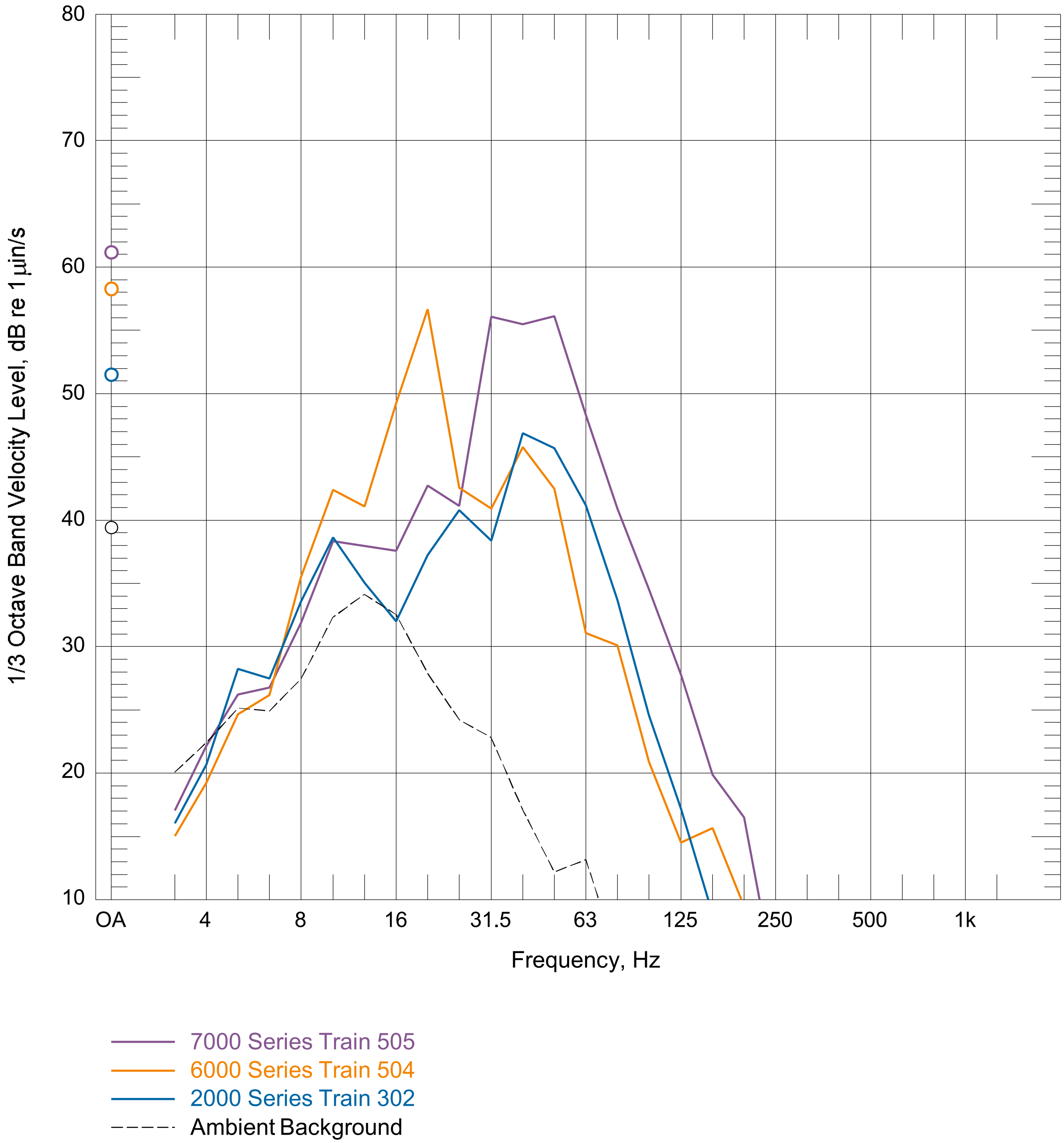


Figure 222: ***Site 12 at Location V1 Outside Far***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

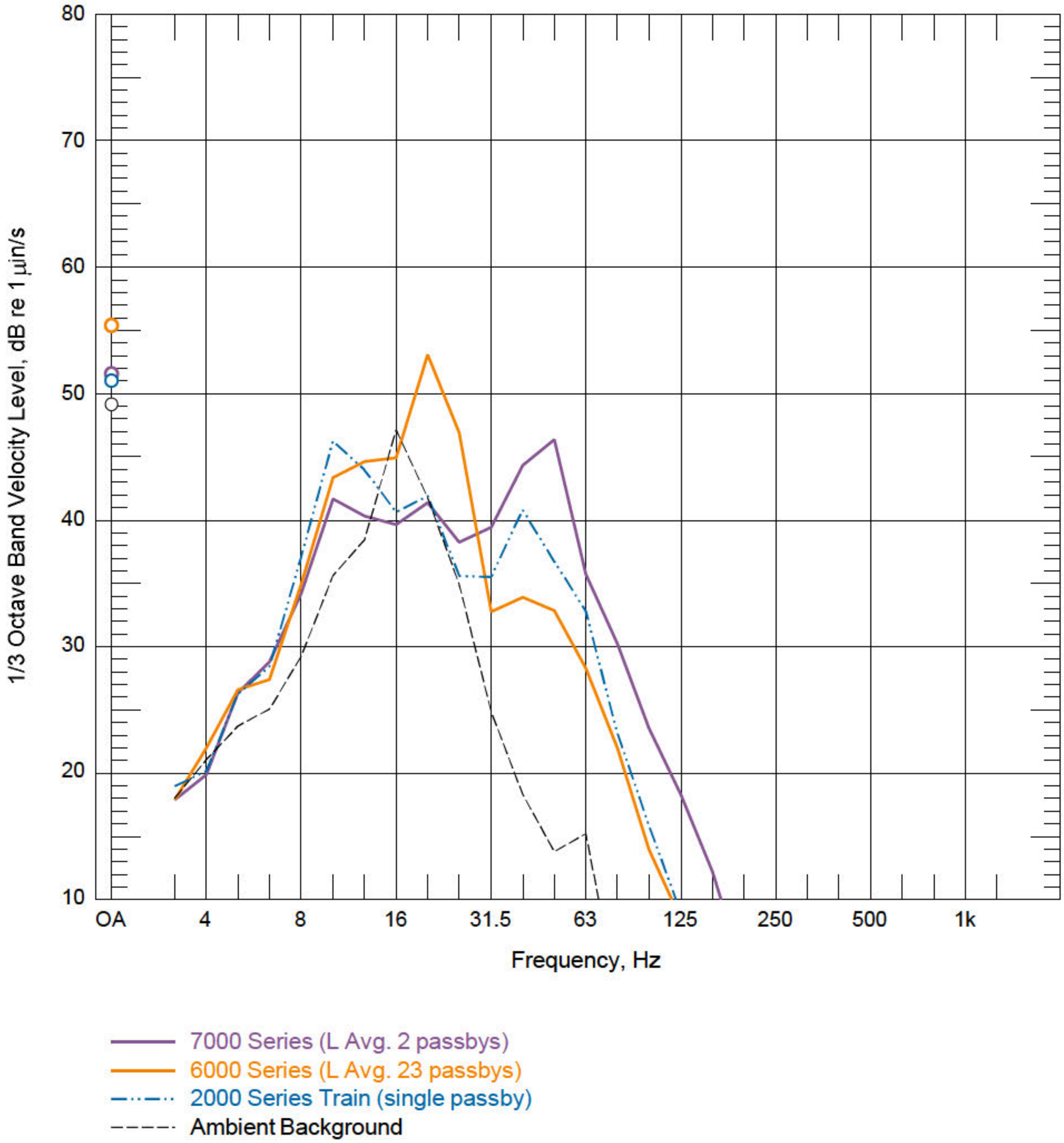


Figure 223: Site 12 at Location V2 Outside Near Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

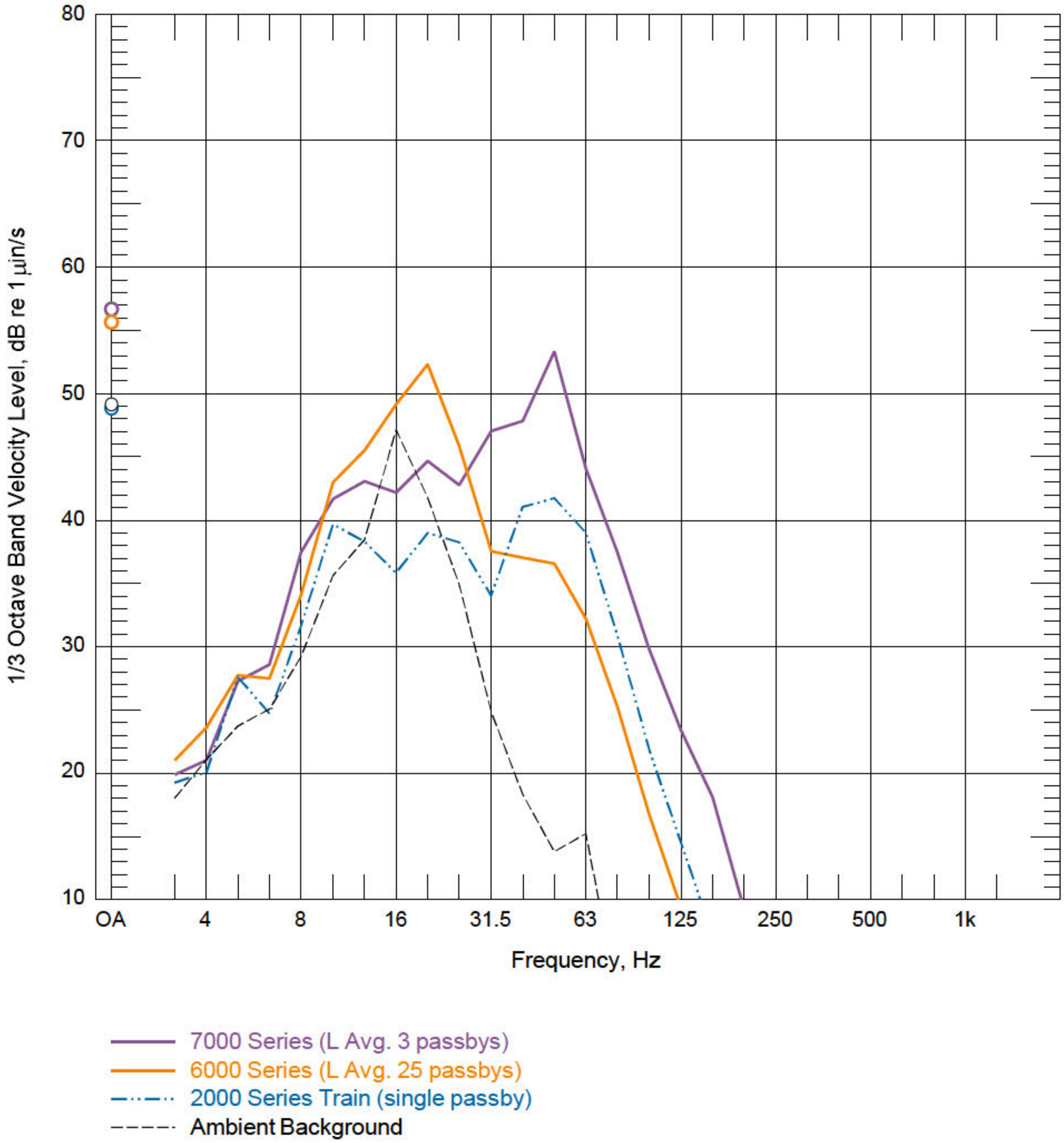


Figure 224: ***Site 12 at Location V2 Outside Near Inbound Trains on Track 2***
Average Vibration Levels by Vehicle Type

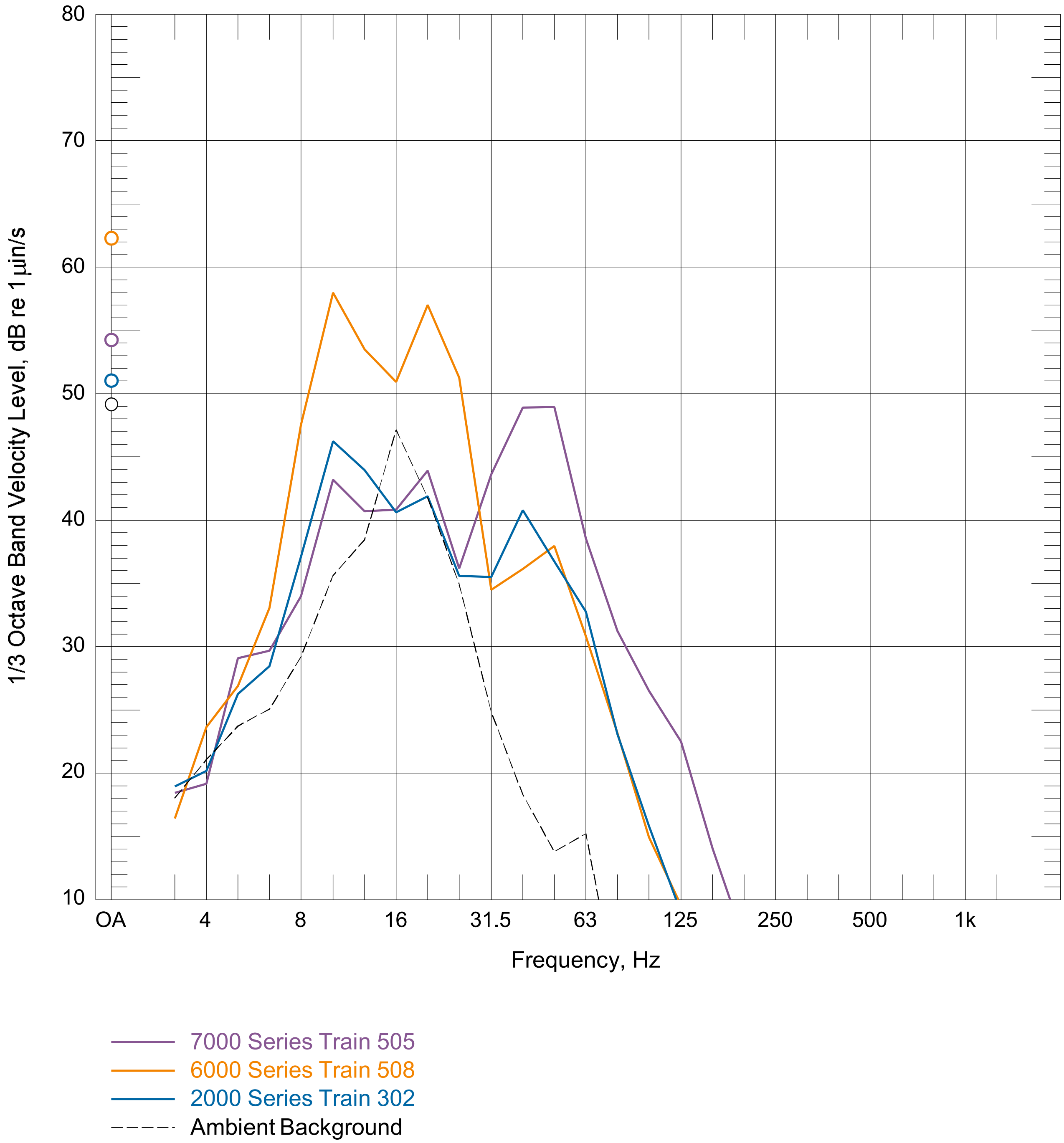


Figure 225: ***Site 12 at Location V2 Outside Near Outbound Trains on Track 1***
Individual Train with Highest Overall Vibration

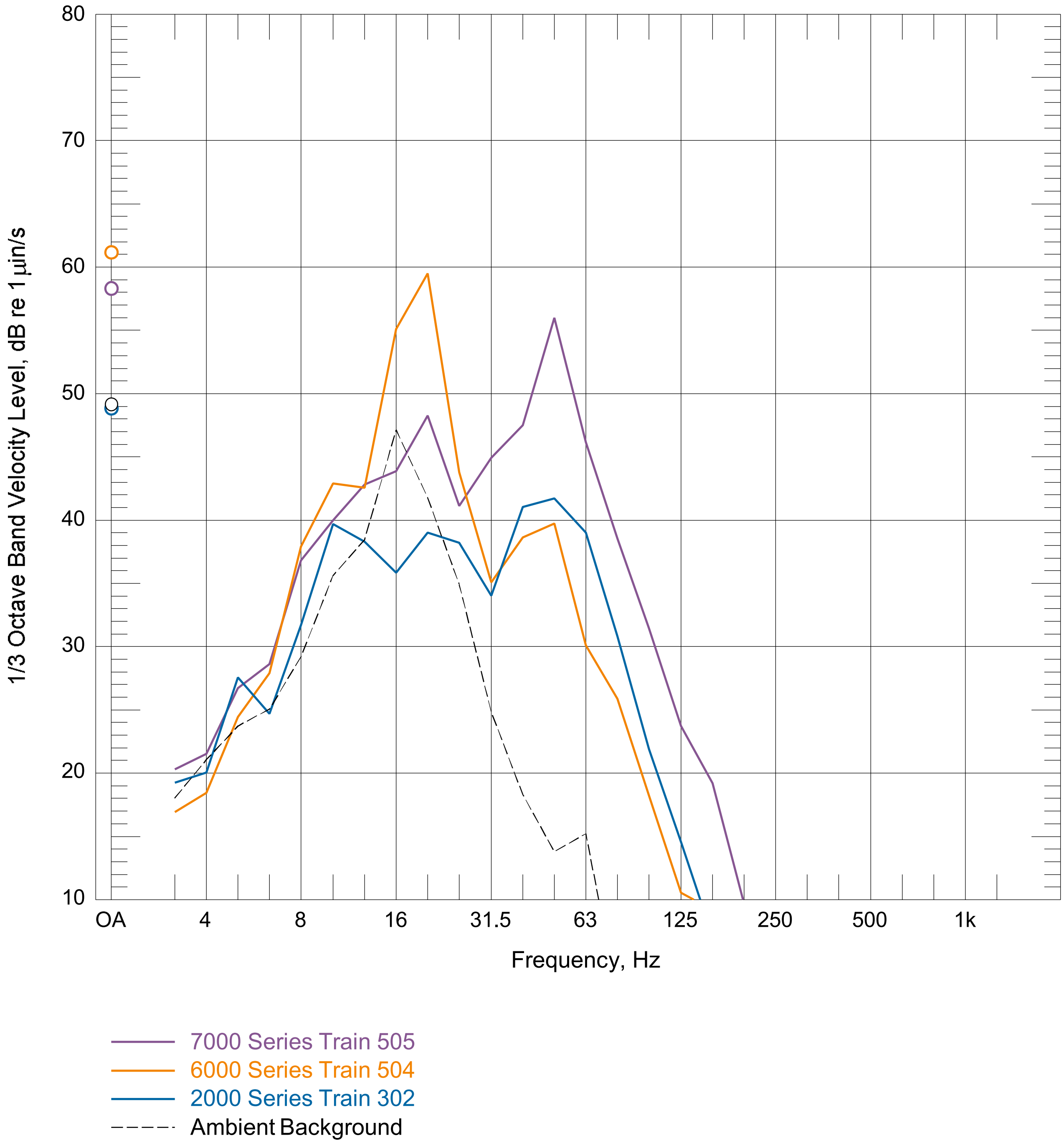


Figure 226: ***Site 12 at Location V2 Outside Near***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

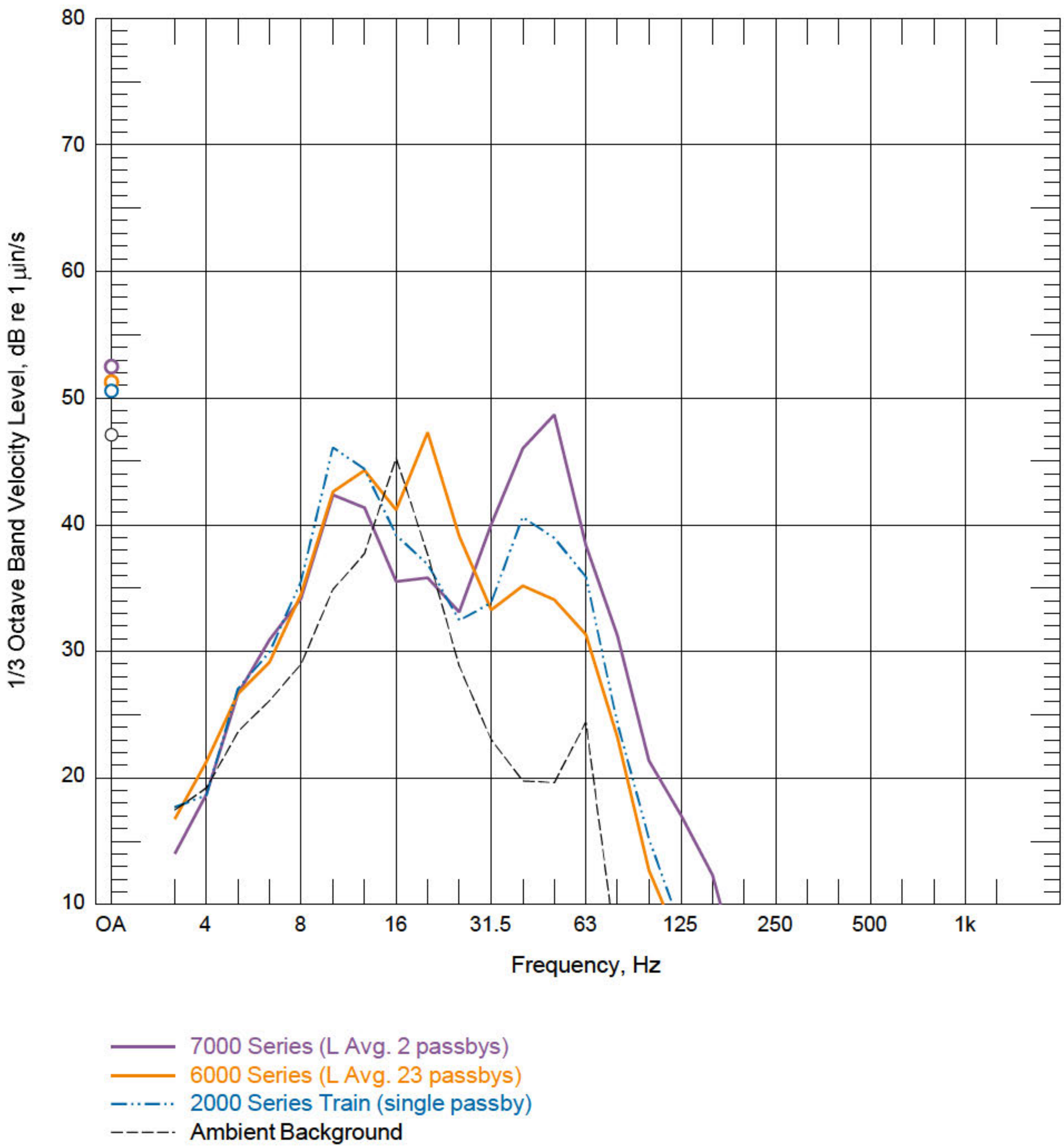


Figure 227: ***Site 12 at Location V3 Basement Bedroom***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

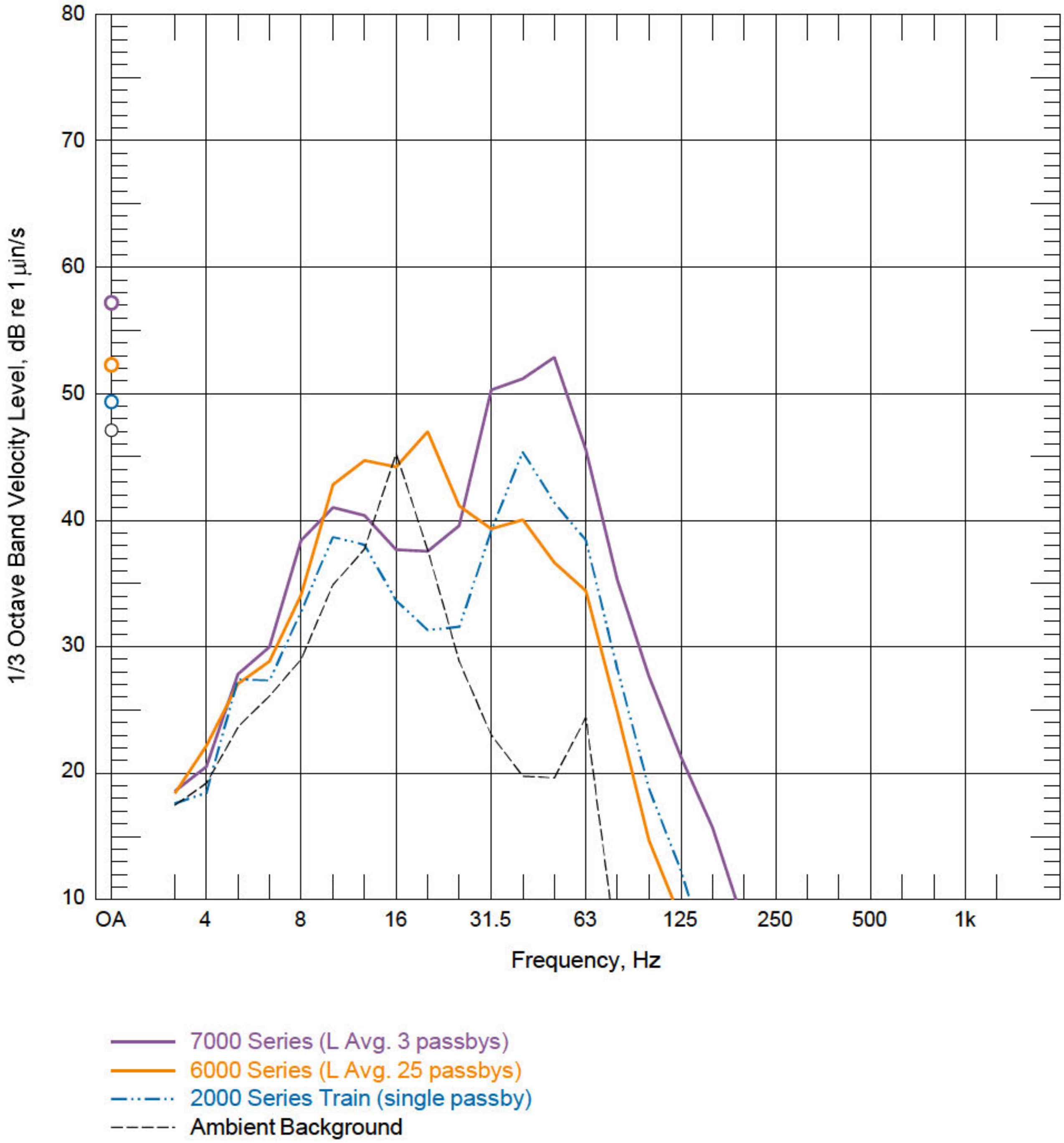


Figure 228: ***Site 12 at Location V3 Basement Bedroom***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

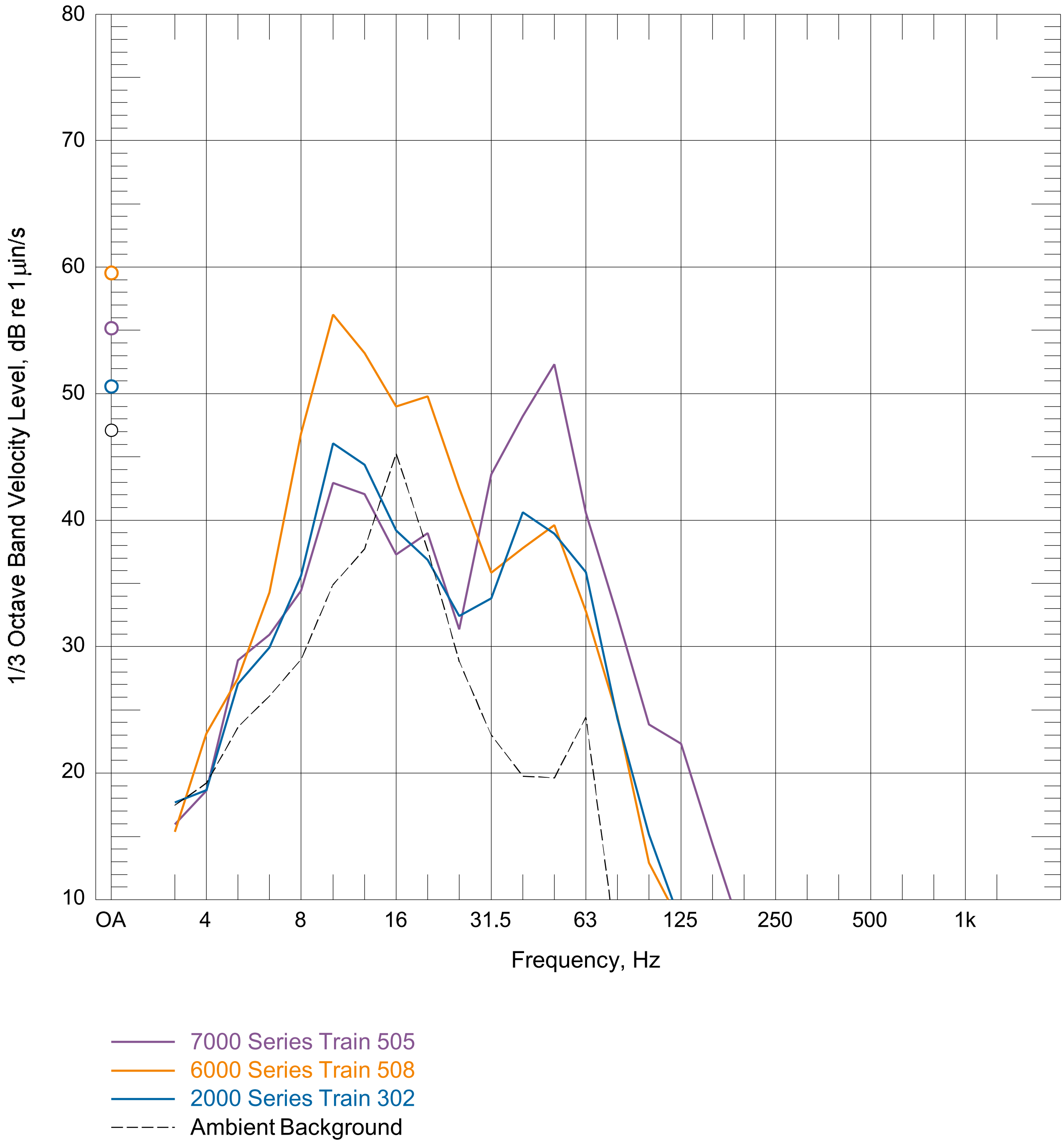


Figure 229: ***Site 12 at Location V3 Basement Bedroom***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

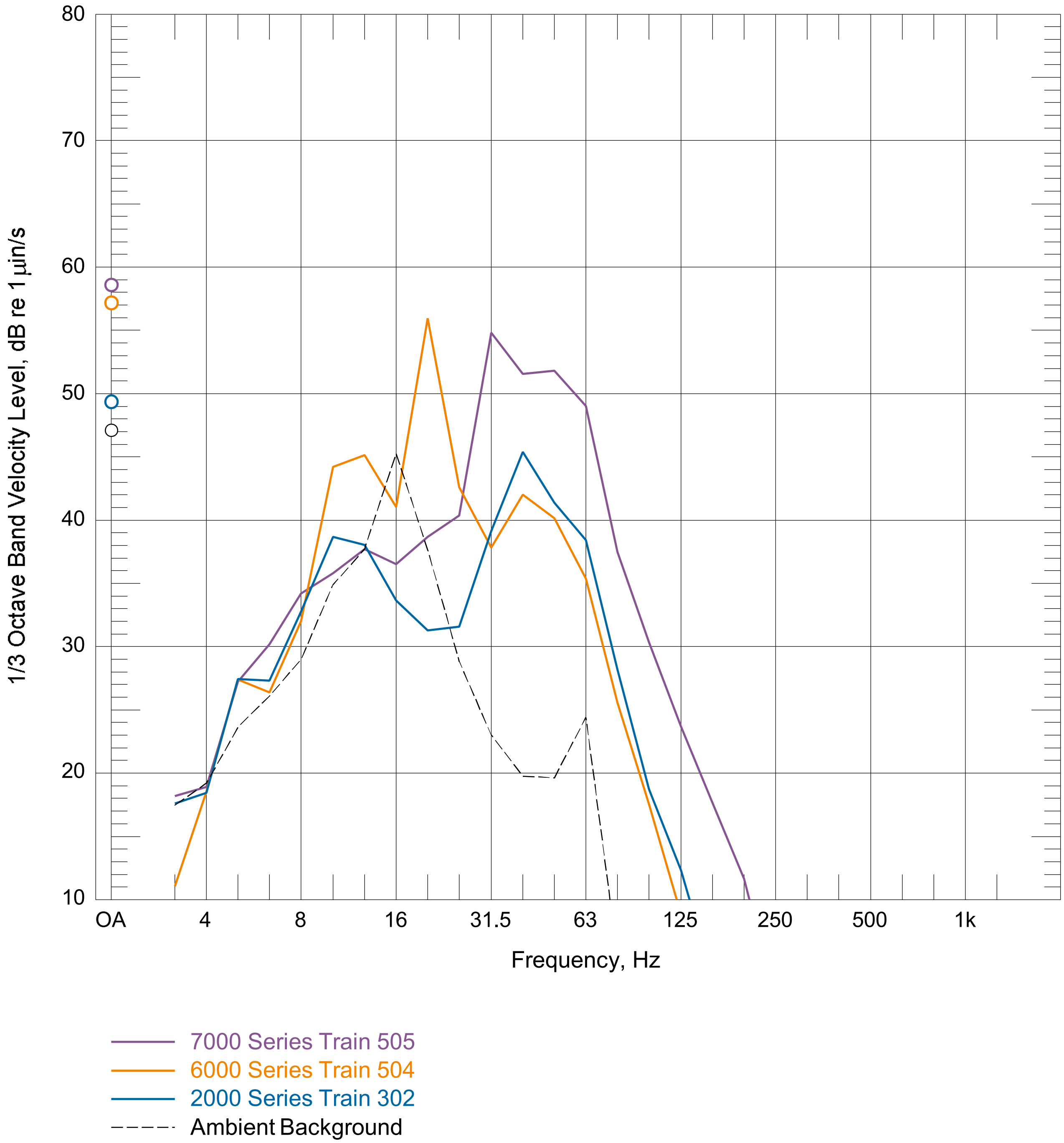


Figure 230: ***Site 12 at Location V3 Basement Bedroom***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

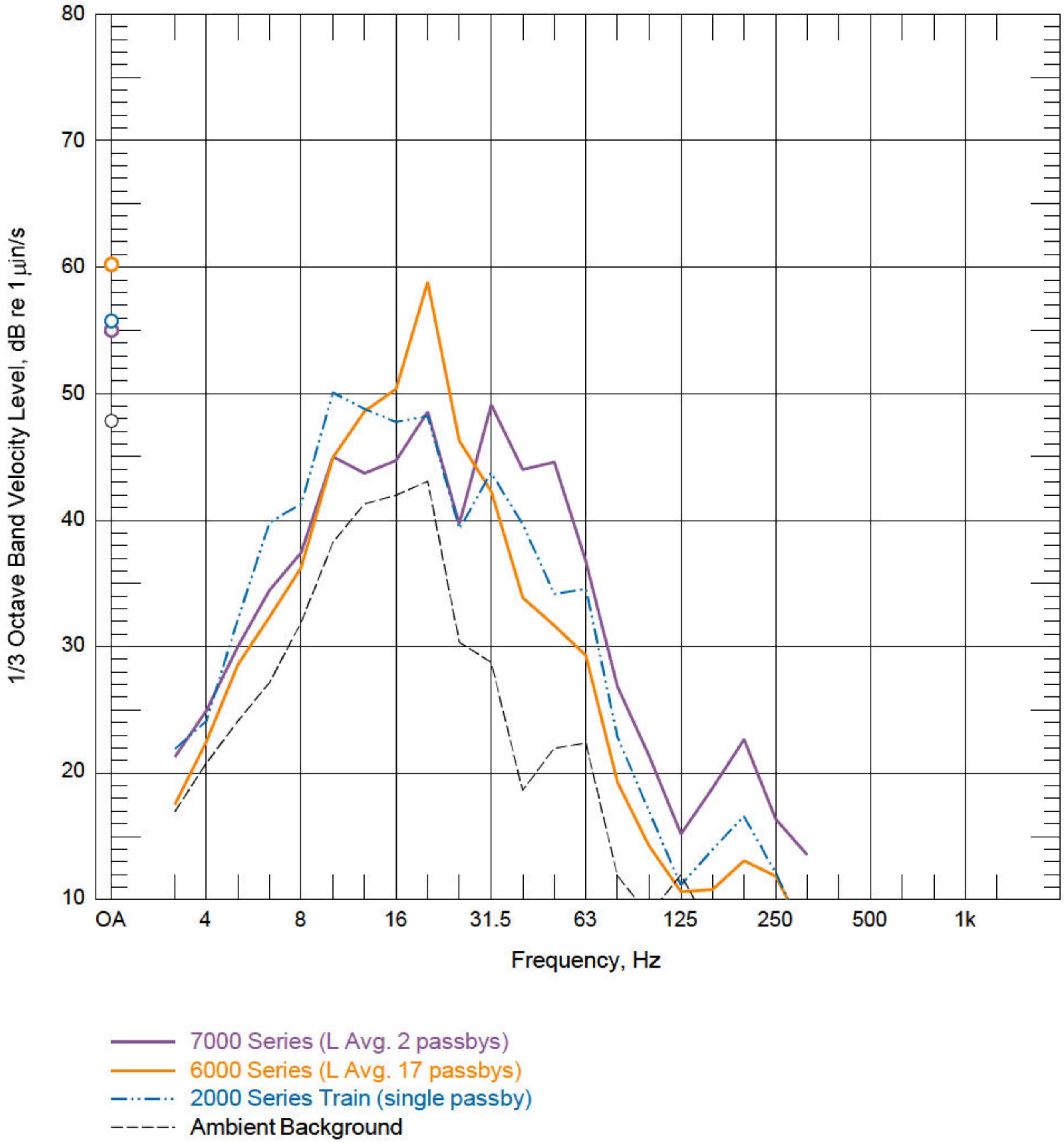


Figure 231: ***Site 12 at Location V4 First Floor Dining Room***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

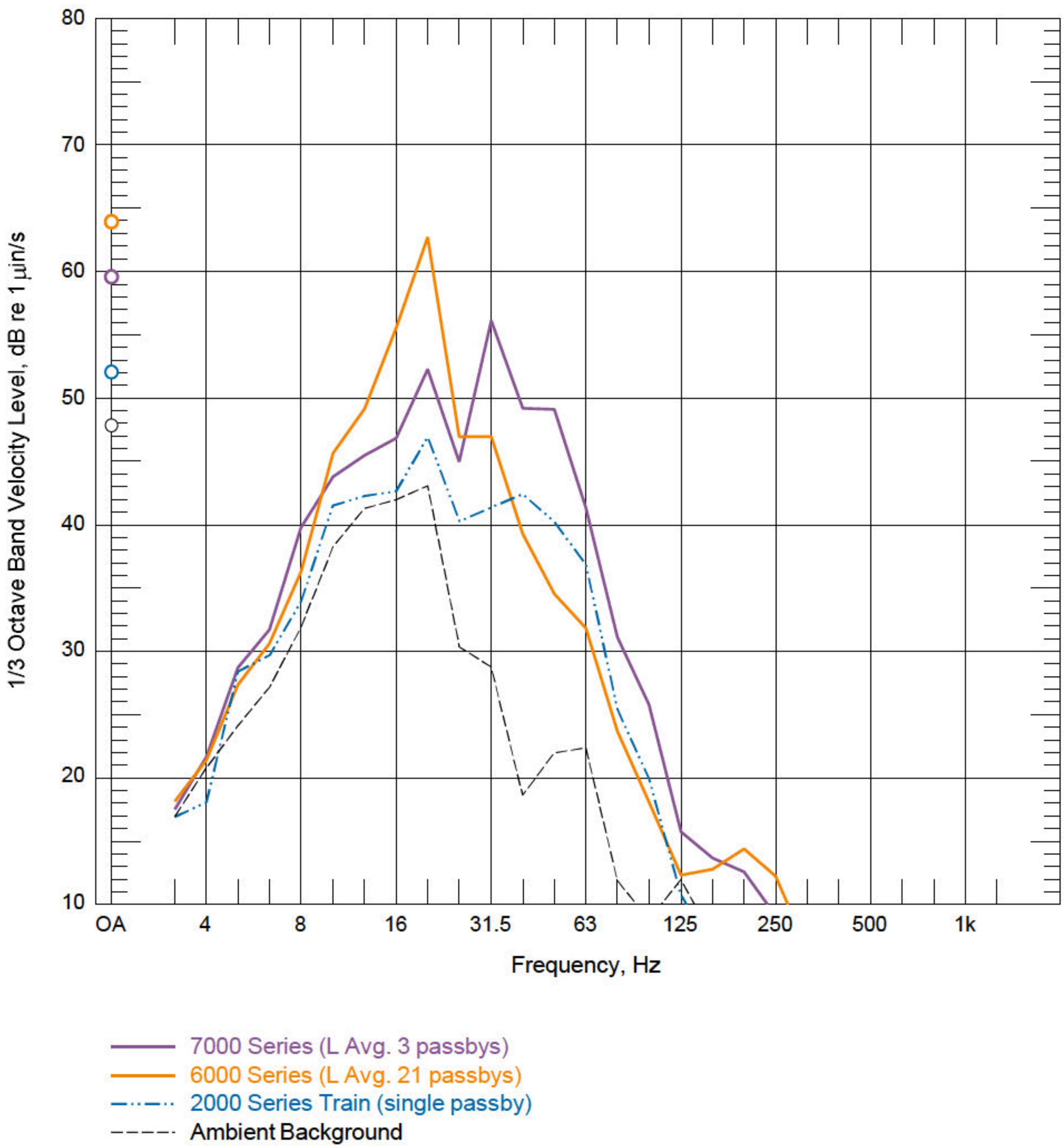


Figure 232: ***Site 12 at Location V4 First Floor Dining Room***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

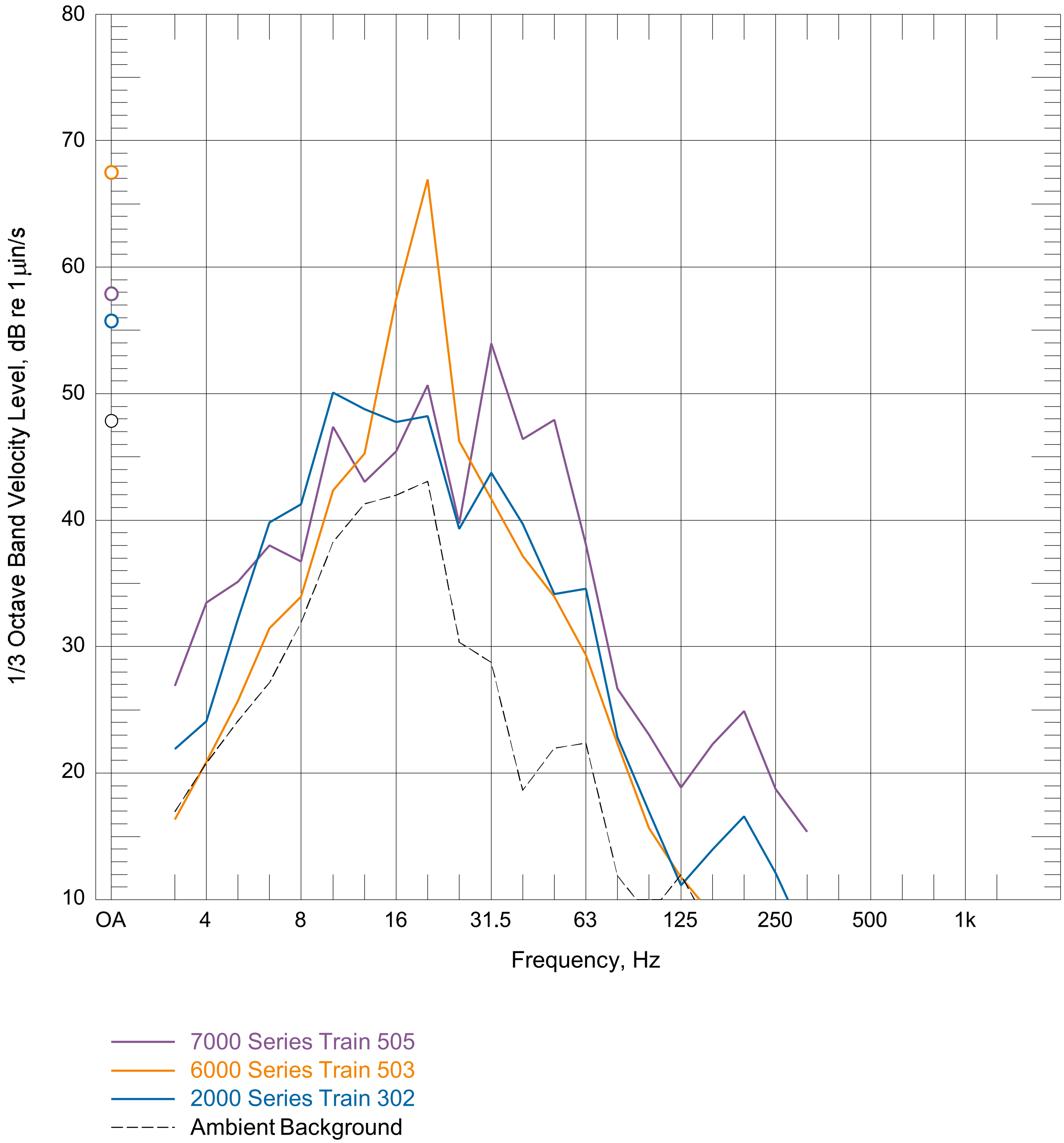


Figure 233: ***Site 12 at Location V4 First Floor Dining Room***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

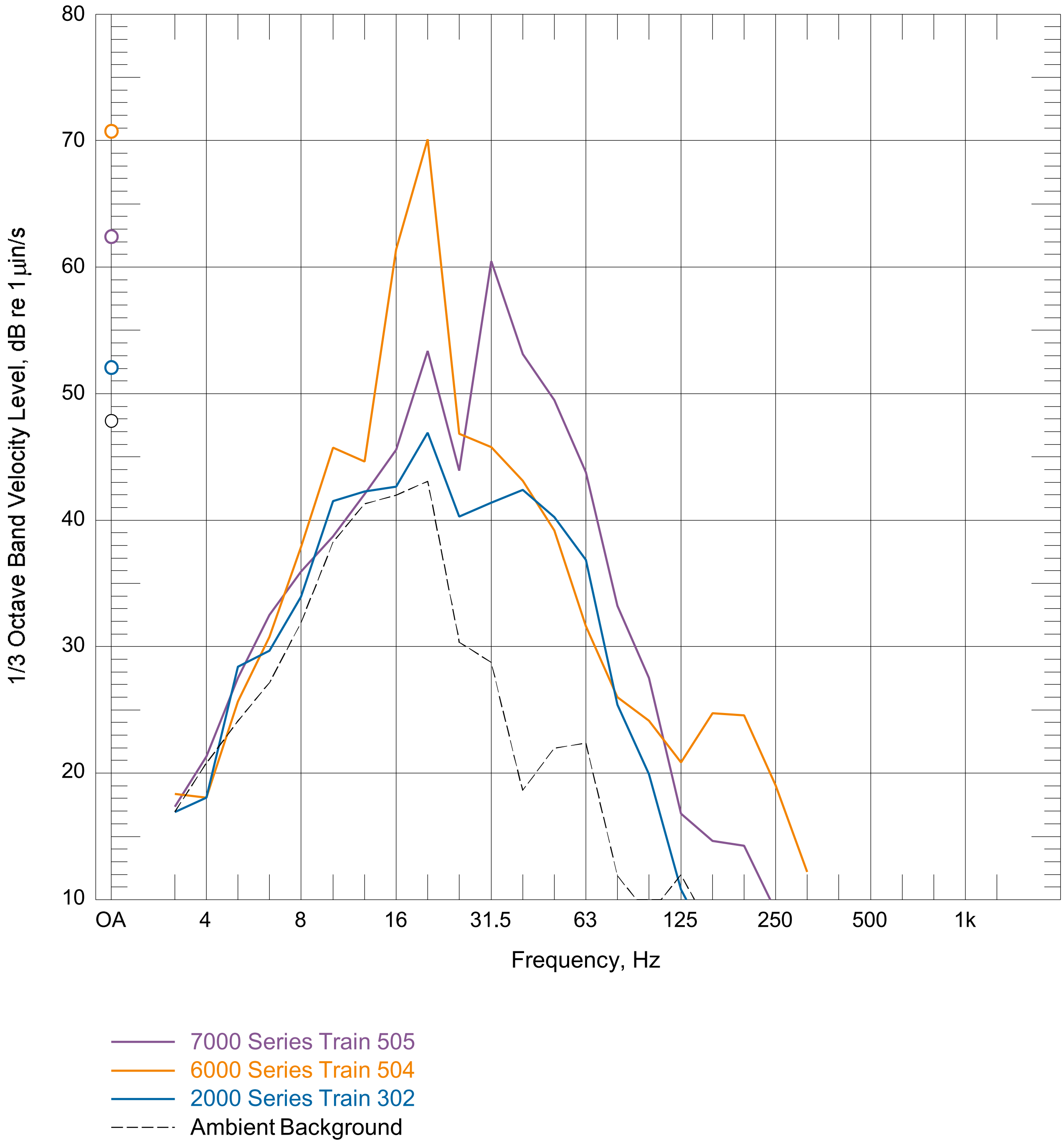


Figure 234: ***Site 12 at Location V4 First Floor Dining Room***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

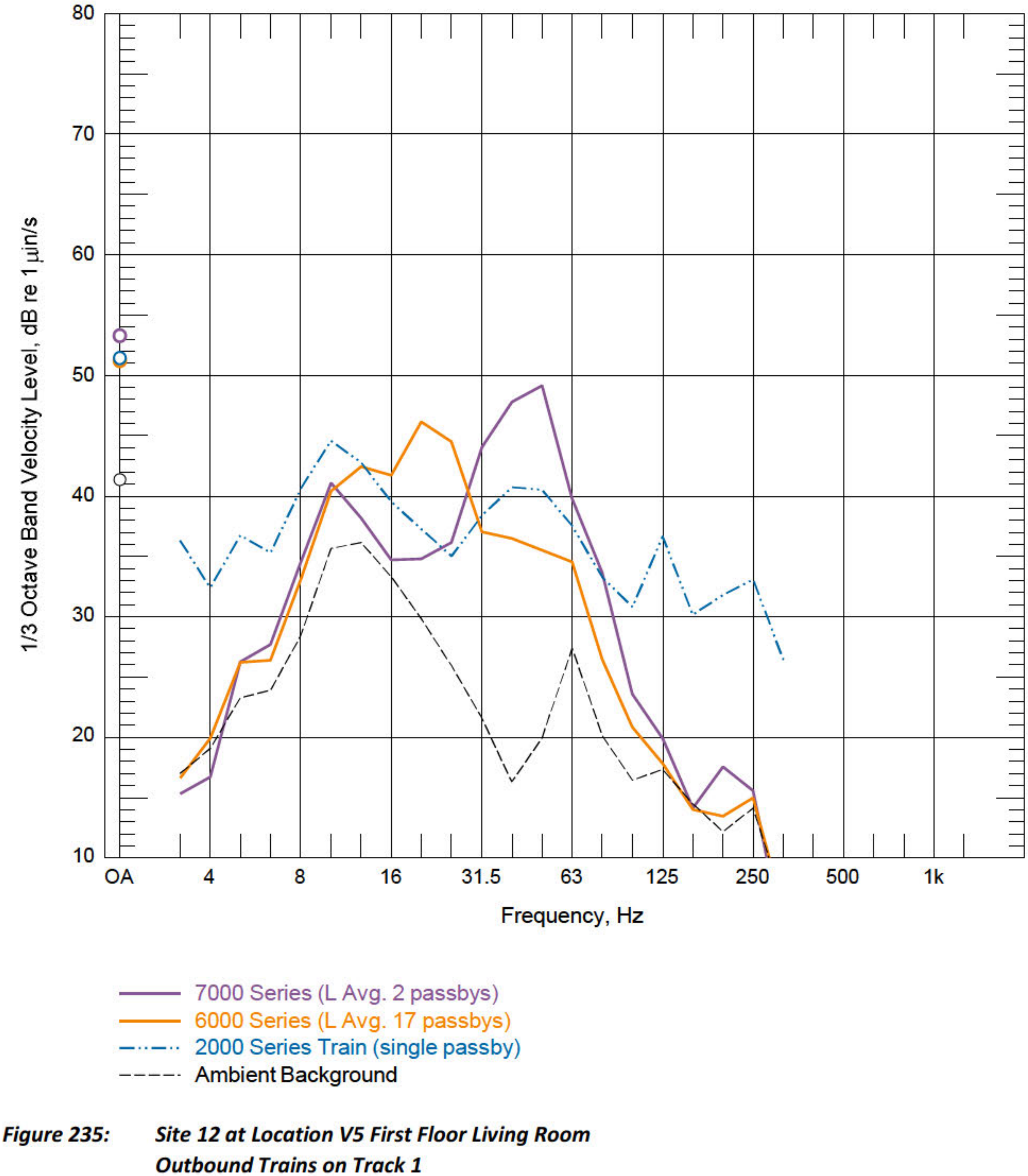


Figure 235: ***Site 12 at Location V5 First Floor Living Room***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

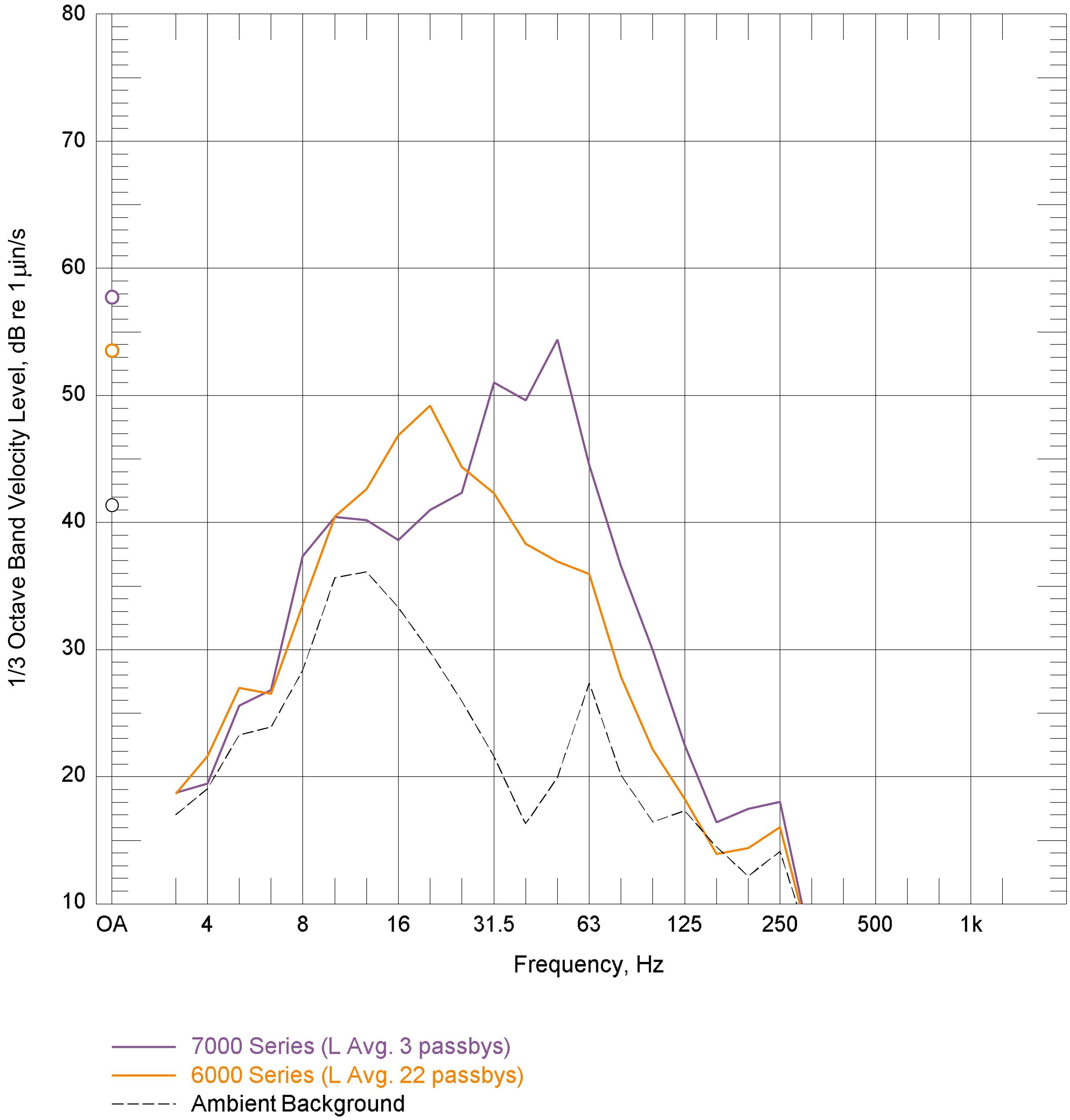


Figure 236: ***Site 12 at Location V5 First Floor Living Room***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

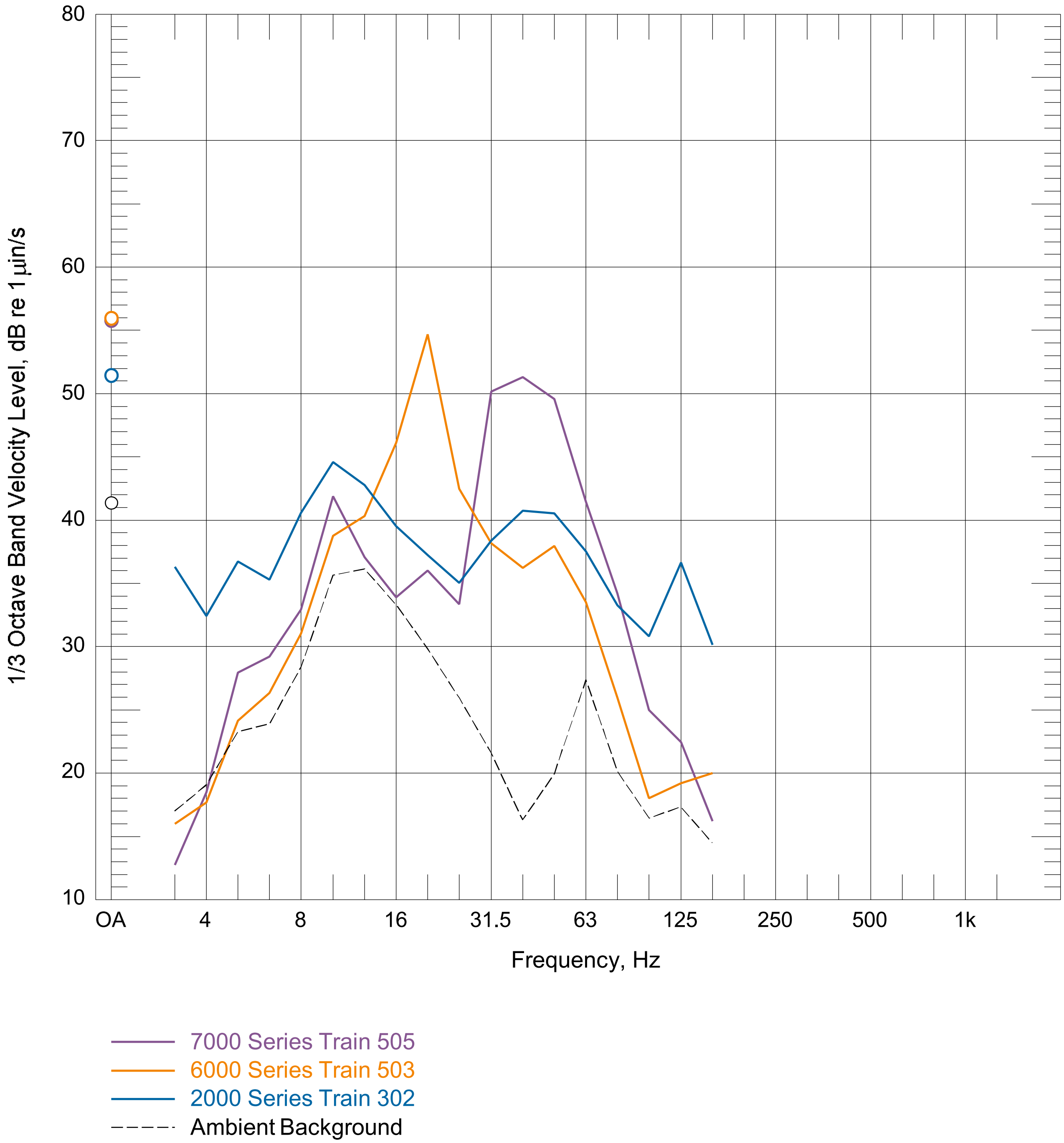


Figure 237: ***Site 12 at Location V5 First Floor Living Room***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

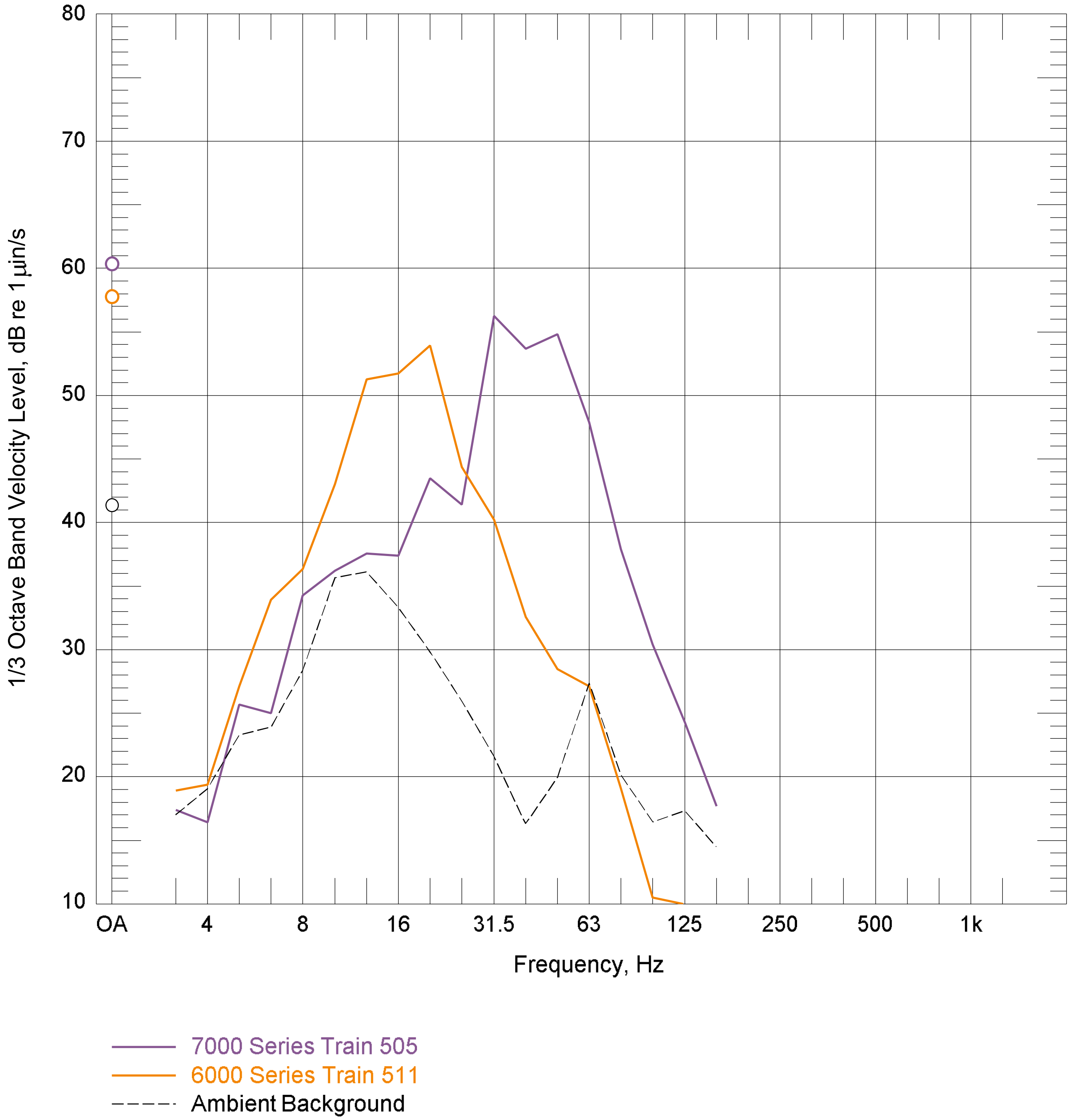


Figure 238: ***Site 12 at Location V5 First Floor Living Room***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

B.12.6 Passby Ground-borne Noise Spectra and A-weighted Levels

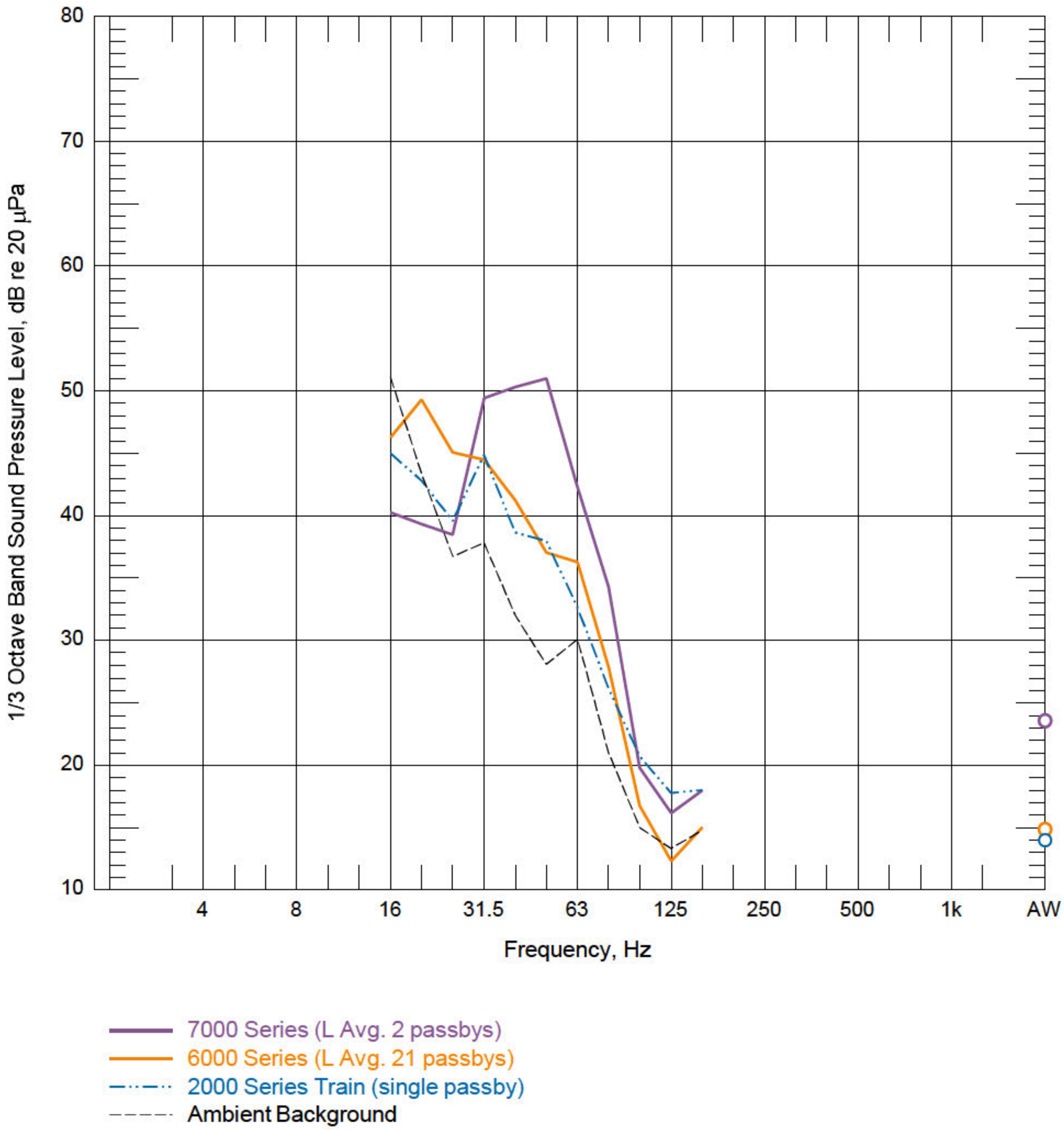


Figure 239: ***Site 12 at Location N1 Basement Bedroom***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

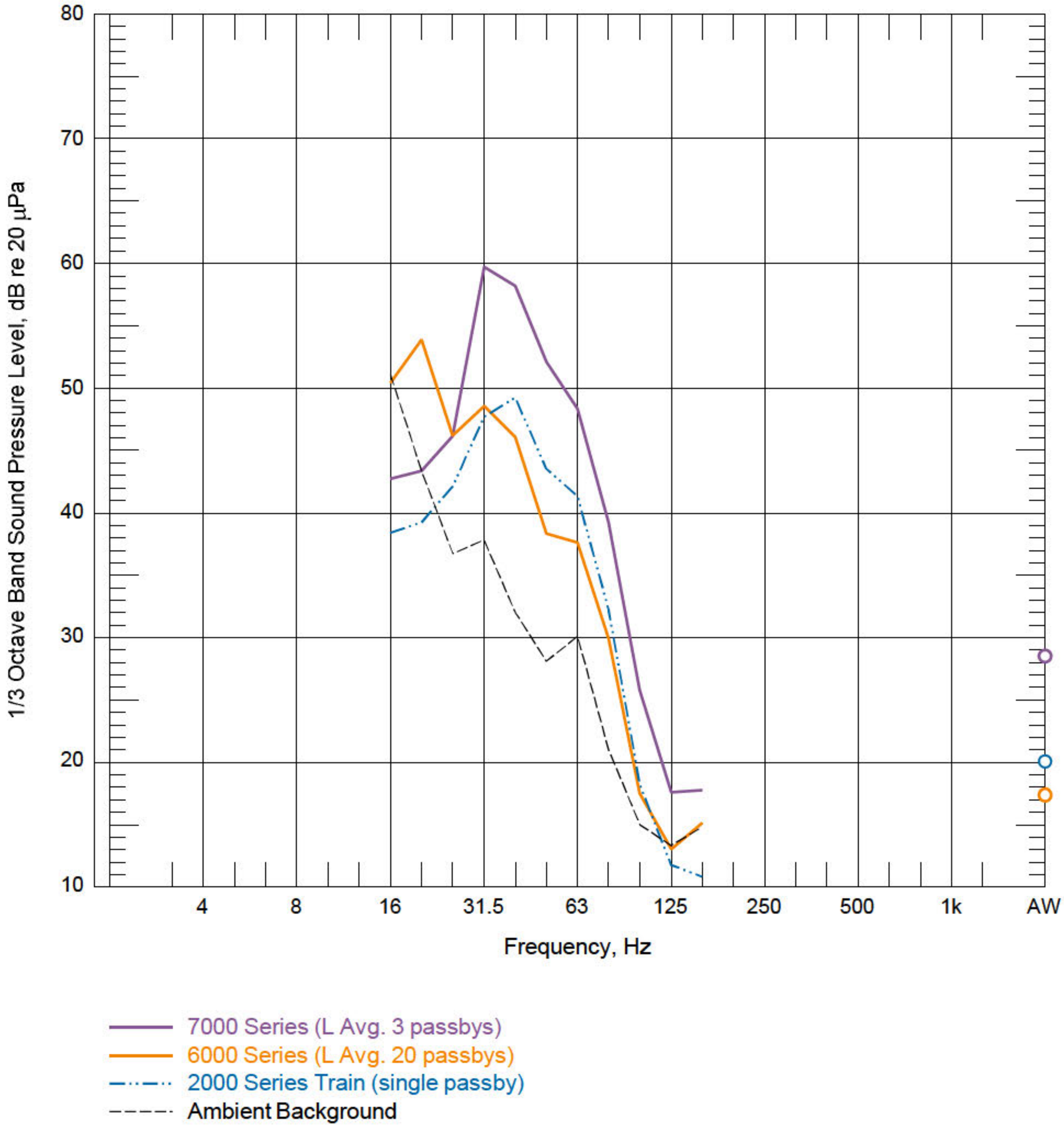


Figure 240: ***Site 12 at Location N1 Basement Bedroom***
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

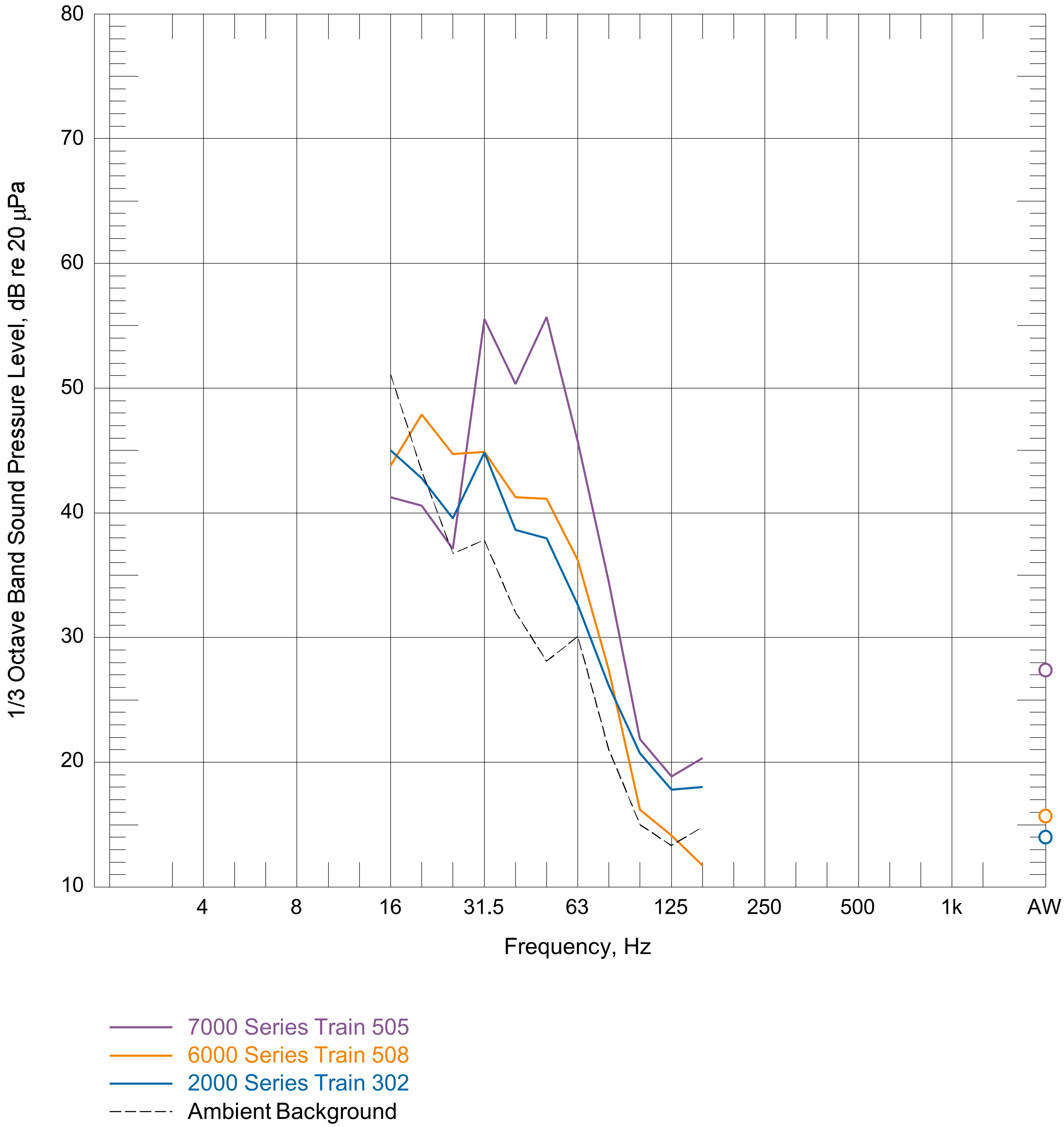


Figure 241: ***Site 12 at Location N1 Basement Bedroom***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

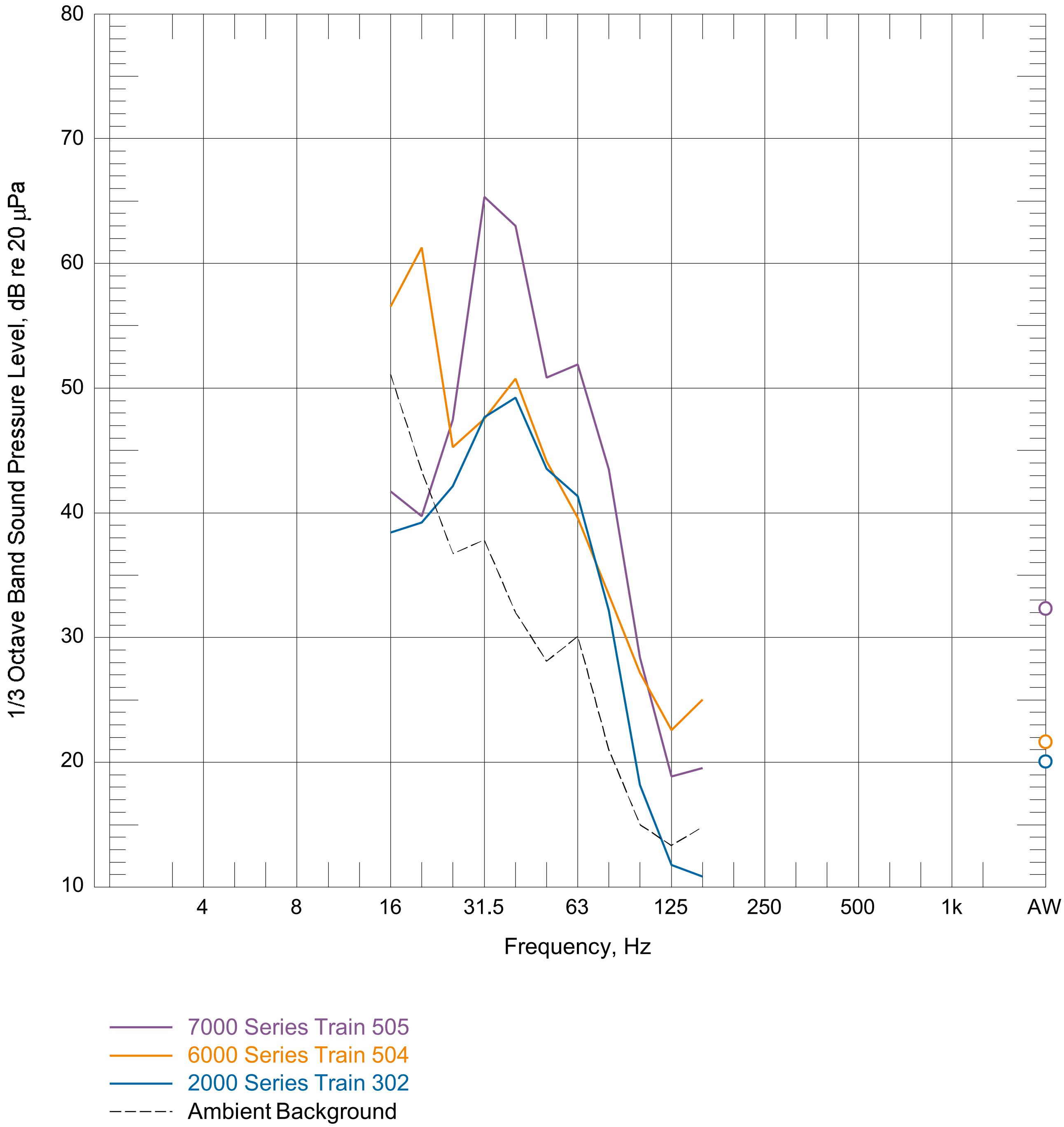


Figure 242: ***Site 12 at Location N1 Basement Bedroom***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

B.13 Site 13 – 4600 block of New Hampshire Avenue NW (Residence)

B.13.1 Building and Tunnel Notes

Location:	Inbound track 2 side at 216+10
Building Notes:	single-family residential townhouse, attached rowhouse, 3 floors comprised of partial underground basement plus 2 upper floors, exterior wall of brick and interior wood frame construction
Tunnel Structure:	Earth Tunnel
Track Type:	Direct Fixation
T/R Depth:	97 to 98 feet
Train Speed:	43 to 74 mph
Measurement Period:	Thursday, 8 June 2017, 14:58 to 19:26
Field Observations:	2nd floor noise mostly due to street traffic coming through windows

B.13.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Sensor[a,b,c]	Location / Room Occupancy	Horizontal Distance[d] (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)	Horizontal Distance (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)
Tri-axial geophone	Basement Family Room	87	98	131	124	97	157
V1	Basement Family Room						
N1	Basement Family Room						
V2	First Floor Living Room						
N2	Second Floor Bedroom						
V3	Second Floor Bedroom						
V4	Outside House	59	98	114	95	97	136

Notes:

a) Tri-axial geophone mounted on floor, logging peak particle velocity
b) V# vibration locations with accelerometer mounted on floor in vertical direction
c) N# noise locations with microphone/sound level meter mounted on tripod 48 inches above floor
d) Horizontal distance from track to building façade for indoor locations, not accounting for tunnel depth.
e) T/R depth = top-of-rail depth
f) Total slant distance to T/R = total distance from building to track, accounting for tunnel depth

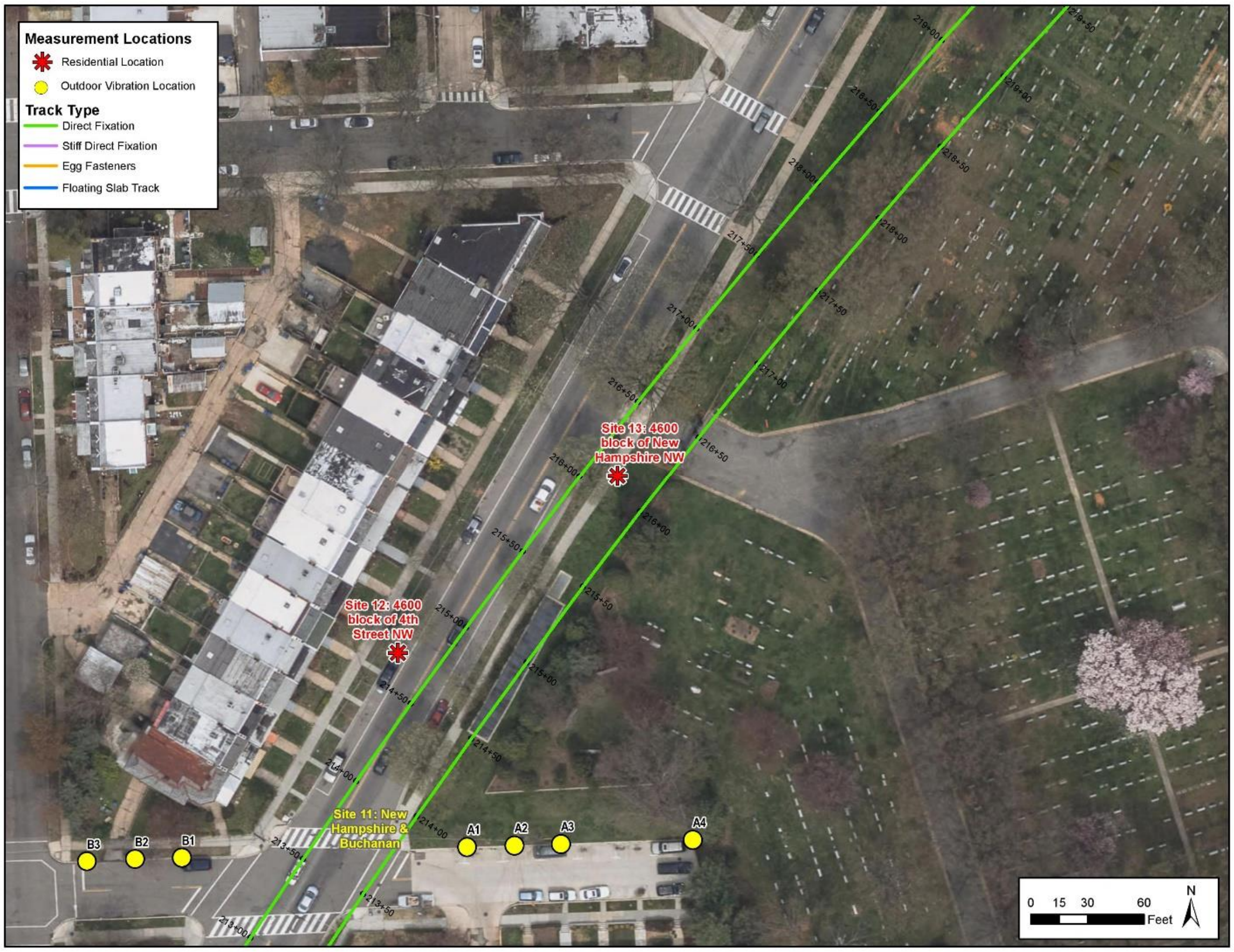


Figure 243: Aerial Map of 4600 block of New Hampshire Residence and Exterior Measurement Location at Site 13 (with nearby Sites 11 and 12 shown for reference)

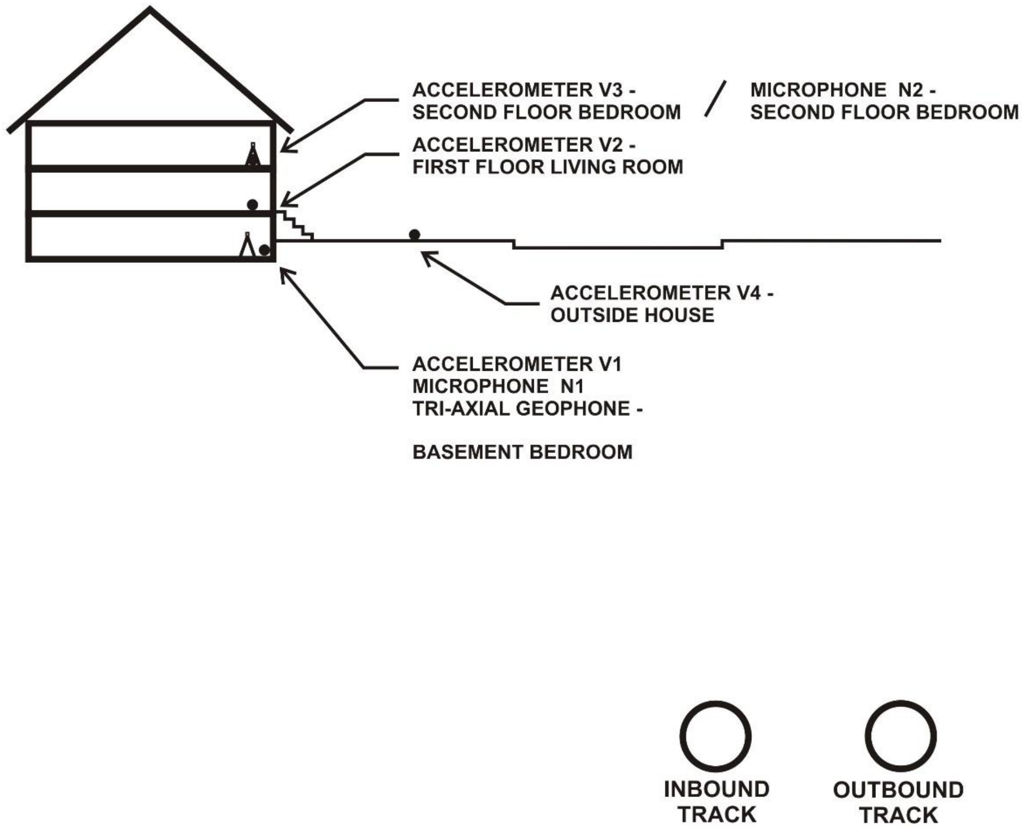


Figure 244: Cross-section Sketch (not to scale) of 4600 block of New Hampshire Avenue NW Indoor and Exterior Measurement Locations

B.13.3 GBNV Assessment Summary

SITE 13	4600 block of NEW HAMPSHIRE AVENUE NW – ATTENDED PASSBY MEASUREMENT GBNV ASSESSMENT		
	Ground-borne Vibration (GBV)	**>70 VdB?**	**Notes**
	7000 Series - Average of Multiple Passbys	NO	
	6000 Series - Average of Multiple Passbys	NO	
	4000 Series - Average of Multiple Passbys	NO	
	3000 Series - Average of Multiple Passbys	NO	
	Mixed Legacy without 4000 Series - Average of Multiple Passbys	NO	
	7000 Series - Individual Train with Highest Overall Vibration	YES	
	6000 Series - Individual Train with Highest Overall Vibration	YES	V3
	4000 Series - Individual Train with Highest Overall Vibration	YES	V3
	3000 Series - Individual Train with Highest Overall Vibration	NO	
	Mixed Legacy without 4000 Series - Individual Train with Highest Overall Vibration	YES	V2 and V3
	Ground-borne Noise (GBN)	**>40 dBA?**	**Notes**
	7000 Series - Average of Multiple Passbys	NO	
	6000 Series - Average of Multiple Passbys	NO	
	4000 Series - Average of Multiple Passbys	NO	
	3000 Series - Average of Multiple Passbys	NO	
	Mixed Legacy without 4000 Series - Average of Multiple Passbys	NO	
	7000 Series - Individual Train with Highest A-weighting	NO	
	6000 Series - Individual Train with Highest A-weighting	NO	
	4000 Series - Individual Train with Highest A-weighting	NO	
	3000 Series - Individual Train with Highest A-weighting	NO	
	Mixed Legacy without 4000 Series - Individual Train with Highest A-weighting	NO	

B.13.4 PPV Results

SITE 13	**4600 block of NEW HAMPSHIRE AVENUE NW – POTENTIAL FOR BUILDING VIBRATION DAMAGE ASSESSMENT**						
	>0.2 in/sec PPV in any direction?	Average PPV (in/s)			PPV Range (in/s)		
		Tran	Vert	Long	Tran	Vert	Long
	NO	0.0005	0.0006	0.0003	0 - 0.0022	0 - 0.0115	0 - 0.0102
Basement 8-Jun-17, 3:04:16 PM to 7:00:48 PM							

B.13.5 Passby Vibration Spectra and Overall Levels

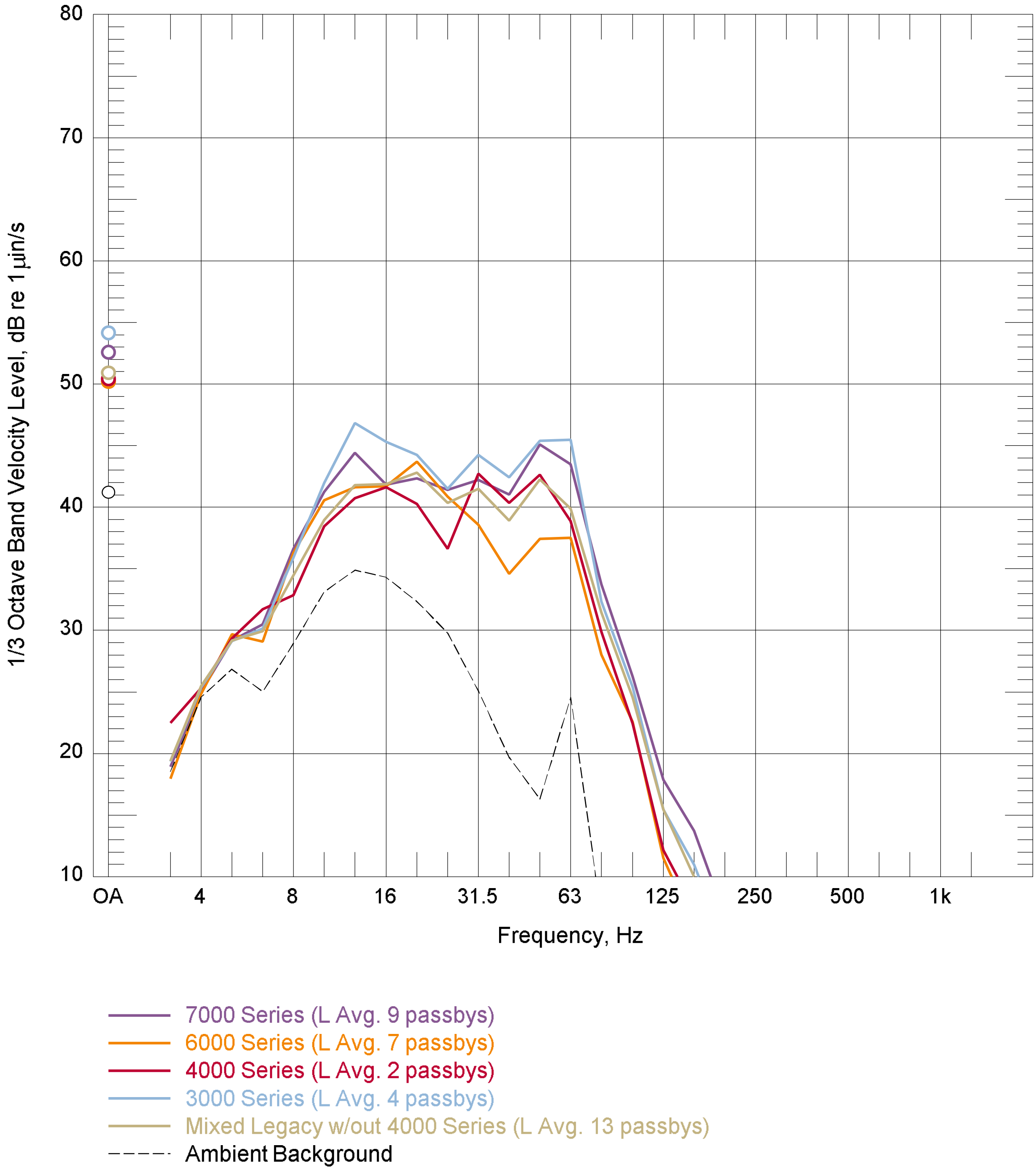


Figure 245: ***Site 13 at Location V1 Basement Family Room***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

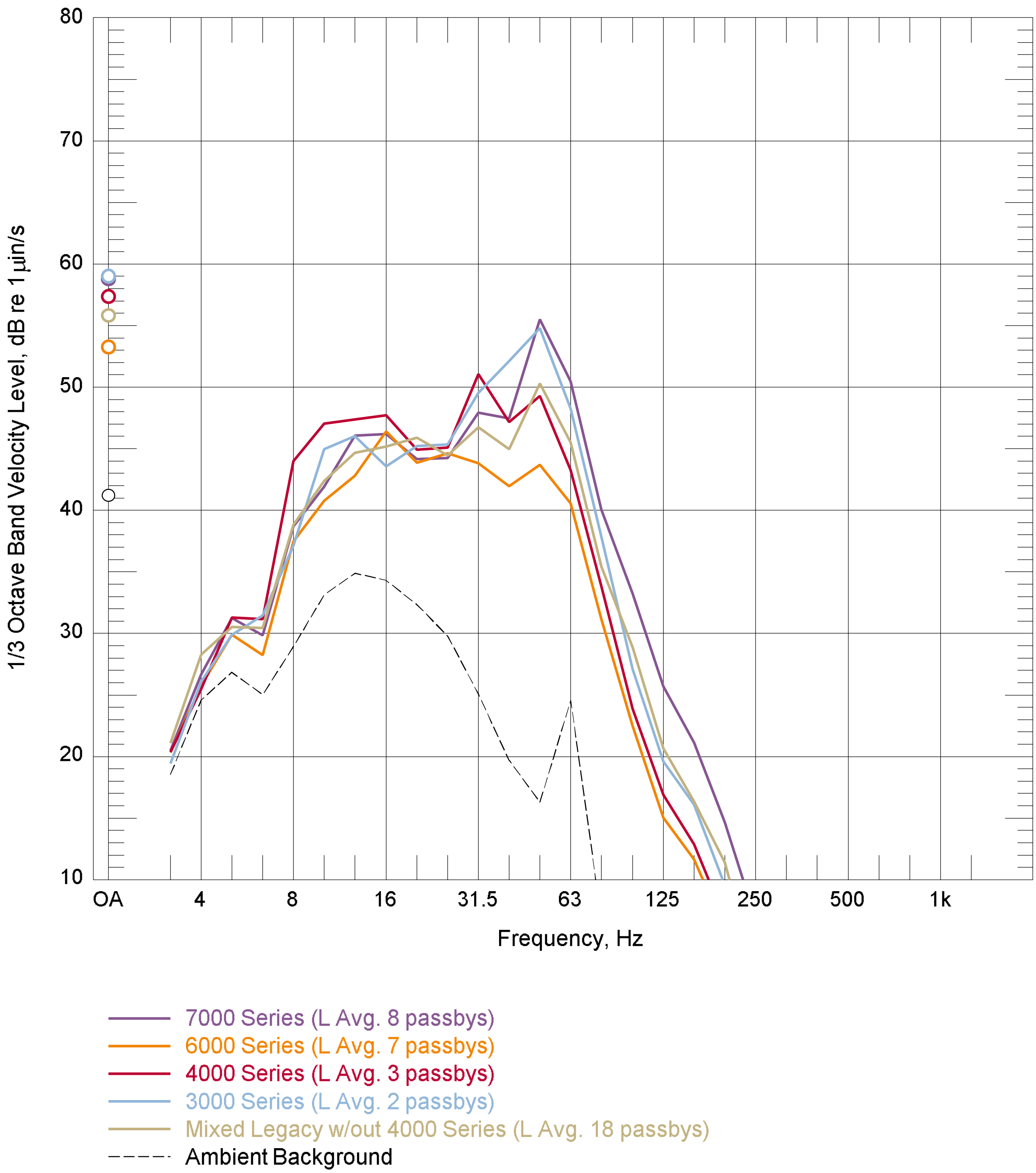


Figure 246: ***Site 13 at Location V1 Basement Family Room***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

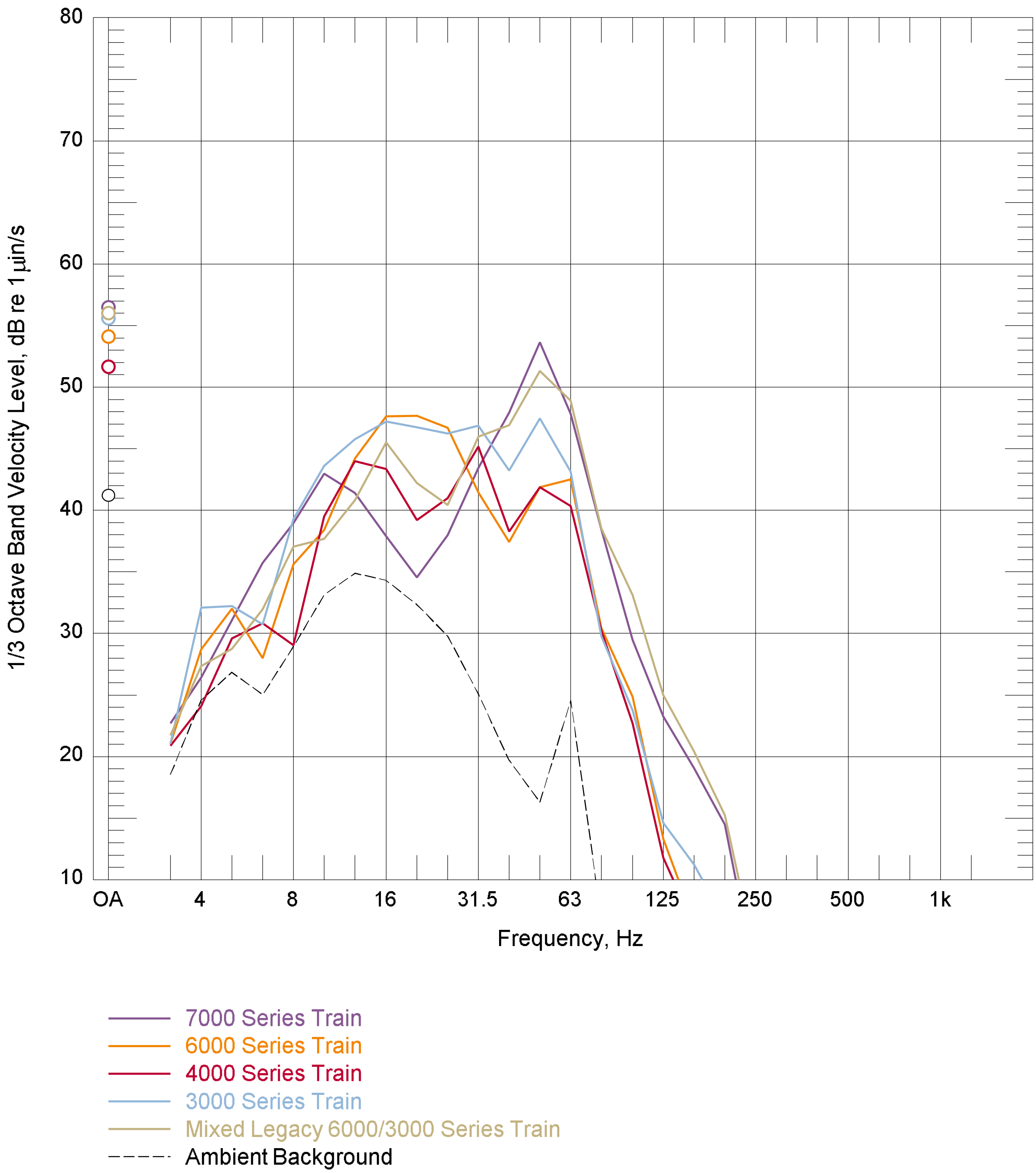


Figure 247: ***Site 13 at Location V1 Basement Family Room***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

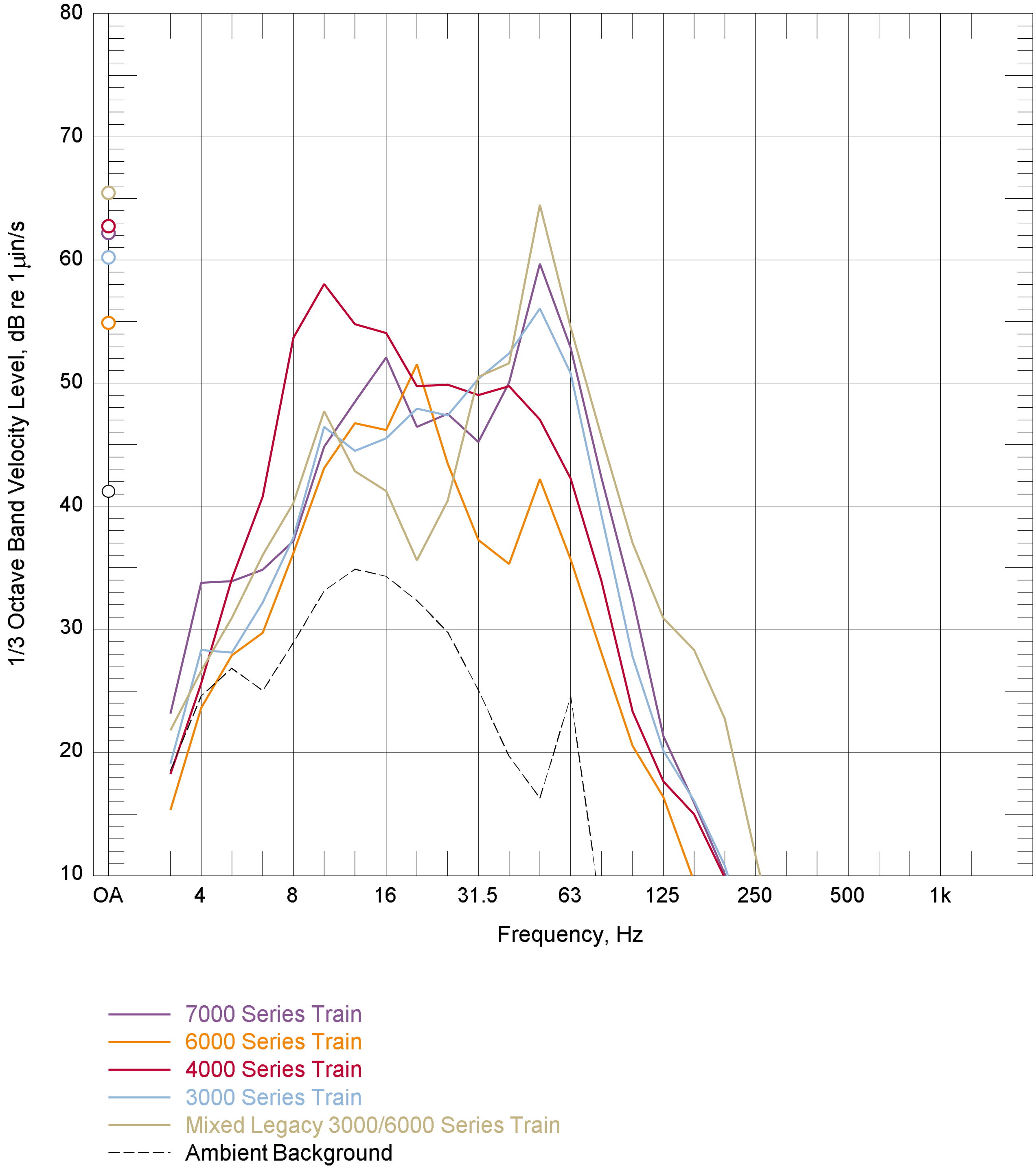


Figure 248: ***Site 13 at Location V1 Basement Family Room***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

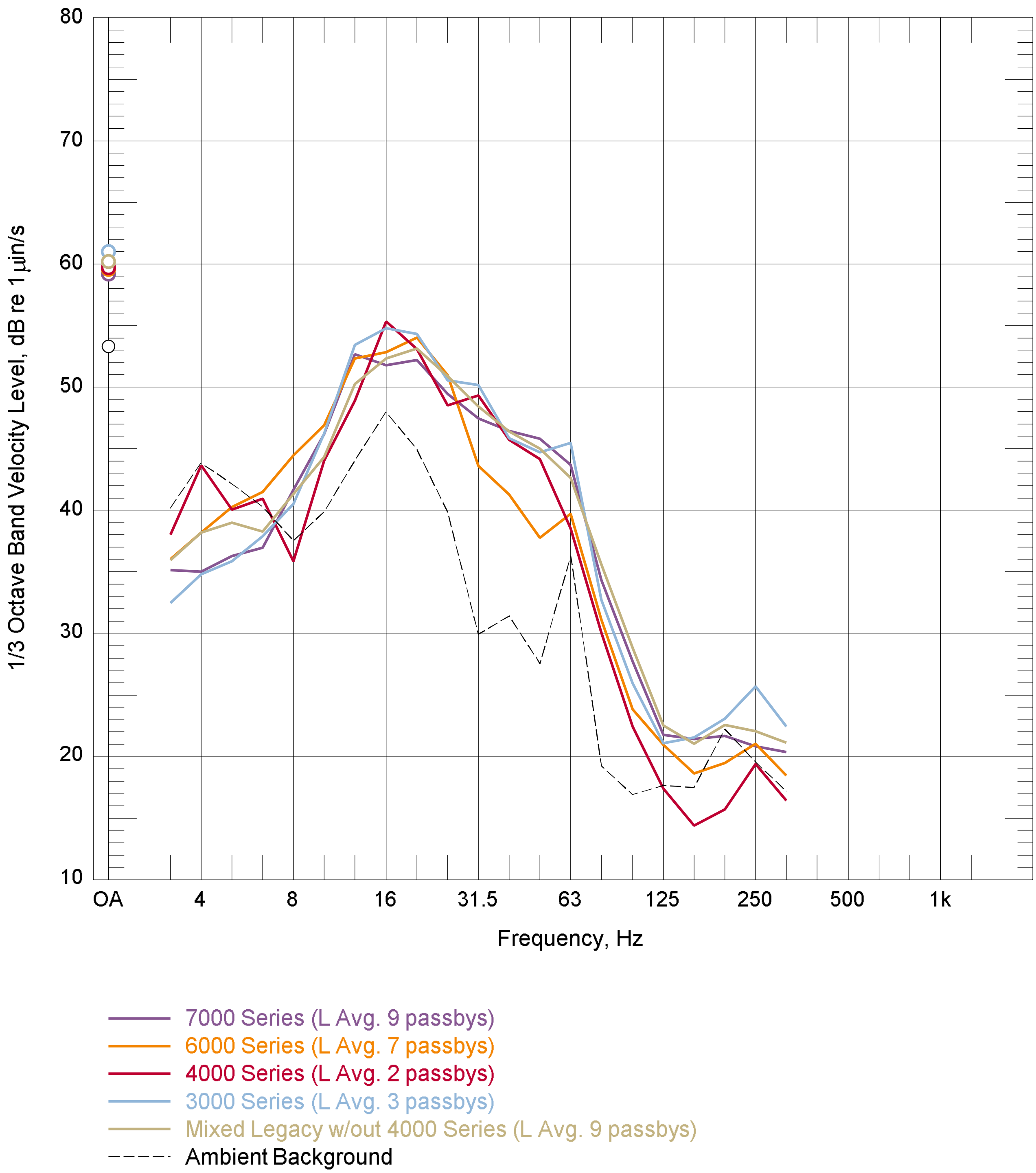


Figure 249: ***Site 13 at Location V2 First Floor Living Room***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

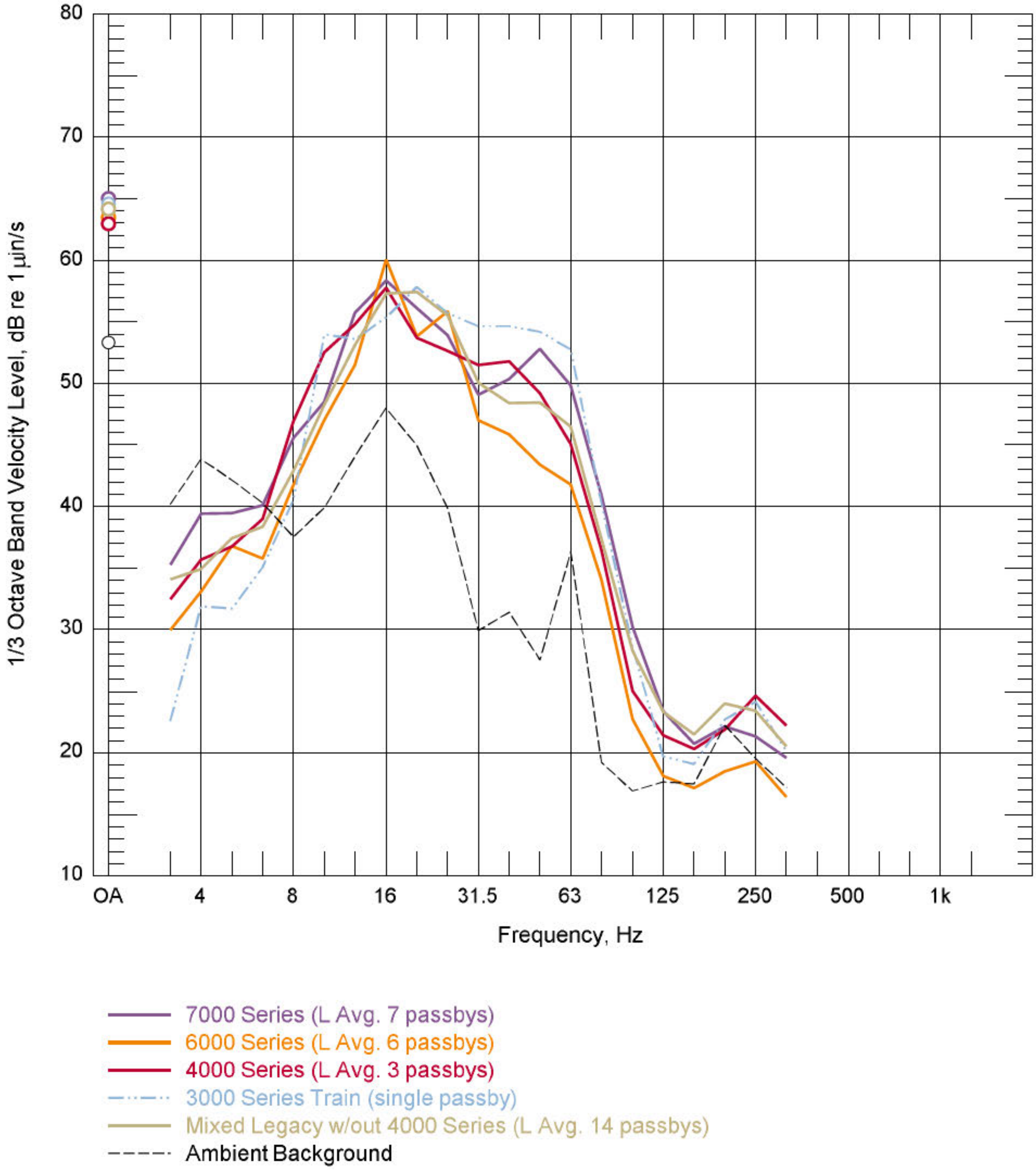


Figure 250: ***Site 13 at Location V2 First Floor Living Room***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

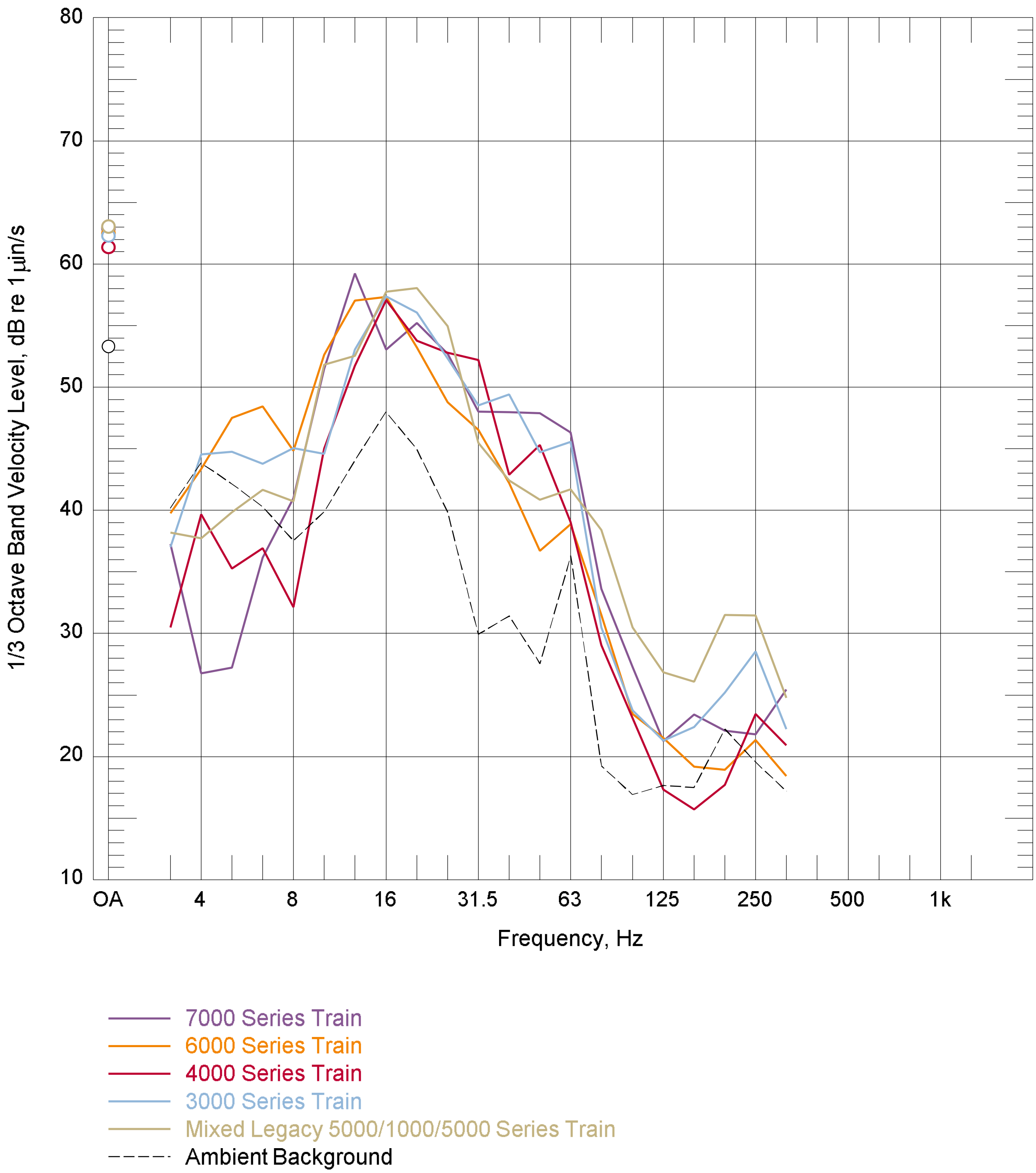


Figure 251: ***Site 13 at Location V2 First Floor Living Room***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

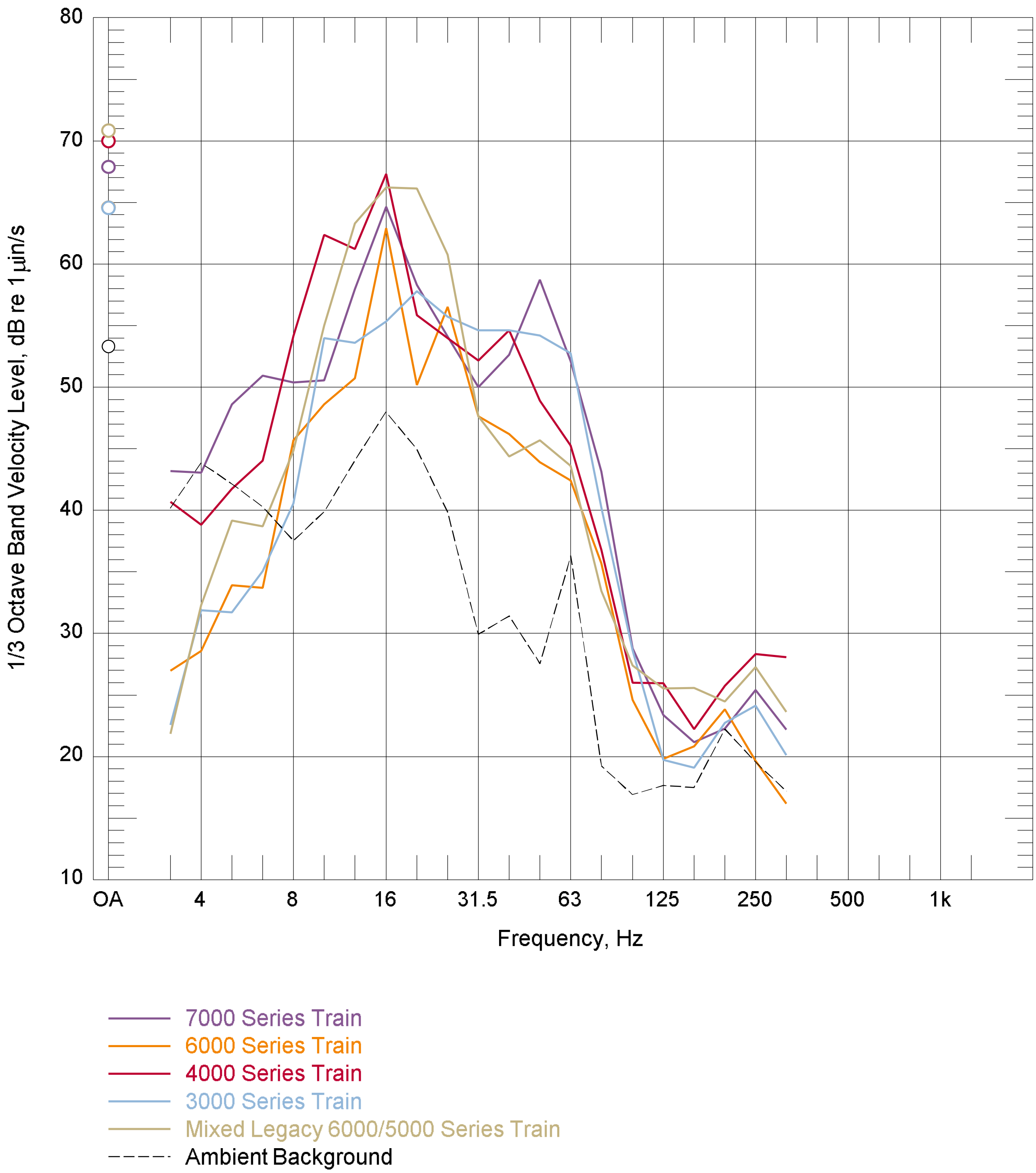


Figure 252: ***Site 13 at Location V2 First Floor Living Room***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

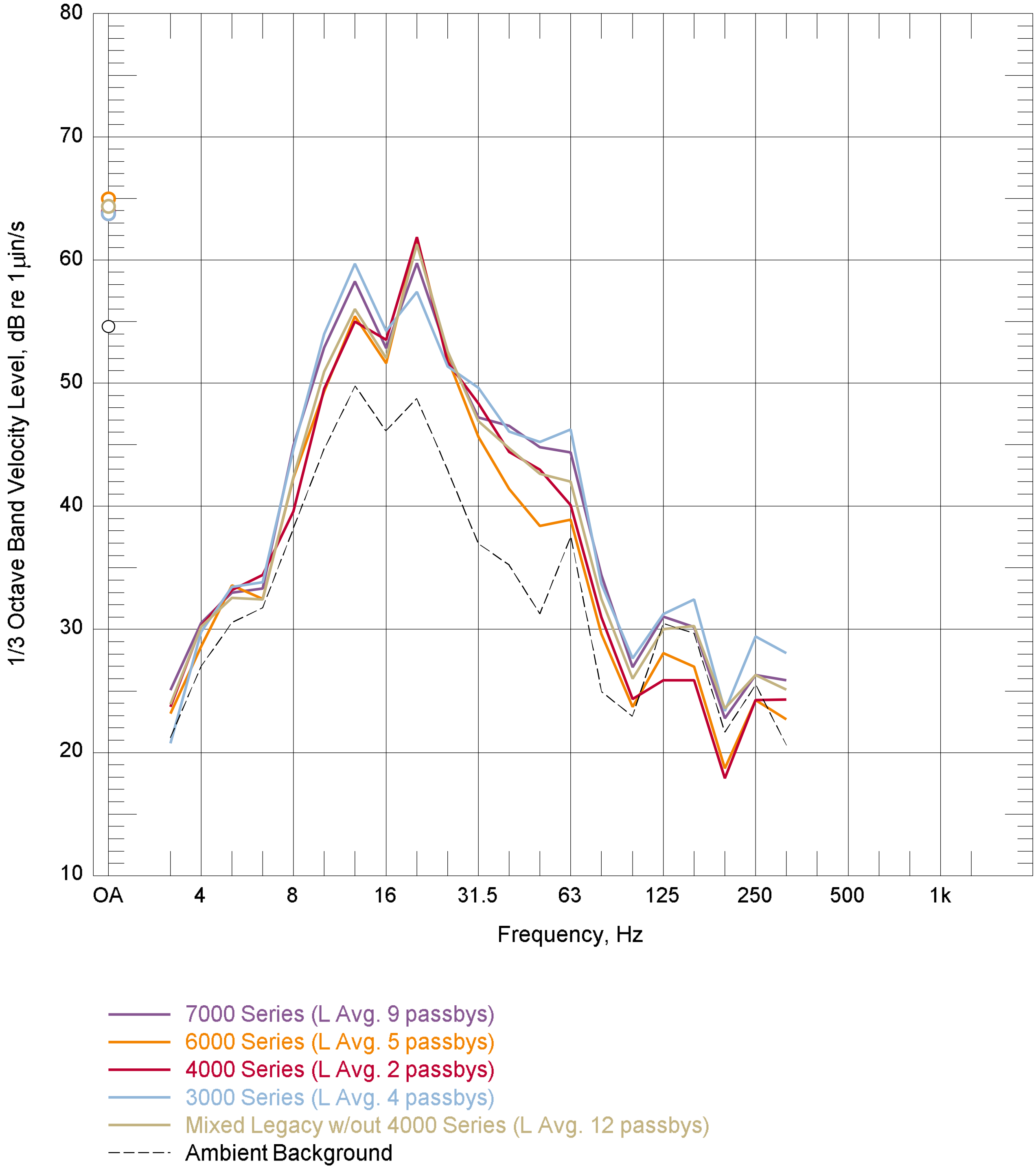


Figure 253: ***Site 13 at Location V3 Second Floor Bedroom***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

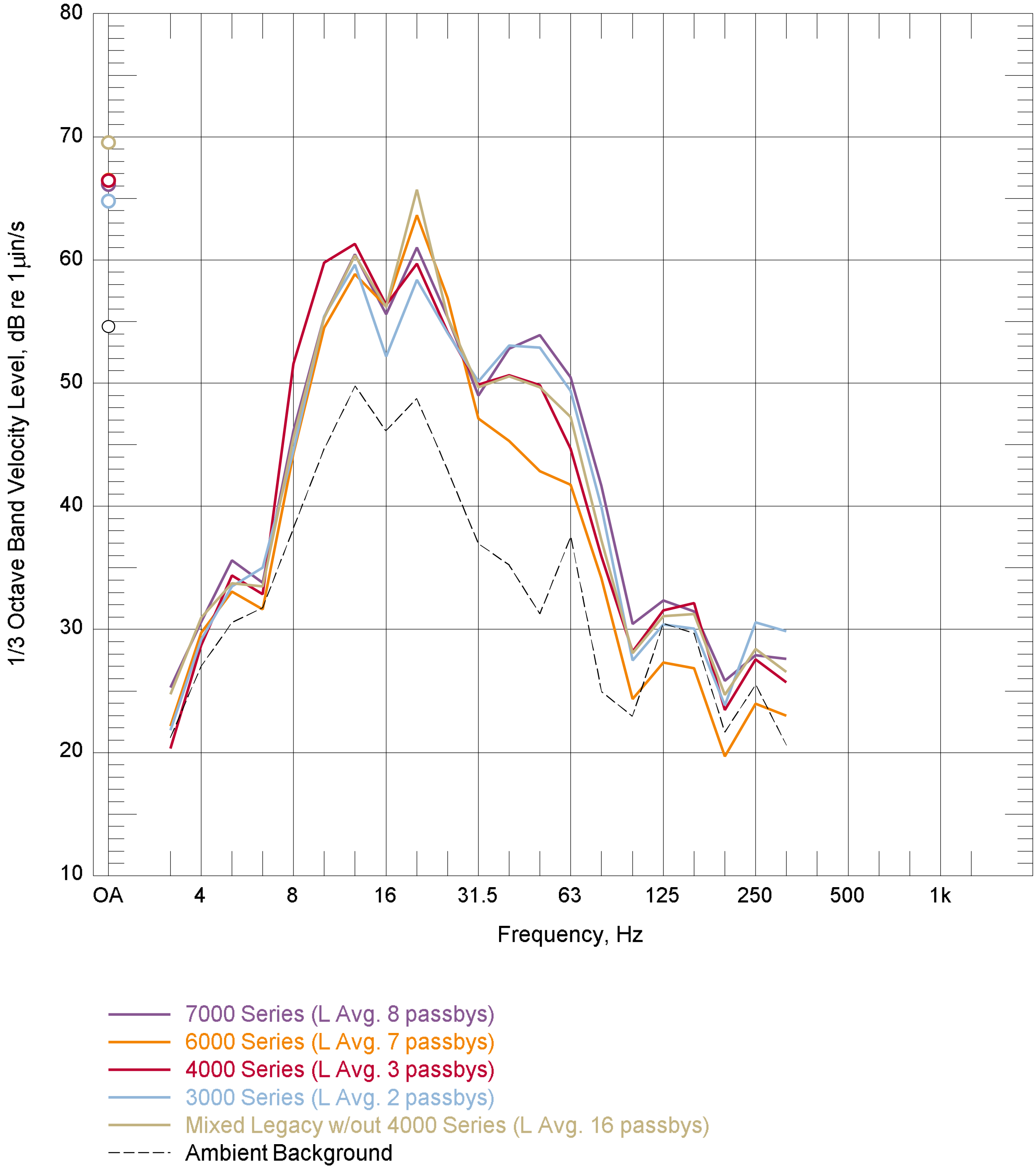


Figure 254: ***Site 13 at Location V3 Second Floor Bedroom***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

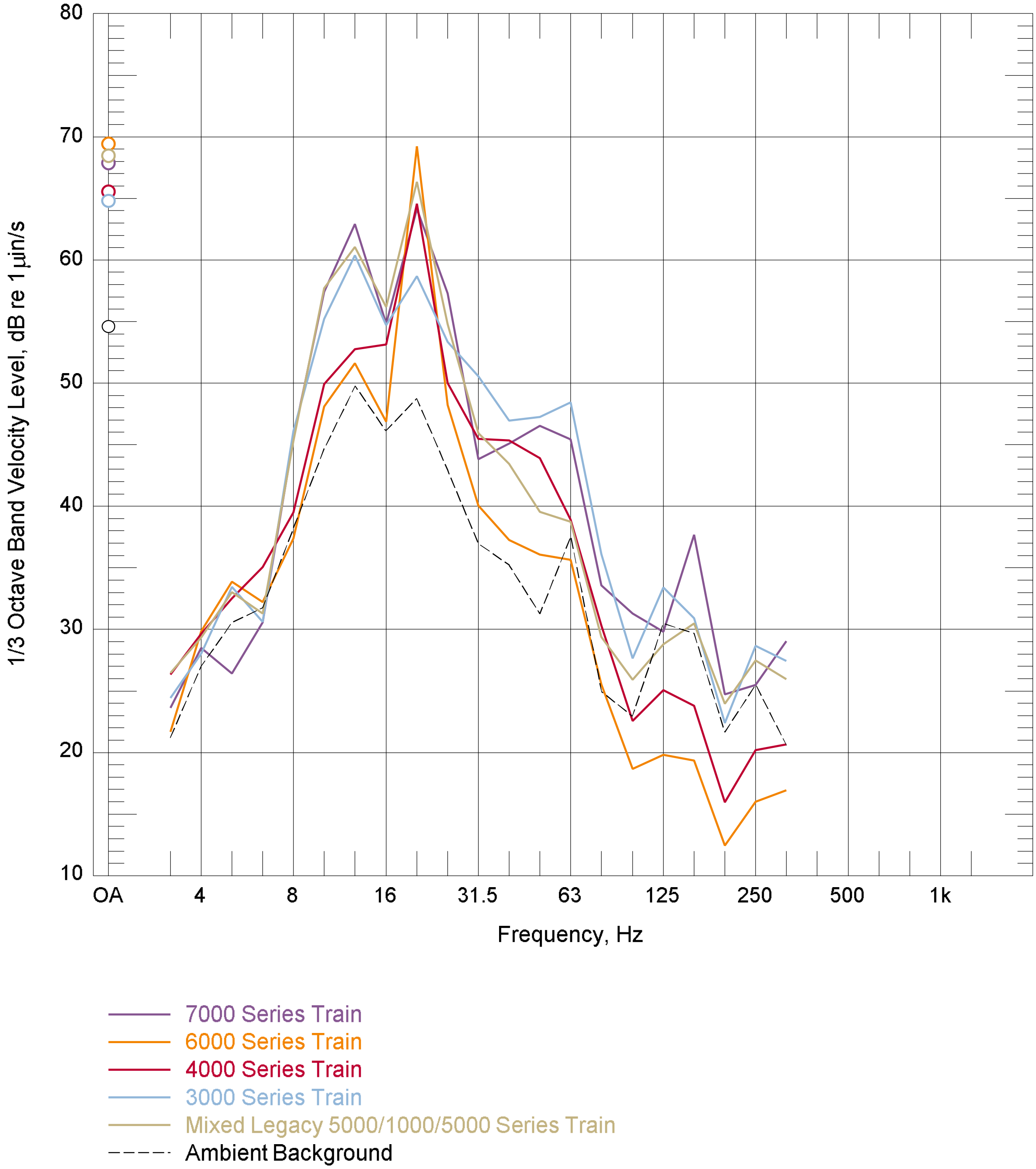


Figure 255: Site 13 at Location V3 Second Floor Bedroom
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

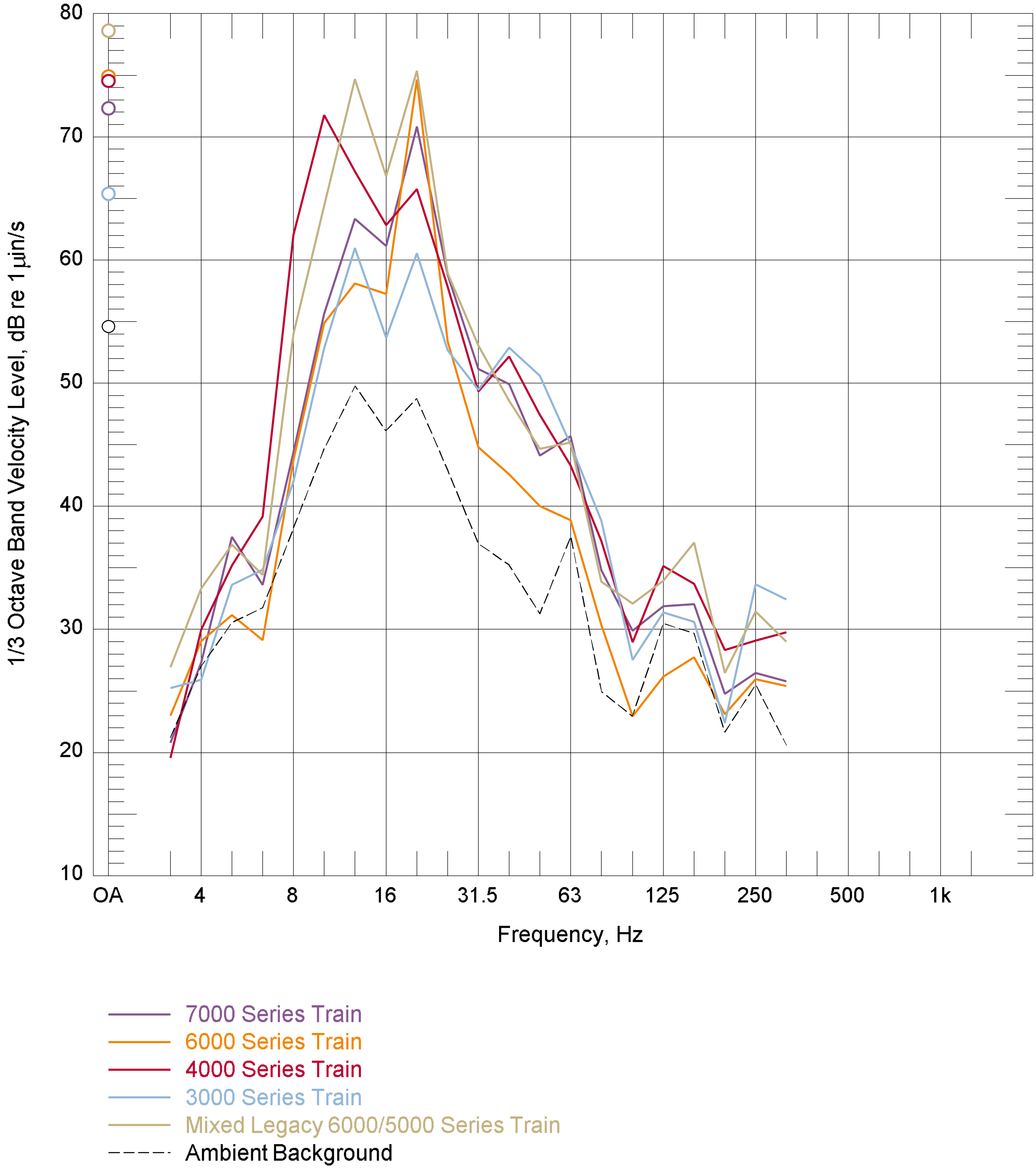


Figure 256: ***Site 13 at Location V3 Second Floor Bedroom***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

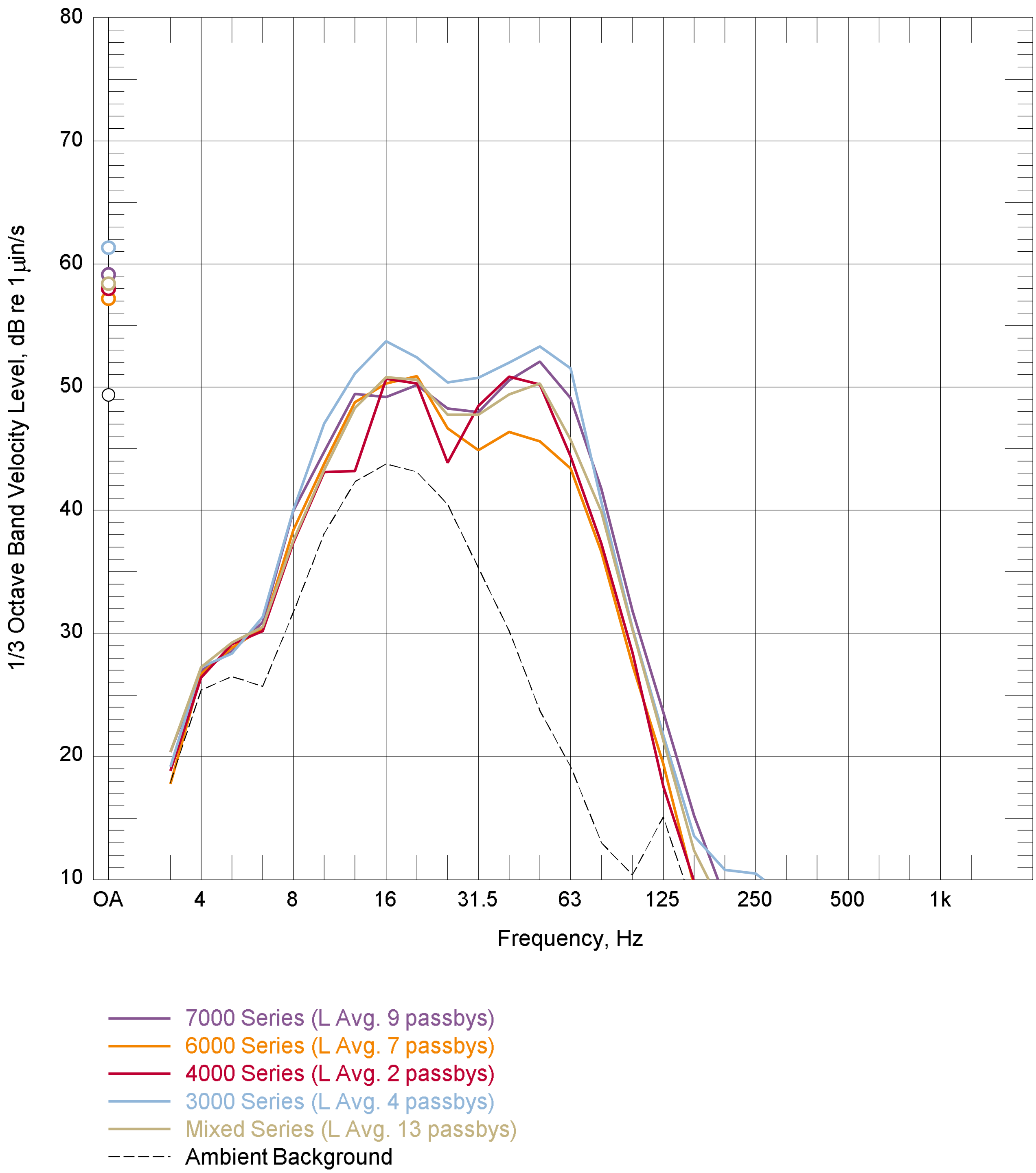


Figure 257: ***Site 13 at Location V4 Outside***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

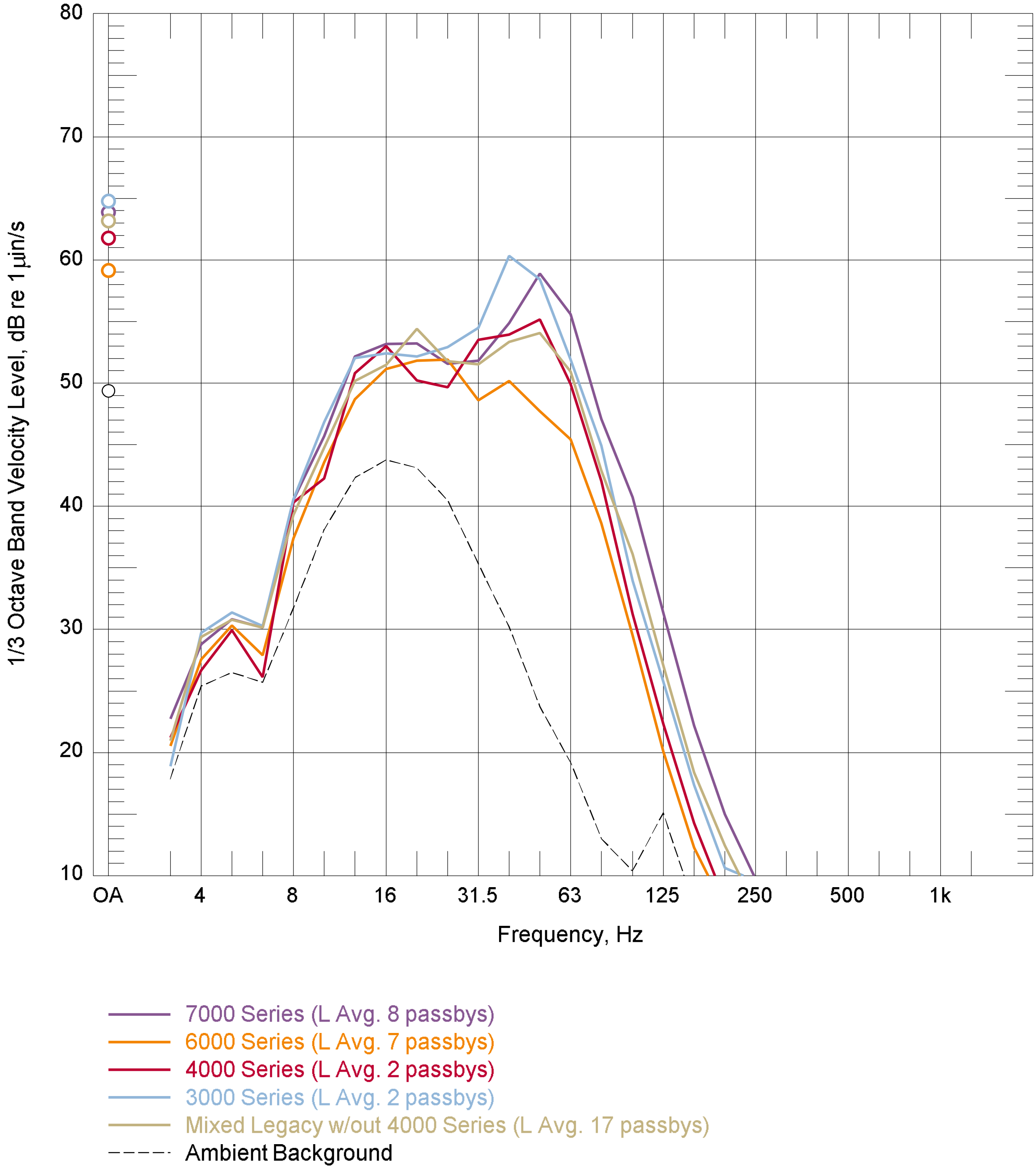


Figure 258: ***Site 13 at Location V4 Outside***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

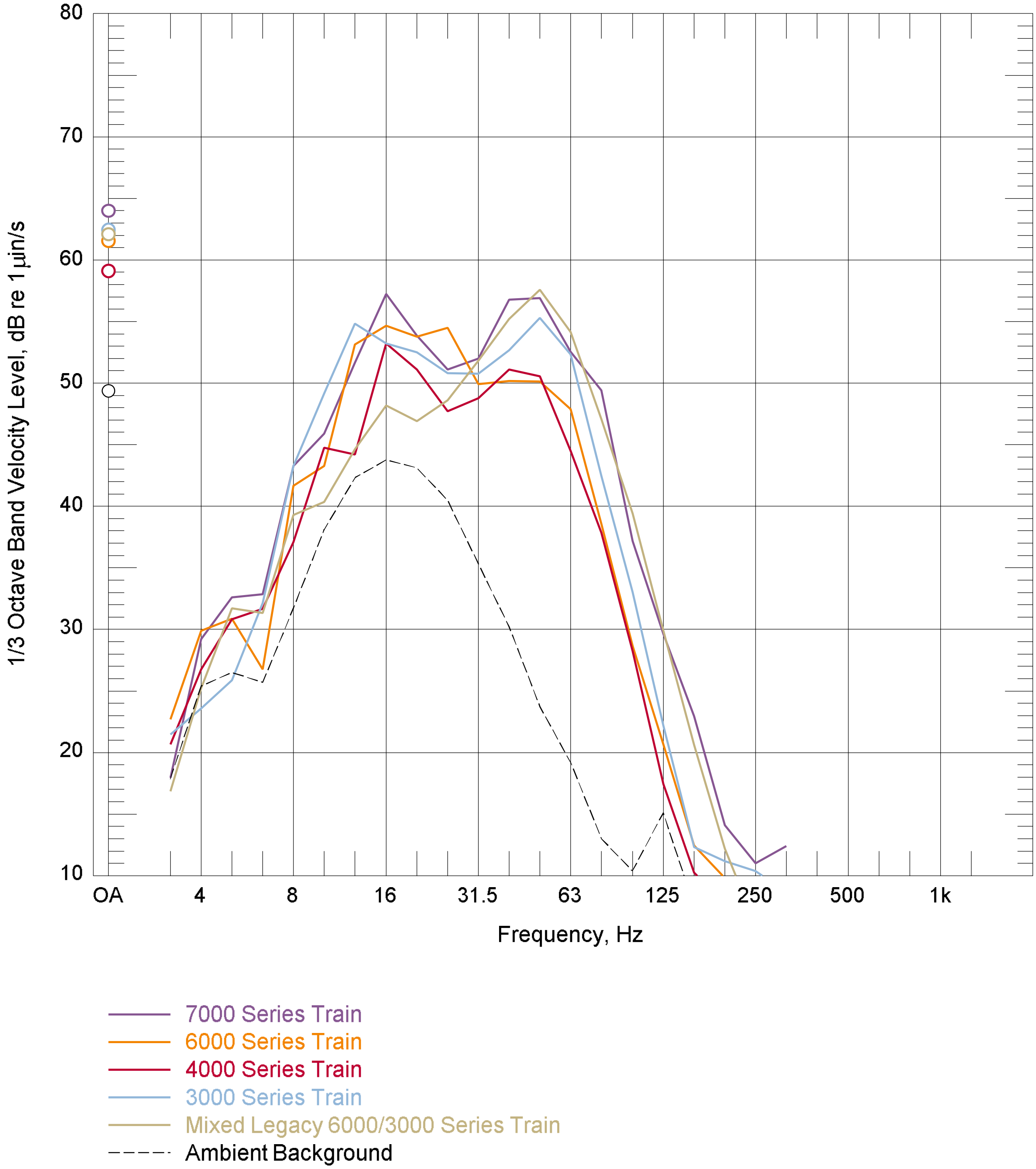


Figure 259: ***Site 13 at Location V4 Outside***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

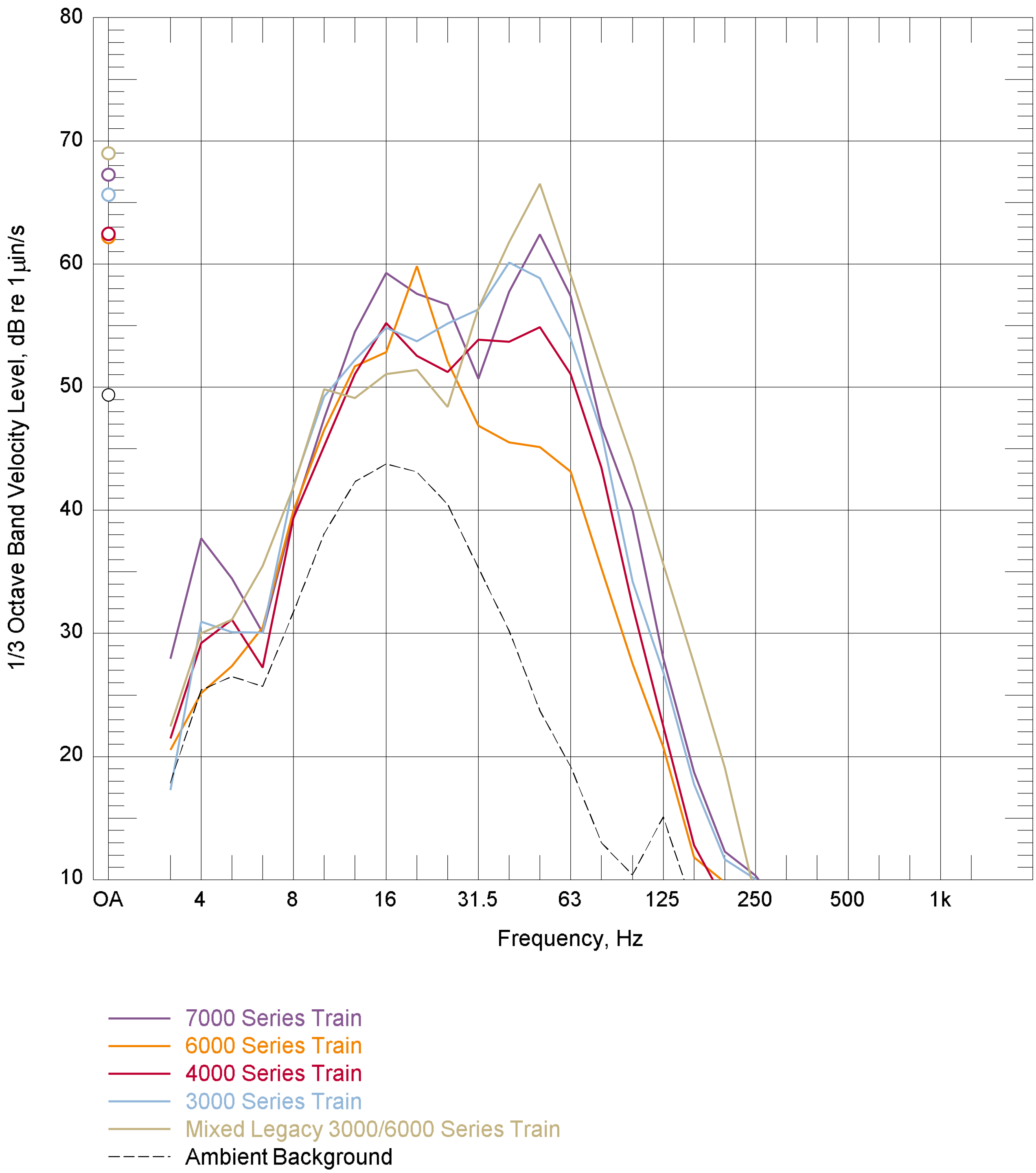


Figure 260: ***Site 13 at Location V4 Outside***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

B.13.6 Passby Ground-borne Noise Spectra and A-weighted Levels

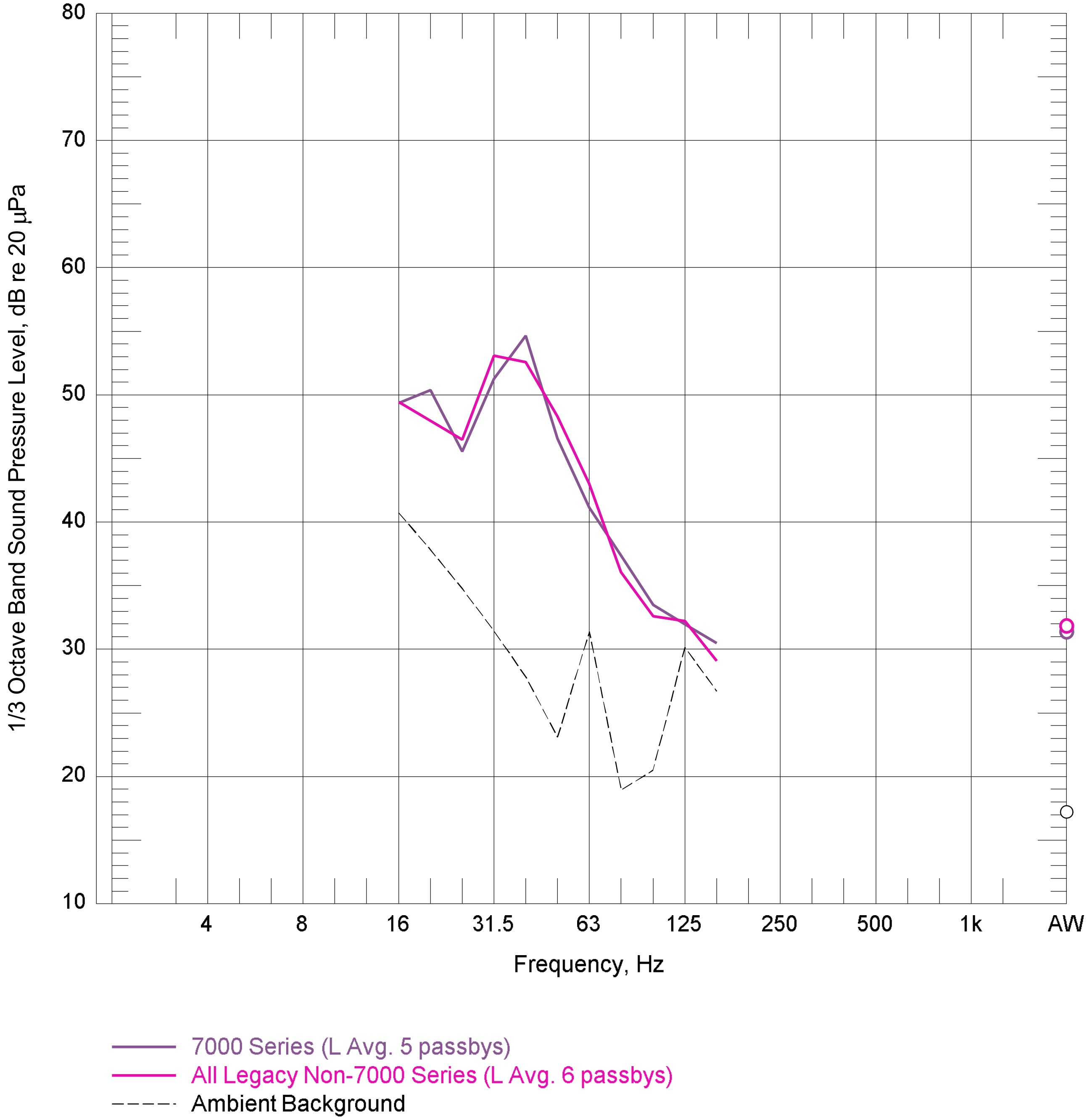


Figure 261: ***Site 13 at Location N1 Basement Family Room***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

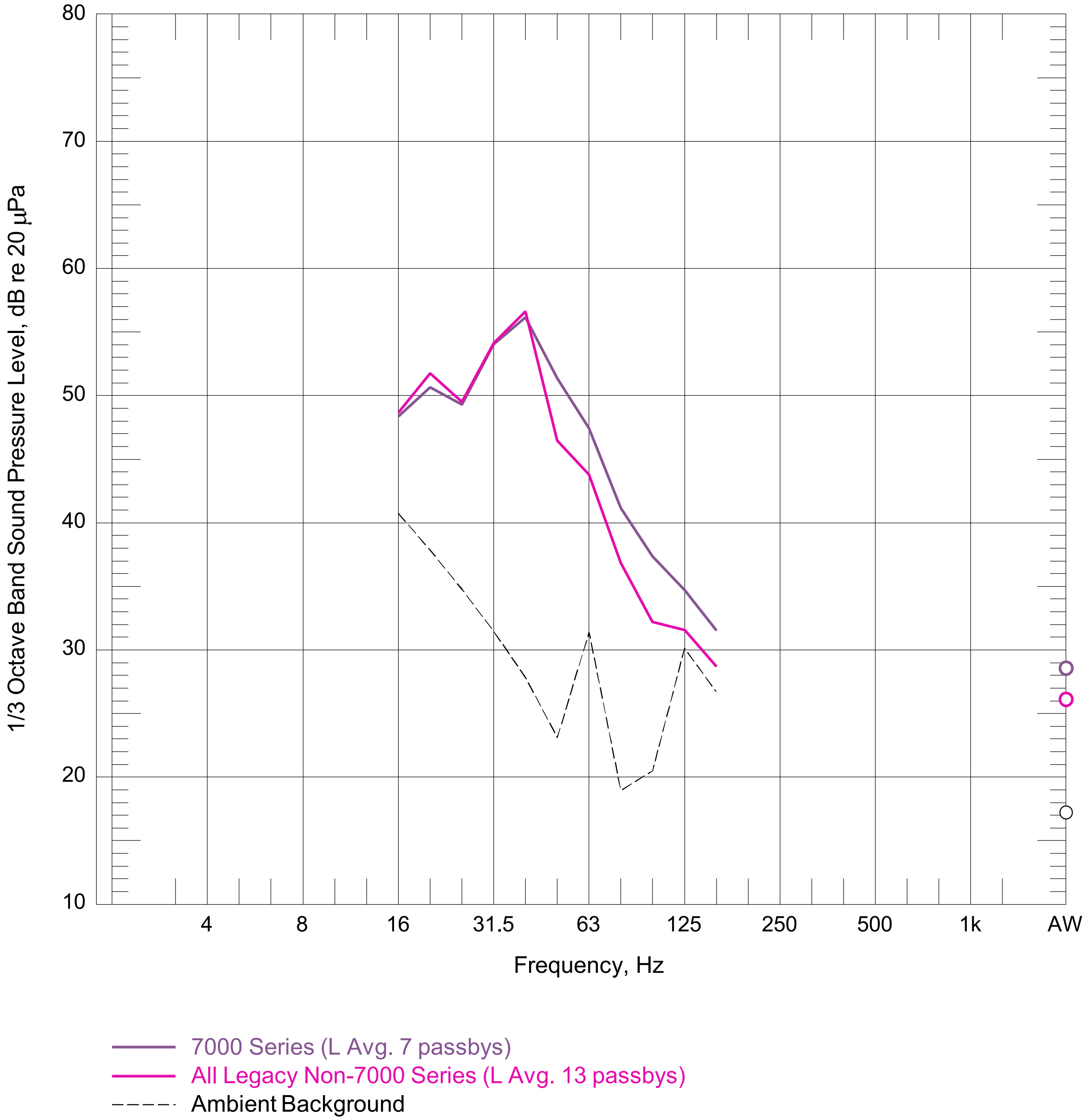


Figure 262: ***Site 13 at Location N1 Basement Family Room***
Outbound Trains on Track 2
Average Noise Levels by Vehicle Type

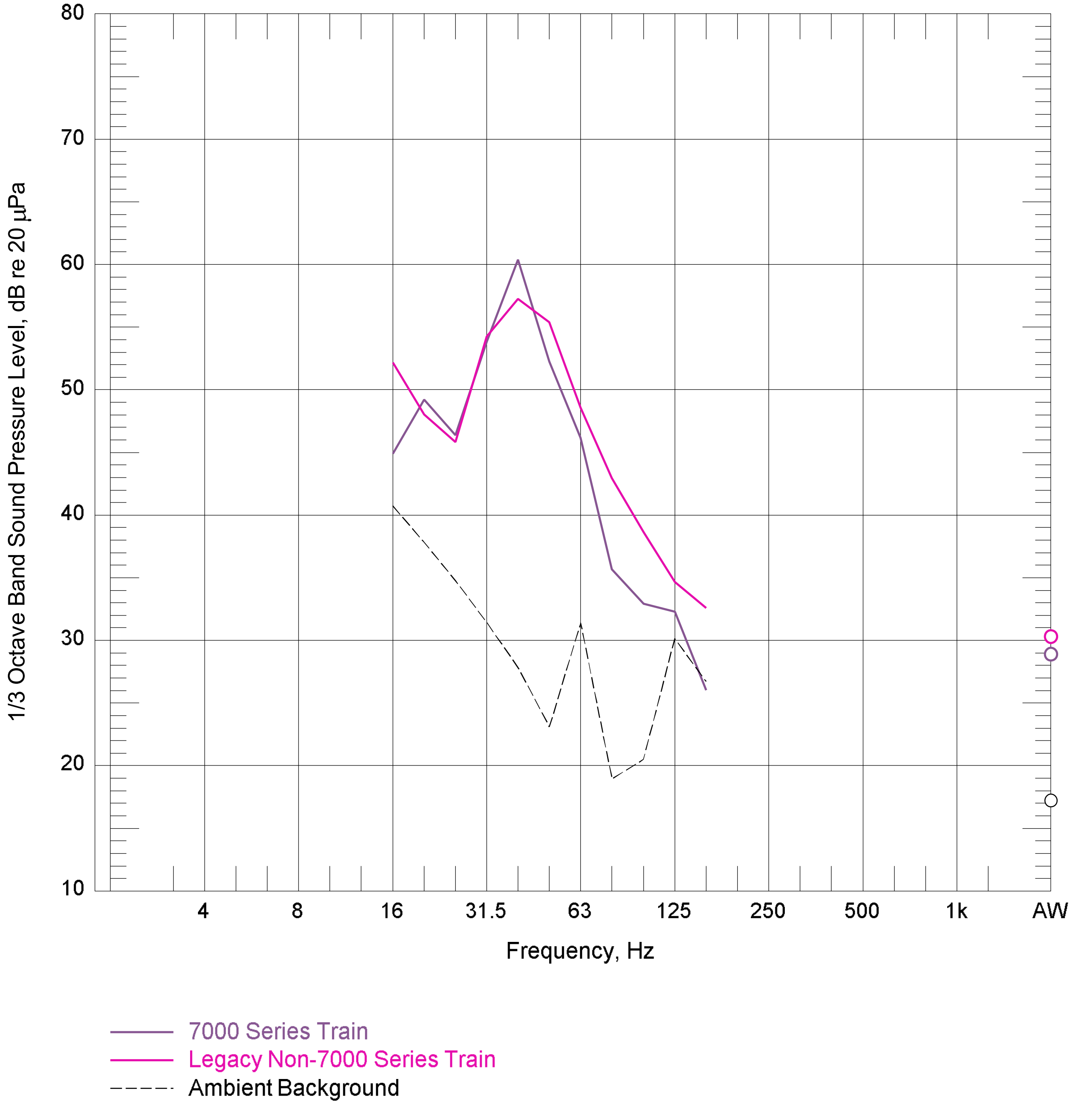


Figure 263: ***Site 13 at Location N1 Basement Family Room***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

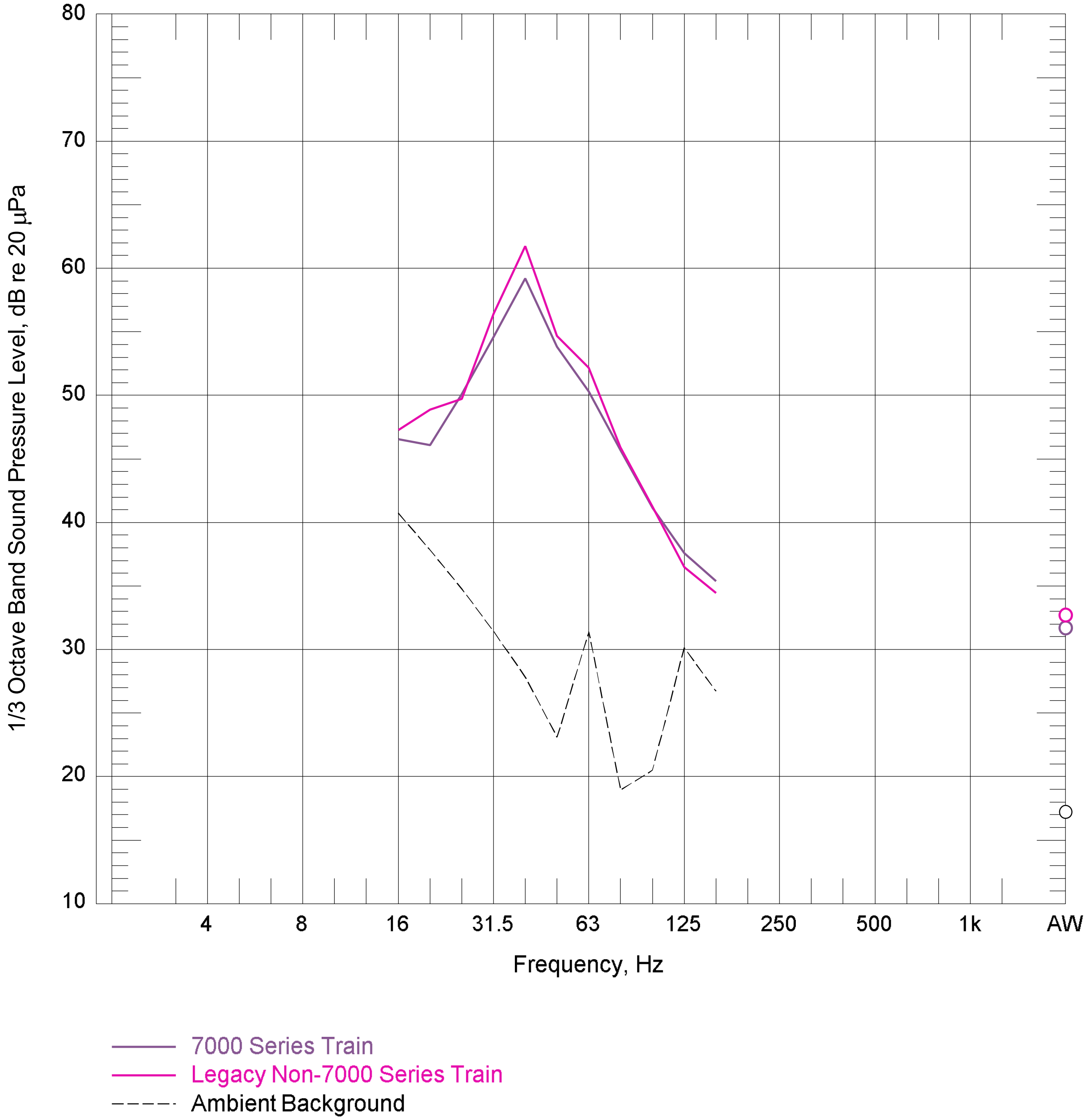


Figure 264: ***Site 13 at Location N1 Basement Family Room***
Outbound Trains on Track 2
Individual Train with Highest A-weighted Level

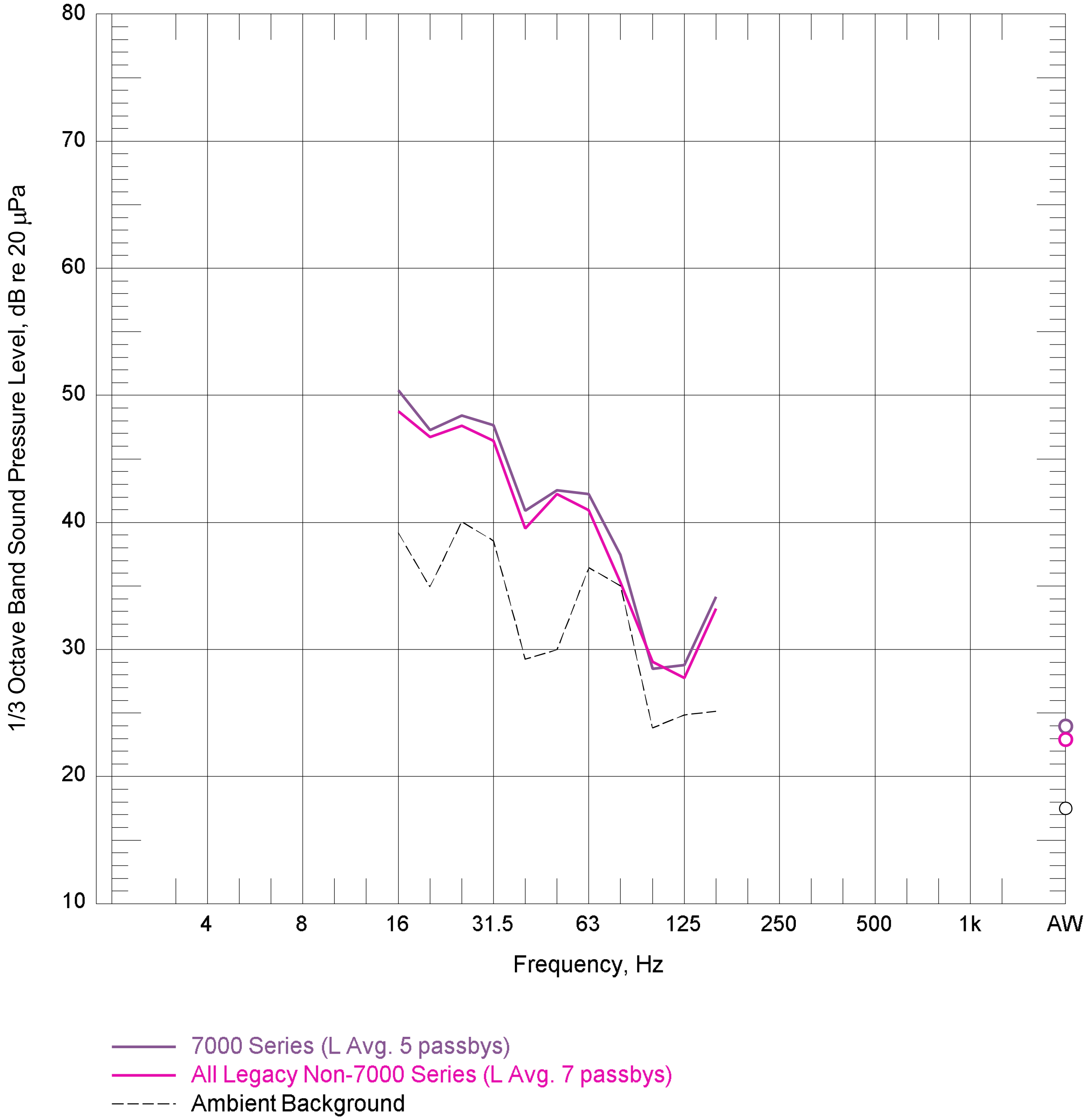


Figure 265: ***Site 13 at Location N2 Second Floor Bedroom***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

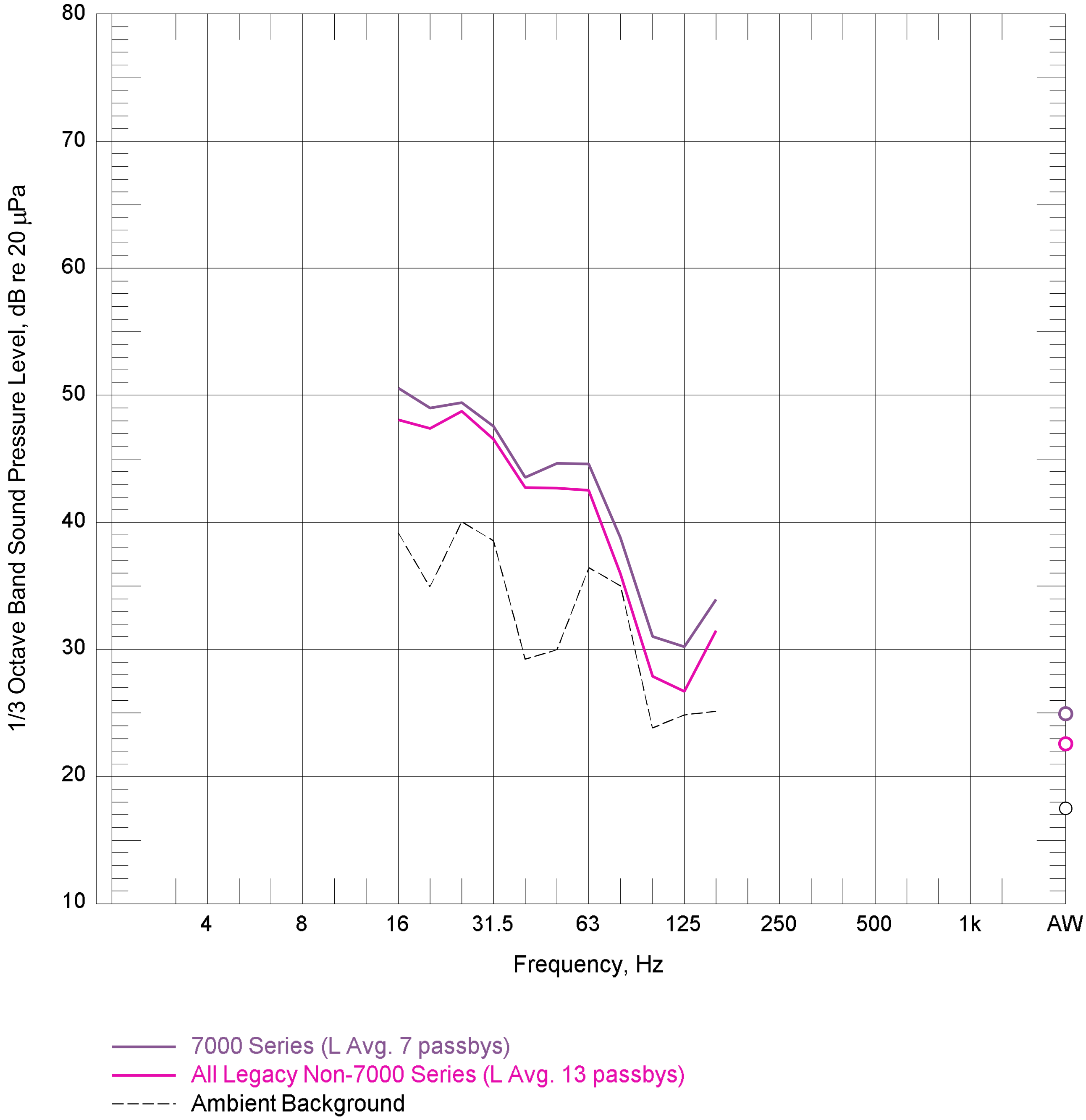


Figure 266: ***Site 13 at Location N2 Second Floor Bedroom***
Outbound Trains on Track 2
Average Noise Levels by Vehicle Type

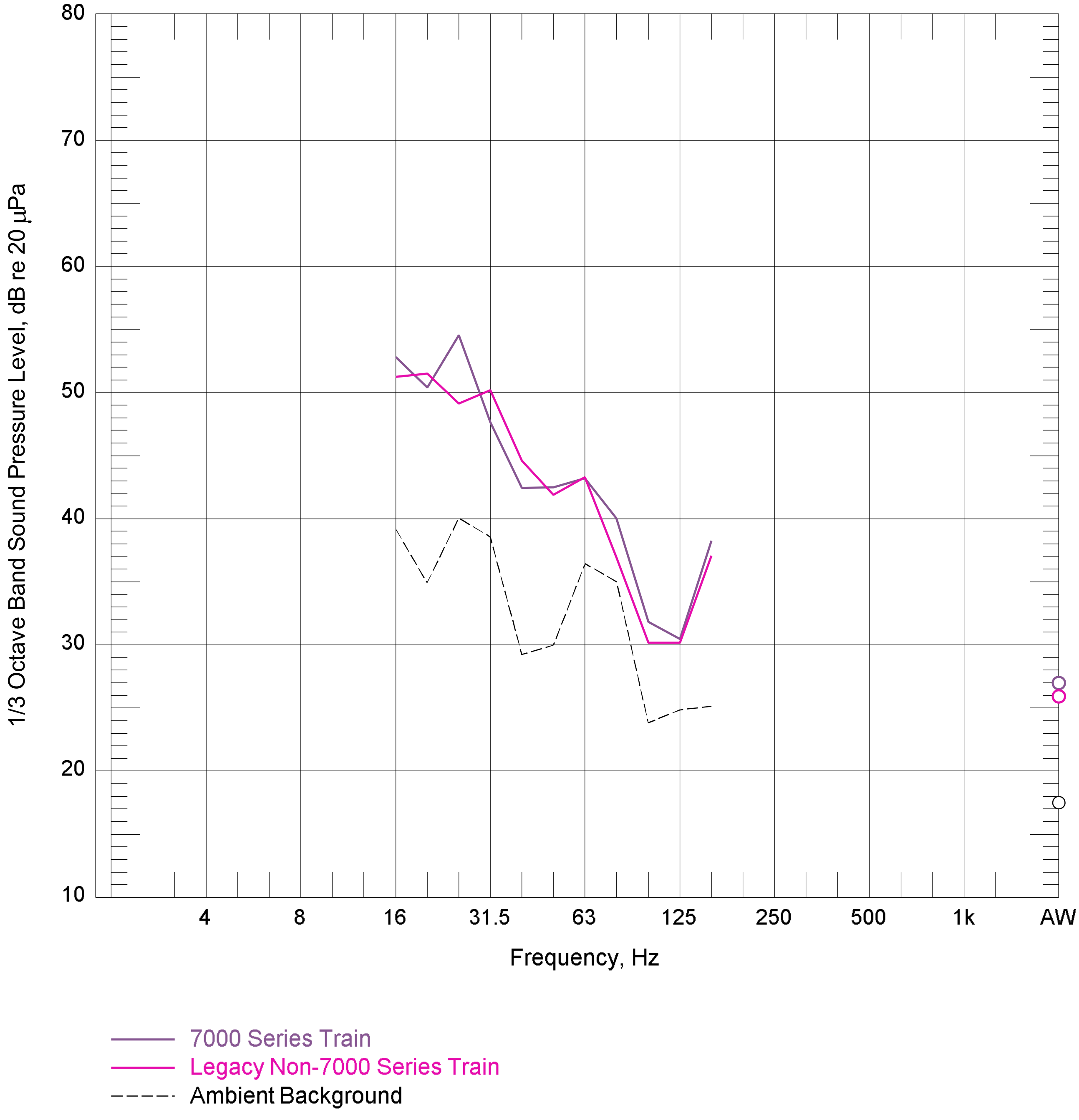


Figure 267: ***Site 13 at Location N2 Second Floor Bedroom***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

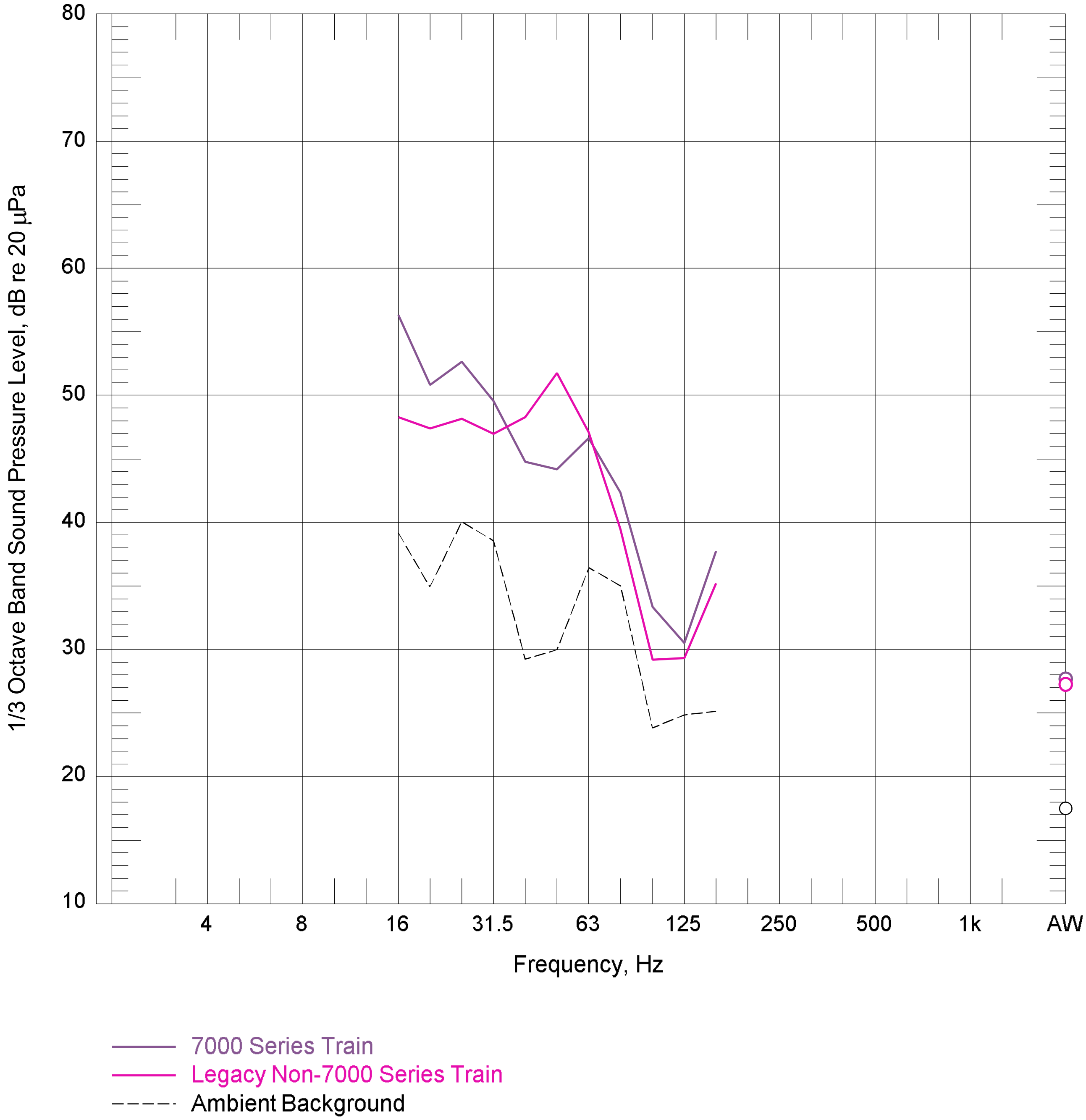


Figure 268: ***Site 13 at Location N2 Second Floor Bedroom***
Outbound Trains on Track 2
Individual Train with Highest A-weighted Level

B.14 Site 14 – Gallatin Street NE & 8th Street NE (Outdoor Only)

B.14.1 Tunnel Notes

Tunnel Structure: Cut and Cover

Track Type: Standard DF, Crossover

T/R Depth: 33 to 46 feet

Measurement Period: Thursday, 1 June 2017, 16:45 to 19:55

Field Observations: Quieter street with less road traffic, some Metro buses along Gallatin. Perceptible vibration on the ground. Trains are audible through vent shaft grates across the street. Accelerometers mounted to sidewalk. Street plate in intersection caused high vibration when buses and trucks rolled over plate.

B.14.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Recorder Channel	Chainage (50 ft)	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)
A1	284+50	114	34	119	93	34	99
A2	285+50	102	33	107	79	33	86
A3	286+00	96	34	102	71	34	79
A4	286+50	97	36	103	70	36	79
B1	287+50	123	46	131	94	46	105
B2	287+50	152	46	159	123	46	131
B3	287+50	197	46	202	168	46	174
B4	287+50	231	46	236	203	46	208

Perp. distance = perpendicular distance to track, not accounting for tunnel depth
T/R depth = top-of-rail depth
Total slant distance = total distance to track, accounting for tunnel depth

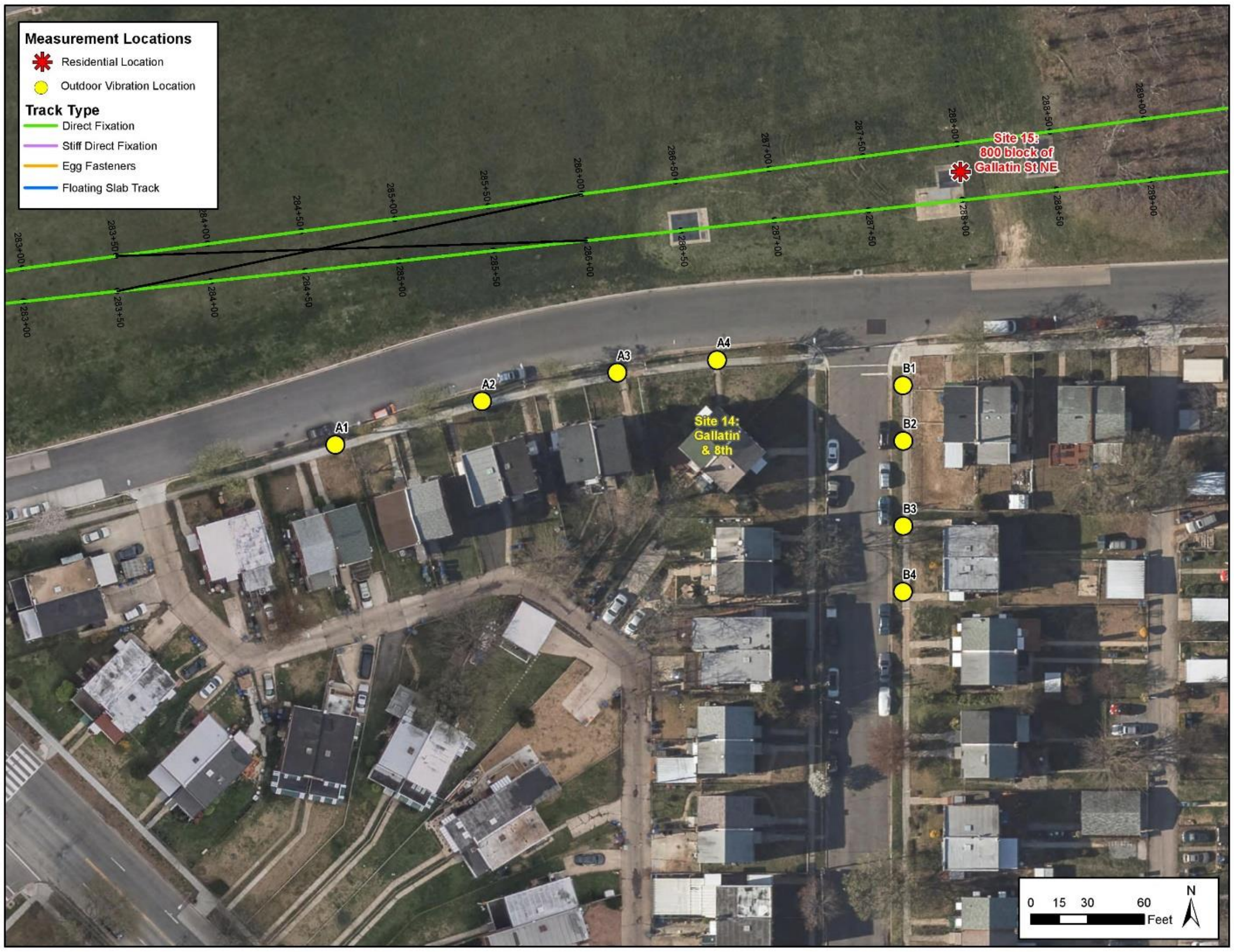


Figure 269: Aerial Map of Site 14 Measurement Positions (nearby Site 15 exterior positions also shown)

B.14.3 Overall Level vs Distance Plot

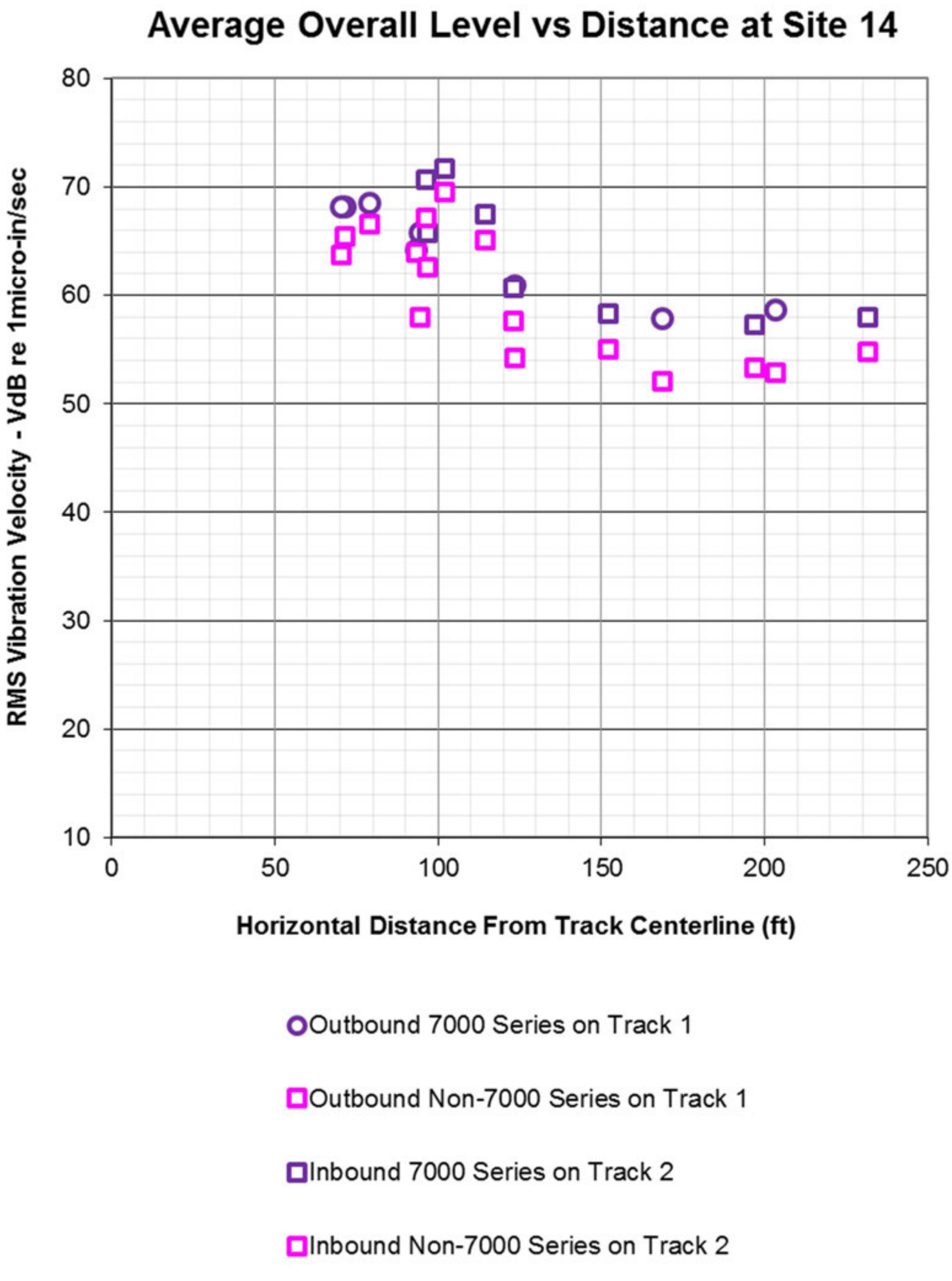


Figure 270: Site 14 Average Overall Level vs Distance

B.15 Site 15 – 800 block of Gallatin Street NE (Residence)

B.15.1 Building and Tunnel Notes

Location: Outbound Track 1 side at 288+00

Building Notes: Single-family residential, detached duplex building, brick wood frame, renovated

Tunnel Structure: Tunnel

Track Type: Direct Fixation Fasteners

T/R Depth: 42 feet

Train Speed: 31 to 59 mph

Measurement Period: Wednesday, 16 August 2017, 17:00 to 20:15

Field Observations: street plate at intersection of Gallatin and 8th, central air conditioning and other interior mechanical sources interfere at times

B.15.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Sensor[a,b,c]	Location / Room Occupancy	Horizontal Distance[d] (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)	Horizontal Distance (feet)	T/R Depth[e] (feet)	Total Slant Distance to T/R[f] (feet)
V1	Outside House	127	42	134	97	42	106
Triaxial Geophone	Basement	126	42	133	97	42	106
V2							
N1							
V3	First Floor Living Room						
N2							
V4	Second Floor Bedroom						
N3							

Notes:

a) Tri-axial geophone mounted on floor, logging peak particle velocity

b) V# vibration locations with accelerometer mounted on floor in vertical direction

c) N# noise locations with microphone/sound level meter mounted on tripod 48 inches above floor

d) Horizontal distance from track to building façade for indoor locations, not accounting for tunnel depth.

e) T/R depth = top-of-rail depth

f) Total slant distance to T/R = total distance from building to track, accounting for tunnel depth

Figure 271: Aerial Map of 800 block of Gallatin Street NE Residence and Exterior Measurement Location V1 at Site 15 (nearby Site 14 exterior positions also shown)

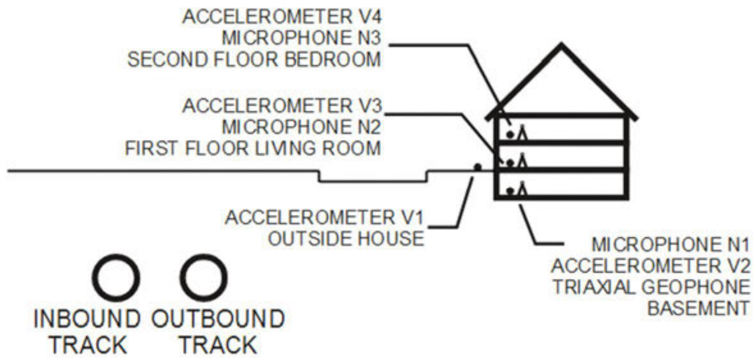


Figure 272: Cross-section Sketch (not to scale) of 800 block of Gallatin Street NE Residence Measurement Locations

B.15.3 GBNV Assessment Summary

SITE 15	800 block of GALLATIN STREET NE – ATTENDED PASSBY MEASUREMENT GBNV ASSESSMENT		
	Ground-borne Vibration (GBV)	**>70 VdB?**	**Notes**
	7000 Series - Average of Multiple Passbys*	NO	
	6000 Series - Average of Multiple Passbys	NO	
	5000* Series - Single Passby	NO	Track 2 only
	Mixed Legacy without 4000 Series - Average of Multiple Passbys	NO	
	Ground-borne Noise (GBN)	**>35 dBA?**	**Notes**
	7000 Series - Single Passby	NO	
	6000 Series - Average of Multiple Passbys	NO	
	Mixed Legacy without 4000 Series	NO	
	7000 Series - Individual Train with Highest A-weighting	NO	
	6000 Series - Individual Train with Highest A-weighting	NO	

B.15.4 PPV Results

SITE 15	800 block of GALLATIN STREET NE – POTENTIAL FOR BUILDING VIBRATION DAMAGE ASSESSMENT						
	>0.2 in/sec PPV in any direction?	Average PPV (in/s)			PPV Range (in/s)		
		Tran	Vert	Long	Tran	Vert	Long
	NO	0.003	0.0029	0.002	0.002 - 0.008	0.002 - 0.014	0.002 - 0.007
Basement 8-Jun-17, 5:19:12 PM to 8:33:06 PM							

B.15.5 Passby Vibration Spectra and Overall Levels

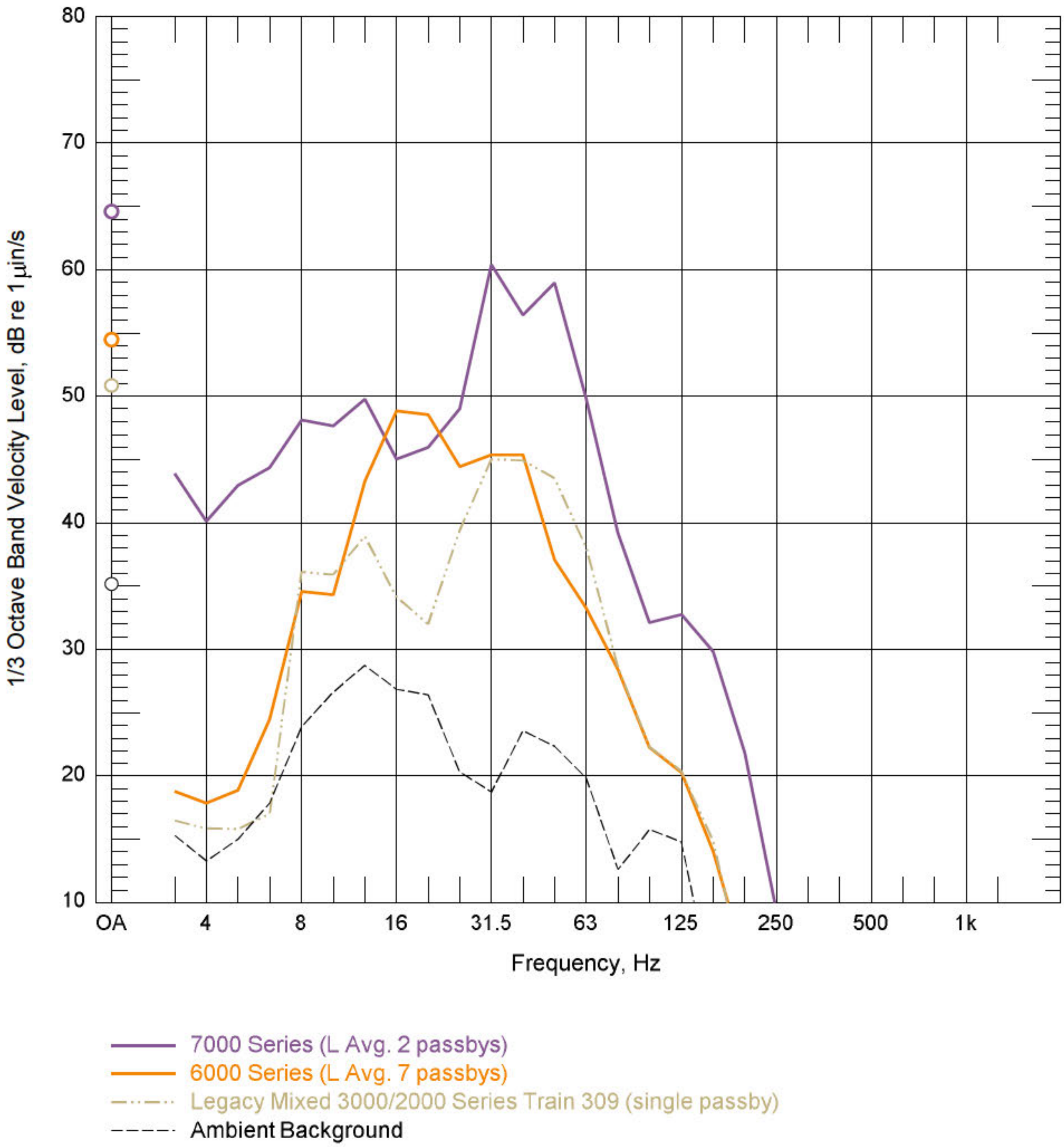


Figure 273: ***Site 15 at Location V1 Outside***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

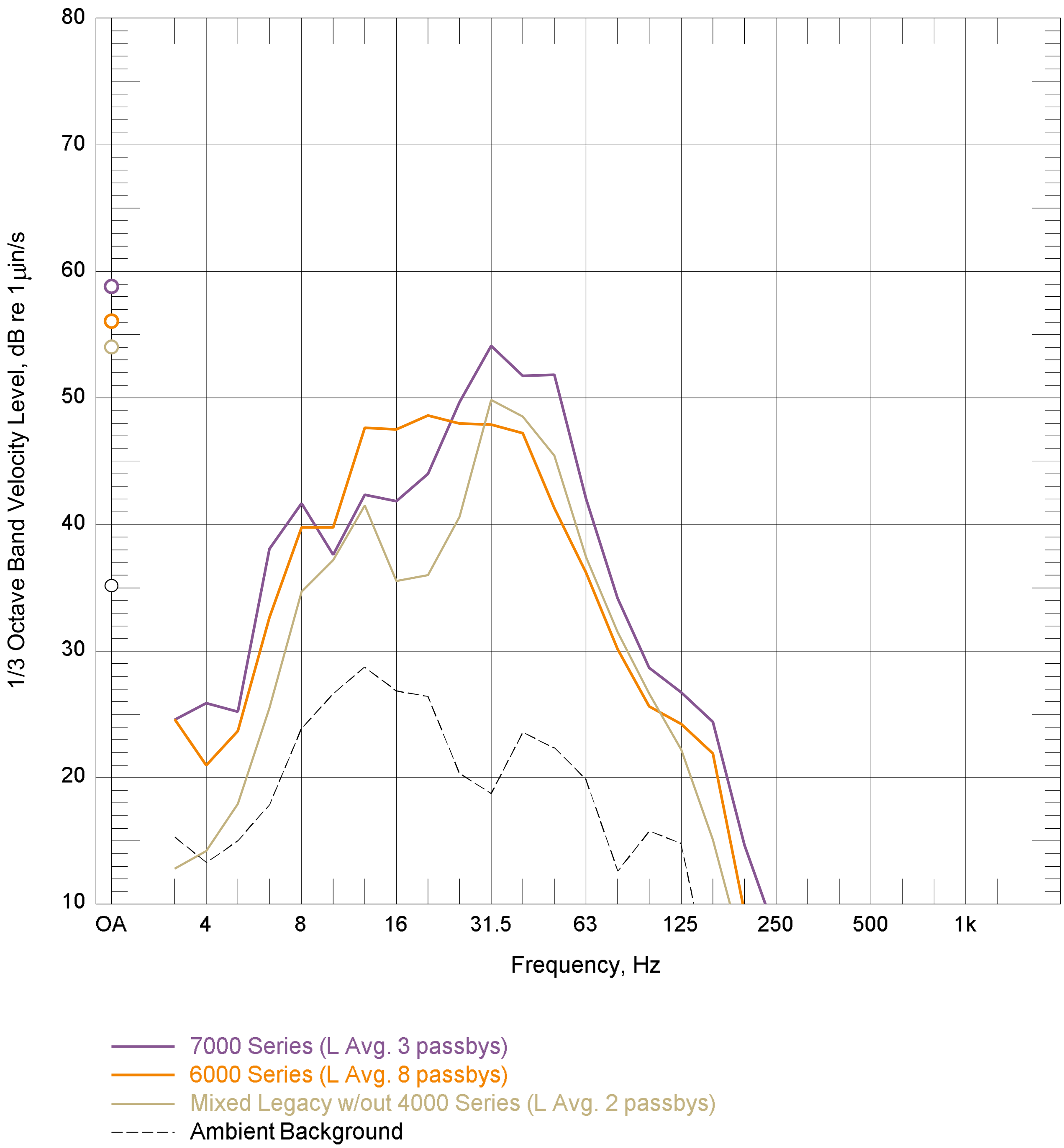


Figure 274: ***Site 15 at Location V1 Outside***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

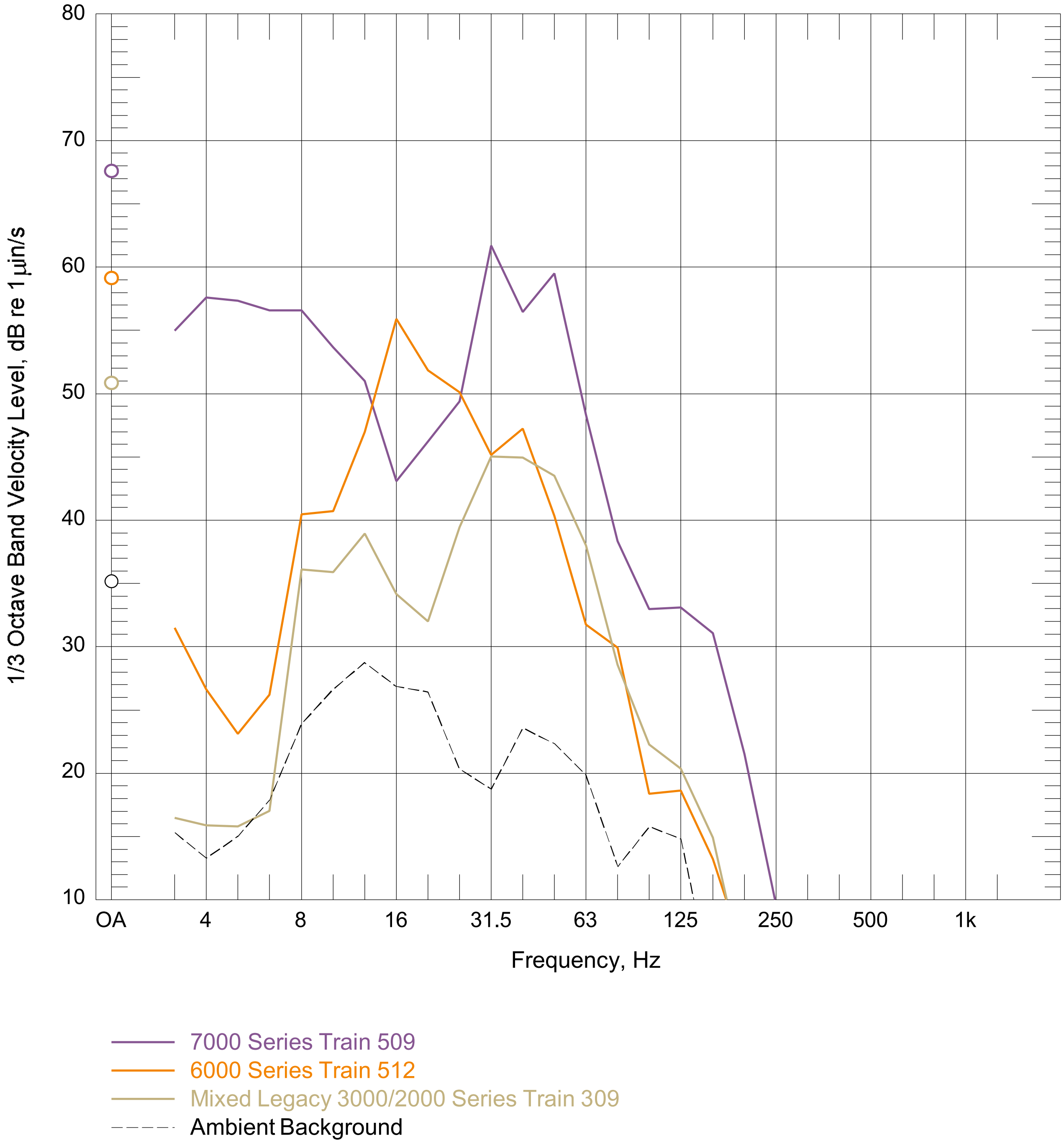


Figure 275: ***Site 15 at Location V1 Outside***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

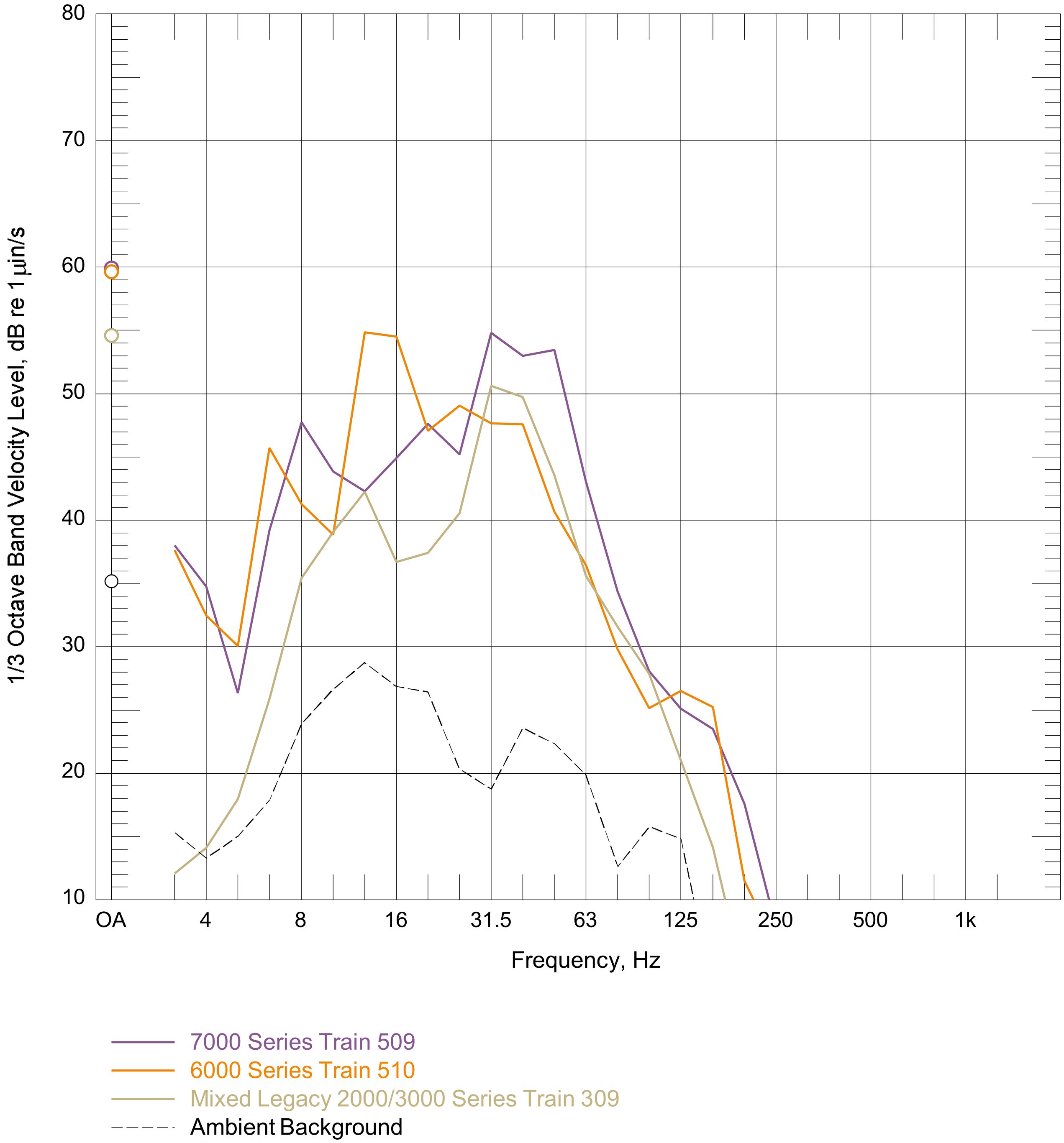


Figure 276: ***Site 15 at Location V1 Outside***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

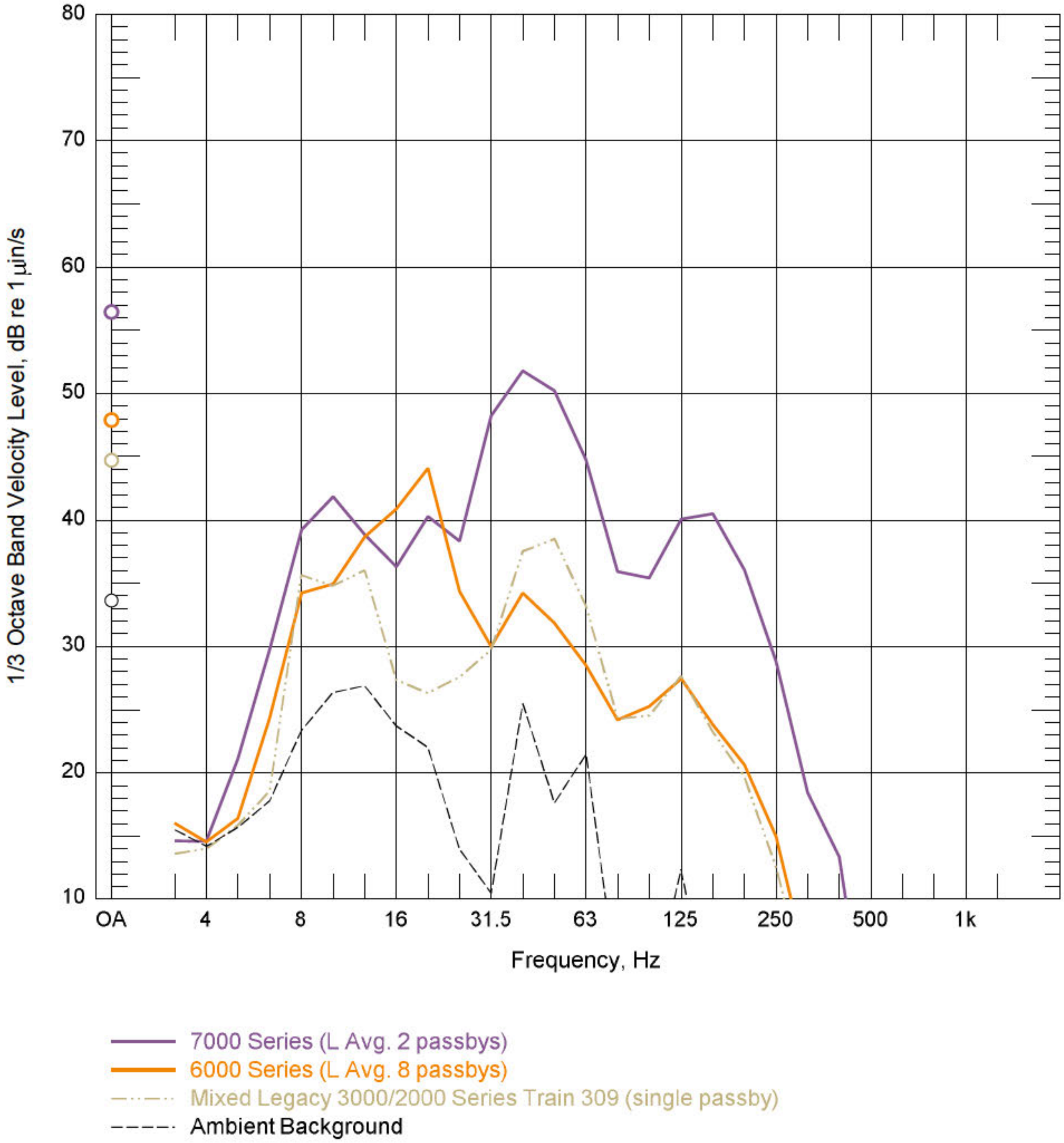


Figure 277: ***Site 15 at Location V2 Basement***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

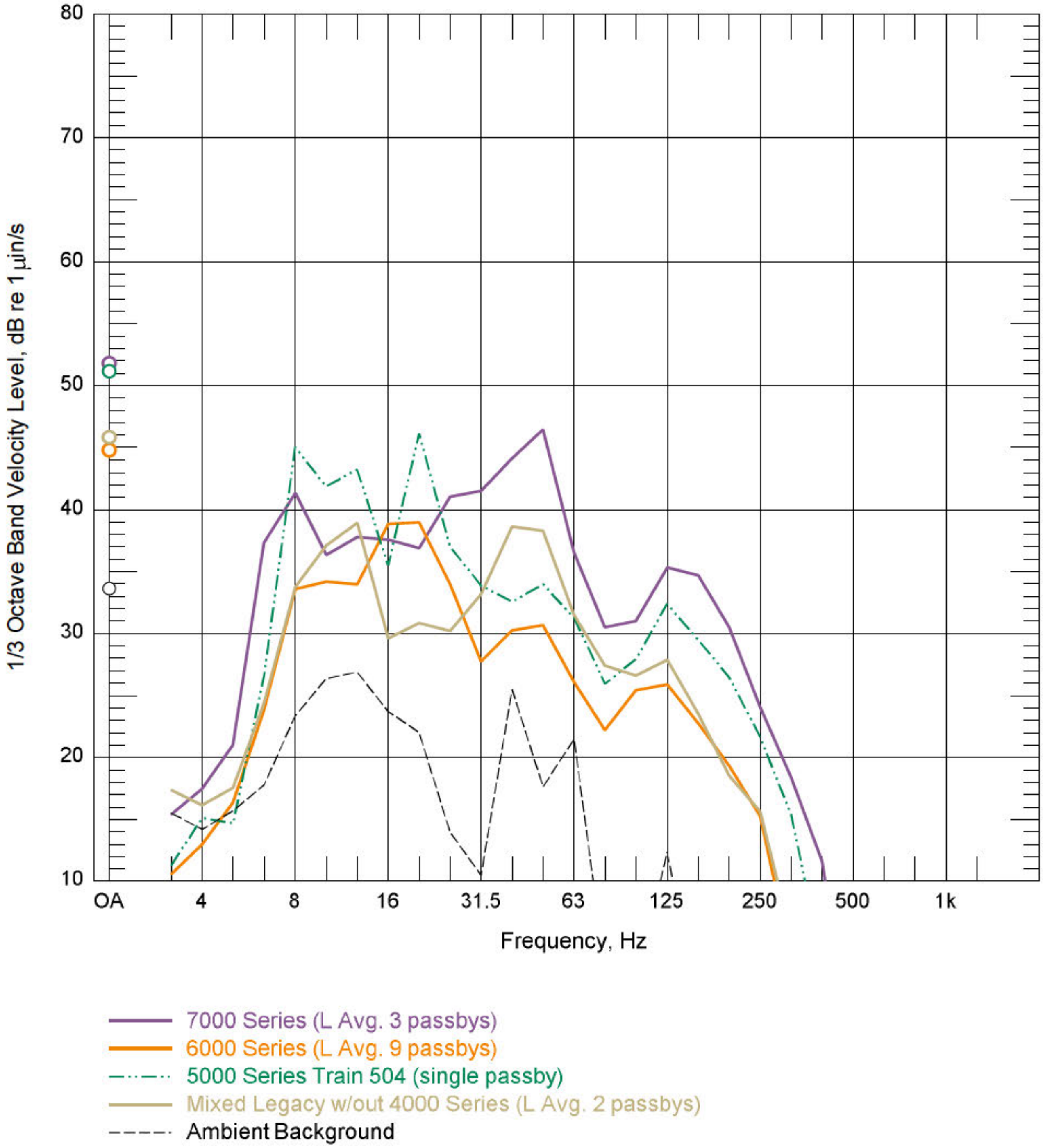


Figure 278: ***Site 15 at Location V2 Basement***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

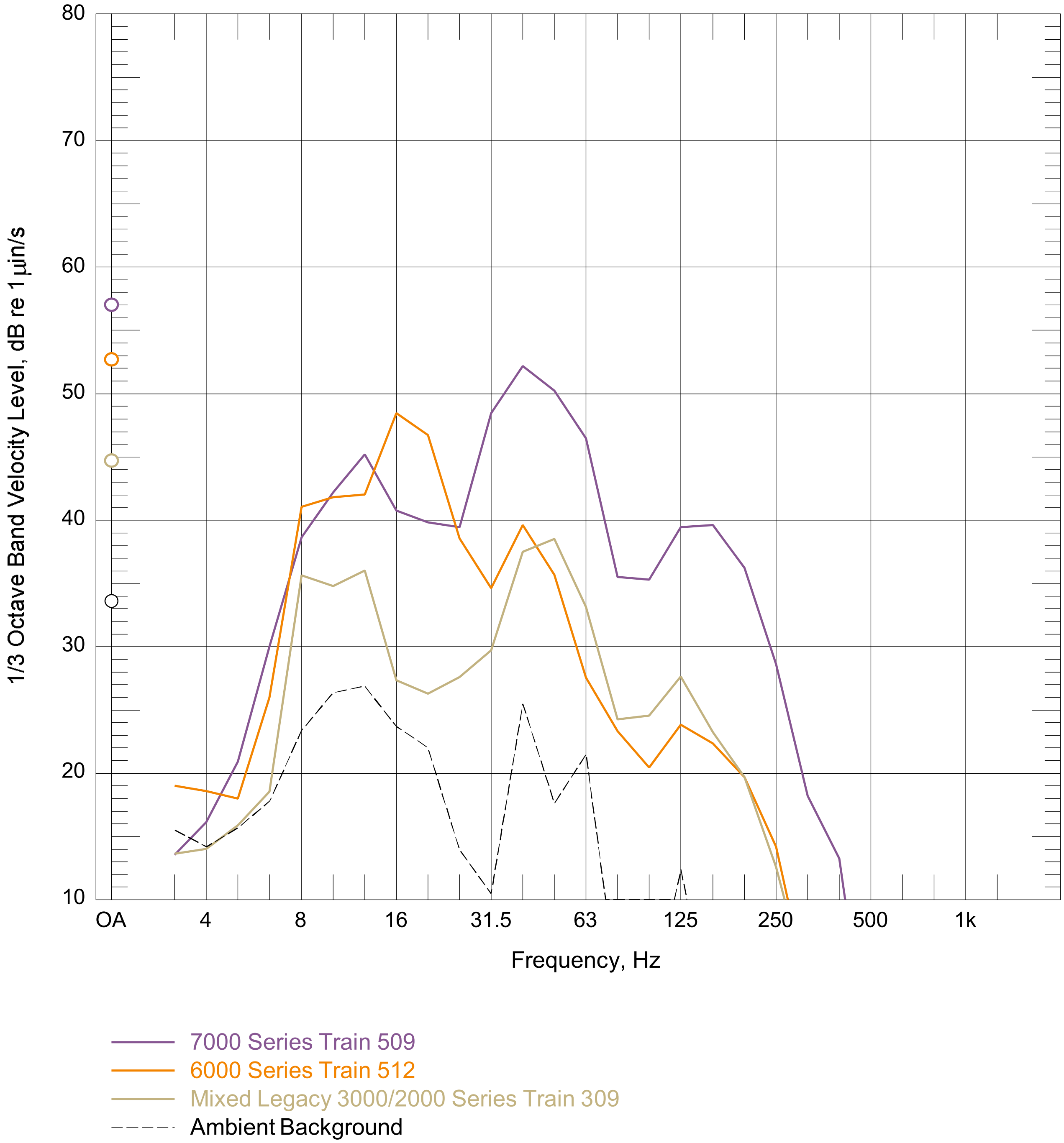


Figure 279: ***Site 15 at Location V2 Basement***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

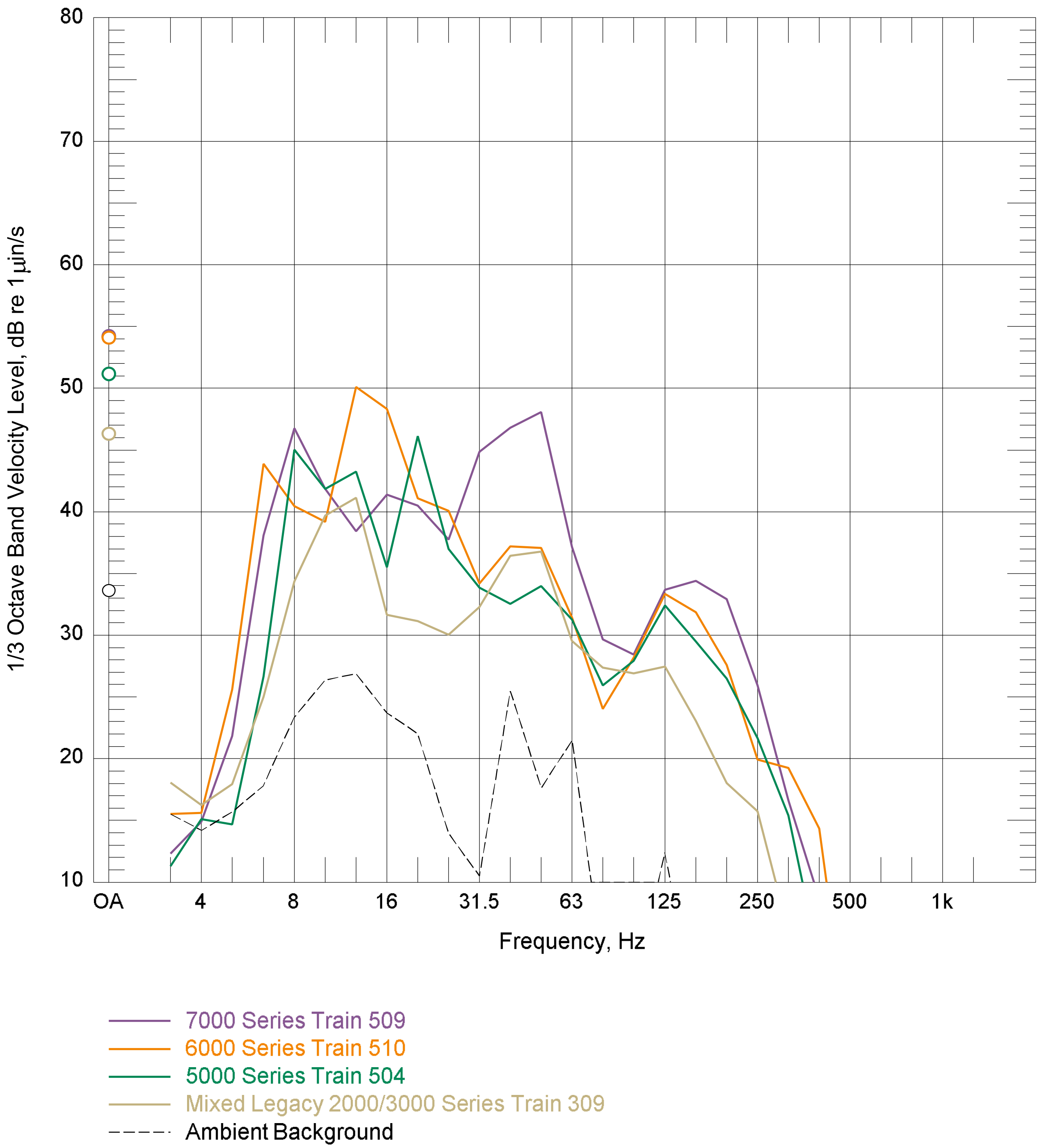


Figure 280: ***Site 15 at Location V2 Basement***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

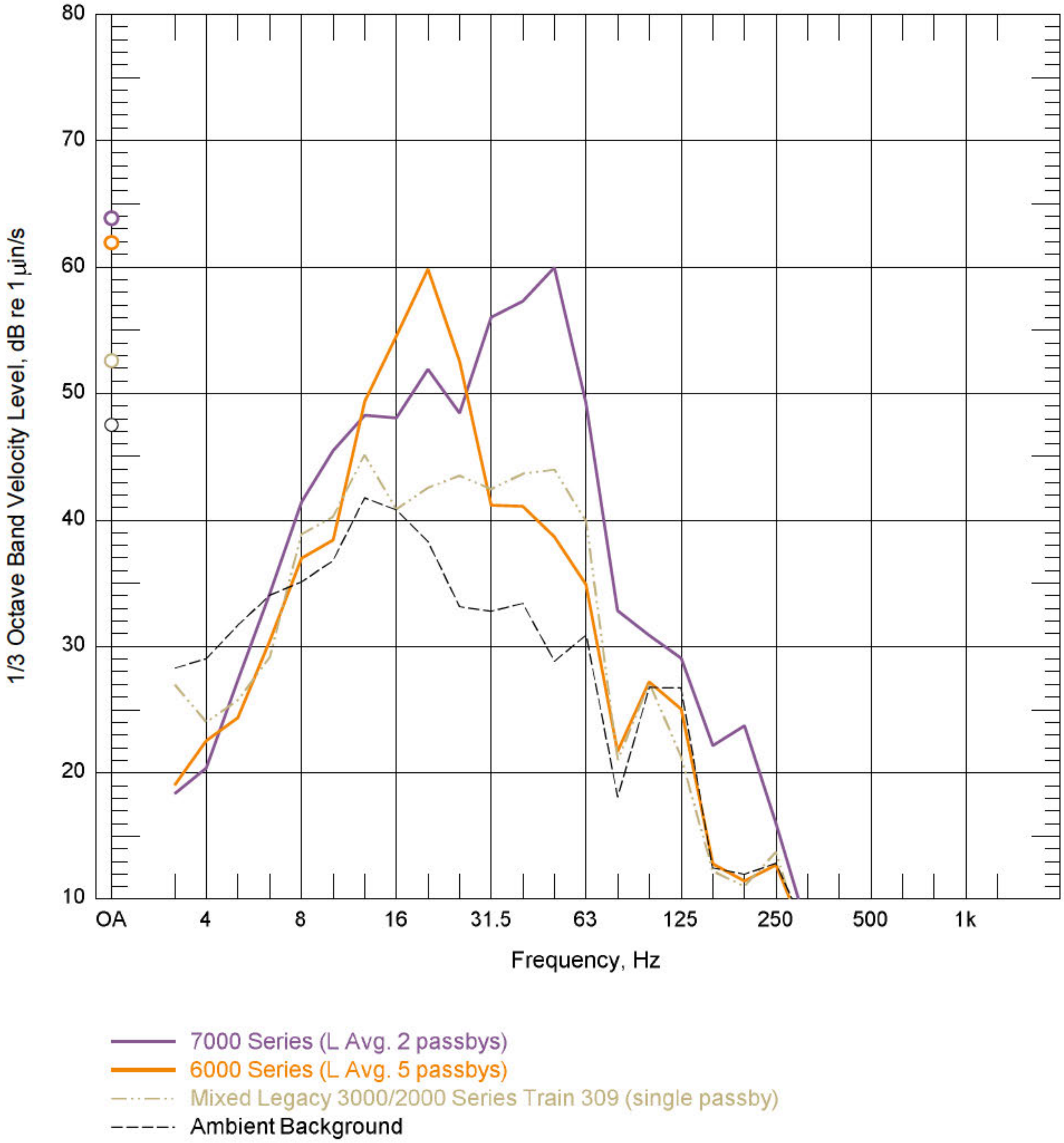


Figure 281: ***Site 15 at Location V3 First Floor Living Room***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

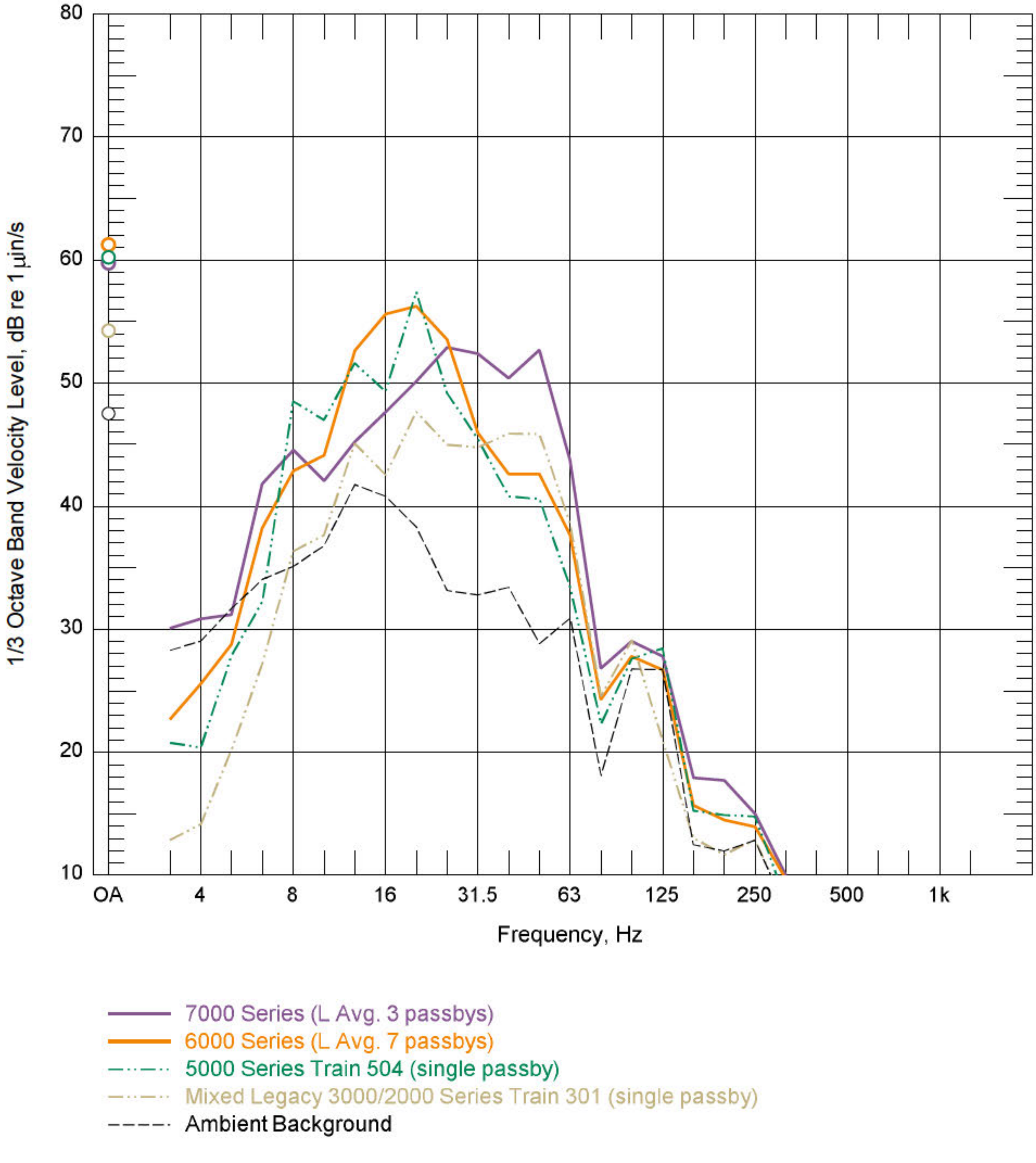


Figure 282: ***Site 15 at Location V3 First Floor Living Room***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

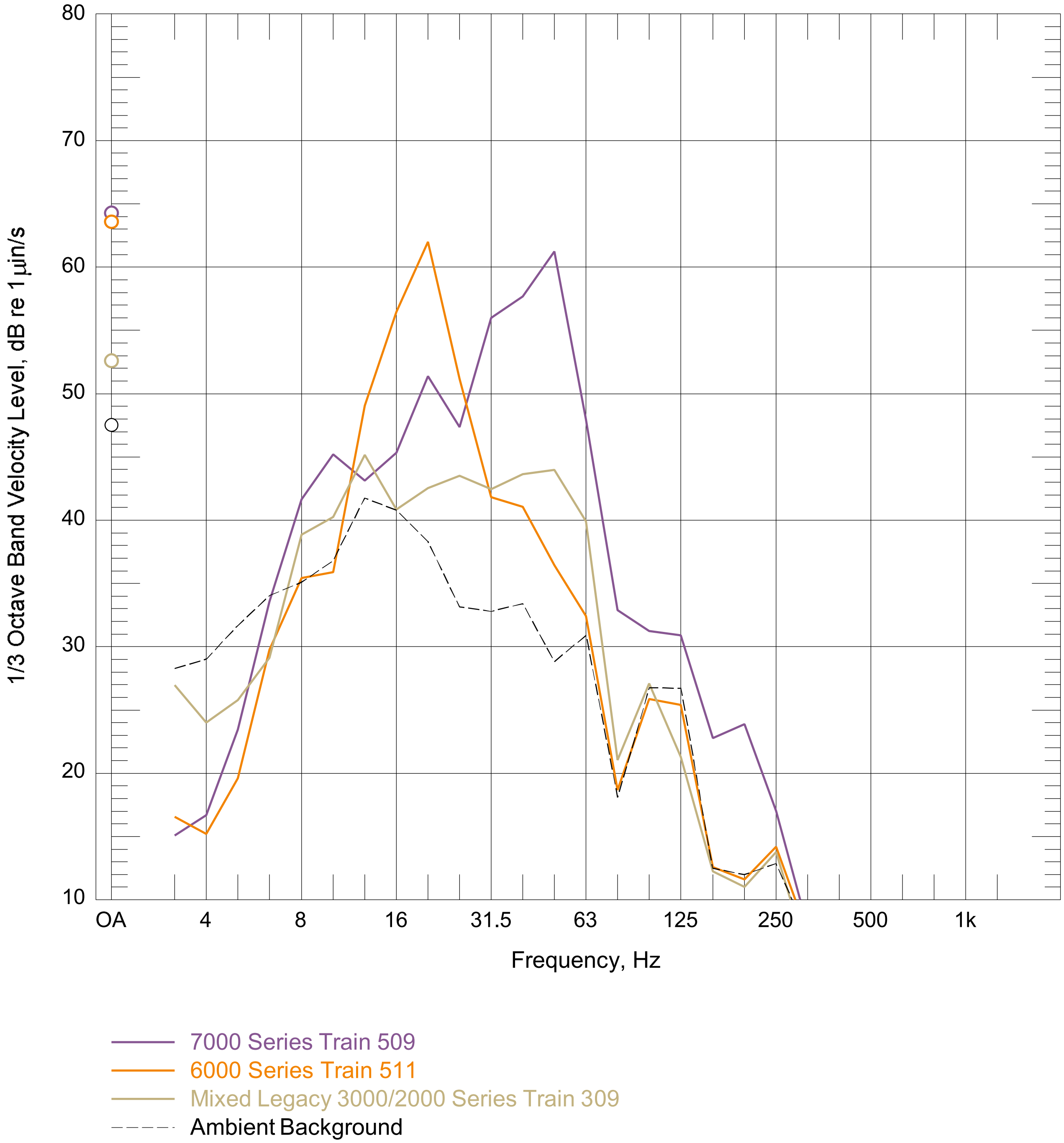


Figure 283: ***Site 15 at Location V3 First Floor Living Room***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

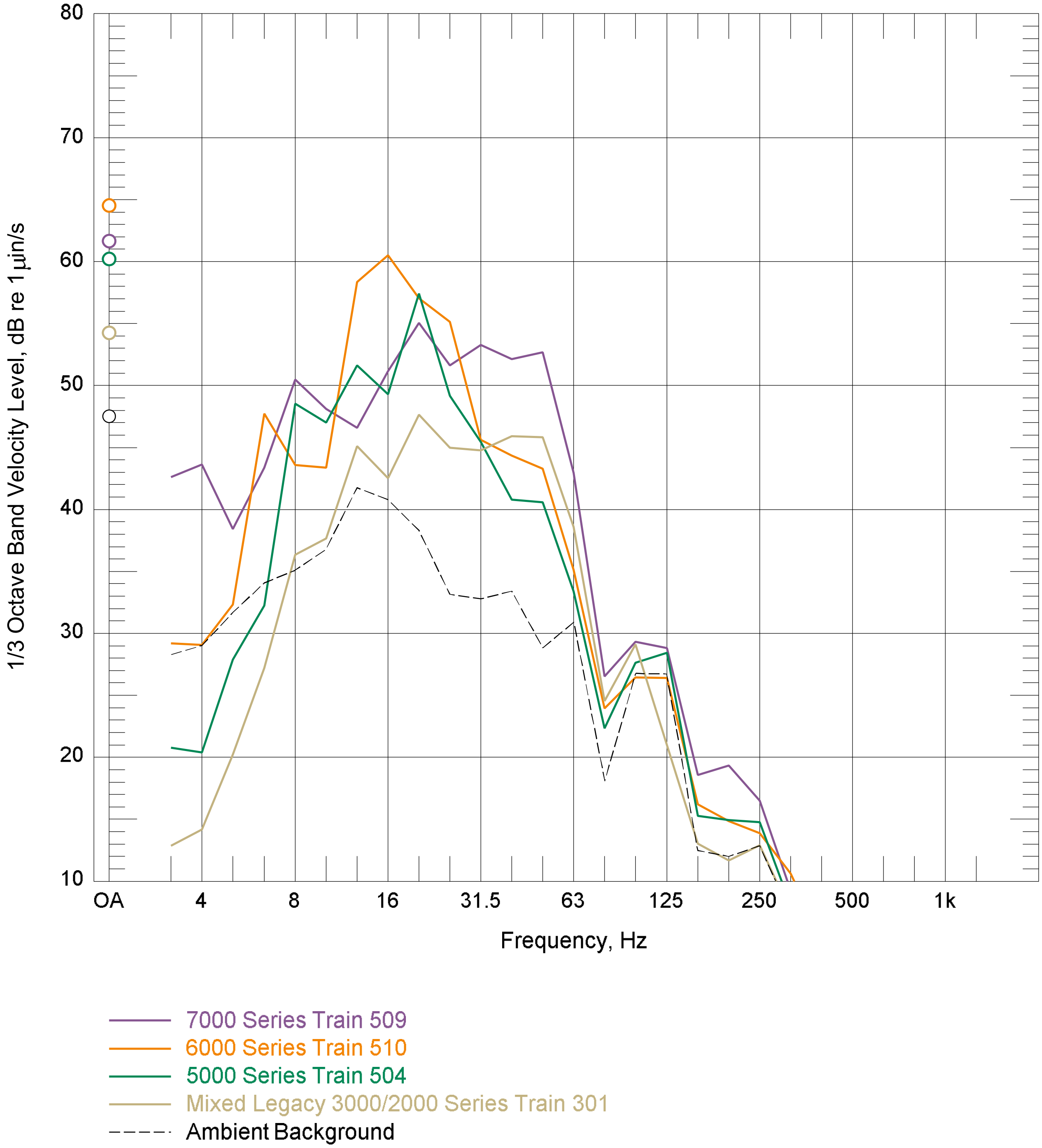


Figure 284: ***Site 15 at Location V3 First Floor Living Room***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

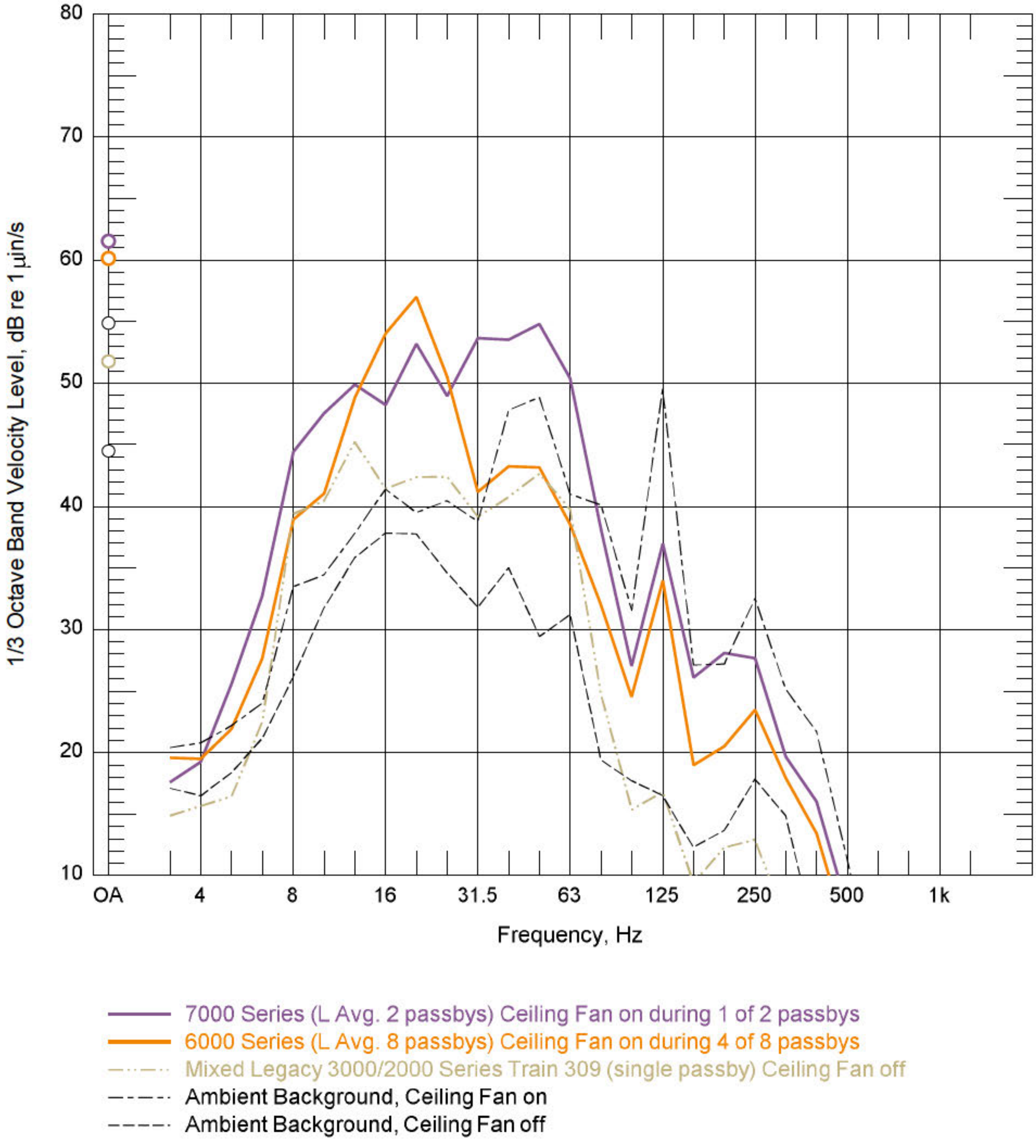


Figure 285: ***Site 15 at Location V4 Second Floor Bedroom***
Outbound Trains on Track 1
Average Vibration Levels by Vehicle Type

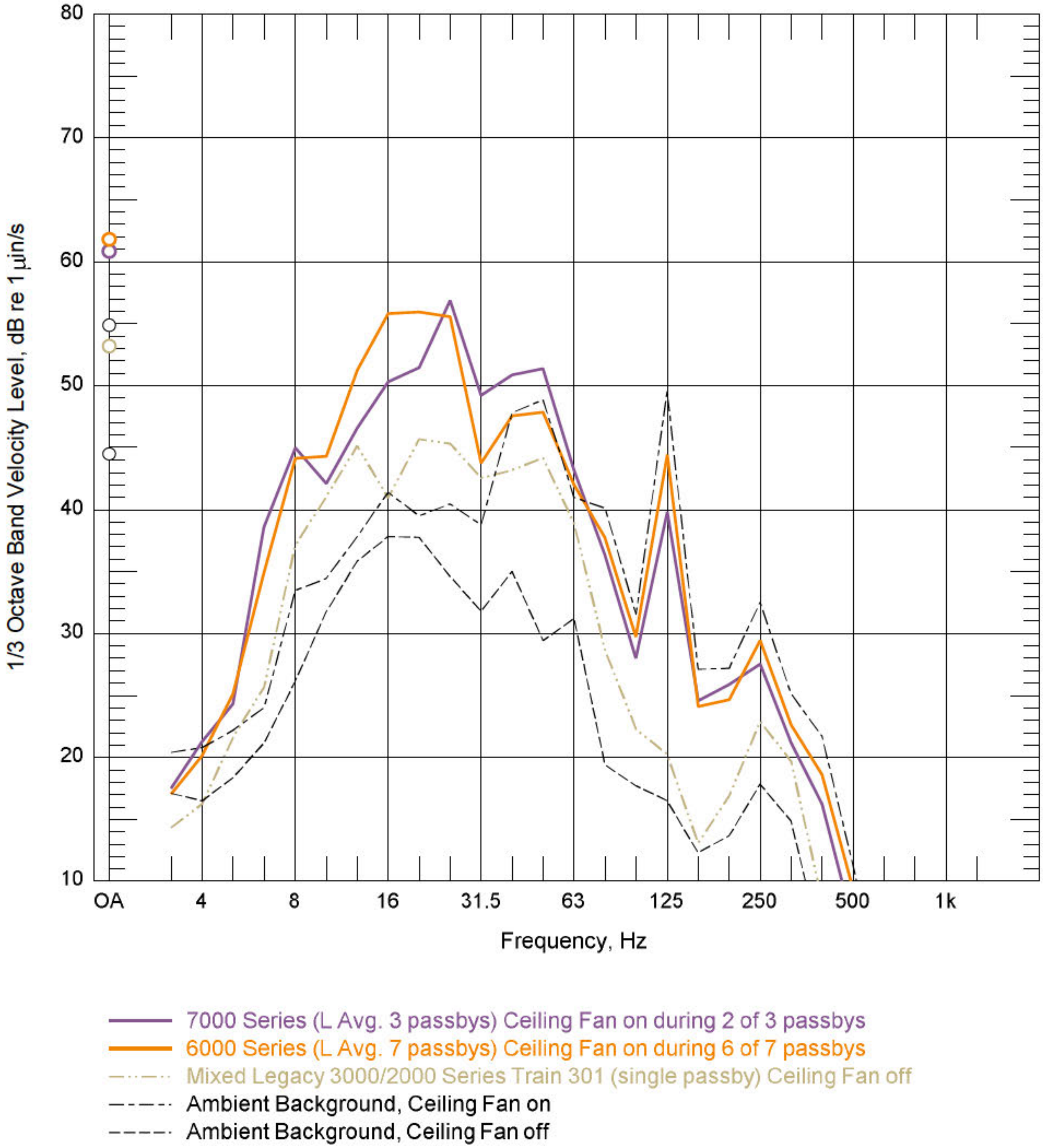


Figure 286: ***Site 15 at Location V4 Second Floor Bedroom***
Inbound Trains on Track 2
Average Vibration Levels by Vehicle Type

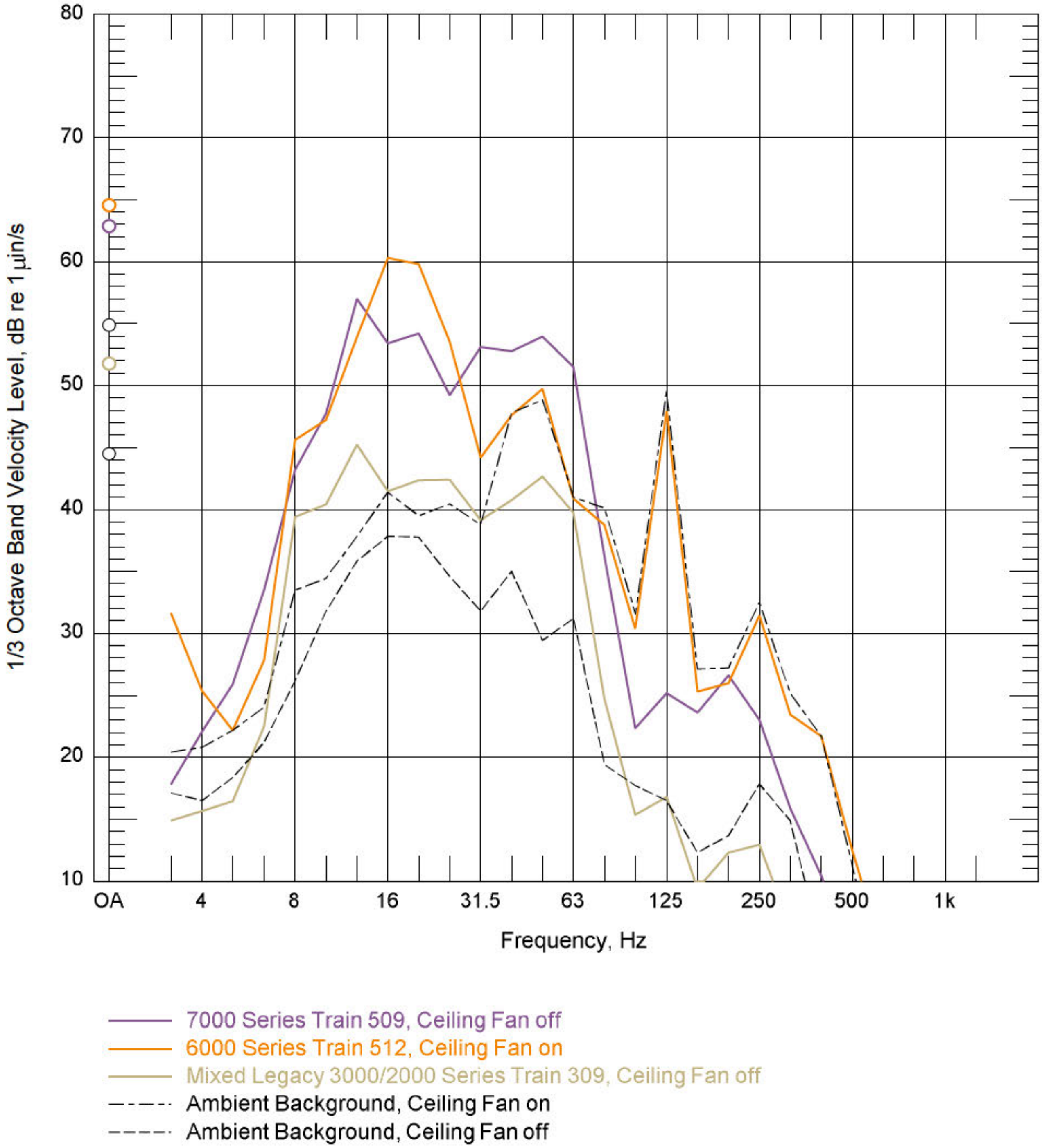


Figure 287: ***Site 15 at Location V4 Second Floor Bedroom***
Outbound Trains on Track 1
Individual Train with Highest Overall Vibration

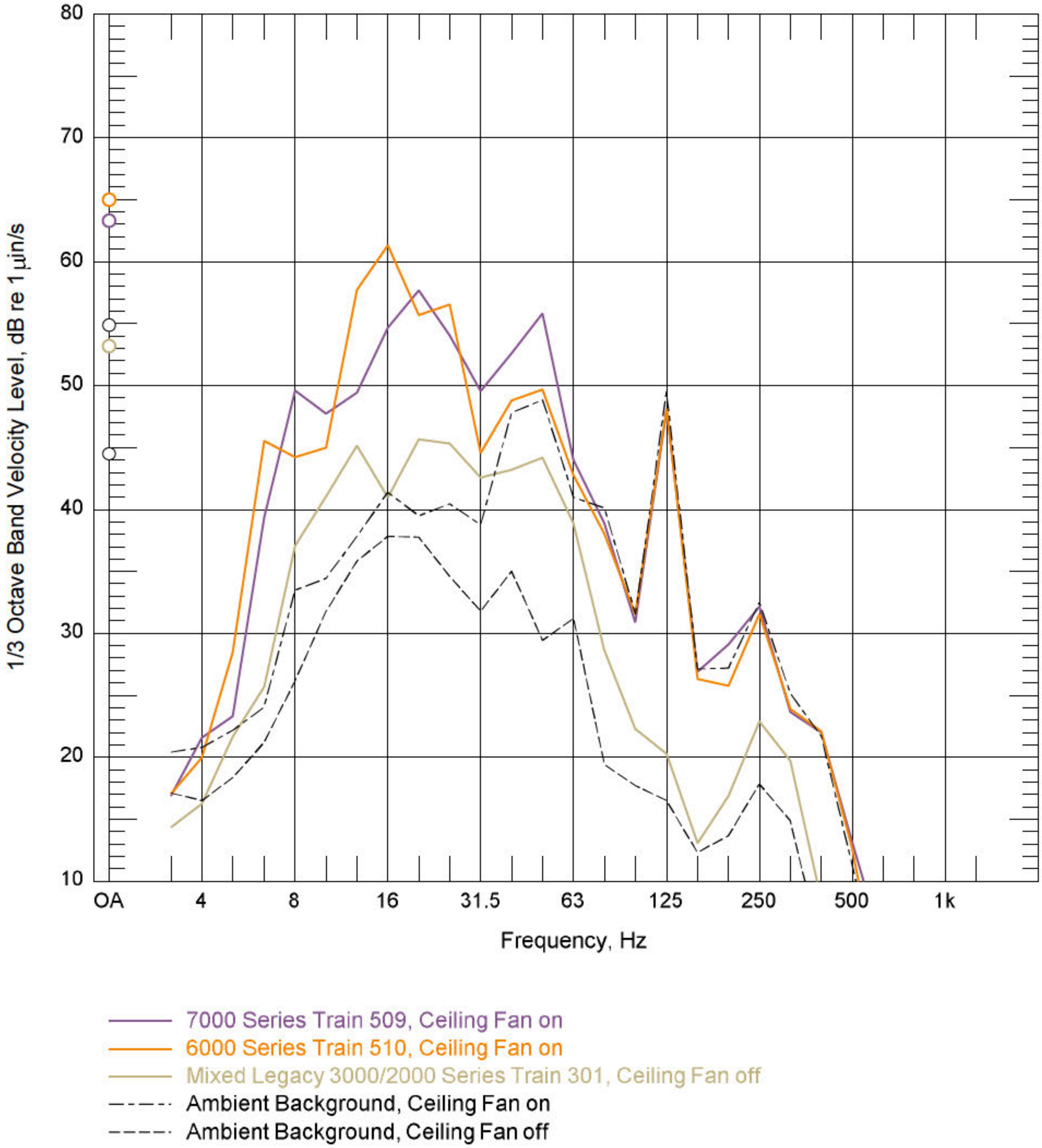


Figure 288: ***Site 15 at Location V4 Second Floor Bedroom***
Inbound Trains on Track 2
Individual Train with Highest Overall Vibration

B.15.6 Passby Ground-borne Noise Spectra and A-weighted Levels

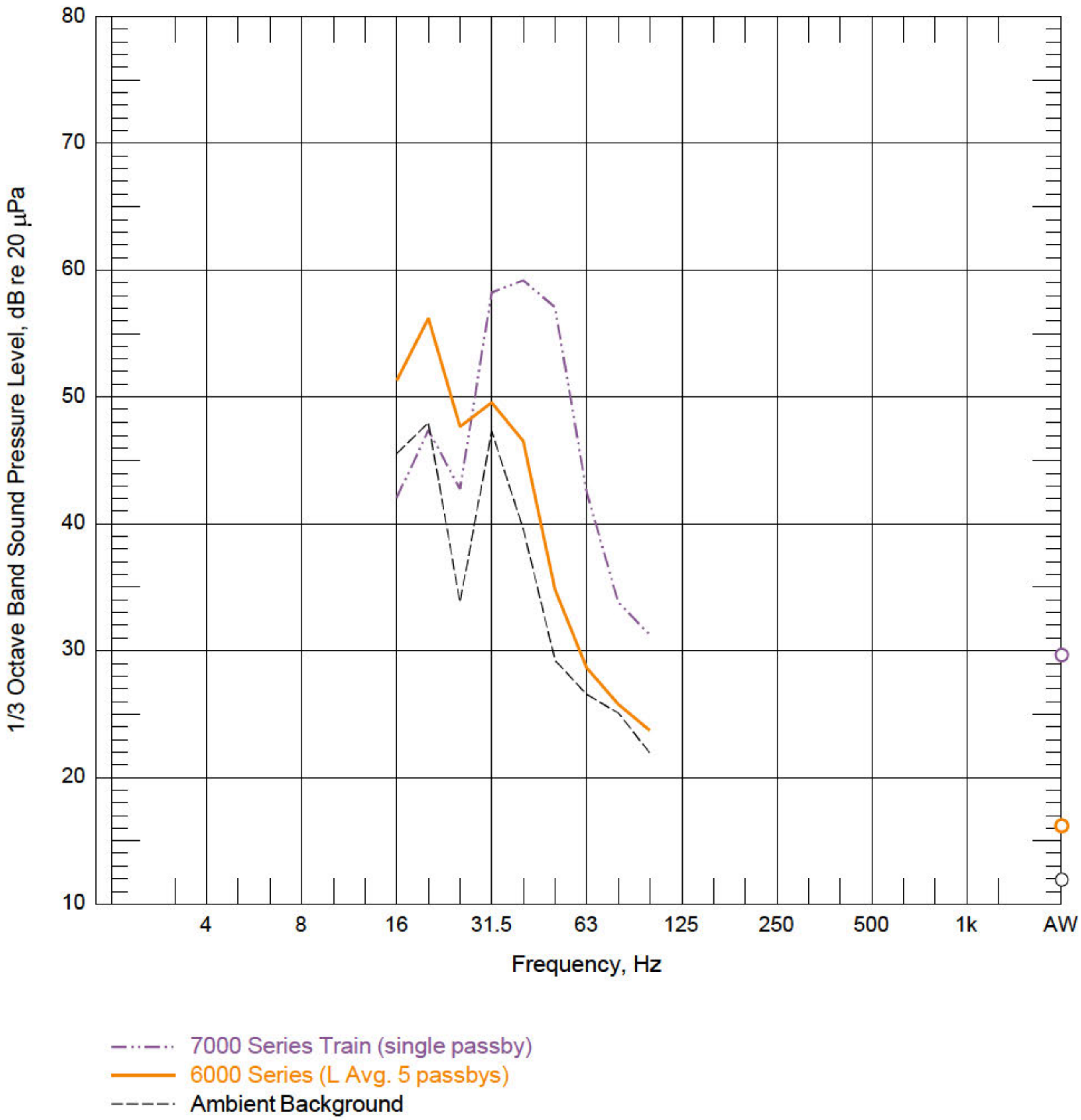


Figure 289: ***Site 15 at Location N1 Basement***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

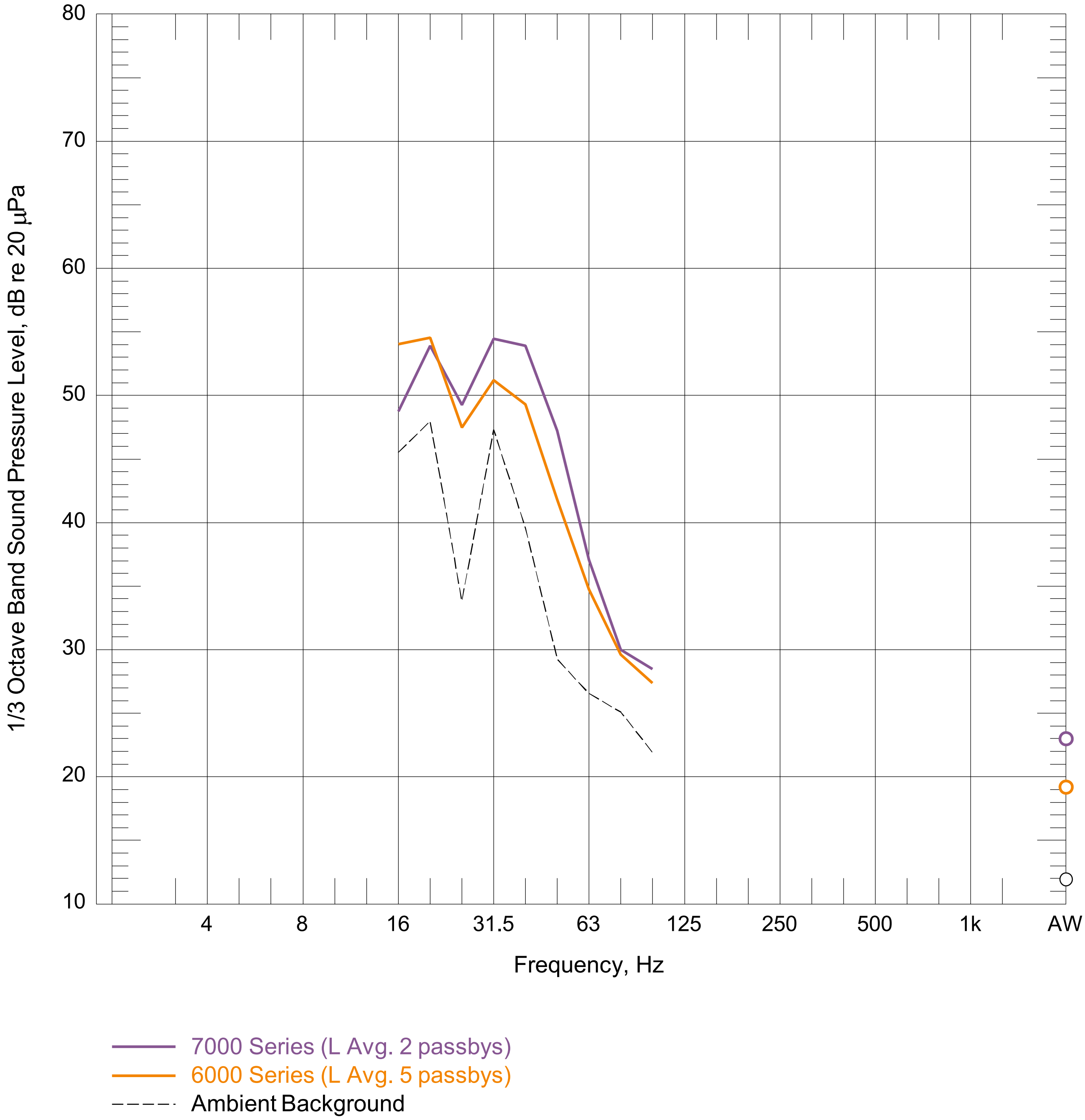


Figure 290: ***Site 15 at Location N1 Basement***
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

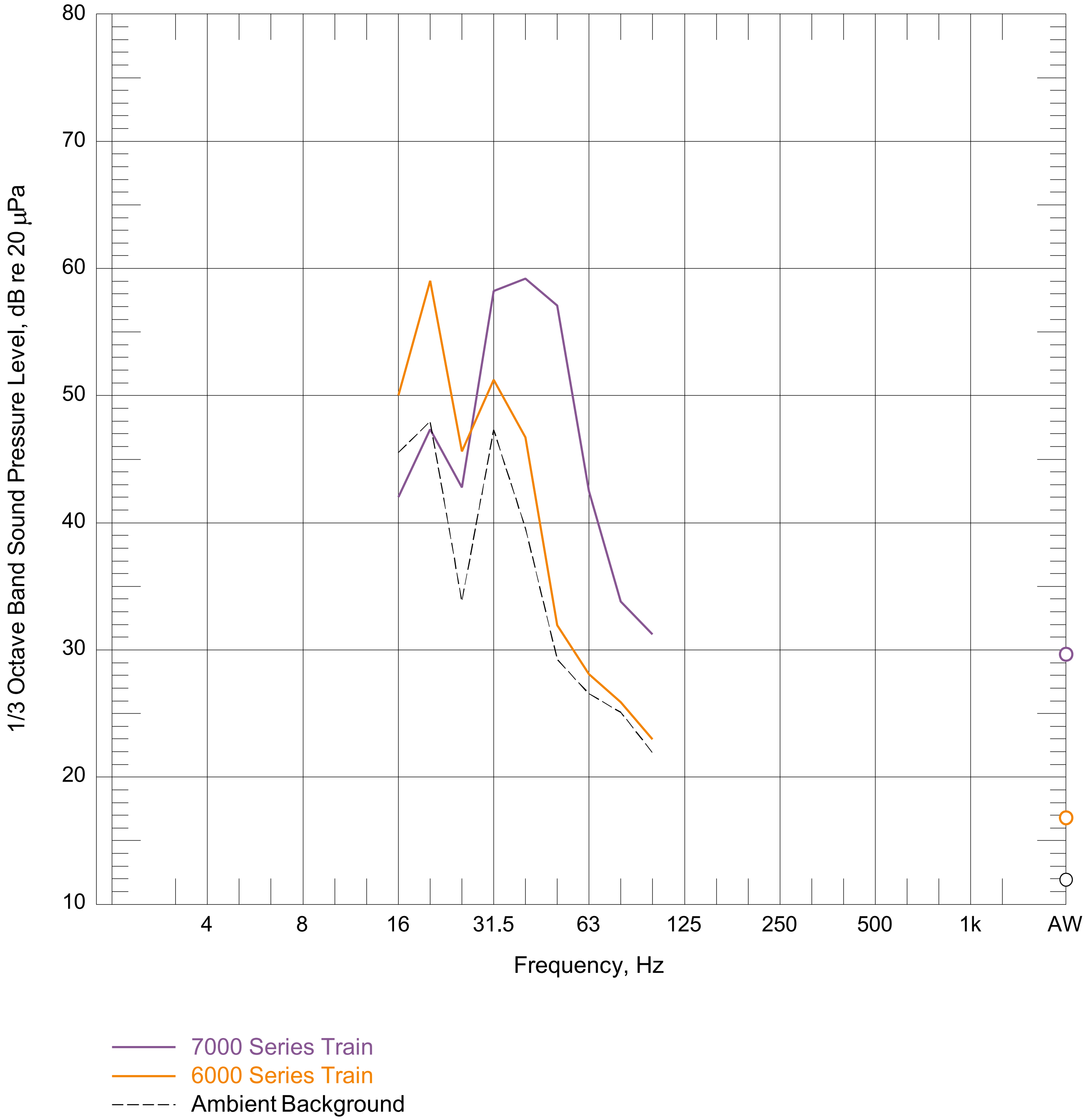


Figure 291: ***Site 15 at Location N1 Basement***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

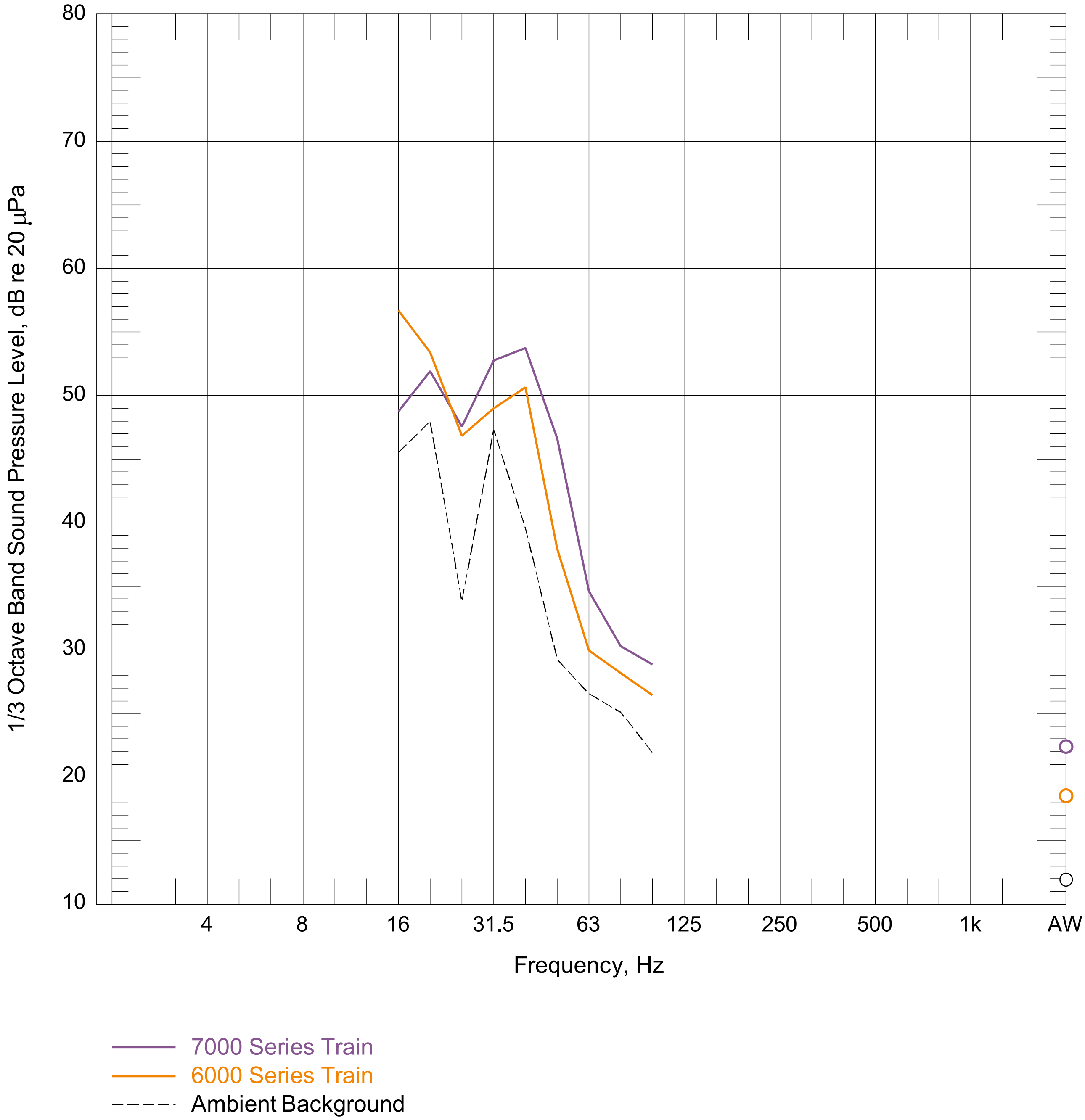


Figure 292: ***Site 15 at Location N1 Basement***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

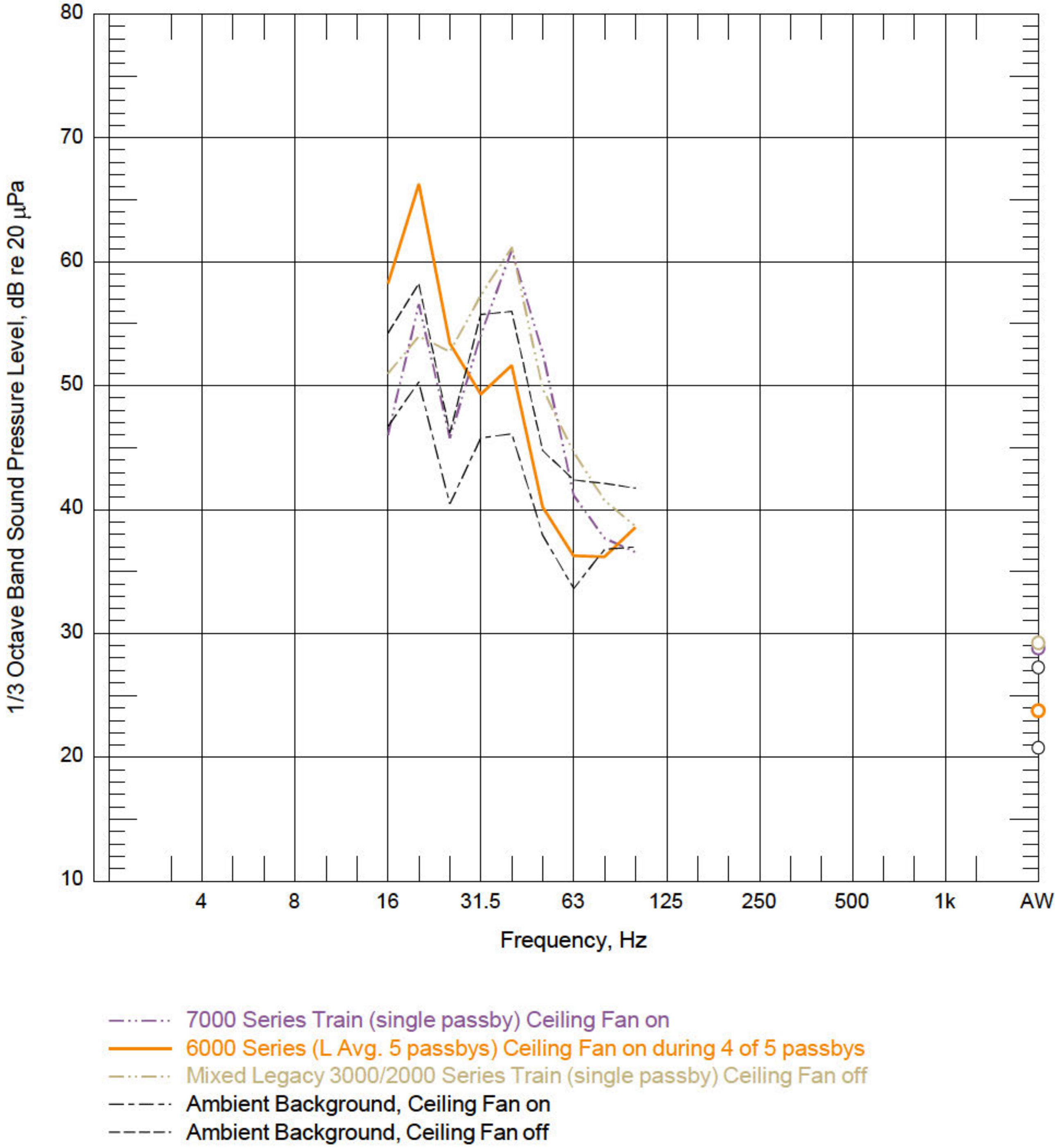


Figure 293: ***Site 15 at Location N2 First Floor Living Room***
Outbound Trains on Track 1
Average Noise Levels by Vehicle Type

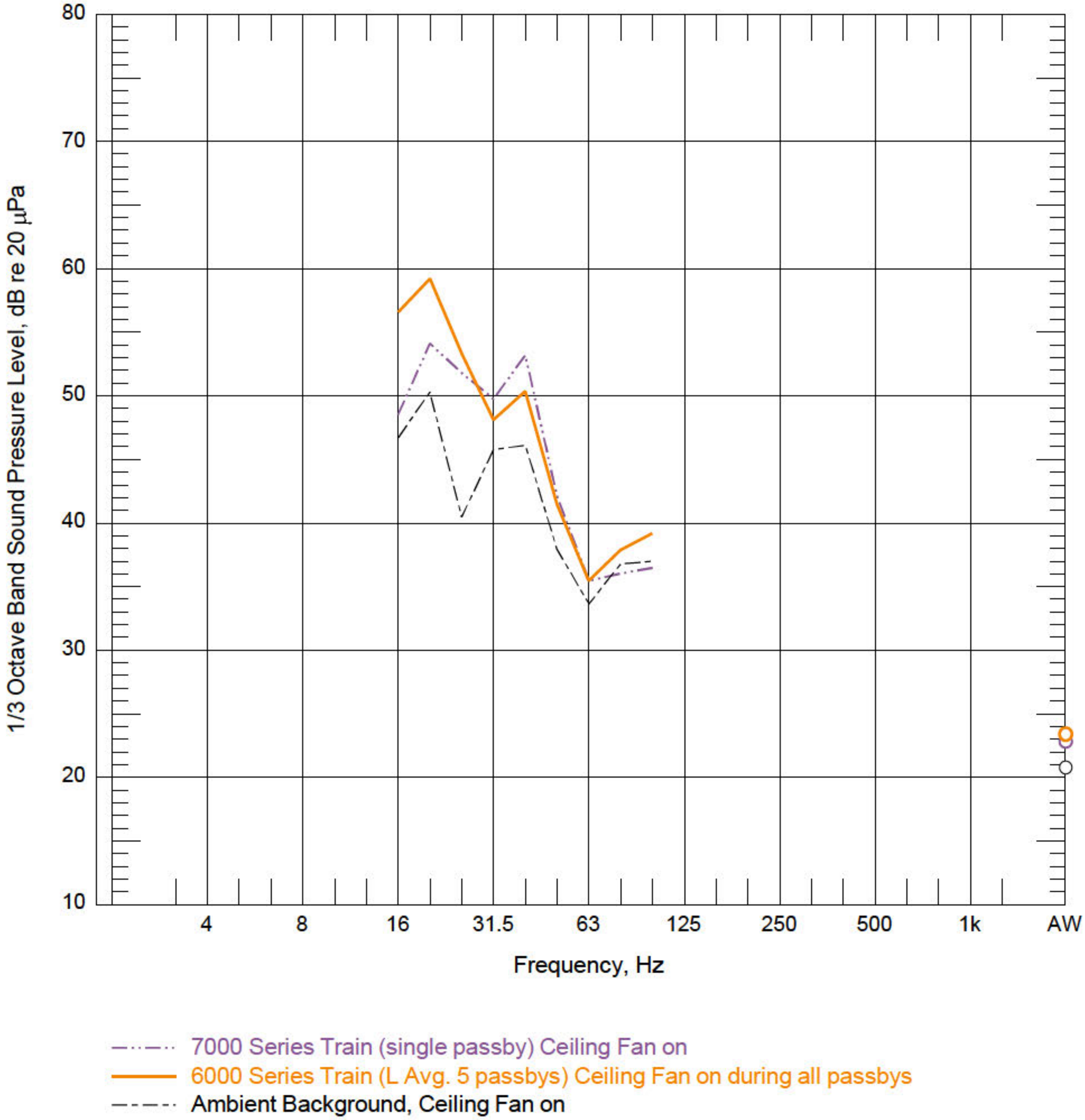


Figure 294: ***Site 15 at Location N2 First Floor Living Room***
Inbound Trains on Track 2
Average Noise Levels by Vehicle Type

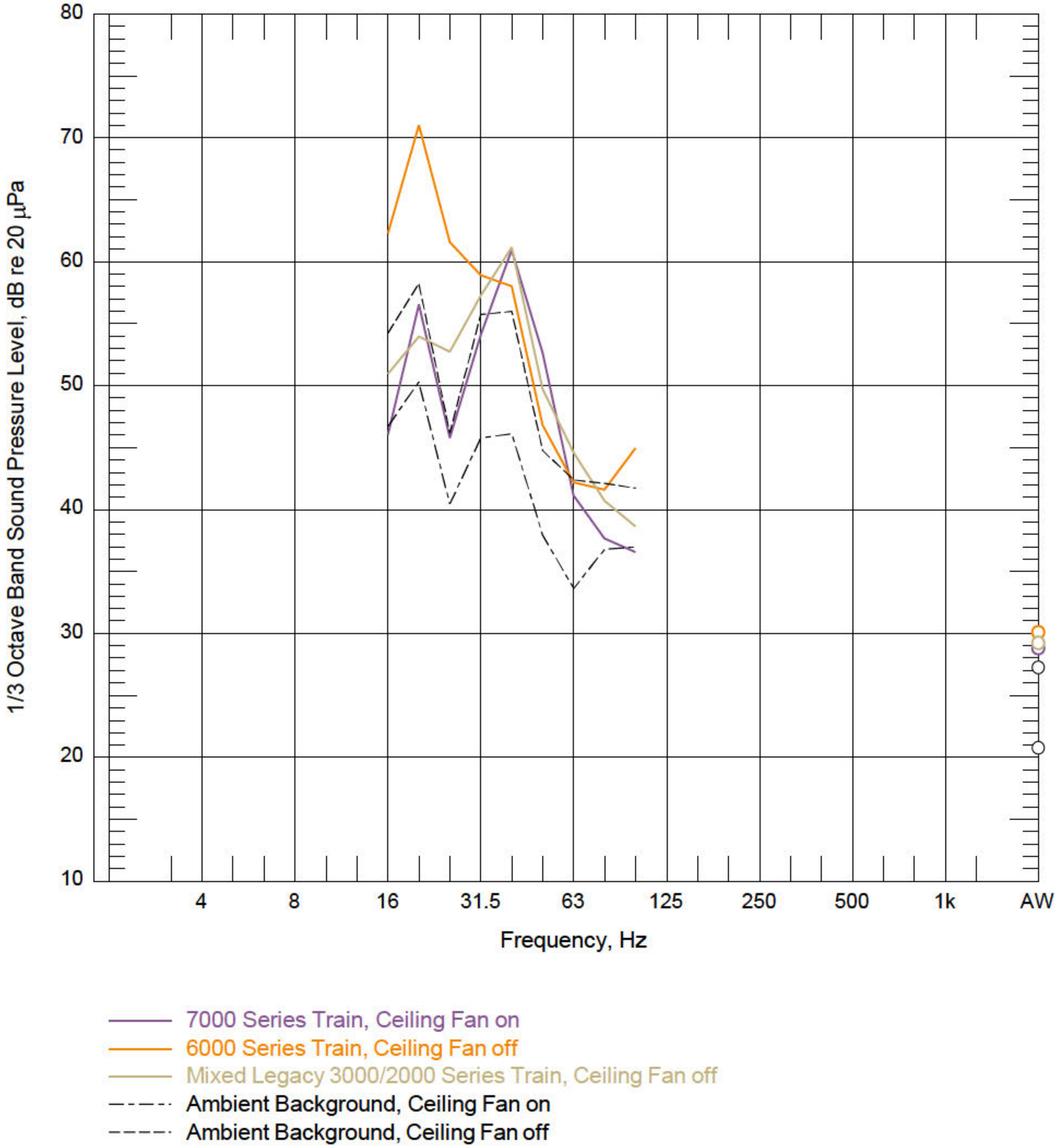


Figure 295: ***Site 15 at Location N2 First Floor Living Room***
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

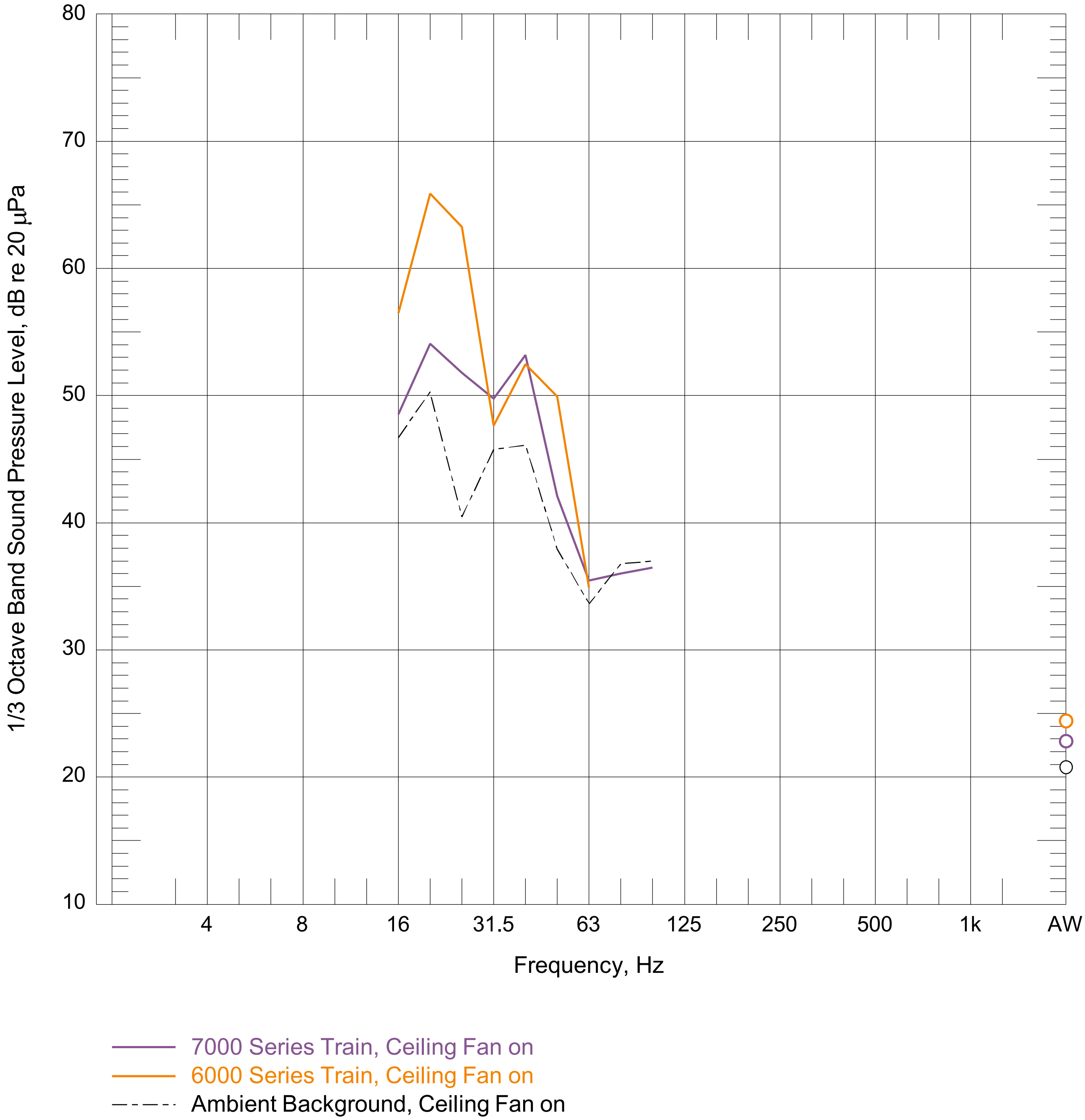


Figure 296: ***Site 15 at Location N2 First Floor Living Room***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

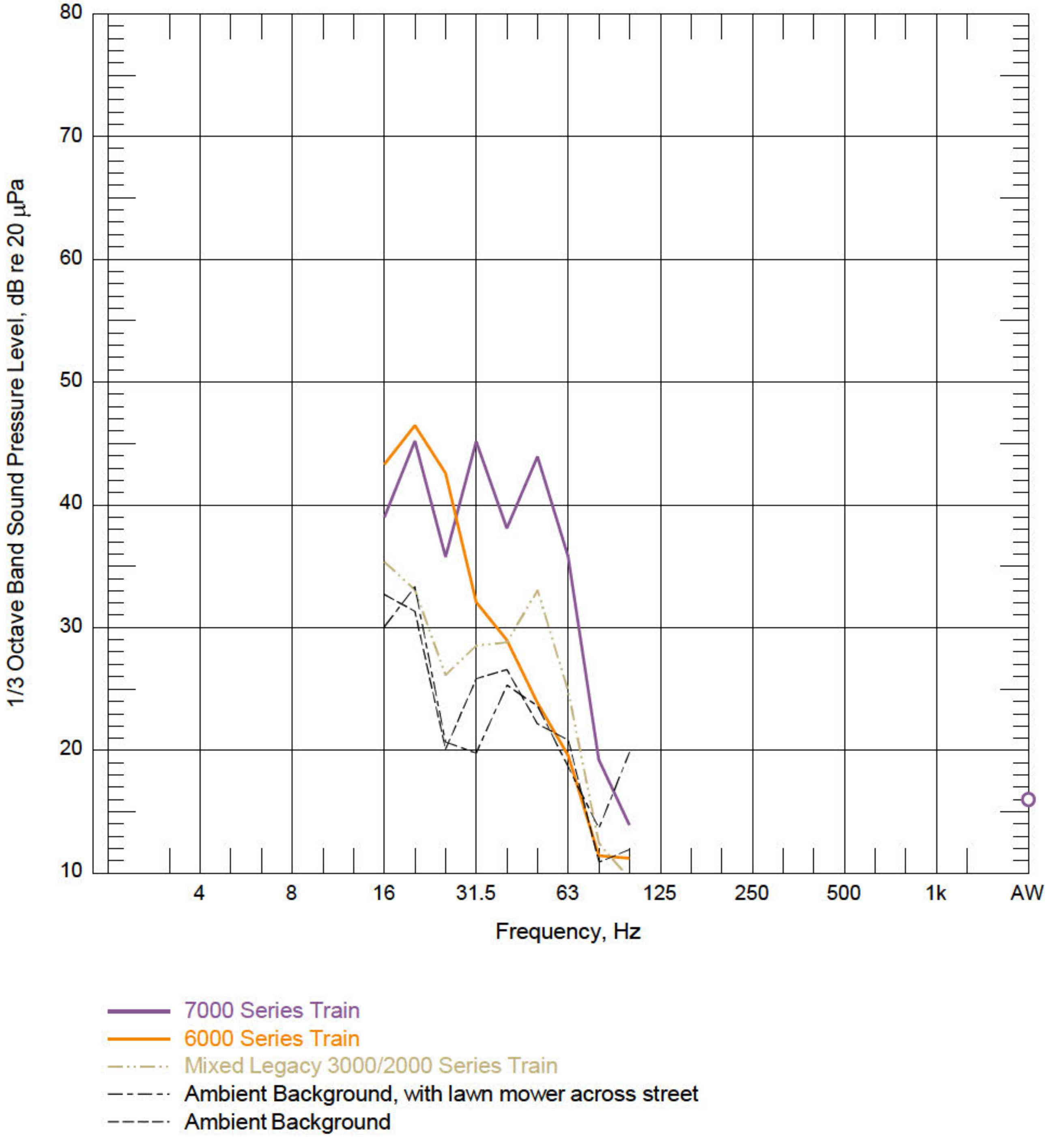


Figure 297: Site 15 at Location N3 Second Floor Bedroom
Outbound Trains on Track 1
Individual Train with Highest A-weighted Level

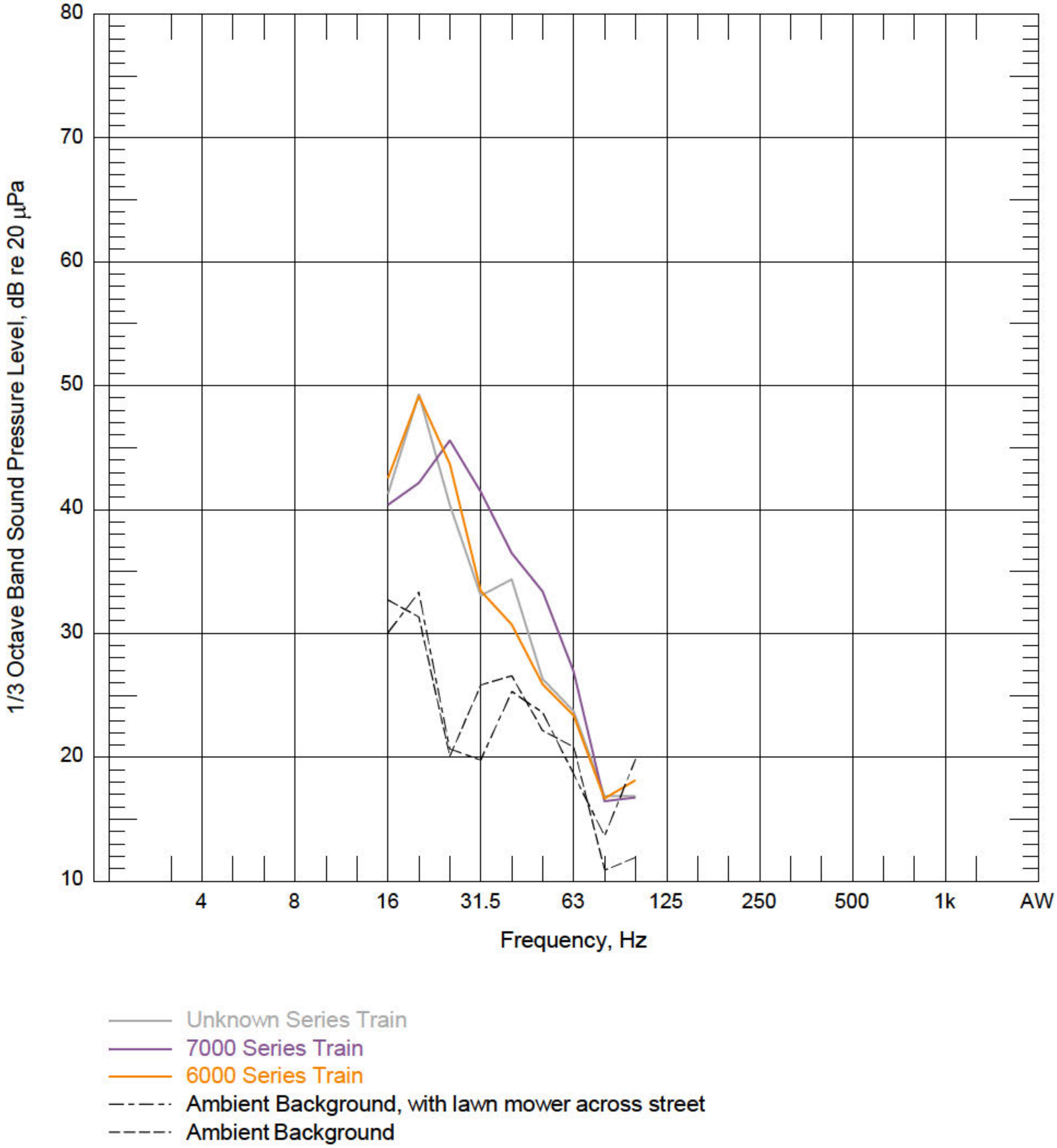


Figure 298: ***Site 15 at Location N3 Second Floor Bedroom***
Inbound Trains on Track 2
Individual Train with Highest A-weighted Level

B.16 Site 16 – Gallatin Street NE (Outdoor Only)

B.16.1 Tunnel Notes

Tunnel Structure: Tunnel

Track Type: Direct Fixation

T/R Depth: 55 to 60 feet

Measurement Period: Wednesday, 16 August 2017, 17:45 to 19:45

B.16.2 Measurement Positions

		INBOUND TRACK 2			OUTBOUND TRACK 1		
Recorder Channel	Chainage (50 ft)	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)	Perp. distance (feet)	T/R Depth (feet)	Total slant distance (feet)
V1	304+25	106	56	120	69	56	89
V2	303+35	95	60	112	59	60	84

Perp. distance = perpendicular distance to track, not accounting for tunnel depth
T/R depth = top-of-rail depth
Total slant distance = total distance to track, accounting for tunnel depth

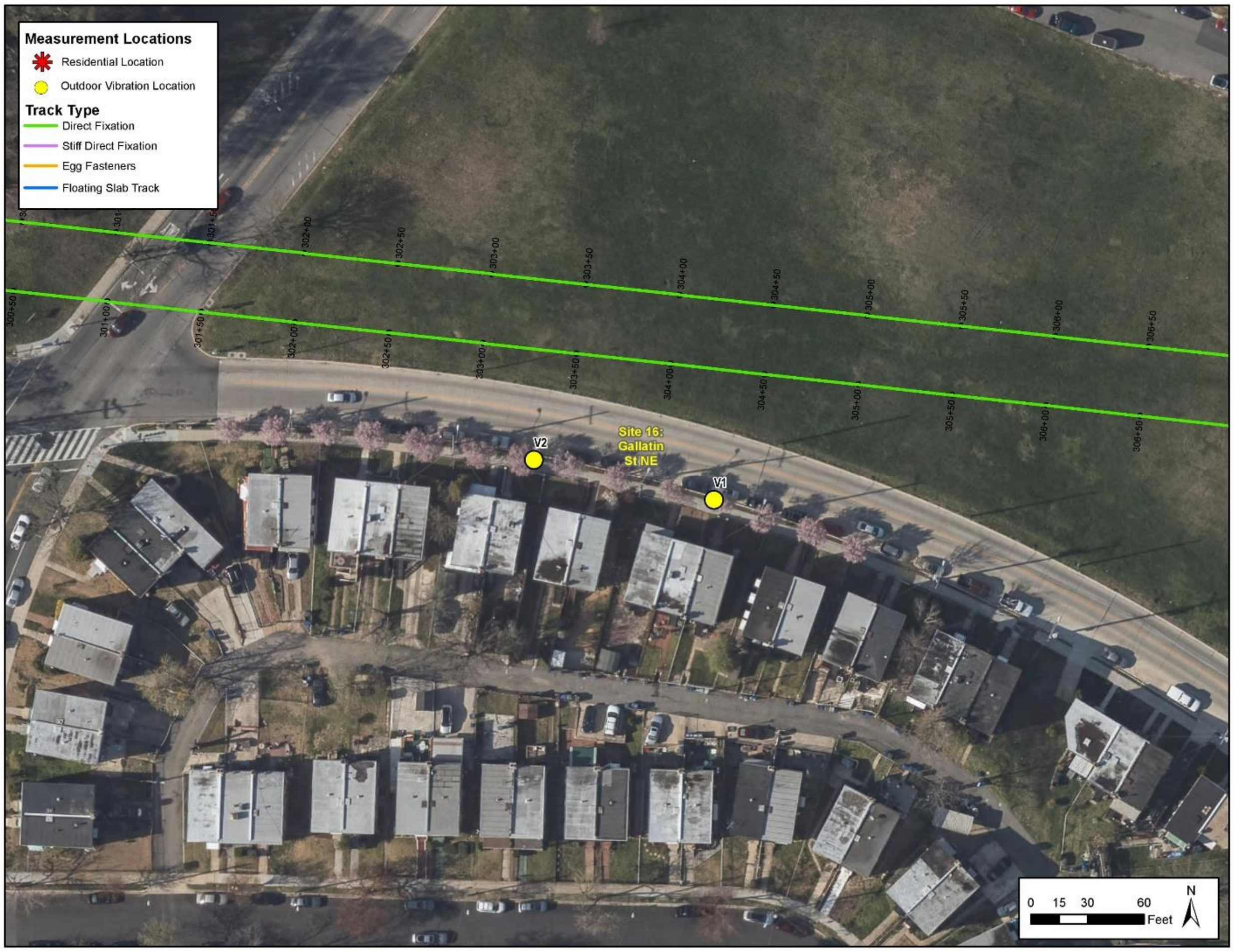


Figure 299: Aerial Map of Site 16 Measurement Positions

B.16.3 Overall Level vs Distance Plot

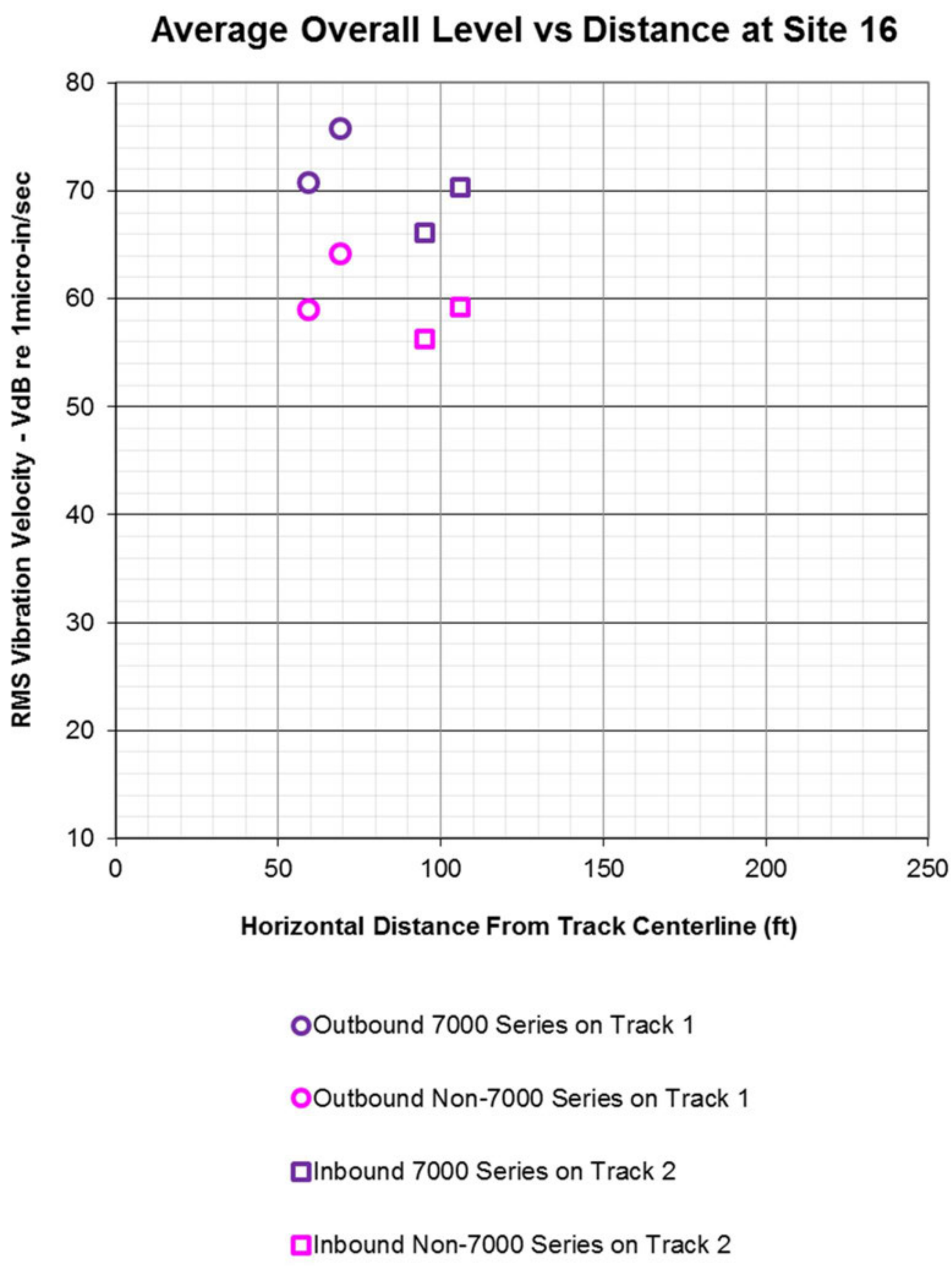


Figure 300: Site 16 Average Overall Level vs Distance