Appendix K

Supplemental Tire Derived Aggregate Information

Appendix K Index:

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2. Peer Review of TDA Vibration Tests at VTA

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EVALUATION OF TIRE DERIVED AGGREGATE AS INSTALLED BENEATH BALLAST AND TIE LIGHT RAIL TRACK

– Results of 2009 Field Tests --

June 2009

Final Report

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INTRODUCTION AND SUMMARY

This report presents the results of a third set of field tests performed to determine the vibration attenuating and damping properties of tire derived aggregate (shredded tires, also known as TDA) as installed beneath ballast and tie rail transit track on the Vasona Line of the Santa Clara Valley Transportation Authority (VTA). This third set of tests was undertaken to verify the performance of the TDA underlayment after approximately three and one-half years of revenue operations.

As with the first series of tests performed in March and May 2005 (Ref. 1), and the second series of tests performed in August 2006 (Ref. 2), the 2009 tests were performed at specific locations along the VTA Vasona Line, and the results should be applicable to other locations and other rail transit systems where reduction of wayside groundborne vibration from transit train operations is necessary. The line sections tested were installed with TDA underlayment as a result of the need to provide wayside groundborne vibration reduction from future operations along the VTA Vasona Corridor (Ref. 3) and from the promising test results performed at a landfill using construction equipment as the vibration source (Ref.4) and from a test section installed at the VTA maintenance facility in San Jose, California (Ref. 5).

Test data were obtained at three locations adjacent to sections with TDA underlayment and two locations with standard ballast and tie track, for comparison purposes. Field tests were performed over a five day period between April 4 and April 8, 2009. The primary vibration source consisted of two articulated VTA Kinkisharyo low-floor light rail vehicles which operated at three speeds to assess the vibration attenuation of the installed sections with TDA underlayment with respect to those sections of track with standard ballast and tie construction. Since the test train was interspersed between revenue train passbys, additional vibration data were obtained from these revenue trains. However, due to the variability in speed, loading and train length (most were single-car trains but some were two-car trains), these were not used as the primary source for evaluating the performance of the TDA underlayment. In addition to wayside groundborne vibration data, rail strain and deflection data were also obtained, the latter obtained by Armin Wright as a consultant to Wilson, Ihrig & Associates (WIA). Track elevations were obtained through a field survey by BKF from March 23 through 25, 2009 as a consultant to VTA.

As indicated after the 2005 and 2006 studies, the use of TDA as an underlayment beneath ballast and tie track as a means for reducing wayside groundborne vibration appears to be both practical and viable in addition to finding a new use for scrap tires. As with the previous tests, there are some inconsistencies involved at making comparisons of the performance of operations on the sections with TDA underlayment in comparison with sections of standard ballast and tie tracks due to differences at the various measurement locations. To make exact comparisons, a study would need to be made with and without the TDA underlayment at the exact same location. Of course, this is not practical, so comparisons with data from the control sections must suffice.

However, the overall performance based on most of the measurements obtained as part of these three sets of tests at VTA indicates that the reduction of wayside groundborne vibration due to transit train passbys is generally superior to that of a ballast mat, but not as effective as an appropriately designed floating slab trackbed particularly where reduction of low frequency vibration (<15 Hz) is necessary.

These conclusions are essentially the same as those made following an assessment of the test section installed at the VTA maintenance facility (Ref. 5). In addition, the incremental cost savings (based on 2003 costs) over either ballast mat or floating slab installations have been realized. Considering an approximate additional cost of $500 per track ft for the installation of floating slab track, an approximate additional cost of $200 per track ft for the installation of ballast mat and an approximate additional cost of $50 per track ft for the installation of the TDA underlayment in comparison with standard ballast and tie track, the cost savings are substantial.

MEASUREMENT LOCATIONS AND INSTALLATION DETAILS

The sections of track with TDA underlayment are underlain with 12 in of Type A TDA (nominally 3 in size shreds or chips) with 12 in of sub-ballast above that and 12 in of ballast above the sub-ballast to the base of the ties. The TDA material is wrapped with filter fabric. Figure 1 presents a cross-section of the trackwork details. The Vasona Line uses continuous welded rail (CWR) and concrete ties.

There are four sites with the TDA underlayment. Table 1 presents the location and extent of each of these four sites. For the 2006 and 2009 tests, wayside groundborne measurements were obtained at three of these sites. No vibration measurements were obtained at site No. 2 since this section contains both at grade and a raised alignment section which acts as a bridge abutment for the Hamilton Avenue overcrossing. Strain and deflection measurements were obtained at site Nos. 1, 3 and 4. Two comparison or control sites were used to obtain the vibration insertion loss or attenuation characteristics of the TDA underlayment in comparison with standard ballast and tie track. These two control sites were also used to provide a comparison of the rail strain and track deflection properties.

TABLE 1 SUMMARY INFORMATION ON FOUR SITES OF TDA UNDERLAYMENT ON THE VTA VASONA LINE

Site No.	Description	Civil Limits of TDA Underlayment (m)	Length of Installation (route ft.)	Track Type
1	North of Kennedy Ave./Railway Ave.	106+60 to 108+40	590	Double
2	North of Hamilton Ave./Borello Dr. & Rojo Ct.	123+88 to 125+80	630	Single
3	North of Leigh Ave. at South-West Expressway	141+60 to 142+00	130	Double
4	Between Fruitdale and Meridian Aves./Deland Ave.	147+80 to 150+45	870	Single

The Vasona alignment where measurements were obtained is south of downtown San Jose and it generally runs in a northeast/southwest orientation paralleling an existing railroad alignment. For the purposes of this report, trains operating away from downtown San Jose are considered southbound trains and in areas with double track, operate on the southbound track on the west side of the alignment. Trains operating towards downtown San Jose are considered northbound trains and in areas with double track operate on the northbound track on the east side of the alignment. The railroad alignment is located immediately east of the Vasona alignment.

As indicated, the vibration source consisted of two articulated VTA Kinkisharyo low-floor light rail vehicles which operated at three speeds (15, 30 & 50 mph) to assess the vibration, rail strain and rail deflection. For these measurements, the two vehicles were #919 and #921. For the 2005 and 2006 tests, the test vehicles were loaded to the equivalent of a seated load (AW-1, 65 passengers), with a total added weight of 10,008 lbs per car. For the 2009 tests, the bricks used to load the vehicles were no longer available, so the total weight of each car was approximately 97,600 lbs (AW-0).

Profile rail grinding of the Vasona Line took place in the Fall of 2008. No tamping or leveling has been necessary at any of the alignment sections with the TDA underlayment.

Details of each of the measurement locations follow:

Site No. 1 - North of Kennedy Avenue/Railway Avenue

Vibration measurements were obtained at 8 measurement locations summarized in Table 2. Measurements on the west side of the alignment were located on the sidewalk of Sunnyside Avenue, which is roughly perpendicular to the alignment, but ends prior to crossing the alignment with a sound barrier wall. The installation of the TDA underlayment is to reduce the groundborne vibration transmitted to the residential buildings in this area around Sunnyside Avenue. Measurements between the tracks and on the east side of the alignment were to supplement the data obtained on the west side of the alignment. The measurements on the east side of the alignment were between the railroad alignment and Railway Avenue, which parallels the alignment in this area.

Table 2 Summary of Measurement Locations at Site No. 1

Location No.	Apx. Civil Station Location (m)	Description	Distance from Track Centerline
1	107+37	West of alignment, on sidewalk, on south side of Sunnyside Ave.	25 ft from SB
2	107+45	West of alignment, on sidewalk on north side of Sunnyside Ave.	50 ft from SB

Location No.	Apx. Civil Station Location (m)	Description	Distance from Track Centerline
3	107+46	West of alignment, on sidewalk on north side of Sunnyside Ave.	50 ft from NB
4	107+47	West of alignment, on sidewalk on north side of Sunnyside Ave.	25 ft from SB
5	107+60	On base of guy wire support for catenary pole between tracks	7.5 ft from both tracks
6	107+90	East of alignment, on pavement near ancillary building	25 ft from NB
7	107+90	East of alignment, on pavement near ancillary building	50 ft from SB
8	107+90	East of alignment, on curb of Railway Ave.	40 ft from NB

Figures 2 through 6 present photographs of the measurement locations and the configuration of the alignment, including rail condition after approximately one year of revenue operations.

Site No. 2 - North of Hamilton Avenue/Borello Drive & Rojo Court

As previously indicated, vibration measurements were not obtained at Site No. 2, since strain and deflection measurements were not obtained here in 2005, and it was felt that the vibration, strain and deflection data obtained at the other locations would adequately determine how the TDA underlayment has continued to perform since the commencement of revenue service.

Site No. 3 - North of Leigh Avenue at South-West Expressway

Vibration measurements were obtained at 8 measurement locations summarized in Table 3. Measurements on the west side of the alignment were located on and near the driveway behind 1012 Leigh Avenue. The installation of the TDA underlayment is specifically to reduce the groundborne vibration transmitted to this multi-family residential building. Measurements on the east side were between the railroad alignment and South-West Expressway, which parallels the alignment in this area.

Figures 7 through 9 present photographs of the measurement locations and the configuration of the alignment.

Table 3 Summary of Measurement Locations at Site No. 3

Location No.	Apx. Civil Station Location (m)	Description	Distance from Track Centerline
1	141+75	West of alignment, on driveway of 1012 Leigh Ave.	25 ft from NB
2	141+75	West of alignment, on driveway of 1012 Leigh Ave.	25 ft from SB
3	141+70	West of alignment, on driveway of 1012 Leigh Ave.	50 ft from NB
4	141+65	West of alignment, on driveway of 1012 Leigh Ave.	50 ft from SB
5	141+85	East of alignment, on tie of adjacent railroad	25 ft from SB
6	141+85	East of alignment, on concrete footing of fence	25 ft from NB
7	141+85	East of alignment, on ground spike mounted in dirt	50 ft from SB
8	141+85	East of alignment, on sidewalk of South-West Expressway	40 ft from NB

Site No. 4 - Between Fruitdale and Meridian Avenues/Deland Avenue

Vibration measurements were obtained at 7 measurement locations summarized in Table 4. Measurements on the west side of the alignment were located in the rear driveway/parking areas of the multi-family buildings at 794 and 798 Deland Avenue. These buildings are representative of the buildings for which the TDA was installed for reducing groundborne vibration from train operations. Measurements on the east side were between the railroad alignment and South-West Expressway, which parallels the alignment in this area.

Figures 10 through 13 present photographs of the measurement locations and the configuration of the alignment.

Table 4 Summary of Measurement Locations at Site No. 4

Location No.	Apx. Civil Station Location (m)	Description	Distance from Track Centerline
1	149+05	West of alignment, on driveway behind 794 Deland Ave.	25 ft
2	149+05	West of alignment, on driveway behind 794 Deland Ave.	50 ft
3	149+35	West of alignment, on driveway behind 798 Deland Ave.	25 ft
4	149+35	West of alignment, on driveway behind 798 Deland Ave.	50 ft
5	149+09	East of alignment on base of guy wire support for catenary pole	7.5 ft
6	149+09	East of alignment, on concrete footing of fence	25 ft
7	149+09	East of alignment, on edge of South-West Expressway	50 ft

Control Site No. 1 - North of Stokes Street at South-West Expressway

Vibration measurements were obtained at 8 measurement locations summarized in Table 5. This measurement site is south of TDA Sites 3 and 4 and north of TDA Sites 1 and 2. All of the measurement locations west of the alignment were located below the prevailing rail grade by approximately 6 ft, adjacent to a school athletic field. There were no nearby buildings in the measurement area, except some multi-family dwellings south of Stokes Street near the Bascom Station.

Figures 14 and 15 present photographs of the measurement locations and the configuration of the alignment.

Table 5 Summary of Measurement Locations at Control Site No. 1

Location No.	Apx. Civil Station Location (m)	Description	Distance from Track Centerline
1	133+68	West of alignment, on stake in ground adjacent to athletic field	50 ft from NB
2	133+68	West of alignment, on stake in ground adjacent to athletic field	25 ft from NB
3	133+90	West of alignment, on stake in ground adjacent to athletic field	50 ft from NB
4	133+90	West of alignment, on stake in ground adjacent to athletic field	25 ft from NB
5	133+68	East of alignment, on concrete footing of fence	25 ft from NB
6	133+90	East of alignment, on concrete footing of fence	25 ft from NB
7	133+68	East of alignment, on sidewalk of South-West Expressway	40 ft from NB
8	133+90	East of alignment, on sidewalk of South-West Expressway	40 ft from NB

Control Site No. 2 - South of Race Street/North of I-280

Vibration measurements were obtained at 6 measurement locations summarized in Table 6. This measurement site is north of all of the TDA Sites, just north of the I-280 overcrossing, and south of Race Street. The single measurement location west of the alignment was located on the walkway to an office building. Additional measurements west of the alignment were not possible due to the presence of this office building. The remaining measurement locations were located east of the alignment on this same walkway that connects between a parking lot and the office building, in the parking lot, or on a ground spike between the alignment and the parking lot.

Figures 16 and 17 present photographs of the measurement locations and the configuration of the alignment.

Table 6 Summary of Measurement Locations at Control Site No. 2

Location No.	Apx. Civil Station Location (m)	Description	Distance from Track Centerline
1	154+45	West of alignment, on walkway to office building	25 ft
2	154+45	East of alignment, on walkway to office building	25 ft
3	154+45	East of alignment, near walkway in parking lot	50 ft
4	154+08	East of alignment, on stake in ground adjacent, 115' south of walkway	25 ft
5	153+85	East of alignment, on stake in ground adjacent, 180' south of walkway	25 ft
6	154+05	East of alignment, in parking lot, 125' south of walkway	50 ft

INSTRUMENTATION AND DATA ANALYSIS

Vibration

A vibration velocity transducer (geophone) was located at each of the ground surface measurement locations. Each geophone (AMF Geospace Model GS 200X) was mounted with wax on a concrete or asphalt surface, or on a specially designed spike embedded in the ground. The output of the geophones was conditioned and amplified by WIA Type 116 geophone preamplifiers and a Type 228 8-channel decade amplifier. The output of the decade amplifier was recorded on a Teac Model LX-10 16-channel data recorder for subsequent data processing. The recording and monitoring instrumentation is shown in Figure 19.

Each geophone is calibrated with a shaker in the WIA laboratory using a cross calibration system with a reference accelerometer. The reference accelerometer is used solely for this purpose and is a Kistler Type 808K. The Kistler accelerometer's output is traceable to NIST (National Institute of Standards and Technology).

The recorded vibration data were subsequently analyzed in the WIA laboratory with a Larson-Davis Laboratories Model 2900B Real Time Analyzer interfaced to a Pentium based Personal Computer. The analyses sampled the vibration when the test train was passing-by in line with the appropriate transducer over the duration of the passby. The attenuation of the groundborne vibration with the use of the TDA underlayment can then be determined by comparing the results at the TDA sections with the control sections.

Rail Strain

As indicated, measurements of rail strain were obtained during train operations at three sections with TDA underlayment and at both control sections. At each location, a set of six strain gages were used to measure tension(elongation) and compression of the rail head and foot in the longitudinal direction, positioned both over a tie and at the mid point between two adjacent ties. At each position, one gage was mounted on the outside edge of the head, aligned laterally with two gages mounted on the inside and outside of the rail foot. Figure 18 shows a typical strain gage installation.

The selected gages were Vishay Micro-Measurements LWK-06-W250B-350 weldable strain gages, which were welded to each prepared section of rail with a Vishay Micro-Measurements Model 700 battery powered spot welder. After mounting the gages, a silicone compound was applied for protection, and shielded cables were attached to the gage leads and run under the tracks to a rack of Vishay Model 2311 strain gage signal conditioning amplifiers. Each pair of gages at the rail foot was combined into one channel, giving a total of four channels per location. The outputs of the amplifier were recorded on four channels of the Teac LX-10 16-channel data recorder, simultaneously with track deflection and ground vibration signals. Since these strain gages were originally applied to the rail prior for the 2005 tests, field testing and repair of the strain gages occurred prior to the 2009 tests to ensure that all strain gages functioned properly.

Calibration of the strain measurement system is based on the excitation voltage, gage factor, system gain, and bridge configuration of each channel. A 200 micro strain and 1000 micro strain shunt calibration is incorporated in each channel of the 2311 amplifiers, and was recorded in the field at each location. The accuracy of the calibration voltage was verified in the WIA laboratory with a Hewlett Packard 34401A bench top multimeter, which is calibrated traceable to NIST.

Prior to each train passby, each channel was zeroed with the auto zero function incorporated in the 2311 amplifiers to remove long term drift due to temperature variation in the rail.

The rail strain data files stored on the LX-10 recorder were read out and converted to ASCII format, stored in a spreadsheet as voltage versus time data. A calibration factor was then applied to convert the voltage to micro strains. Plots of the rail strain were developed and stored for subsequent presentation.

Rail Deflection

Deflection of the rail was measured optically from a remote position between 35 and 50 ft from the track. This method of measuring rail deflection was selected because of the unavailability of an absolute spacial reference in the immediate vicinity of the track that would allow straightforward deflection measurement by such standard transducers as LVDTs. The absence of an absolute position reference is a result of the resilience of both the ballast (rock or TDA) and the subgrade.

As part of the Superconducting Supercollider Project, WIA performed an extensive analysis of soil deflection beneath railroad track. Based on that analysis, it was determined that rail deflection should be measured from a distance of approximately 50 ft from the track to minimize disturbance of the measurements due to soil deflection under the weight of the train. Because the accuracy of the measurement technique is dependent upon having the optical measurement device immobile during the passby, every effort was made to position the measurement device at the greatest feasible distance from the track up to the preferred distance of 50 ft. Feasible setback distances were actually limited to the range of 32 to 50 ft by the presence of roads adjacent to the alignment.
The measurement technique uses a light source (the target) mounted on the rail and a telescope at the instrument location with a PSD (Position Sensing Detector) at the focal point of the telescope. The telescope and PSD set up at Site 1 is shown in Figure 5. The characteristic of a PSD is that it generates currents from each end of the sensitive region of the detector, and the ratio of these two currents is directly related to the position of the centroid of the light spot falling on the sensor. PSDs are available in many sizes of sensitive areas and in one or two-dimensional configurations. For this project, a two-dimensional PSD with a sensitive area of about 4 x 4 mm was used. The horizontal axis was not recorded, but was used with a local, digital readout for horizontal alignment of the telescope axis with the target on the rail.

These measurements included use of a moderately high-powered HeNe (Helium-Neon) laser as the light source and use of an extremely narrow bandpass optical interference filter at the sensor to block the great majority of the ambient radiation. The wavelength of a HeNe laser is, however, extremely precise, even under field temperature and power fluctuations and can, therefore, be isolated from ambient radiation with a 1 nm. bandpass optical interference filter.

Calibration of an optical displacement measurement system of this nature is inherently variable with distance from the target because both the intensity of the light spot and the amount of motion of the light spot on the detector are functions of the distance between the target and the telescope. For this reason, calibration was performed in the field at each measurement location by mounting the target to the rail on a micrometer slide and recording the signal while moving the target over the measurement range in a series of precisely known steps. Calibrations subsequently read out in the lab were found to have excellent linearity over the required measurement range.

The displacement data were also recorded on the Teac LX-10 in conjunction with the strain and groundborne vibration.

The deflection data files stored on the LX-10 recorder were read out and converted to ASCII format, stored in a spreadsheet as voltage versus time data. A calibration factor was then applied to convert the voltage to inches of deflection. Plots of the deflection were developed and stored for subsequent presentation.

TEST PROCEDURES

As indicated, train passbys generated the vibration used to determine the vibration attenuation characteristics of the TDA underlayment. The order of the tests went from lowest to highest train speed with data from all transducers recorded simultaneously at each location. Passbys in both directions were made with at least 2 passbys in each direction at each speed to ensure that characteristic data were obtained. For the 2009 tests, measurements of the test train operating on the southbound track at TDA Site No. 3 were limited to single passbys and 30 mph and 50 mph due to the limited availability of a test train operator on the day of these tests. However, a complete set of test runs were made on the northbound track.

MEASUREMENT RESULTS

Wayside Groundborne Vibration

As indicated, the arithmetic difference between the vibration measured at appropriate distances at each of the TDA sites and the corresponding control section sites provides a direct measure of the vibration reduction, or insertion loss, provided by the TDA underlayment. This assumes that soil conditions are similar at all measurement locations. In order to determine if there were significant differences in soil conditions, surface impact tests to determine the relative vibration propagation characteristics were obtained at TDA sites 1, 3 and 4, and at both control sites as part of the 2005 tests. The procedures for performing the impact tests are fully documented in References 1 and 2, and are not detailed here. As indicated in the report of the 2005 tests (Ref. 1), that with the exception of the 25 ft location adjacent to the northbound track at TDA site 3, the other locations at 25 ft and all locations at 50 ft exhibit similar vibration propagation characteristics. As with the data from 2005, it is believed that the soil conditions are similar and the effect on the groundborne vibration data are within experimental error and no corrections have been made to the vibration data from the train passbys with the exception of the 25 ft locations for the northbound track at TDA site 3. These data have been corrected to fall within the average response for the 25 ft data, as the 2009 passby data at this location have shown the same characteristics as the 2005 and 2006 data, and we believe that such corrections are justified.

Data analysis of just the train passby data for the various conditions and locations has resulted in over 1200 1/3 octave band samples. Most of these samples have been averaged in some way in order to reduce the specific number of samples used in the comparisons between the test and control sections. The review and averaging process has also indicated some locations with unusual or uncharacteristic results. Generally, the passby data are very consistent for passbys at the same location and train speed. However, there are some locations at the same measurement site at the same distance from the track that exhibit very different spectra. These differences are undoubtedly due to local conditions or other unknown factors which cannot be reconciled, and thus for those locations where the data appear to be very inconsistent with respect to expectations have not been used in the comparison process. Specifically the measurement locations not used for comparison (other than the reference measurements at 7.5 ft from track centerline) were Location 5 at TDA Site No. 1, Locations 2 & 4 at Control Site No. 1 and Locations 2 & 5 at Control Site No. 2. At Control Site No.1 it is believed that the west side 25 ft measurements are affected by the 6 ft elevation of the trackbed immediately adjacent to these measurement locations. Although data have been obtained at these specific measurement locations throughout the three measurement programs (2005, 2006 and 2009), these specific measurement locations have not been used to determine TDA characteristics due to inconsistent data obtained for all of the measurement programs.

Appendix A presents the wayside groundborne vibration data for test train passbys in terms of 1/3 octave band vibration velocity levels for the TDA and control sites with respect to distance from the track and train speed. Review of these figures indicates that the spectra show level increases with speed and three distinct frequency-based groupings of maximum levels (particularly evident at 50 mph) in the region of the 10 and 12.5 Hz 1/3 octave bands, the 25 and 31.5 Hz octave bands and the 63 Hz and 80 Hz 1/3 octave bands. The relative levels of these three groupings vary from site to site, but are dependent on the characteristics of the vehicle trucks, the type of soil in a particular area and the interaction of the trucks and soil or TDA underlayment. This phenomenon is evident for operations at the TDA and control sites.

Figures 20 through 32 present the wayside groundborne vibration data for test train passbys in terms of 1/3 octave band vibration levels for the TDA and control sections that have been used to determine the insertion loss of the TDA underlayment. Revenue train passbys, usually single-car trains, were also recorded and are presented for general information on these figures. But as previously indicated, these data were not included in determining the insertion loss of the TDA underlayment. Figure 33 presents the insertion loss determined for each location using both the 25 ft and 50 ft data. These results are consistent with what was determined for the tests performed in 2005 and 2006. The insertion loss at TDA Site 1 shows low frequency reduction which is simply a factor of the comparison at control sections with higher levels of low-frequency vibration. The insertion loss at TDA Site 3 has been compromised to some degree by its short length that allows a certain amount of flanking vibration, and undoubtedly accounts for the TDA underlayment reduction in effectiveness at this location. Finally at TDA Site 4, a long single track section, the overall performance of the TDA underlayment is quite effective, with its relative amplification at the low frequencies, a factor of the comparison at the control sections which have lower levels of low frequency vibration. Figure 34 presents the average insertion loss for TDA Sites 1, 3 and 4 from the 2005, 2006 and 2009 tests along with a recommended design curve developed in 2006 for use on future designs. The 2009 tests show almost identical results to those from 2006. We believe that the design curve developed in 2006 is still valid, as it is expected that the average insertion loss for all locations would improve to what was determined from the 2005 tests when the insertion loss for TDA Site 2 had been included as part of the test program in 2006 and 2009.

Review of Figure 34 indicates that the average insertion loss is similar for all three tests with some slight variations in the range of 25 to 80 Hz. These slight variations may be due to the fact that, as previously indicated, the insertion loss is based on a comparison of the groundborne vibration obtained at the TDA Sites in comparison with the groundborne vibration obtained at the control sites. Surface impact tests to determine vibration propagation characteristics were used to minimize differences between sites. However, since these sites are not in the same physical locations, there will still be some differences that are site specific and not related to the performance of the TDA underlayment. However, the overall attenuation curve is quite similar to that determined from all of the tests of TDA underlayment.

Figure 35 presents a comparison of the insertion loss generated from these tests compared with those from the previous tests. For the 2005 tests, the results at TDA Site 2 has also been included. As expected, the insertion loss of the longer sections characterized by the TDA installations on the Vasona Line when compared with the 2001 tests at the Younger Yard indicates that the TDA underlayment is somewhat more effective at lower frequencies. It is not expected that a consistent reduction of the very low frequency groundborne vibration (< 12.5 Hz 1/3 octave band) will be achieved, but rather that this very low frequency reduction shown by Figure 34 for the 2005, 2006 and 2009 tests is simply a function of the averaging process and the fact that the very low frequency data were consistently lower at Control Site #1 (north of Stokes St.) than at Control Site #2 (south of Race St.). It is also believed that the TDA underlayment is still quite effective above 80 or 100 Hz and that the decrease in attenuation at the higher frequencies is simply the result of a decrease in the signal to noise ratio at these higher frequencies, since the wayside groundborne vibration generated by the trains at these higher frequencies is relatively low and not always significantly above the background vibration.

Review of the insertion loss of the TDA underlayment with other mitigation methods such as a ballast mat or floating slab trackbed was extensively discussed in Reference 5. The conclusions have remained unchanged, specifically that the reduction of wayside groundborne vibration due to transit train passbys is superior to that of a ballast mat, but not as effective as an appropriately designed floating slab trackbed particularly where reduction of low frequency vibration (<15 Hz) is necessary.

Additional comparisons of the vibration attenuation with respect to train speed and the vibration attenuation over time (a direct comparison of test results from 2005, 2006 and 2009 at specific measurement locations) are included as part of Appendix E. Appendix E was developed due to questions regarding (1) the vibration reduction performance over time and (2) a well-defined attenuation design curve to be used for prediction purposes.

Rail Strain

Plots of the rail strain are shown in Appendix B with the rail foot shown in red, and the rail head shown in blue on each plot. Six plots were created for each measurement location, for speeds of nominally 15, 30 and 50 mph at each gage set either over or between ties. For moving trains, maximum strain in the range of 40 -90 microstrains occurred as each wheel passed directly over a gage, seen as 12 peaks in each plot for a two car train passby. Results of the measurement are summarized in Table 7.

For these 2009 tests, the results show that the average strain in the rail head is 11% higher over the tie and 6% higher between ties for the TDA sections. In the rail foot the strain is 4% higher over the tie and 6% higher between the ties for the TDA sections. These differences are less than for the 2006 tests, and are more similar to the measurements made in 2005. Overall, the range of rail strains are consistent with previous test data from 2005 and 2006, and show that the differences in rail strain between those sections with TDA underlayment are similar to the control sections with standard ballast and tie track.

Rail Deflection

Plots of the rail deflection are shown in Appendix C. Results of the rail deflection measurements are summarized along with the Rail Strain in Table 7.

The average rail deflection was 55% greater for the sections with TDA when compared with the deflection data obtained at the control sections, although deflections at all locations are somewhat lower than the tests performed in 2005 and 2006. This is to be expected to some degree, as the two-car test train was not loaded for the 2009 tests and the effect of using a vehicle weight equivalent to AW-0 rather than AW-1 would account for approximately 10% of this reduction. As with the measurements from 2005 and 2006, the rail deflection is considerably less than 0.125 in which is generally considered the maximum acceptable deflection for good track design by track design engineers.

Table 7 Summary of Rail Strain and Deflection Measurements

Speed	Strain Over Tie - $\mu\epsilon$[1]		Strain Between - $\mu\epsilon$[1]		Deflection - Inches
	Rail Head	Rail Foot	Rail Head	Rail Foot	
TDA Location 1 - Railway Avenue - Southbound Track					
15 mph	-70	65	-70	60	0.050
30 mph	-70	65	-70	55	0.050
50 mph	-65	65	-60	55	0.055
TDA Location 1 - Railway Avenue - Northbound Track					
15 mph	-60	50	-90	50	0.030
30 mph	-55	55	-80	50	0.035
50 mph	-60	55	-90	55	0.030
TDA Location 3 - Leigh Ave/Southwest Expressway					
15 mph	-50	50	-70	65	---- /.025[2]
30 mph	-45	45	-75	50	0.050 /.020
50 mph	-50	45	-80	55	0.050/0.020
TDA Location 4 - Between Fruitdale & Meridian Aves.					
15 mph	-70	55	-90	55	0.067
30 mph	-70	50	-90	55	0.055
50 mph	-70	50	-90	55	0.057
TDA Average					
	-61.3	54.2	-79.6	55.4	0.042

Speed	Strain Over Tie - $\mu\epsilon$[1]		Strain Between - $\mu\epsilon$[1]		Deflection - Inches
	Rail Head	Rail Foot	Rail Head	Rail Foot	
Control Location 1 - Stokes St. at South-West Expressway					
15 mph	-45	50	-55	45	0.020
30 mph	-40	50	-65	40	0.020
50 mph	-45	45	-75	45	0.020
Control Location 2 - South of Race St./North of I-280					
15 mph	-70	55	-85	50	0.035
30 mph	-65	55	-85	50	0.030
50 mph	-65	60	-85	55	0.035
Control Locations Average					
	-55.0	52.5	-75.0	47.5	0.027

[1] Tension - microstrains [2] SB/NB track

Track Elevation Survey Results

As indicated, track elevation surveys were performed by BKF under contract to VTA from March 23 through 25, 2009. These surveys were obtained at TDA Sites 1, 3 and 4. The detailed results are presented as prepared by BKF in Appendix D. Overall the results still show relatively small changes since the as-built surveys of 2003, although the differences are typically greater after approximately three and one-half years of revenue service (2009) than after one year of revenue service (2006). Table 8 presents a summary of the changes in elevation for both the lead-in sections to the TDA underlayment as well as the TDA underlayment sections themselves. Review of Table 8 indicates that for Locations 1 and 4, typical elevation changes for both the lead-in sections and the TDA sections are on the order of 10 mm lower. At Location 3 the typical elevation changes for both the lead-sections and the TDA sections are marginally greater than for Locations 1 and 3. The TDA sections at this location have settled marginally more than the lead-in section, but the differences are only a few millimeters. Based on these data it not only appears that the changes are typically less than ½ in, but the lead-in sections with no TDA underlayment and the TDA sections show elevation changes that are virtually the same.

Table 8 Summary of Track Elevation Changes

TDA Location	Track Section	Length (ft)	Range of Change (mm)	Typical or Average Change (mm)	Date of Original Survey
1 - SB	Lead-ins	330	-2 to -27	-4 to -10	9/03
	TDA	590	-5 to -12	-6 to -8	9/03
1 - NB	Lead-ins	330	-2 to -16	-4 to -9	9/03
	TDA	590	-3 to -12	-7 to -8	9/03
3 - SB	Lead-ins	330	-7 to -15	-10 to -14	12/03
	TDA	130	-10 to -20	-13 to -17	12/03
3 - NB	Lead-ins	330	-3 to -12	-6 to -10	12/03
	TDA	130	-10 to -16	-11 to -13	12/03
4	Lead-ins	395	-3 to -22	-8 to -12	12/03
	TDA	870	-1 to -15	-6 to -10	12/03

REFERENCES

1. S.L. Wolfe, "Evaluation of Tire Derived Aggregate as Installed Beneath Ballast and Tie Light Rail Track -- Results of 2005 Field Tests -- ", prepared by Wilson, Ihrig & Associates, Inc., for Dana N. Humphrey, Consulting Engineer, Final Report, March 2006.

2. S.L. Wolfe, "Evaluation of Tire Derived Aggregate as Installed Beneath Ballast and Tie Light Rail Track – Results of 2006 Field Tests –", prepared by Wilson, Ihrig & Associates, Inc., for Dana N. Humphrey, Consulting Engineer, Final Report, February 2007.

3. D.L. Watry, "SCVTA Vasona Corridor: Vibration Study for Final Design", prepared by Wilson, Ihrig & Associates, Inc., for the Santa Clara Valley Transportation Authority, Final Report, 18 January 2001.

4. S.L. Wolfe, "Vibration Attenuation Properties of Tire Shreds – Results of Field Tests –", prepared by Wilson, Ihrig & Associates, Inc., for Dana N. Humphrey, Consulting Engineer, Final Report, September 1999.

5. S.L. Wolfe, "Vibration Attenuation Performance of Tire Shred Underlayment for Light Rail Transit Ballast and Tie Track – Results of Field Tests –", prepared by Wilson, Ihrig & Associates, Inc. for Santa Clara Valley Transportation Authority, April 2001.

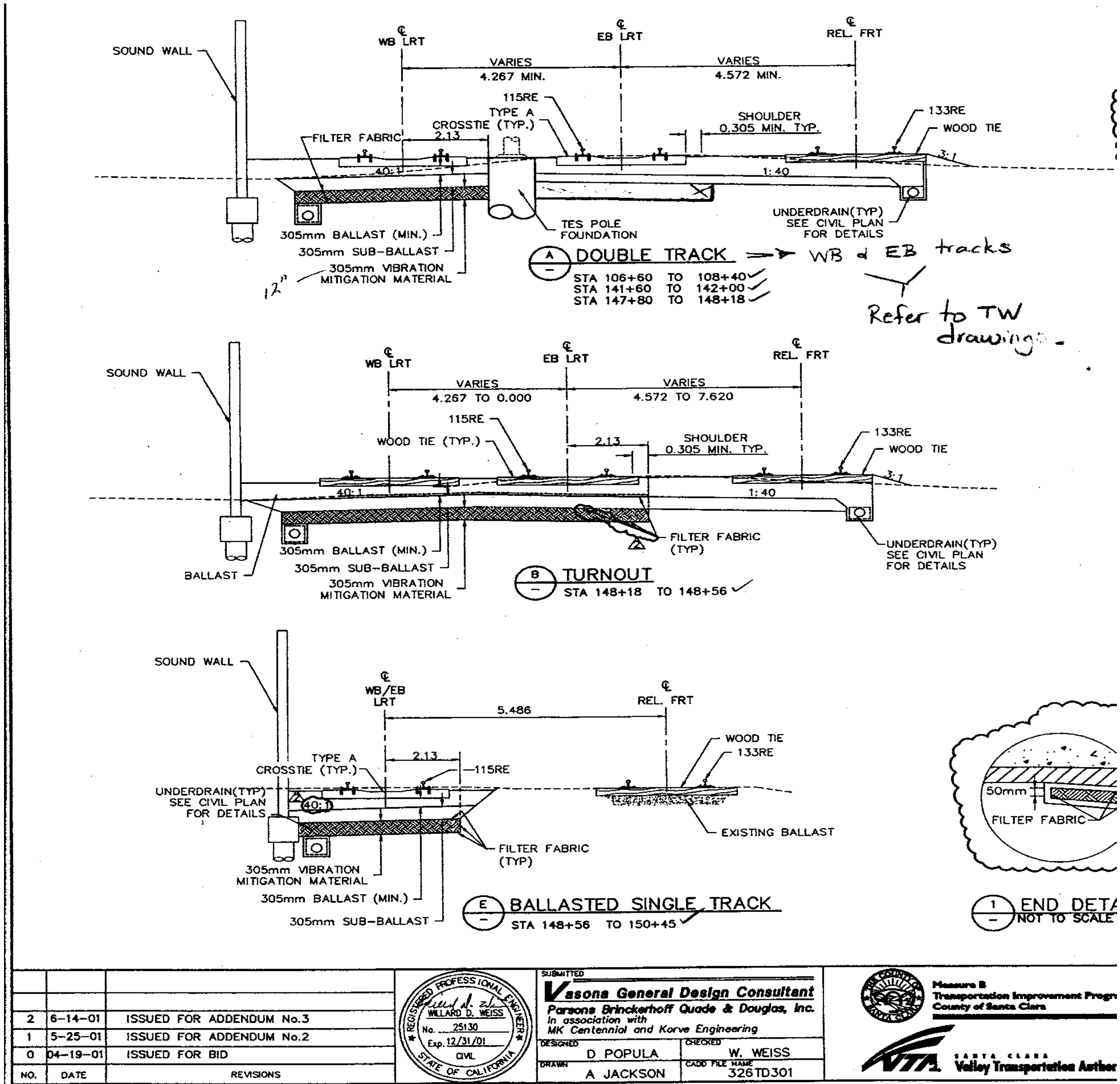


FIGURE 1 - CROSS SECTIONS OF TDA UNDERLAYMENT INSTALLATION

FIGURE 2 - SITE 1 MEASUREMENT LOCATIONS 2-4

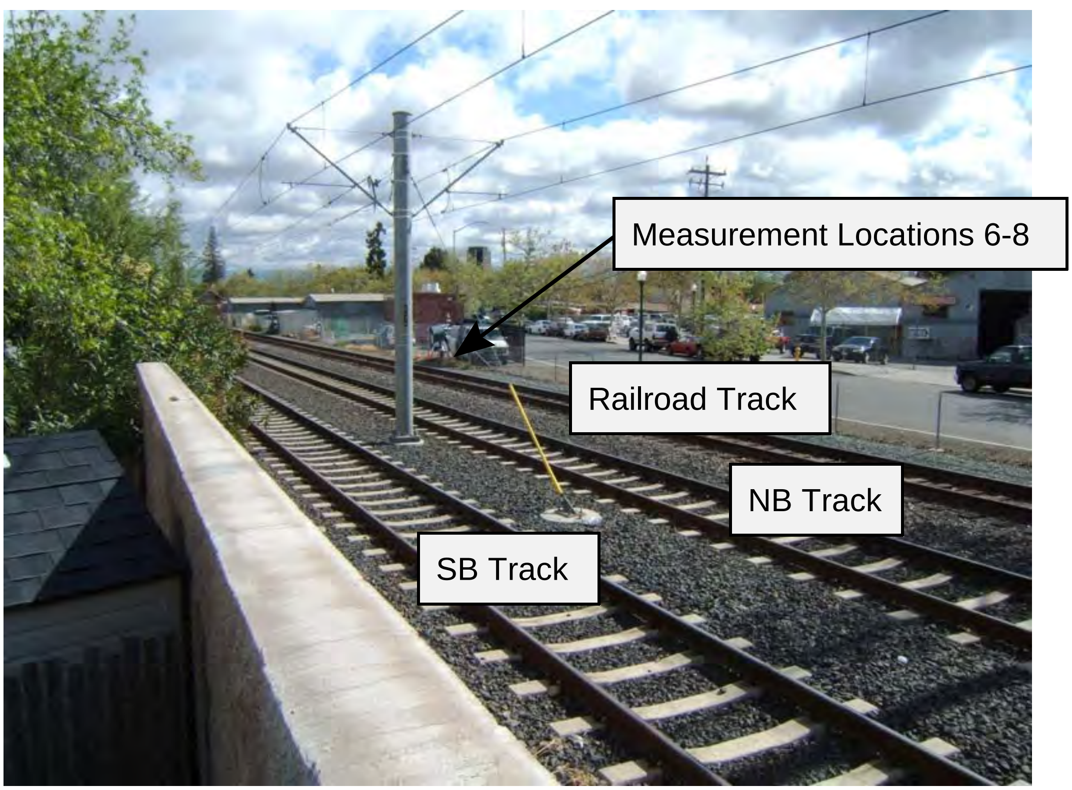


FIGURE 3 - SITE 1 VIEW FROM TOP OF WEST BARRIER WALL

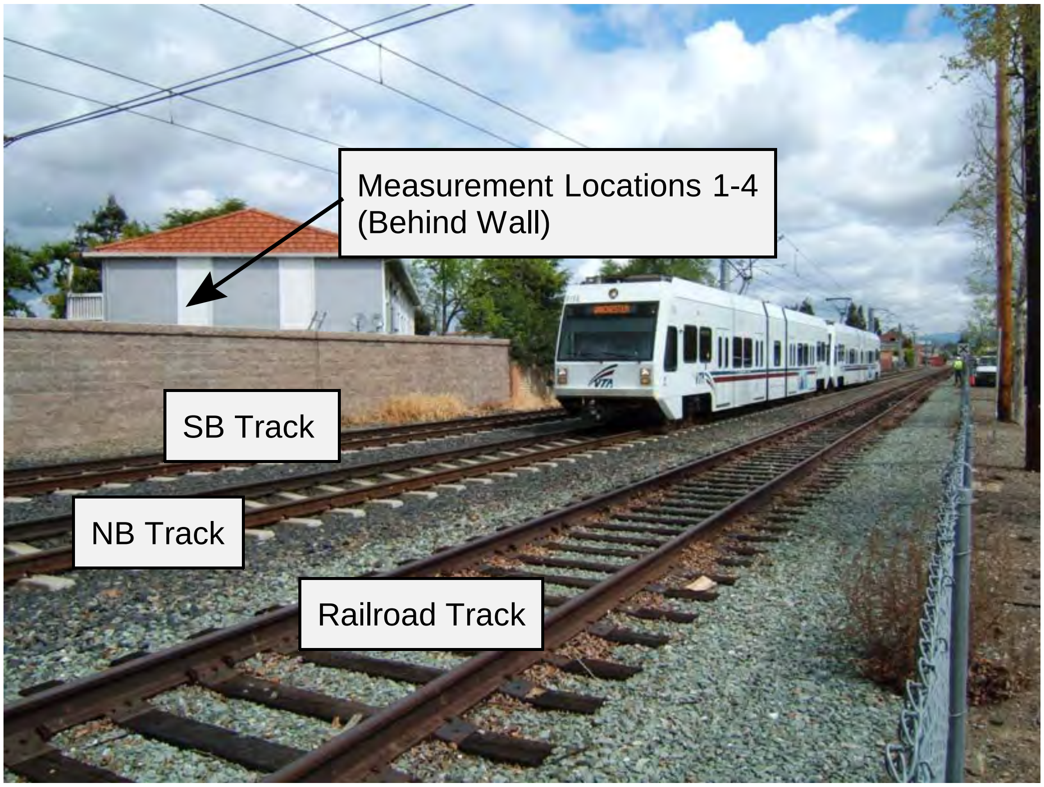


FIGURE 4 - SITE 1 WITH SB TEST TRAIN ON NB TRACK

FIGURE 5 - OPTICAL RAIL DEFLECTION MEASURE DEVICE AT SITE 1

FIGURE 6 - RAIL CONDITION AT SITE 1

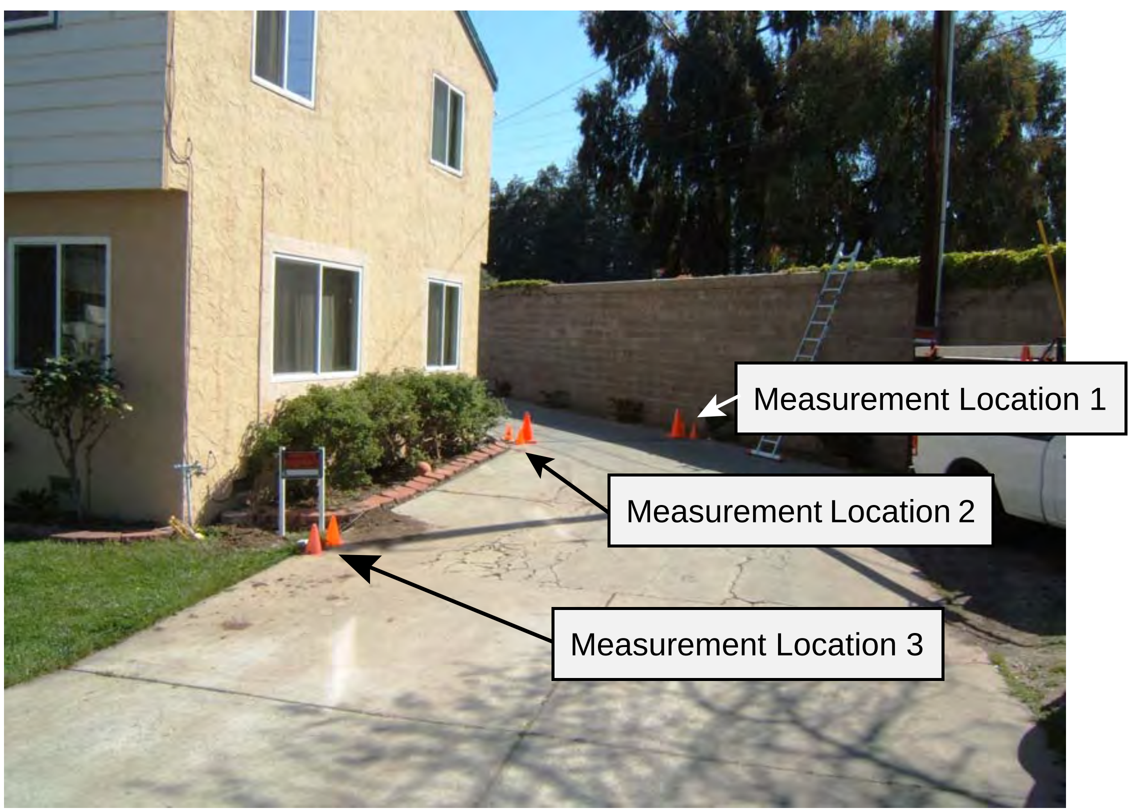


FIGURE 7-SITE 3 WEST SIDE OF ALIGNMENT BY 1102 LEIGH AVE.

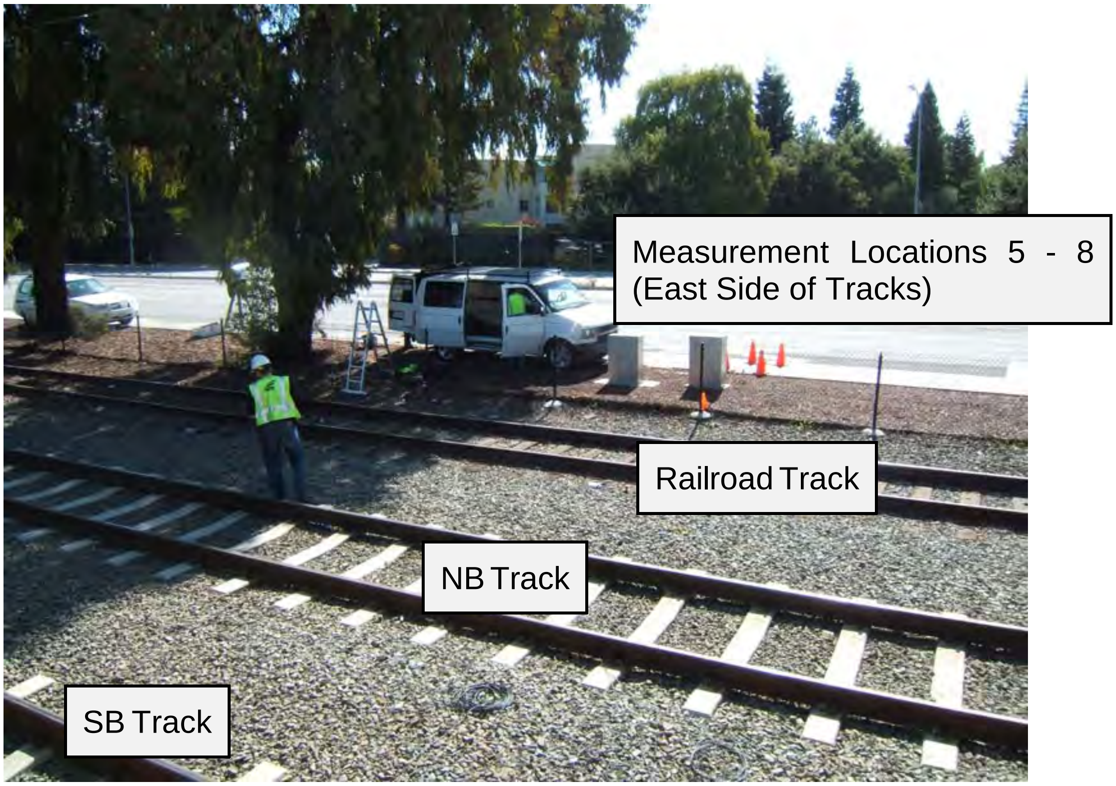


FIGURE 8 - SITE 3 VIEW LOOKING EAST FROM TOP OF SOUND WALL

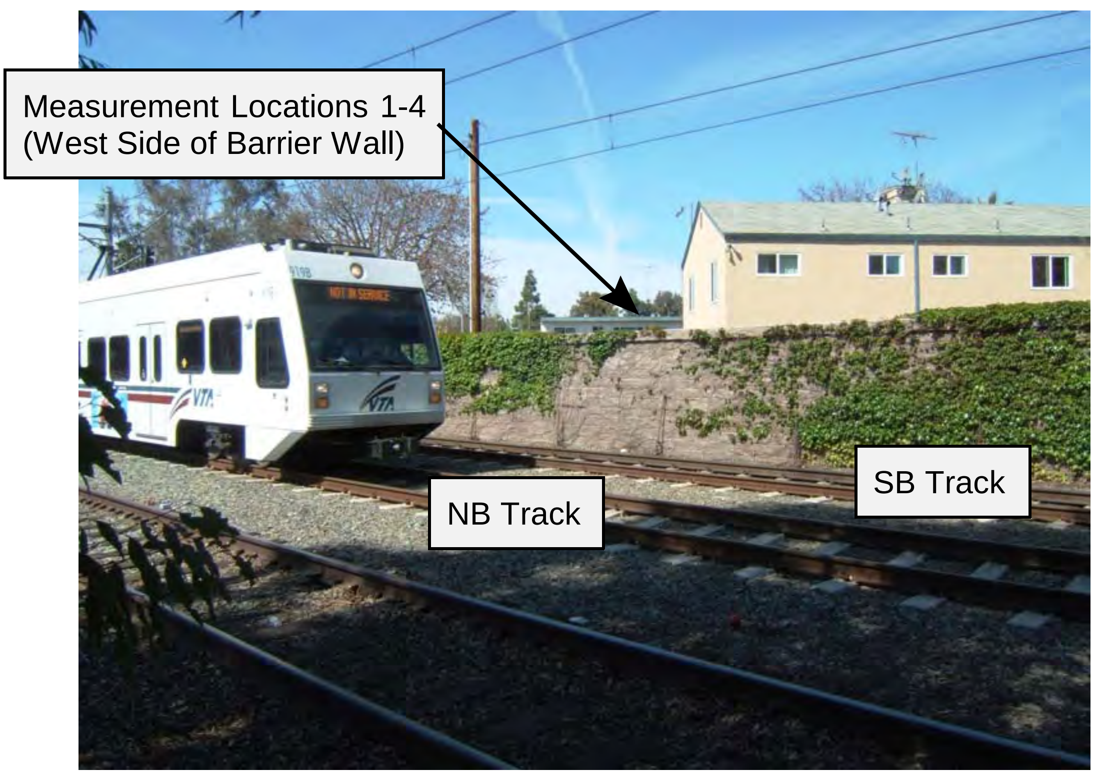


FIGURE 9 - SITE 3 WITH TEST TRAIN TRAVELING ON NB TRACK

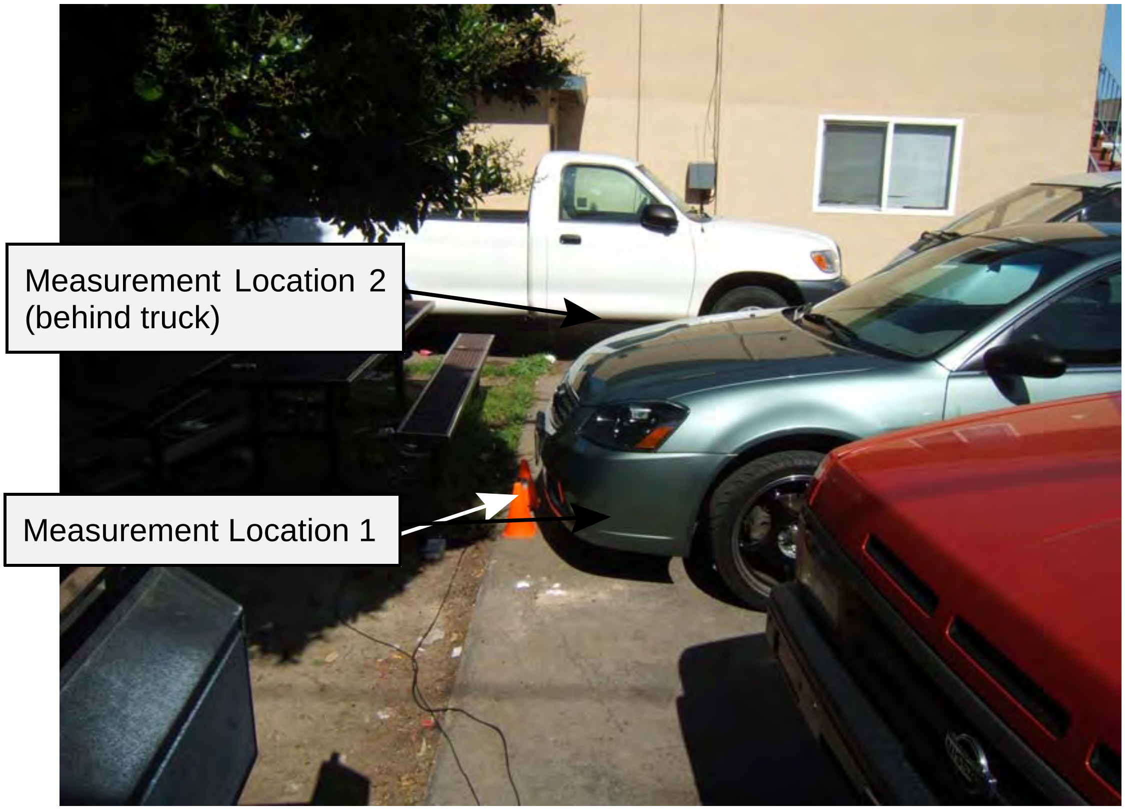


FIGURE 10 - SITE 4 MEASUREMENT LOCATIONS 1 & 2 (WEST OF WALL)

FIGURE 11 - SITE 4 MEASUREMENT LOCATIONS 3 & 4 (WEST OF WALL)

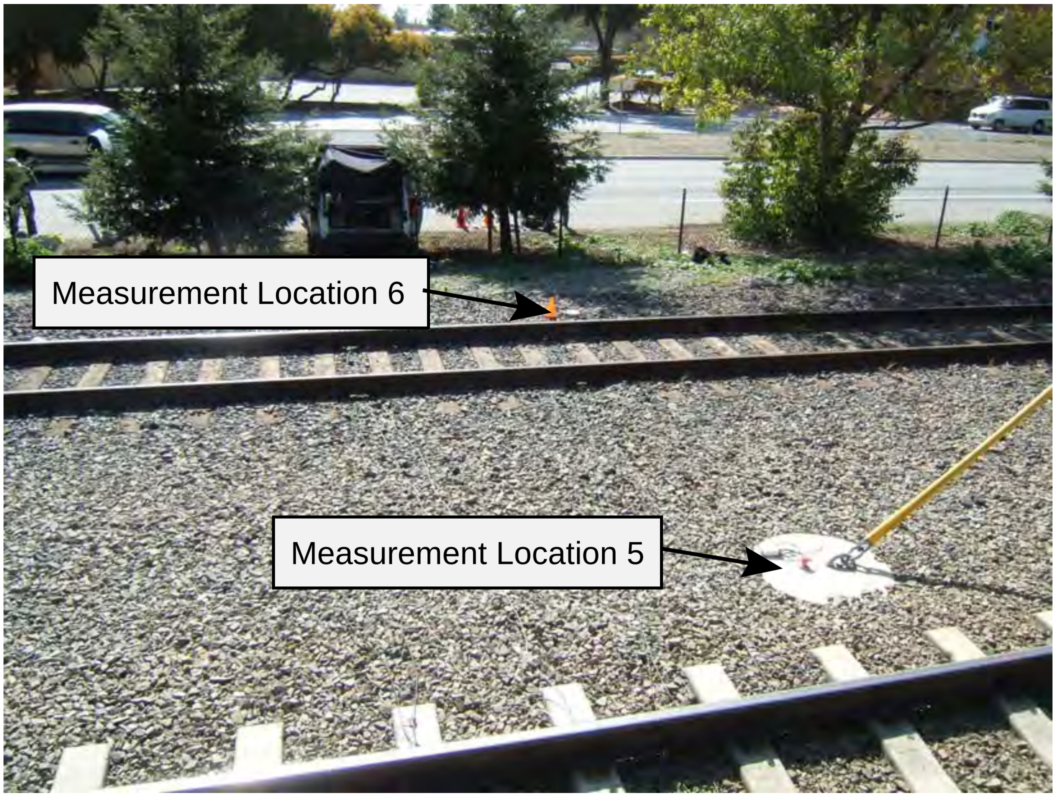


FIGURE 12 - SITE 4 LOOKING EAST AT MEASUREMENT LOCATIONS 5 & 6

FIGURE 13 - SITE 4 LOOKING SOUTH FROM BARRIER WALL WITH REVENUE TRAIN TRAVELING NB ON SINGLE TRACK

FIGURE 14 - CONTROL SITE 1 LOOKING NORTH (FROM 2005 TESTS)

FIGURE 15 - CONTROL SITE 1 WITH TEST TRAIN TRAVELING NB ON NB TRACK (FROM 2006 TESTS)

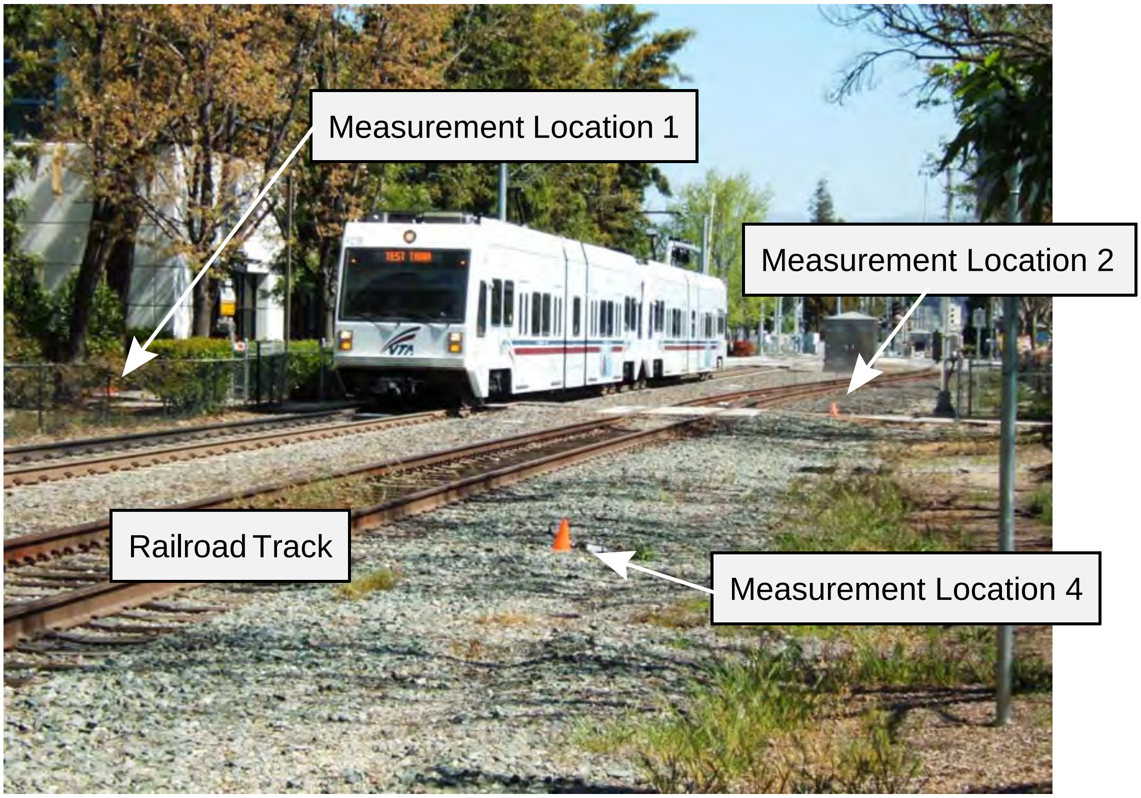


FIGURE 16 - CONTROL SITE 2 LOOKING NORTH

FIGURE 17 - CONTROL SITE 2 LOOKING SOUTH WITH NB TEST TRAIN ON SINGLE TRACK

FIGURE 18 - STRAIN GAGE INSTALLATION AT SITE 1 (FROM 2005 TESTS)

FIGURE 19 - MEASUREMENT MONITORING AND RECORDING INSTRUMENTATION (FROM 2006 TESTS)

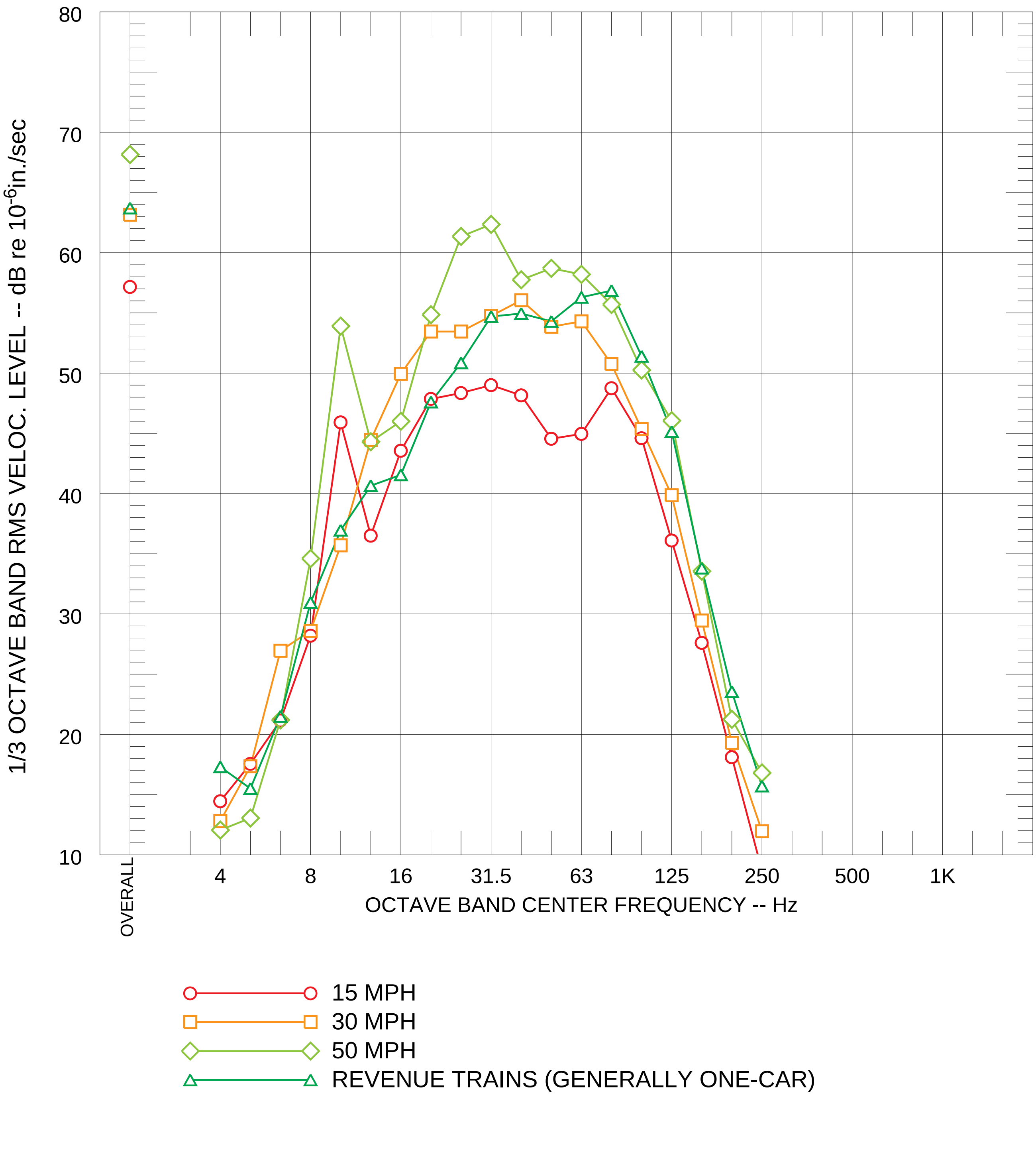


FIGURE 20 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #1 (NORTH OF KENNEDY AVE./RAILWAY AVE.)-25 FT WEST OF TRACK CENTERLINE

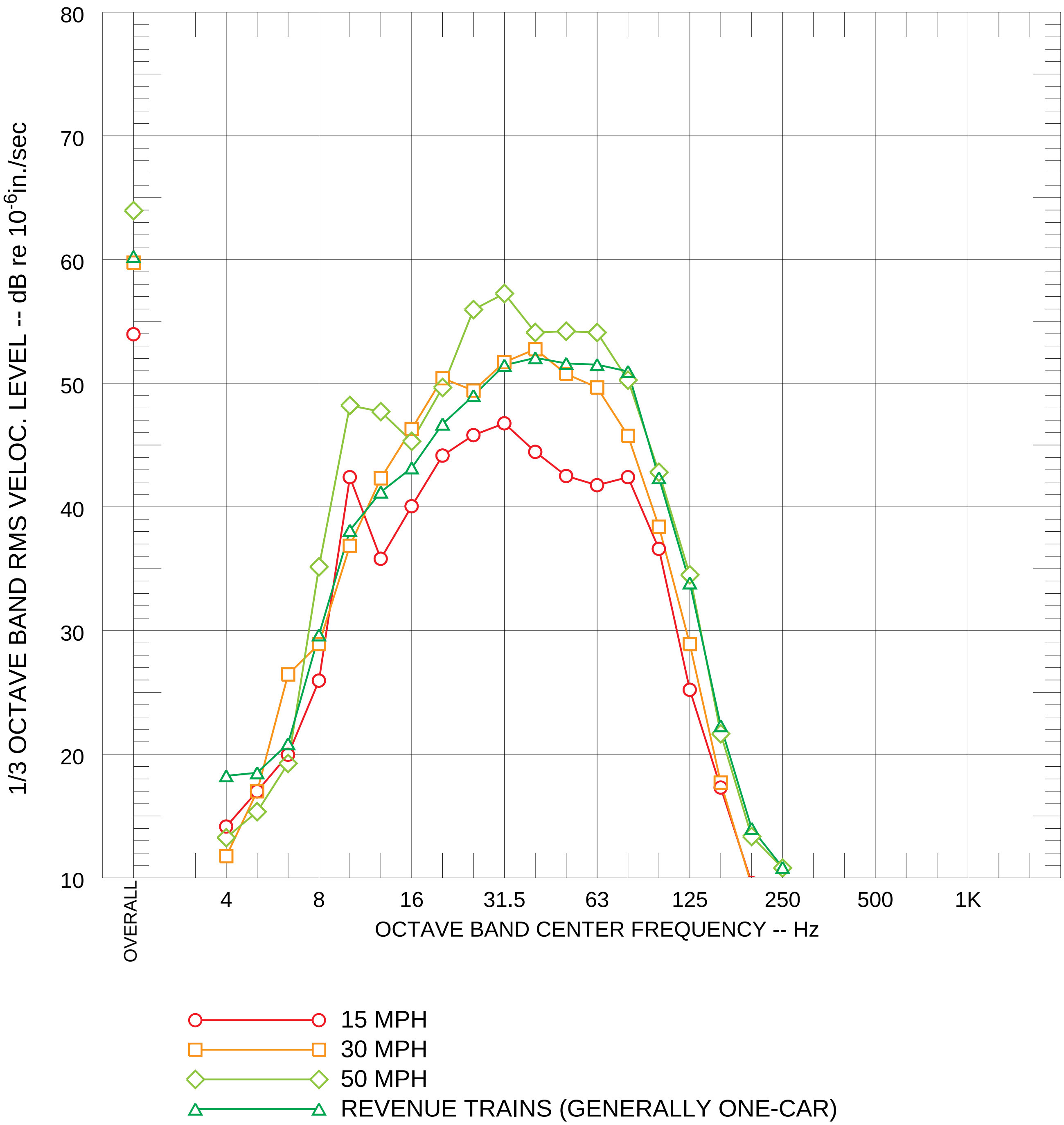


FIGURE 21 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #1 (NORTH OF KENNEDY AVE./RAILWAY AVE.)-50 FT WEST OF TRACK CENTERLINE

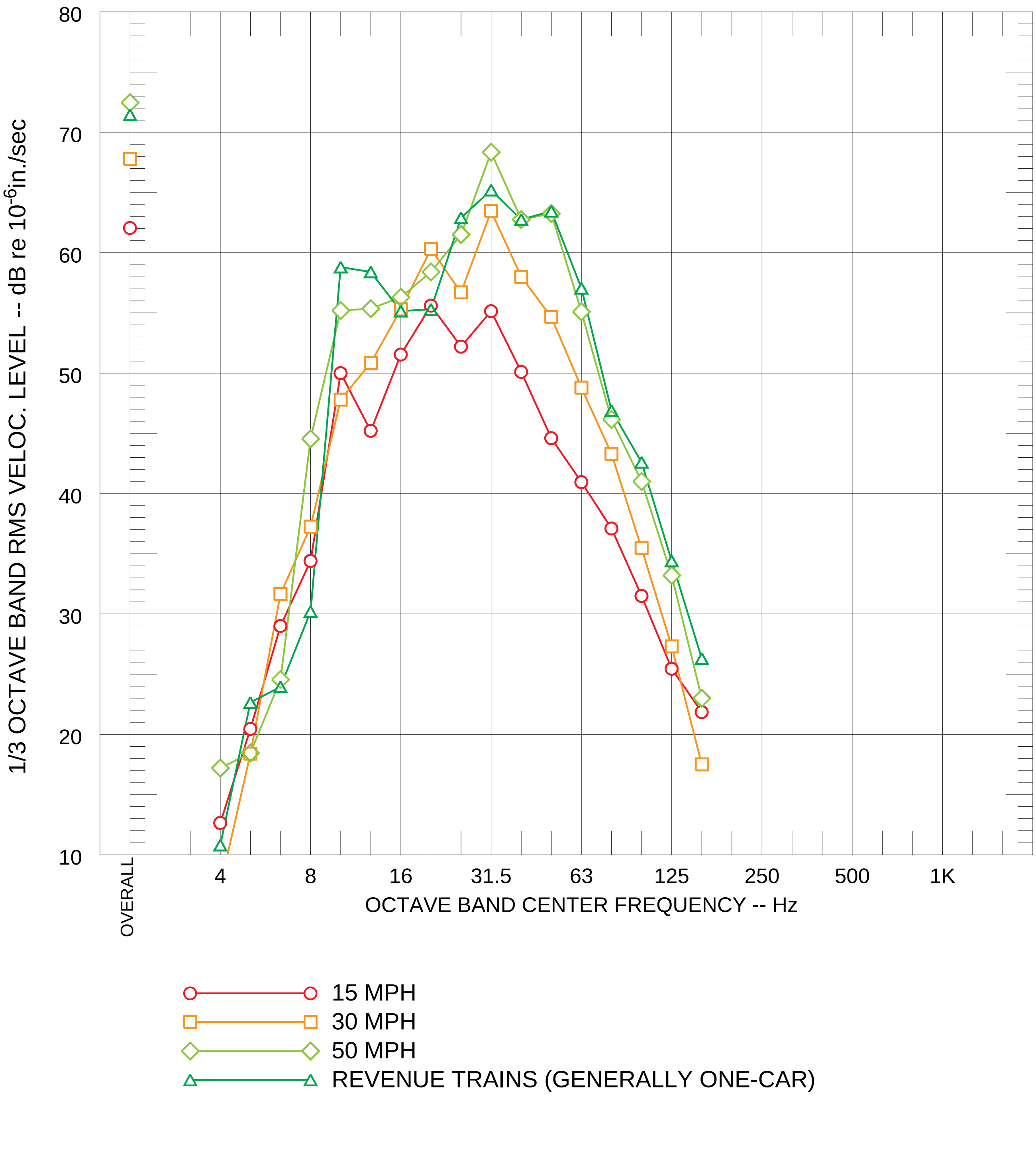


FIGURE 22 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #3 (NORTH OF LEIGH AVE.) - 25 FT FROM NB TRACK CENTERLINE

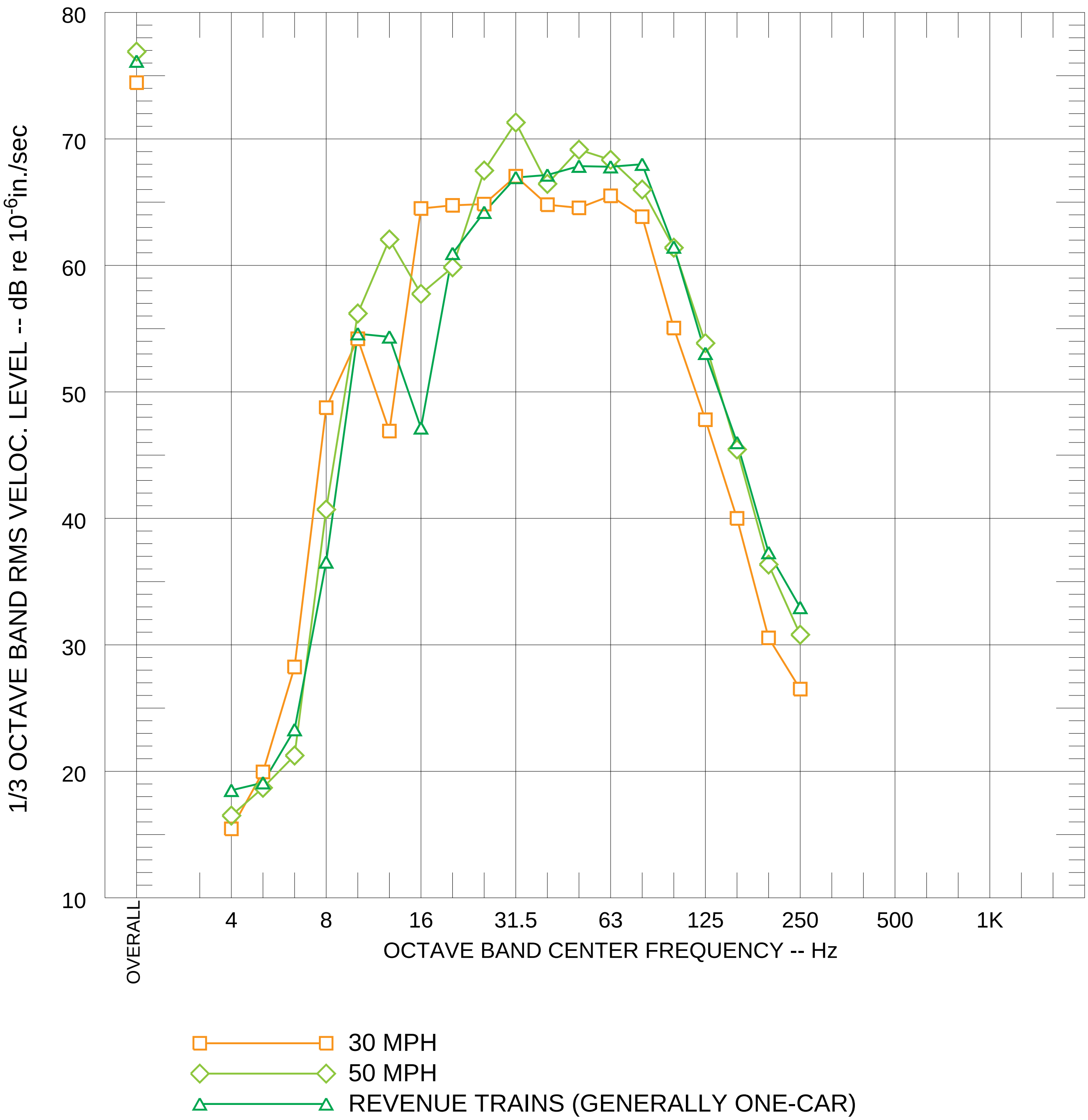


FIGURE 23 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #3 (NORTH OF LEIGH AVE.) - 25 FT FROM SB TRACK CENTERLINE

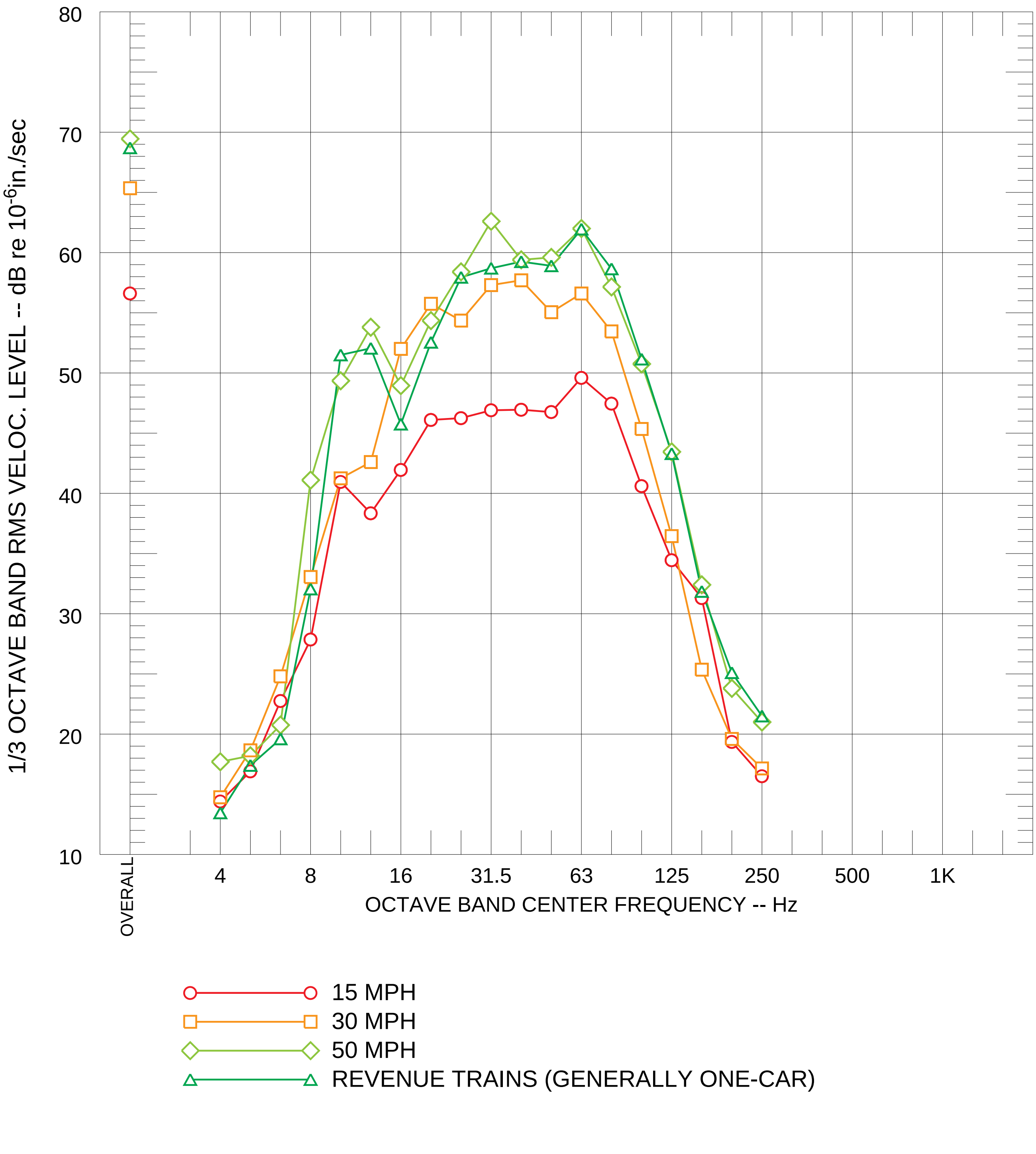


FIGURE 24 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #3 (NORTH OF LEIGH AVE.) - 50 FT FROM TRACK CENTERLINE

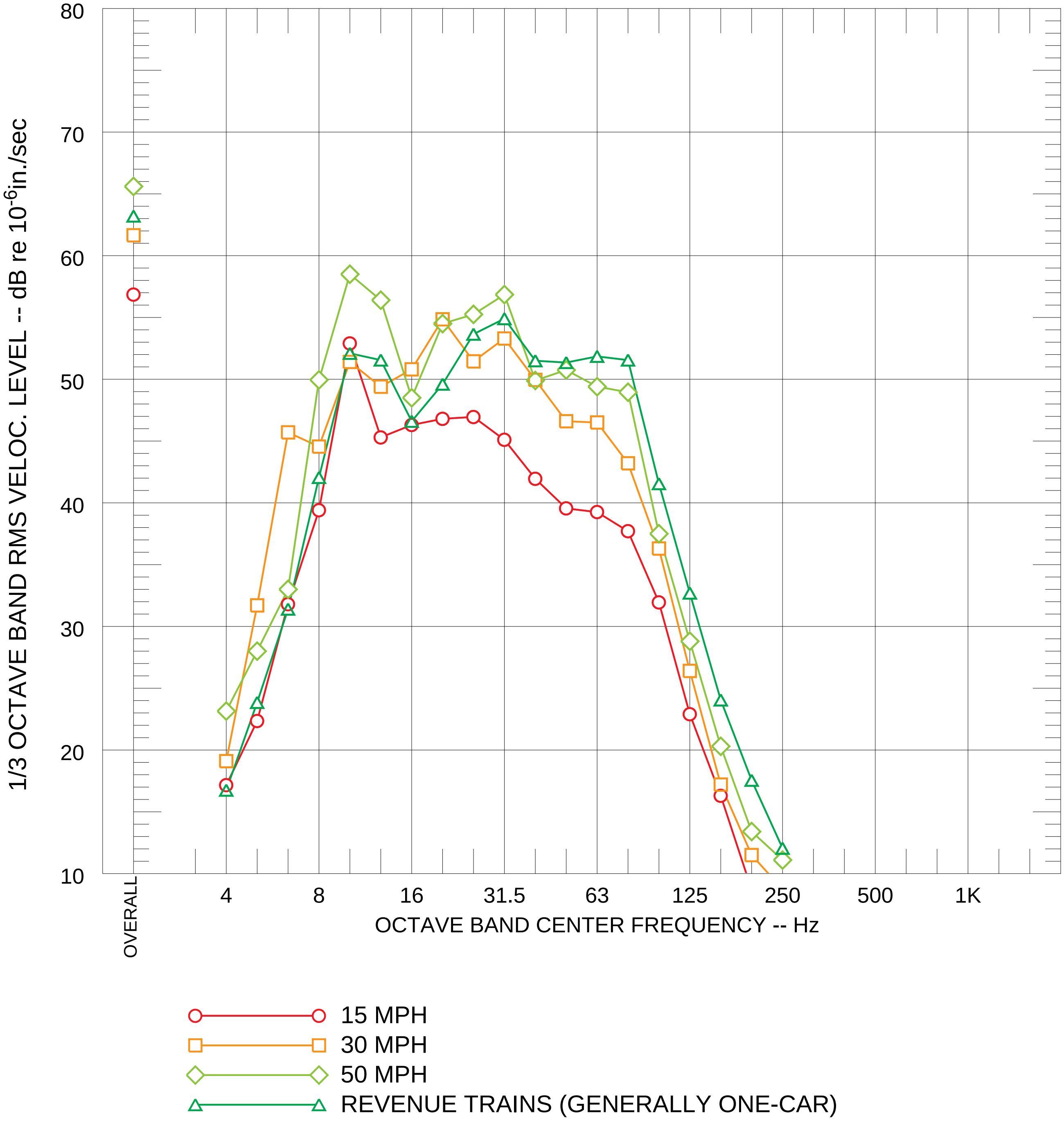


FIGURE 25 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #4 (BETWEEN FRUITDALE & MERIDIAN AVES./DELAND AVE.) - 25 FT WEST OF TRACK CENTERLINE

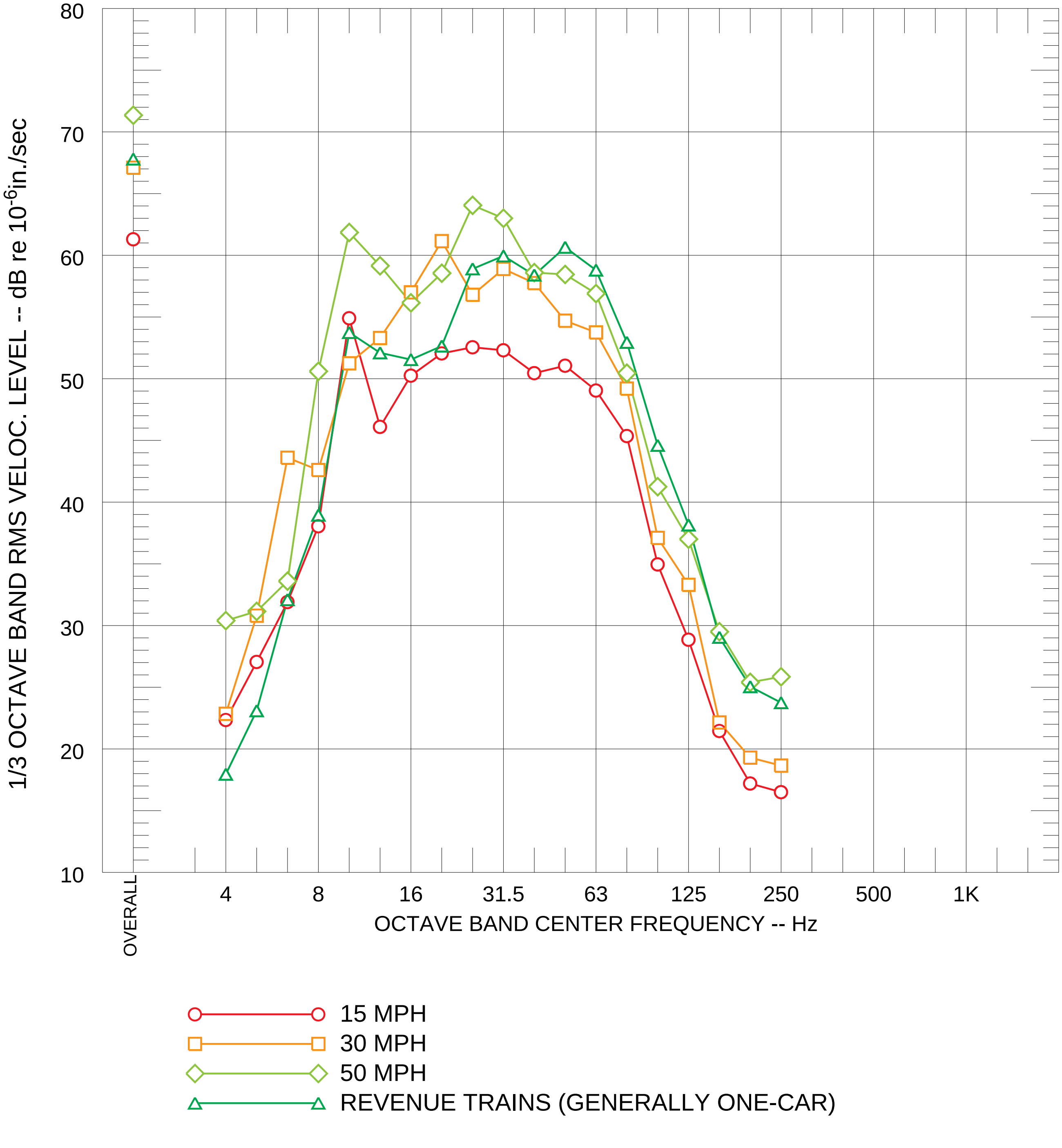


FIGURE 26 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #4 (BETWEEN FRUITDALE & MERIDIAN AVES./DELAND AVE.) - 25 FT EAST OF TRACK CENTERLINE

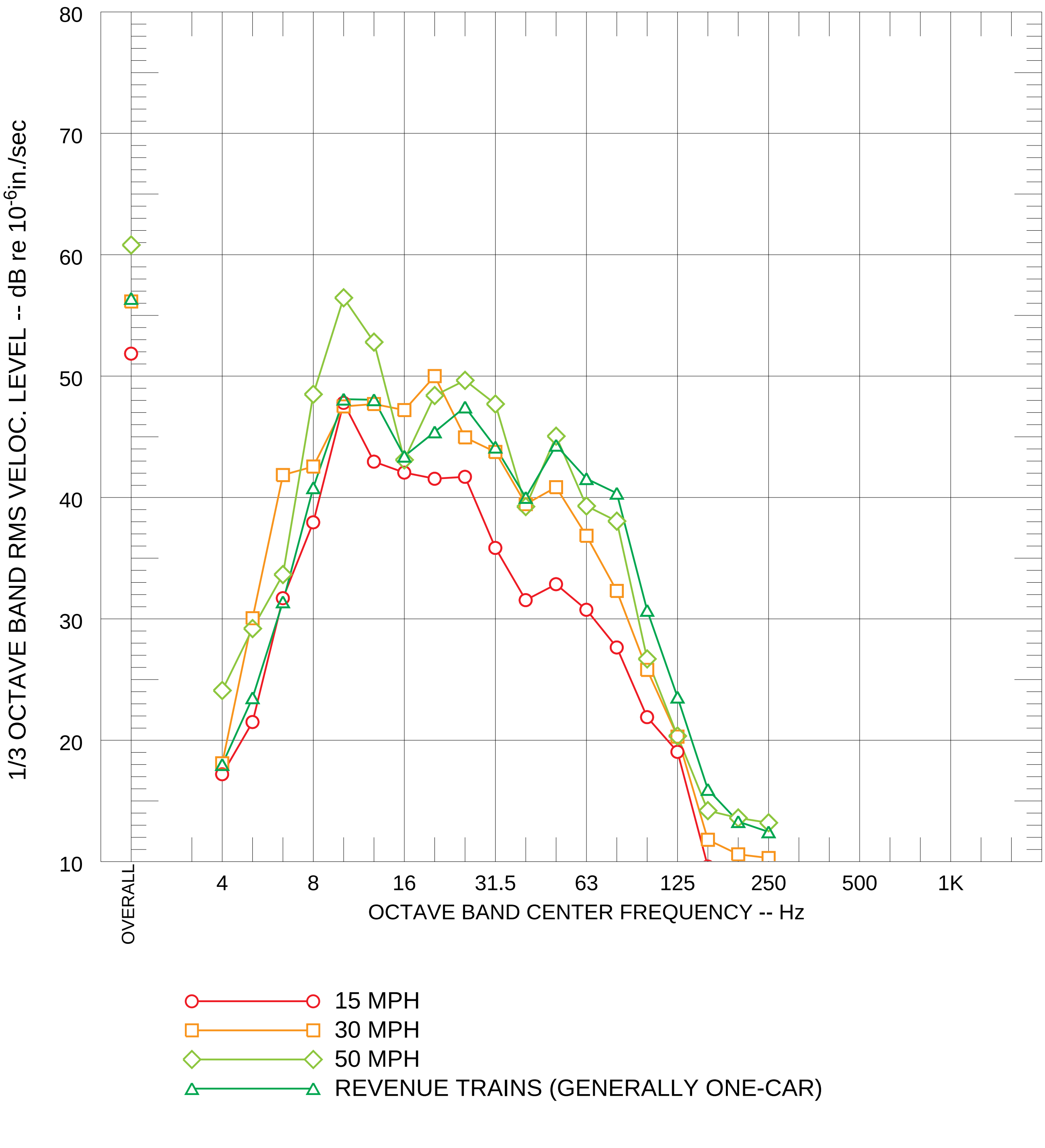


FIGURE 27 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #4 (BETWEEN FRUITDALE & MERIDIAN AVES./DELAND AVE.) - 50 FT WEST OF TRACK CENTERLINE

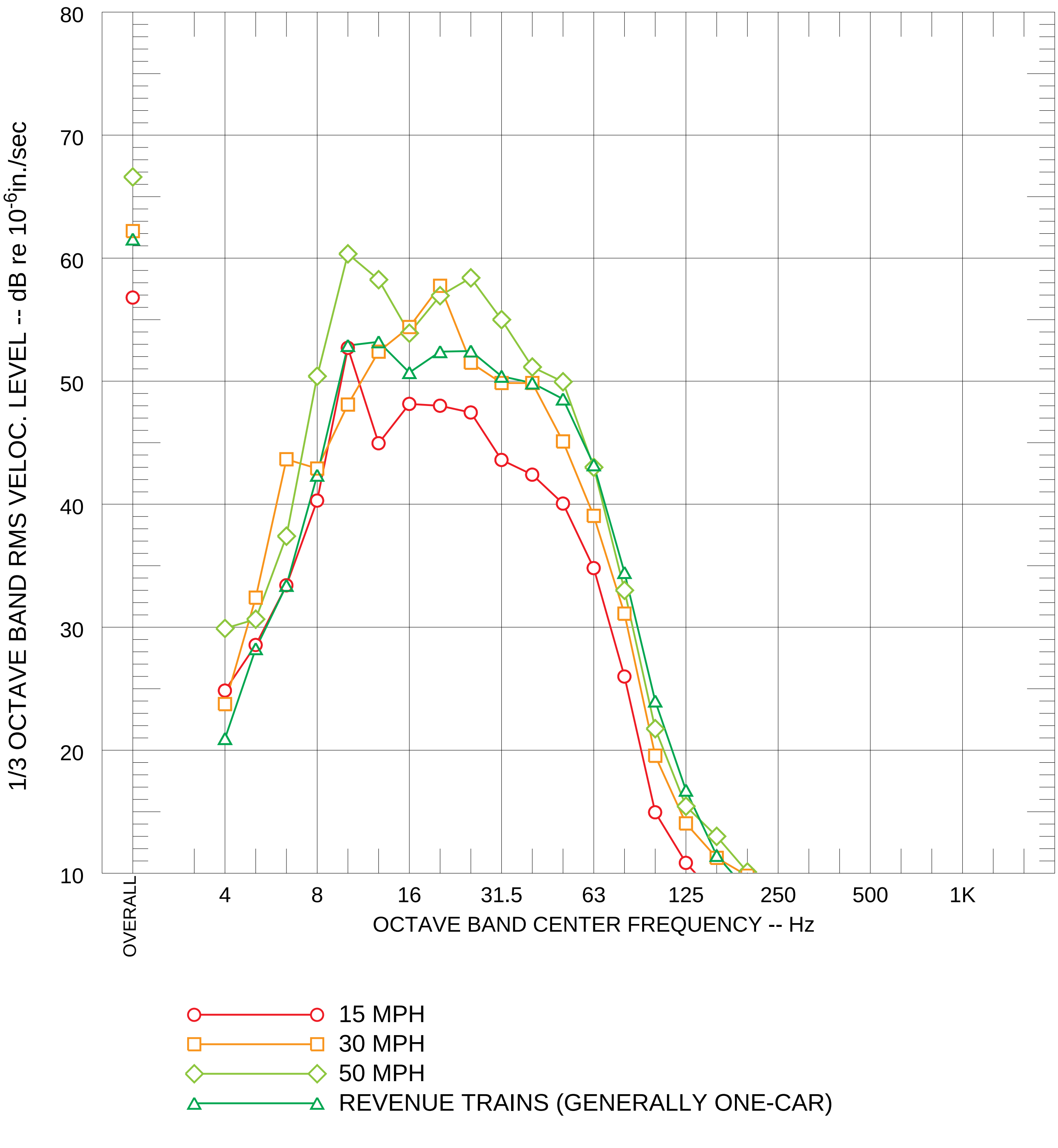


FIGURE 28 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #4 (BETWEEN FRUITDALE & MERIDIAN AVES./DELAND AVE.) - 50 FT EAST OF TRACK CENTERLINE

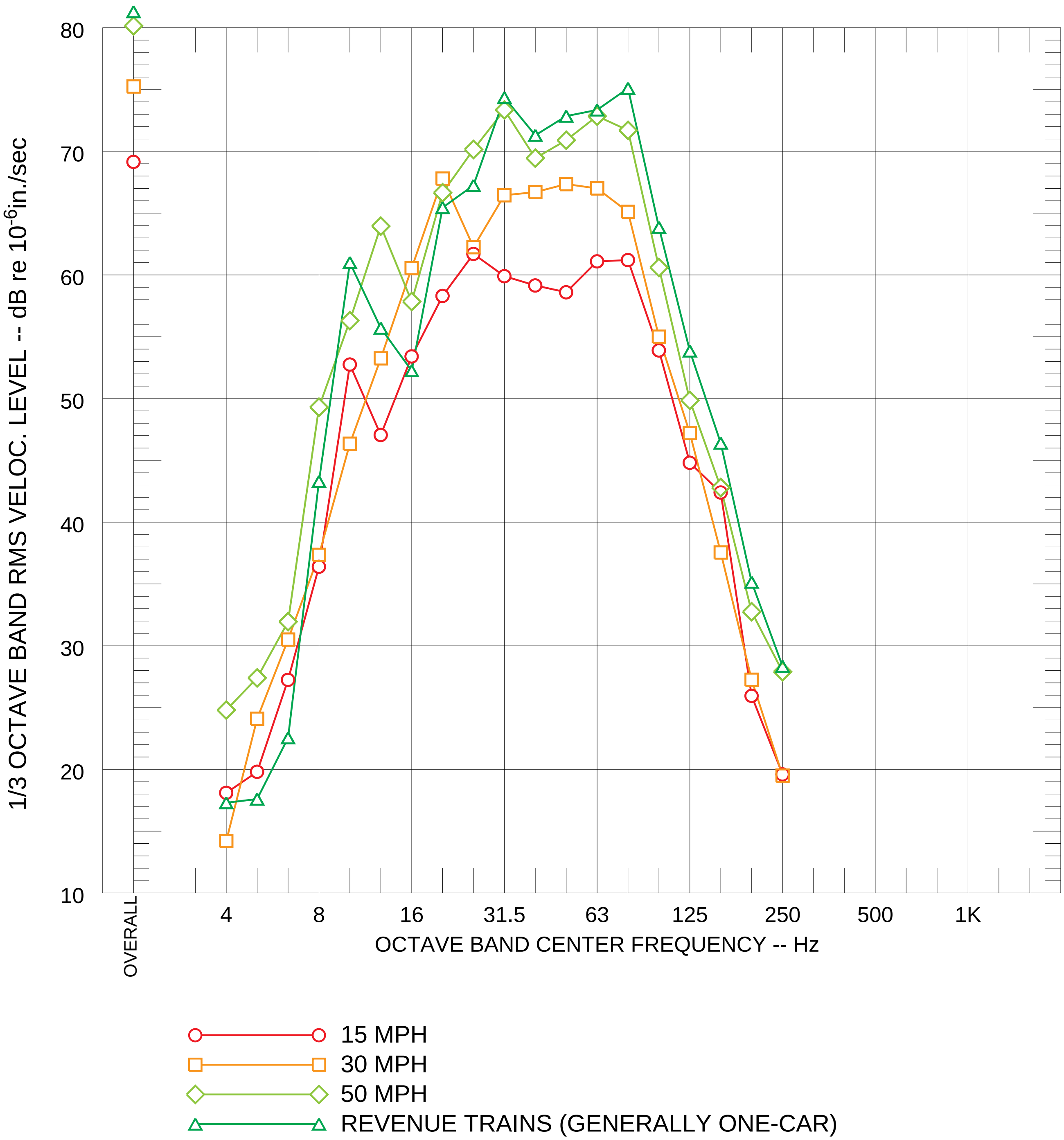


FIGURE 29 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #1 (NORTH OF STOKES ST.) - 25 FT EAST OF TRACK CENTERLINE

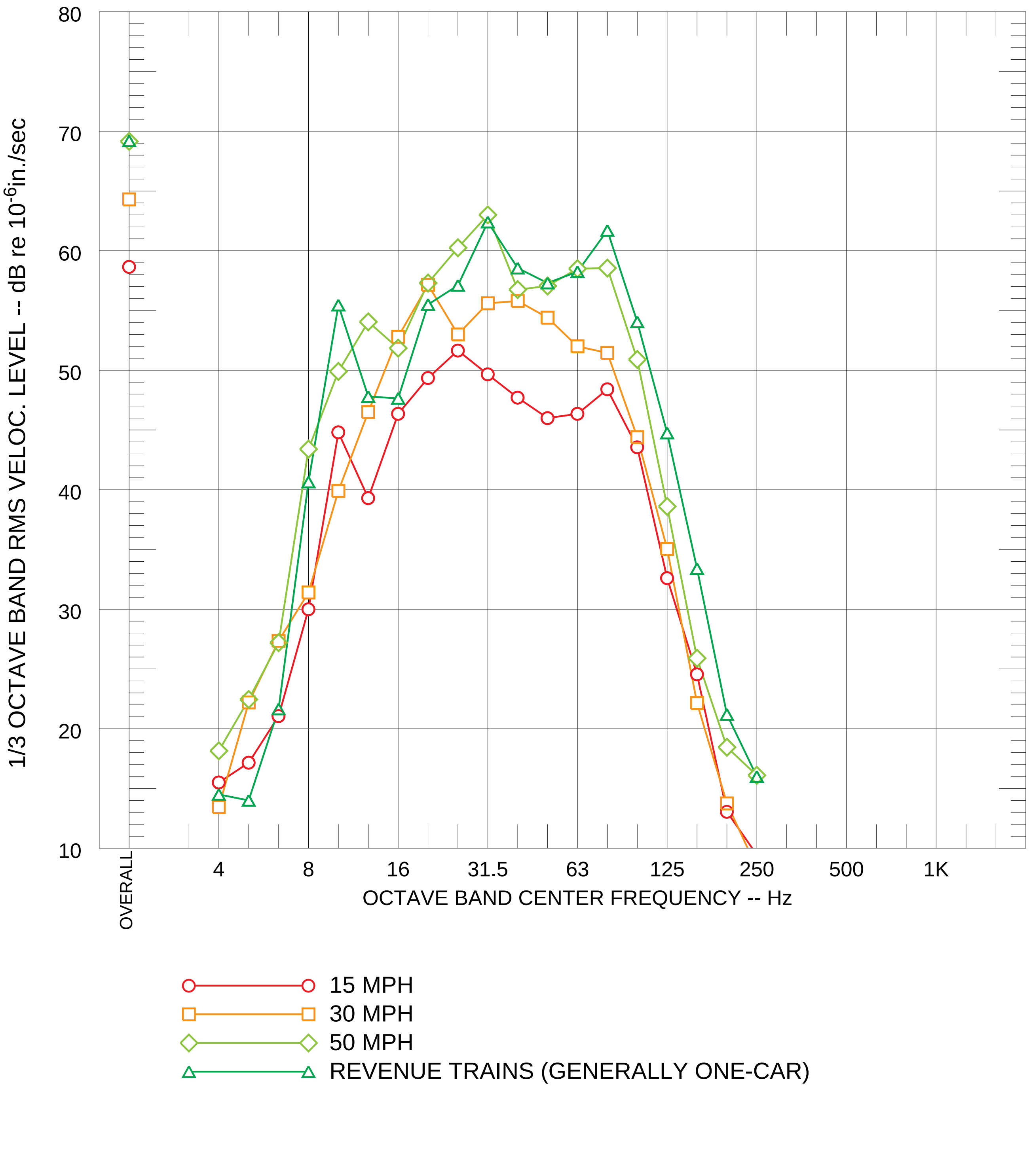


FIGURE 30 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #1 (NORTH OF STOKES ST.) - 50 FT FROM TRACK CENTERLINE

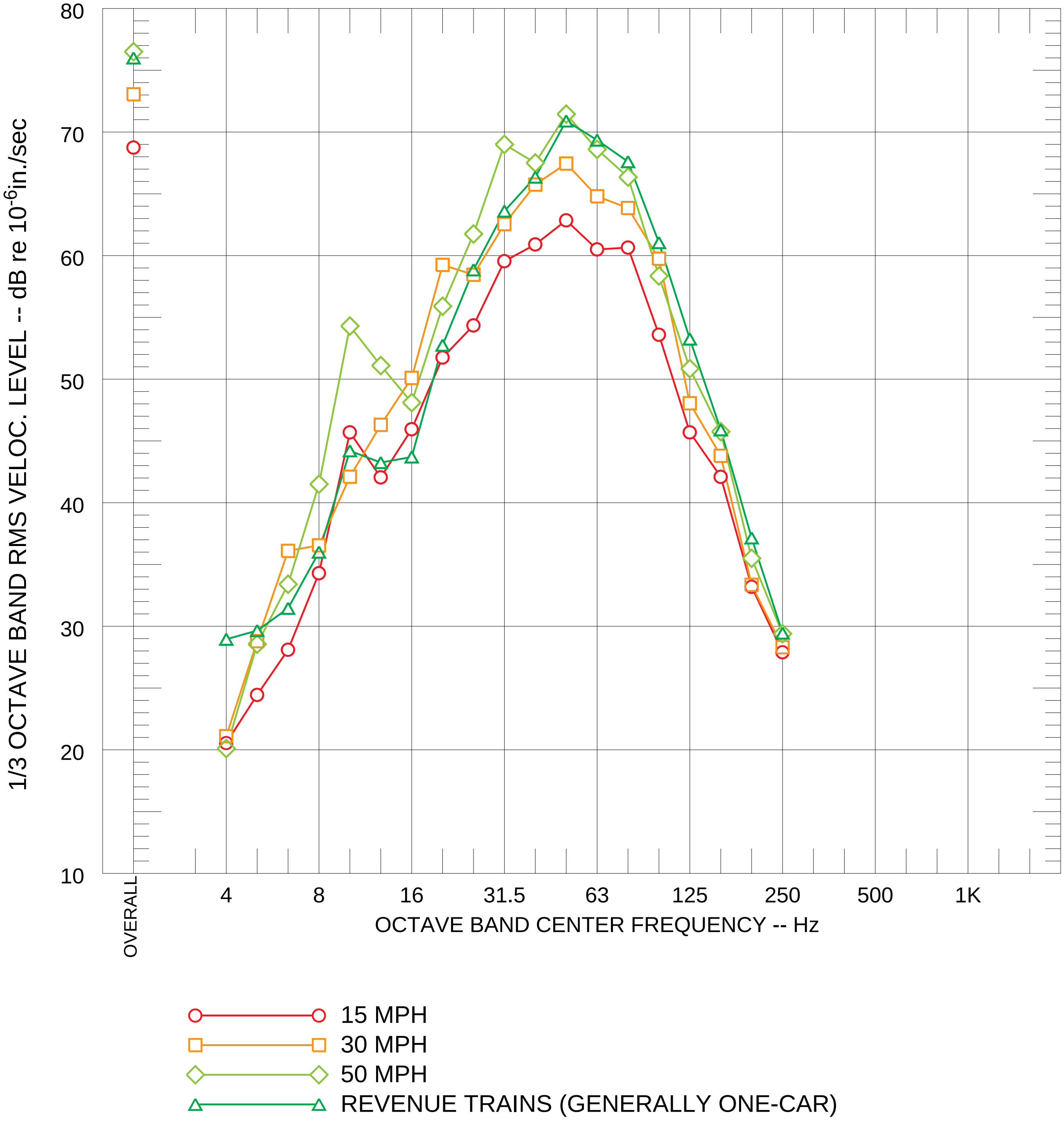


FIGURE 31 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #2 (SOUTH OF RACE ST.) - 25 FT FROM TRACK CENTERLINE (LOCS. 1&4)

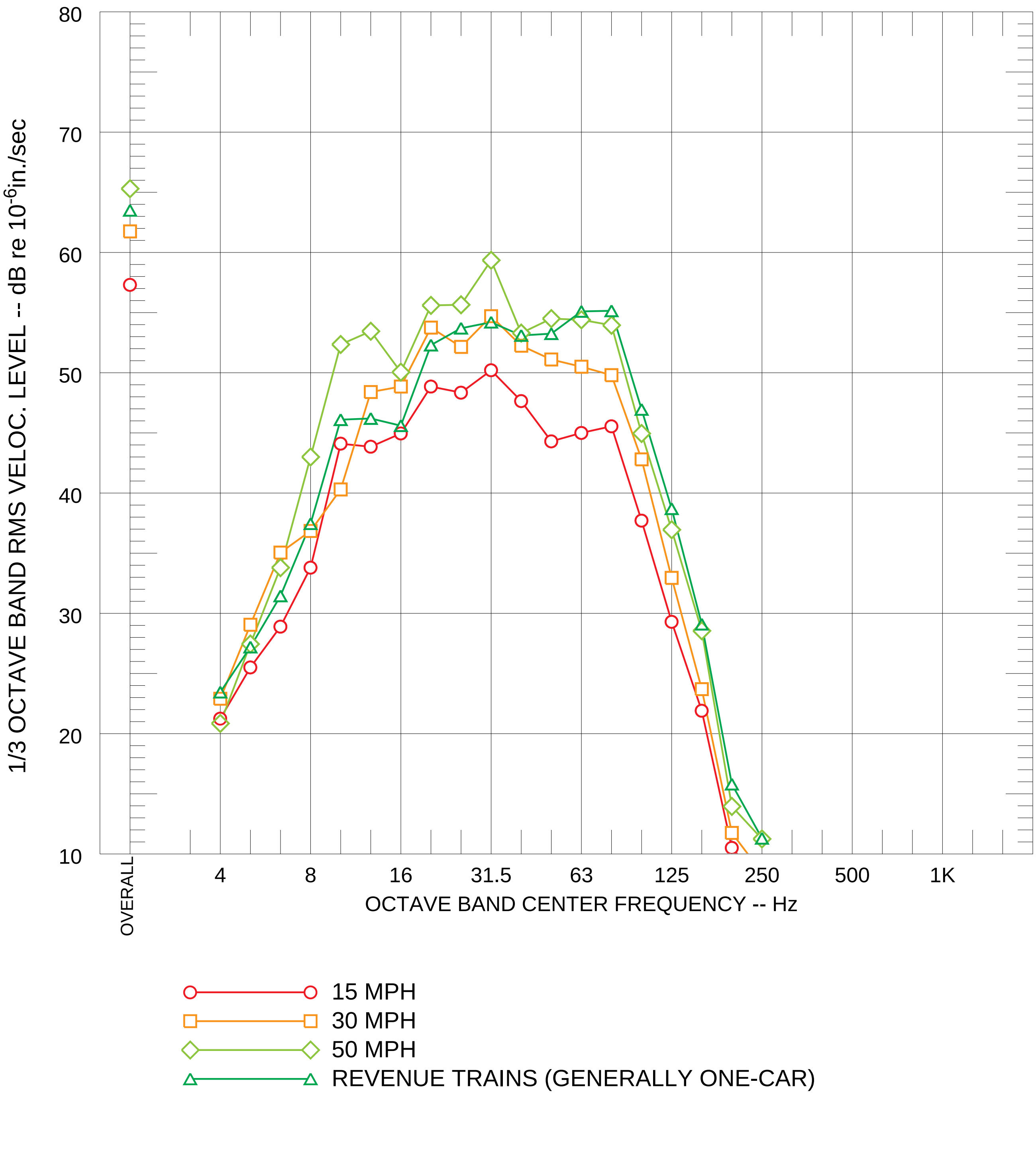


FIGURE 32 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #2 (SOUTH OF RACE ST.) - 50 FT FROM TRACK CENTERLINE

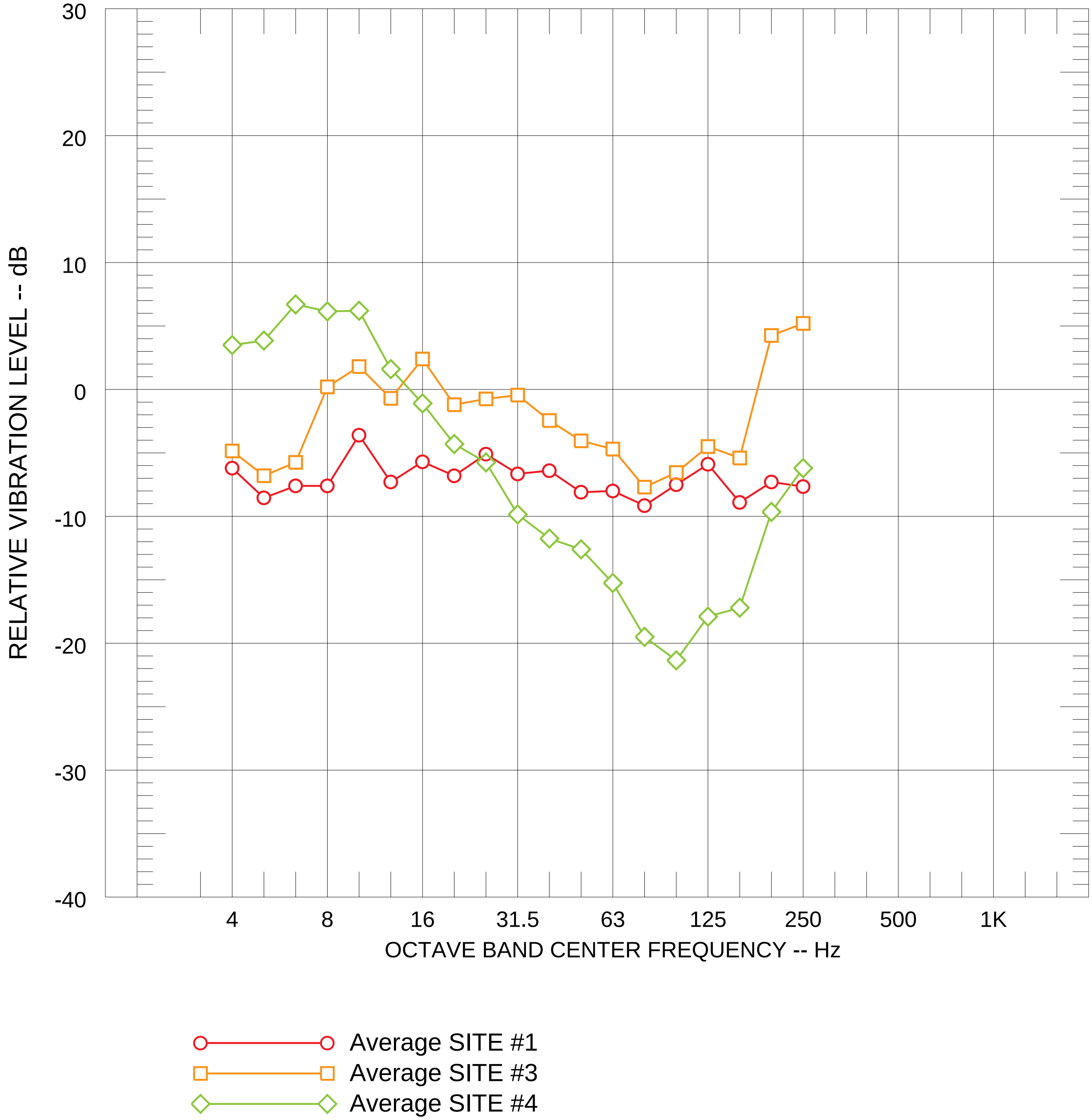


FIGURE 33 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN OPERATIONS FOR 3 TRAIN SPEEDS AND 2 MEASUREMENT DISTANCES

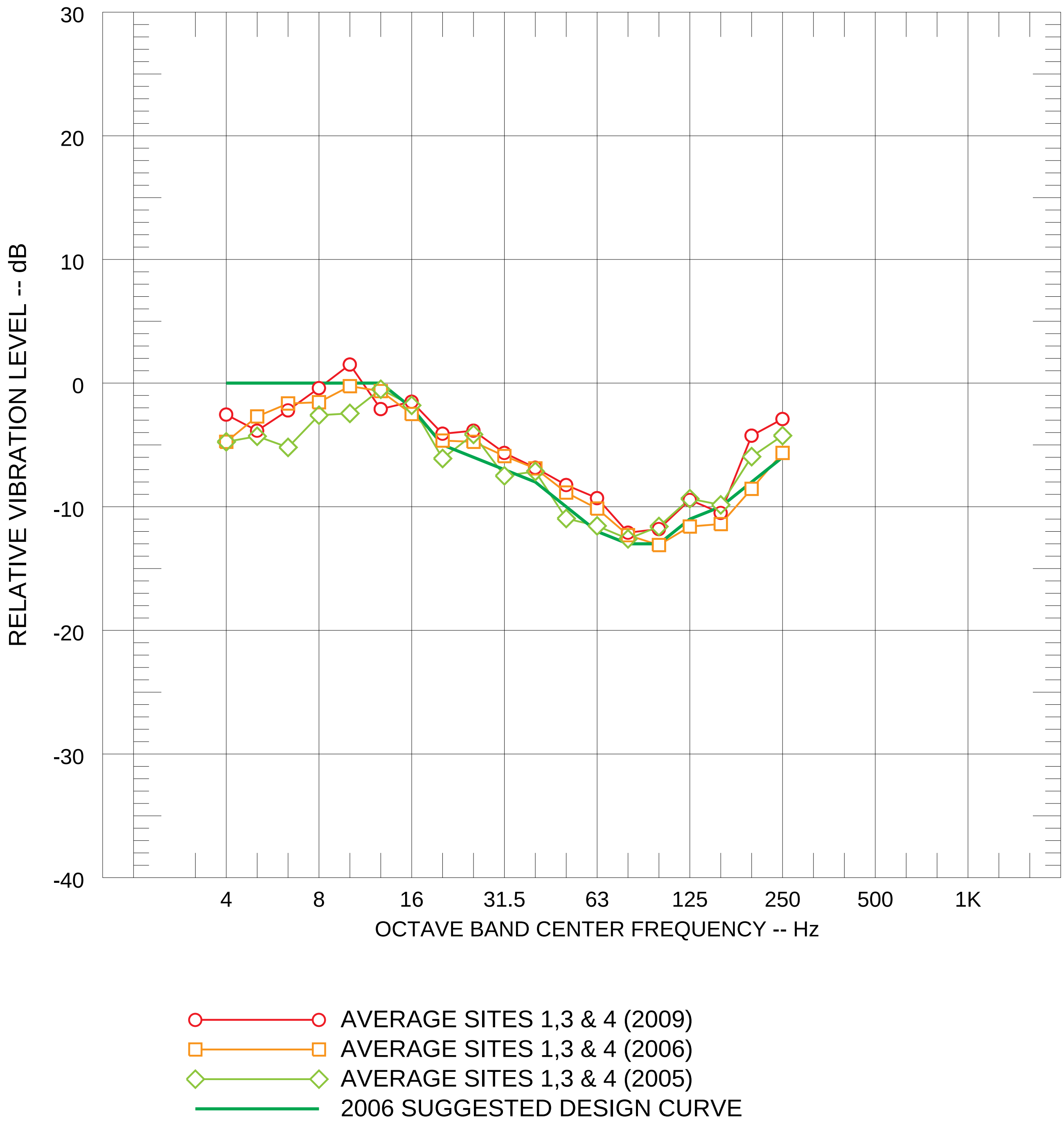


FIGURE 34 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN OPERATIONS FOR 3 TRAIN SPEEDS AND 2 MEASUREMENT DISTANCES

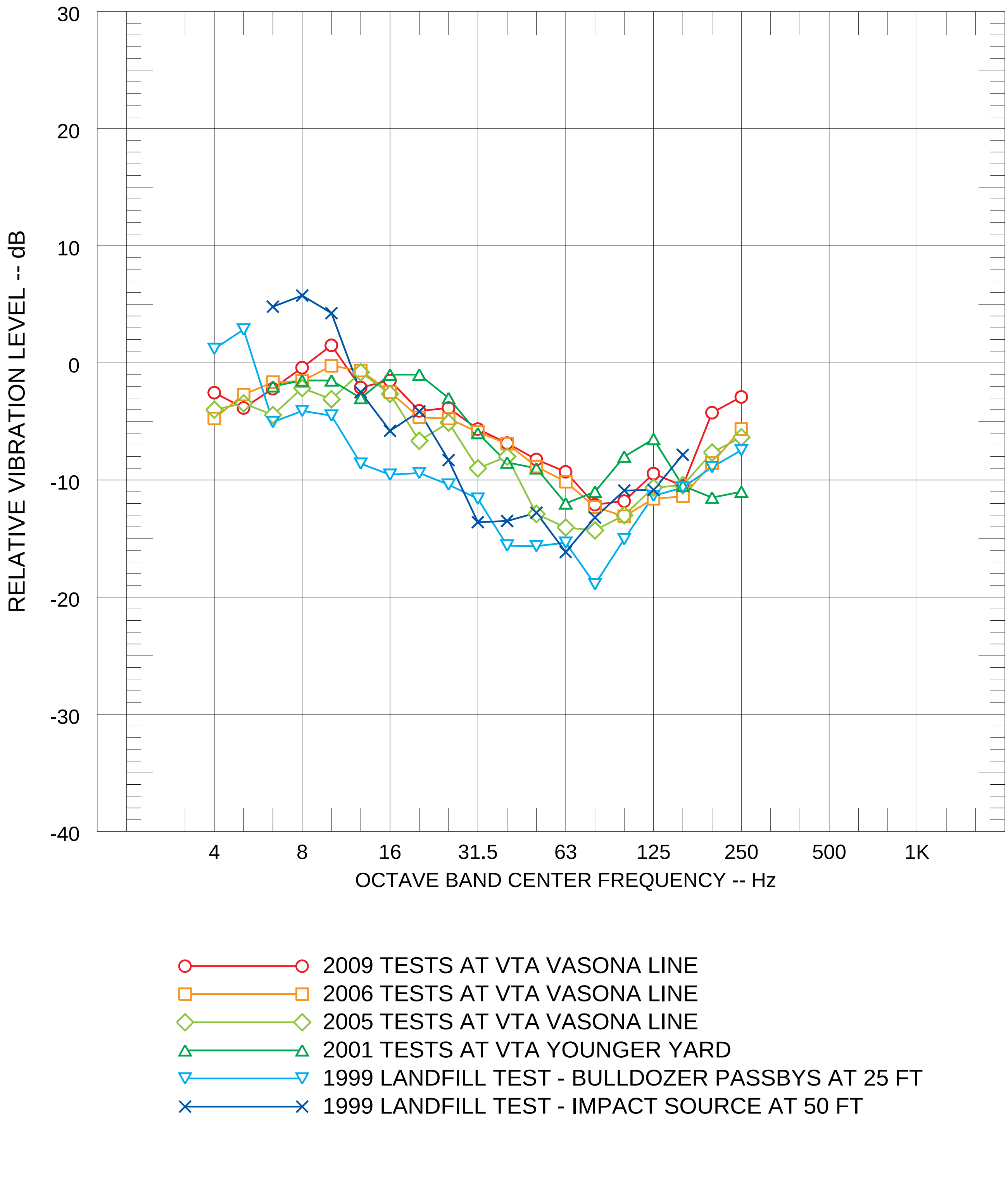


FIGURE 35 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - COMPARISON WITH PREVIOUS TESTS (REF. 1,2,4 & 5)

APPENDIX A

Detailed Plots of Groundborne Vibration

Page

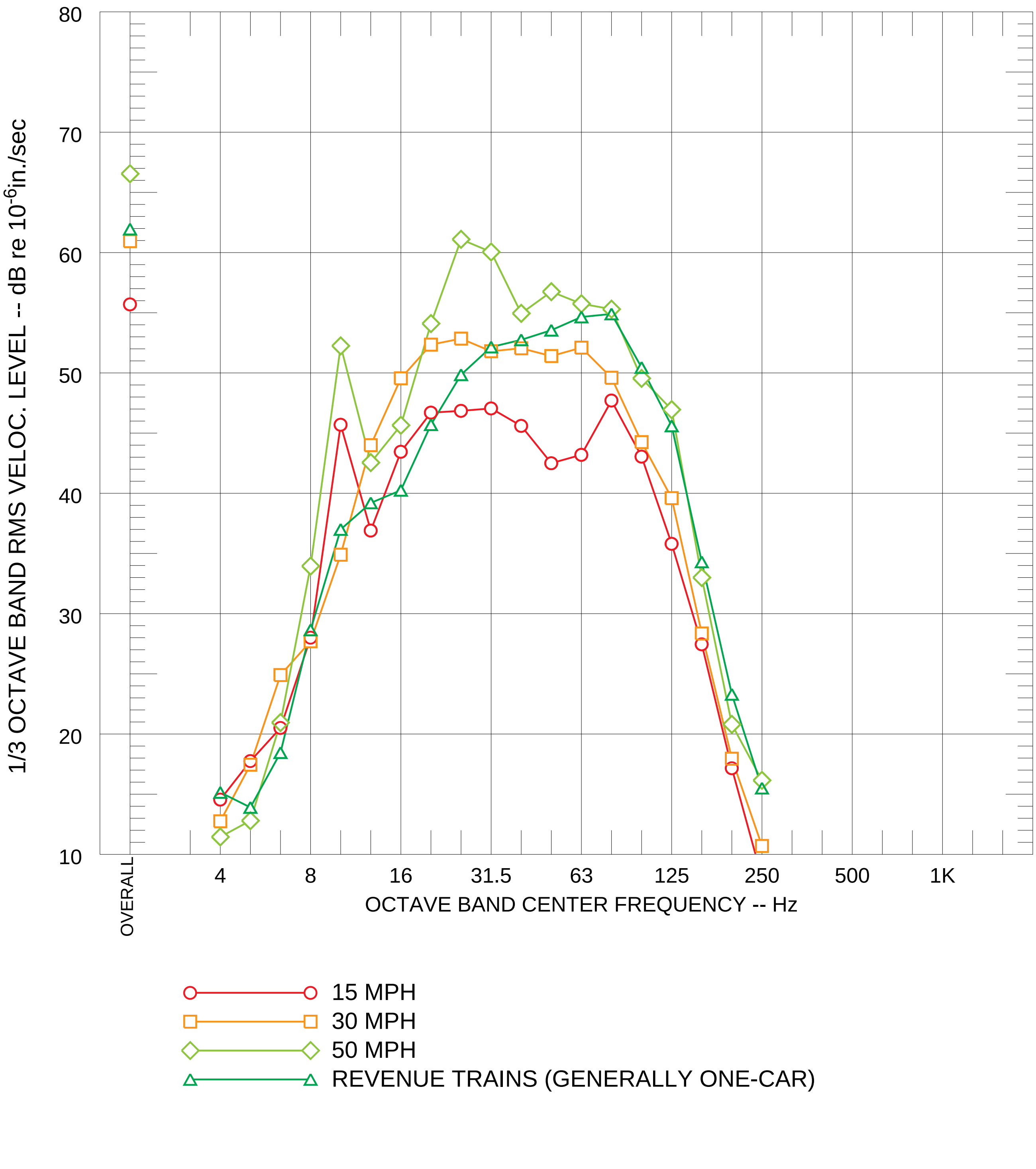


FIGURE A-1 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #1 - LOCATION 1 - 25 FT WEST OF TRACK CENTERLINE AT STATION 107+37

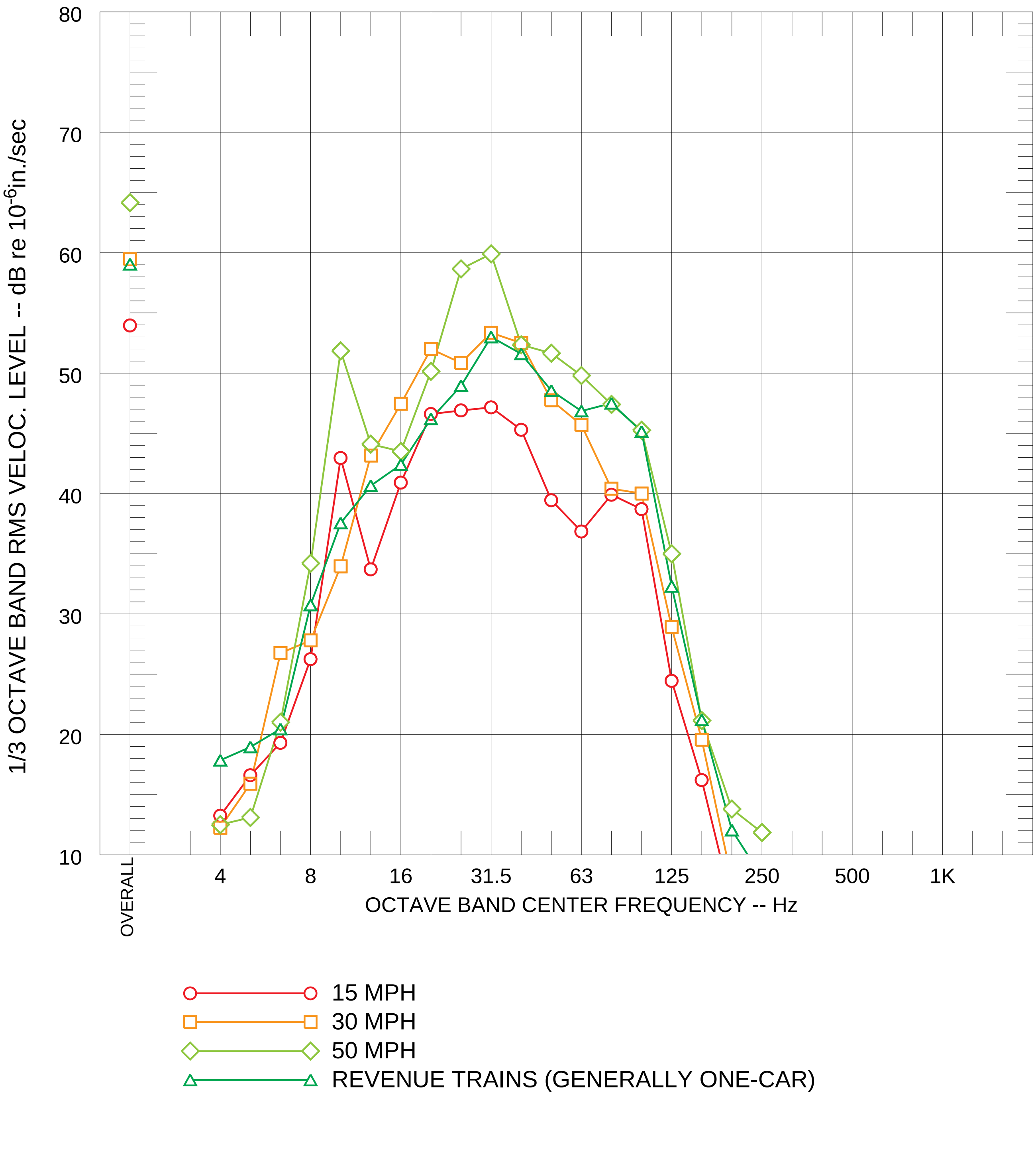


FIGURE A-2 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #1 - LOCATION 2 - 50 FT WEST OF TRACK CENTERLINE AT STATION 107+45

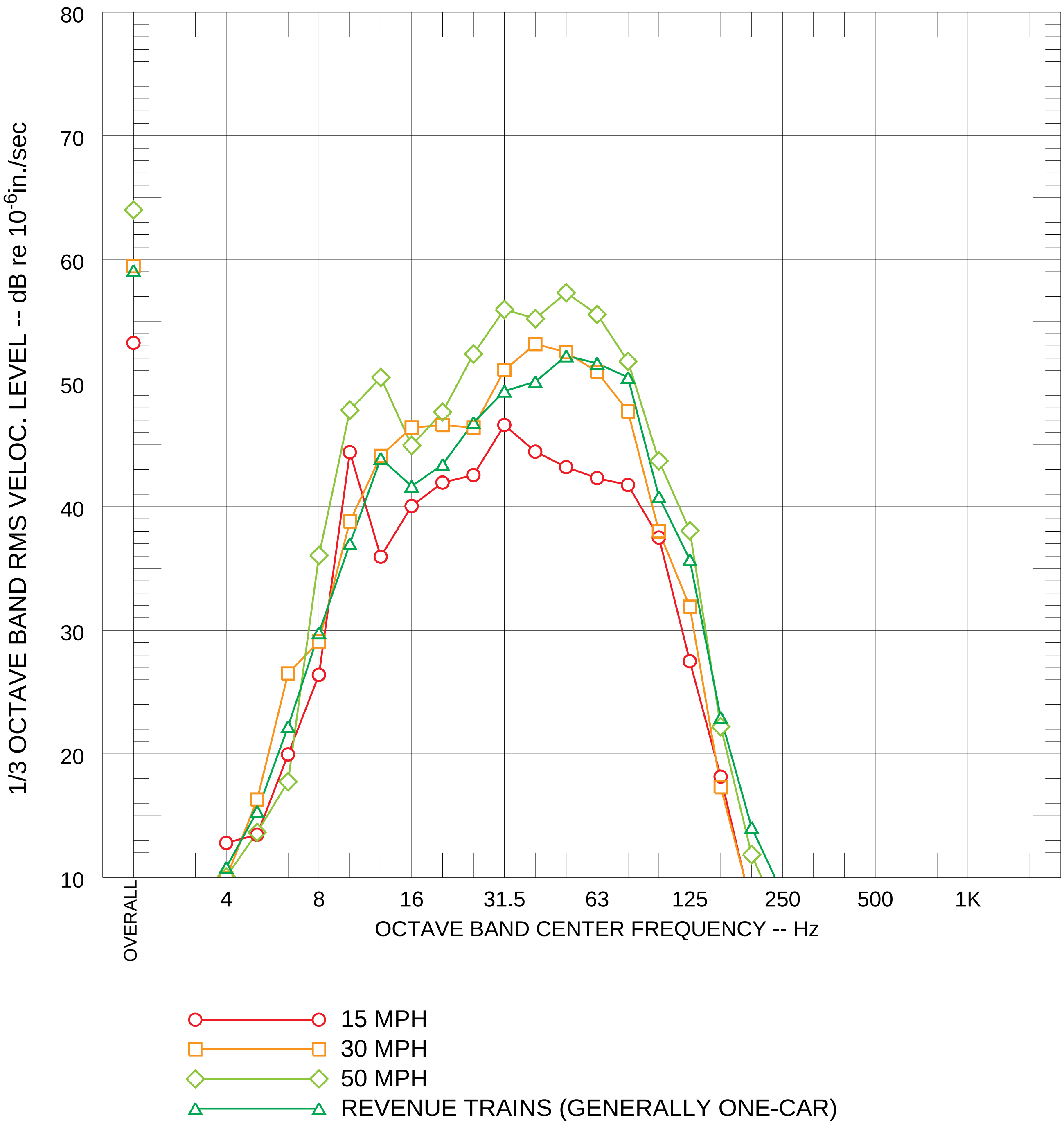


FIGURE A-3 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #1 - LOCATION 3 - 50 FT WEST OF TRACK CENTERLINE AT STATION 107+46

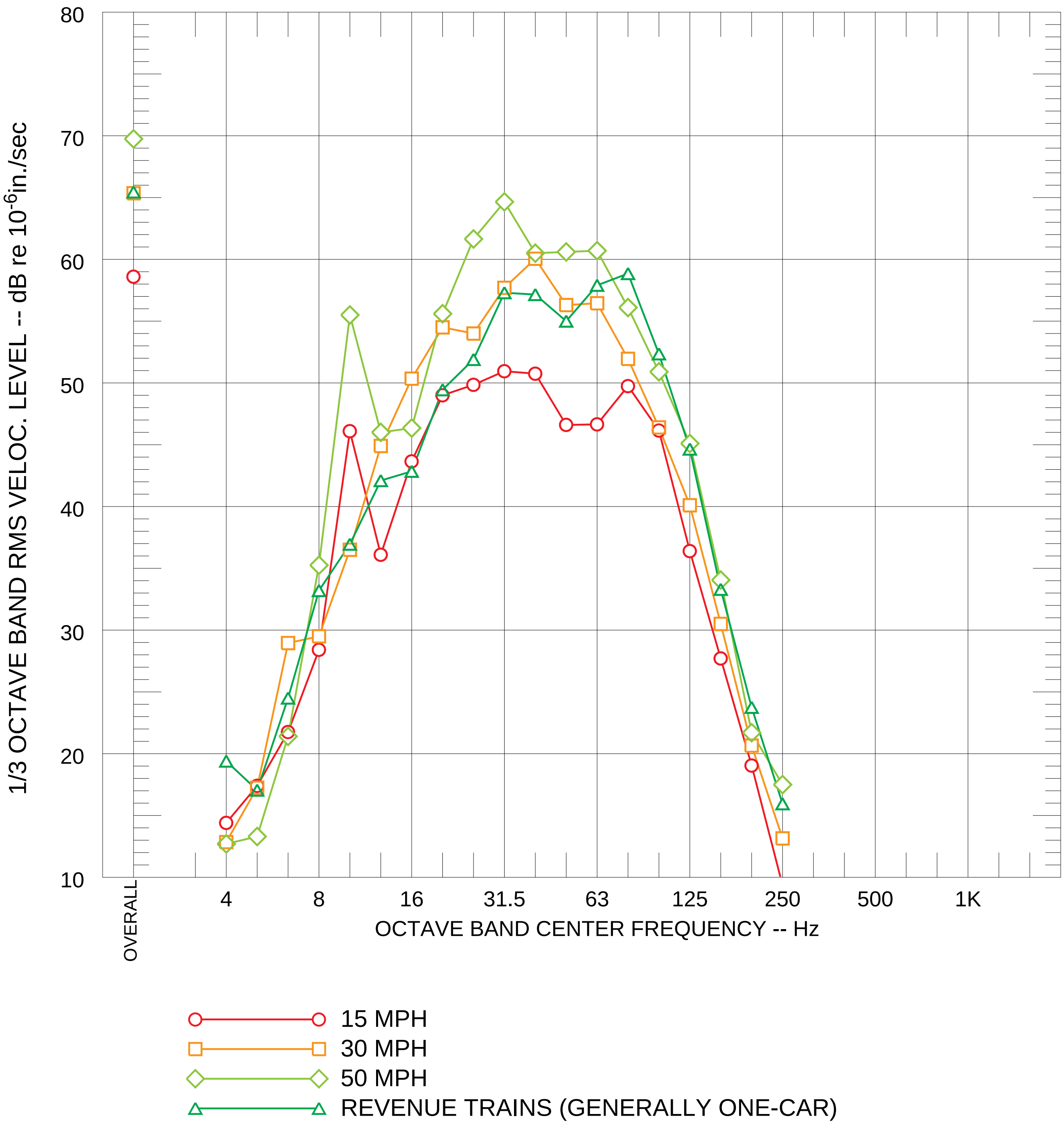


FIGURE A-4 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #1 - LOCATION 4 - 25 FT WEST OF TRACK CENTERLINE AT STATION 107+47

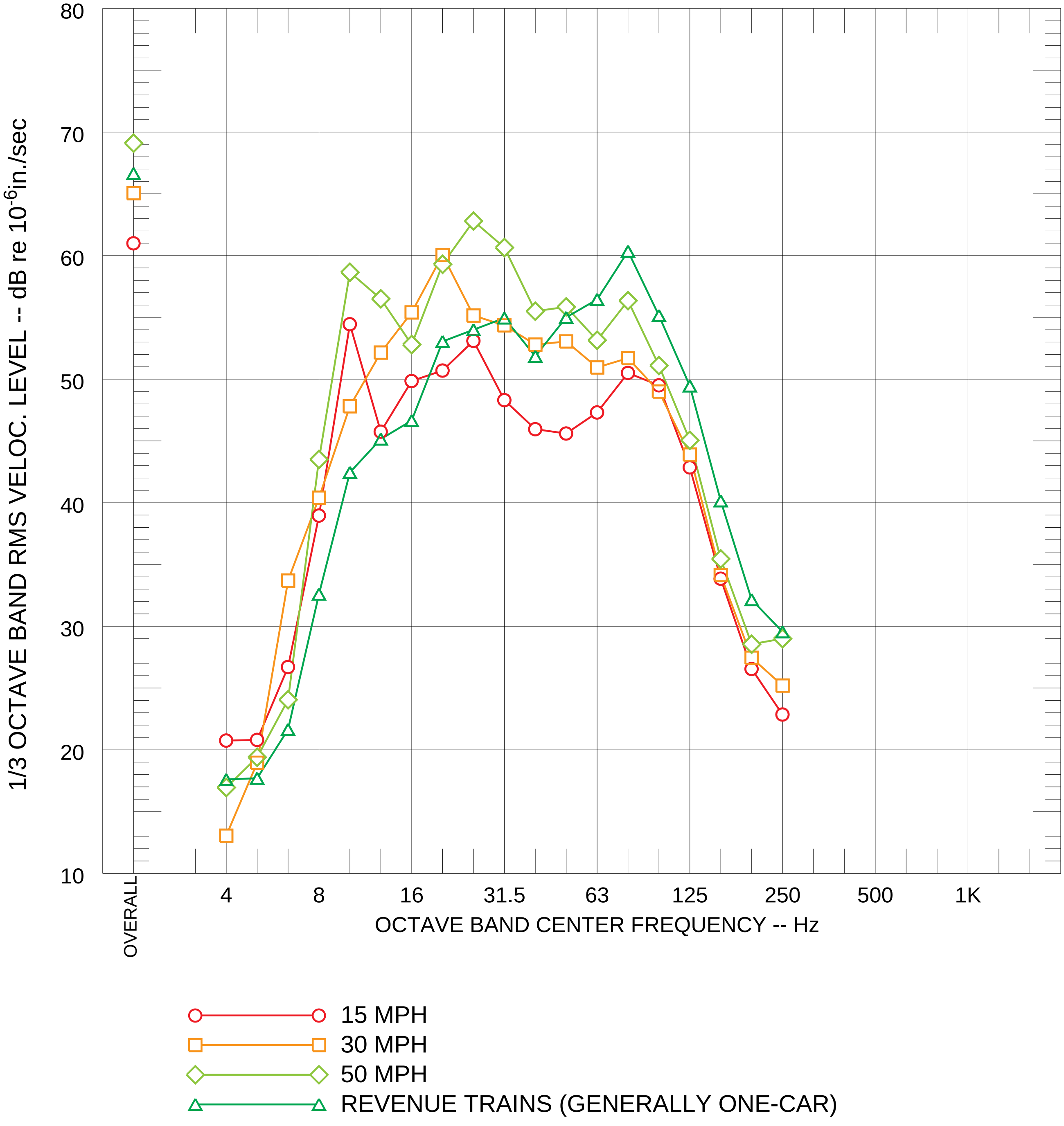


FIGURE A-5 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #1 - LOCATION 5 - 7.5 FT FROM TRACK CENTERLINE AT STATION 107+60

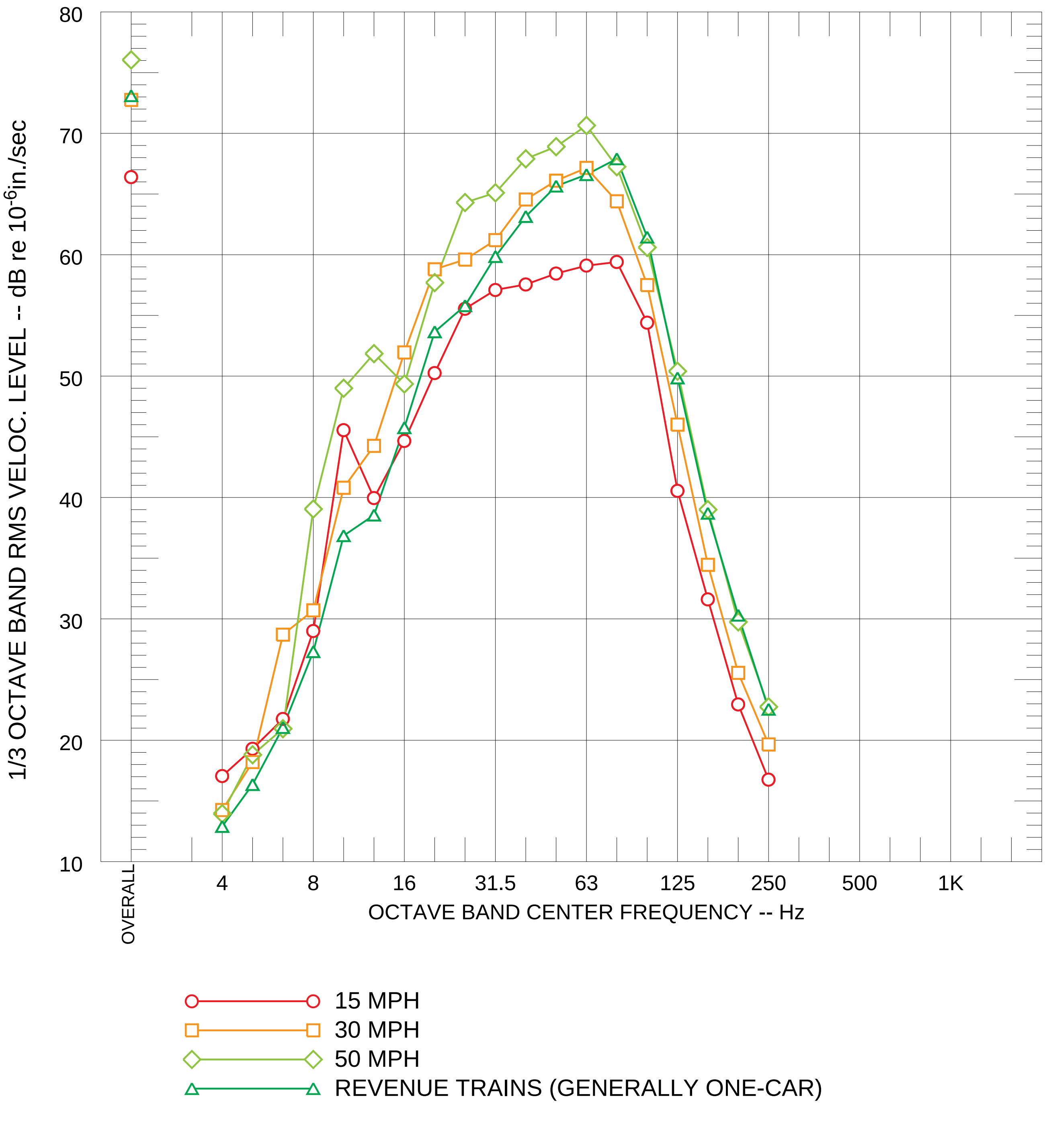


FIGURE A-6 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #1 - LOCATION 6 - 25 FT EAST OF TRACK CENTERLINE AT STATION 107+90

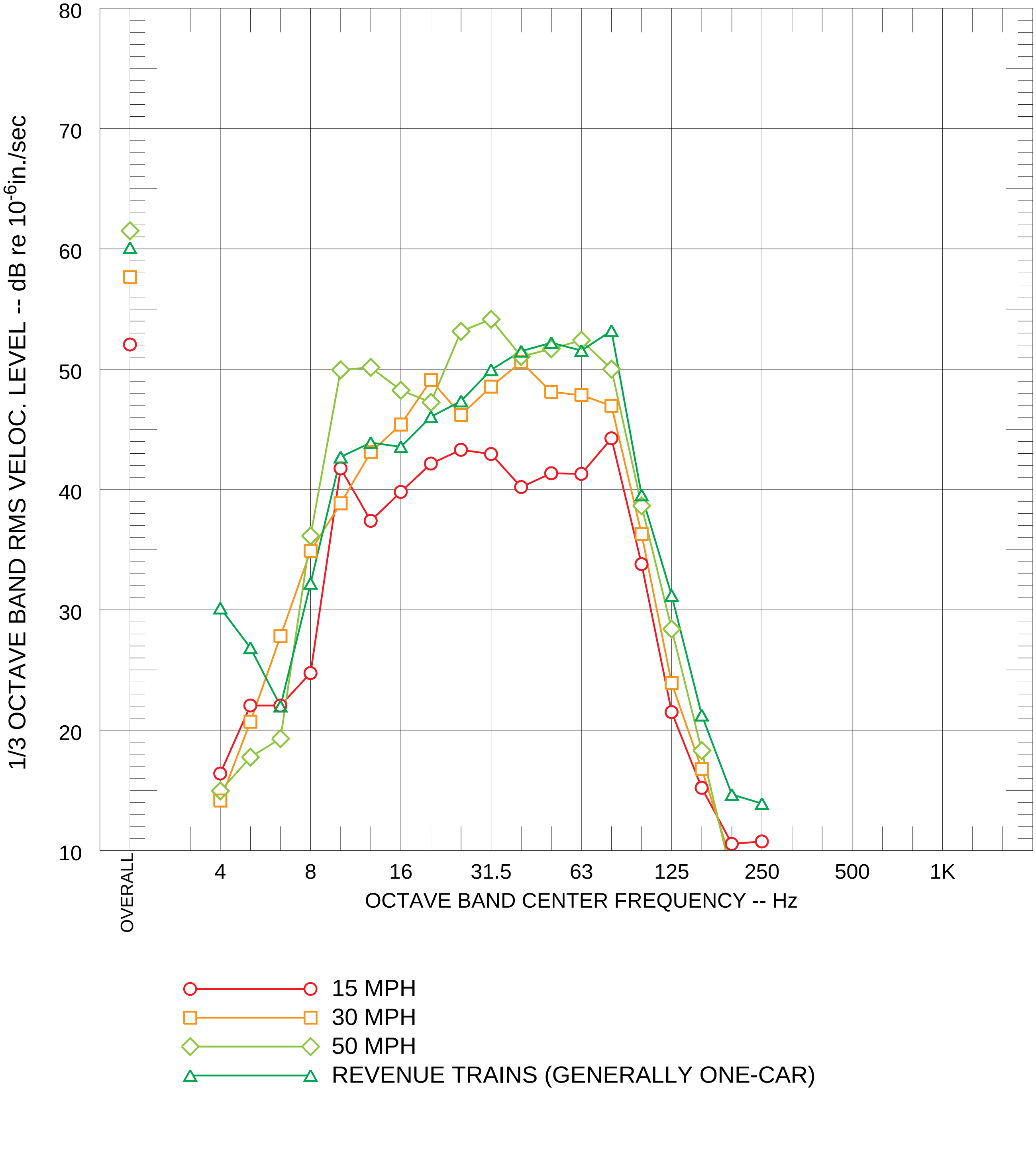


FIGURE A-7 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #1 - LOCATION 7 - 50 FT EAST OF TRACK CENTERLINE AT STATION 107+90

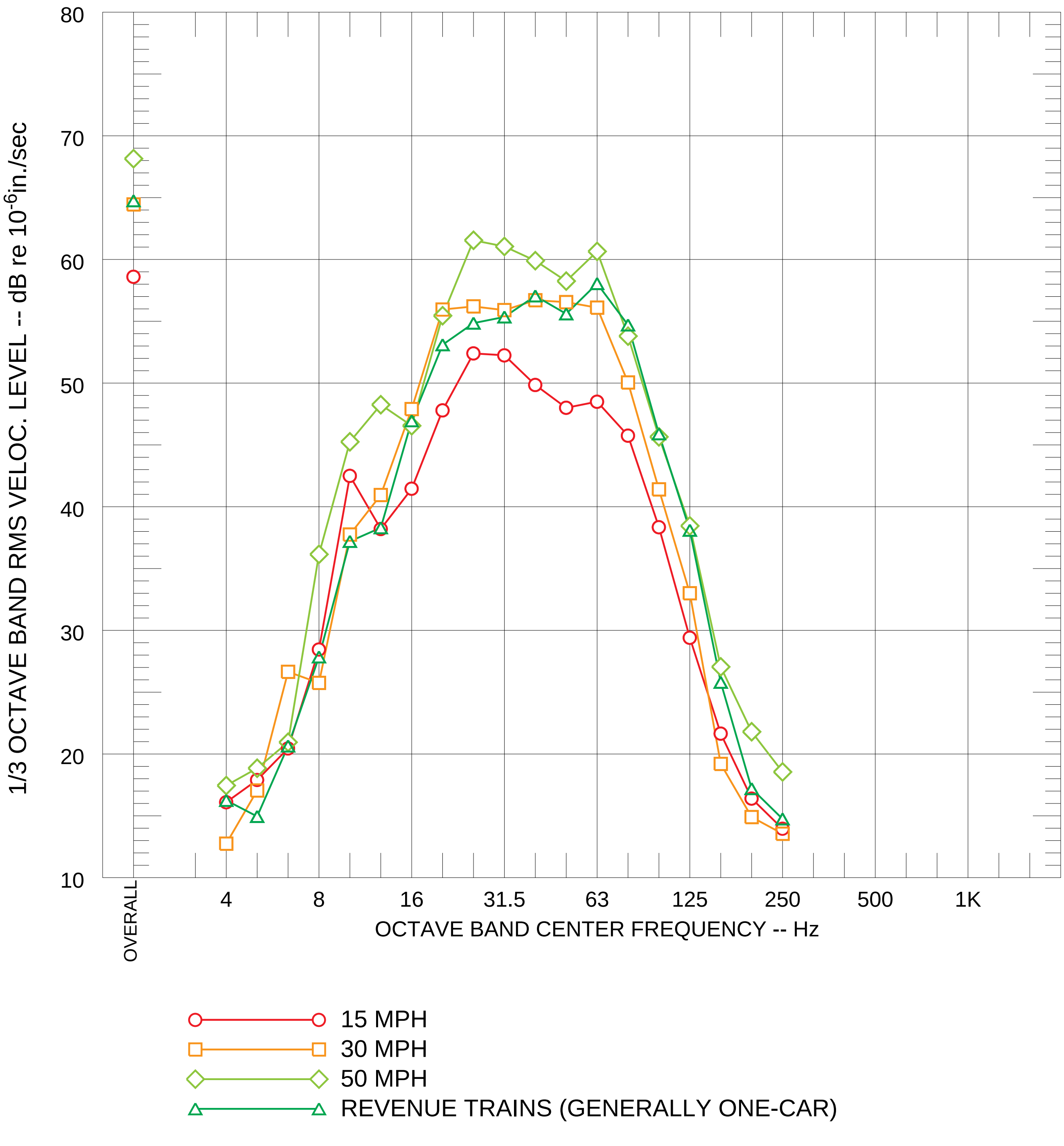


FIGURE A-8 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #1 - LOCATION 8 - 40 FT EAST OF TRACK CENTERLINE AT STATION 107+90

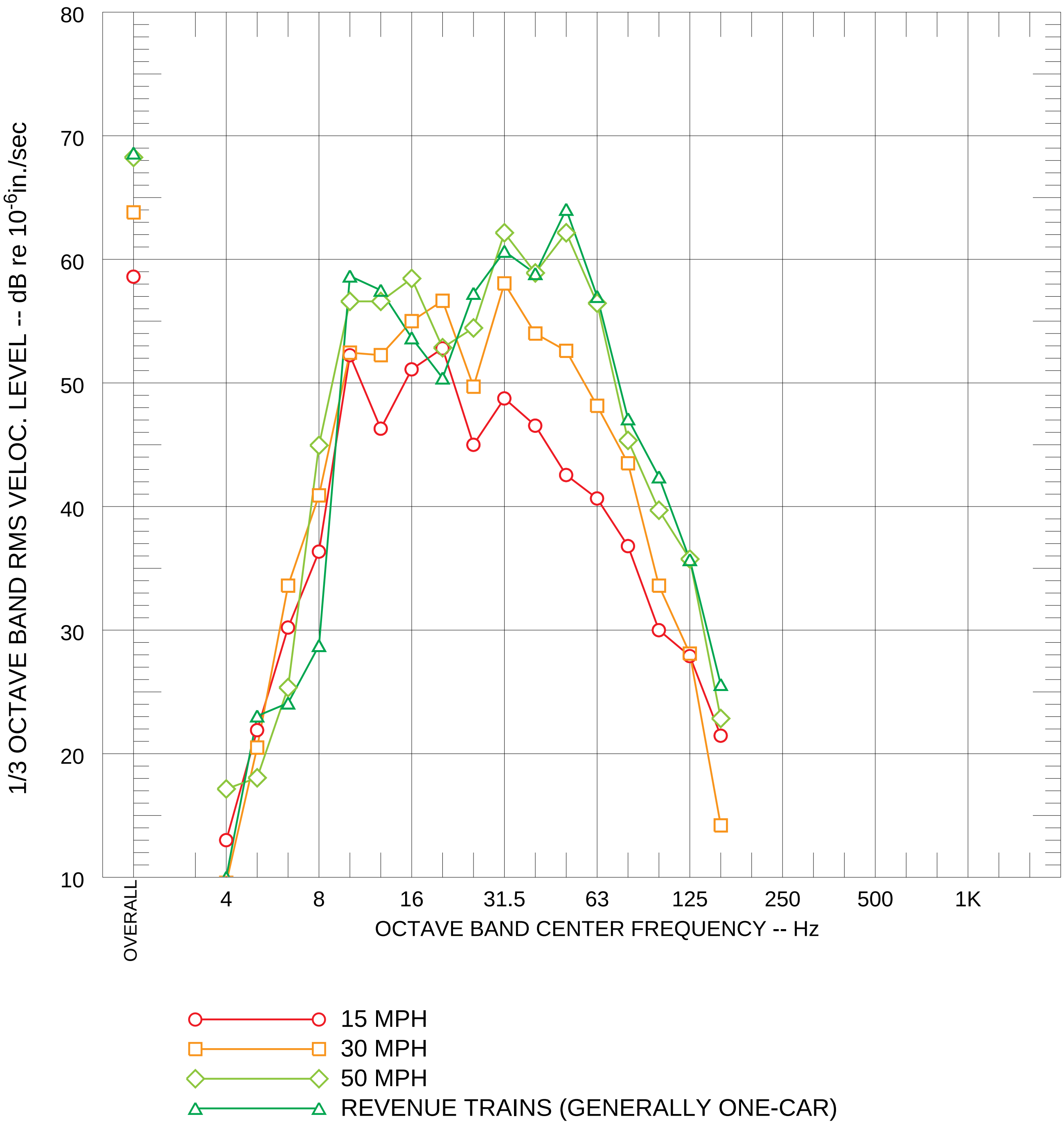


FIGURE A-9 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #3 - LOCATION 1 - 25 FT WEST OF TRACK CENTERLINE AT STATION 141+75

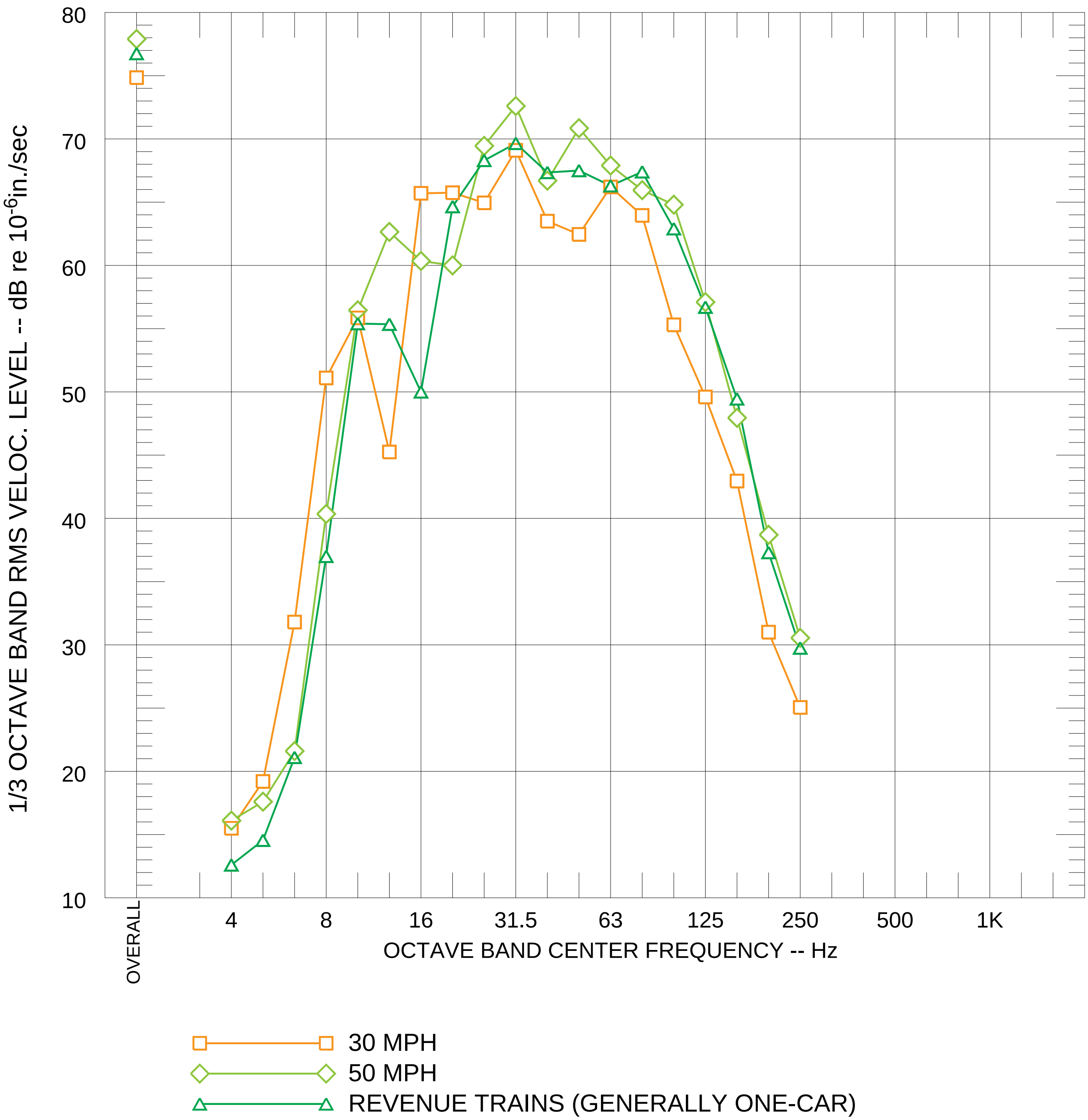


FIGURE A-10 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #3 - LOCATION 2 - 25 FT WEST OF TRACK CENTERLINE AT STATION 141+75

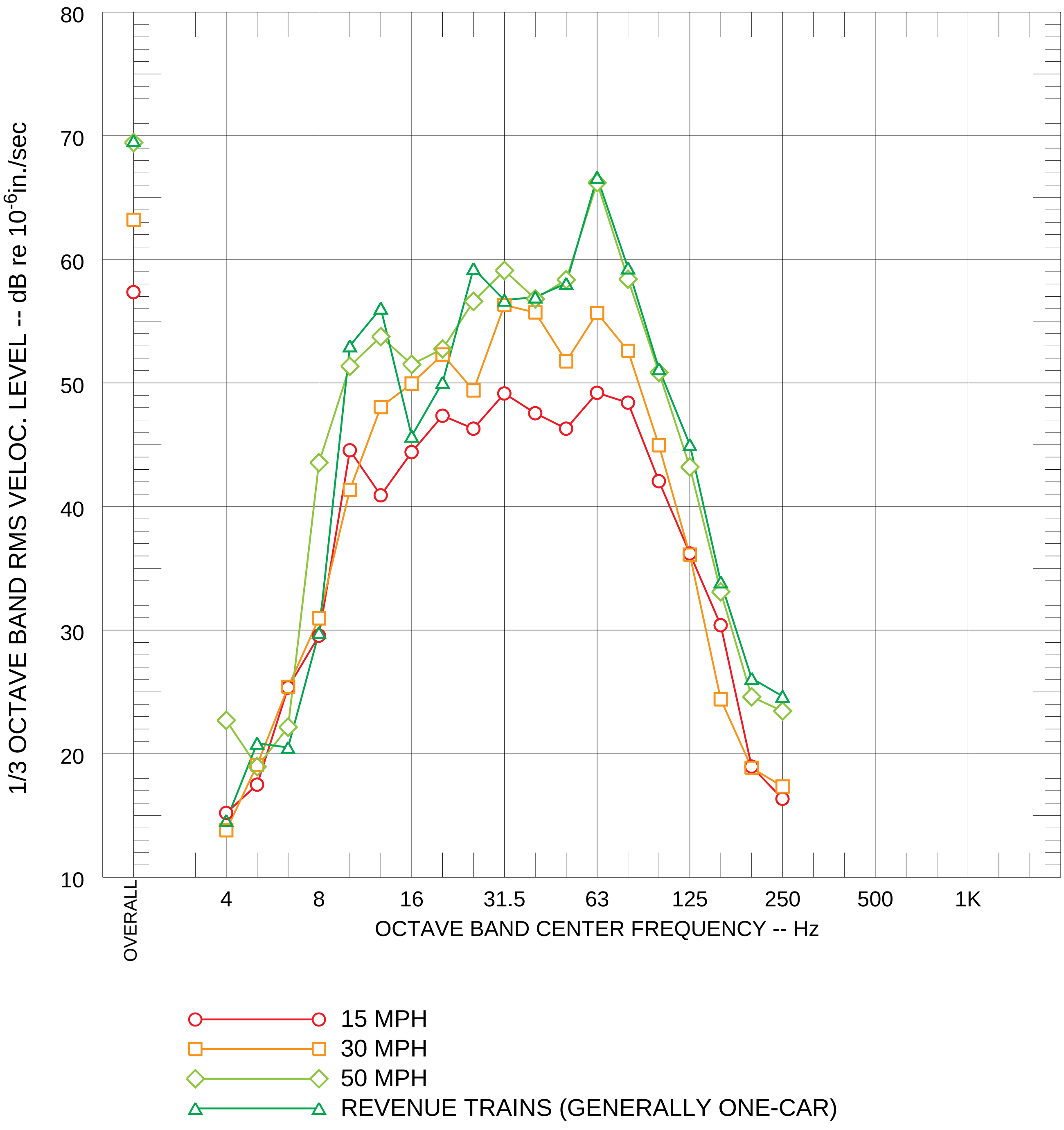


FIGURE A-11 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #3 - LOCATION 3 - 50 FT WEST OF TRACK CENTERLINE AT STATION 141+70

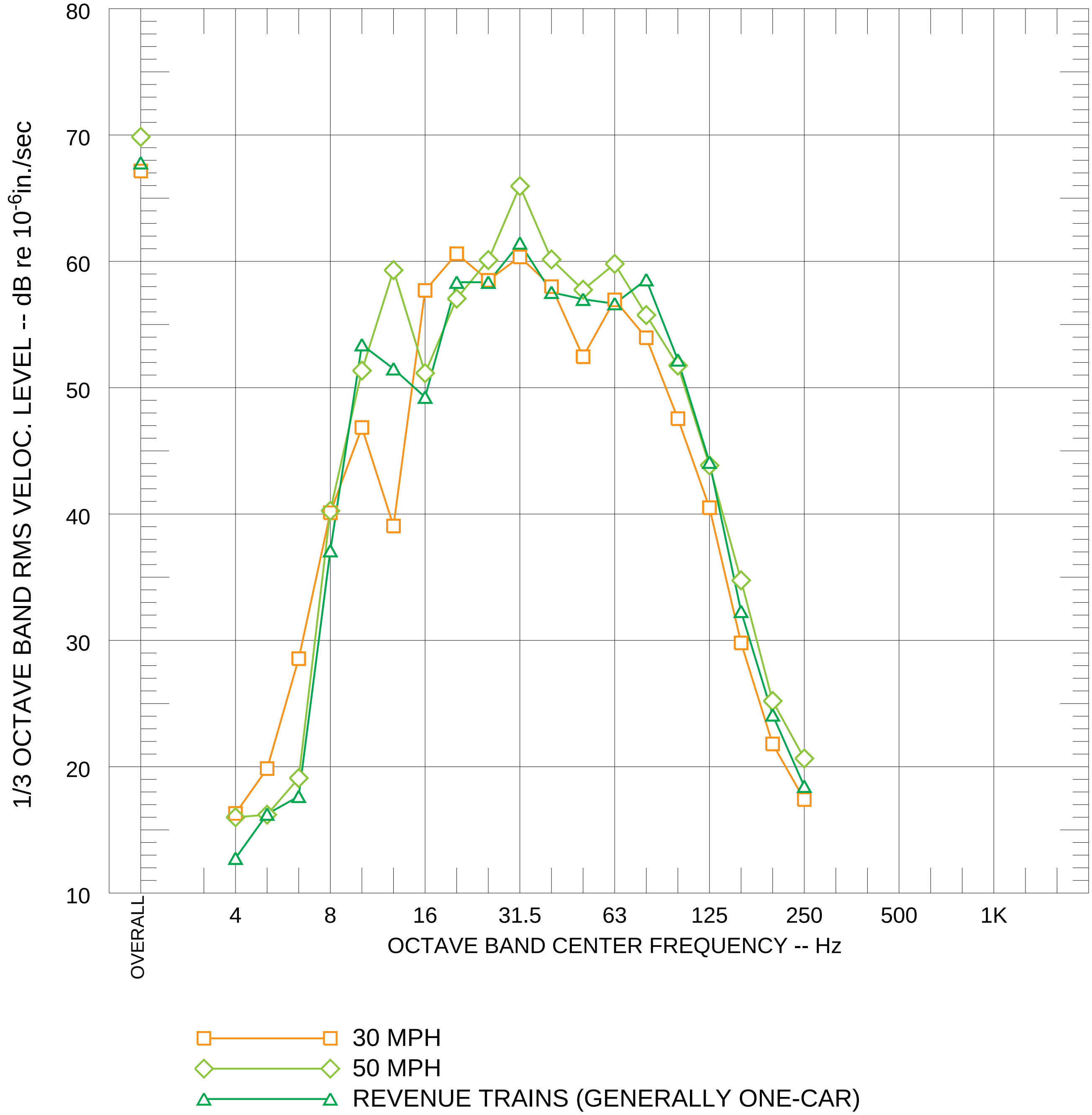


FIGURE A-12 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #3 - LOCATION 4 - 50 FT WEST OF TRACK CENTERLINE AT STATION 141+65

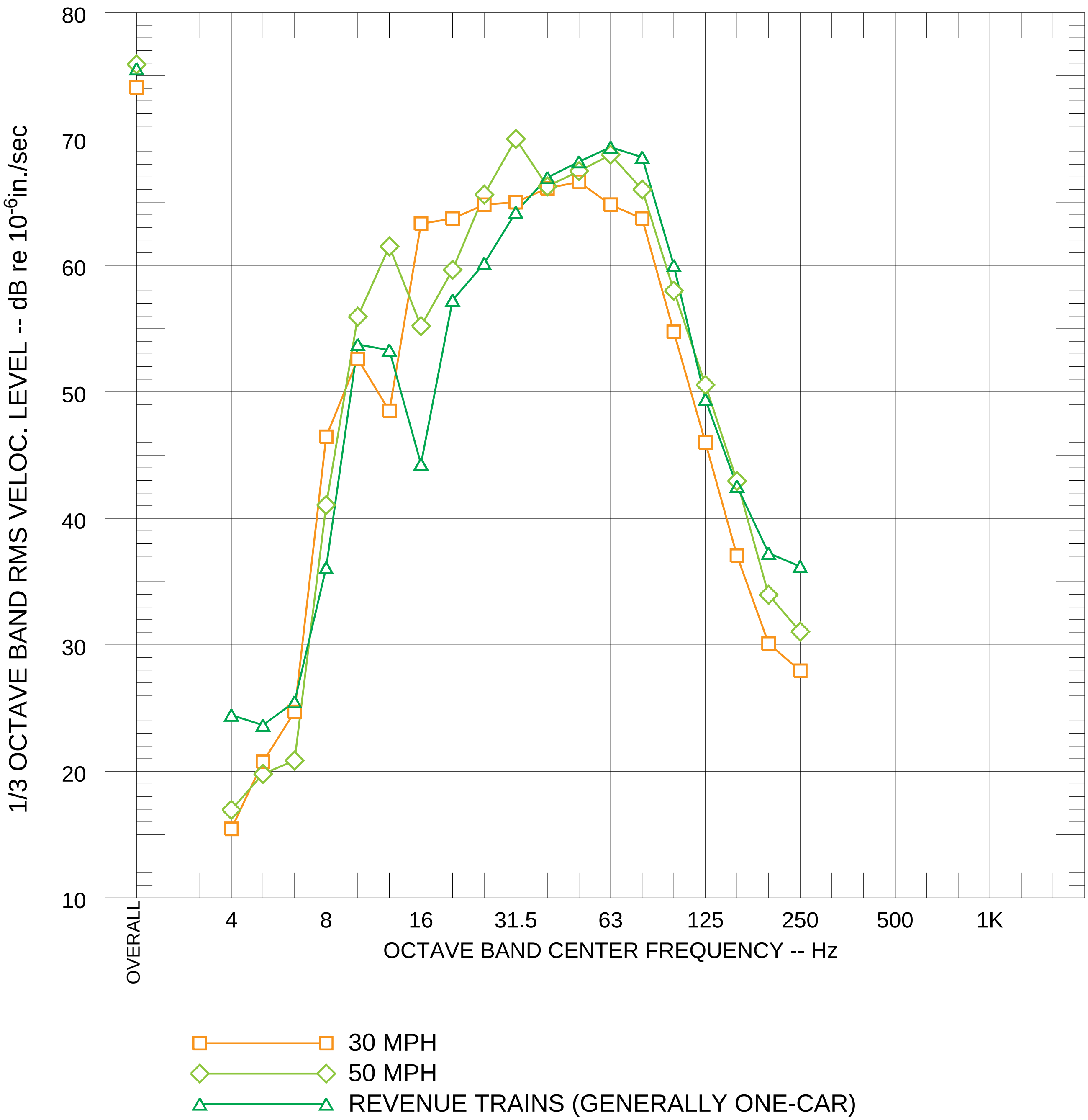


FIGURE A-13 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #3 - LOCATION 5 - 25 FT EAST OF TRACK CENTERLINE AT STATION 141+85

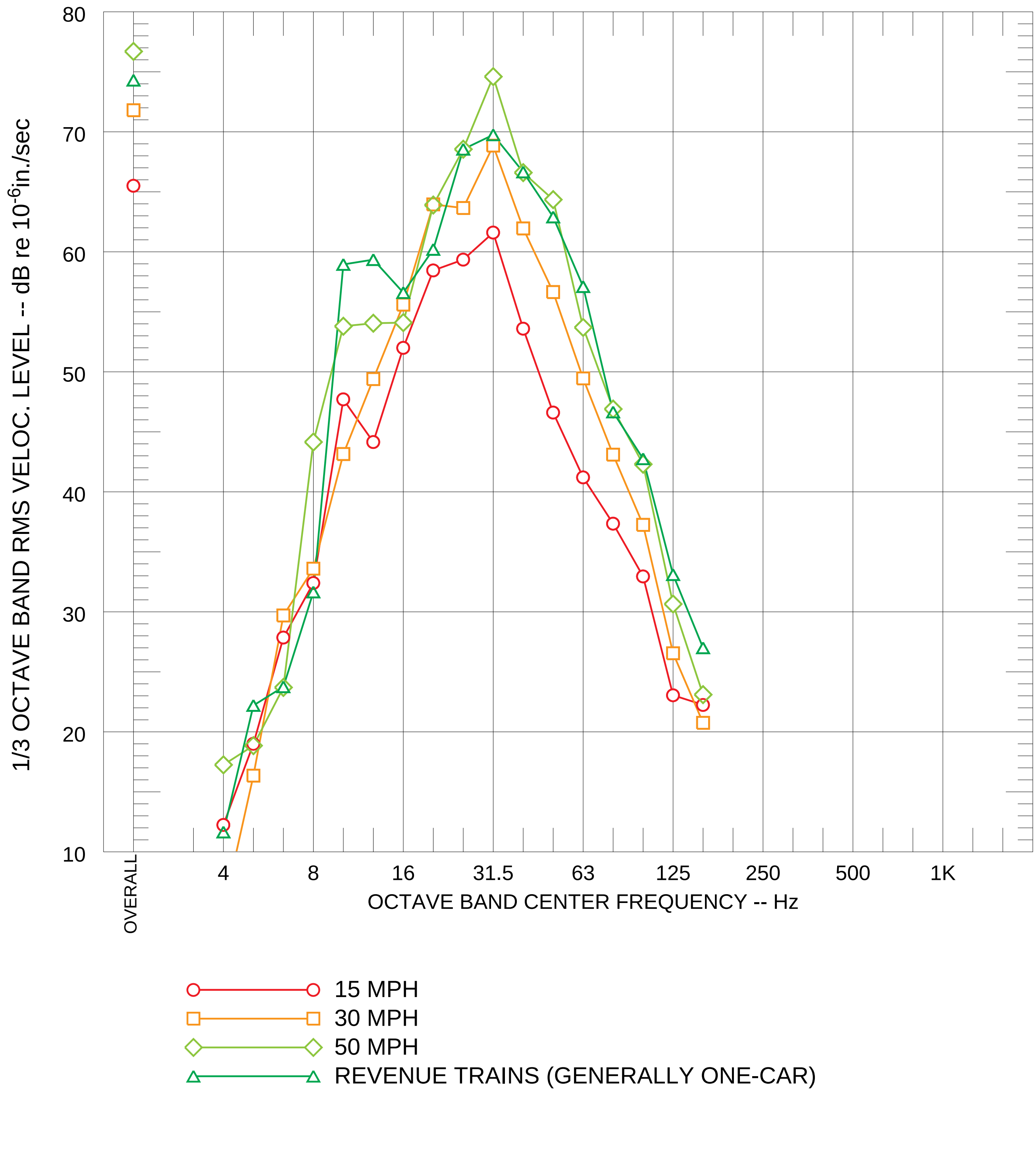


FIGURE A-14 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #3 - LOCATION 6 -
25 FT EAST OF TRACK CENTERLINE AT STATION 141+85

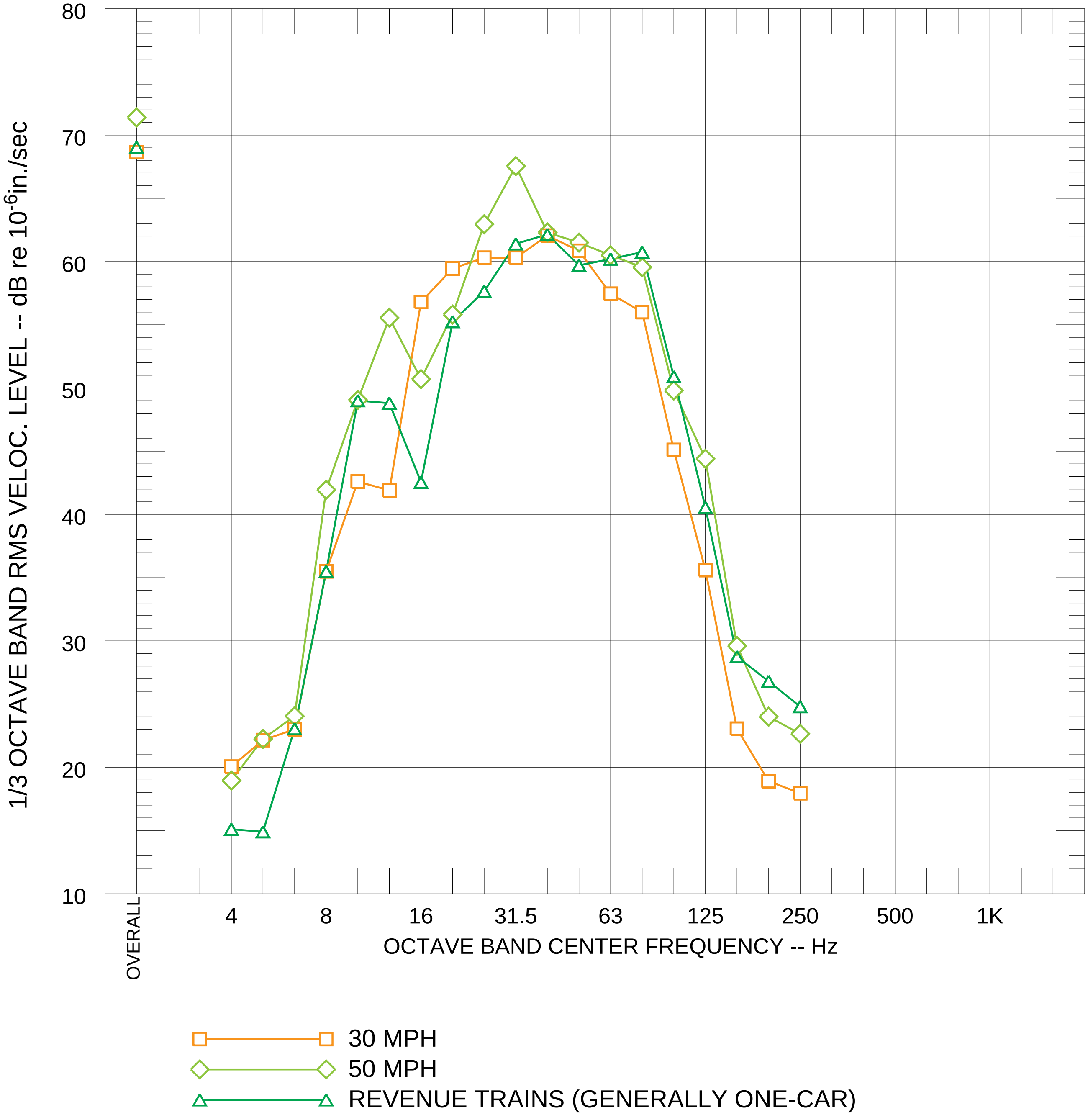


FIGURE A-15 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #3 - LOCATION 7 - 50 FT EAST OF TRACK CENTERLINE AT STATION 141+85

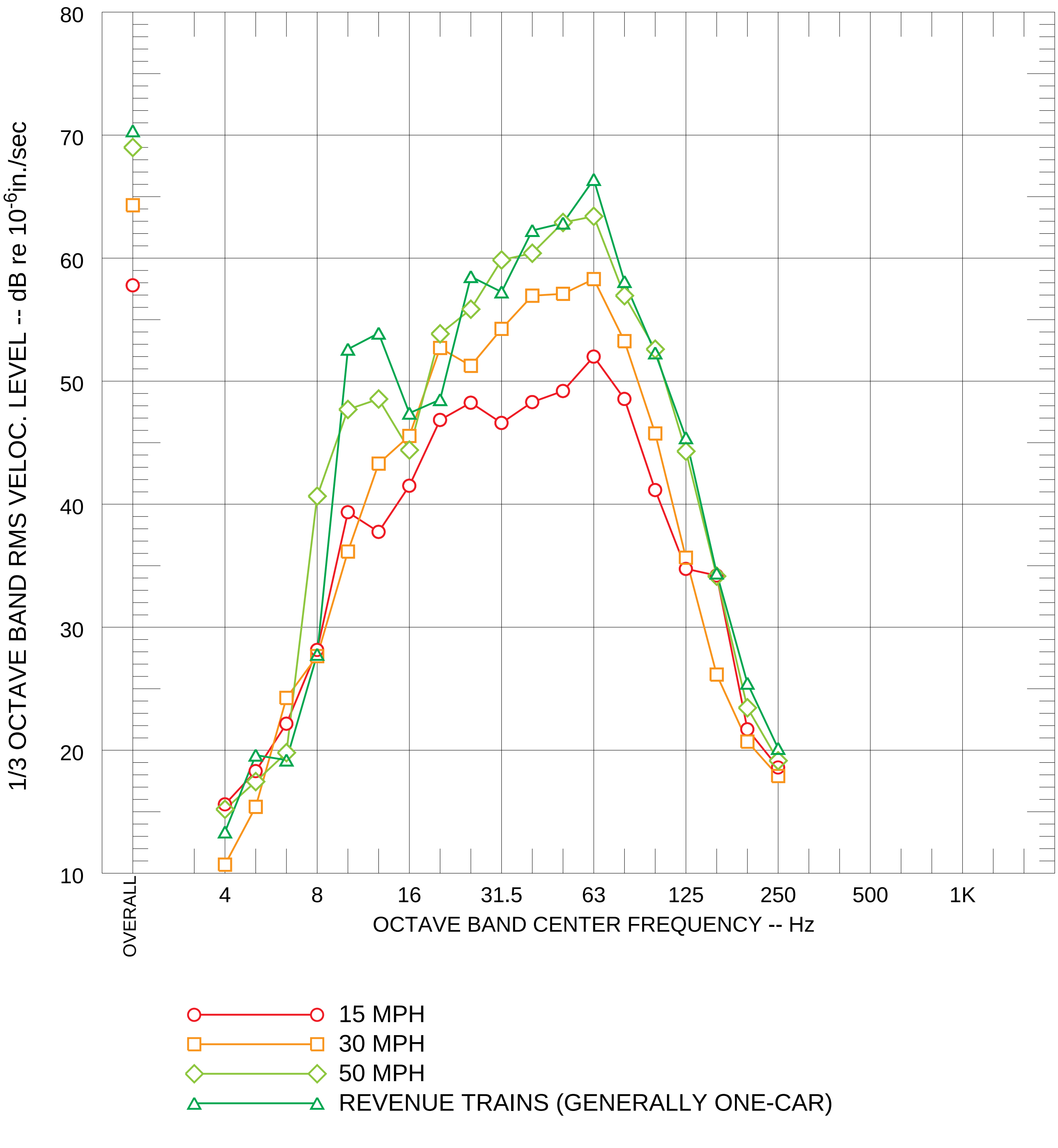


FIGURE A-16 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #3 - LOCATION 8 - 50 FT EAST OF TRACK CENTERLINE AT STATION 141+85

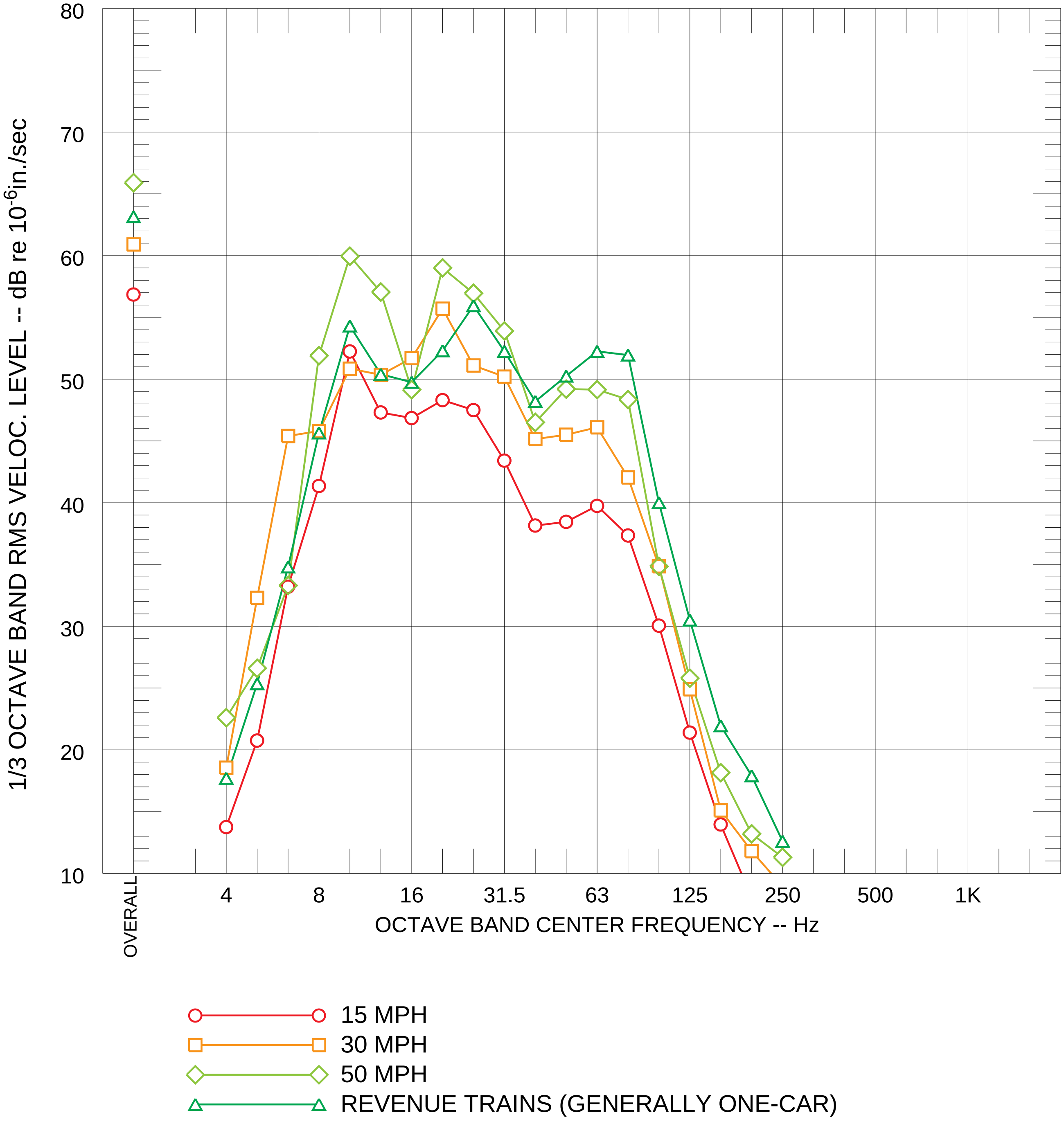


FIGURE A-17 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #4 - LOCATION 1 - 25 FT WEST OF TRACK CENTERLINE AT STATION 149+05

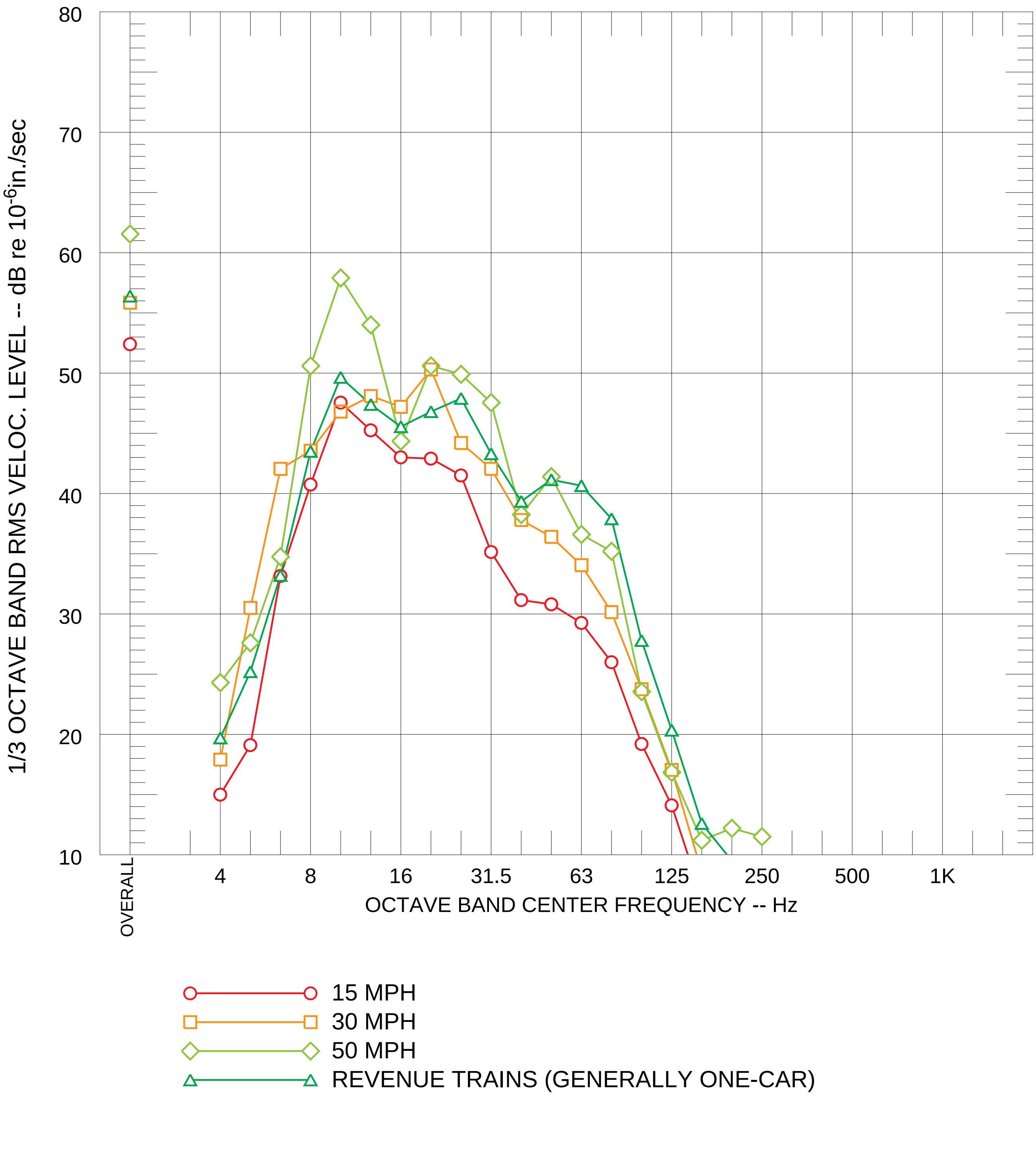


FIGURE A-18 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #4 - LOCATION 2 - 50 FT WEST OF TRACK CENTERLINE AT STATION 149+05

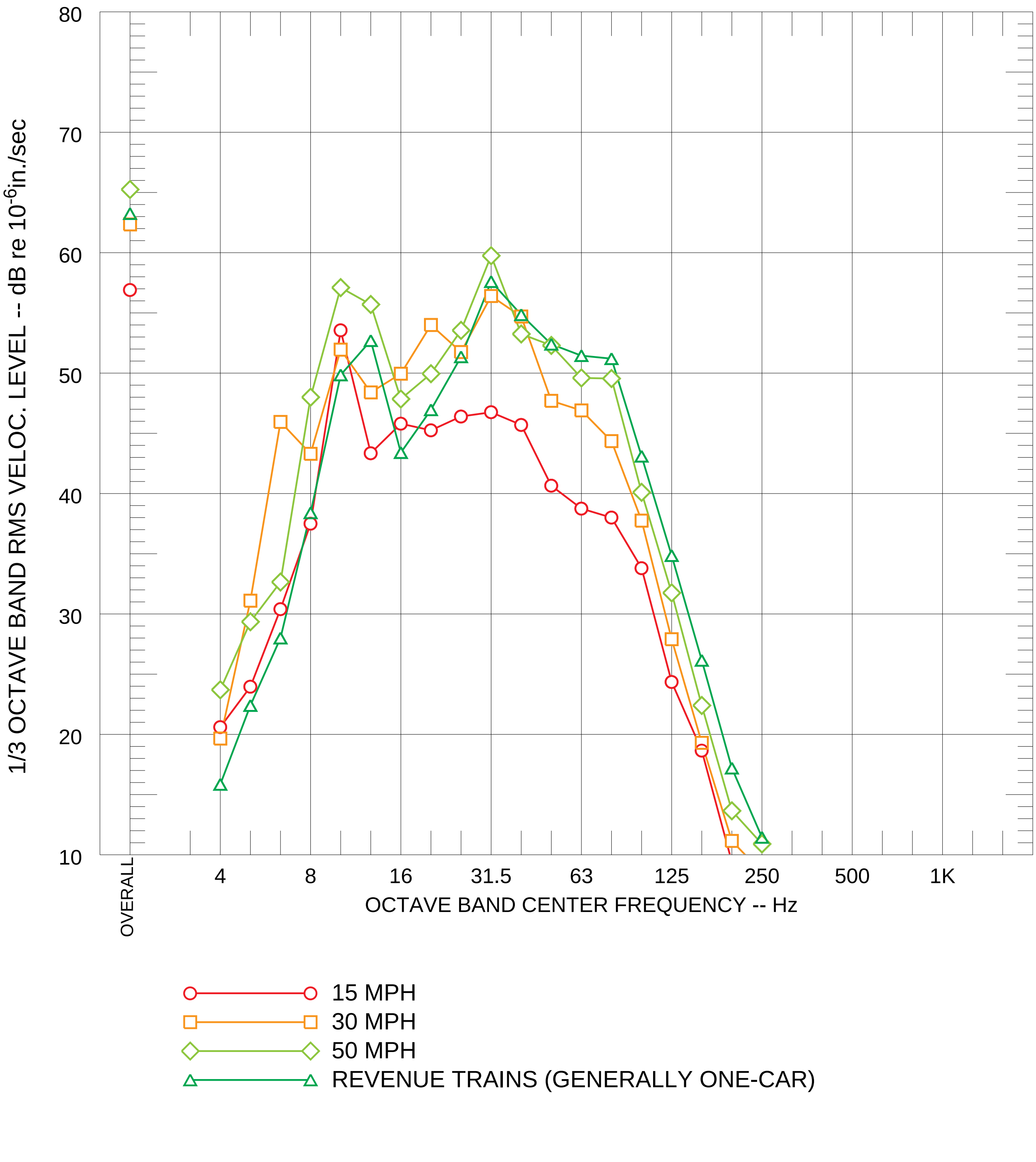


FIGURE A-19 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #4 - LOCATION 3 - 25 FT WEST OF TRACK CENTERLINE AT STATION 149+35

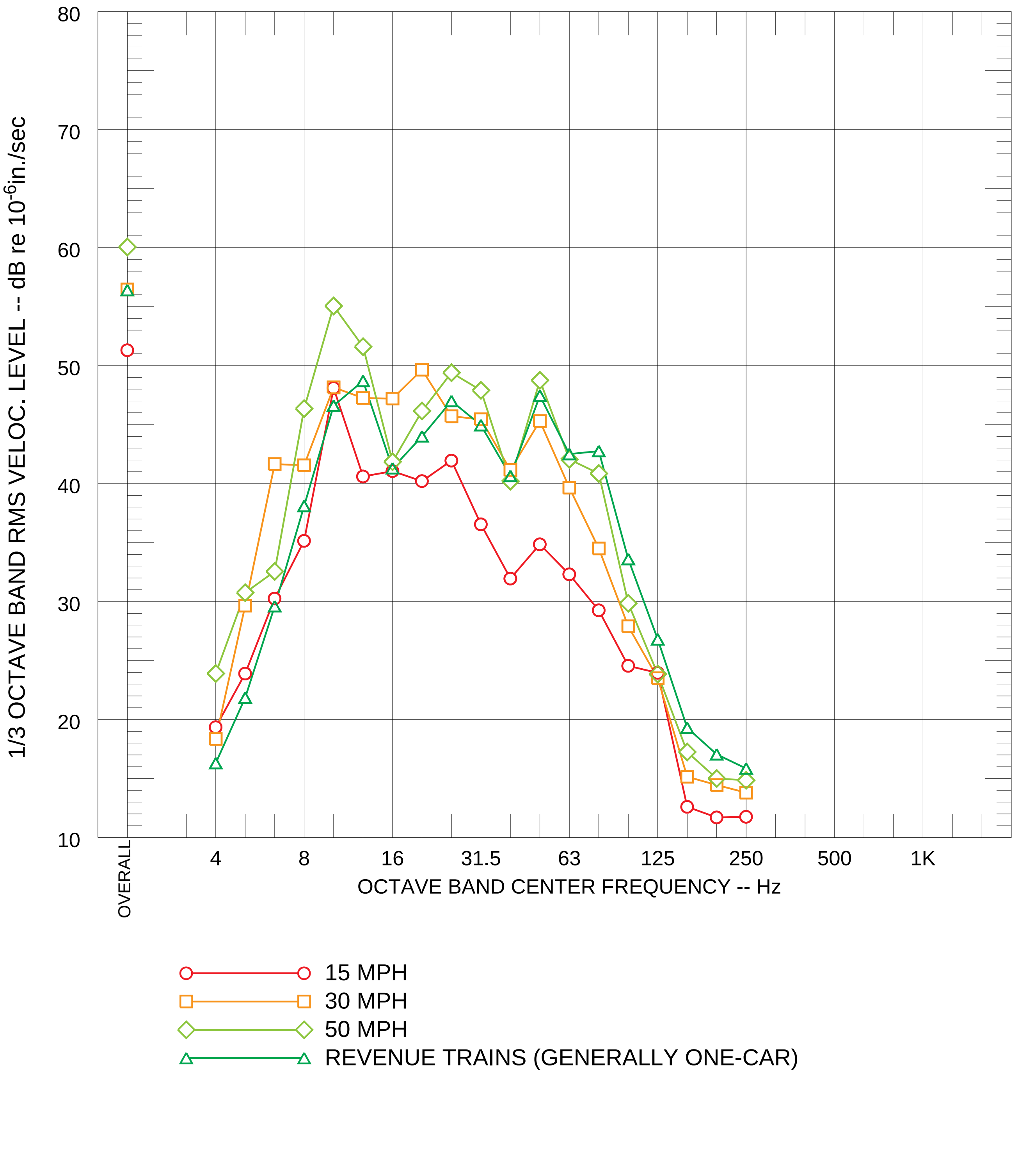


FIGURE A-20 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #4 - LOCATION 4 - 50 FT WEST OF TRACK CENTERLINE AT STATION 149+35

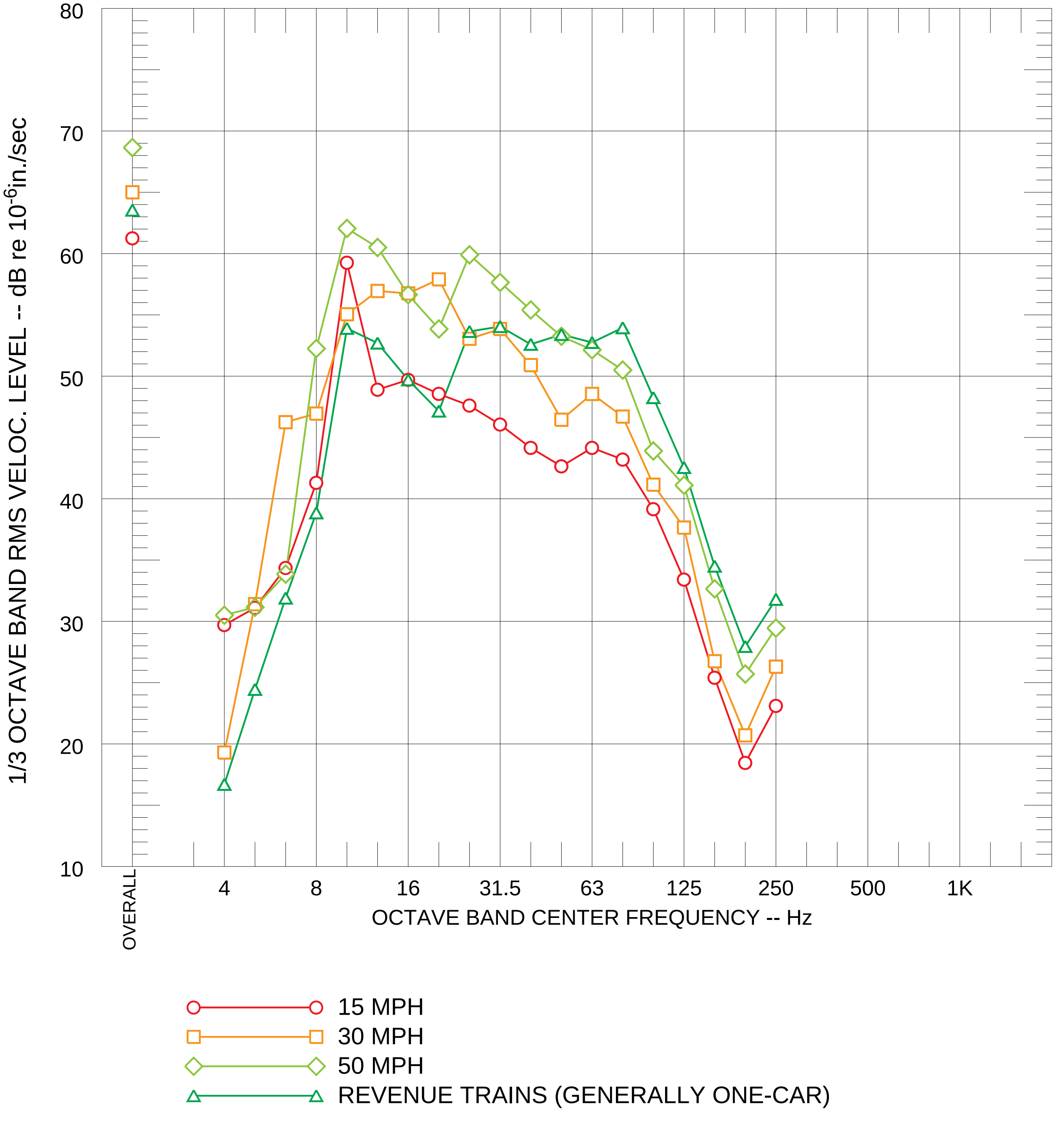


FIGURE A-21 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #4 - LOCATION 5 - 7.5 FT EAST OF TRACK CENTERLINE AT STATION 149+09

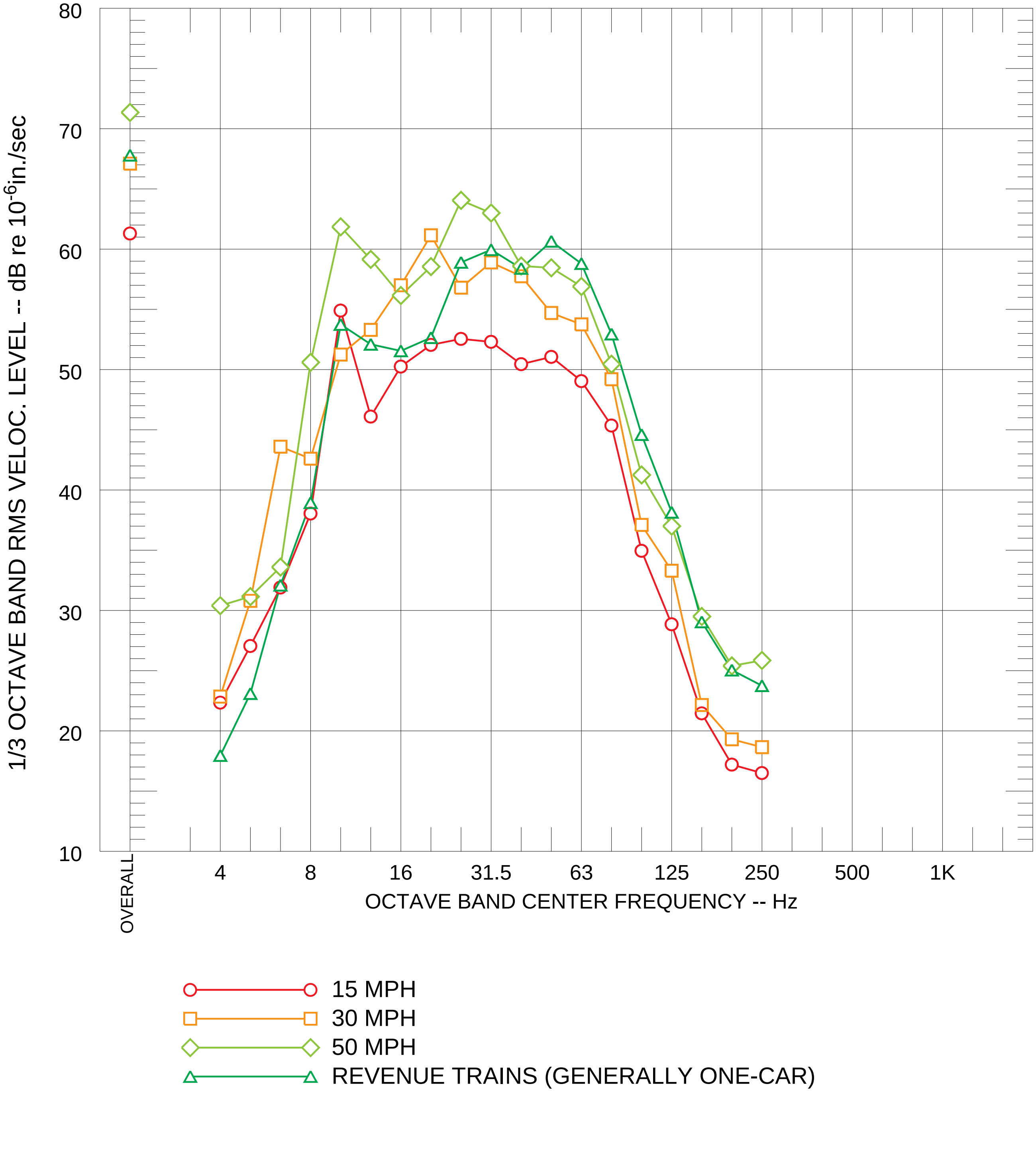


FIGURE A-22 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #4 - LOCATION 6 - 25 FT EAST OF TRACK CENTERLINE AT STATION 149+09

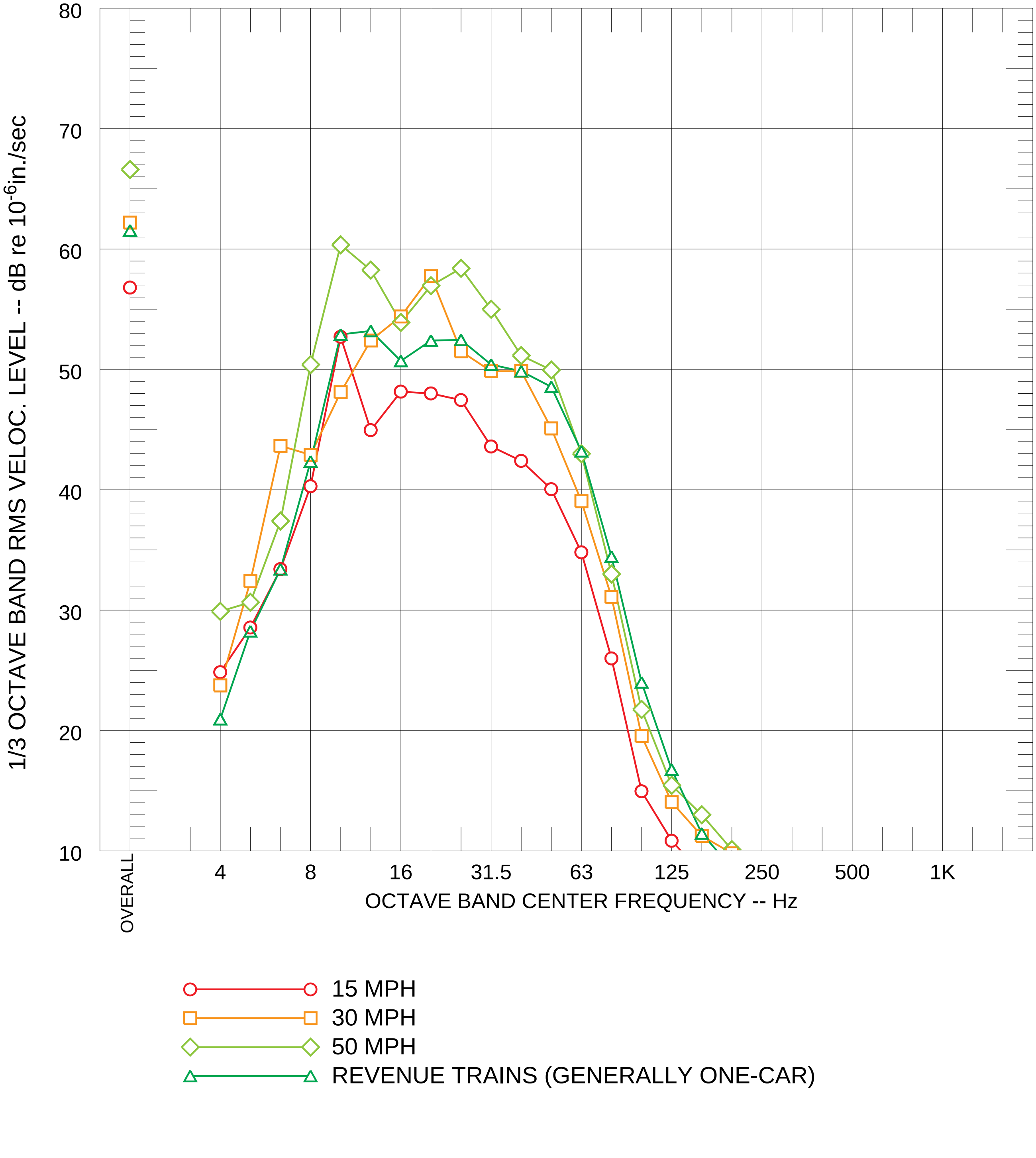


FIGURE A-23 TWO-CAR TEST TRAIN PASSBYS AT TDA SITE #4 - LOCATION 7 - 50 FT EAST OF TRACK CENTERLINE AT STATION 149+09

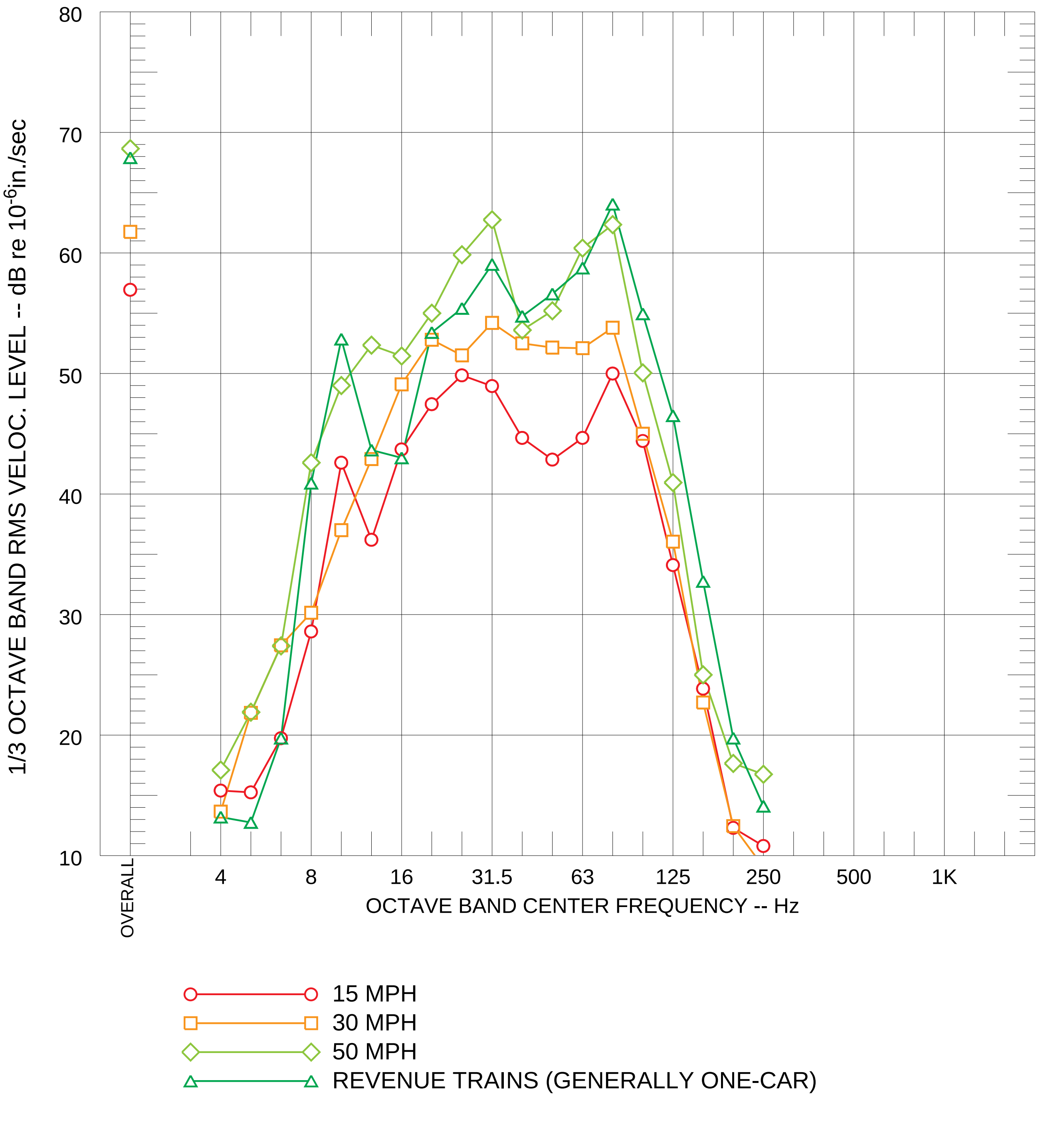


FIGURE A-24 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #1 - LOCATION 1 - 50 FT WEST OF TRACK CENTERLINE AT STATION 133+68

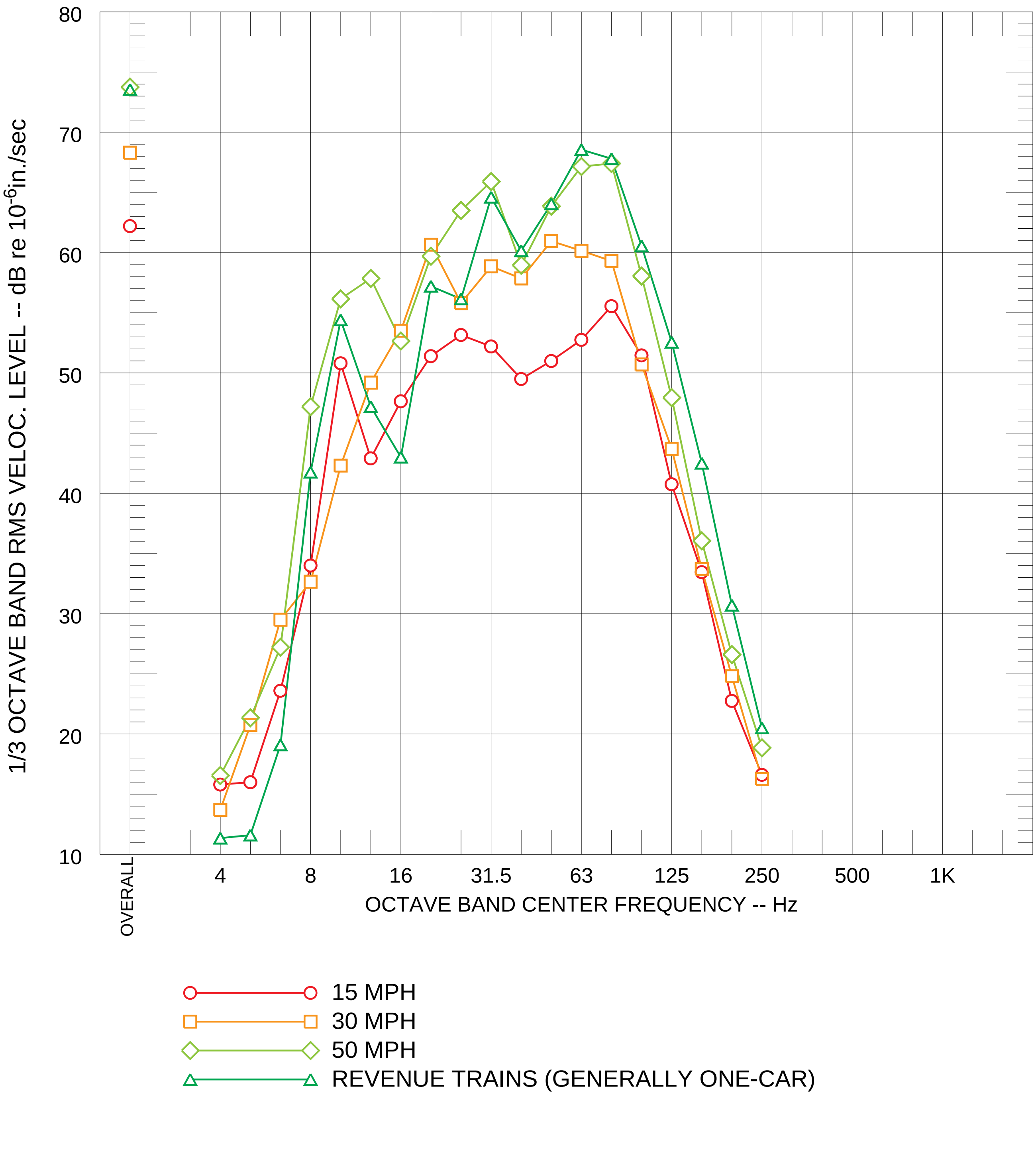


FIGURE A-25 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #1 - LOCATION 2 - 25 FT WEST OF TRACK CENTERLINE AT STATION 133+68

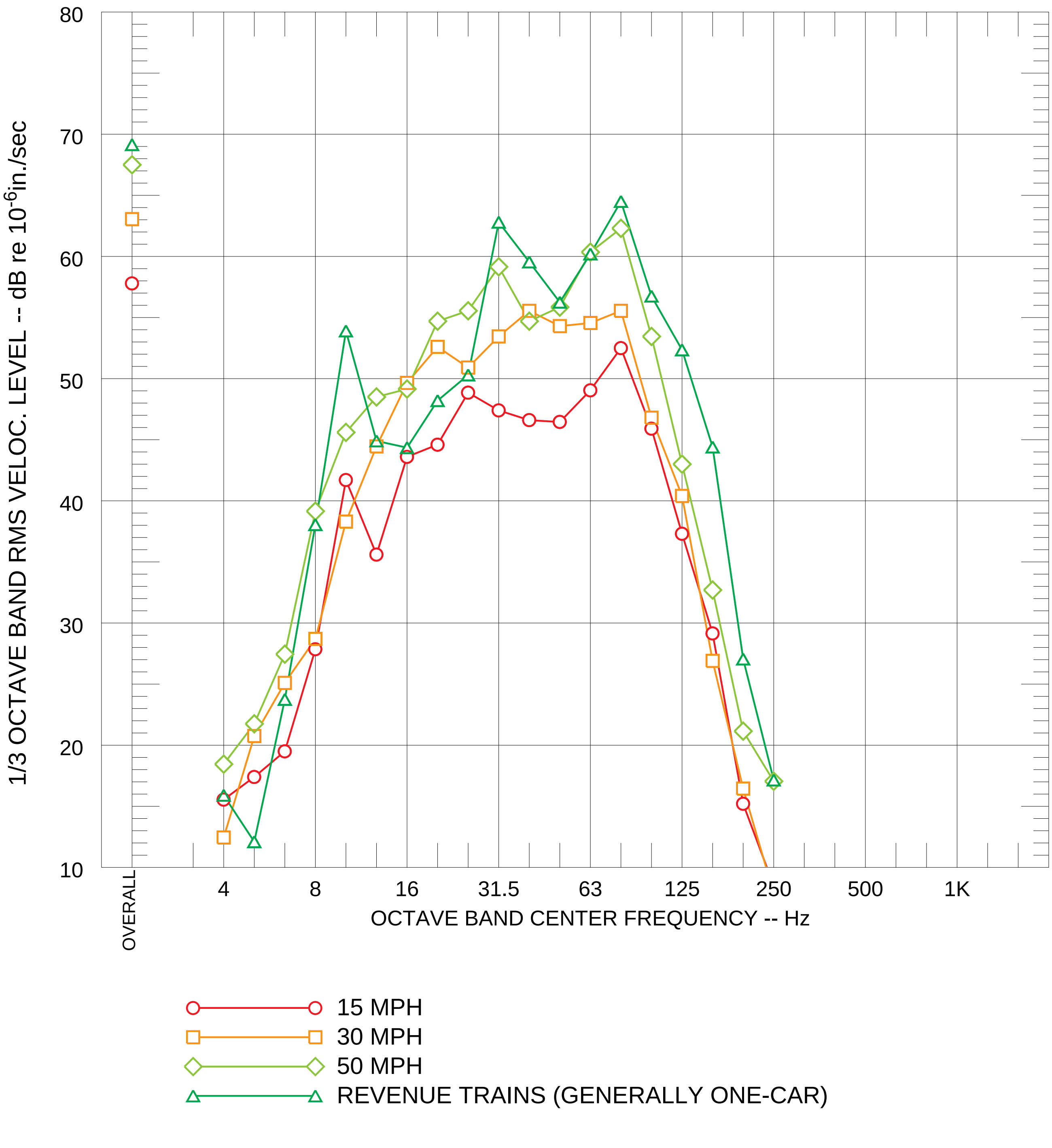


FIGURE A-26 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #1 - LOCATION 3 - 50 FT WEST OF TRACK CENTERLINE AT STATION 133+90

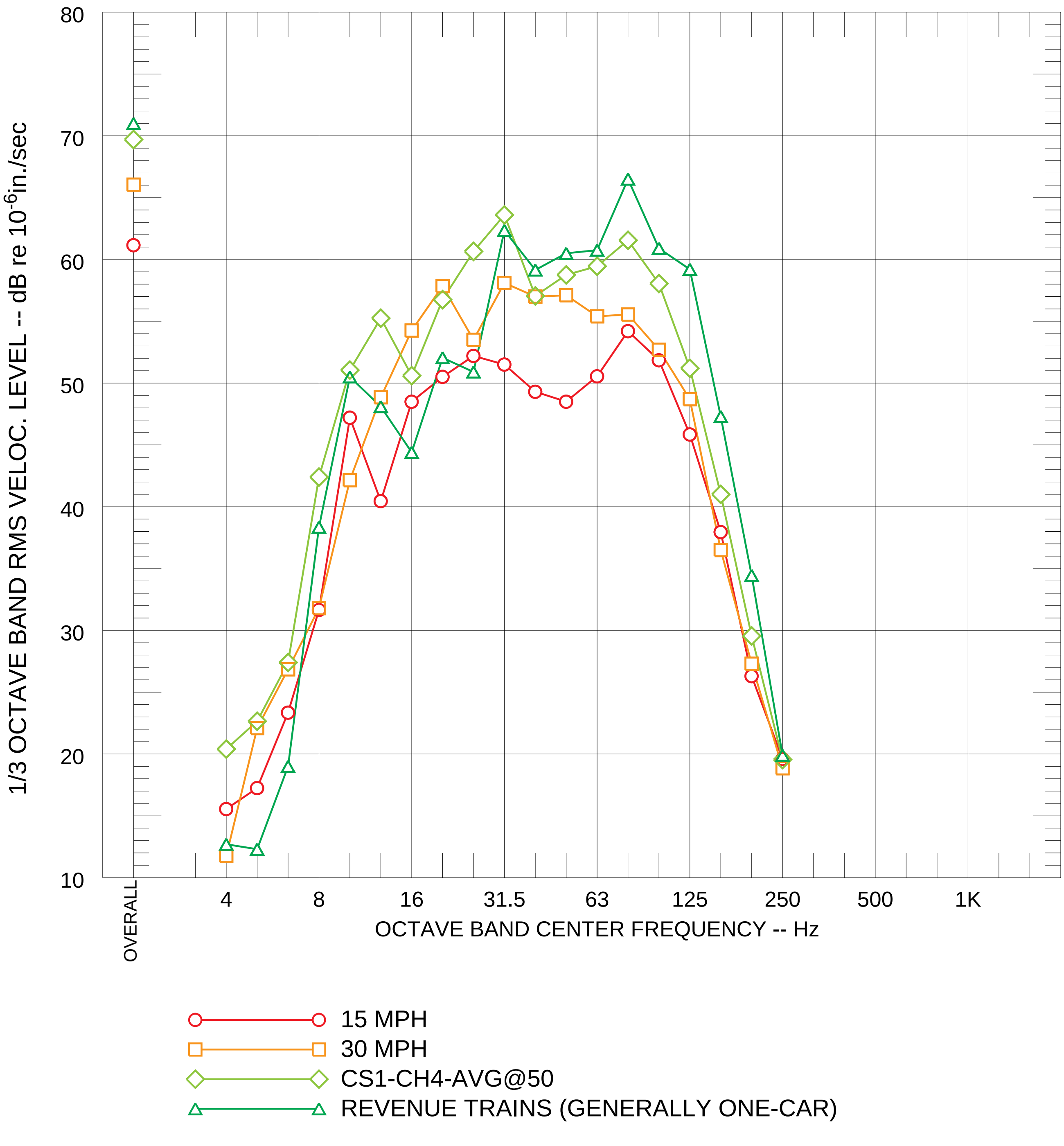


FIGURE A-27 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #1 - LOCATION 4 - 25 FT WEST OF TRACK CENTERLINE AT STATION 133+90

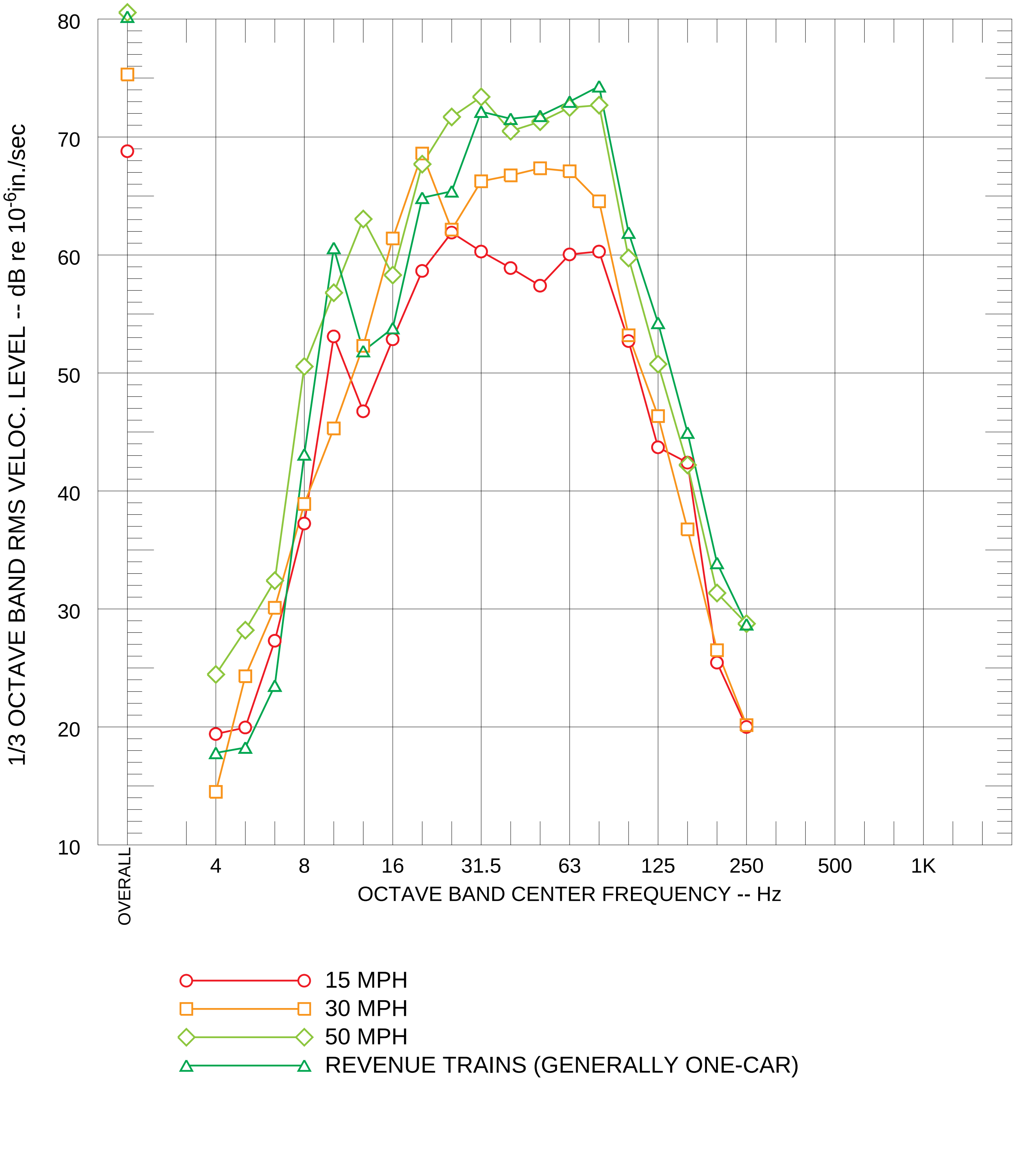


FIGURE A-28 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #1 - LOCATION 5 - 25 FT WEST OF TRACK CENTERLINE AT STATION 133+68

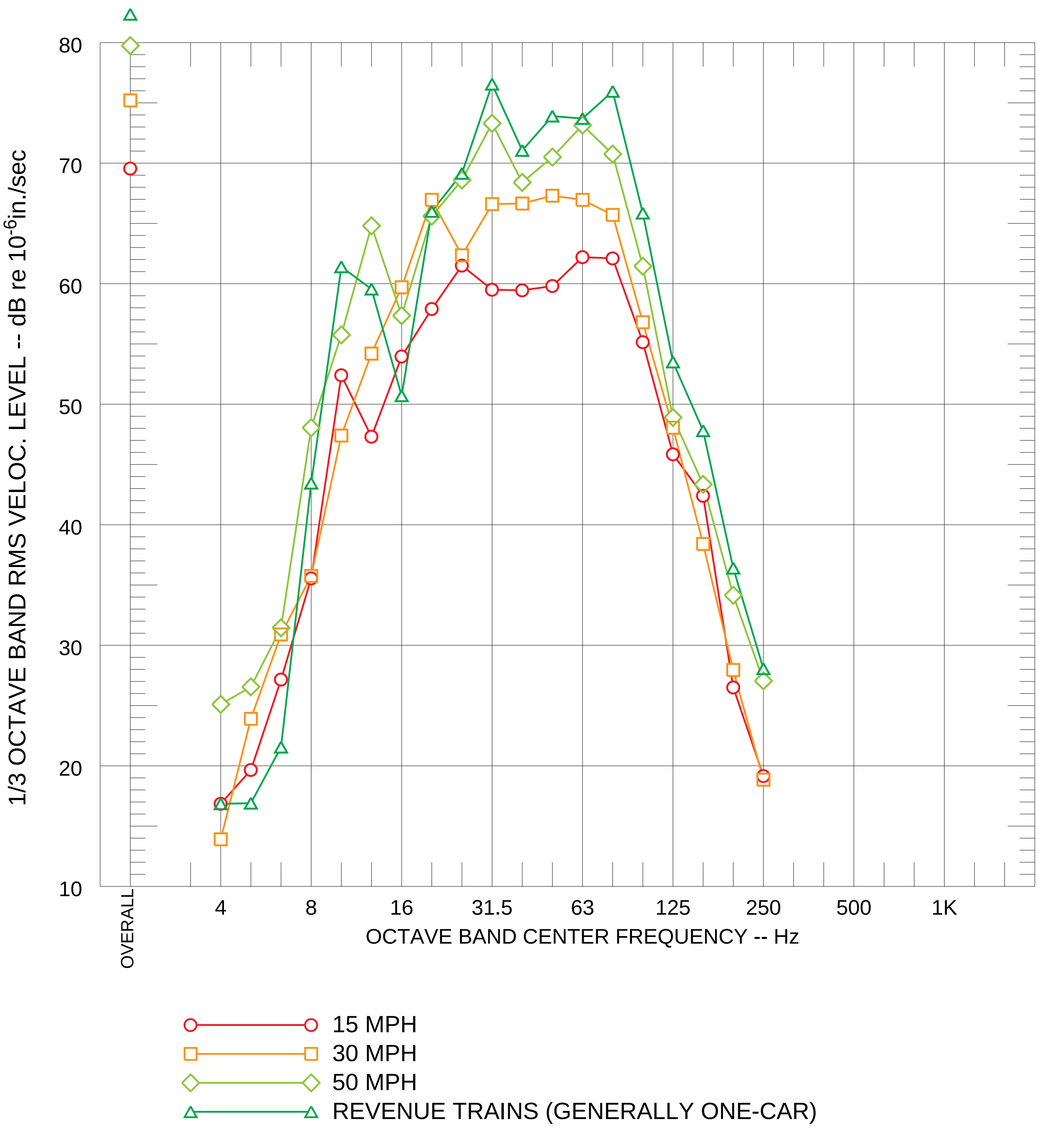


FIGURE A-29 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #1 - LOCATION 6 - 25 FT WEST OF TRACK CENTERLINE AT STATION 133+90

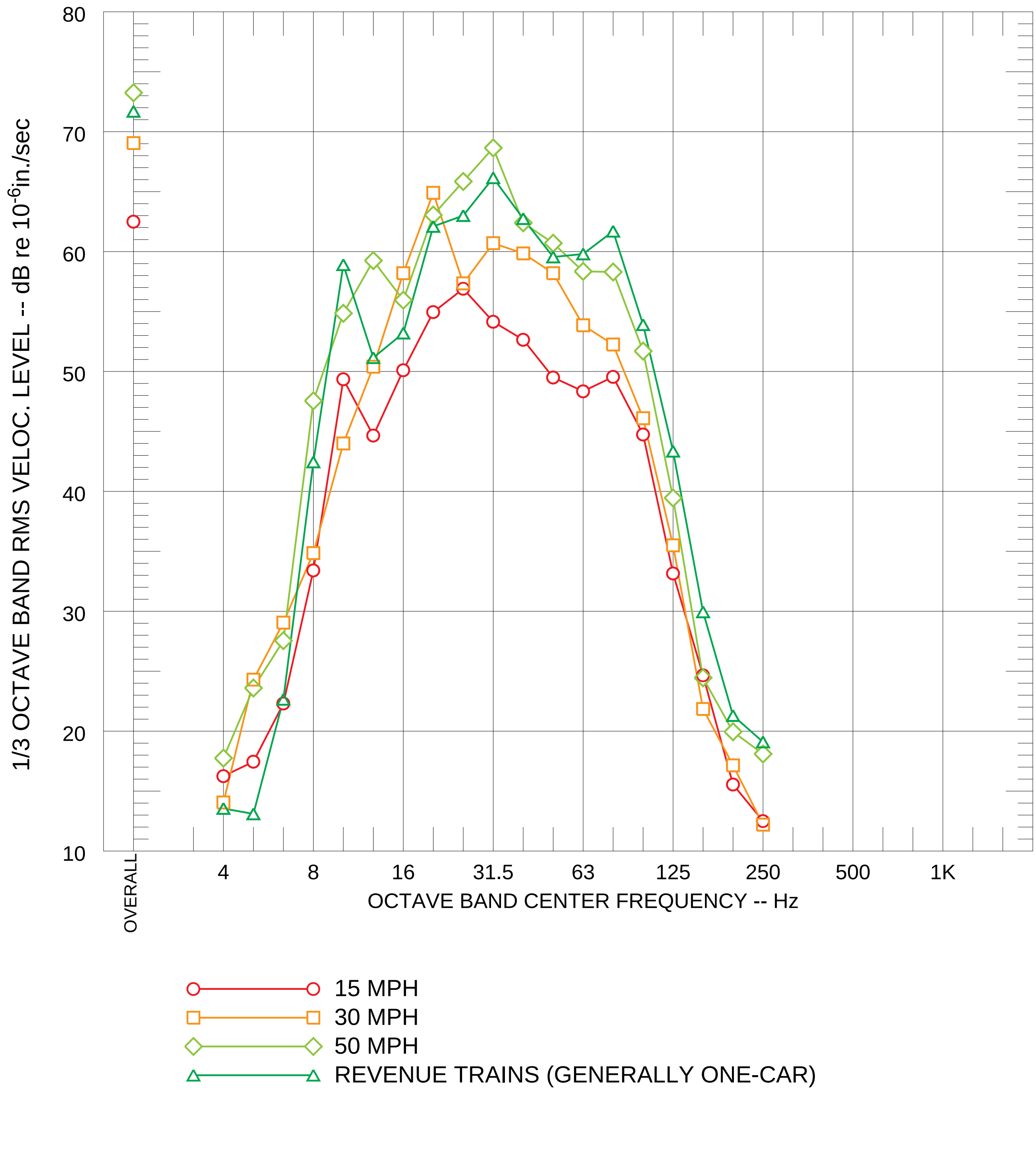


FIGURE A-30 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #1 - LOCATION 7 - 40 FT WEST OF TRACK CENTERLINE AT STATION 133+68

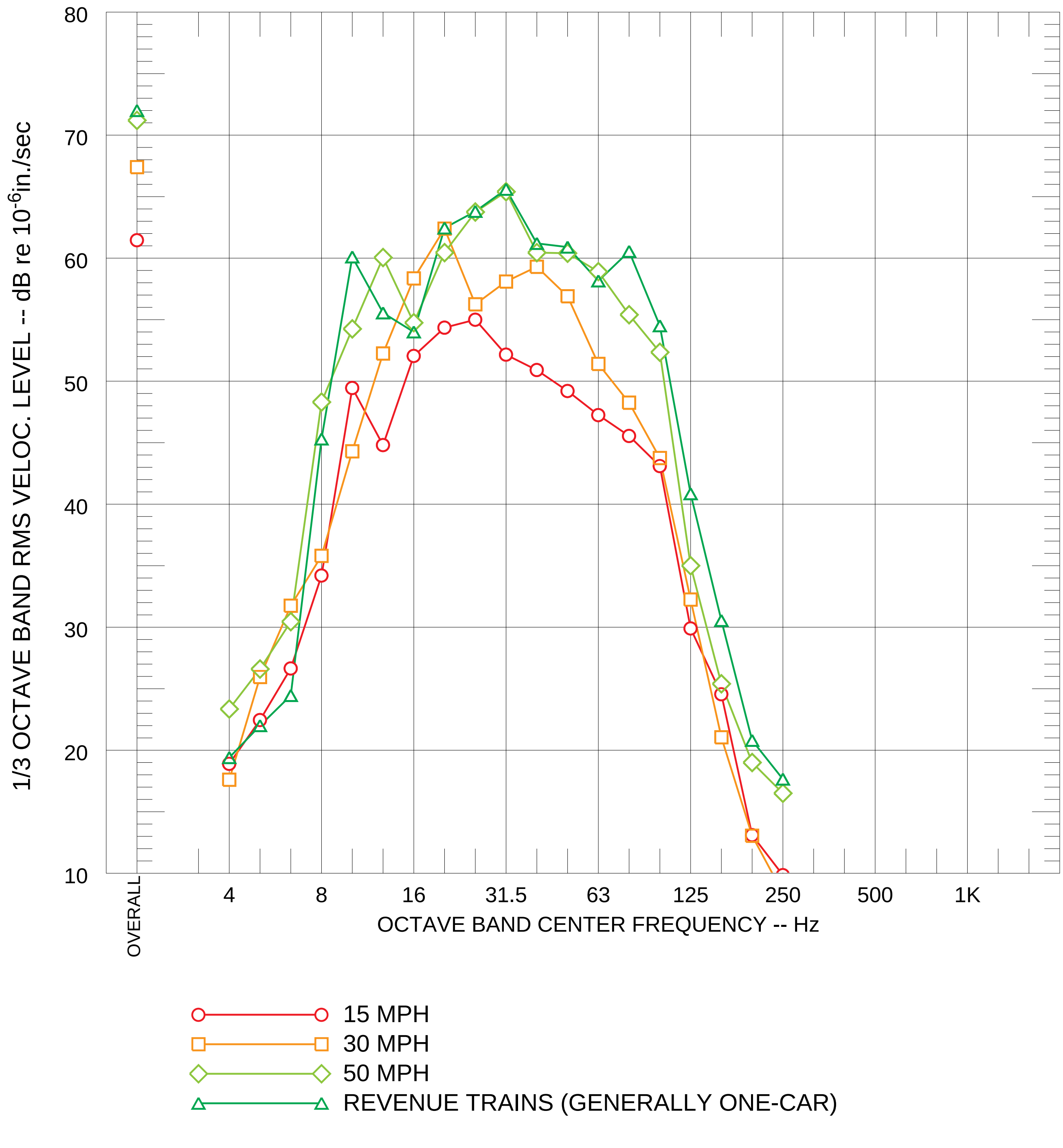


FIGURE A-31 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #1 - LOCATION 8 - 40 FT WEST OF TRACK CENTERLINE AT STATION 133+90

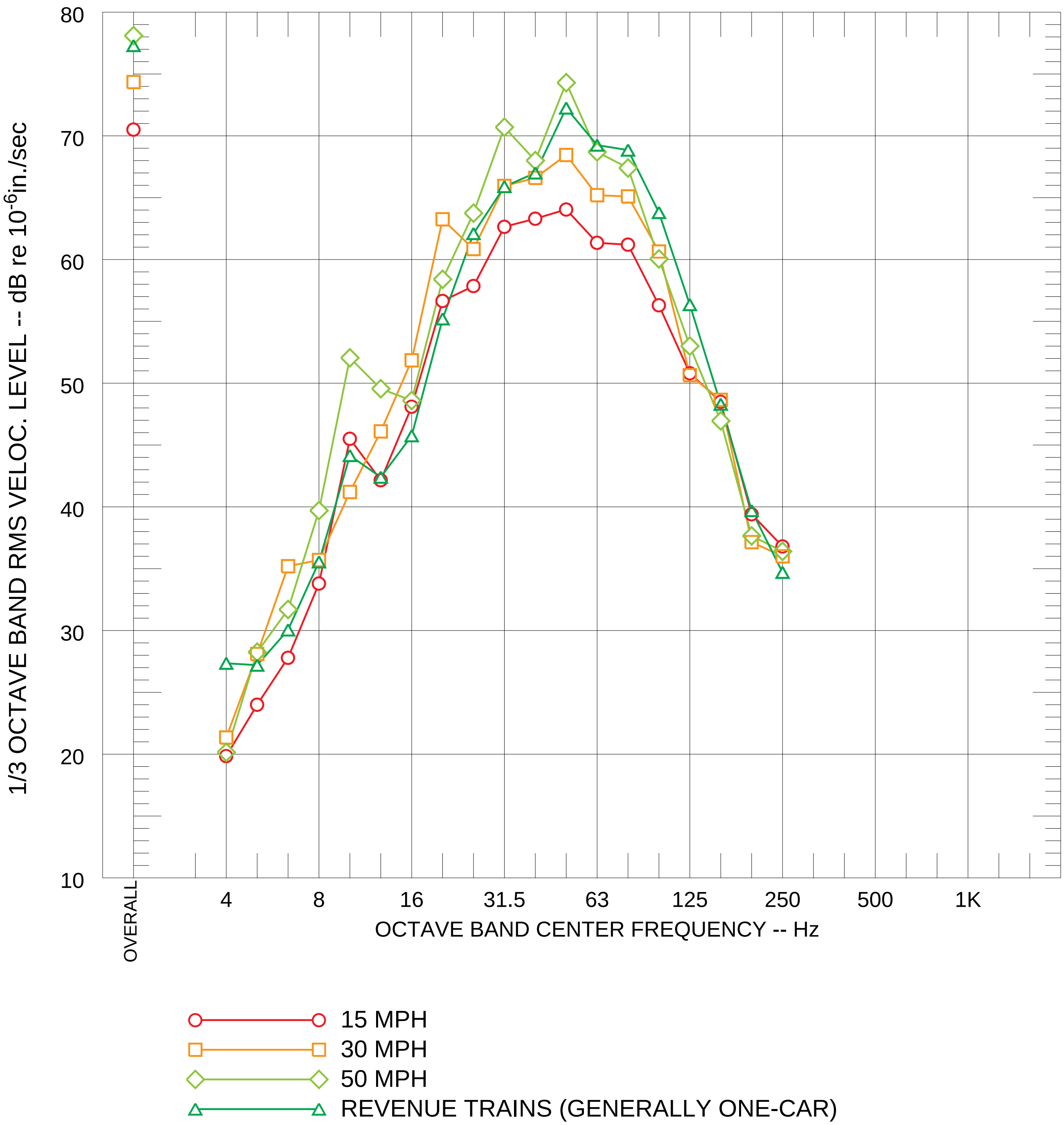


FIGURE A-32 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #2 - LOCATION 1 - 25 FT WEST OF TRACK CENTERLINE AT STATION 154+45

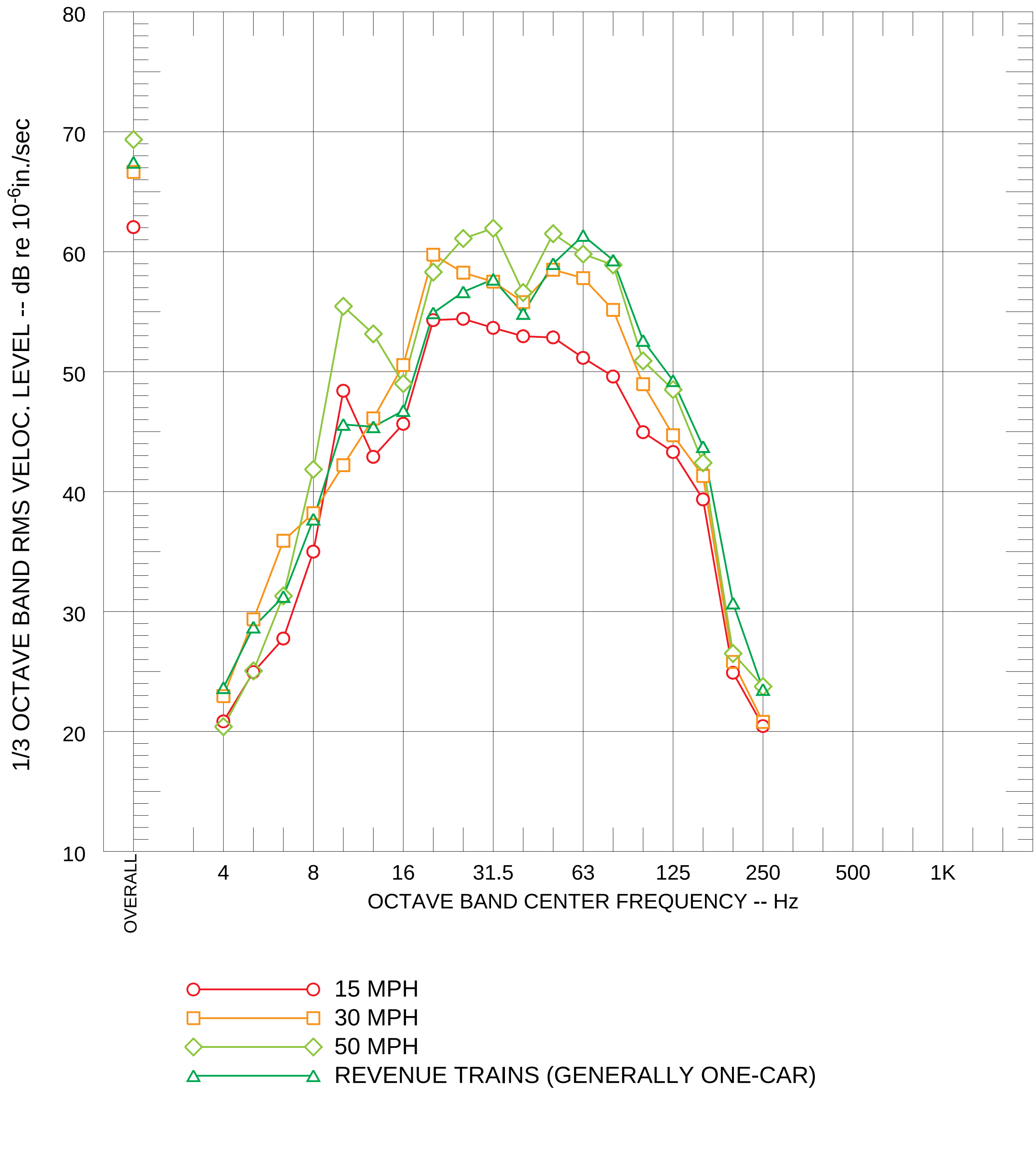


FIGURE A-33 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #2 - LOCATION 2 - 25 FT EAST OF TRACK CENTERLINE AT STATION 154+45

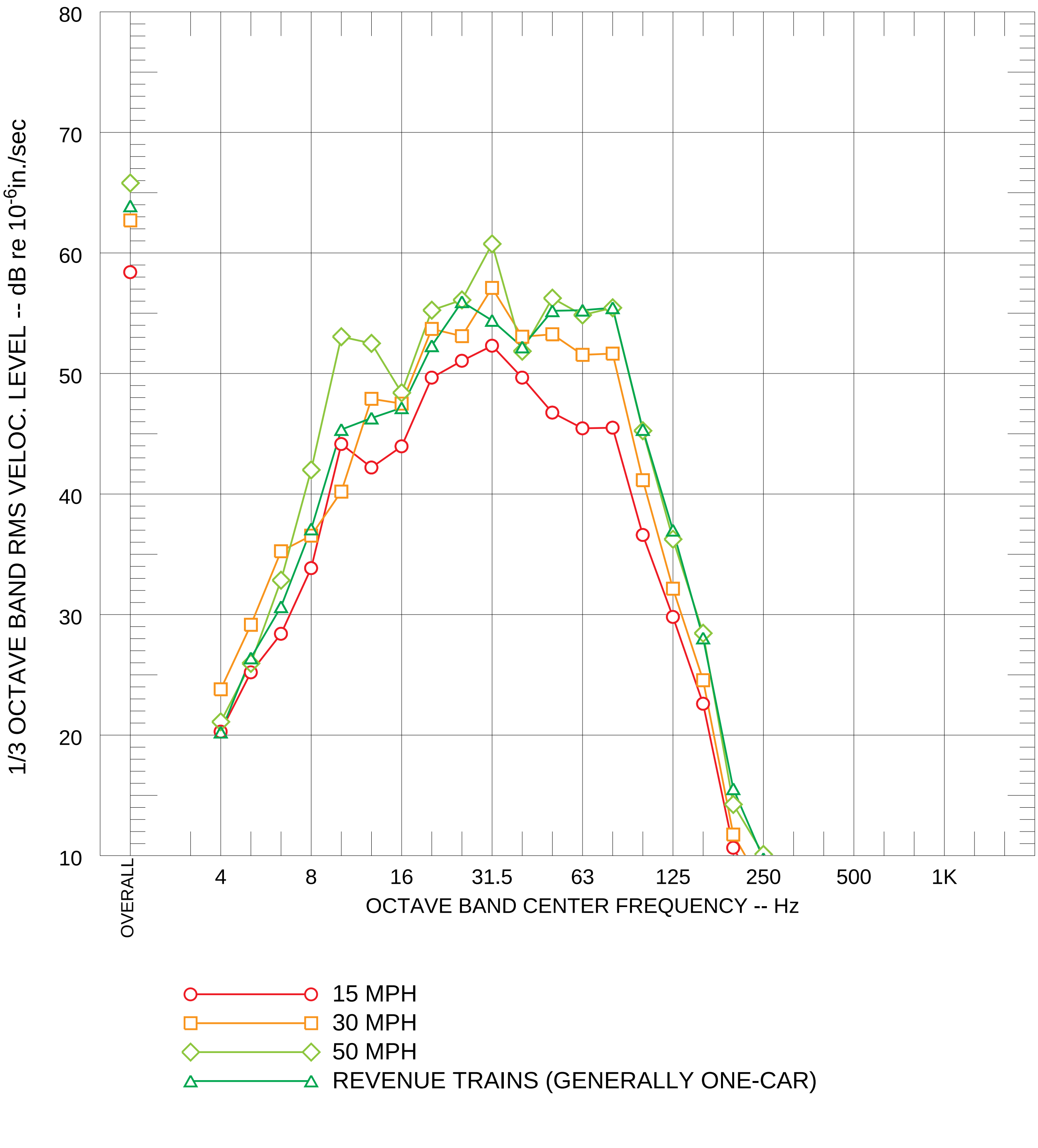


FIGURE A-34 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #2 - LOCATION 3 - 50 FT EAST OF TRACK CENTERLINE AT STATION 154+45

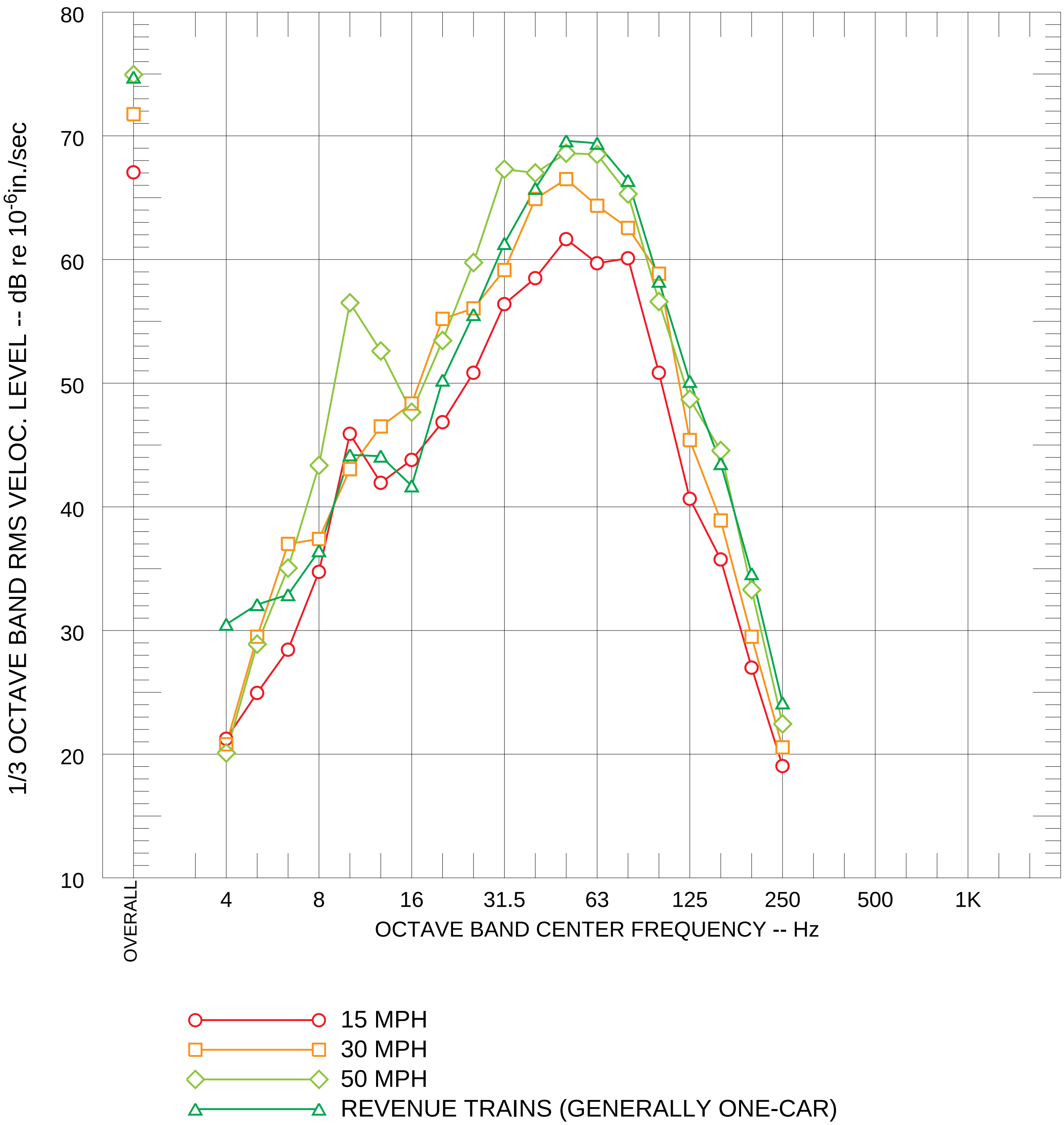


FIGURE A-35 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #2 - LOCATION 4 - 25 FT EAST OF TRACK CENTERLINE AT STATION 154+08

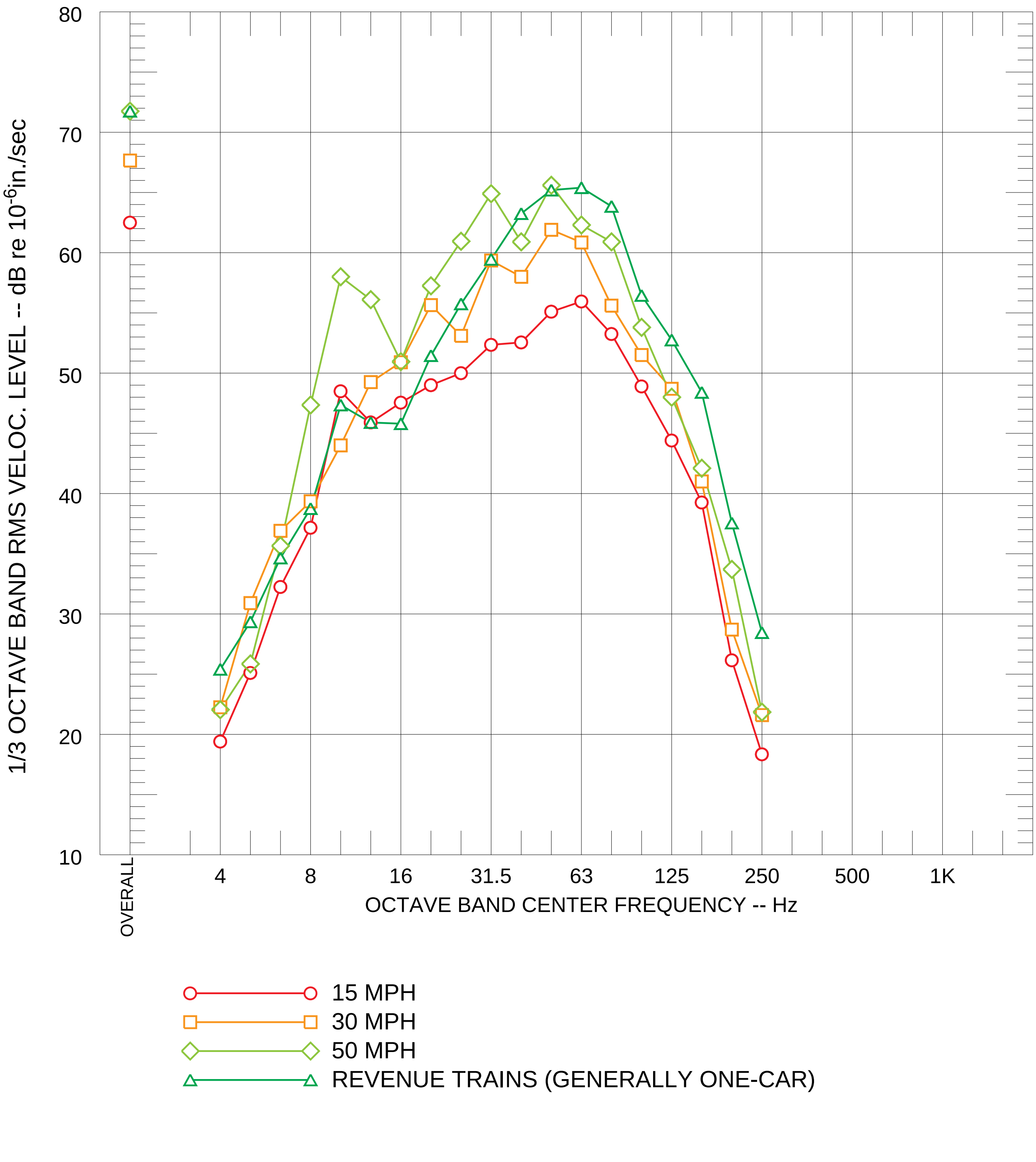


FIGURE A-36 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #2 - LOCATION 5 - 25 FT EAST OF TRACK CENTERLINE AT STATION 153+85

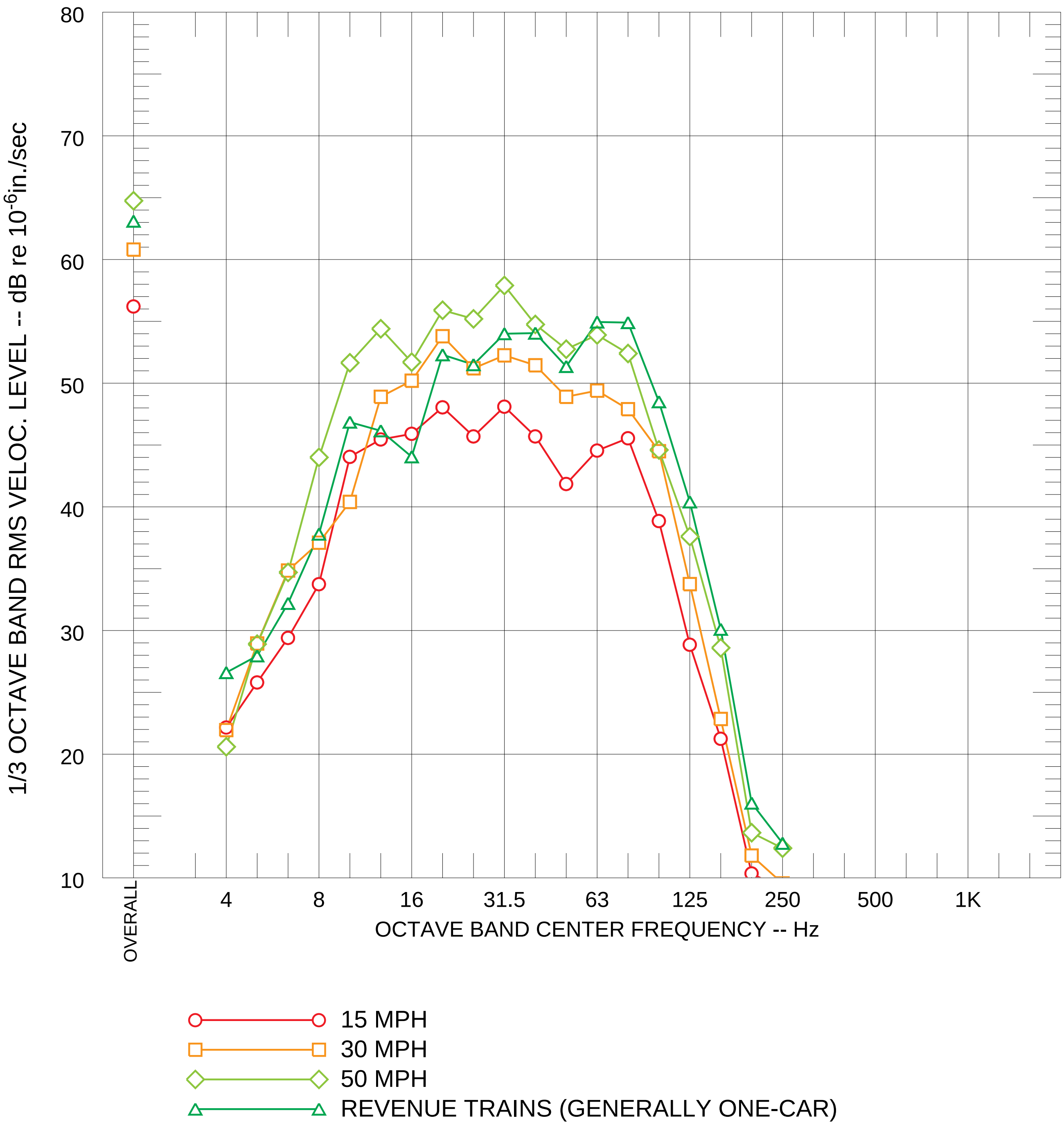


FIGURE A-37 TWO-CAR TEST TRAIN PASSBYS AT CONTROL SITE #2 - LOCATION 6 - 50 FT EAST OF TRACK CENTERLINE AT STATION 154+08

APPENDIX B

Plots of Rail Strain

Page

Figure B-1 TDA Site #1 Rail Strain Measured over Tie
Southbound Track - 15 mph

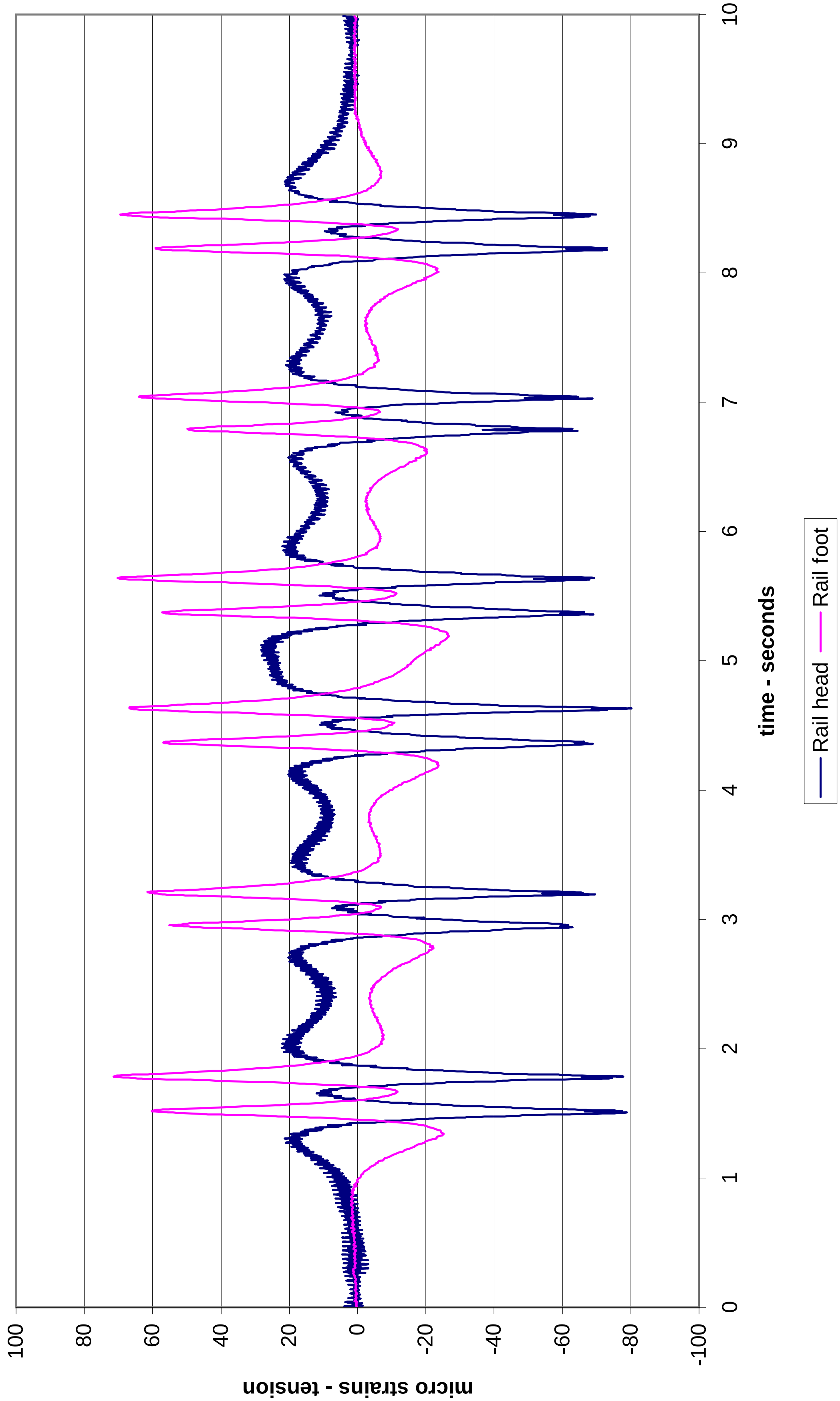


Figure B-2 TDA Site #1 Rail Strain Measured between Ties Southbound Track - 15 mph

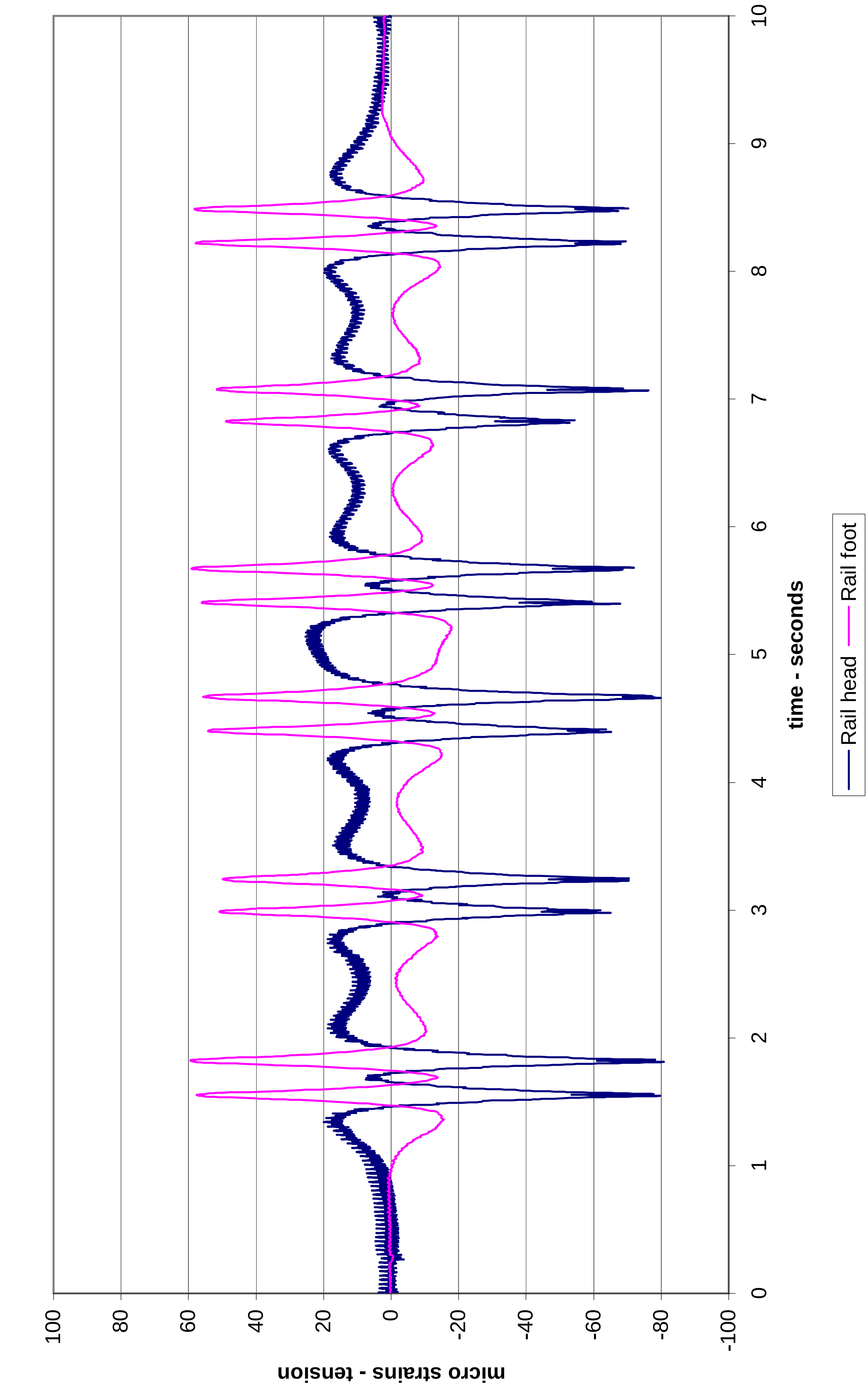


Figure B-3 TDA Site #1 Rail Strain Measured over Tie Southbound Track - 30 mph

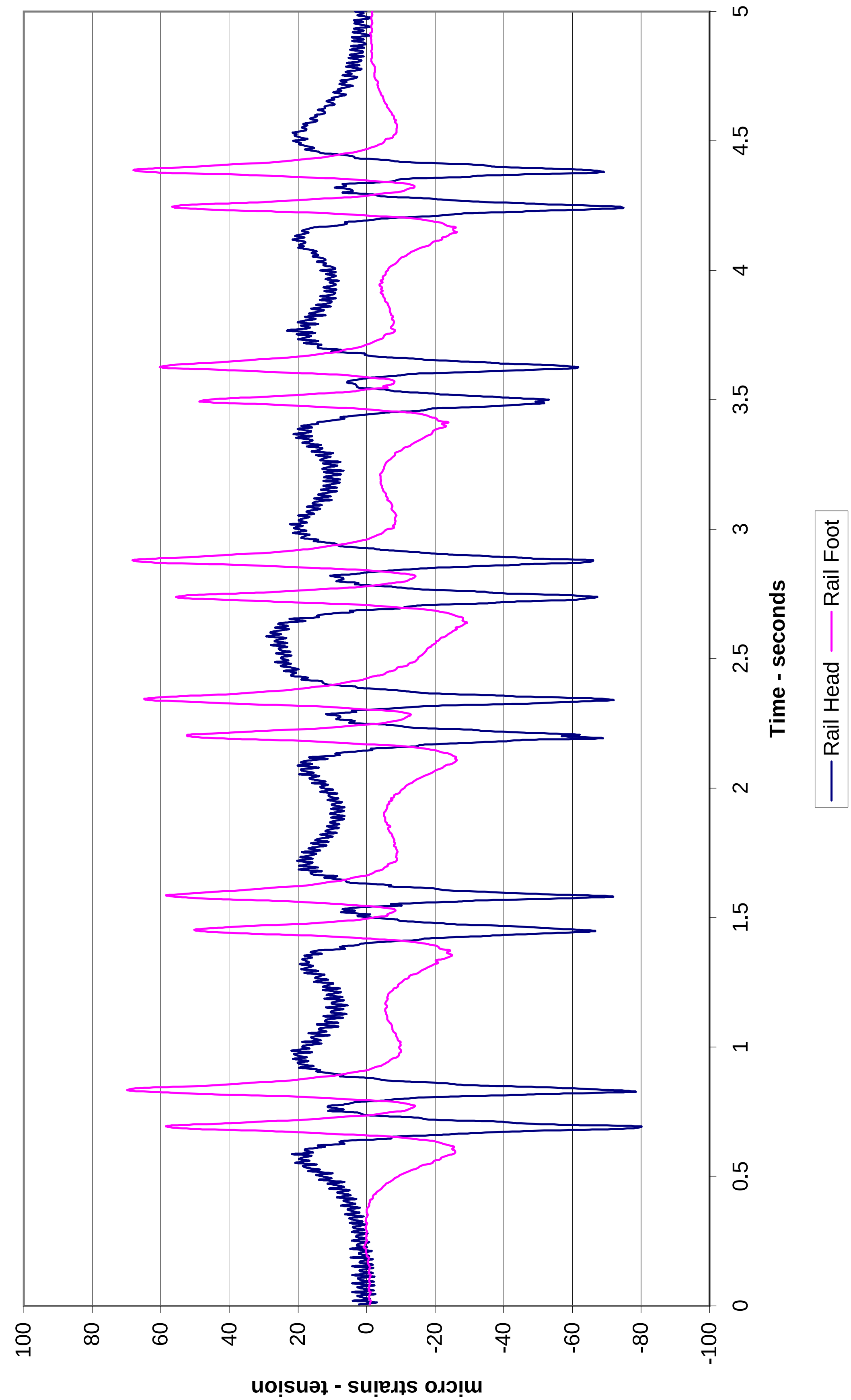


Figure B-4 TDA Site #1 Rail Strain Measured between Ties
Southbound Track - 30 mph

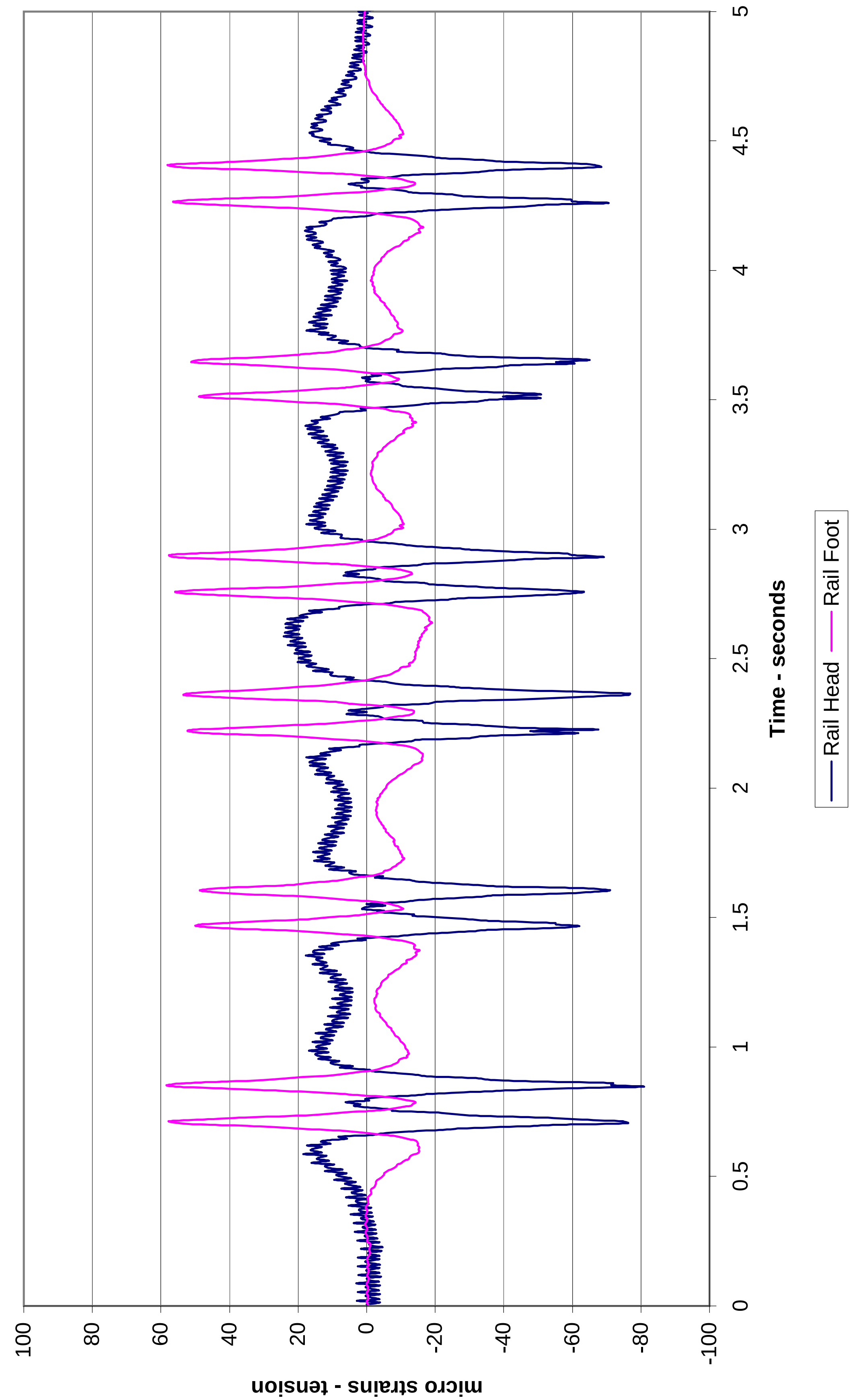


Figure B-5 TDA Site #1 Rail Strain Measured over Tie
Southbound Track - 46 mph

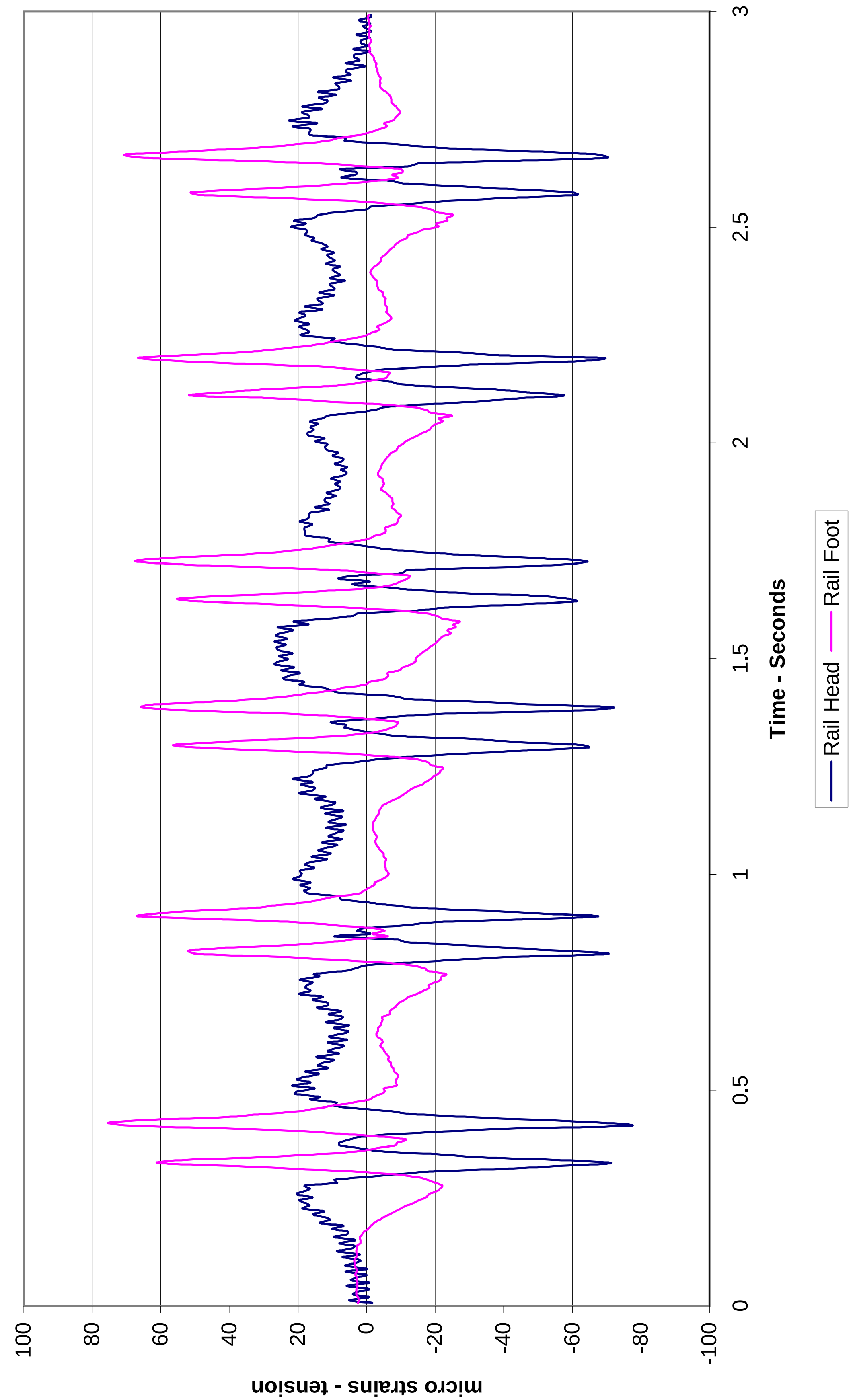


Figure B-6 TDA Site #1 Rail Strain Measured between Ties
Southbound Track - 46 mph

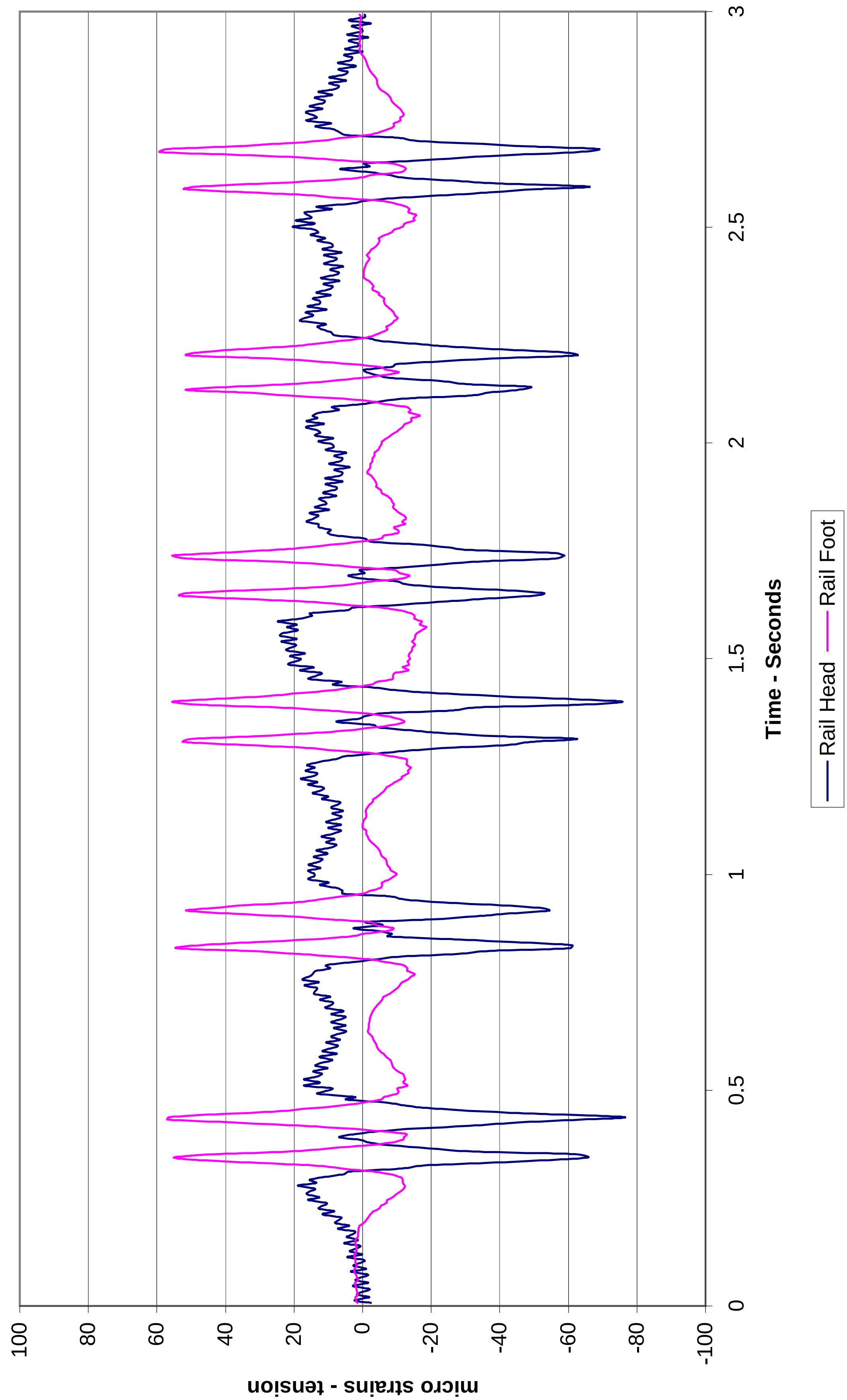


Figure B-7 TDA Site #1 Rail Strain Measured over Tie
Northbound Track - 15 mph

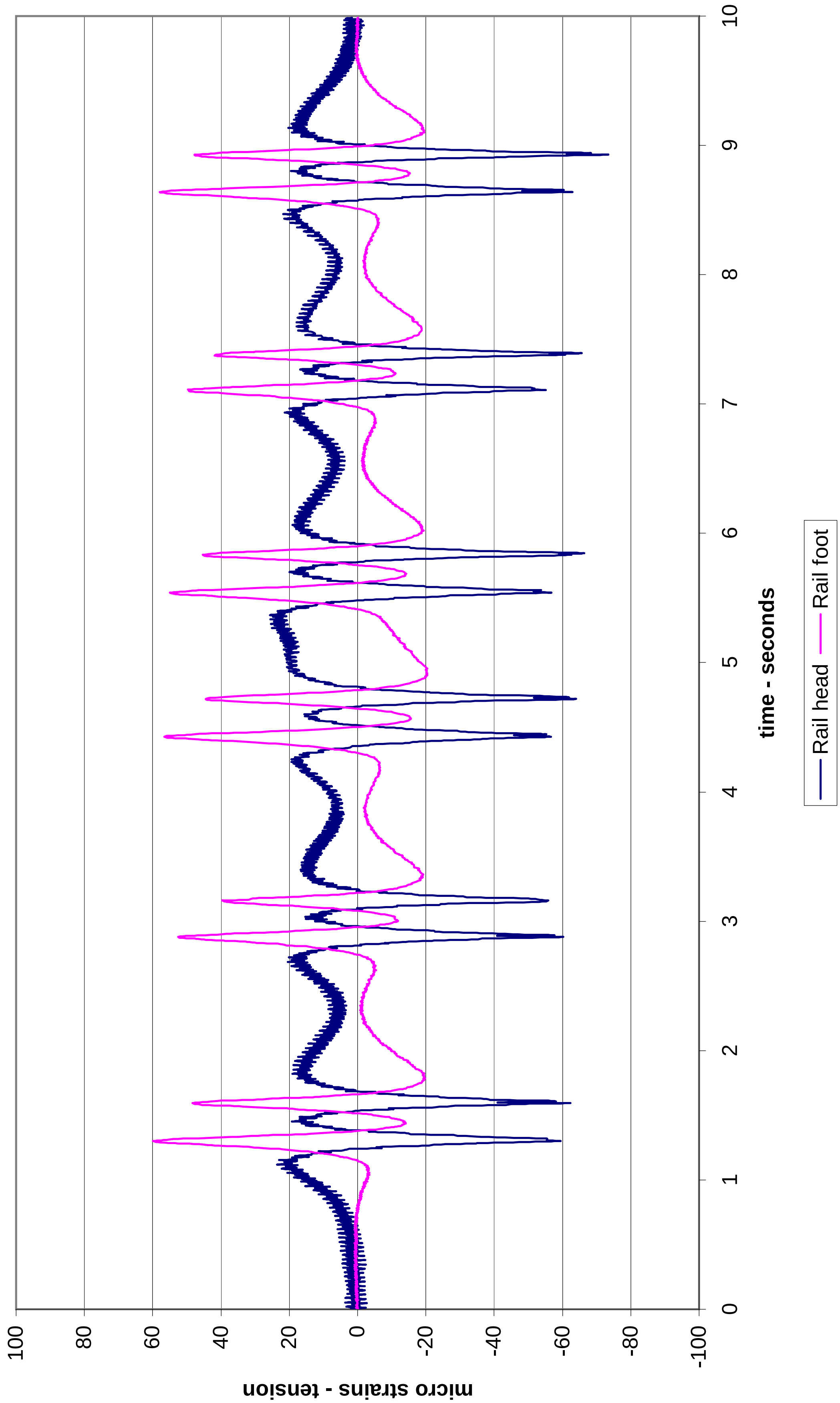


Figure B-8 TDA Site #1 Rail Strain Measured between Ties
Northbound Track - 15 mph

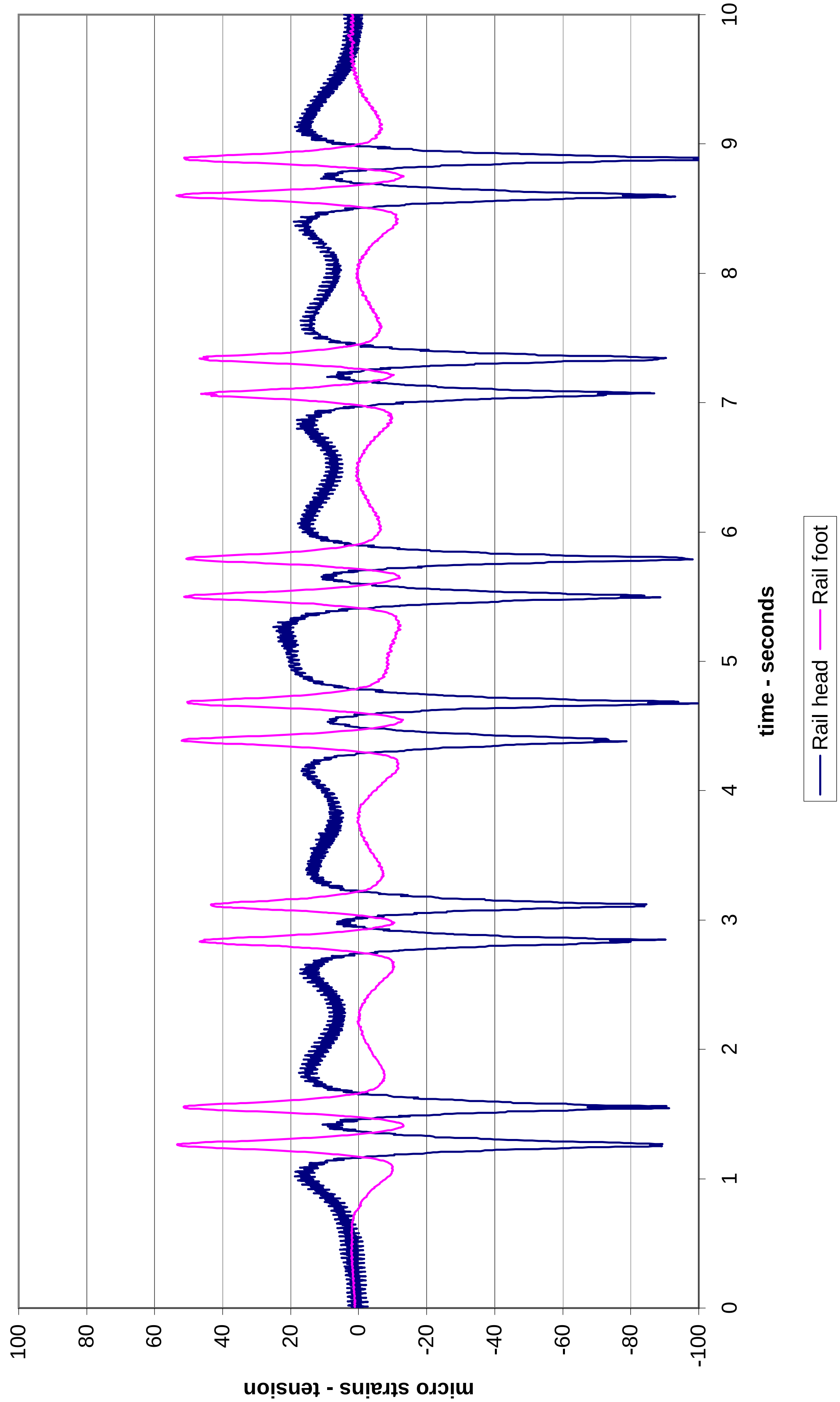


Figure B-9 TDA Site #1 Rail Strain Measured over Tie
Northbound Track - 30 mph

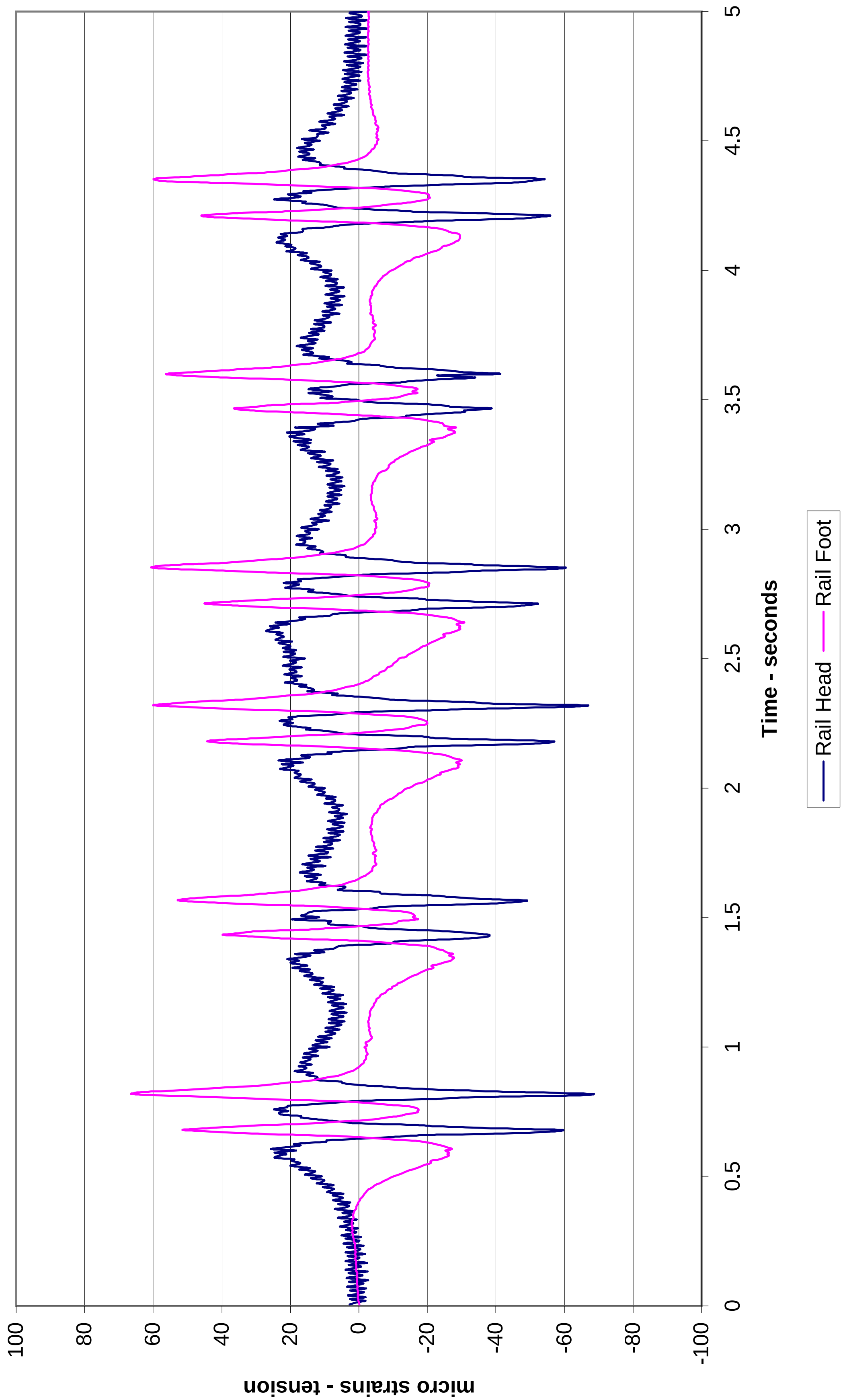


Figure B-10 TDA Site #1 Rail Strain Measured between Ties
Northbound Track - 30 mph

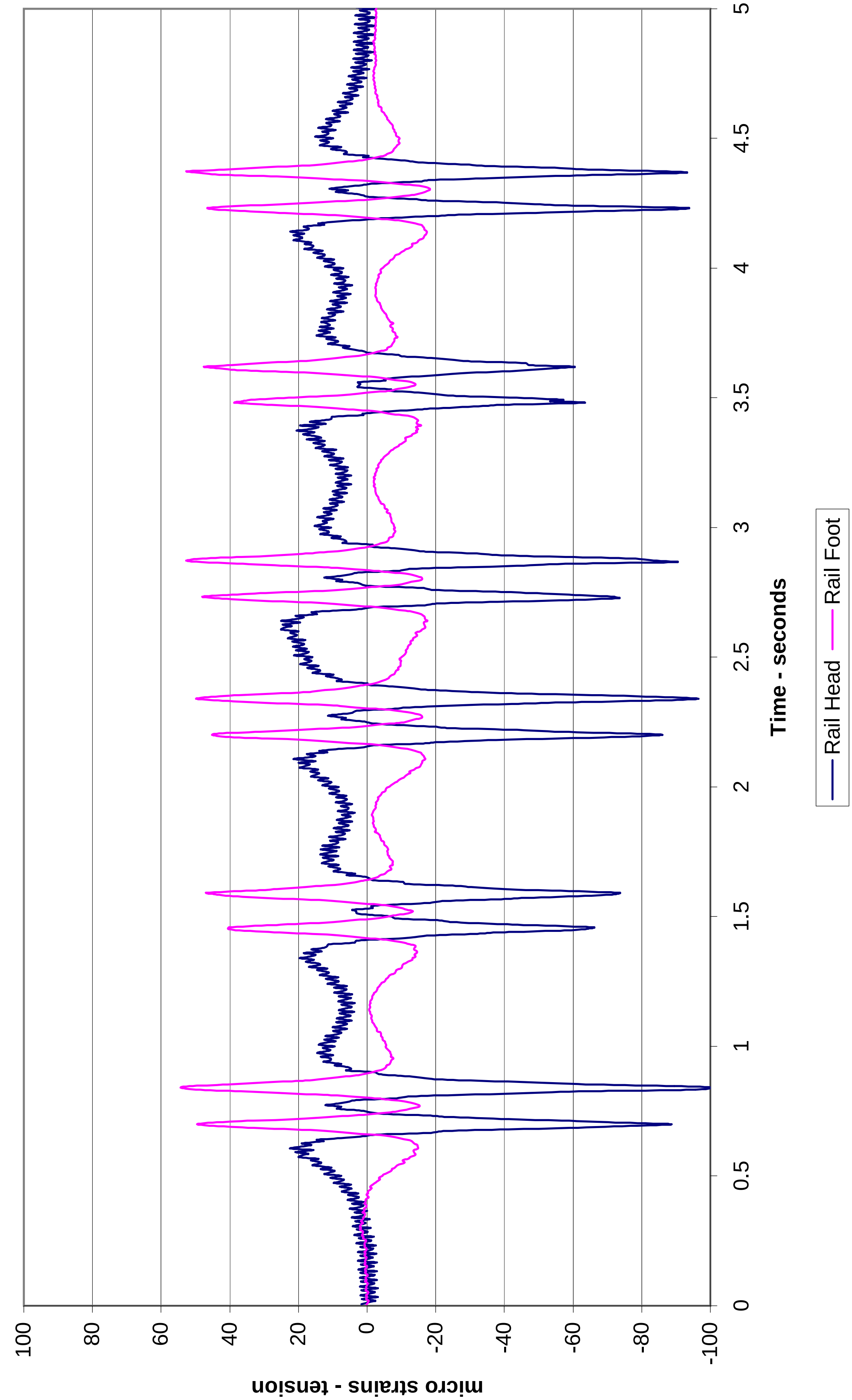


Figure B-11 TDA Site #1 Rail Strain Measured over Tie
Northbound Track - 50 mph

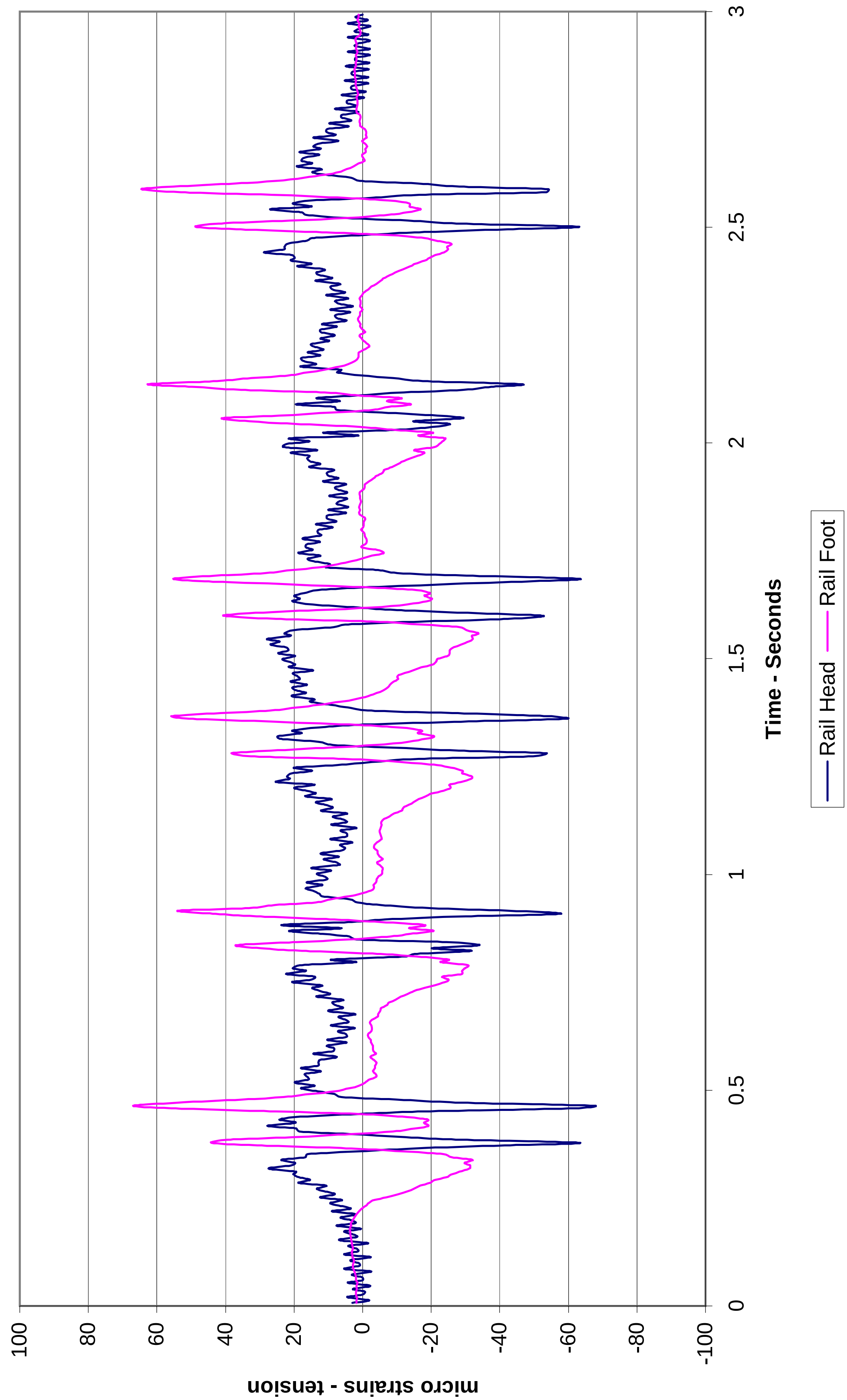


Figure B-12 TDA Site #1 Rail Strain Measured between Ties
Northbound Track - 50 mph

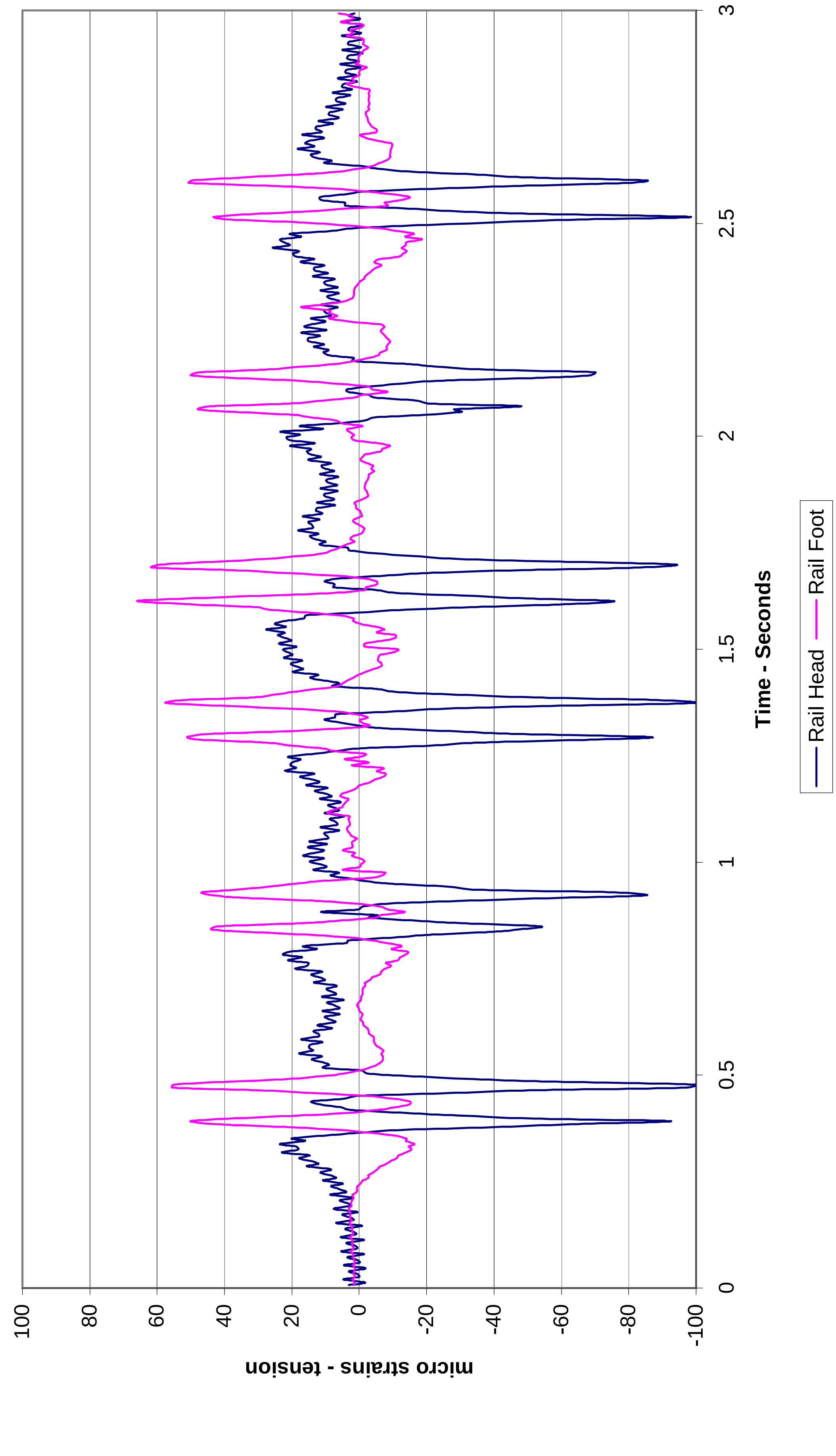


Figure B-13 TDA Site #3 Rail Strain Measured over Tie
15 mph

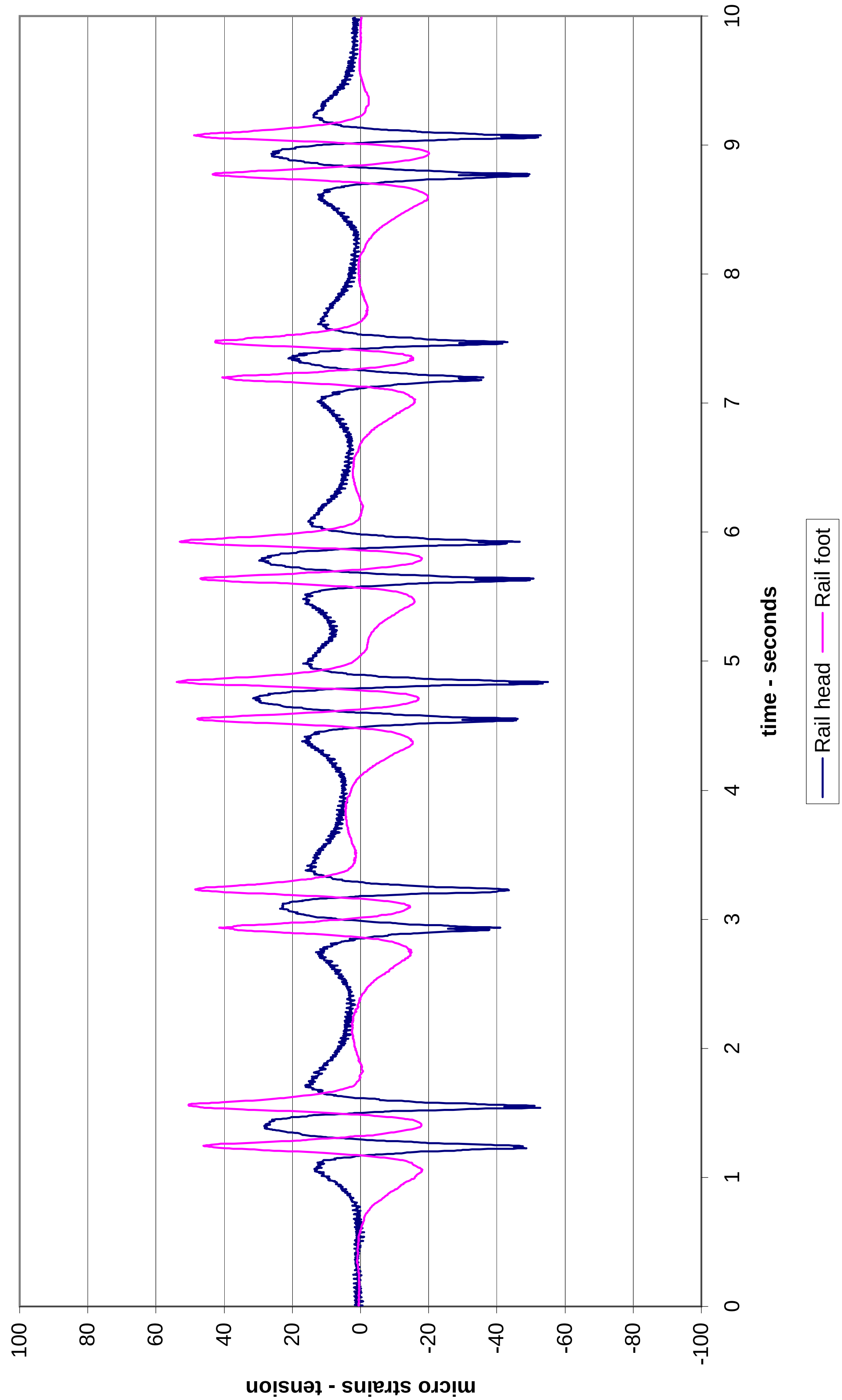


Figure B-14 TDA Site #3 Rail Strain Measured between Ties
15 mph

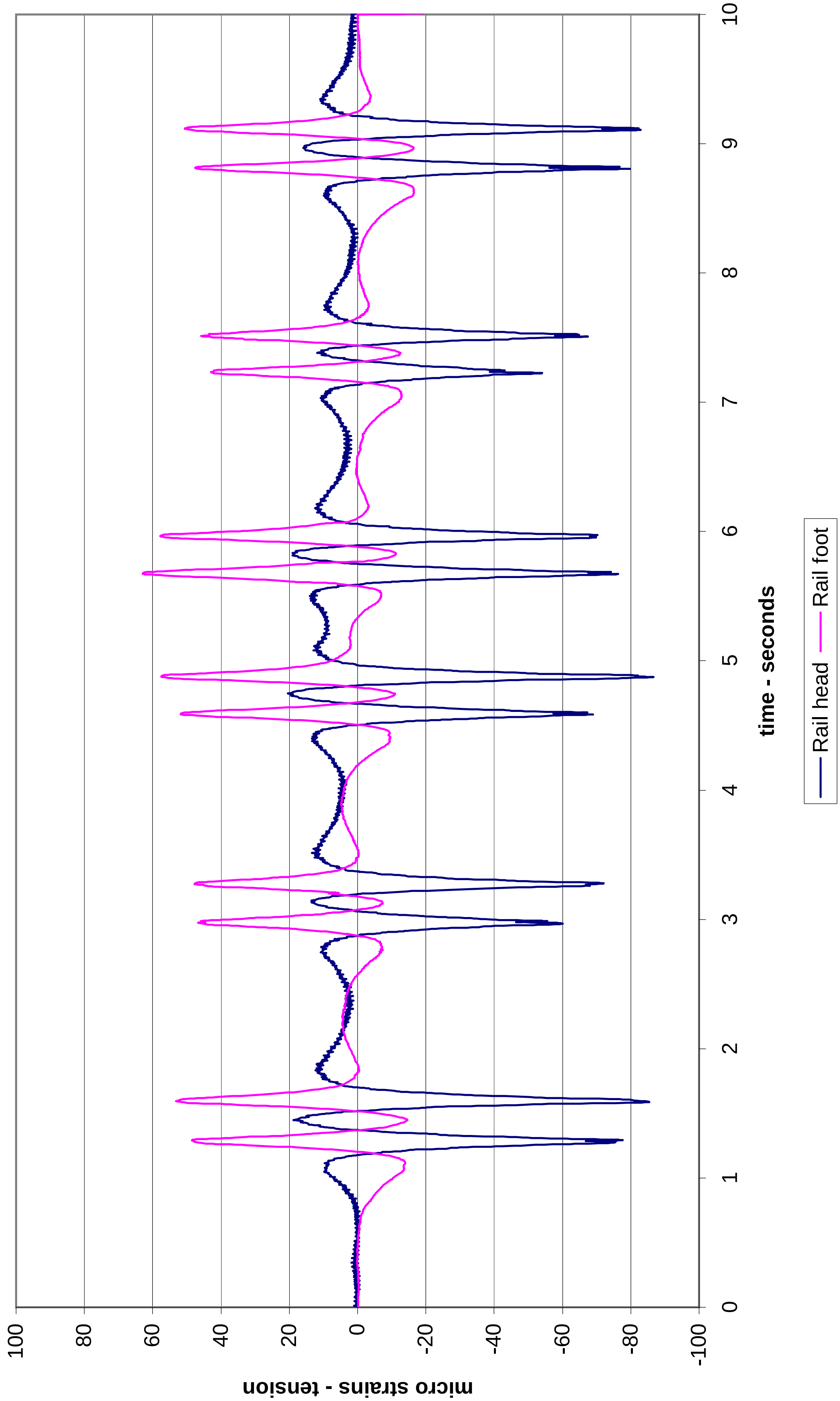


Figure B-15 TDA Site #3 Rail Strain Measured over Tie
30 mph

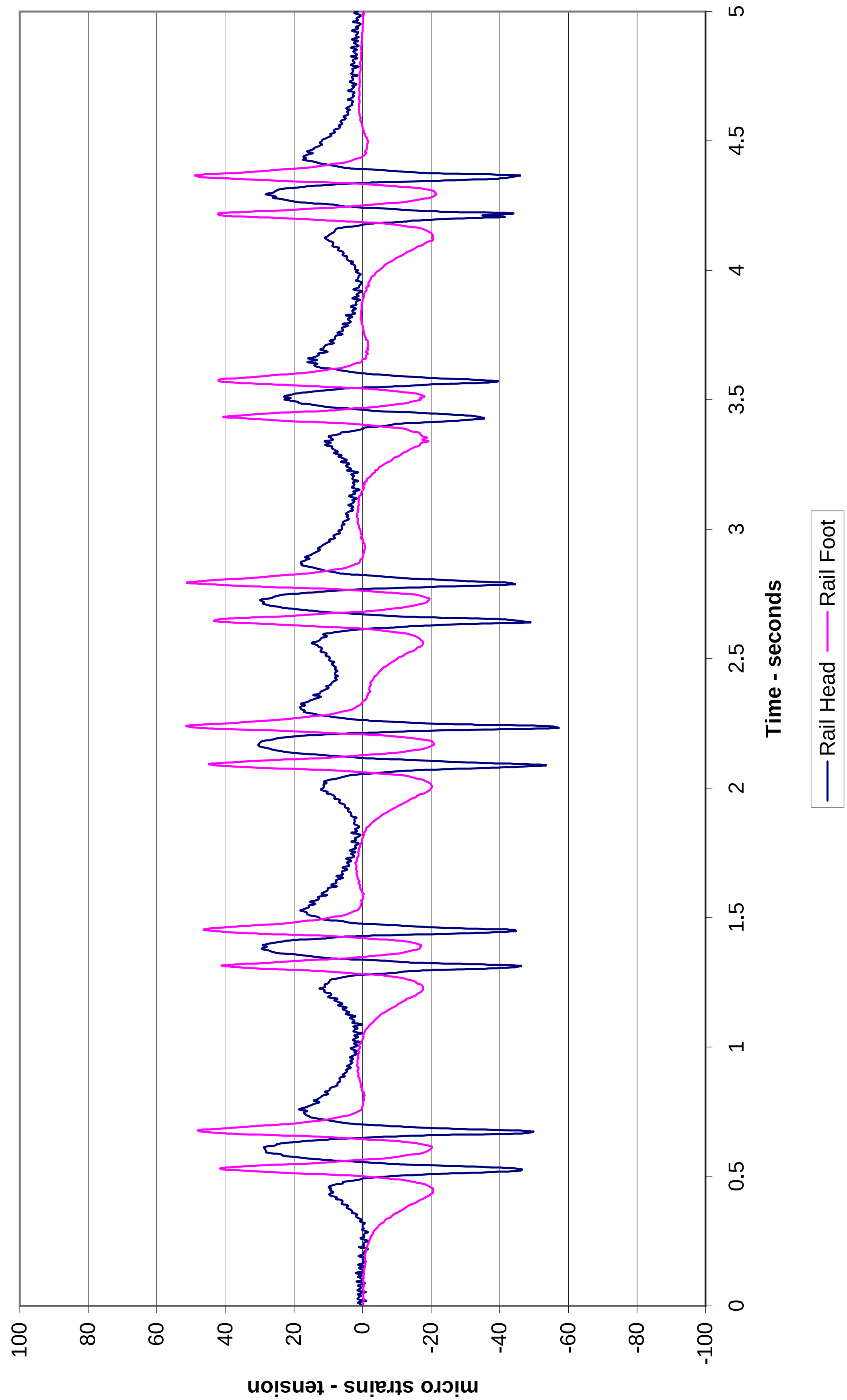


Figure B-16 TDA Site #3 Rail Strain Measured between Ties
30 mph

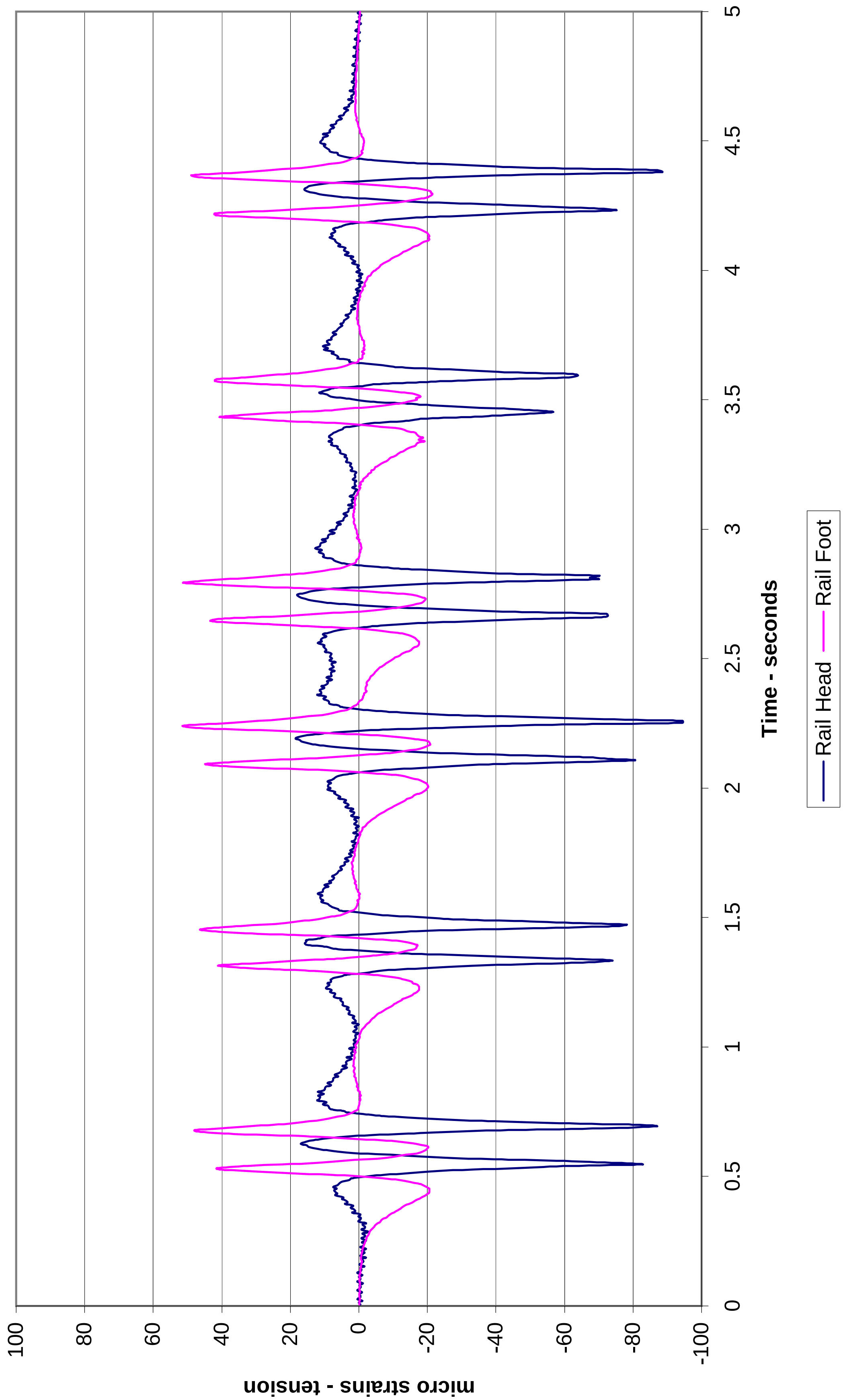


Figure B-17 TDA Site #3 Rail Strain Measured over Tie
50 mph

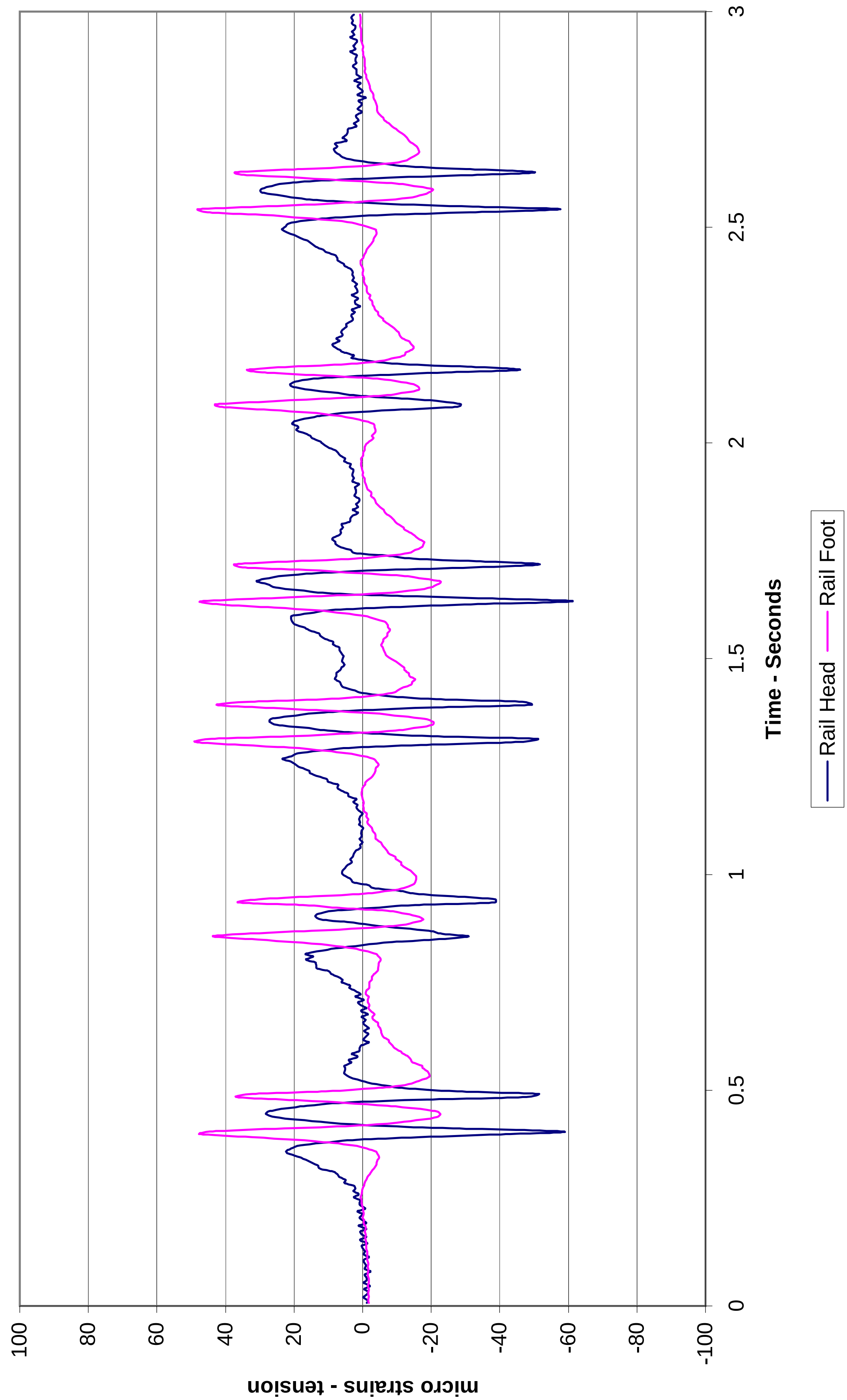


Figure B-18 TDA Site #3 Rail Strain Measured between Ties
50 mph

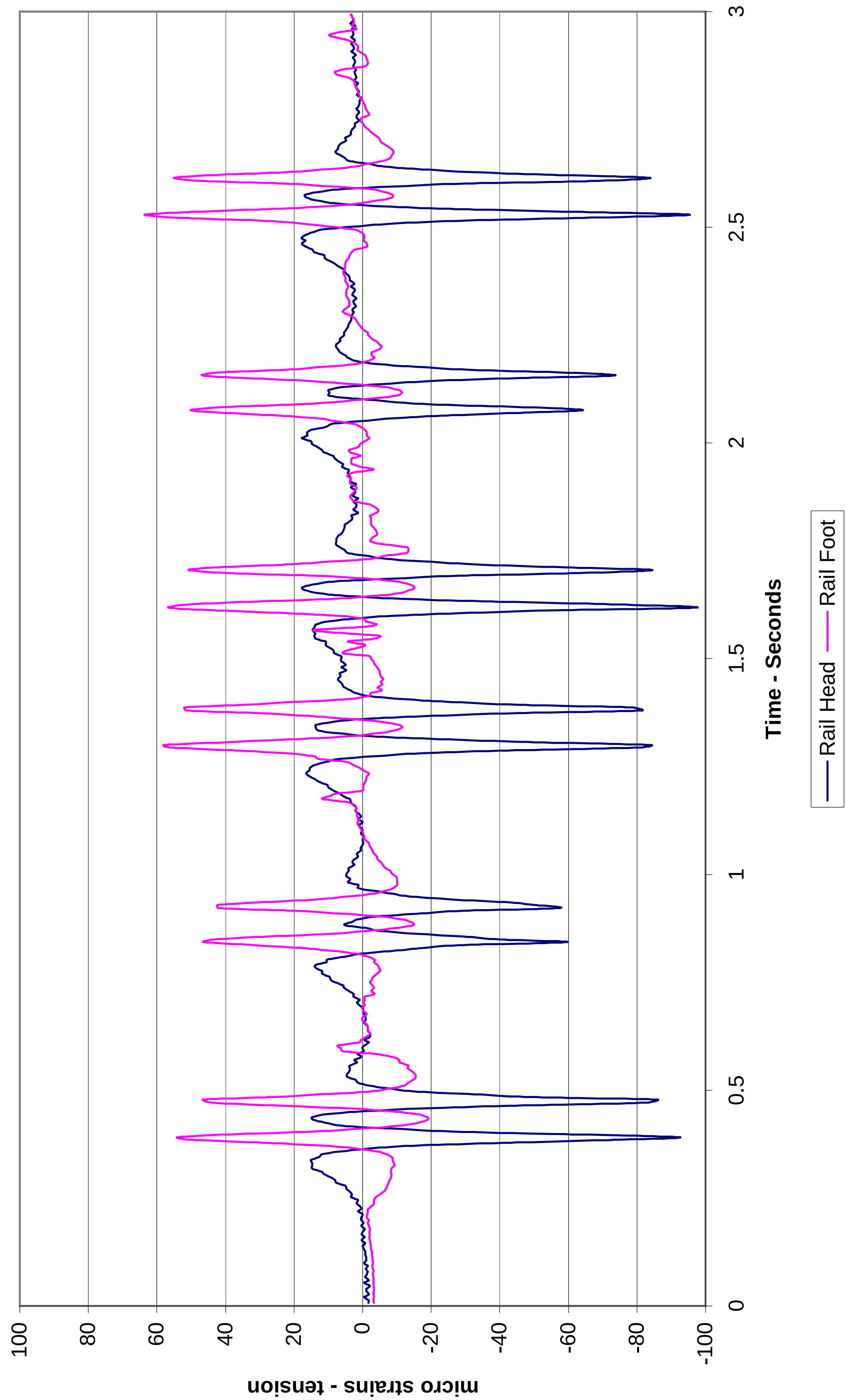


Figure B-19 TDA Site #4 Rail Strain Measured over Tie
15 mph

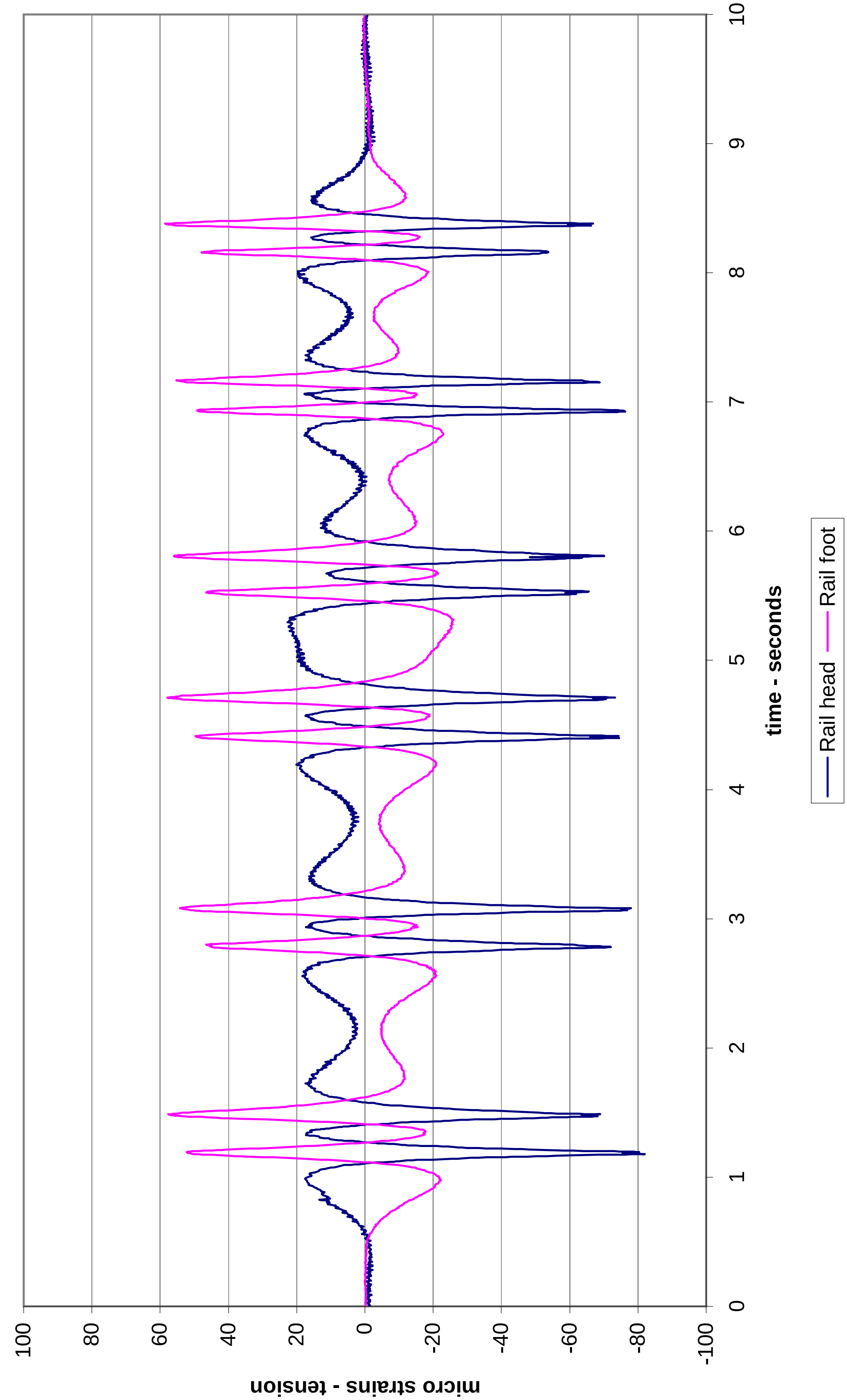


Figure B-20 TDA Site #4 Rail Strain Measured between Ties
15 mph

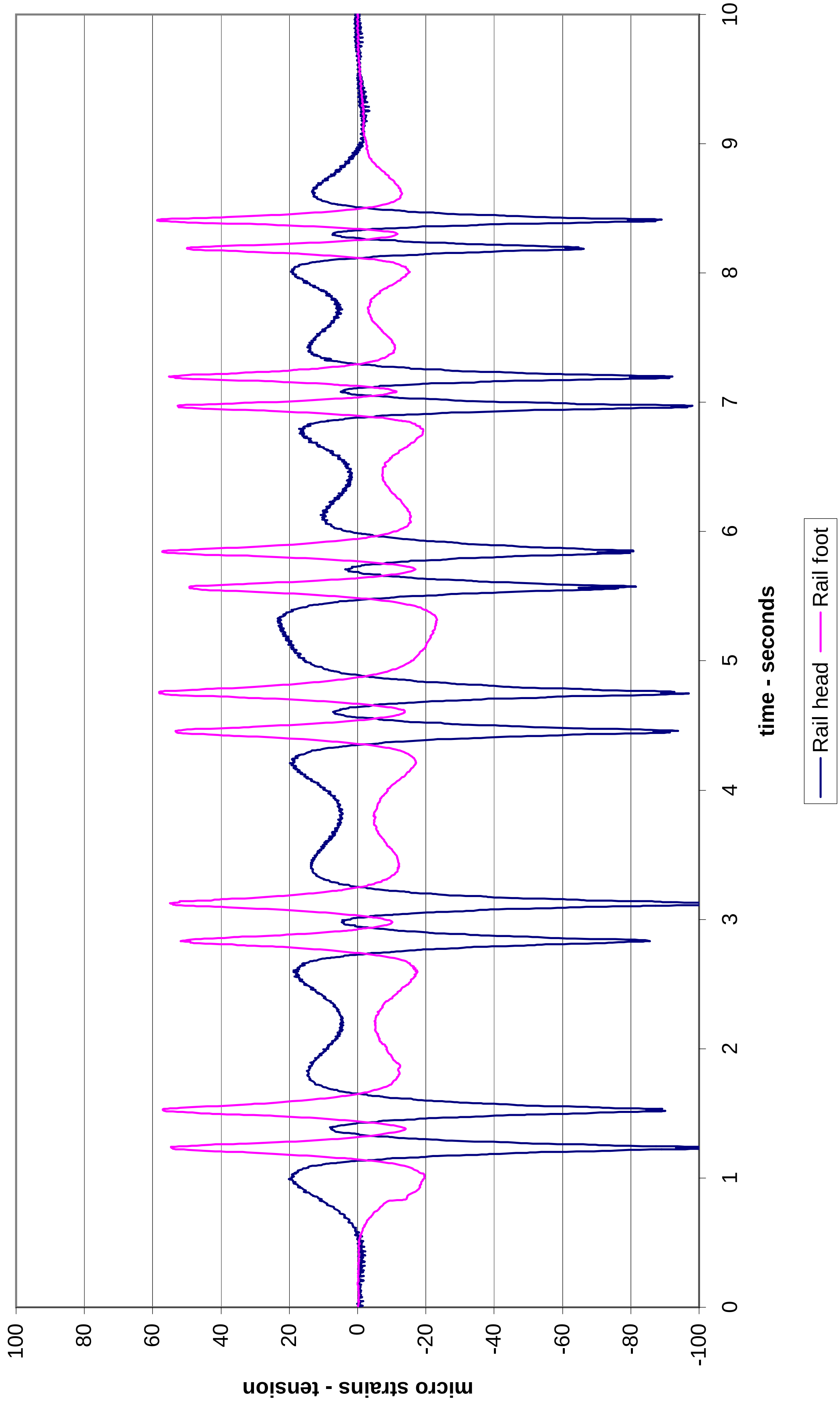


Figure B-21 TDA Site #4 Rail Strain Measured over Tie
30 mph

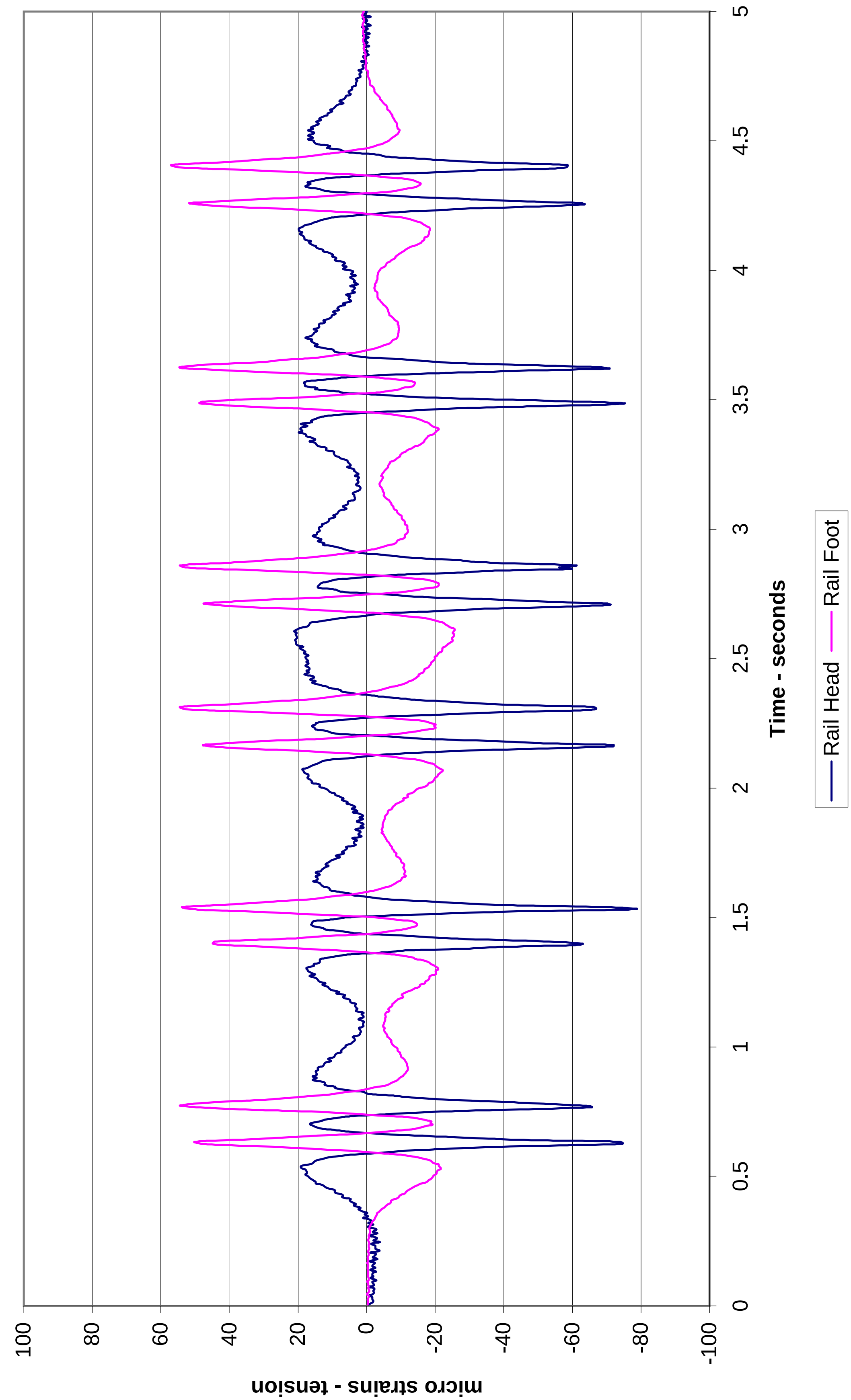


Figure B-22 TDA Site #4 Rail Strain Measured between Ties
30 mph

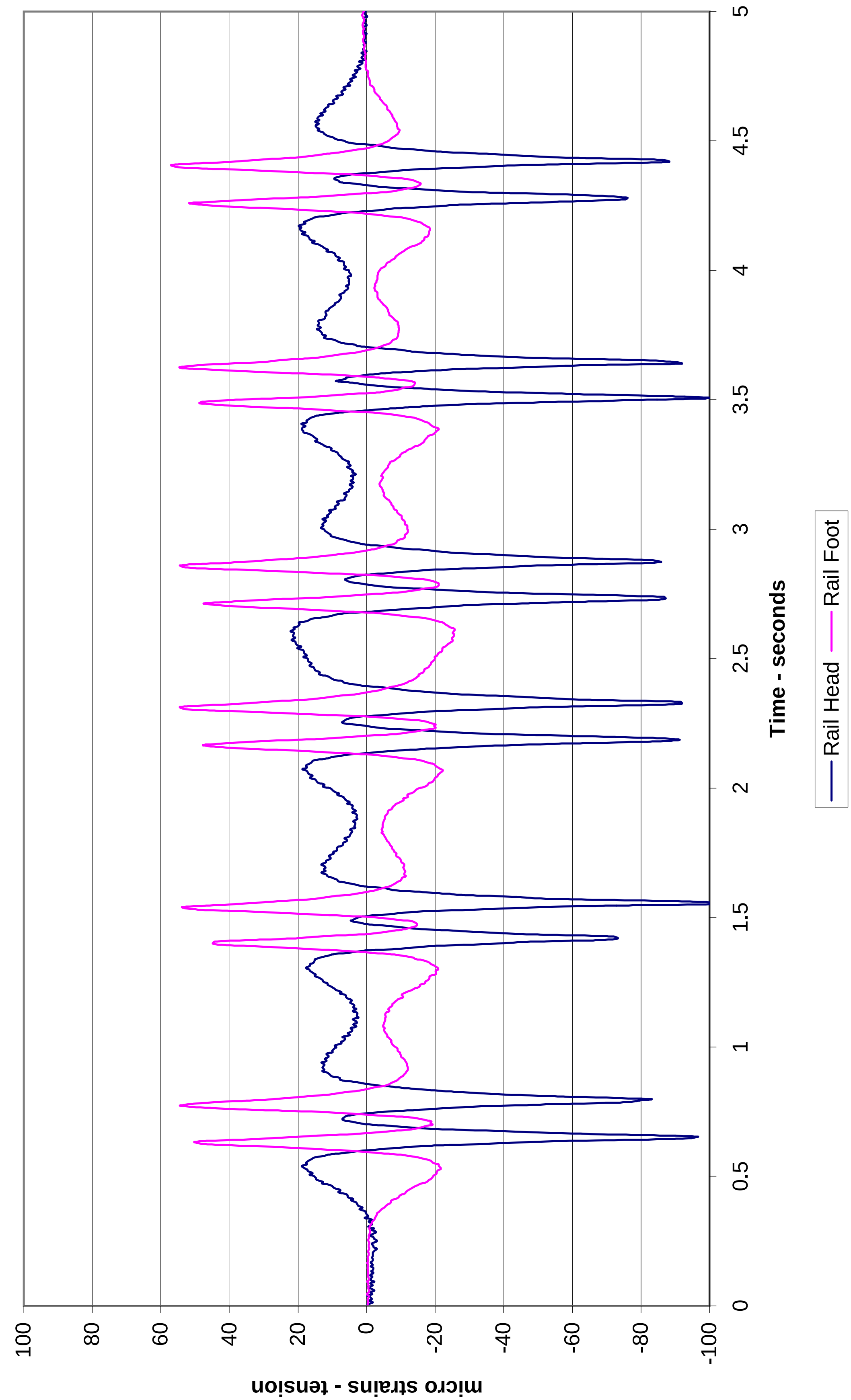


Figure B-23 TDA Site #4 Rail Strain Measured over Tie
50 mph

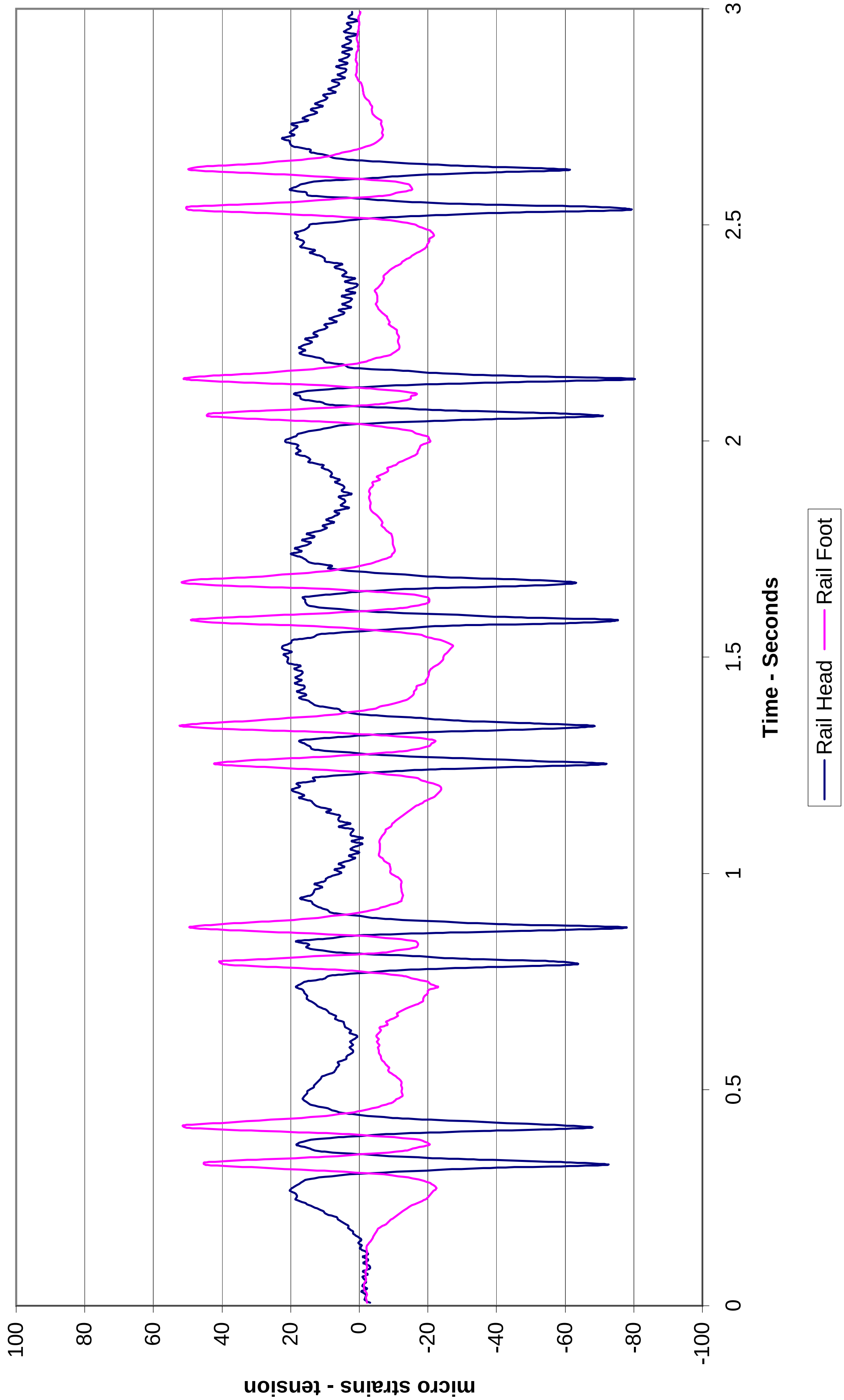
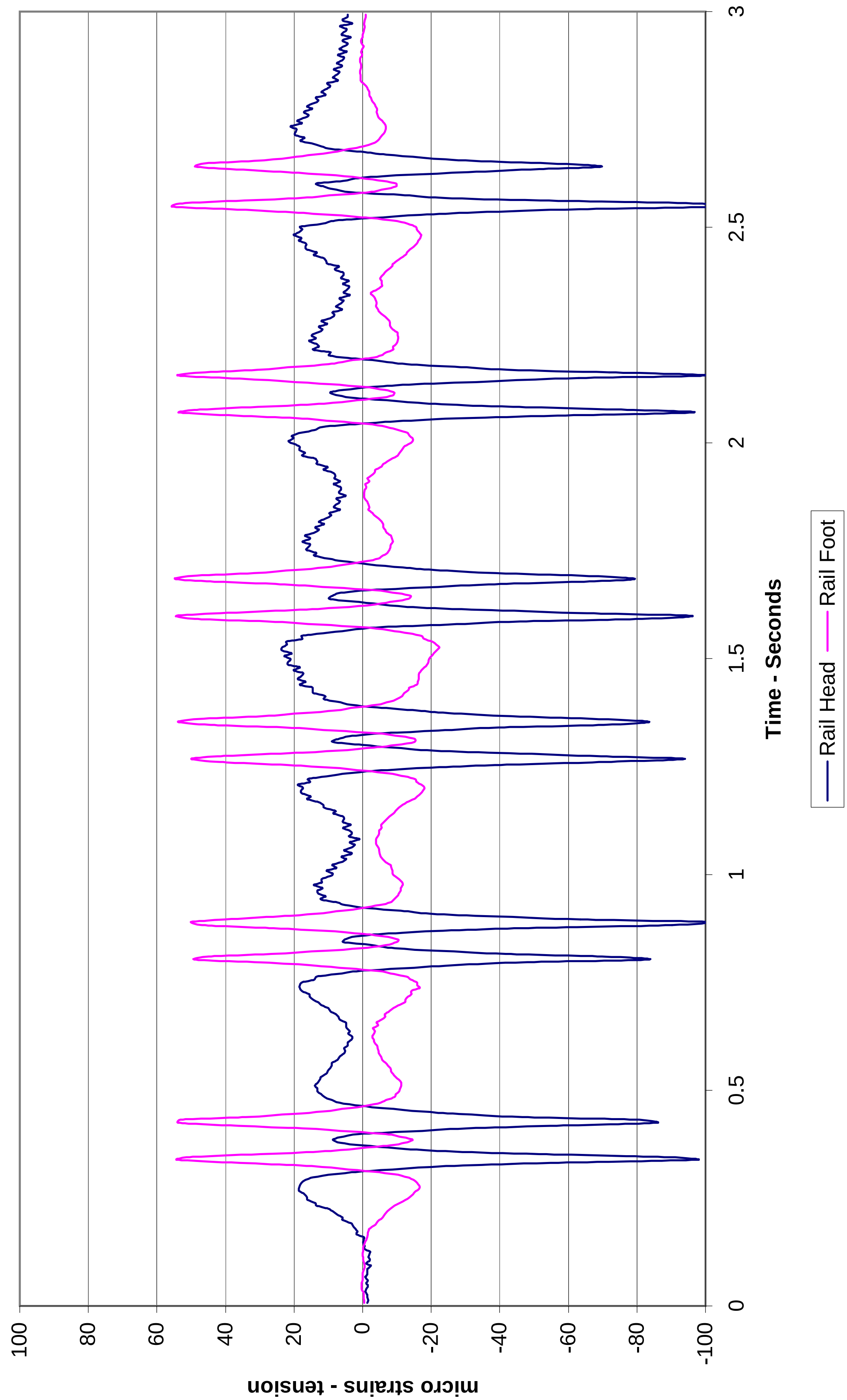


Figure B-24 TDA Site #4 Rail Strain Measured between Ties
50 mph



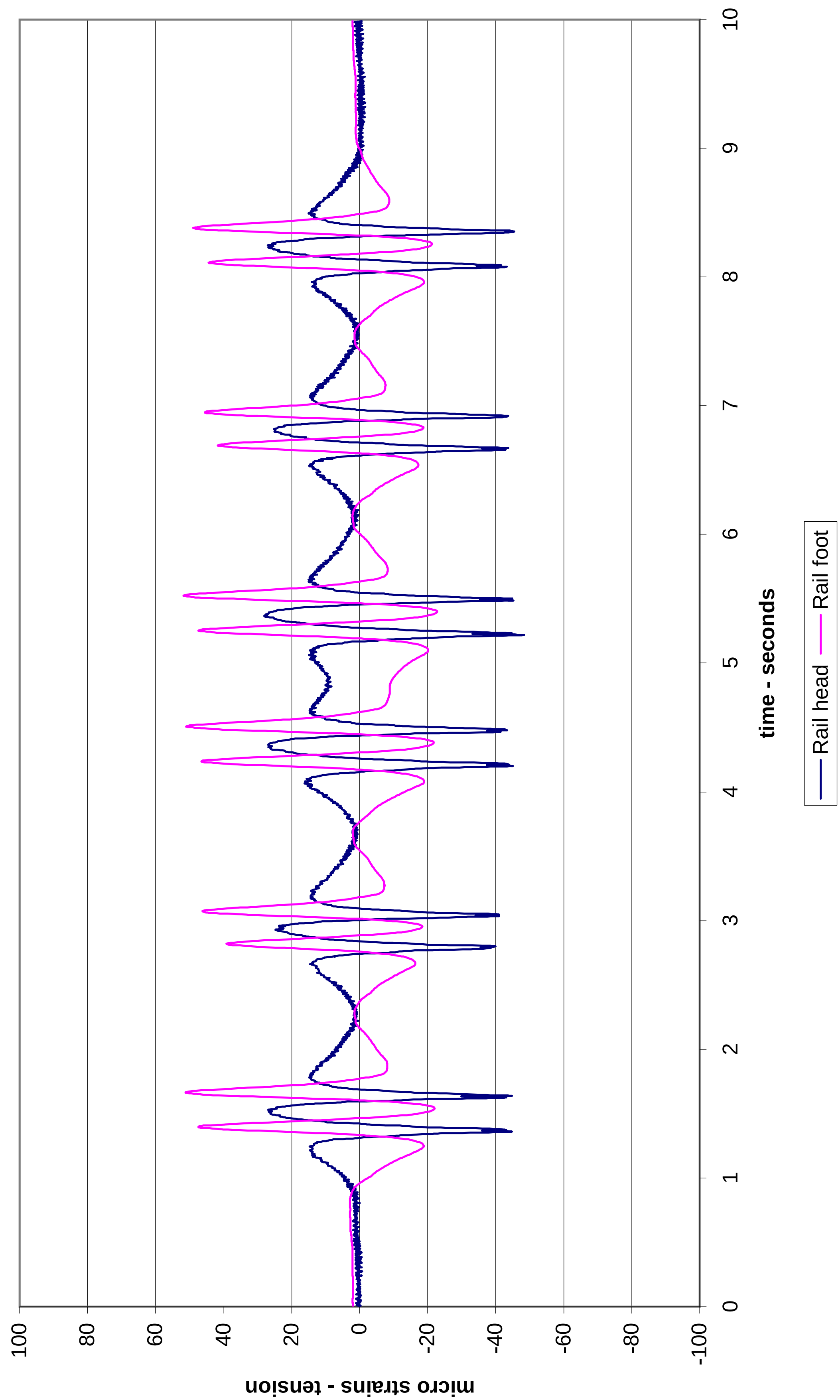


Figure B-25 Control Site #1(North of Stokes St.) Rail Strain Measured over Tie 15 mph

Figure B-26 Control Site #1(North of Stokes St.) Rail Strain Measured between Ties
15 mph

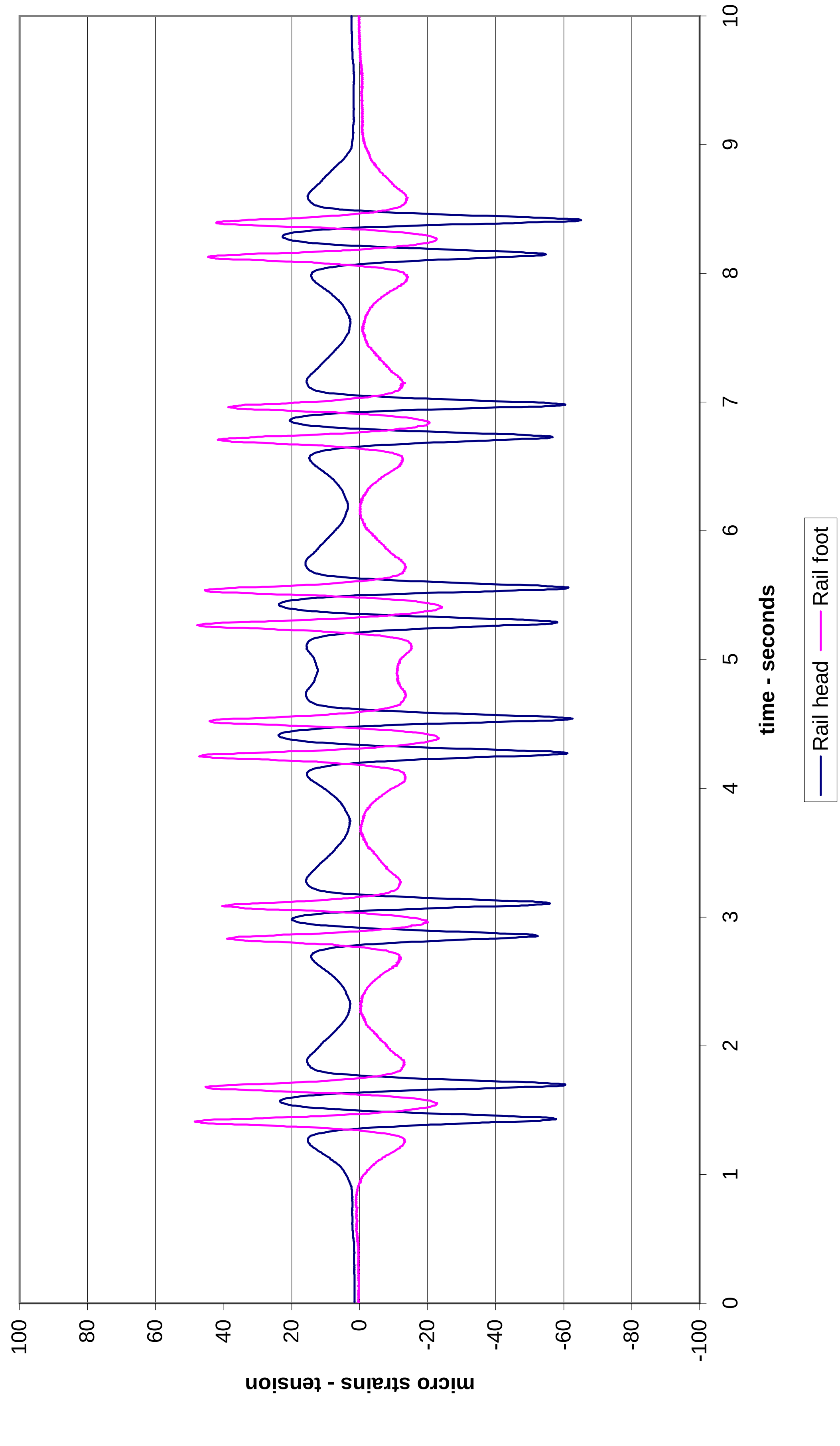


Figure B-27 Control Site #1(North of Stokes St.) Rail Strain Measured Over Tie
30 mph

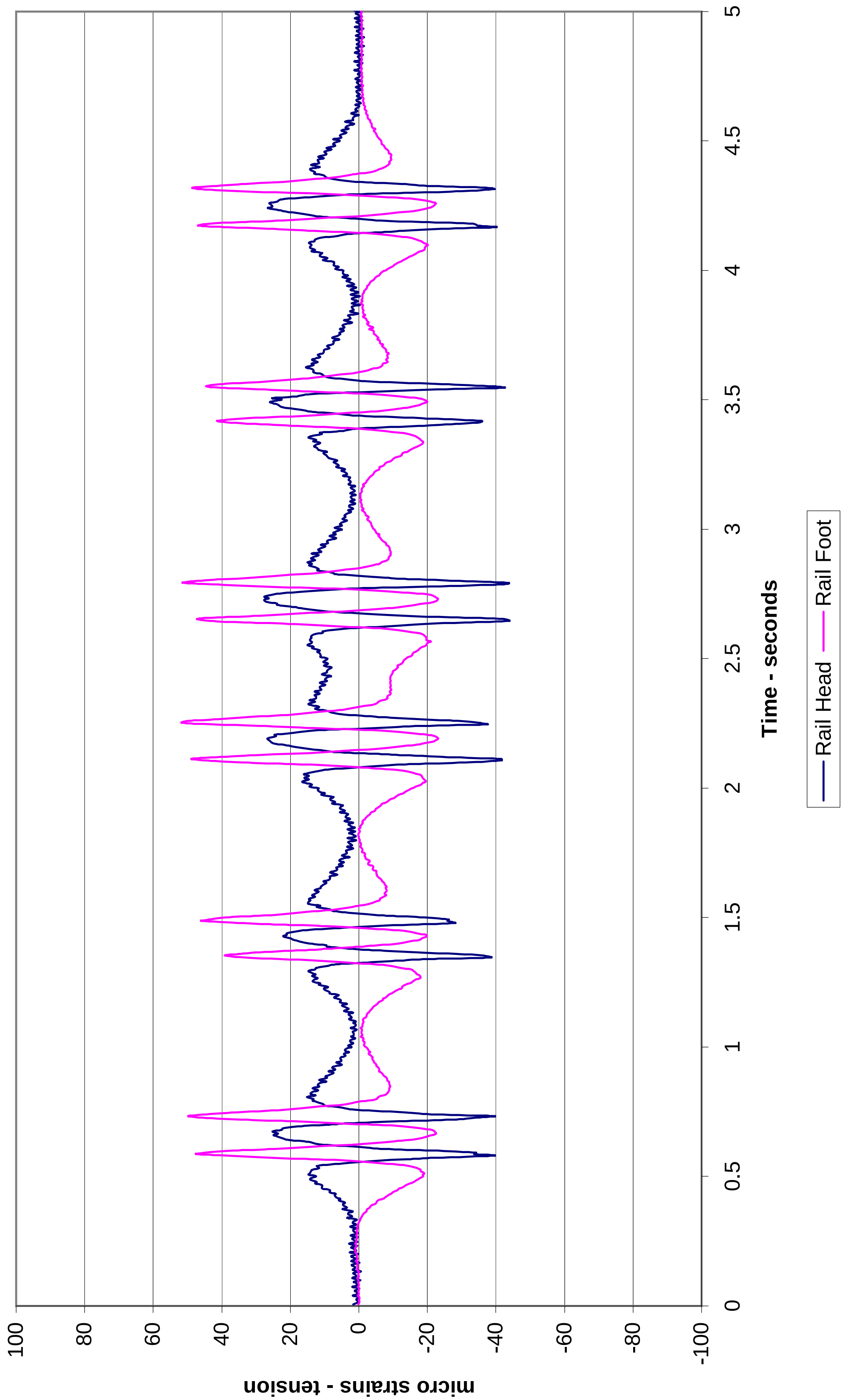


Figure B-28 Control Site #1(North of Stokes St.) Rail Strain Measured between Ties
30 mph

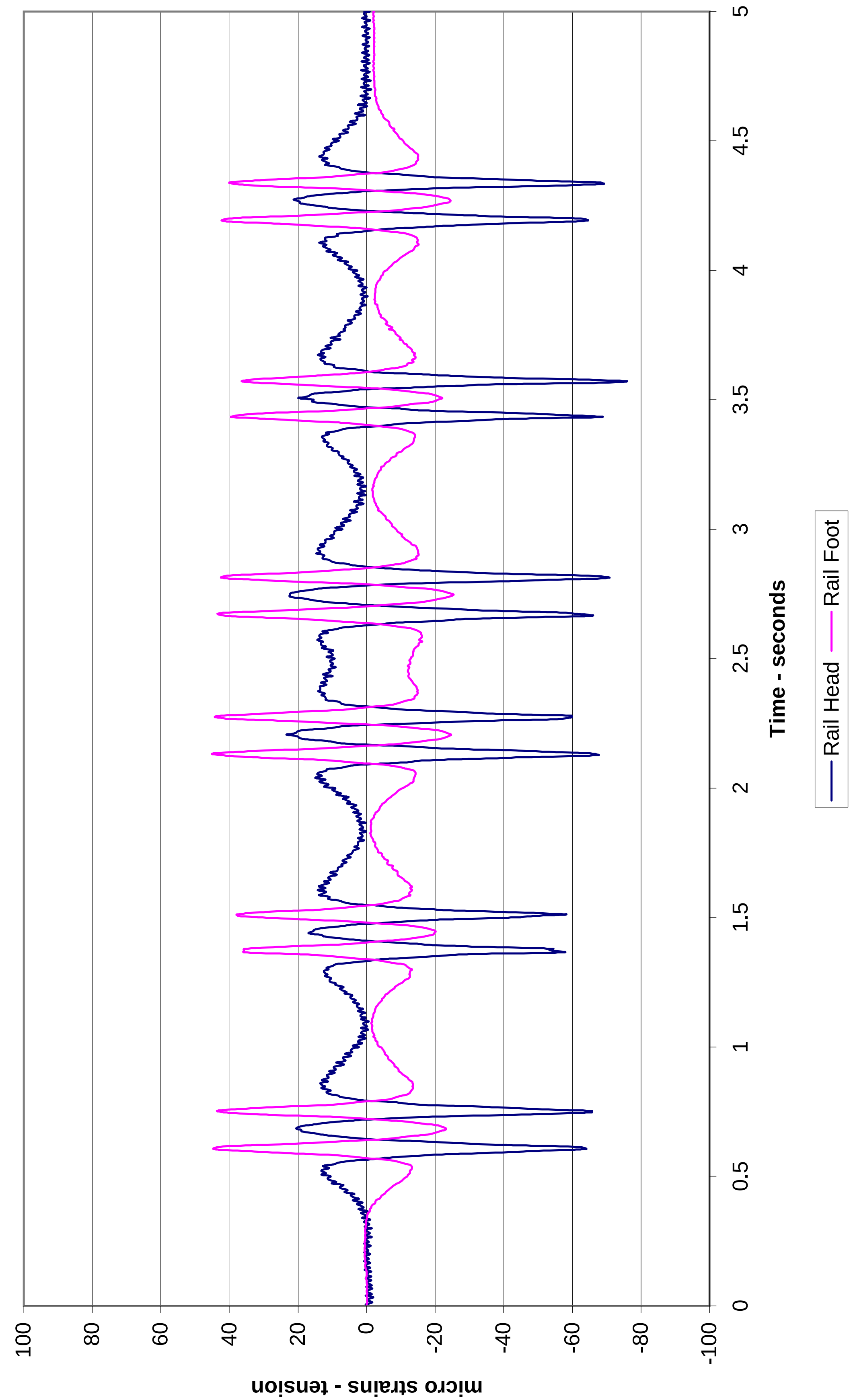


Figure B-29 Control Site #1(North of Stokes St.) Rail Strain Measured over Tie
50 mph

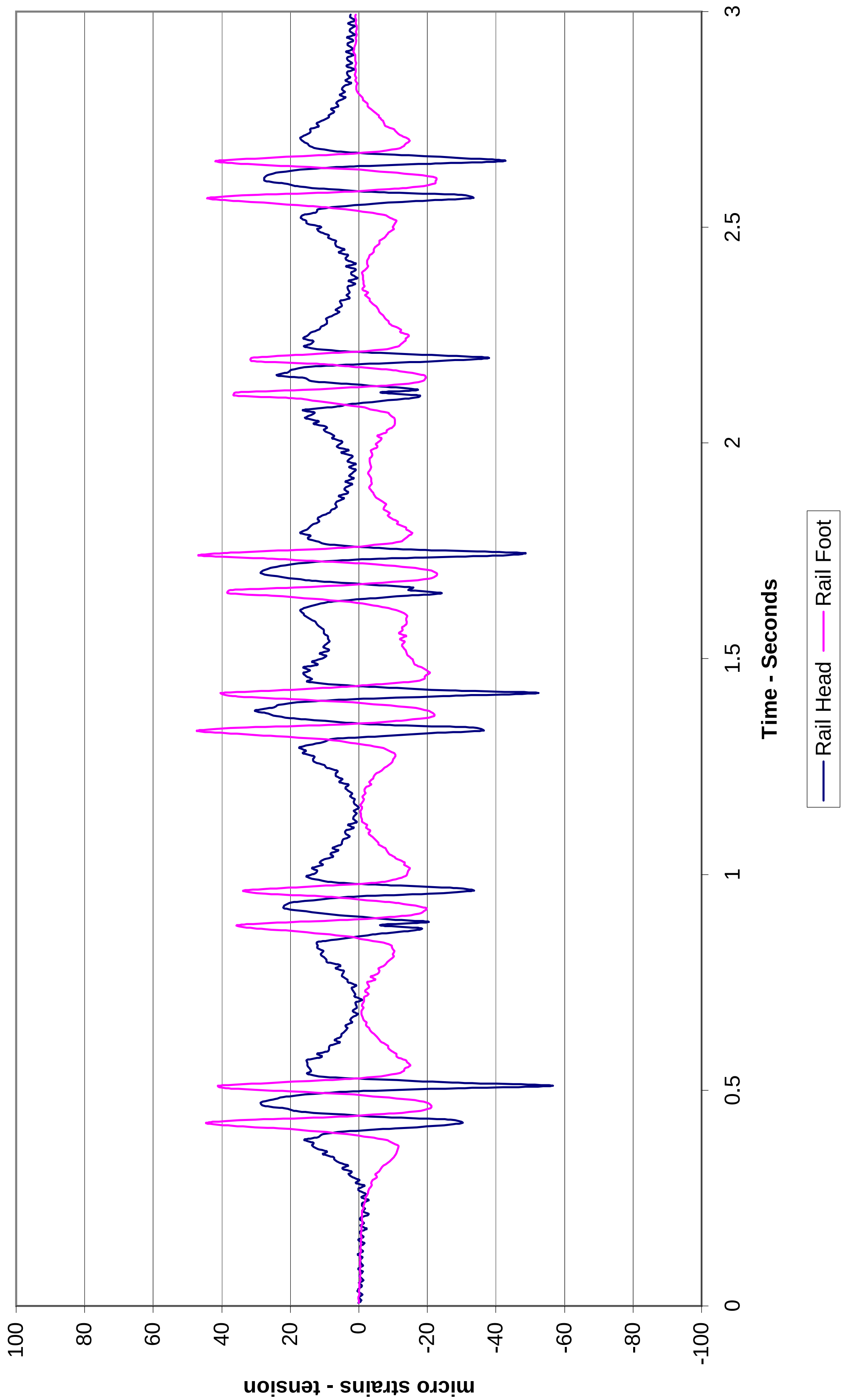


Figure B-30 Control Site #1(North of Stokes St.) Rail Strain Measured between Ties
50 mph

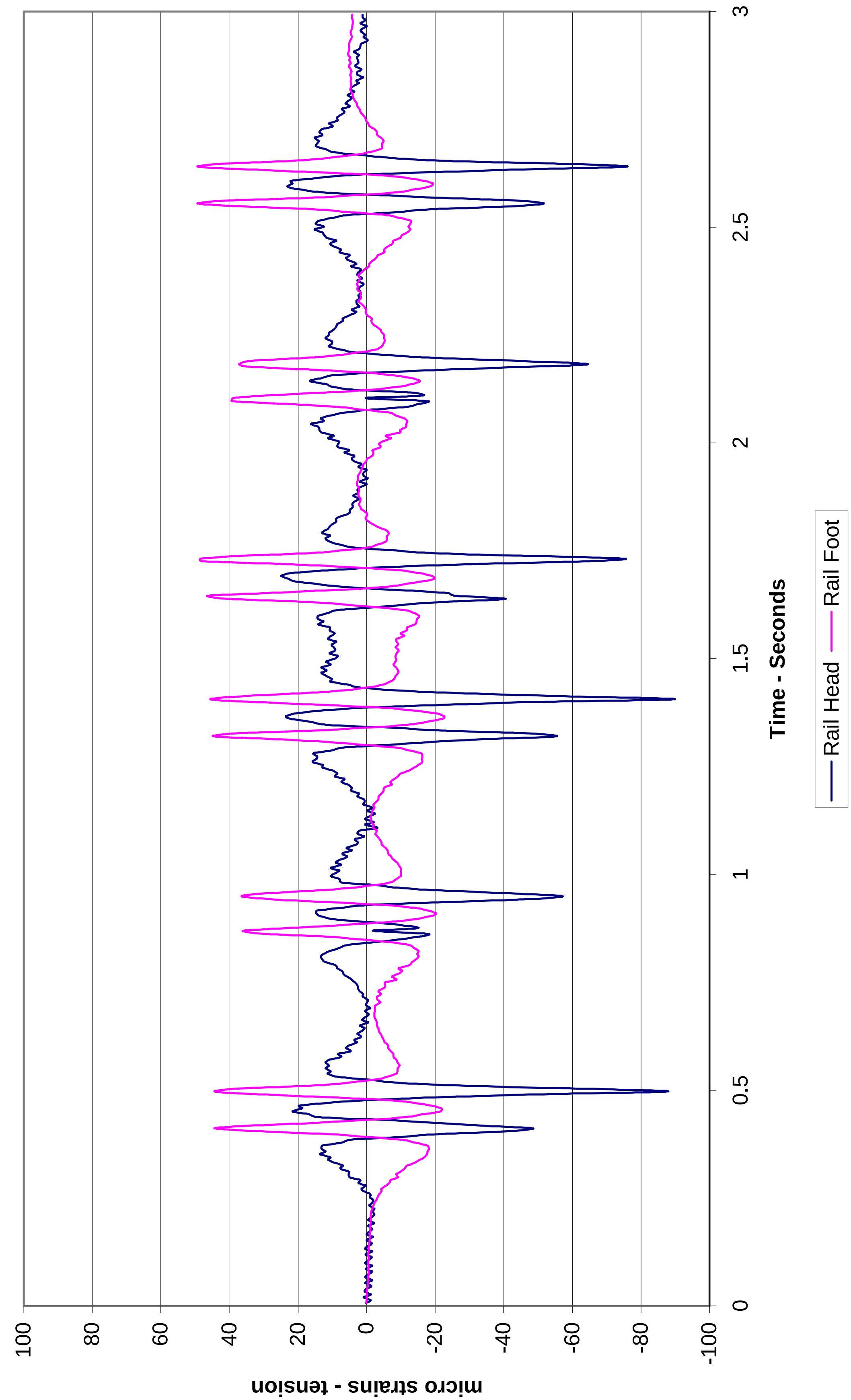


Figure B-31 Control Site #2(South of Race St.) Rail Strain Measured over Tie 15 mph

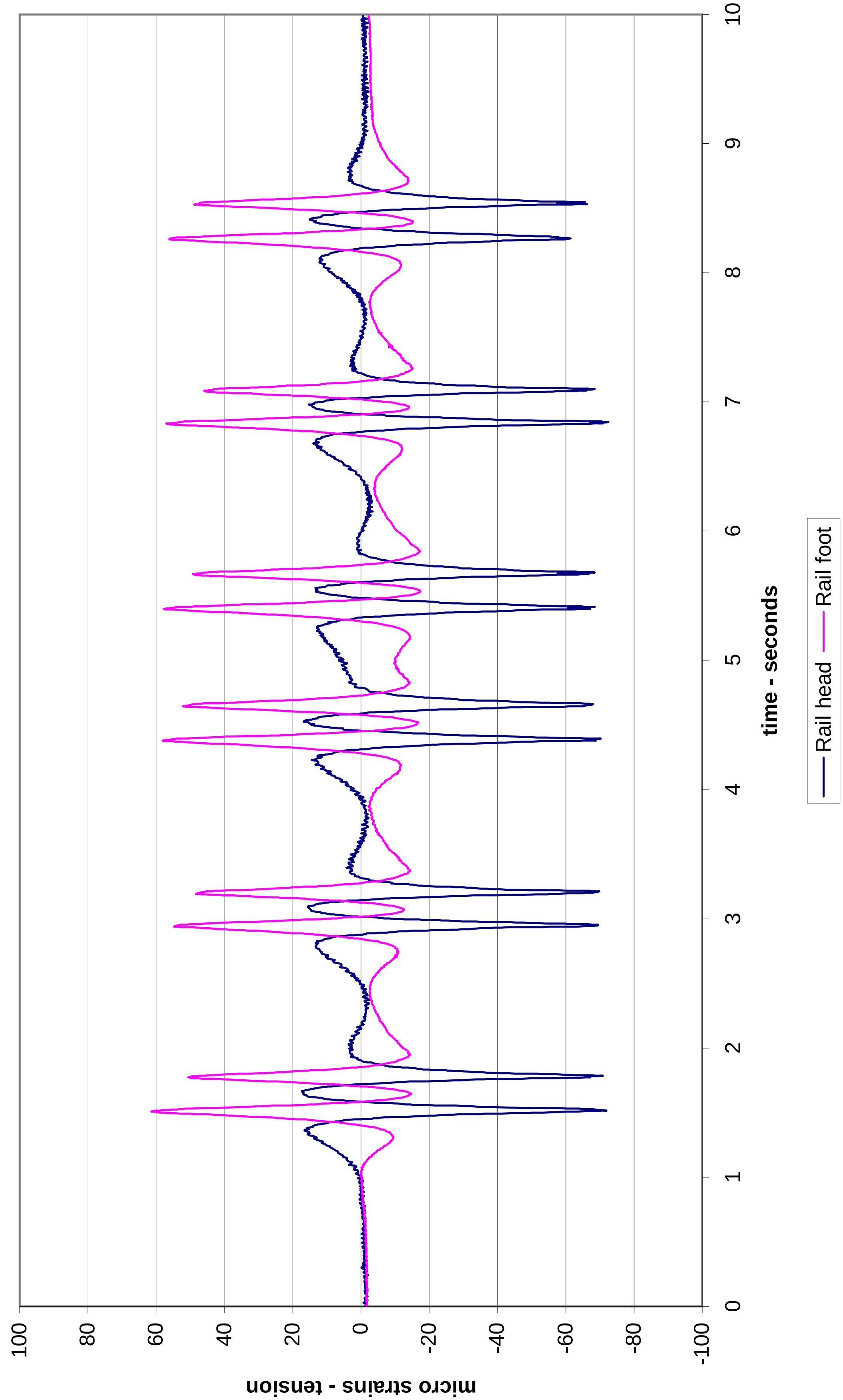


Figure B-32 Control Site #2(South of Race St.) Rail Strain Measured between Ties
15 mph

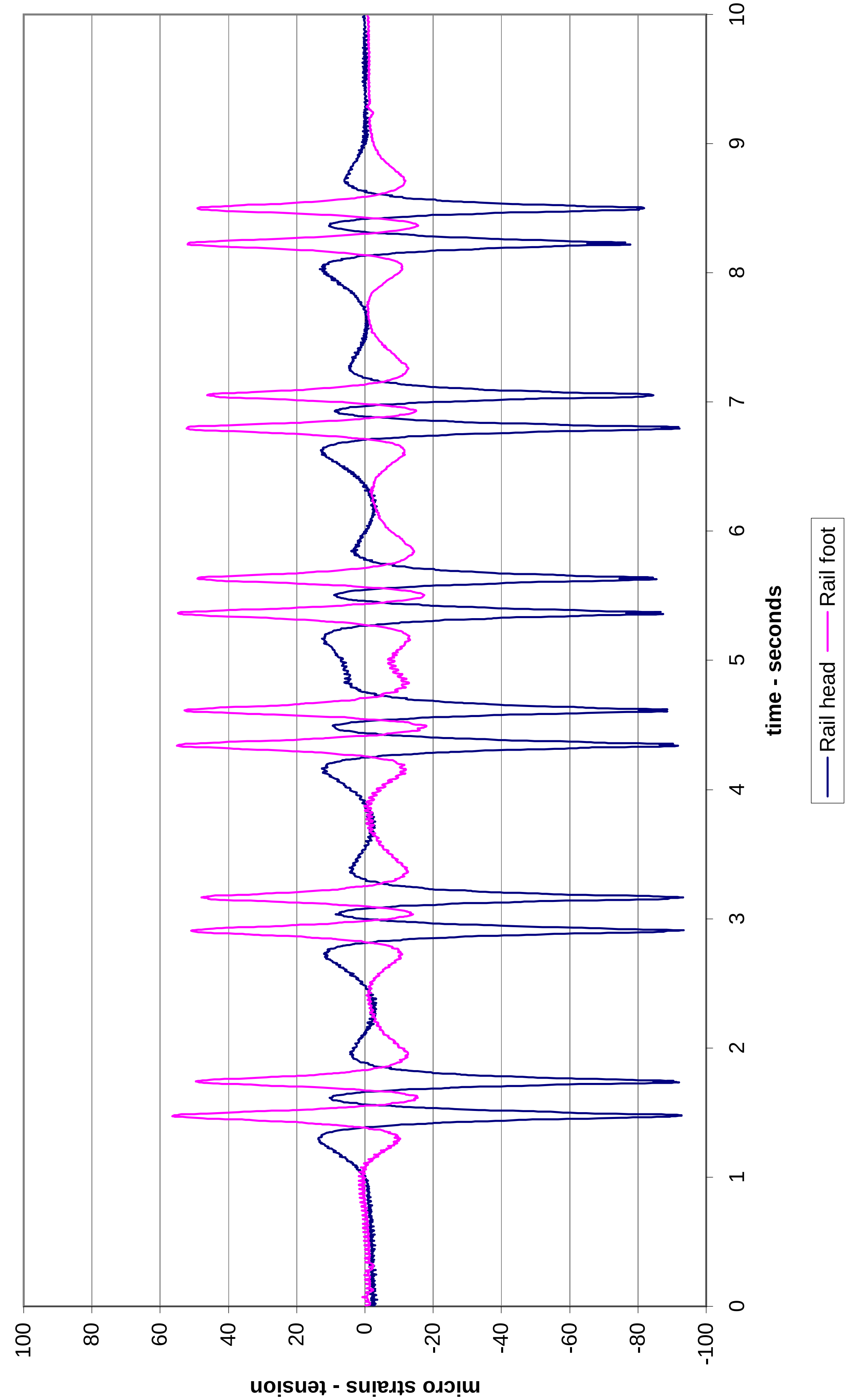
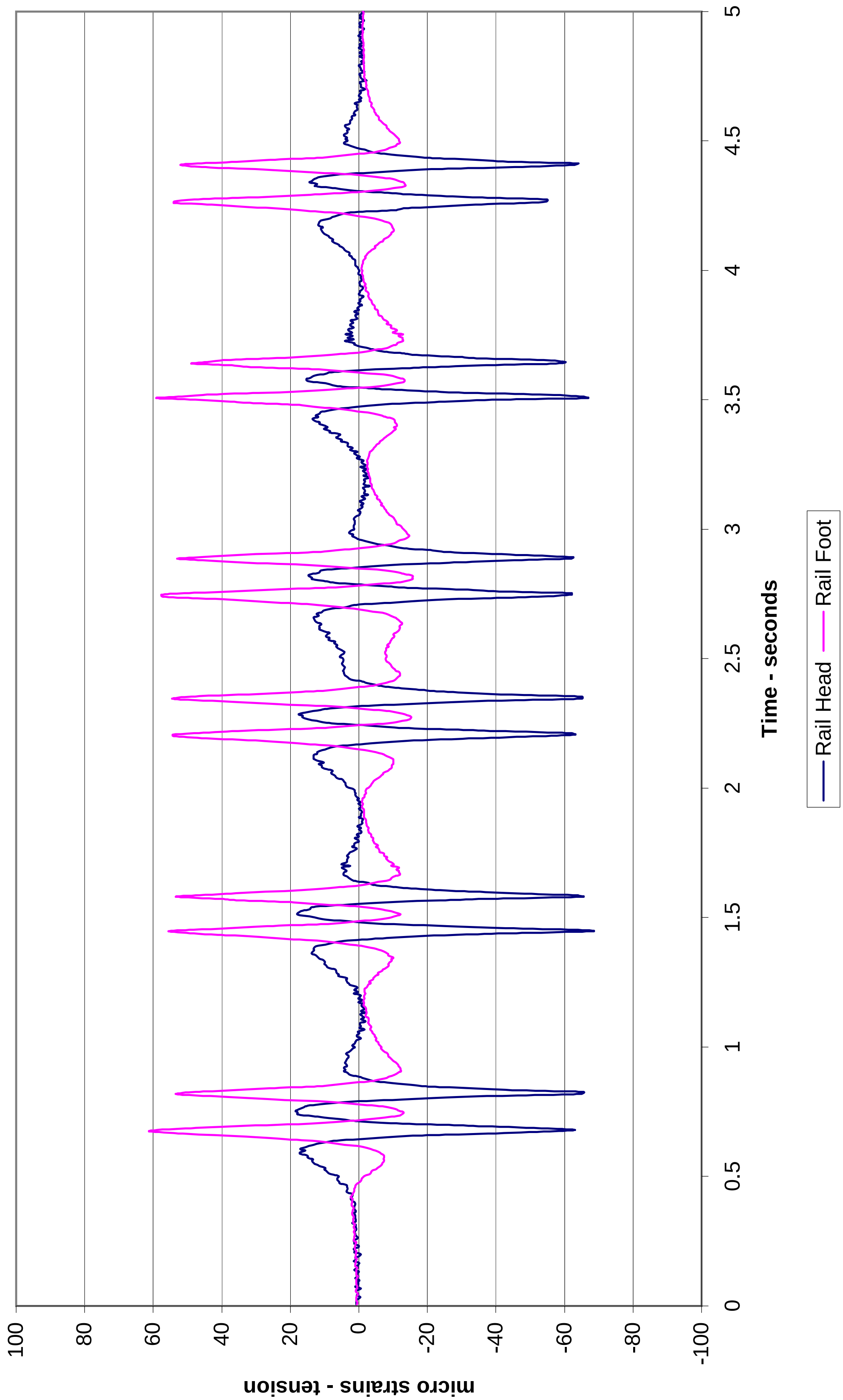


Figure B-33 Control Site #2(South of Race St.) Rail Strain Measured over Tie
30 mph



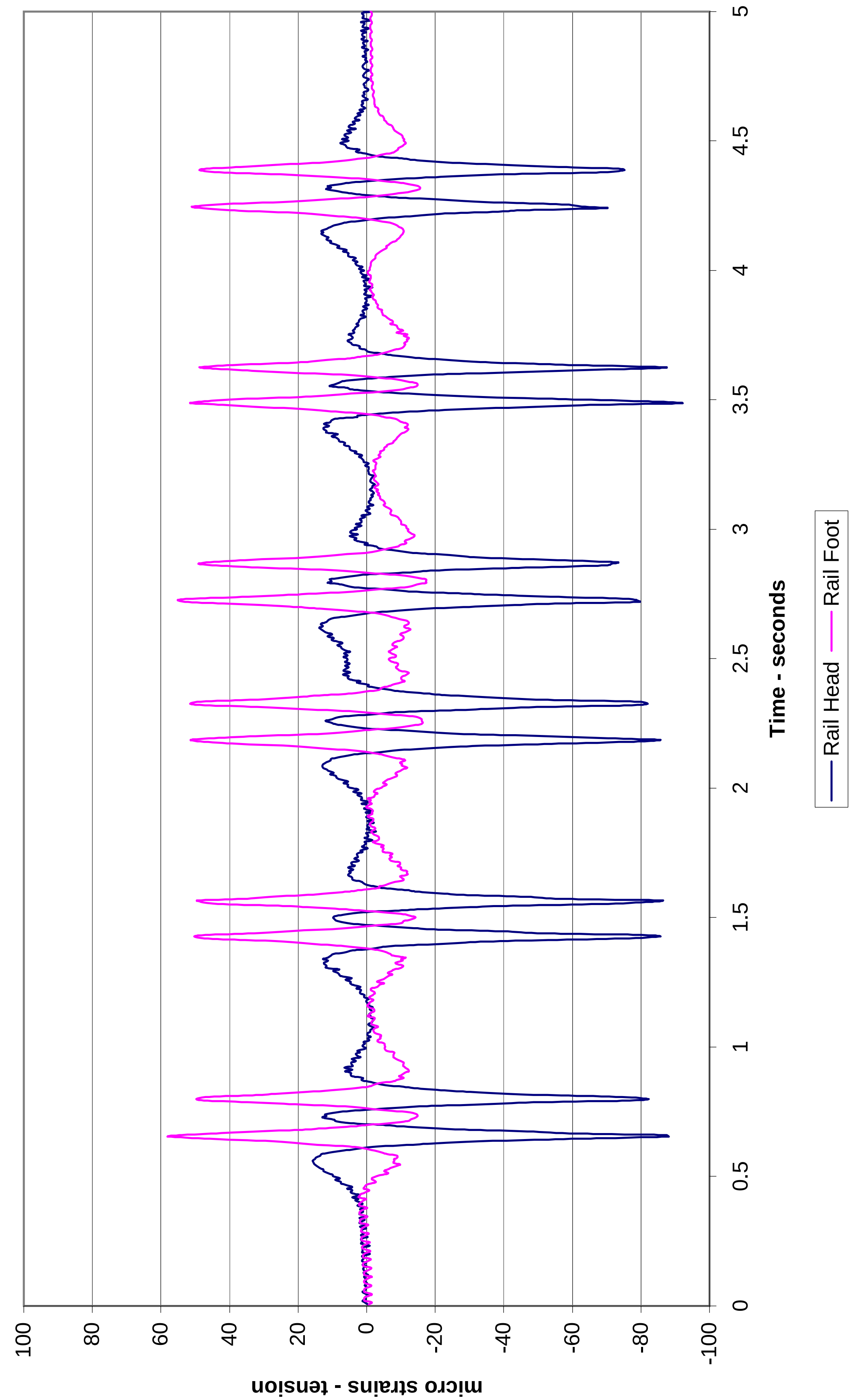


Figure B-34 Control Site #2(South of Race St.) Rail Strain Measured between Ties 30 mph

Figure B-35 Control Site #2(South of Race St.) Rail Strain Measured over Tie
50 mph

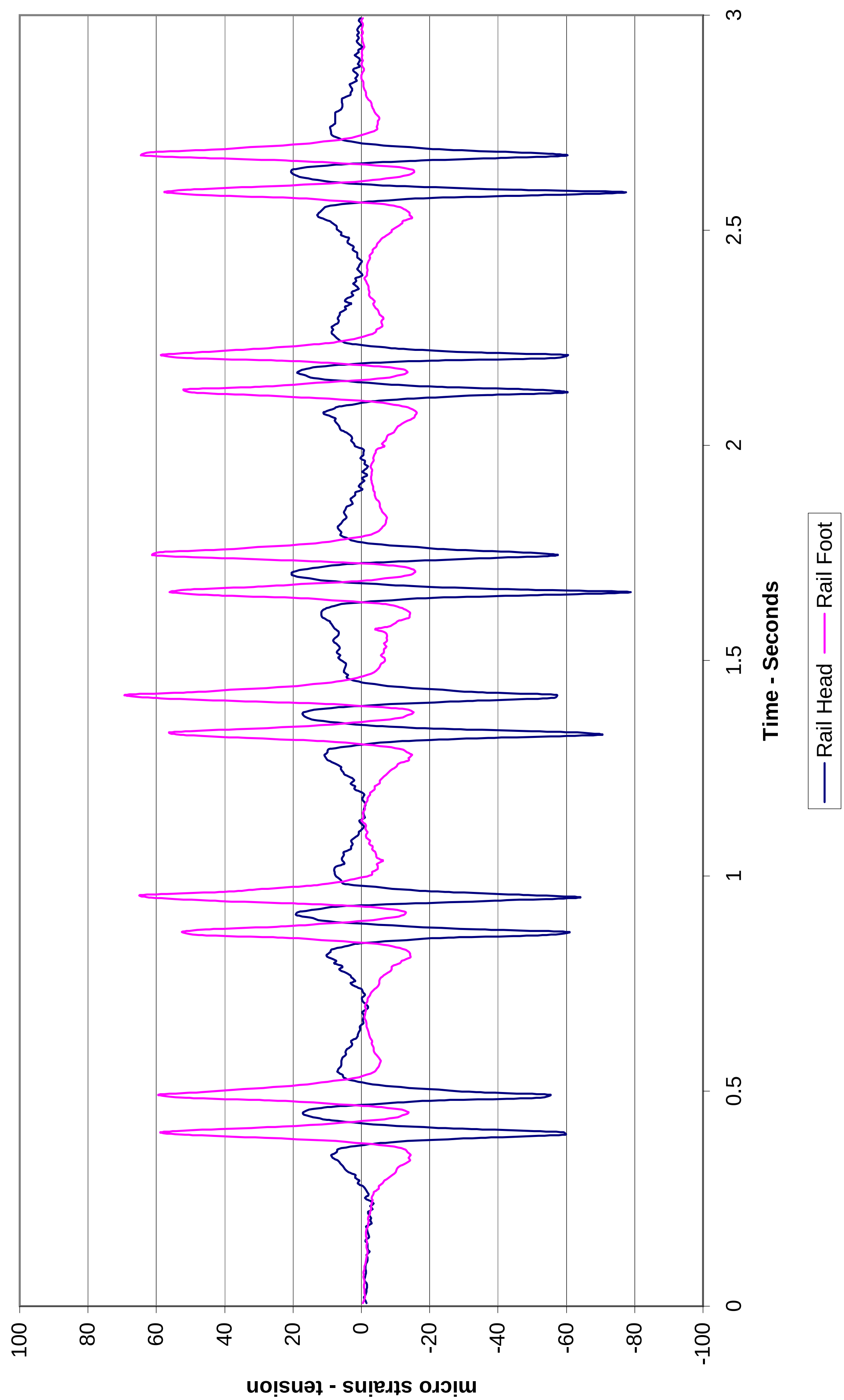
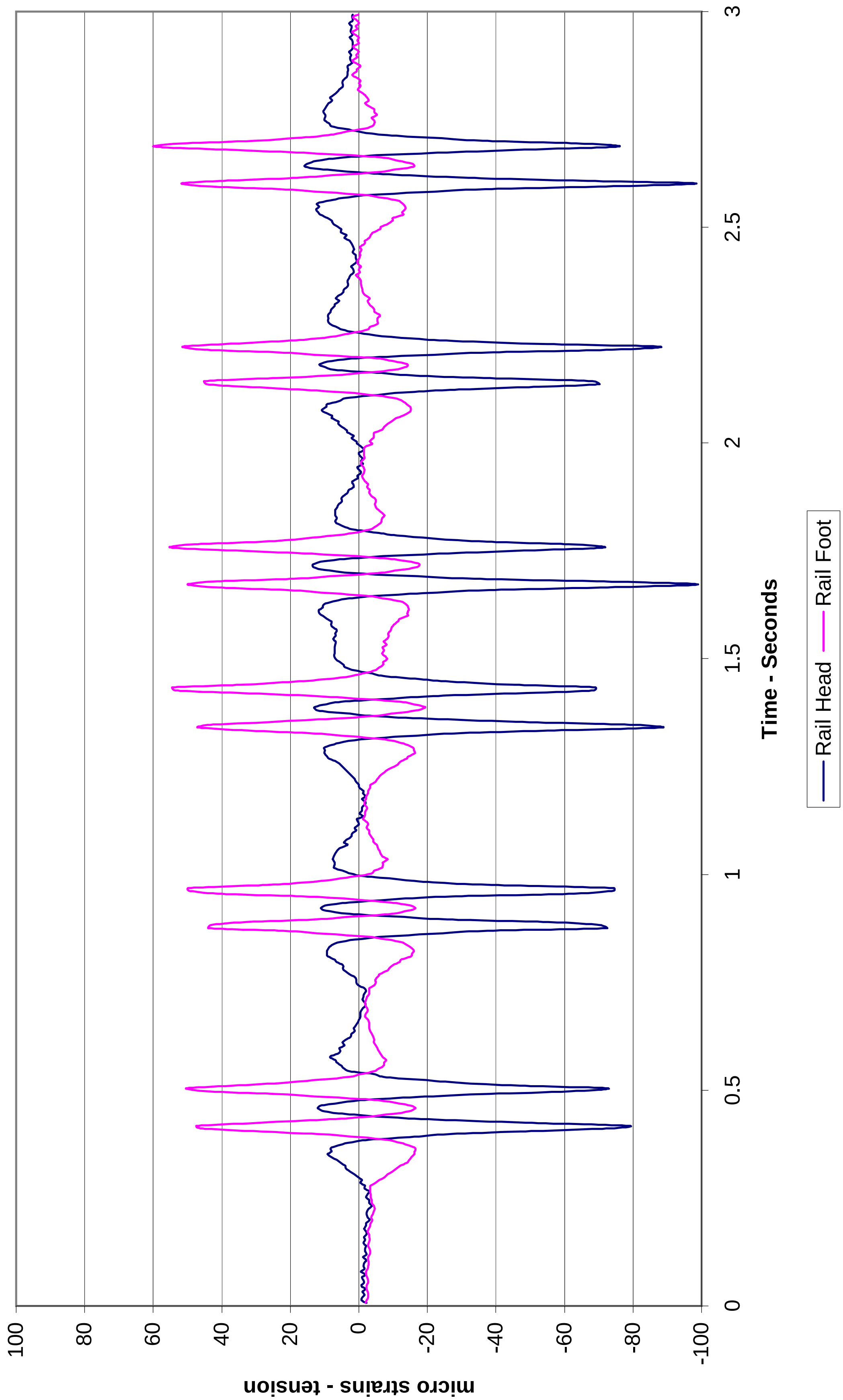


Figure B-36 Control Site #2(South of Race St.) Rail Strain Measured between Ties
50 mph



APPENDIX C

Plots of Rail Deflection

Page

Figure C-1 TDA Site #1 Rail Deflection - Southbound Track
15 mph

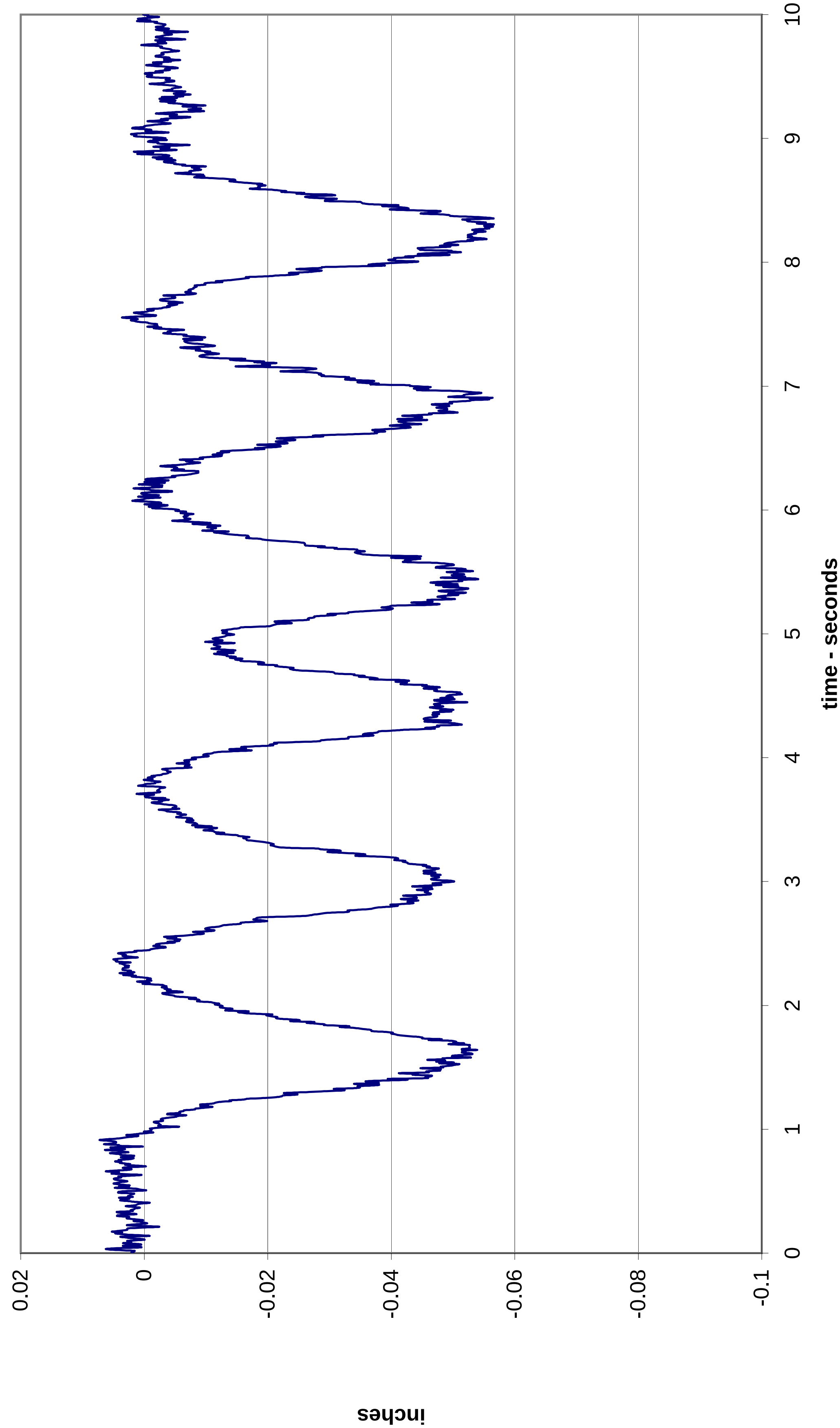


Figure C-2 TDA Site #1 Rail Deflection - Southbound Track
30 mph

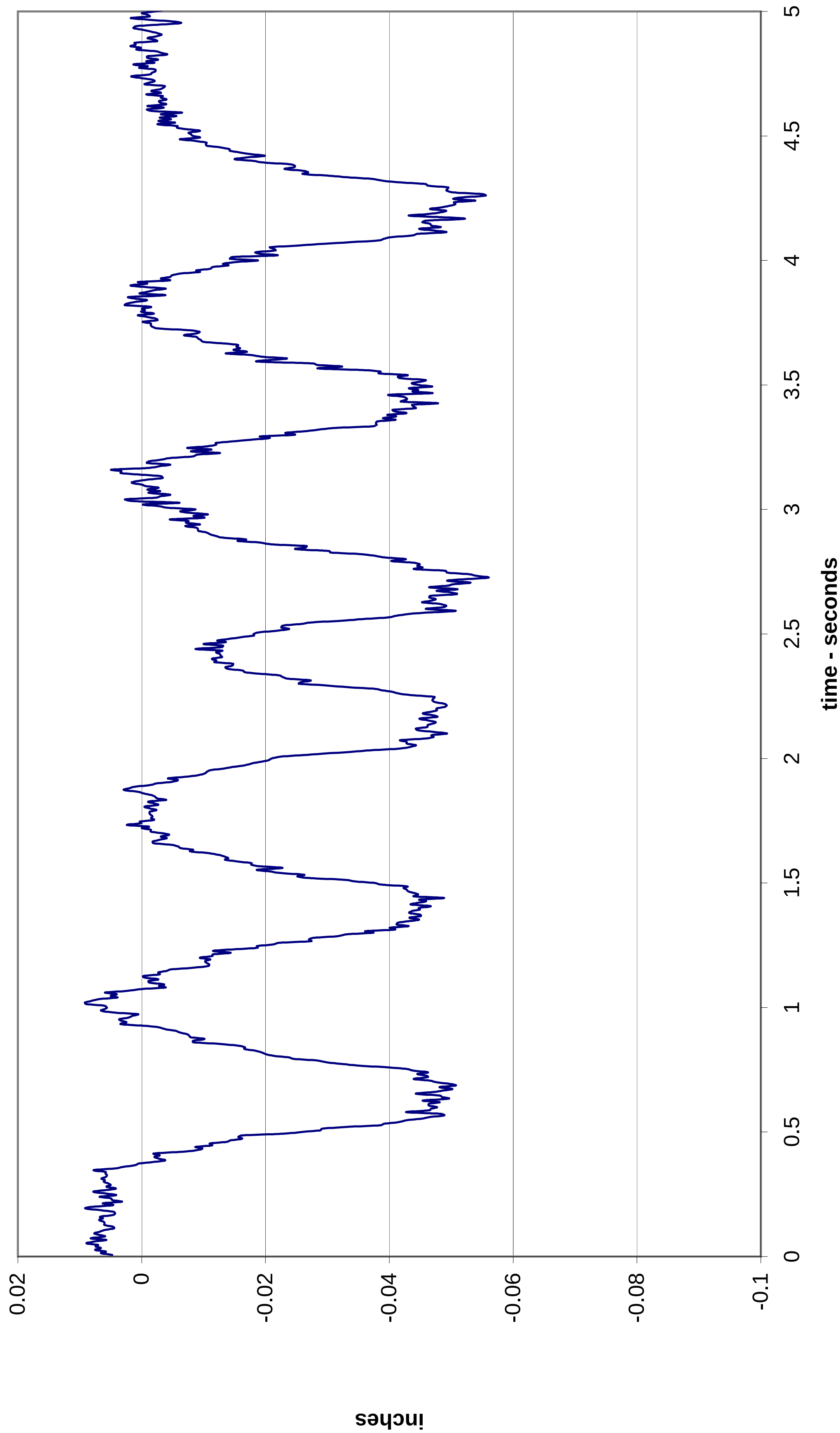


Figure C-3 TDA Site #1 Rail Deflection - Southbound Track
46 mph

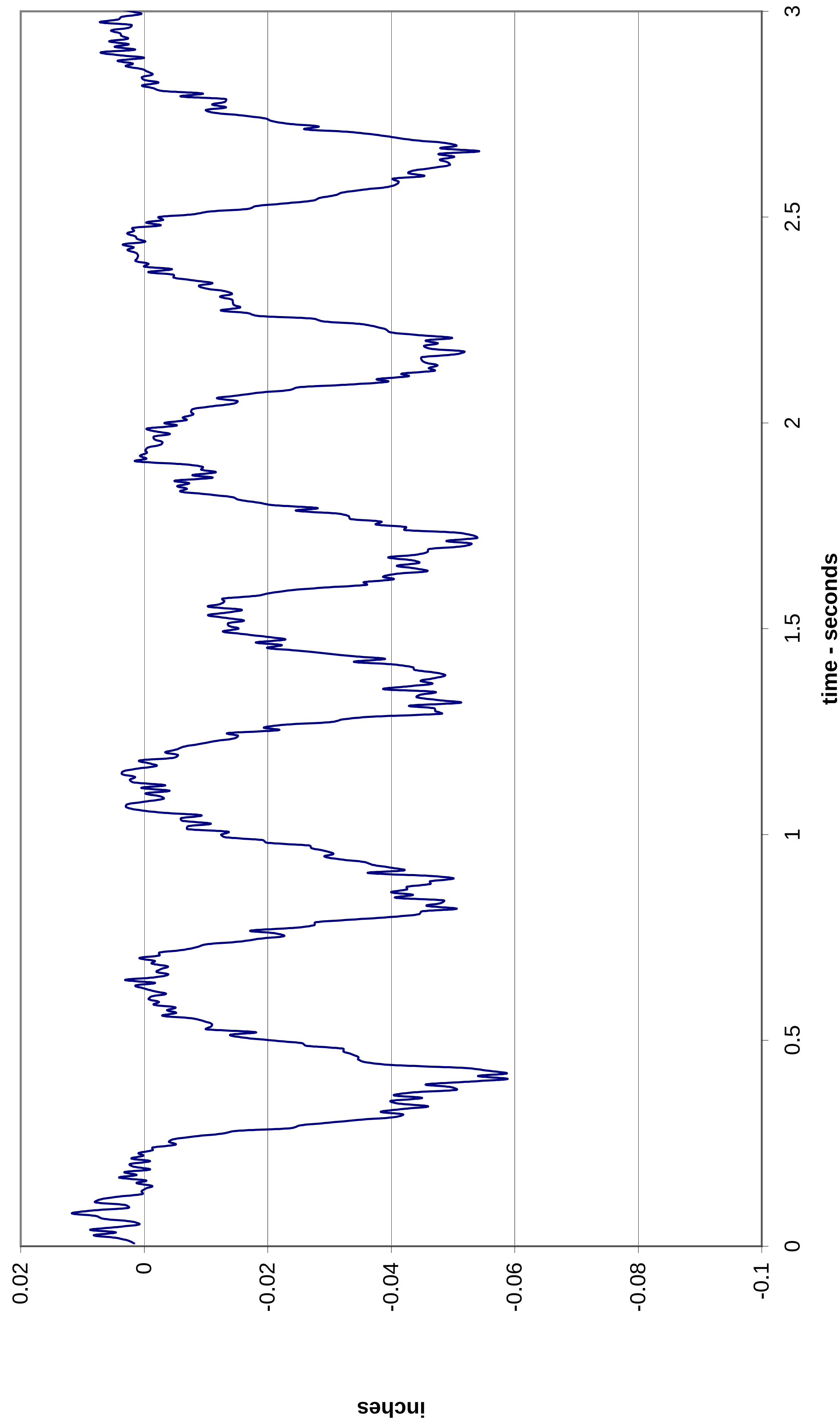


Figure C-4 TDA Site #1 Rail Deflection - Northbound Track
15 mph

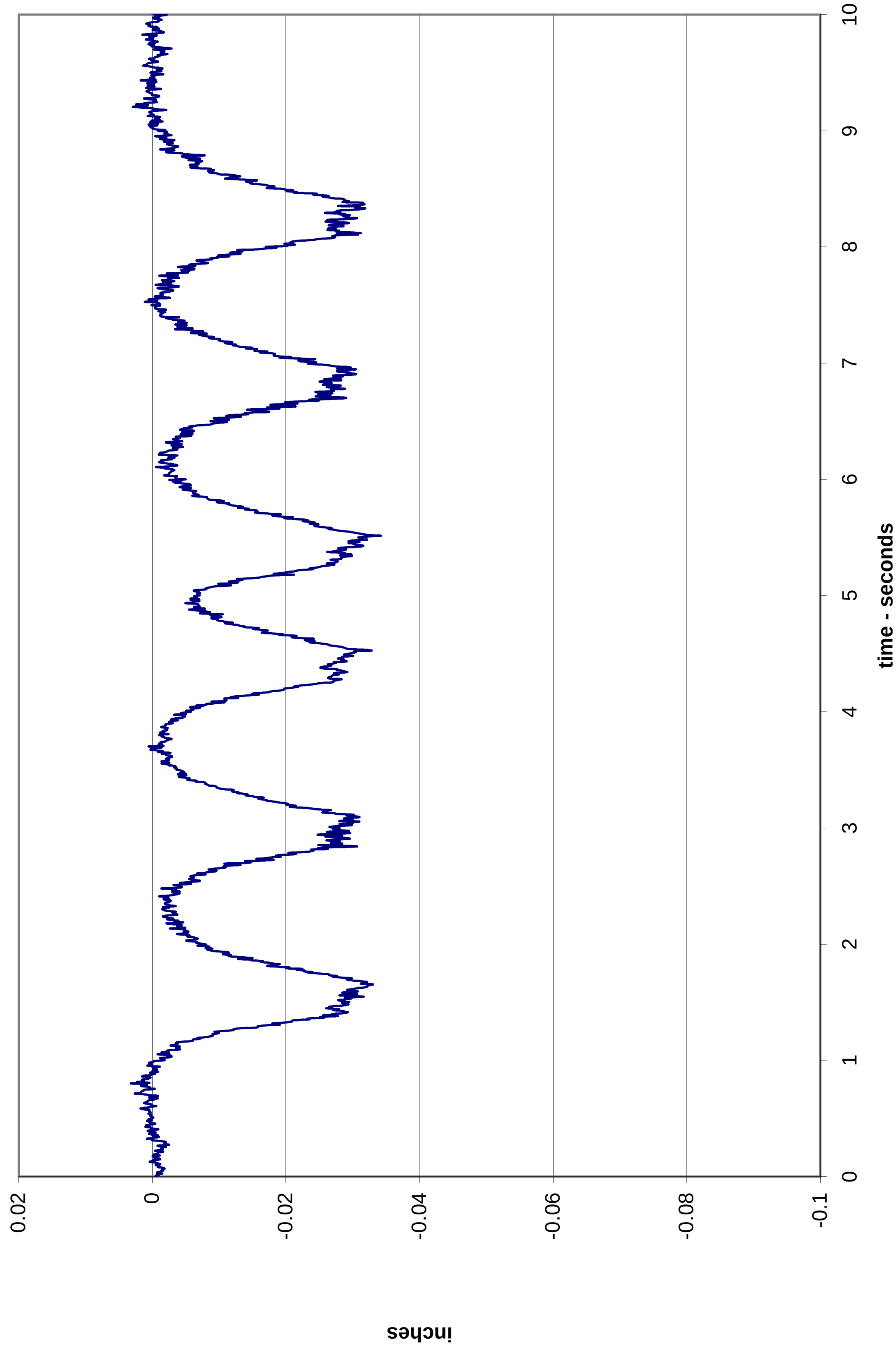


Figure C-5 TDA Site #1 Rail Deflection - Northbound Track
30 mph

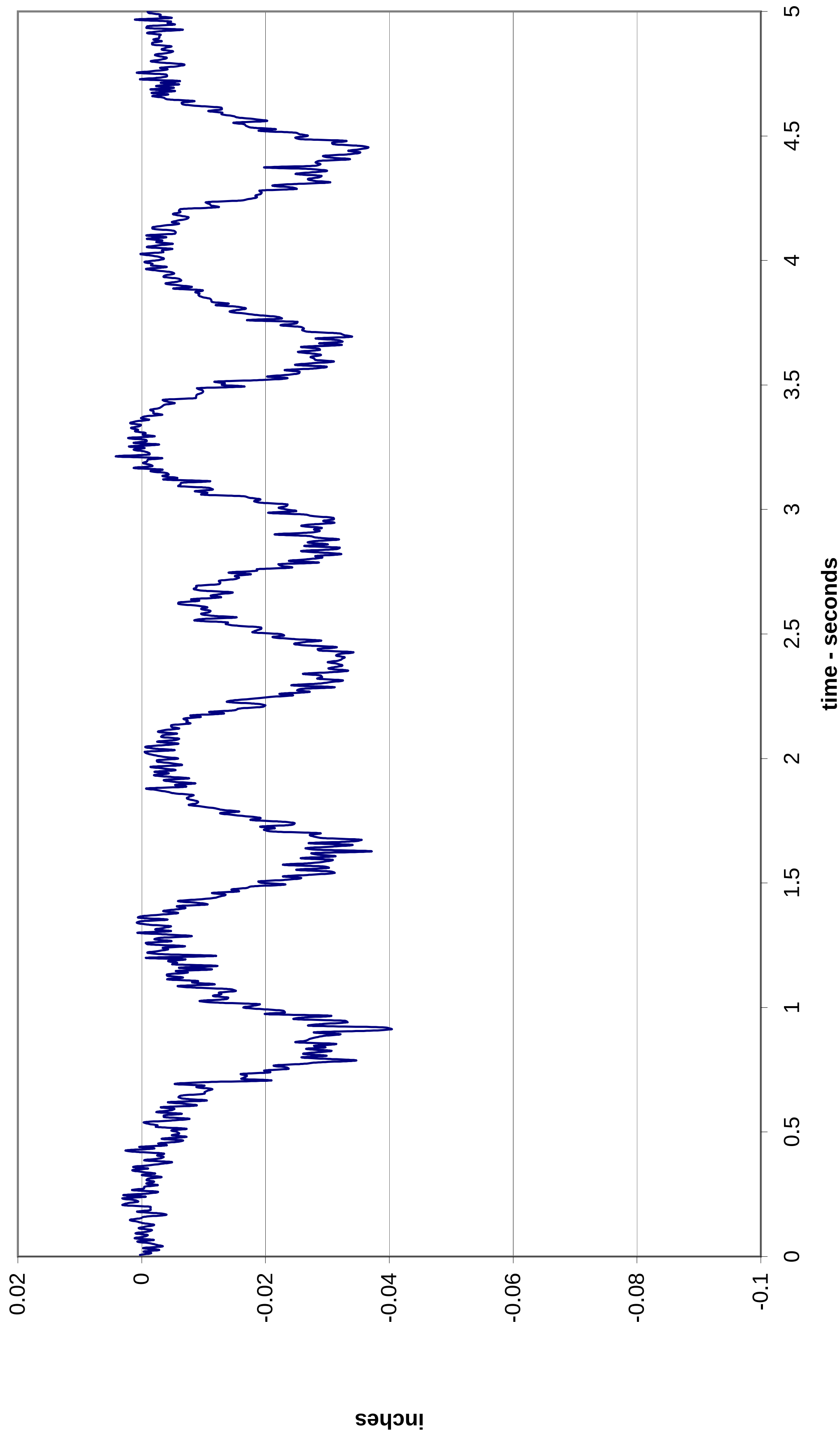


Figure C-6 TDA Site #1 Rail Deflection - Northbound Track
50 mph

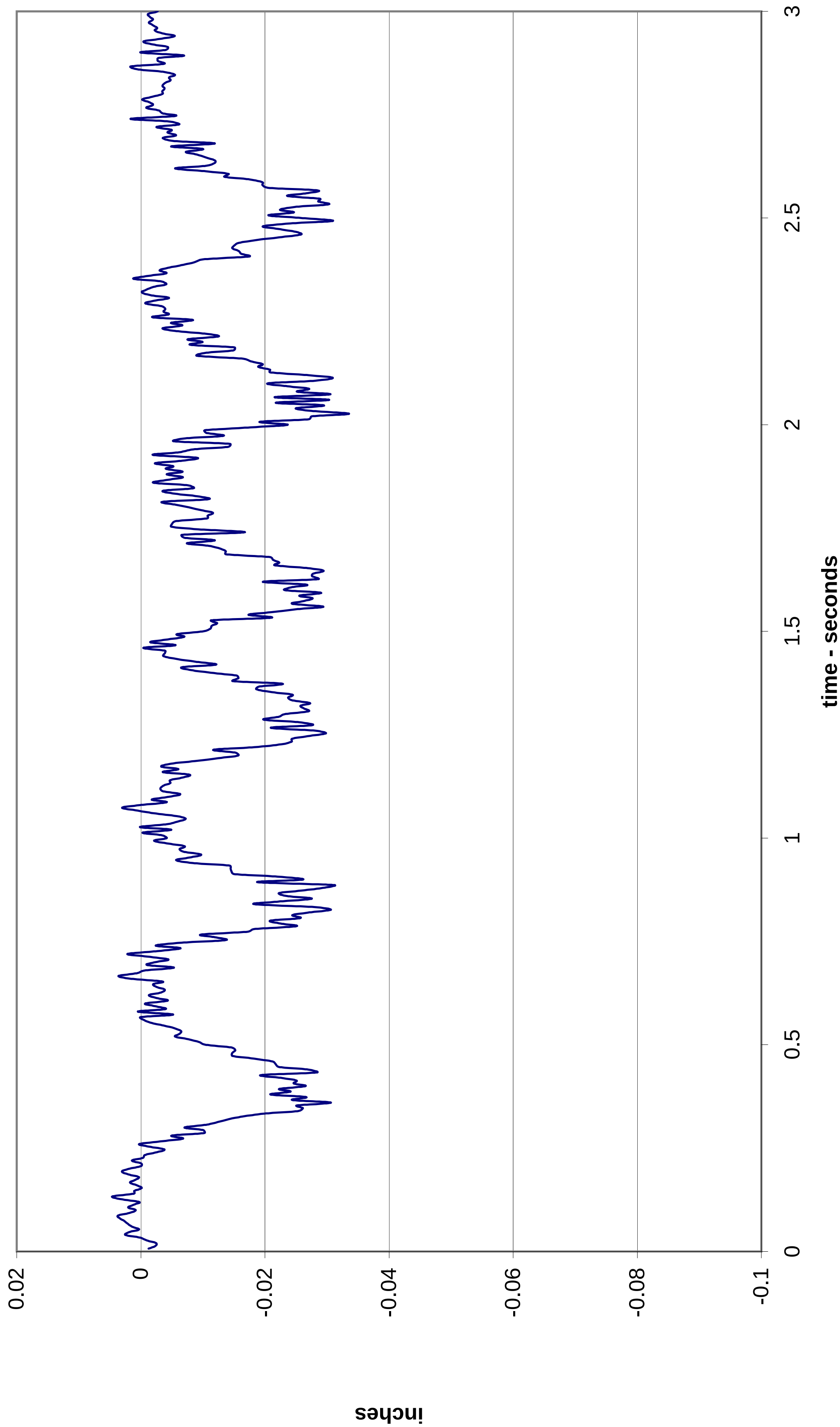


Figure C-7 TDA Site #3 Rail Deflection - Southbound Track
30 mph

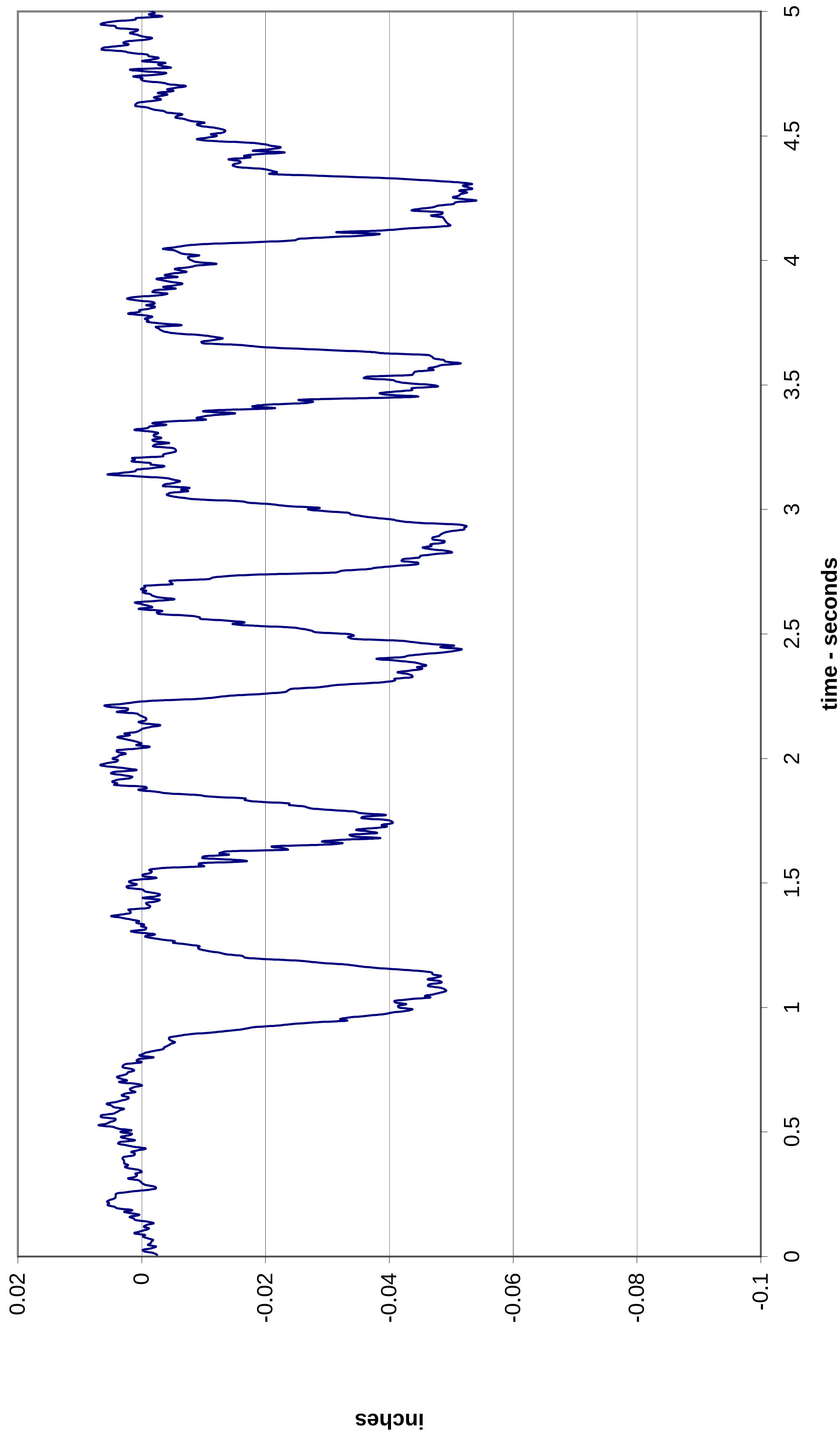
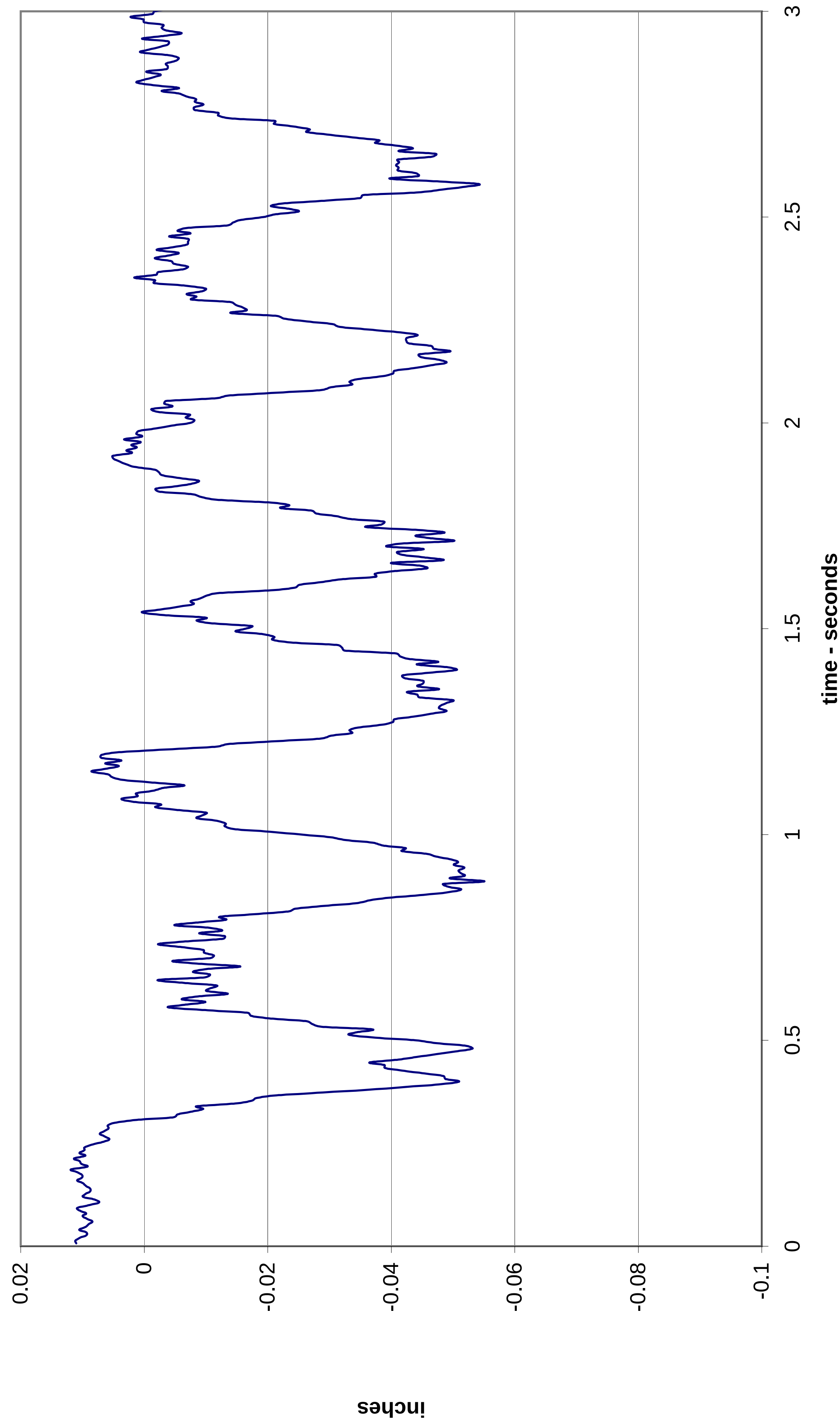


Figure C-8 TDA Site #3 Rail Deflection - Southbound Track
50 mph



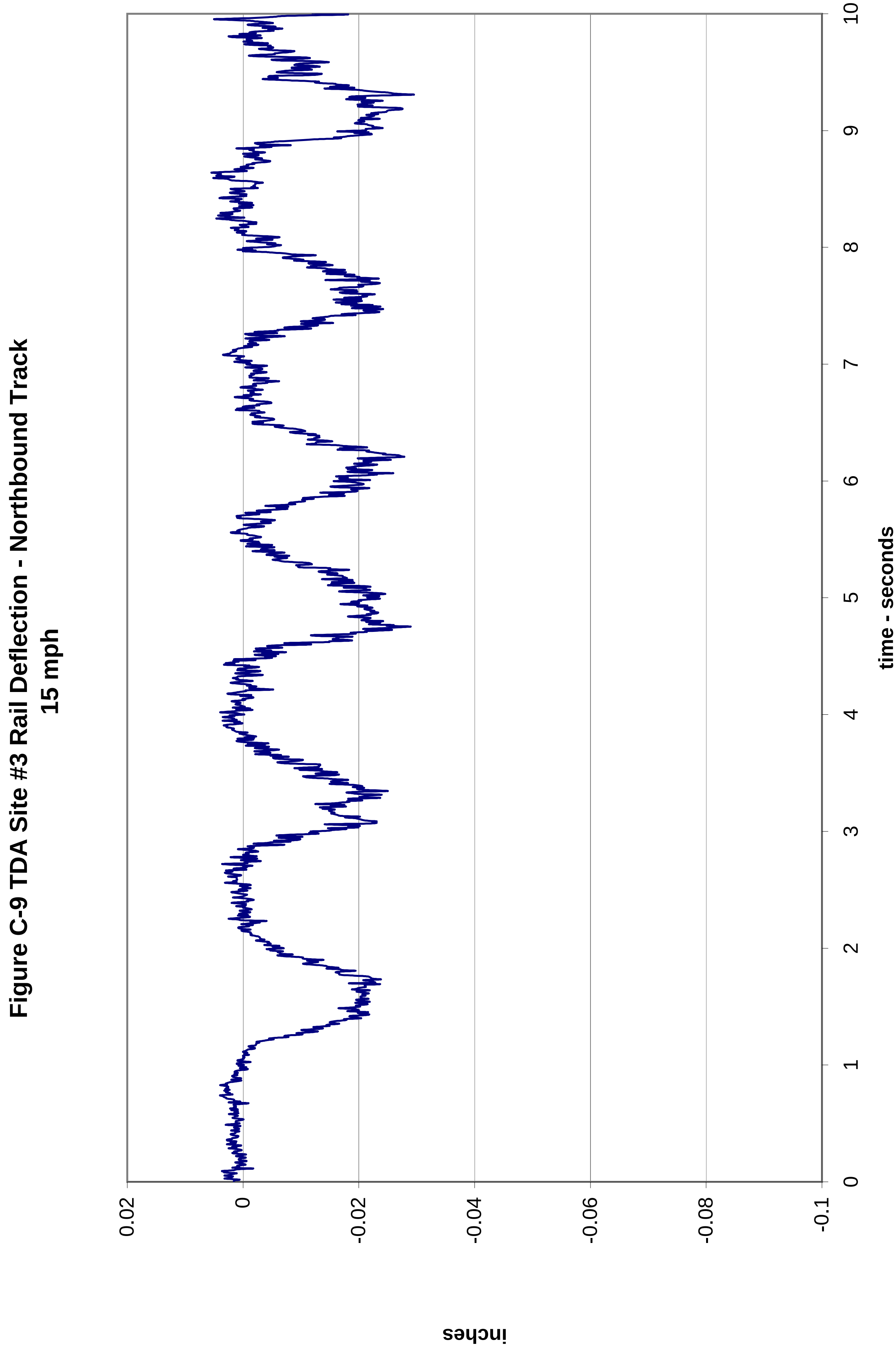


Figure C-9 TDA Site #3 Rail Deflection - Northbound Track
15 mph
inches
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
time - seconds
0
1
2
3
4
5
6
7
8
9
10

Figure C-10 TDA Site #3 Rail Deflection - Northbound Track
30 mph

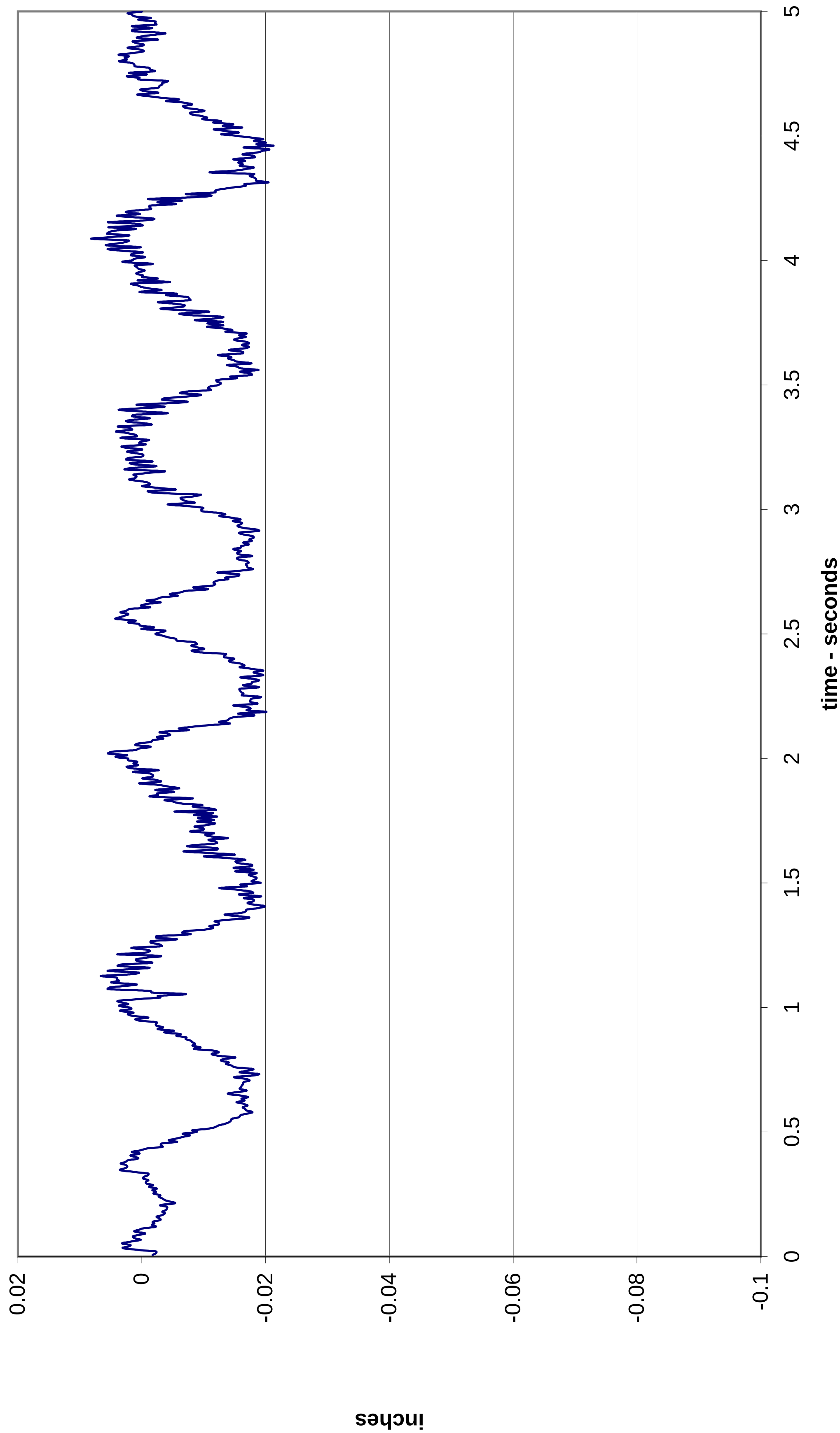


Figure C-11 TDA Site #3 Rail Deflection - Northbound Track
50 mph

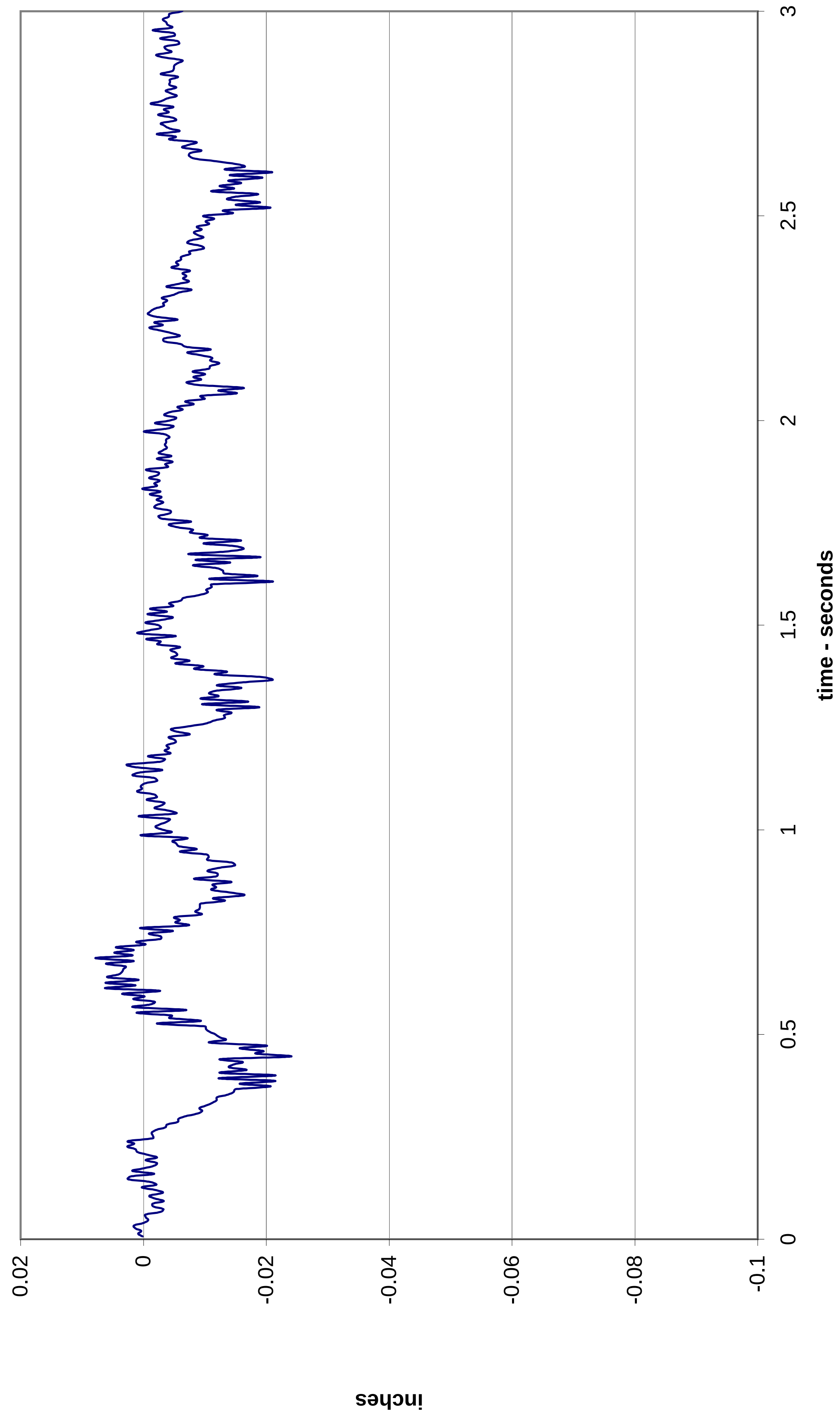
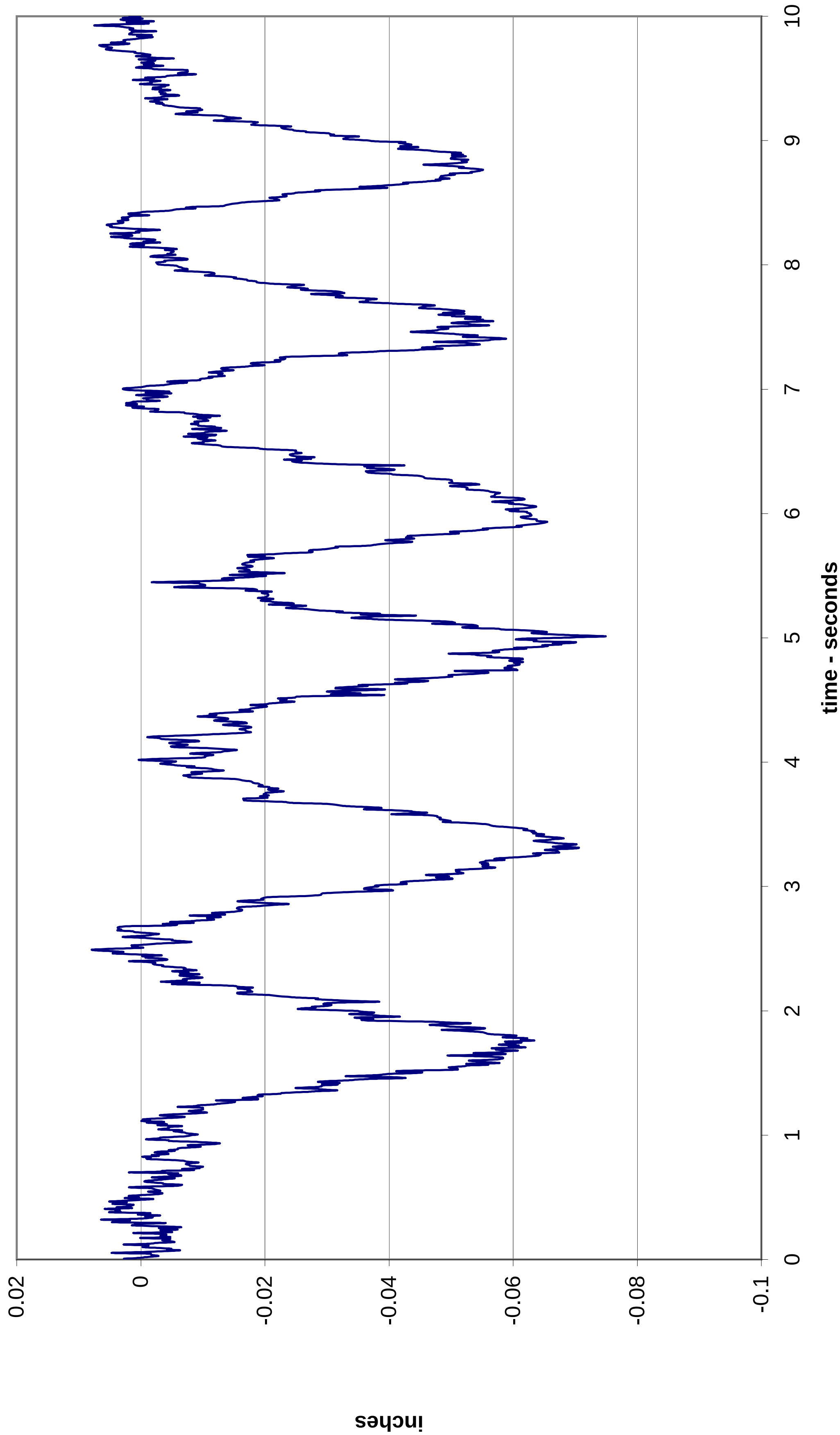


Figure C-12 TDA Site #4 Rail Deflection
15 mph



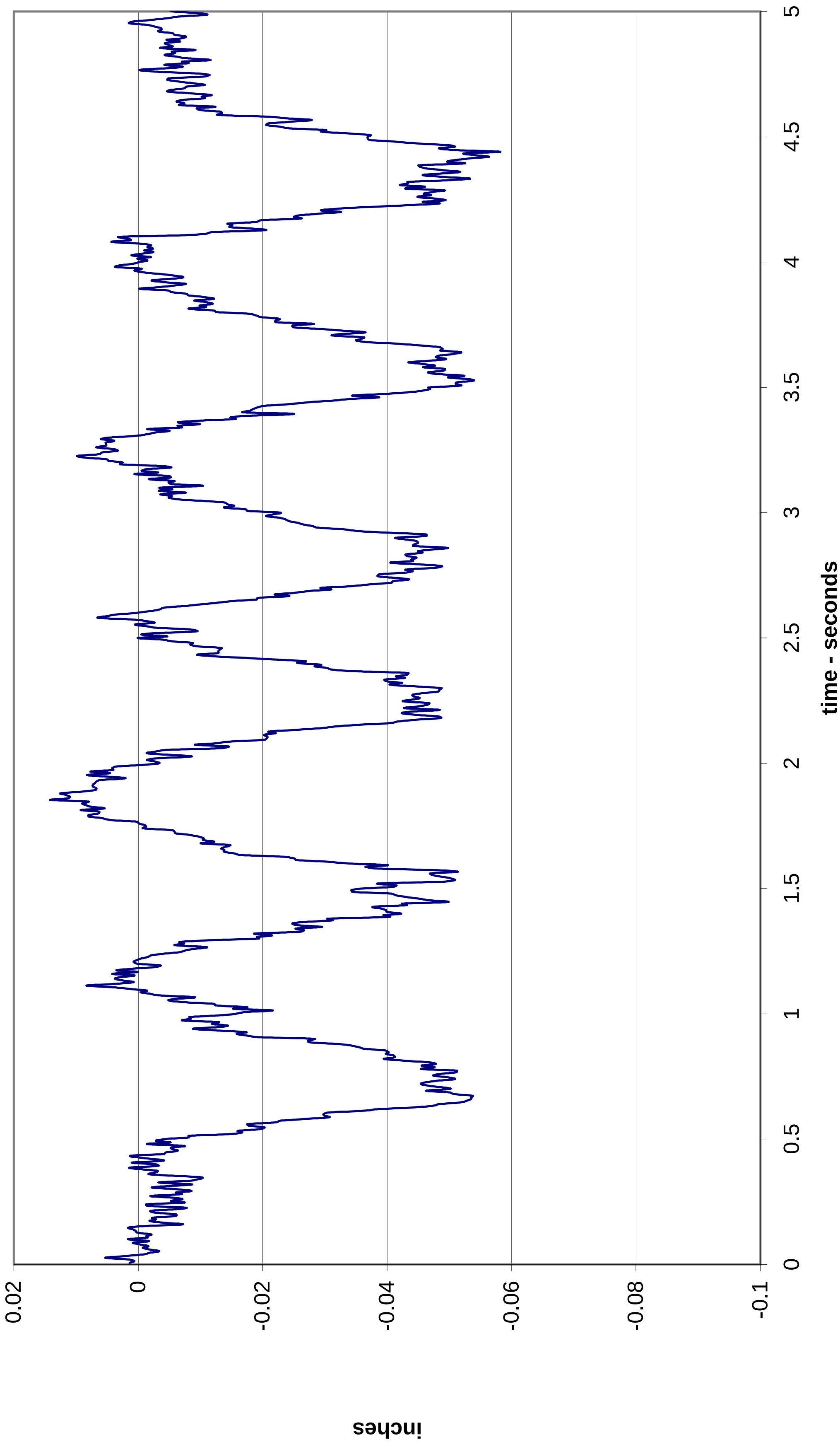


Figure C-13 TDA Site #4 Rail Deflection
30 mph

Figure C-14 TDA Site #4 Rail Deflection
50 mph

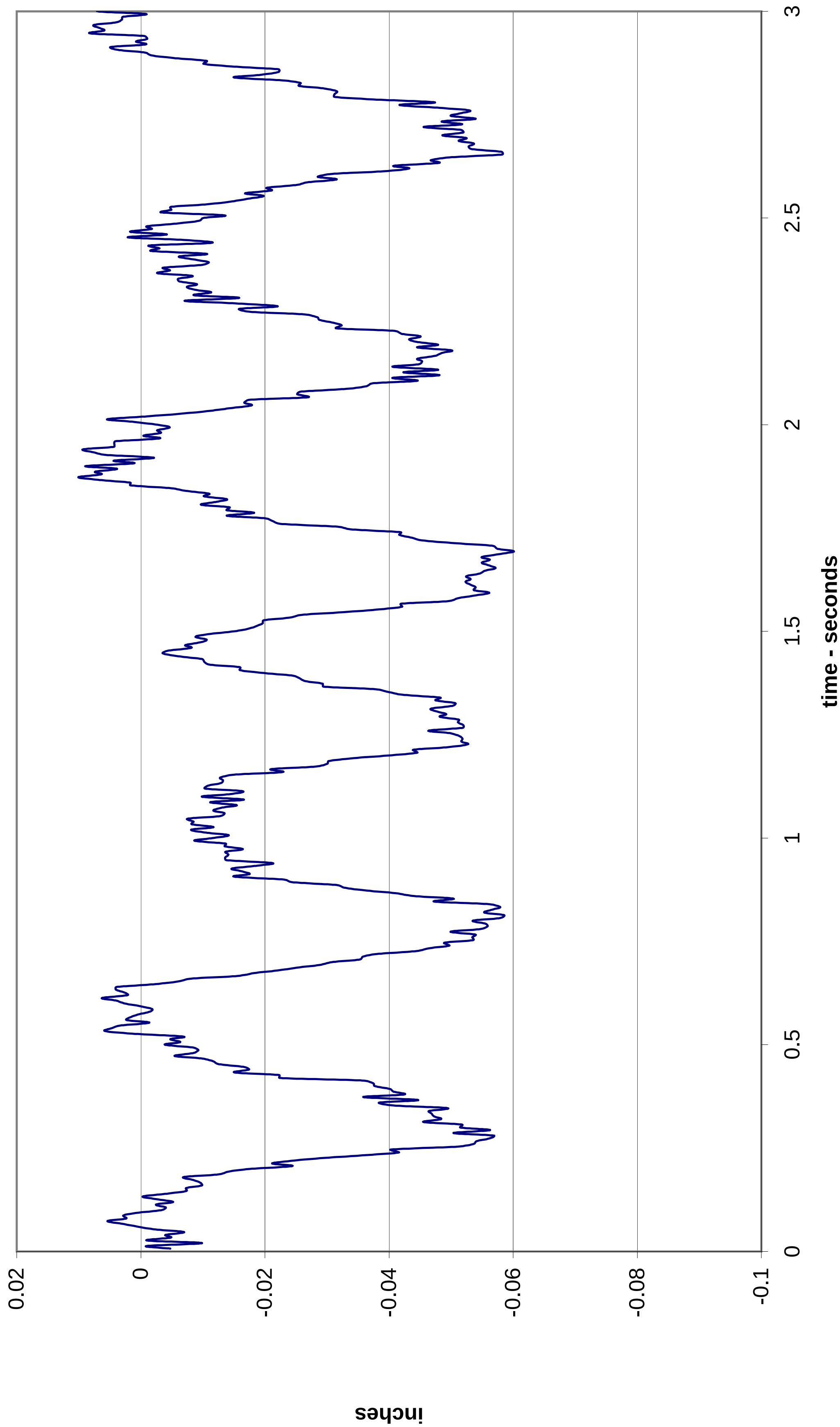
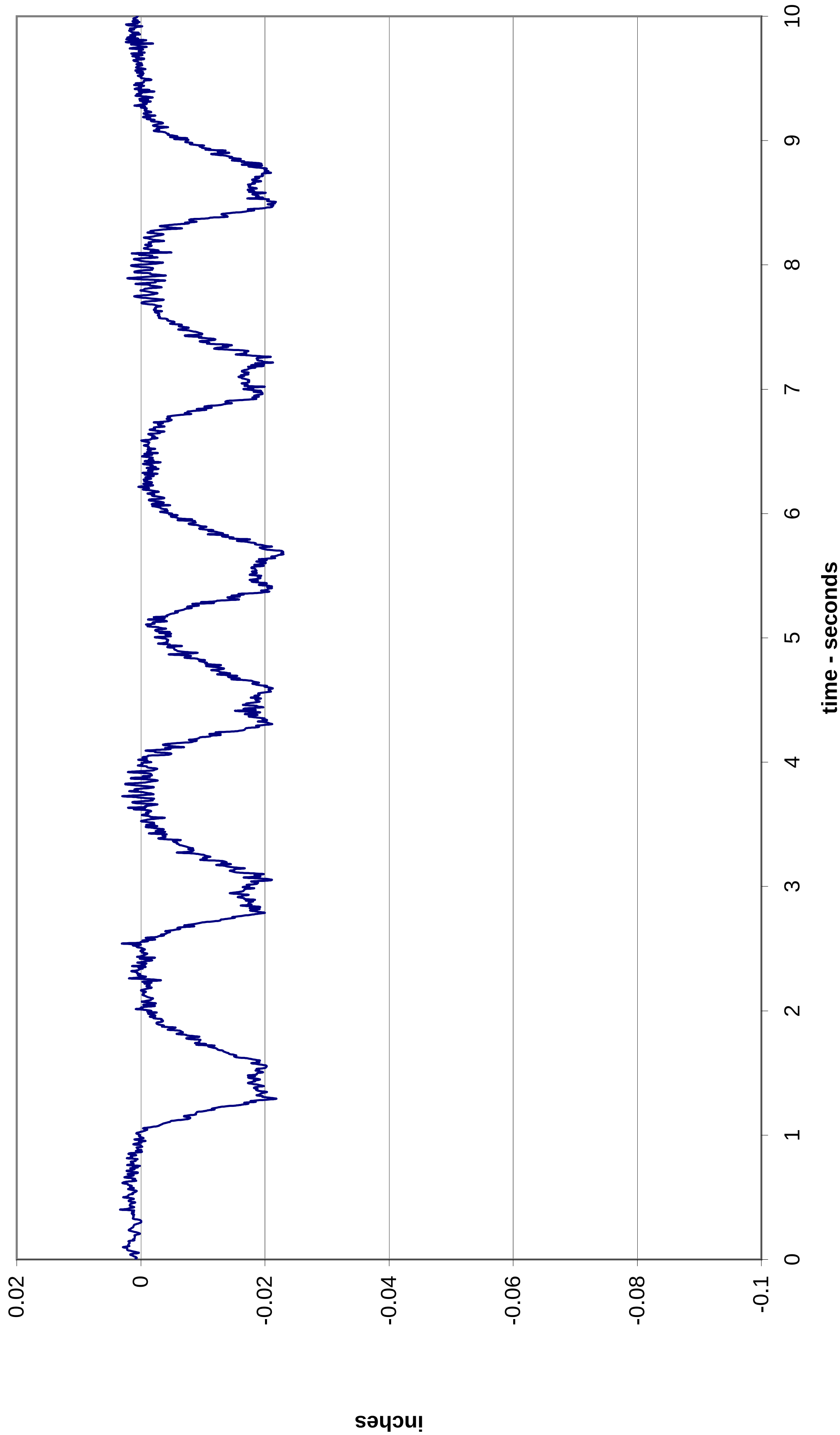


Figure C-15 Control Site #1 (North of Stokes St.) Rail Deflection
15 mph (Northbound Track)



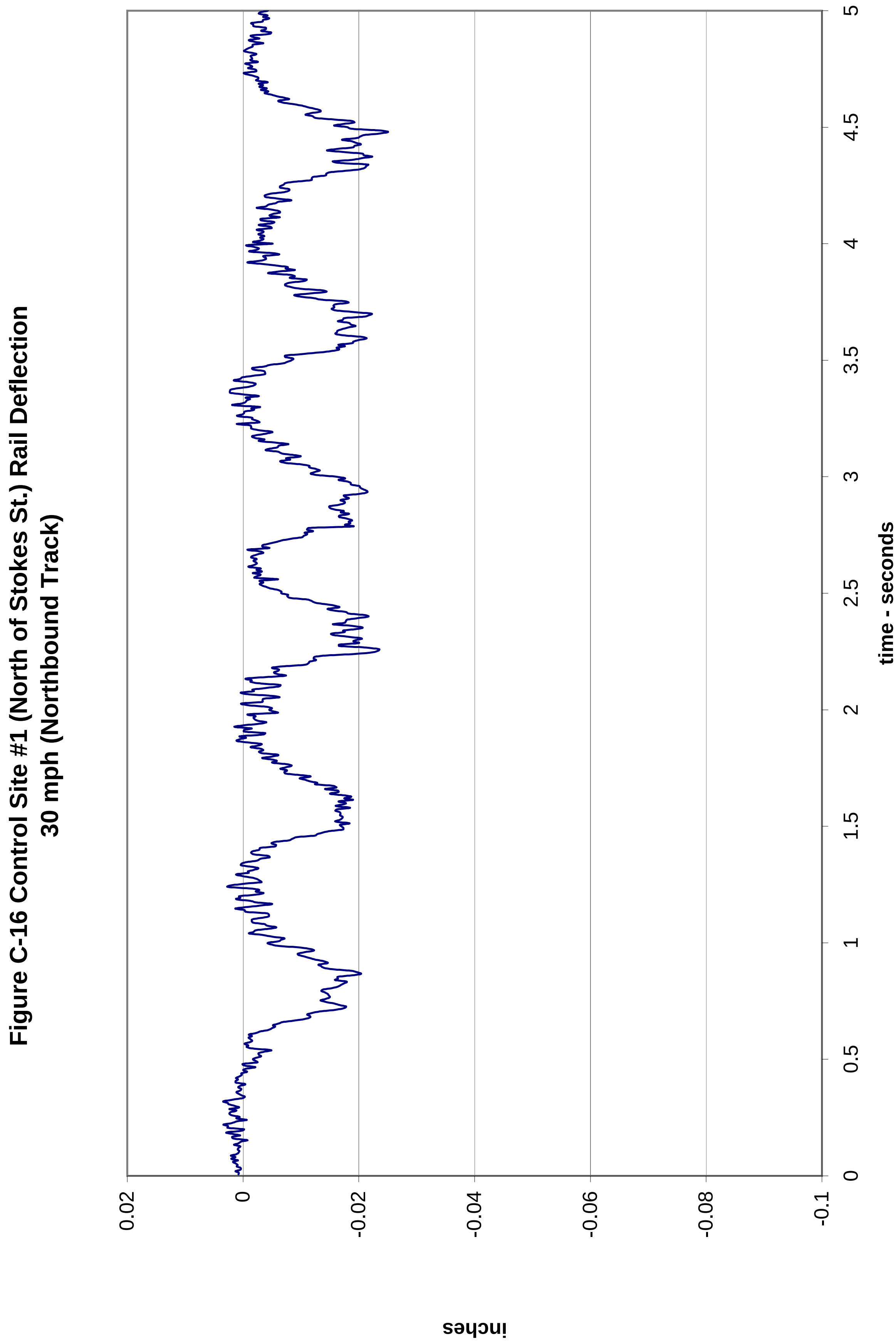


Figure C-16 Control Site #1 (North of Stokes St.) Rail Deflection
30 mph (Northbound Track)
inches
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
time - seconds
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

Figure C-17 Control Site #1 (North of Stokes St.) Rail Deflection
50 mph (Northbound Track)

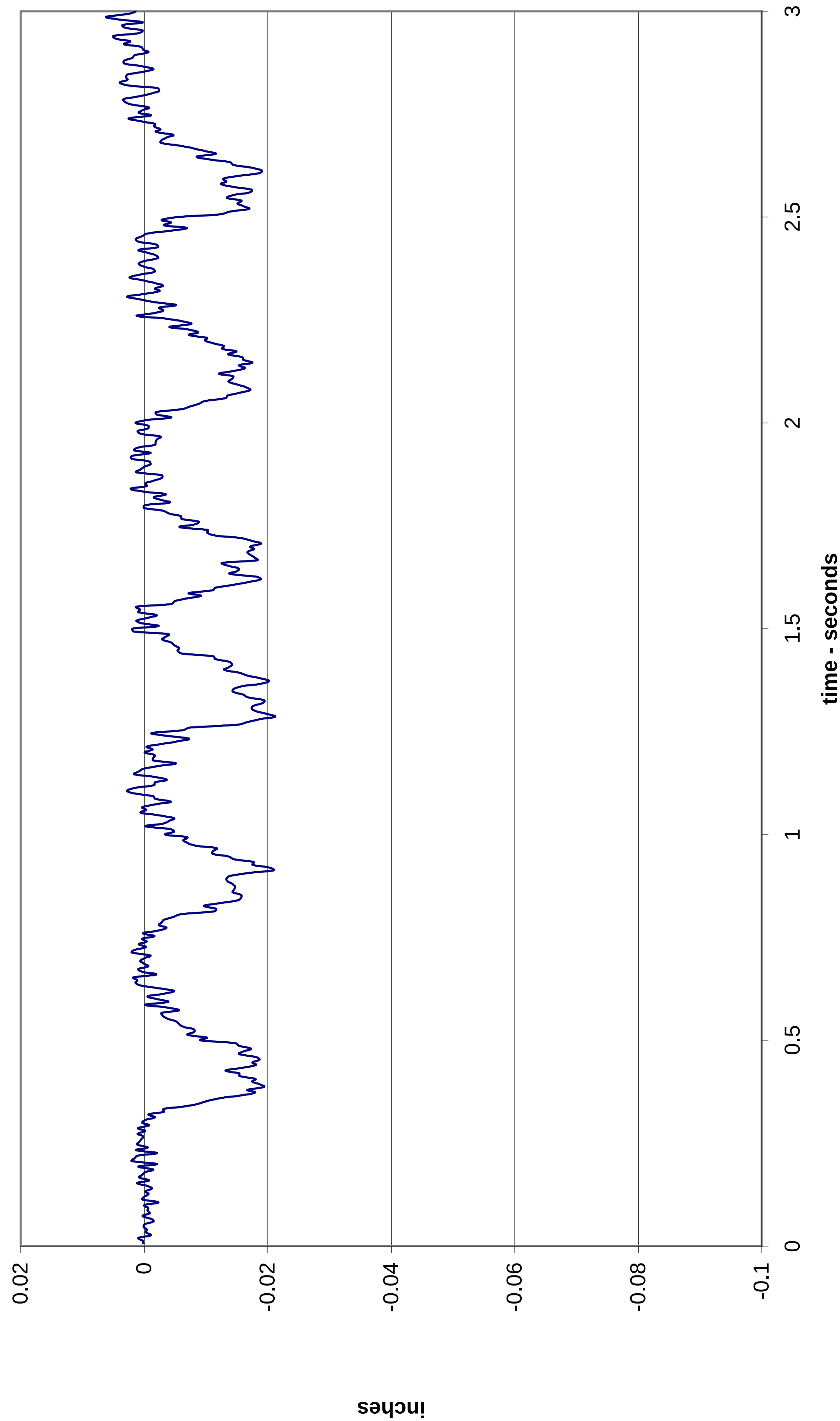


Figure C-18 Control Site #2 (South of Race St.) Rail Deflection
15 mph

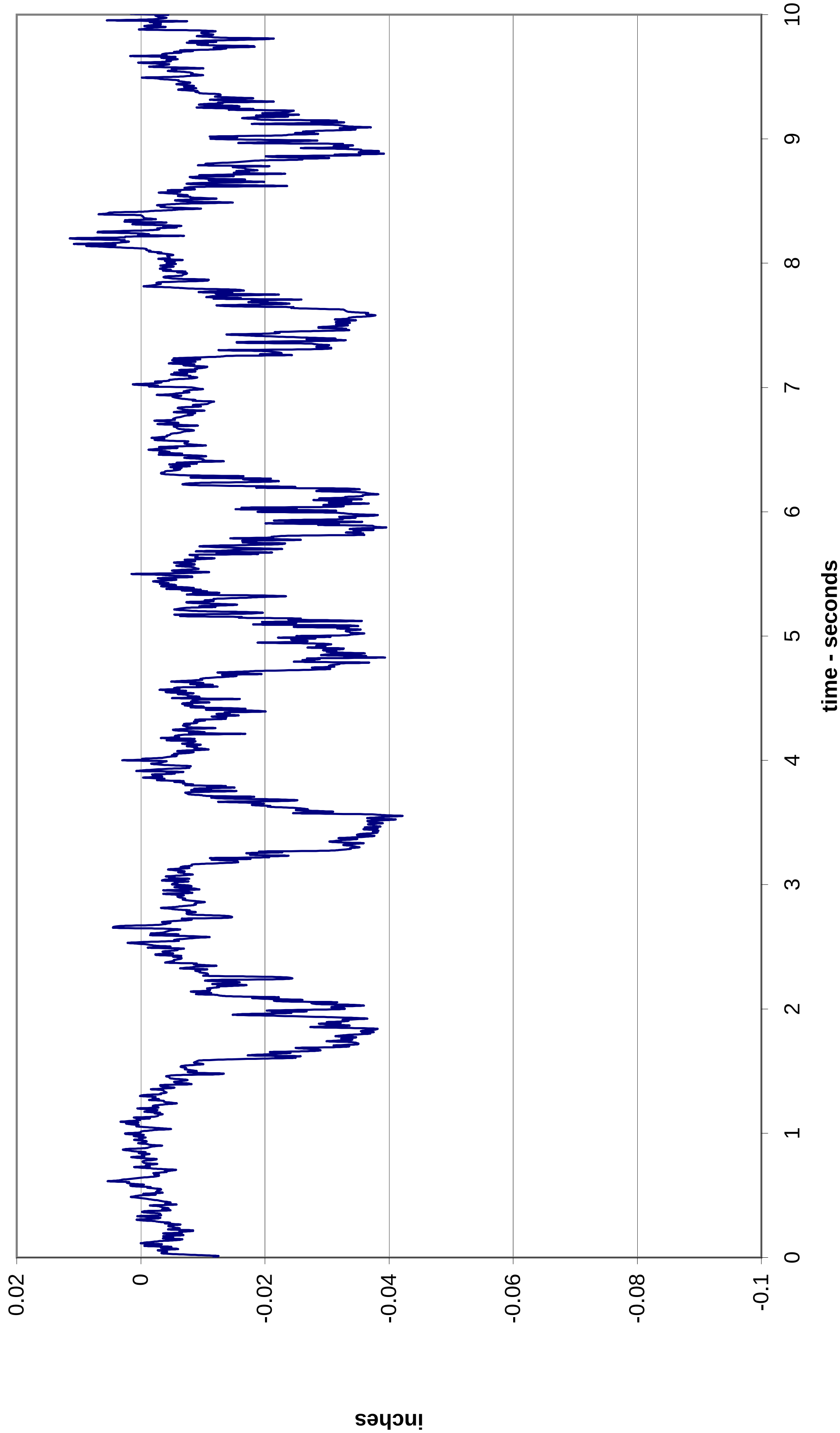
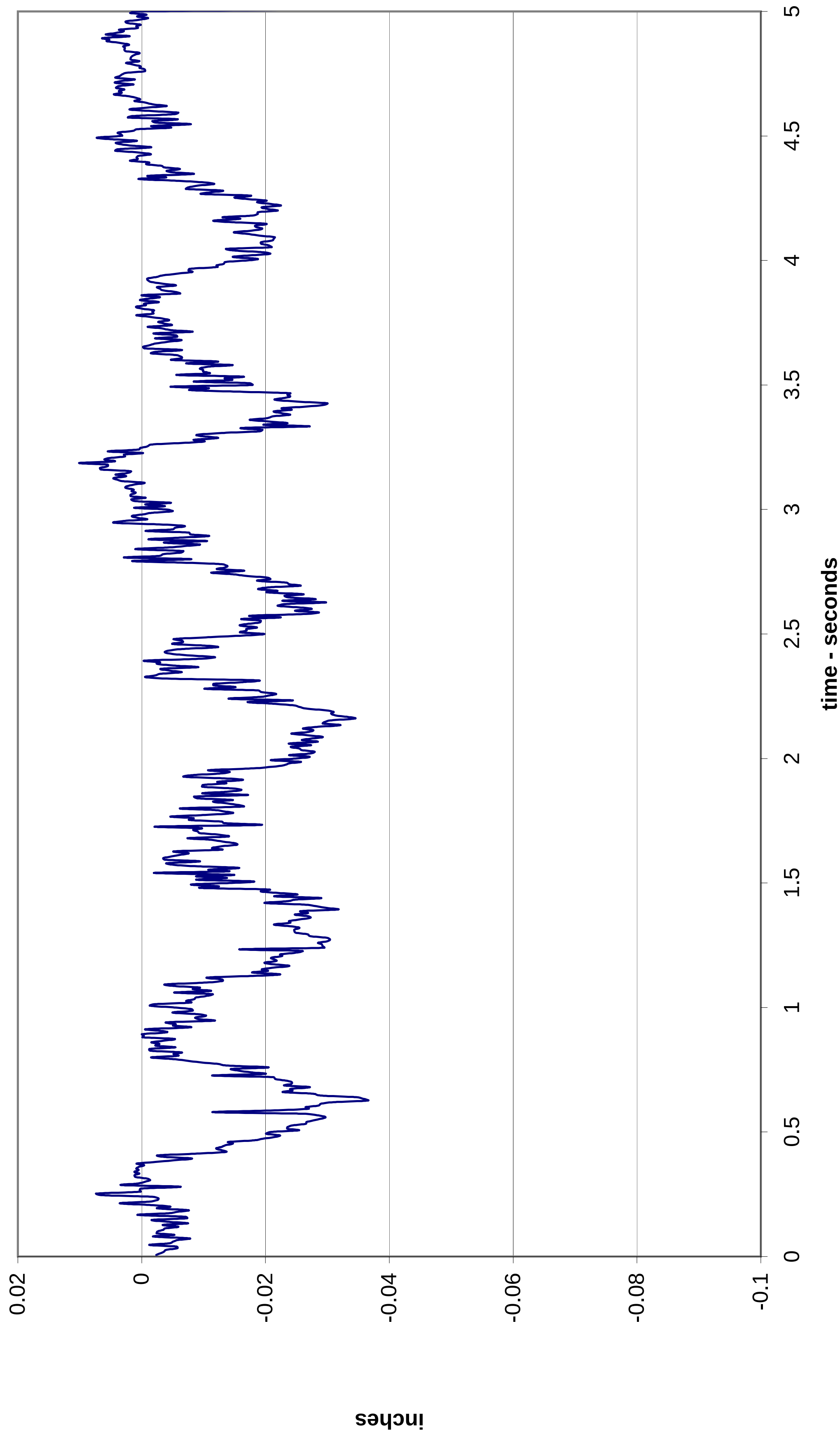


Figure C-19 Control Site #2 (South of Race St.) Rail Deflection
30 mph



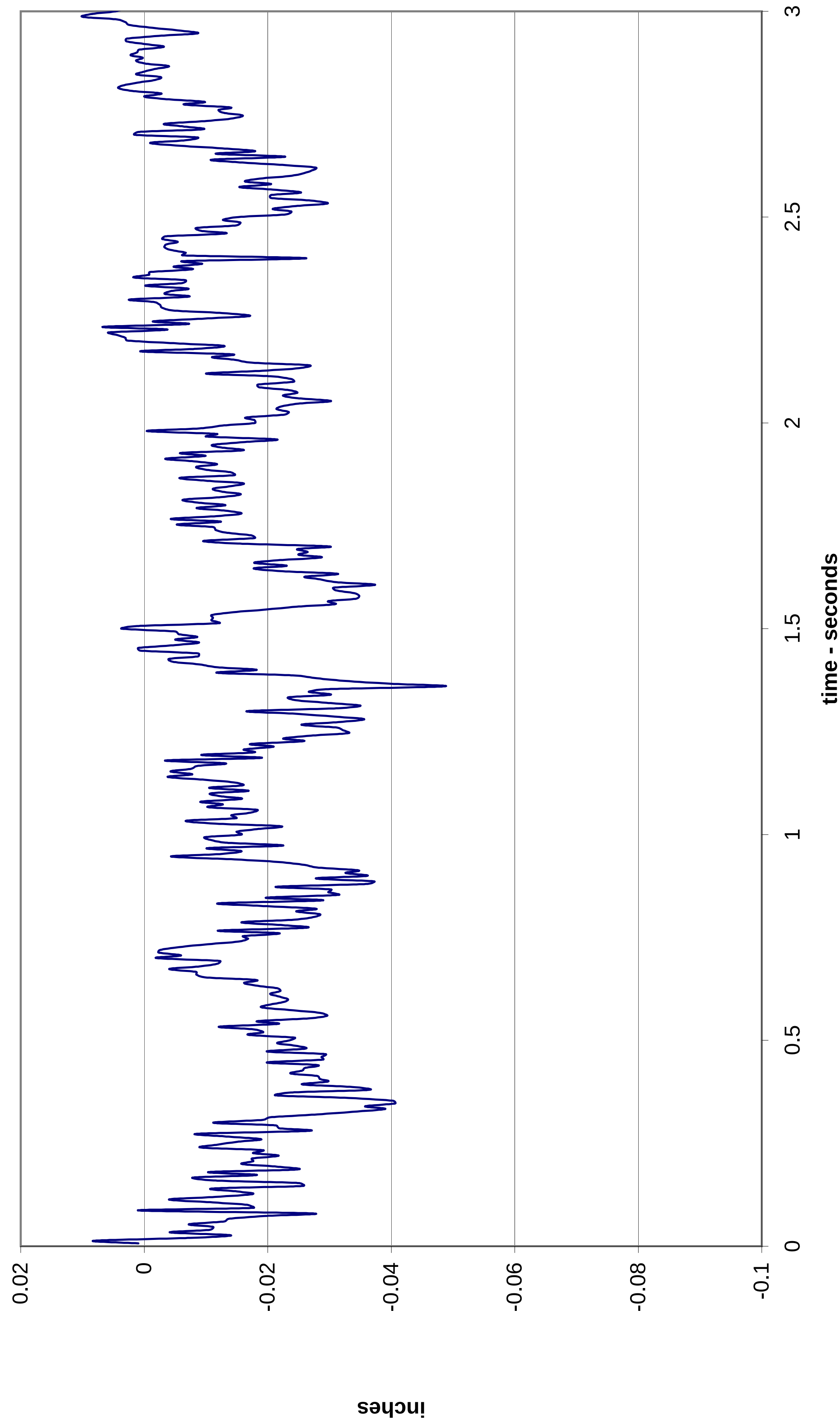


Figure C-20 Control Site #2 (South of Race St.) Rail Deflection
50 mph

APPENDIX D

Track Elevation Survey Results for TDA Sites #1, 3 & 4

FIGURE D-1 TRACK ELEVATION SURVEY RESULTS - TDA SITE 1

WESTBOUND TRACK STATION		TOP/RAIL ELEVATIONS - IN METRIC																
			WESTBOUND LRT								EASTBOUND LRT							
DESC	STATION	T/RAIL DESIGN	AS-BUILT WB 9/2003 LEFT RAIL	MEAS'D 11/06/07 LEFT RAIL	MEAS'D 03/23/09 LEFT RAIL	CHANGE SINCE 9/2003 +=HIGHER -=LOWER	AS-BUILT WB 9/2003 RIGHT RAIL	MEAS'D 11/06/07 RIGHT RAIL	MEAS'D 03/23/09 RIGHT RAIL	CHANGE SINCE 9/2003 +=HIGHER -=LOWER	AS-BUILT EB 9/2003 LEFT RAIL	MEAS'D 11/06/07 LEFT RAIL	MEAS'D 03/23/09 LEFT RAIL	CHANGE SINCE 9/2003 +=HIGHER -=LOWER	AS-BUILT EB 9/2003 RIGHT RAIL	MEAS'D 11/06/07 RIGHT RAIL	MEAS'D 03/23/09 RIGHT RAIL	CHANGE SINCE 9/2003 +=HIGHER -=LOWER
	106+00	63.392	63.368	63.356	63.356	-0.012	63.369	63.362	63.360	-0.009	63.393	63.385	63.383	-0.010	63.391	63.385	63.382	-0.009
	106+10	63.343	63.331	63.327	63.325	-0.006	63.327	63.323	63.330	0.003	63.340	63.336	63.333	-0.007	63.331	63.336	63.333	0.002
	106+20	63.294	63.287	63.295	63.284	-0.003	63.282	63.293	63.280	-0.002	63.285	63.281	63.280	-0.005	63.286	63.282	63.281	-0.005
	106+30	63.245	63.234	63.231	63.230	-0.004	63.232	63.229	63.227	-0.005	63.239	63.237	63.234	-0.005	63.237	63.236	63.234	-0.003
	106+40	63.196	63.196	63.191	63.188	-0.008	63.195	63.190	63.188	-0.007	63.184	63.182	63.180	-0.004	63.183	63.181	63.179	-0.004
	106+50	63.147	63.138	63.133	63.130	-0.008	63.140	63.137	63.135	-0.005	63.135	63.132	63.130	-0.005	63.135	63.131	63.129	-0.006
	106+60	63.098	63.092	63.087	63.085	-0.007	63.091	63.087	63.084	-0.007	63.086	63.079	63.076	-0.010	63.087	63.081	63.079	-0.008
	106+70	63.049	63.044	63.038	63.036	-0.008	63.043	63.039	63.037	-0.006	63.035	63.027	63.025	-0.010	63.037	63.031	63.029	-0.008
	106+80	63.000	62.993	62.988	62.986	-0.007	62.991	62.988	62.985	-0.006	62.995	62.989	62.986	-0.009	62.995	62.988	62.986	-0.009
	106+90	62.951	62.949	62.945	62.942	-0.007	62.946	62.941	62.938	-0.008	62.949	62.942	62.939	-0.010	62.948	62.939	62.936	-0.012
	107+00	62.902	62.903	62.900	62.897	-0.006	62.901	62.898	62.895	-0.006	62.898	62.892	62.890	-0.008	62.897	62.890	62.888	-0.009
	107+10	62.853	62.857	62.851	62.848	-0.009	62.855	62.850	62.847	-0.008	62.852	62.845	62.842	-0.010	62.853	62.846	62.843	-0.010
	107+20	62.804	62.807	62.801	62.799	-0.008	62.805	62.800	62.799	-0.006	62.799	62.790	62.788	-0.011	62.798	62.791	62.789	-0.009
	107+30	62.755	62.759	62.751	62.749	-0.010	62.758	62.752	62.751	-0.007	62.750	62.742	62.739	-0.011	62.751	62.744	62.743	-0.008
	107+40	62.706	62.712	62.704	62.703	-0.009	62.709	62.703	62.701	-0.008	62.707	62.700	62.699	-0.008	62.709	62.703	62.702	-0.007
	107+50	62.657	62.664	62.656	62.655	-0.009	62.662	62.657	62.656	-0.006	62.660	62.653	62.652	-0.008	62.659	62.652	62.653	-0.006
	107+60	62.608	62.612	62.604	62.604	-0.008	62.611	62.605	62.605	-0.006	62.611	62.602	62.603	-0.008	62.610	62.603	62.603	-0.007
	107+70	62.559	62.562	62.554	62.554	-0.008	62.560	62.553	62.552	-0.008	62.561	62.553	62.554	-0.007	62.564	62.555	62.555	-0.009
	107+80	62.510	62.509	62.500	62.500	-0.009	62.510	62.502	62.502	-0.008	62.512	62.503	62.503	-0.009	62.512	62.505	62.504	-0.008
	107+90	62.461	62.460	62.450	62.449	-0.011	62.459	62.451	62.450	-0.009	62.460	62.449	62.449	-0.011	62.460	62.451	62.450	-0.010
	108+00	62.412	62.412	62.403	62.401	-0.011	62.410	62.403	62.401	-0.009	62.410	62.403	62.401	-0.009	62.410	62.403	62.401	-0.009
	108+10	62.363	62.359	62.352	62.349	-0.010	62.361	62.351	62.349	-0.012	62.361	62.351	62.348	-0.013	62.361	62.352	62.353	-0.008
	108+20	62.314	62.311	62.302	62.302	-0.009	62.310	62.303	62.303	-0.007	62.310	62.302	62.300	-0.010	62.310	62.302	62.299	-0.011
	108+30	62.265	62.261	62.252	62.249	-0.012	62.263	62.256	62.254	-0.009	62.262	62.253	62.252	-0.010	62.263	62.256	62.255	-0.008
	108+40	62.216	62.214	62.207	62.204	-0.010	62.214	62.210	62.209	-0.005	62.214	62.213	62.211	-0.003	62.211	62.208	62.205	-0.006
	108+50	62.167	62.166	62.173	62.171	0.005	62.166	62.173	62.171	0.005	62.168	62.160	62.159	-0.009	62.167	62.161	62.158	-0.009
	108+60	62.118	62.122	62.114	62.111	-0.011	62.123	62.116	62.112	-0.011	62.118	62.112	62.109	-0.009	62.117	62.110	62.109	-0.008
	108+70	62.069	62.072	62.063	62.061	-0.011	62.070	62.063	62.060	-0.010	62.071	62.064	62.061	-0.010	62.071	62.063	62.060	-0.011
	108+80	62.020	62.020	62.011	62.010	-0.010	62.017	62.010	62.009	-0.008	62.020	62.013	62.012	-0.008	62.020	62.013	62.011	-0.009
	108+90	61.971	61.971	61.959	61.957	-0.014	61.974	61.967	61.966	-0.008	61.975	61.973	61.970	-0.005	61.975	61.966	61.964	-0.011
	109+00	61.922	61.925	61.903	61.898	-0.027	61.934	61.915	61.912	-0.022	61.932	61.920	61.916	-0.016	61.932	61.924	61.920	-0.012

FIGURE D-2 TRACK ELEVATION SURVEY RESULTS - TDA SITE 3

WESTBOUND TRACK STATION		TOP/RAIL ELEVATIONS - IN METRIC																
			WESTBOUND LRT								EASTBOUND LRT							
DESC	STATION	T/RAIL DESIGN	AS-BUILT WB 12/2003 LEFT RAIL	MEAS'D 11/07/07 LEFT RAIL	MEAS'D 03/24/09 LEFT RAIL	CHANGE SINCE 12/2003 +=HIGHER -=LOWER	AS-BUILT WB 12/2003 RIGHT RAIL	MEAS'D 11/07/07 RIGHT RAIL	MEAS'D 03/24/09 RIGHT RAIL	CHANGE SINCE 12/2003 +=HIGHER -=LOWER	AS-BUILT EB 12/2003 LEFT RAIL	MEAS'D 11/07/07 LEFT RAIL	MEAS'D 03/24/09 LEFT RAIL	CHANGE SINCE 12/2003 +=HIGHER -=LOWER	AS-BUILT EB 12/2003 RIGHT RAIL	MEAS'D 11/07/07 RIGHT RAIL	MEAS'D 03/24/09 RIGHT RAIL	CHANGE SINCE 12/2003 +=HIGHER -=LOWER
	141+00	45.010	45.009	44.999	44.997	-0.012	45.008	44.998	44.994	-0.014	44.988	44.987	44.984	-0.004	44.995	44.988	44.984	-0.011
	141+10	44.926	44.921	44.912	44.910	-0.011	44.919	44.911	44.907	-0.012	44.910	44.902	44.899	-0.011	44.913	44.906	44.903	-0.010
	141+20	44.840	44.833	44.823	44.820	-0.013	44.832	44.824	44.821	-0.011	44.842	44.838	44.836	-0.006	44.843	44.840	44.836	-0.007
	141+30	44.754	44.751	44.746	44.742	-0.009	44.757	44.752	44.748	-0.009	44.754	44.750	44.749	-0.005	44.756	44.752	44.753	-0.003
	141+40	44.668	44.665	44.660	44.650	-0.015	44.668	44.664	44.660	-0.008	44.669	44.664	44.662	-0.007	44.668	44.664	44.664	-0.004
	141+50	44.581	44.579	44.573	44.569	-0.010	44.582	44.578	44.575	-0.007	44.577	44.572	44.571	-0.006	44.579	44.574	44.573	-0.006
	141+60	44.495	44.478	44.464	44.458	-0.020	44.476	44.462	44.457	-0.019	44.490	44.479	44.474	-0.016	44.484	44.477	44.474	-0.010
	141+70	44.410	44.395	44.384	44.380	-0.015	44.394	44.384	44.381	-0.013	44.413	44.403	44.399	-0.014	44.409	44.401	44.398	-0.011
	141+80	44.333	44.325	44.313	44.309	-0.016	44.322	44.312	44.309	-0.013	44.341	44.331	44.326	-0.015	44.339	44.331	44.327	-0.012
	141+90	44.267	44.259	44.248	44.245	-0.014	44.255	44.246	44.243	-0.012	44.276	44.267	44.264	-0.012	44.277	44.269	44.266	-0.011
	142+00	44.210	44.201	44.189	44.186	-0.015	44.197	44.189	44.187	-0.010	44.217	44.209	44.207	-0.010	44.216	44.209	44.206	-0.010
	142+10	44.162	44.151	44.139	44.136	-0.015	44.147	44.136	44.132	-0.015	44.162	44.153	44.150	-0.012	44.163	44.155	44.152	-0.011
	142+20	44.124	44.113	44.103	44.100	-0.013	44.108	44.099	44.094	-0.014	44.118	44.112	44.109	-0.009	44.118	44.112	44.108	-0.010
	142+30	44.086	44.079	44.071	44.067	-0.012	44.075	44.069	44.065	-0.010	44.083	44.079	44.075	-0.008	44.082	44.079	44.076	-0.006
	142+40	44.049	44.044	44.032	44.030	-0.014	44.040	44.032	44.029	-0.011	44.043	44.038	44.033	-0.010	44.043	44.038	44.035	-0.008
	142+50	44.012	44.004	43.993	43.989	-0.015	44.006	43.998	43.995	-0.011	44.002	43.995	43.991	-0.011	44.003	43.996	43.993	-0.010
	142+60	43.974	43.974	43.964	43.961	-0.013	43.968	43.962	43.959	-0.009	43.967	43.961	43.957	-0.010	43.966	43.960	43.958	-0.008

FIGURE D-3 TRACK ELEVATION SURVEY RESULTS - TDA SITE 4

WESTBOUND TRACK STATION		TOP/RAIL ELEVATIONS - IN METRIC								
			WESTBOUND LRT							
		T/RAIL	AS-BUILT WB 12/2003	MEAS'D 11/09/07	MEAS'D 03/25/09	CHANGE SINCE 12/2003	AS-BUILT WB 12/2003	MEAS'D 11/09/07	MEAS'D 03/25/09	CHANGE SINCE 12/2003
DESC	STATION	DESIGN	LEFT RAIL	LEFT RAIL	LEFT RAIL	+=HIGHER -=LOWER	RIGHT RAIL	RIGHT RAIL	RIGHT RAIL	+=HIGHER -=LOWER
	147+00	41.322	41.353	41.358	41.346	-0.007	41.352	41.356	41.344	-0.008
	147+10	41.255	41.298	41.290	41.276	-0.022	41.294	41.291	41.278	-0.016
	147+20	41.188	41.222	41.219	41.211	-0.011	41.225	41.224	41.214	-0.011
P.O.T.	147+26.135	41.147	41.172	41.167	41.158	-0.014	41.177	41.173	41.163	-0.014
	147+30	41.121	41.145	41.139	41.128	-0.017	41.144	41.141	41.131	-0.013
	147+41.135	41.046	41.058	41.057	41.047	-0.011	41.059	41.063	41.053	-0.006
	147+50	40.987	40.991	40.995	40.984	-0.007	40.992	40.999	40.989	-0.003
	147+60	40.920	40.929	40.930	40.918	-0.011	40.931	40.936	40.924	-0.007
	147+70	40.853	40.861	40.866	40.855	-0.006	40.863	40.869	40.858	-0.005
	147+81	40.785	40.792	40.793	40.782	-0.010	40.796	40.799	40.788	-0.008
	147+90	40.740	40.743	40.742	40.733	-0.010	40.744	40.743	40.732	-0.012
	148+00	40.701	40.694	40.699	40.688	-0.006	40.693	40.700	40.688	-0.005
	148+10	40.672	40.665	40.676	40.664	-0.001	40.666	40.675	40.664	-0.002
	148+20	40.654	40.654	40.663	40.653	-0.001	40.650	40.657	40.646	-0.004
	148+30	40.641	40.637	40.639	40.629	-0.008	40.644	40.642	40.631	-0.013
P.I.T.O.	148+42.415	40.626	40.623	40.626	40.615	-0.008	40.621	40.621	40.611	-0.010
	148+50	40.616	40.608	40.617	40.608	0.000	40.616	40.623	40.608	-0.008
P./S.	148+53.553	40.612	40.604	40.618	40.609	0.005	40.615	40.620	40.610	-0.005
	148+60	40.604	40.600	40.603	40.592	-0.008	40.601	40.606	40.596	-0.005
	148+70	40.591	40.584	40.588	40.575	-0.009	40.583	40.587	40.576	-0.007
	148+80	40.579	40.571	40.574	40.562	-0.009	40.570	40.575	40.564	-0.006
	148+90	40.566	40.559	40.565	40.552	-0.007	40.561	40.566	40.555	-0.006
	149+00	40.554	40.544	40.548	40.536	-0.008	40.545	40.549	40.537	-0.008
	149+10	40.541	40.531	40.536	40.524	-0.007	40.533	40.537	40.525	-0.008
	149+20	40.529	40.524	40.528	40.517	-0.007	40.524	40.530	40.518	-0.006
	149+30	40.516	40.513	40.515	40.505	-0.008	40.513	40.518	40.507	-0.006
	149+40	40.504	40.497	40.495	40.487	-0.010	40.502	40.501	40.492	-0.010
T.S.	149+43.856	40.499	40.493	40.491	40.484	-0.009	40.496	40.496	40.487	-0.009
	149+50	40.491	40.486	40.484	40.475	-0.011	40.492	40.492	40.484	-0.008
	149+60	40.479	40.474	40.470	40.461	-0.013	40.494	40.491	40.483	-0.011
S.S.C.	149+68.856	40.467	40.464	40.462	40.452	-0.012	40.489	40.487	40.478	-0.011
	149+80	40.453	40.452	40.453	40.441	-0.011	40.466	40.469	40.457	-0.009
	149+90	40.441	40.437	40.440	40.428	-0.009	40.445	40.449	40.438	-0.007
S.S.T.	149+93.856	40.436	40.435	40.438	40.425	-0.010	40.437	40.442	40.430	-0.007
	150+00	40.428	40.428	40.430	40.416	-0.012	40.421	40.427	40.414	-0.007
	150+10	40.416	40.424	40.425	40.412	-0.012	40.411	40.413	40.400	-0.011
S.S.C.	150+18.856	40.405	40.431	40.430	40.416	-0.015	40.403	40.407	40.394	-0.009
	150+30	40.391	40.407	40.406	40.394	-0.013	40.388	40.391	40.378	-0.010
	150+40	40.378	40.383	40.384	40.372	-0.011	40.375	40.378	40.367	-0.008
S.T.	150+43.856	40.374	40.374	40.375	40.363	-0.011	40.371	40.373	40.361	-0.010
	150+50	40.366	40.358	40.360	40.348	-0.010	40.361	40.365	40.353	-0.008
	150+60	40.353	40.349	40.350	40.337	-0.012	40.348	40.350	40.338	-0.010
	150+70	40.330	40.322	40.321	40.307	-0.015	40.322	40.322	40.310	-0.012
	150+80	40.286	40.281	40.278	40.264	-0.017	40.279	40.279	40.266	-0.013
	150+90	40.221	40.214	40.213	40.200	-0.014	40.220	40.221	40.208	-0.012
	151+00	40.135	40.137	40.136	40.122	-0.015	40.142	40.142	40.130	-0.012

APPENDIX E

May 22, 2009 Letter Report on TDA Vibration Performance Over Time

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May 22, 2009

Dana N. Humphrey, Ph.D., P.E.
Consulting Engineer
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Subject: TDA Vibration Performance Over Time

Dear Dr. Humphrey:

Following our most recent field tests on the Vasona Line at the Santa Clara Valley Transportation Authority to determine the vibration attenuating and damping properties of tire derived aggregate (shredded tires, referred to as TDA), questions have been raised regarding (1) the vibration reduction performance over time and (2) a well-defined attenuation design curve to be used for prediction purposes. Reference is made to the three reports covering extensive testing performed in 2005 just prior to revenue service, 2006 after approximately one year of revenue service and 2009 after approximately three and one-half years of revenue service. For all of these tests, the vibration reduction due to operations on the TDA underlayment was determined comparing the resulting vibration at locations where the TDA underlayment had been installed with two control sections with standard ballast and tie track. As indicated in those reports, the most reliable method for determining the actual vibration reduction due to the TDA underlayment would be to obtain a series of measurements at the same physical locations with standard ballast and tie track and with the ballast and tie track installed over the TDA underlayment. Since that method was not practical, the evaluation has used the two control sections to determine the vibration reduction.

The outcome of all three tests has shown that the use of TDA underlayment beneath ballast and tie track provides for vibration reduction generally beginning at frequencies above 16 Hz. The actual vibration reduction can only be determined for groundborne vibration at frequencies characteristic of that generated by the passing trains where the signal to noise ratio is sufficiently above the background level. At frequencies above the range of the 125 to 160 Hz 1/3 octave band, the signal to noise ratio begins to decrease, with a consequential decrease in vibration attenuation at higher frequencies. The actual reduction above this range is probably similar to that at somewhat lower frequencies and is only a consequence of the decrease in signal to noise ratio at the higher frequencies. However, this is not believed to be the case for the low frequencies, despite the lack of a significant signal to noise ratio at these lower frequencies. Typically reduction or amplification at these lower and higher frequencies is a consequence of the existing ambient vibration level and not due to any specific characteristics of the TDA. For that reason, we have limited the frequency range of the 1/3 octave band relative vibration level charts in this letter to the range of 12.5 Hz to 250 Hz.

There are many variables that can affect the predicted vibration due to the use of TDA. Specific anomalies, particularly local site-specific soil conditions at the measurement sites, can indicate that the TDA is not providing any vibration reduction while others can indicate that the TDA is providing vibration reduction at frequencies which would be considered unreasonable. Over time the performance could deteriorate if the TDA layer was infiltrated with soil or small rocks or if the TDA were to become excessively compacted. As long as the TDA underlayment is properly wrapped with an appropriate geotextile material, infiltration of soil or small rocks is not anticipated. There is also no indication of any additional compaction of the TDA underlayment based on the track surveys to determine settlement over time.

Vibration reduction at different times could also be affected by changes in the local ground conditions, track conditions and vehicle wheel conditions. Comparison of the actual 1/3 octave band groundborne vibration velocity levels measured between the three tests show differences at both the sites with the TDA underlayment, as well as at the control sections. However, assuming that the same changes affect all of the measurement sites and the TDA underlayment is still providing vibration reduction, then the relative vibration levels would remain relatively unchanged for each of the different test series. Since the three extensive test reports attempted to develop a general performance curve of the TDA underlayment based on many hundreds of data samples, some of the specific comparisons which would assist in evaluating the performance over time were not presented. This letter attempts to show some site specific examples of how the TDA underlayment is performing over time.

Speed Dependency

In order to reduce the number of comparisons but still retain additional detail, a comparison of TDA performance with respect to speed was reviewed. Generally there is minimal variation in vibration reduction with speed, i.e., the vibration reduction at each of the three speeds used for the tests can be averaged together, as there is only a small variation with train speed. For trains with wheel flats or track in poor condition, this might not be true, but these tests were run using test trains with relatively smooth wheels and track in good condition, which had been ground prior to the 2005 tests and again in the fall of 2008 prior to the 2009 tests.

To demonstrate this lack of speed dependency which would allow the relative vibration levels to be determined independent of speed, Figures 1 through 6 show two different sets of measurements with speed dependency. Figures 1 through 3 present the average attenuation of TDA underlayment at TDA Site #1 with respect to Control Site #1 at a distance of 25 ft from track centerline for the 2005, 2006 and 2009 tests. Review indicates relatively consistent reduction for all three tests speeds for each of the tests. Figures 4 through 6 present the average attenuation of TDA underlayment at TDA Site #4 with respect to Control Site #2 at a distance of 50 ft west of track centerline for the three test series. Again, review indicates relatively consistent reduction for all three test speeds for each of the tests. Other speed comparisons show similar results, so for the purpose of comparisons over time, the relative vibration reduction has been determined by averaging the results over the three test speeds.

Site Specific Results – TDA Site #1

Figures 7 through 10 present the site specific results for TDA Site #1. Review indicates that there is some variability with respect to the vibration attenuation depending on distance from the track and on which control site is used for determining attenuation. Two measurement locations were used to determine the 25 ft attenuation while four measurement locations were used to determine the 50 ft attenuation. Additional review of the actual groundborne vibration levels indicates that there is a considerable variability in spectra at the 50 ft measurement locations for the different test series which would explain the variability of the data. However, these differences are not related to a deterioration of attenuation over time.

Site Specific Results – TDA Site #3

Figures 11 through 14 present the site specific results for TDA Site #3 for operations on the southbound track. This site has the shortest length of TDA installed, and it has generally demonstrated inferior attenuation characteristics at the 50 ft measurement locations. Comparisons for the northbound track are not presented since the need of the test train to return to the yard yielded only two passbys on this track for the 2009 tests. At 25 ft from track centerline, review indicates considerable attenuation. These data have been corrected at this distance based on the impact (transfer mobility) test data from this site (performed in 2005 on the nearby sidewalk, not specifically at the measurement locations). Although these data may be over corrected, there is no indication of deterioration of performance with time. For the 50 ft data, no correction has been applied, and the attenuation with respect to control site #2 would indicate that some correction from the impact (transfer mobility) testing may be in order. Figure 13 indicates that the attenuation for the 2009 tests has deteriorated, but this is not supported by the data at 25 ft or when compared to control site #2, and is suspected to be erroneous and should be further reviewed.

Site Specific Results – TDA Site #4

Figures 15 through 22 present the detailed site specific results for TDA Site #4. This measurement site has consistently indicated a high level of vibration attenuation with the use of the TDA underlayment for all three tests. Review indicates that there are some variations depending on which control site is used for comparison, as well as on which side the measurements were obtained. These data clearly show that the vibration attenuation has not deteriorated with time.

Conclusions

This site specific review has been undertaken to show that there is no deterioration of the performance of the TDA underlayment over time. We believe that this is clearly shown by a review of the data presented. Determining a well defined attenuation design curve to be used for prediction purposes is more difficult. As previously stated, there are anomalies, specifically local soil conditions, as would be expected when using control sections. A more detailed and extensive impact (transfer mobility) testing program could provide a refinement to the measurement data that would likely narrow the spread.

A relatively conservative design curve was presented after each of the measurement programs and we believe that the design curve presented after completion of the 2006 tests is still a reasonable and conservative design curve to be used until more data from other installations (e.g., Denver) are obtained. Review of the comparison data indicates that using Control Site #1 for the comparisons presents a more consistent set than does Control Site #2. However, the grand average to determine the recommended attenuation design curve uses all of the TDA sites and both control sites which makes it reasonably conservative. In addition we believe that for almost all measurement locations there has been some reduction in groundborne vibration, and considering the relatively low cost and environmental advantages, it is beneficial, particularly where only a moderate degree of vibration reduction is necessary.

We trust that this addresses the concerns raised in the review of our May 2009 report on the evaluation of TDA installed under light rail track at VTA.

Please let us know if you have additional questions or comments.

Very truly yours,

WILSON, IHRIG & ASSOCIATES, INC.

Steven L. Wolfe

Steven L. Wolfe
President and Principal Consultant

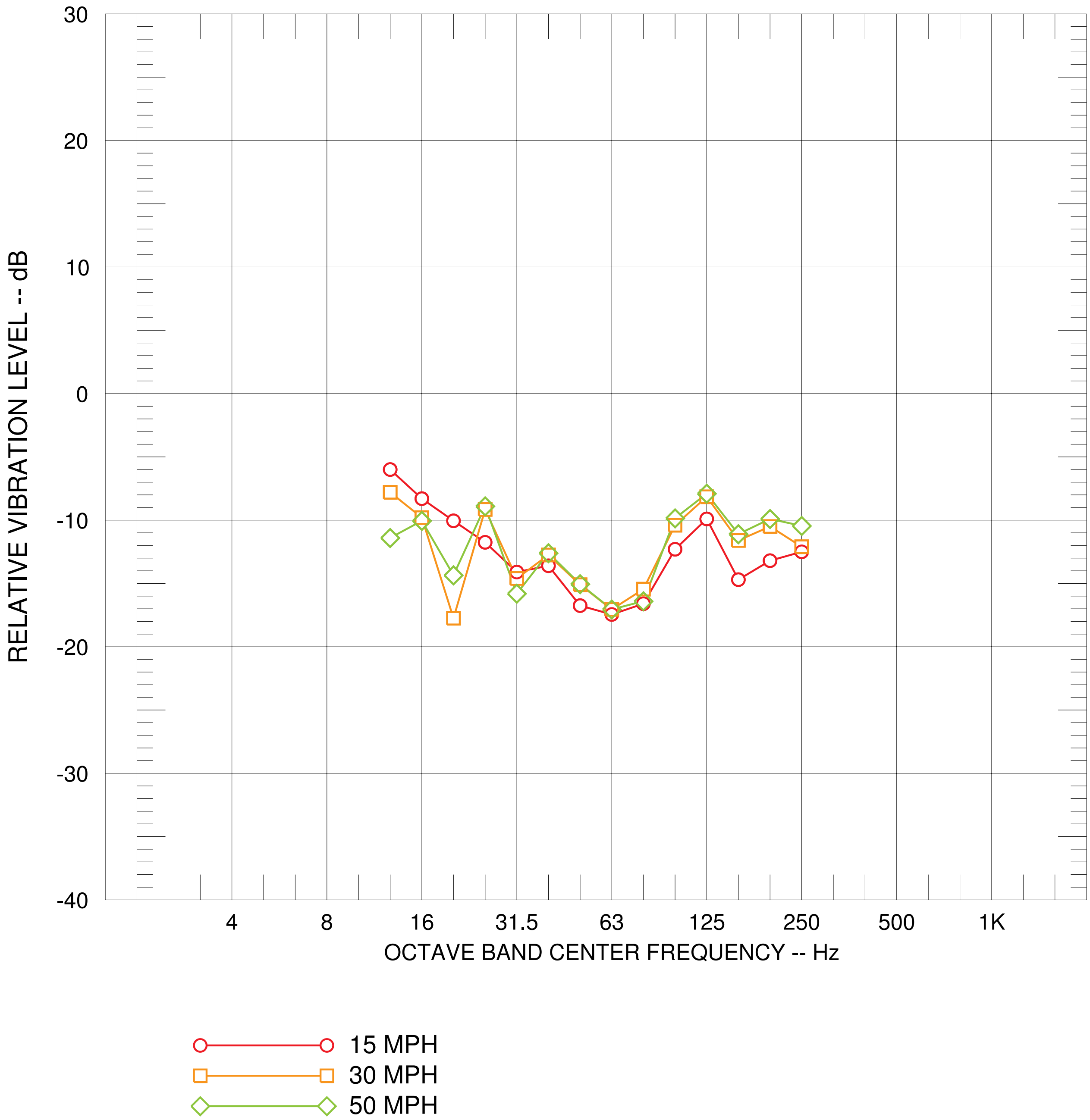

FIGURE 1 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN
TDA SITE #1 RE CONTROL SITE #1 - 25 FT FROM TRACK CENTERLINE
SPEED DEPENDENCY - 2005 TESTS

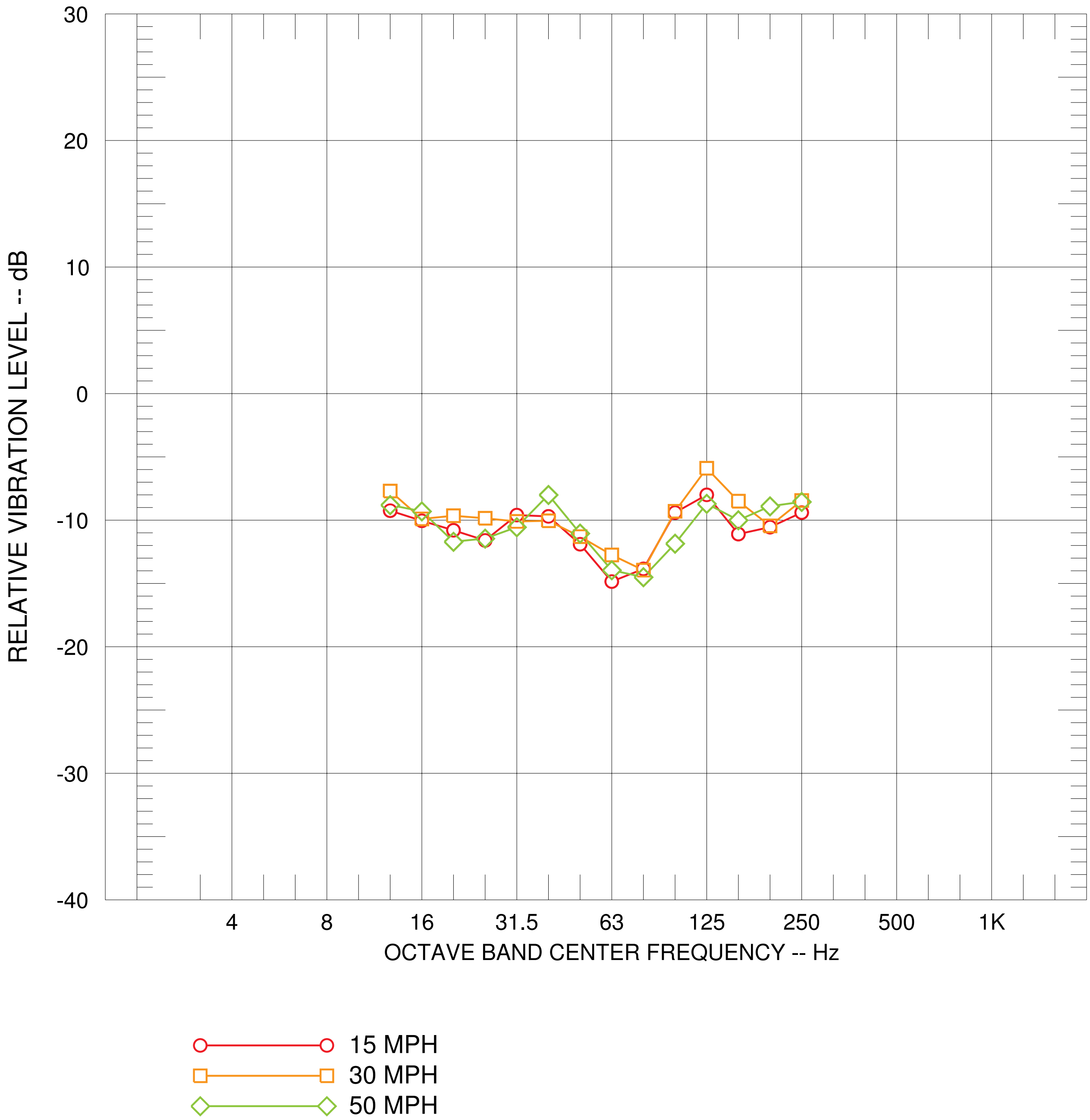

FIGURE 2 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN
TDA SITE #1 RE CONTROL SITE #1 - 25 FT FROM TRACK CENTERLINE
SPEED DEPENDENCY - 2006 TESTS

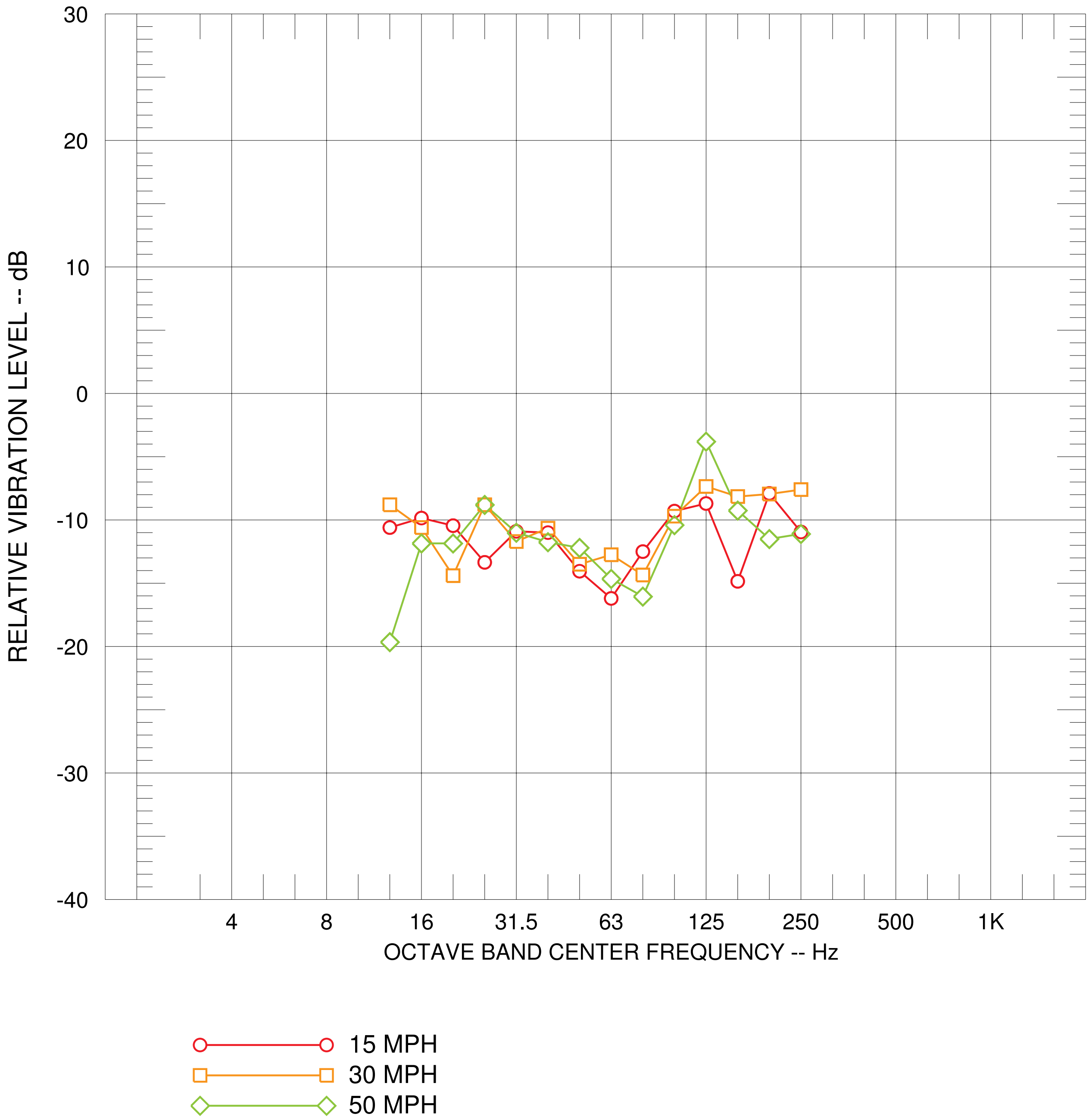

FIGURE 3 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN
TDA SITE #1 RE CONTROL SITE #1 - 25 FT FROM TRACK CENTERLINE
SPEED DEPENDENCY - 2009 TESTS

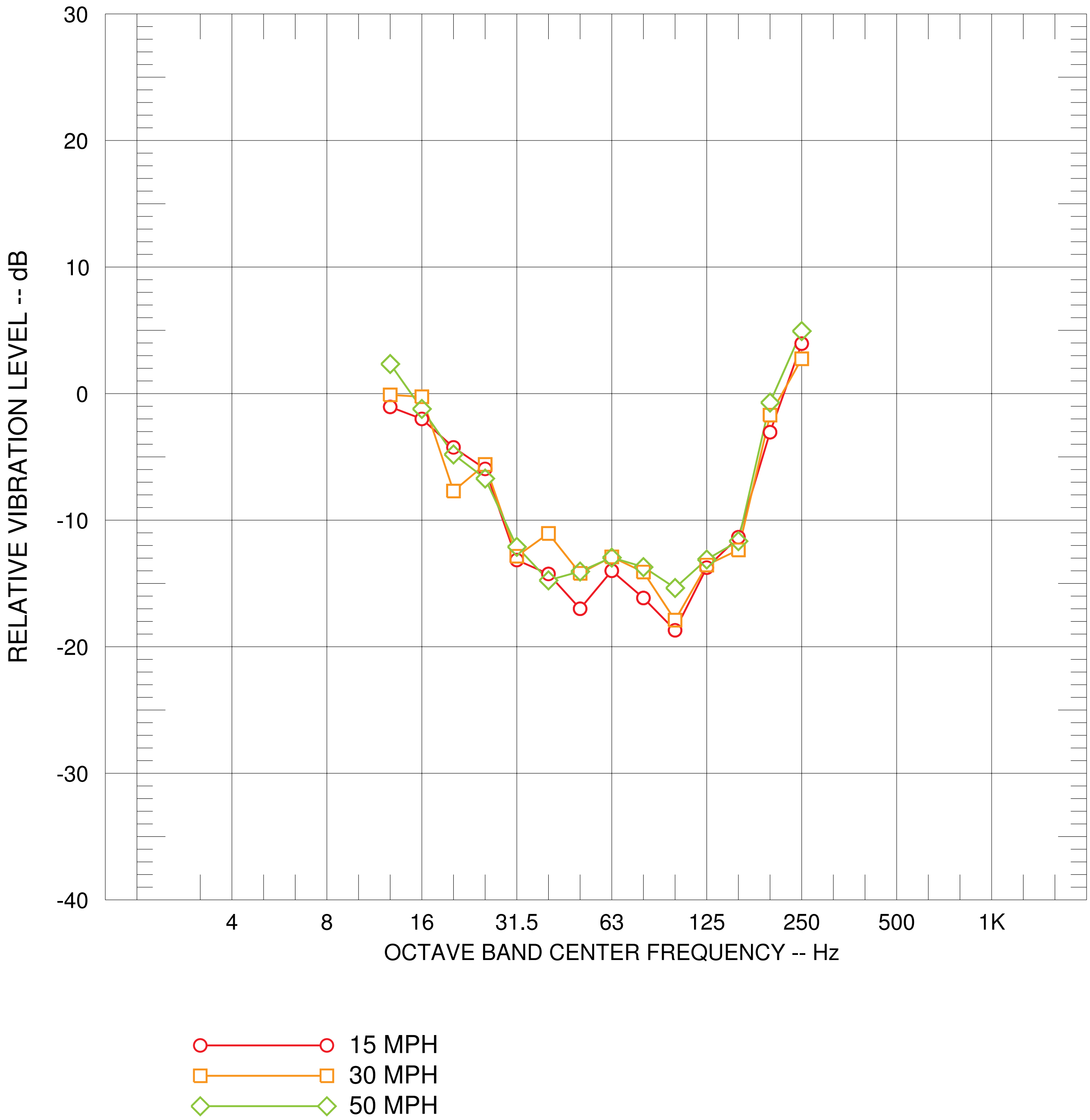

FIGURE 4 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN
TDA SITE #4 RE CONTROL SITE #2 - 50 FT W.OF TRACK CENTERLINE
SPEED DEPENDENCY - 2005 TESTS

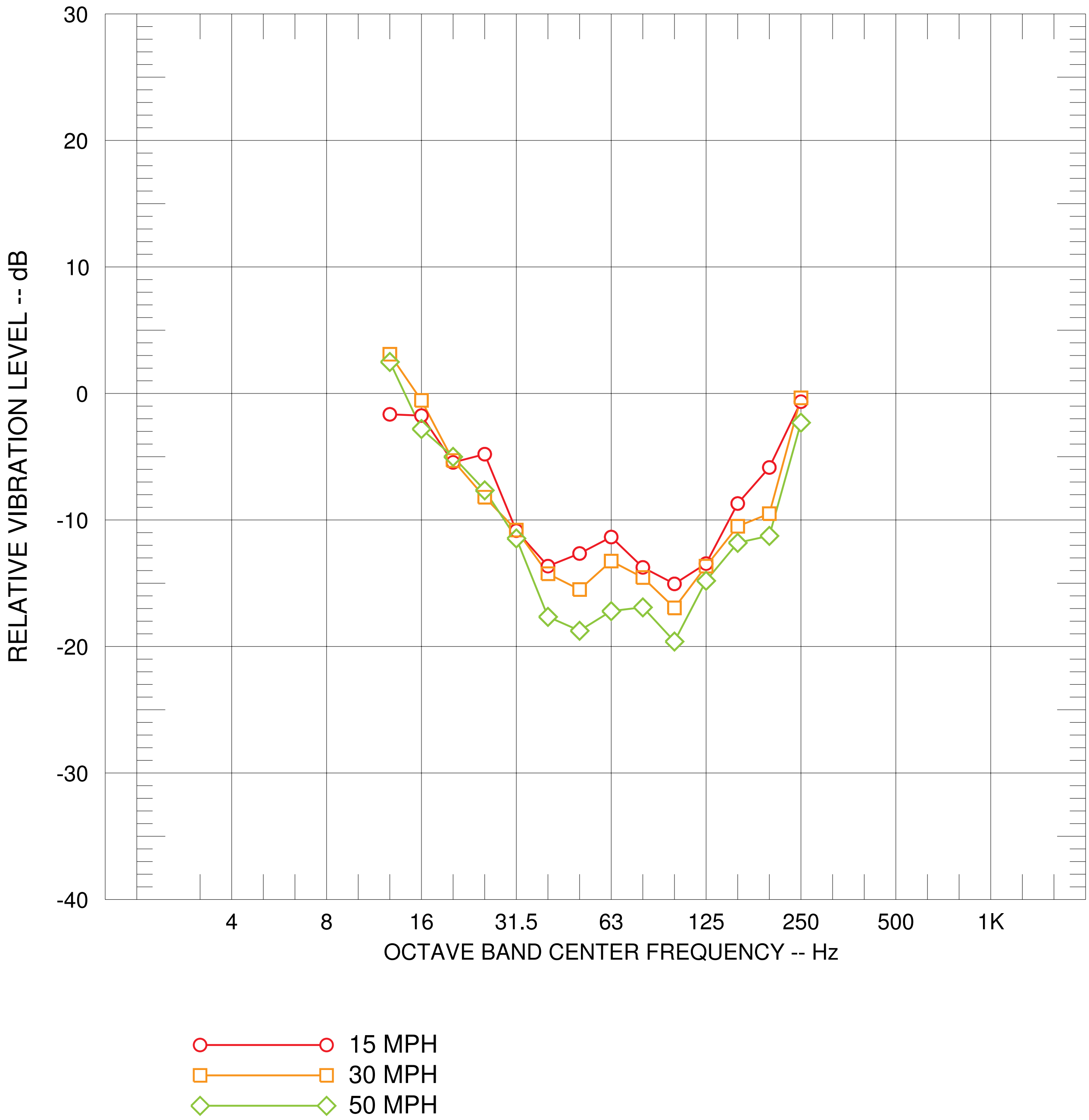

FIGURE 5 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN
TDA SITE #4 RE CONTROL SITE #2 - 50 FT W.OF TRACK CENTERLINE
SPEED DEPENDENCY - 2006 TESTS

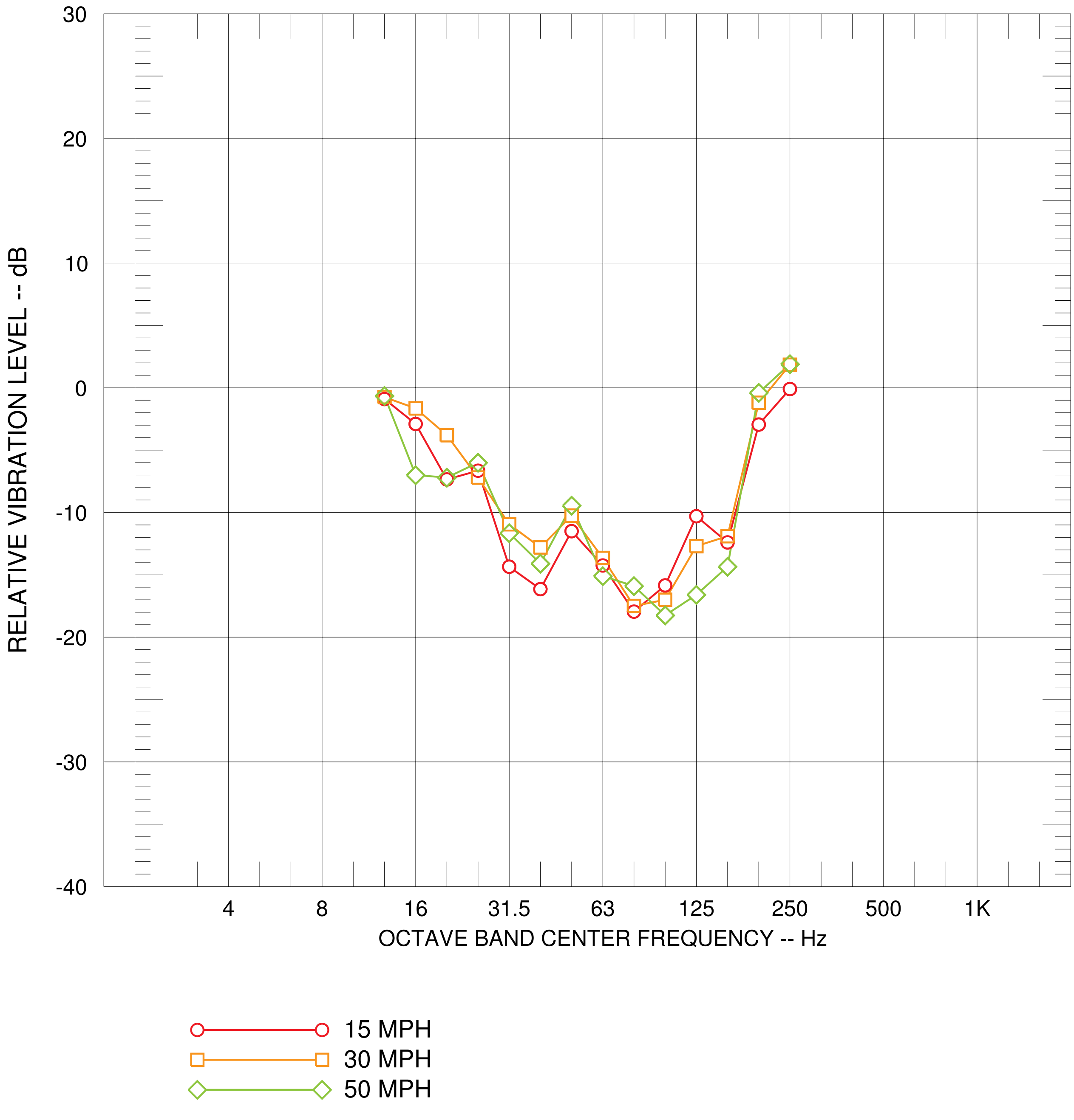

FIGURE 6 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN
TDA SITE #4 RE CONTROL SITE #2 - 50 FT W.OF TRACK CENTERLINE
SPEED DEPENDENCY - 2009 TESTS

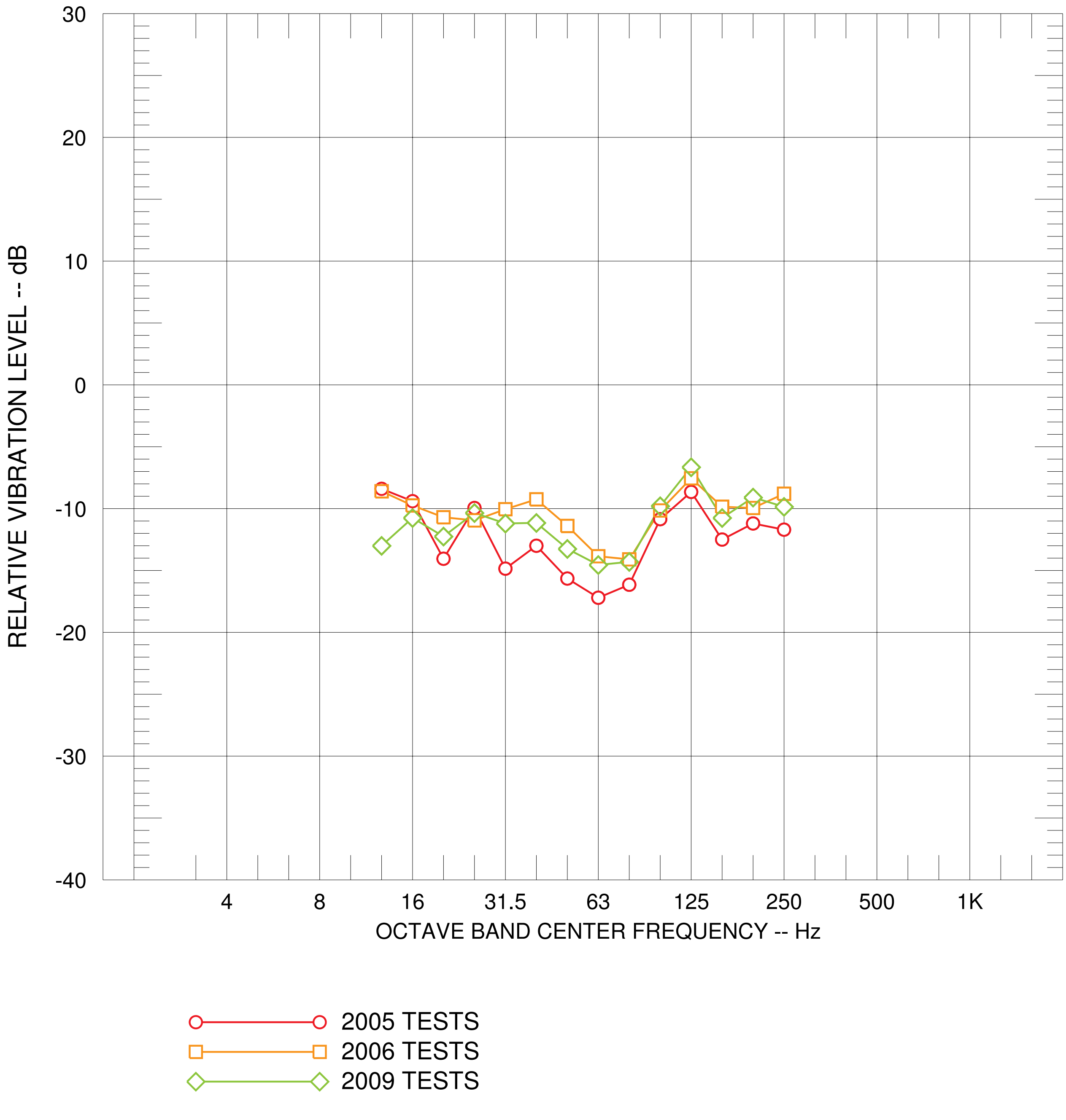

FIGURE 7 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN
TDA SITE #1 RE CONTROL SITE #1 - 25 FT FROM TRACK CENTERLINE

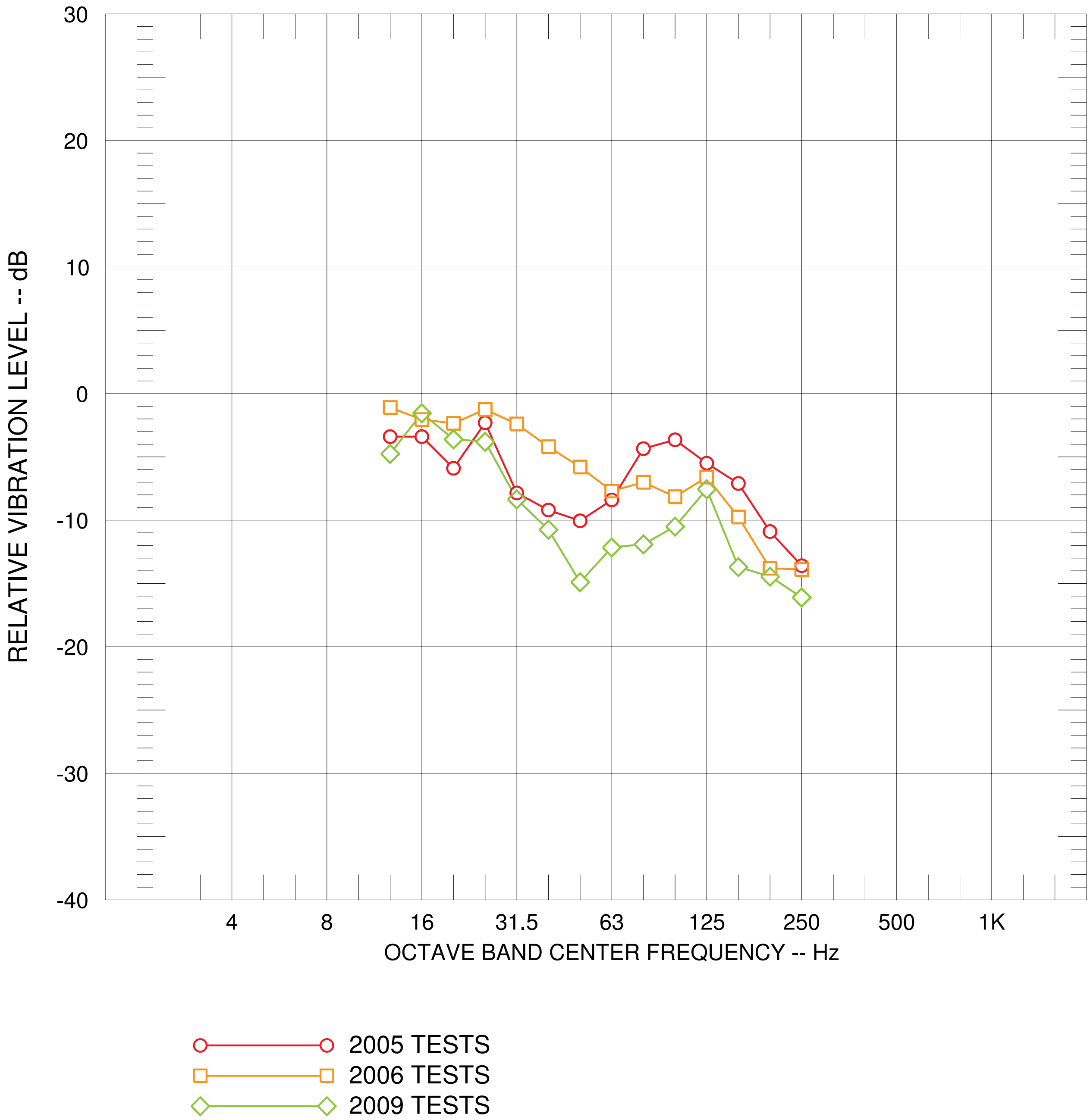

FIGURE 8 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN
TDA SITE #1 RE CONTROL SITE #2 - 25 FT FROM TRACK CENTERLINE

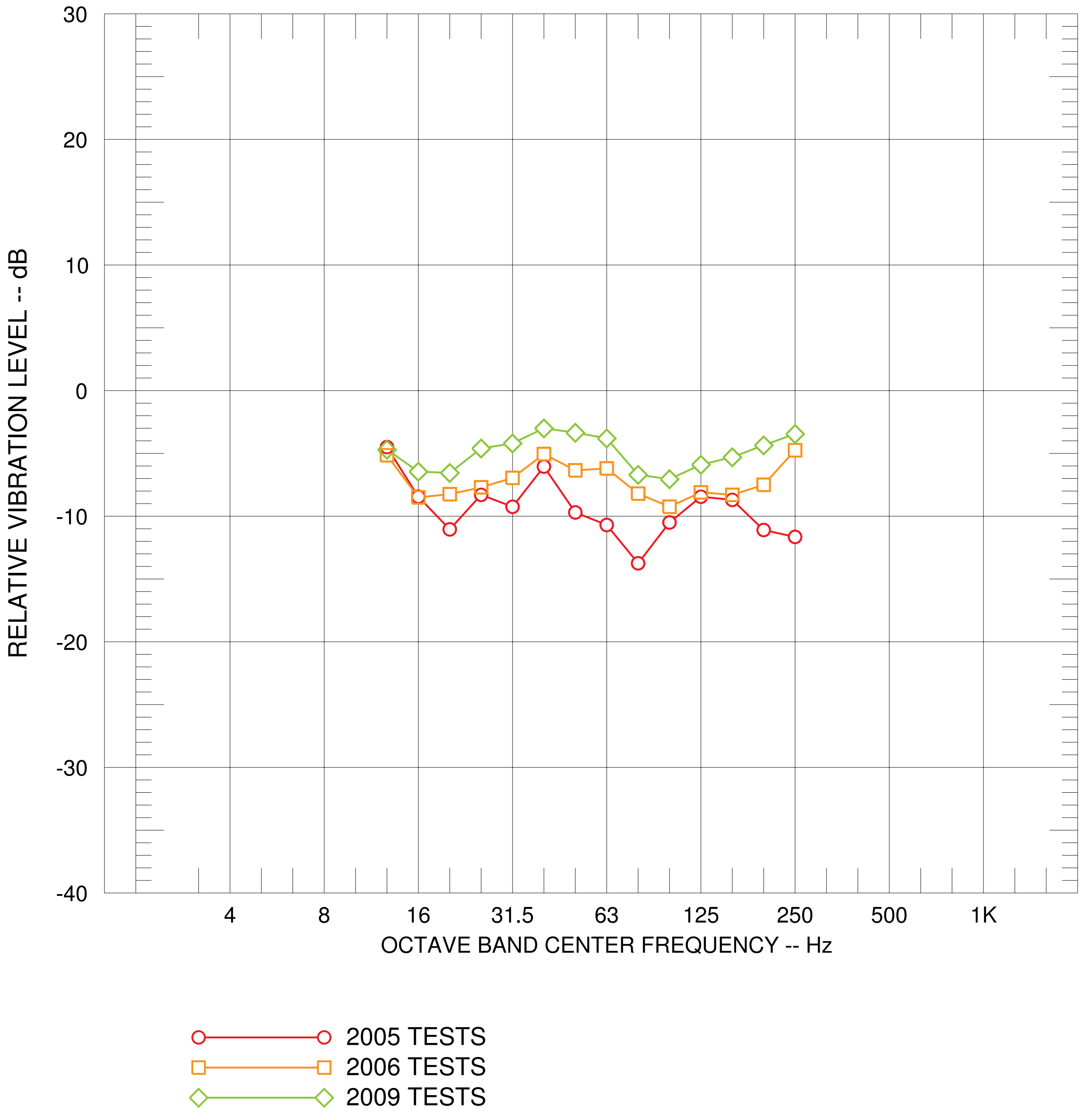

FIGURE 9 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN
TDA SITE #1 RE CONTROL SITE #1 - 50 FT FROM TRACK CENTERLINE

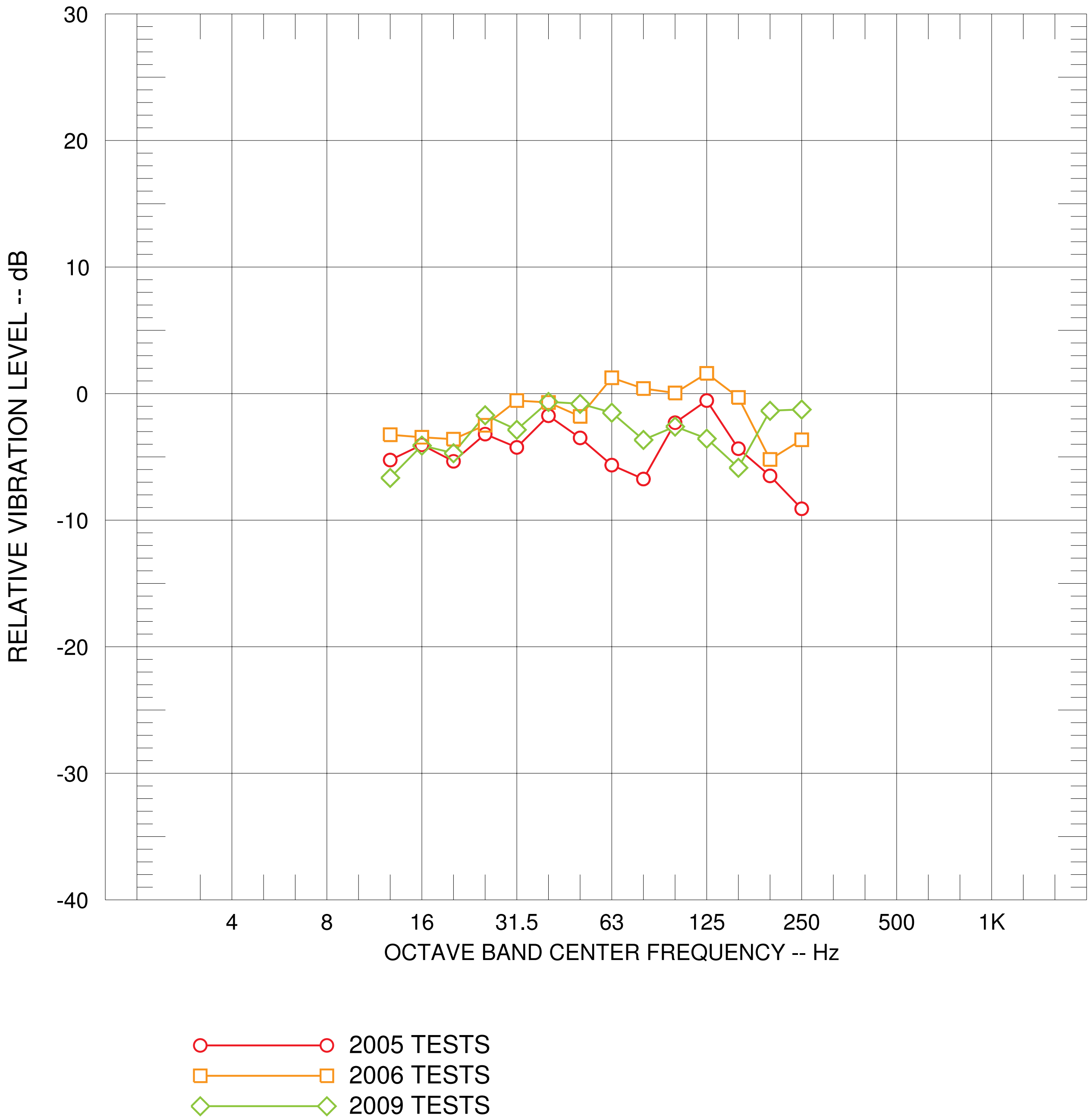

FIGURE 10 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN
TDA SITE #1 RE CONTROL SITE #2 - 50 FT FROM TRACK CENTERLINE

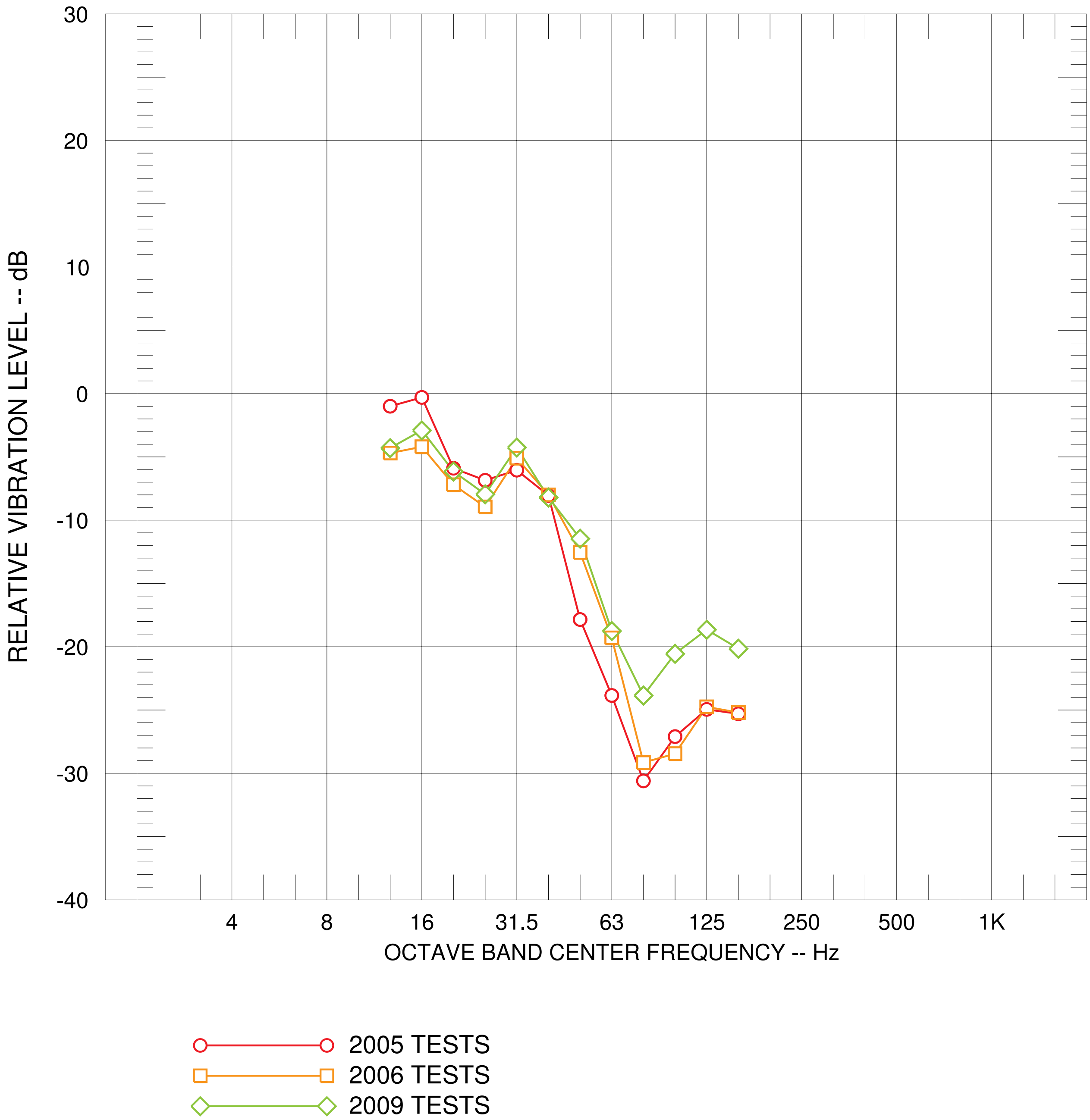

FIGURE 11 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN TDA SITE #3 RE CONTROL SITE #1 - 25 FT FROM SB TRACK CENTERLINE

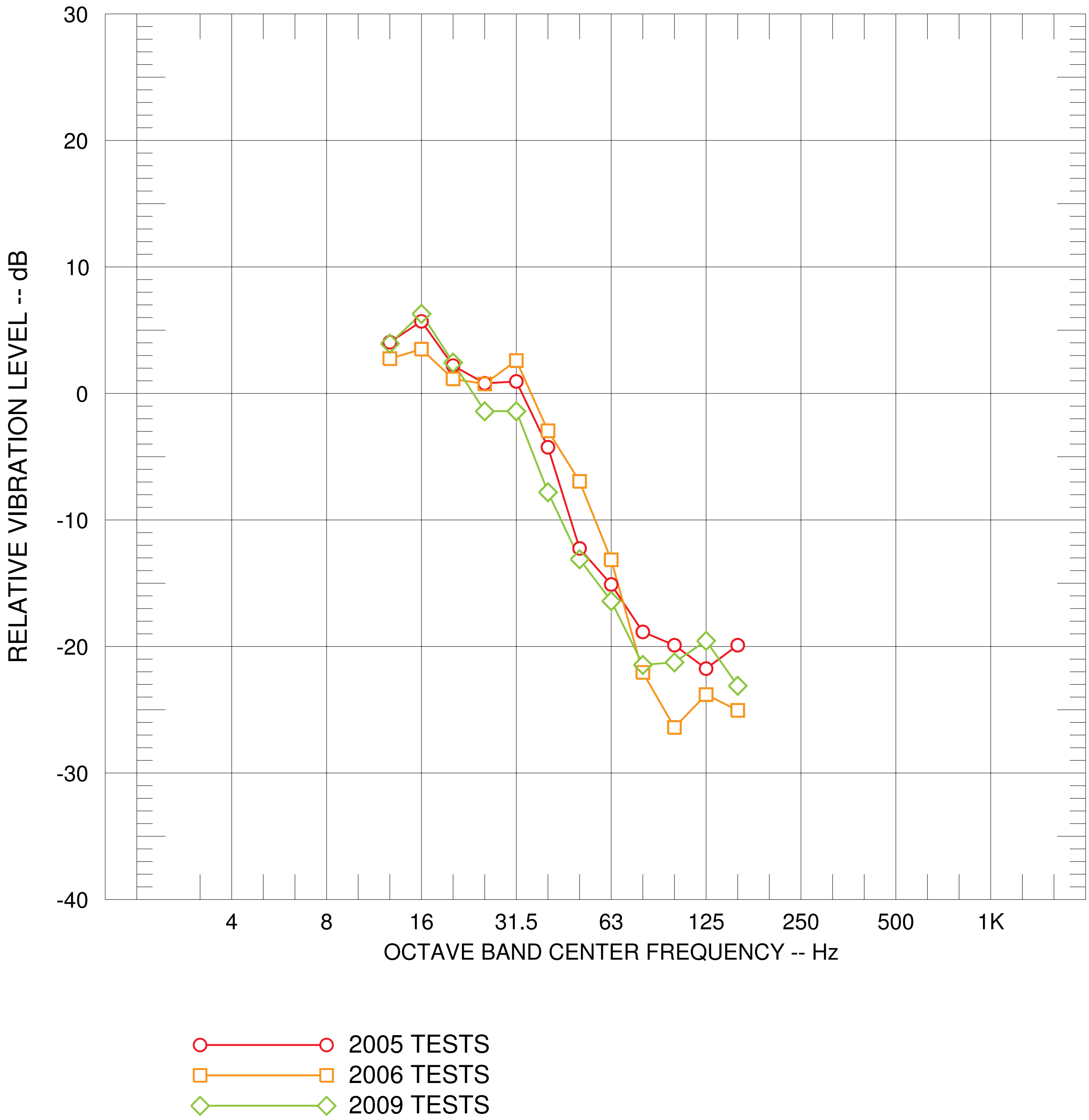

FIGURE 12 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN TDA SITE #3 RE CONTROL SITE #2 - 25 FT FROM SB TRACK CENTERLINE

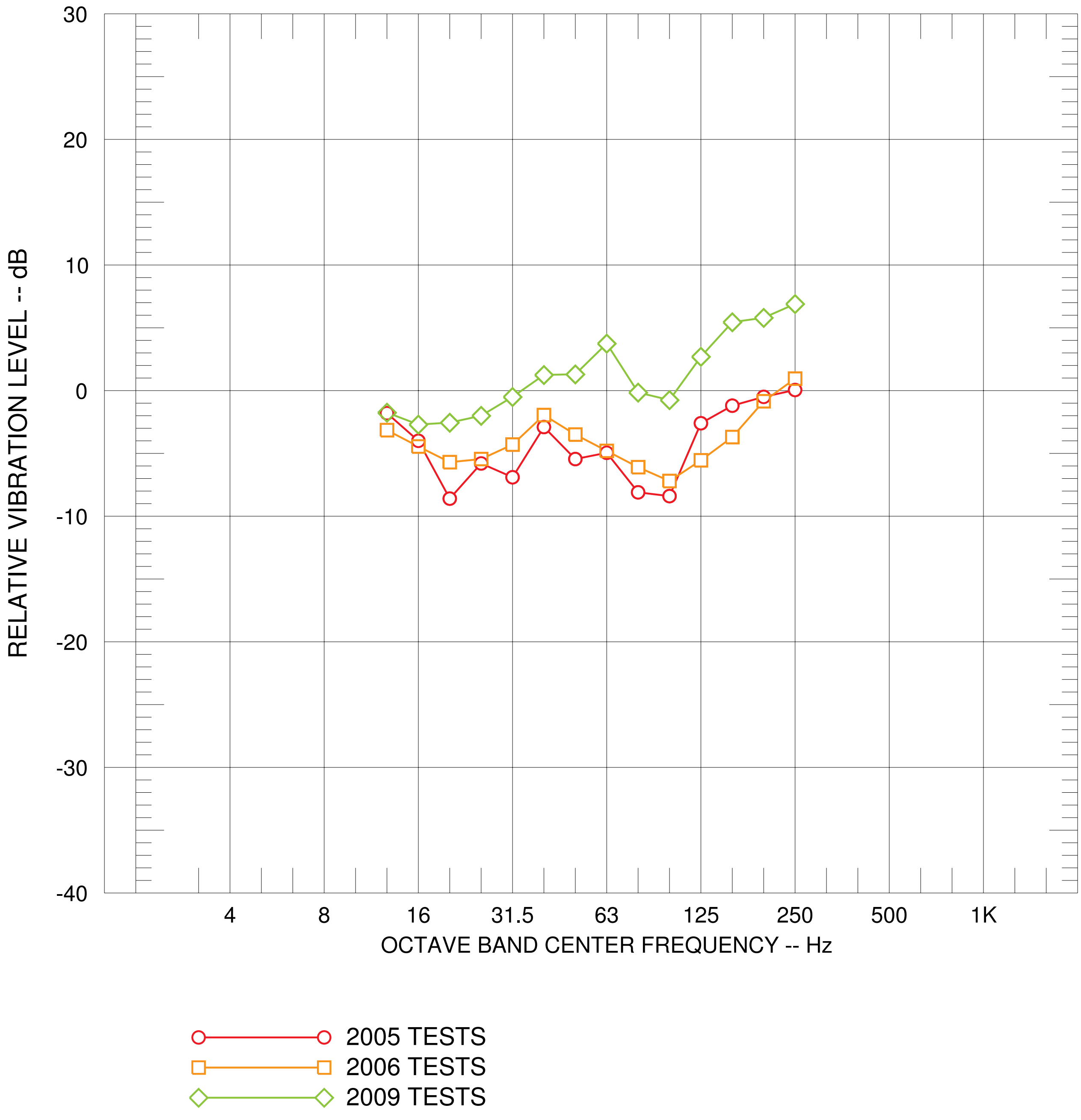

FIGURE 13 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN TDA SITE #3 RE CONTROL SITE #1 - 50 FT FROM SB TRACK CENTERLINE

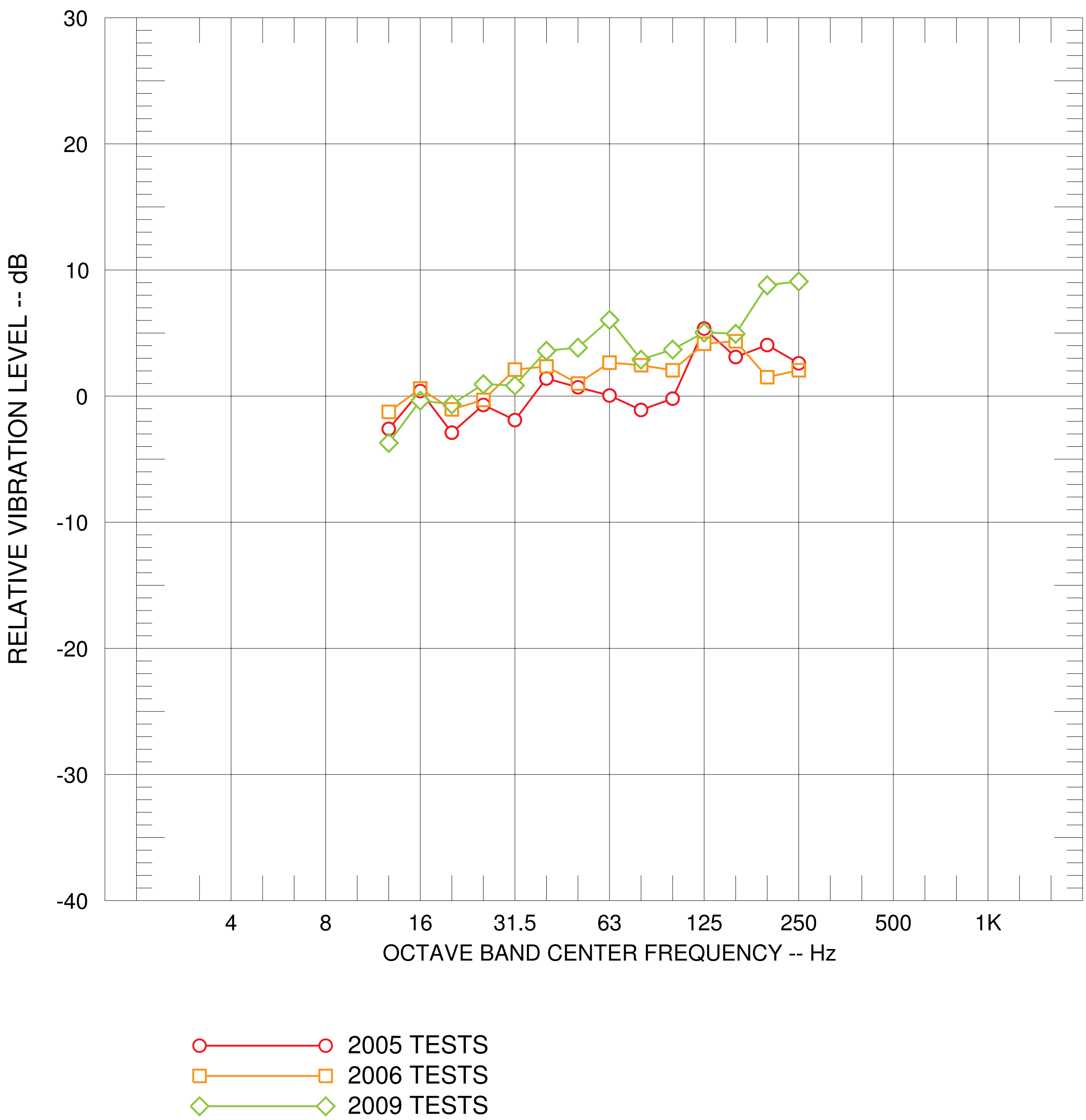

FIGURE 14 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN TDA SITE #3 RE CONTROL SITE #2 - 50 FT FROM SB TRACK CENTERLINE

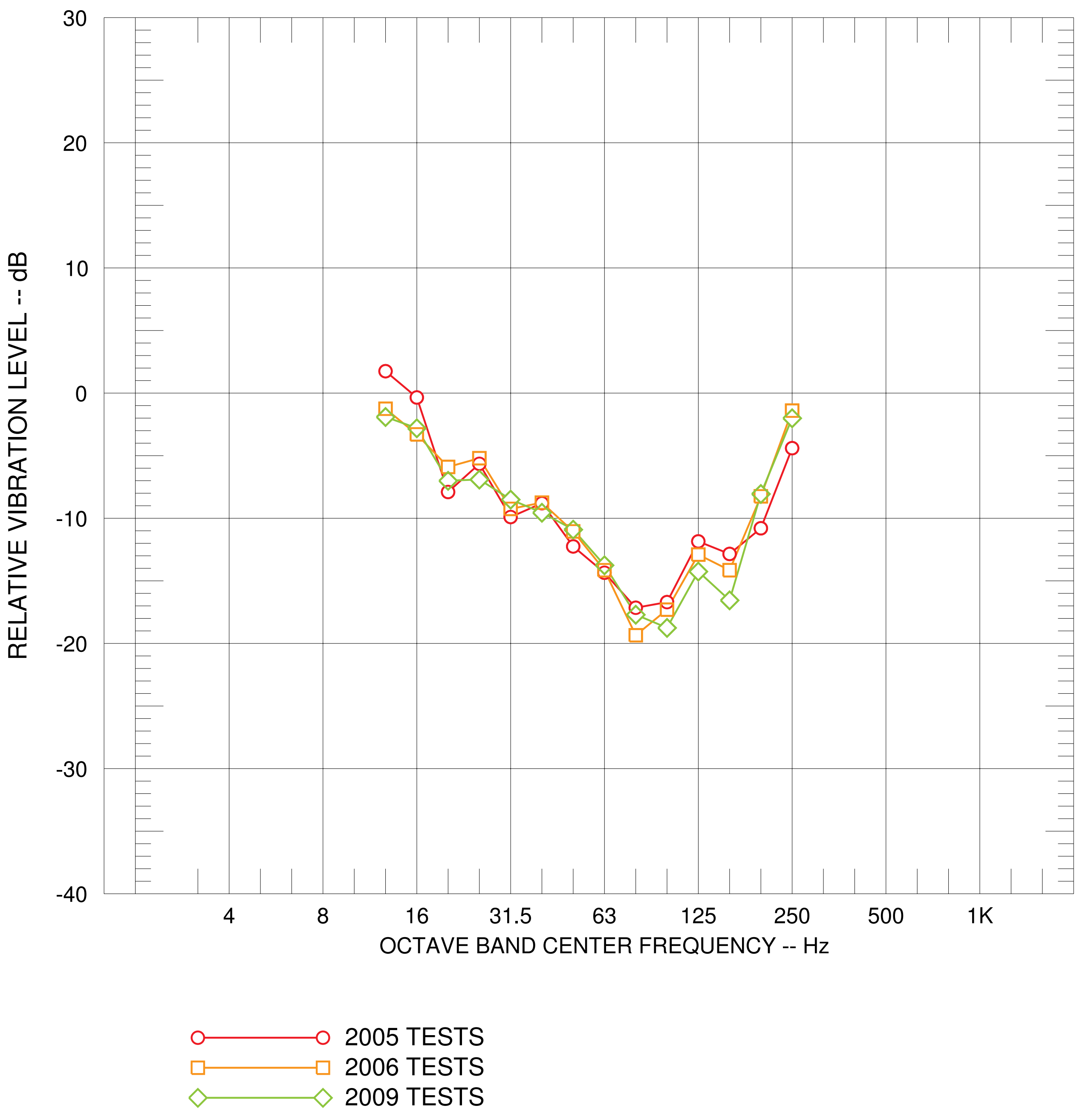

FIGURE 15 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN TDA SITE #4 RE CONTROL SITE #1 - 25 FT EAST OF TRACK CENTERLINE

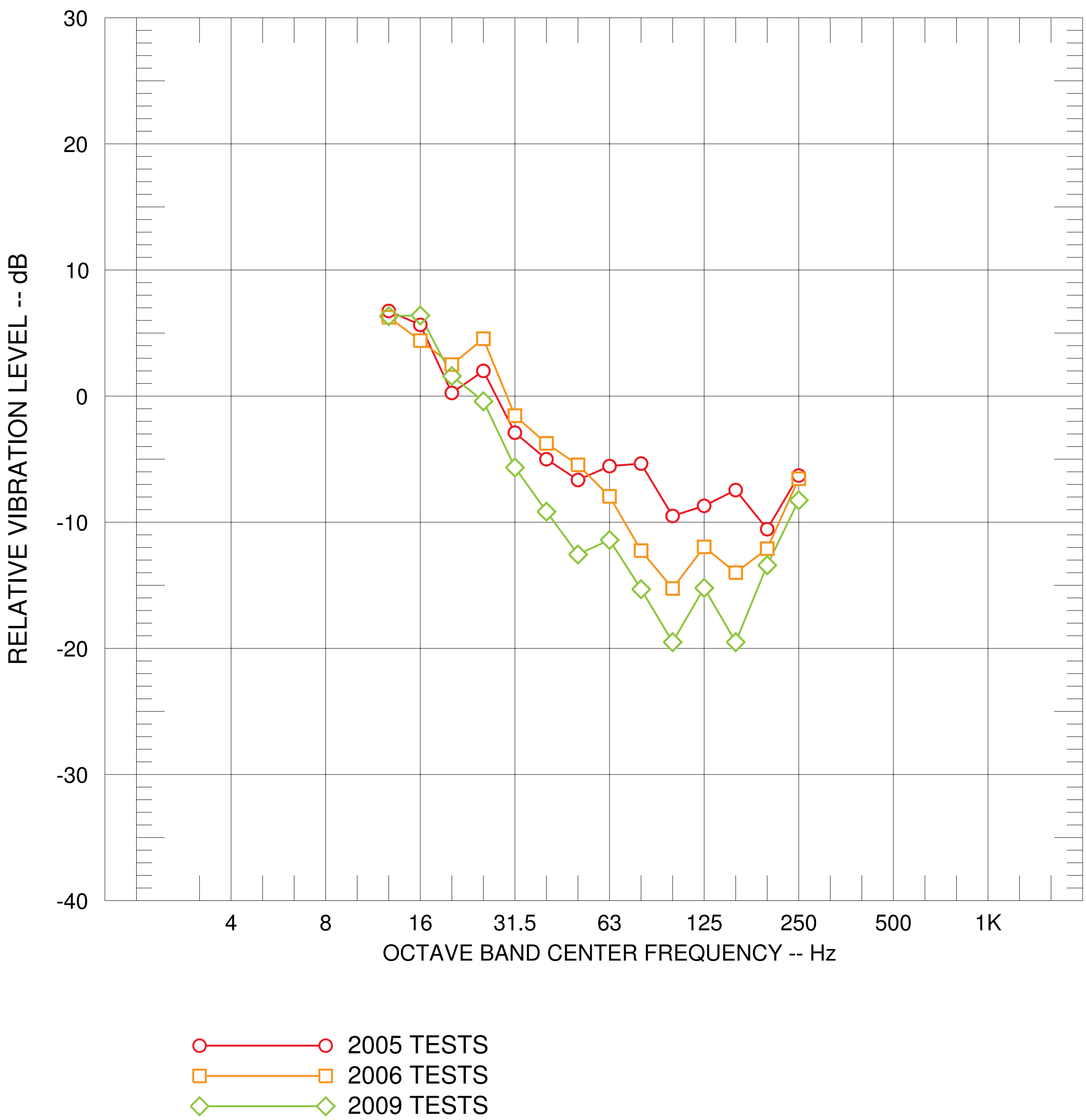

FIGURE 16 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN TDA SITE #4 RE CONTROL SITE #2 - 25 FT EAST OF TRACK CENTERLINE

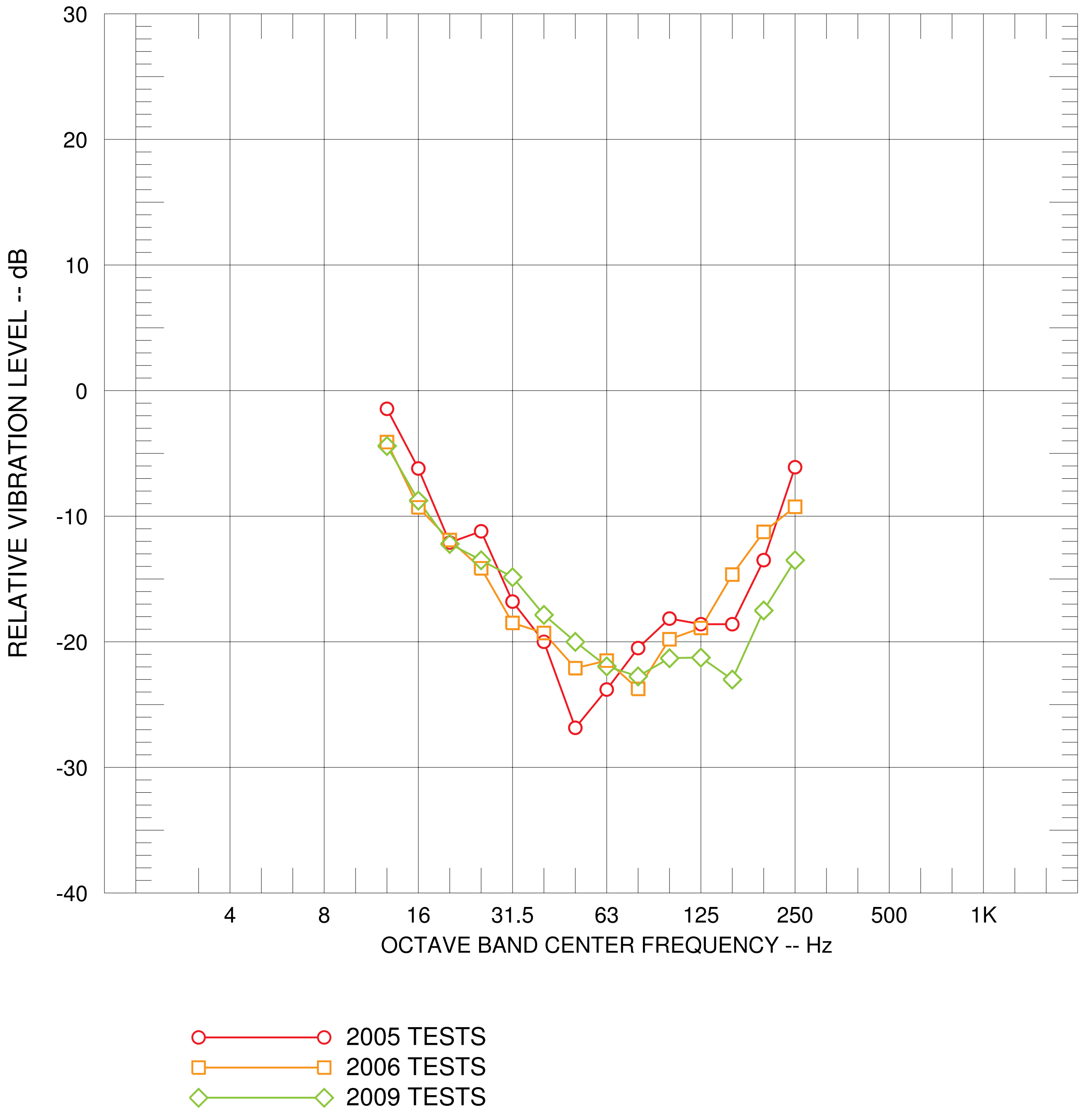

FIGURE 17 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN TDA SITE #4 RE CONTROL SITE #1 - 25 FT WEST OF TRACK CENTERLINE

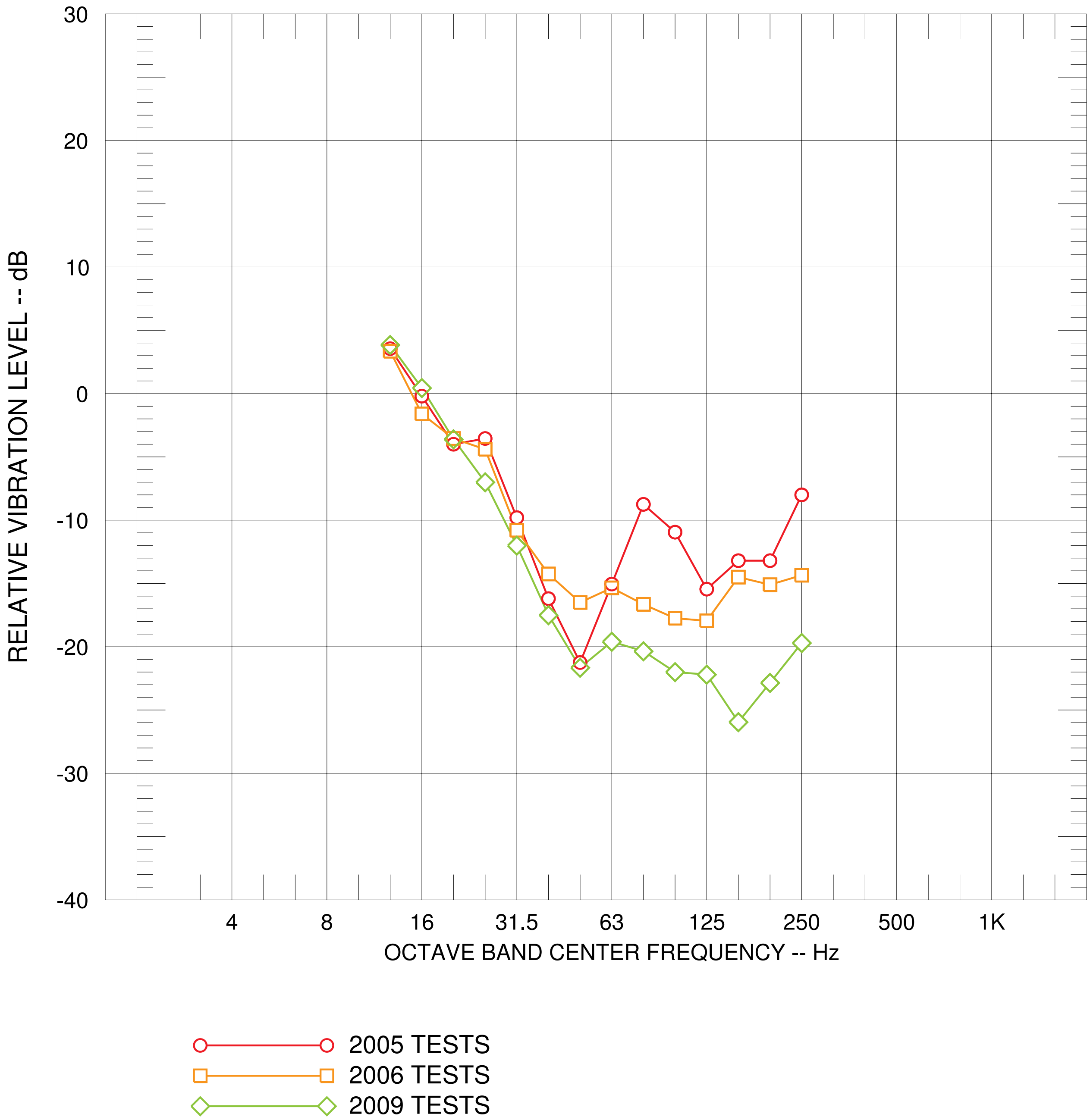

FIGURE 18 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN TDA SITE #4 RE CONTROL SITE #2 - 25 FT WEST OF TRACK CENTERLINE

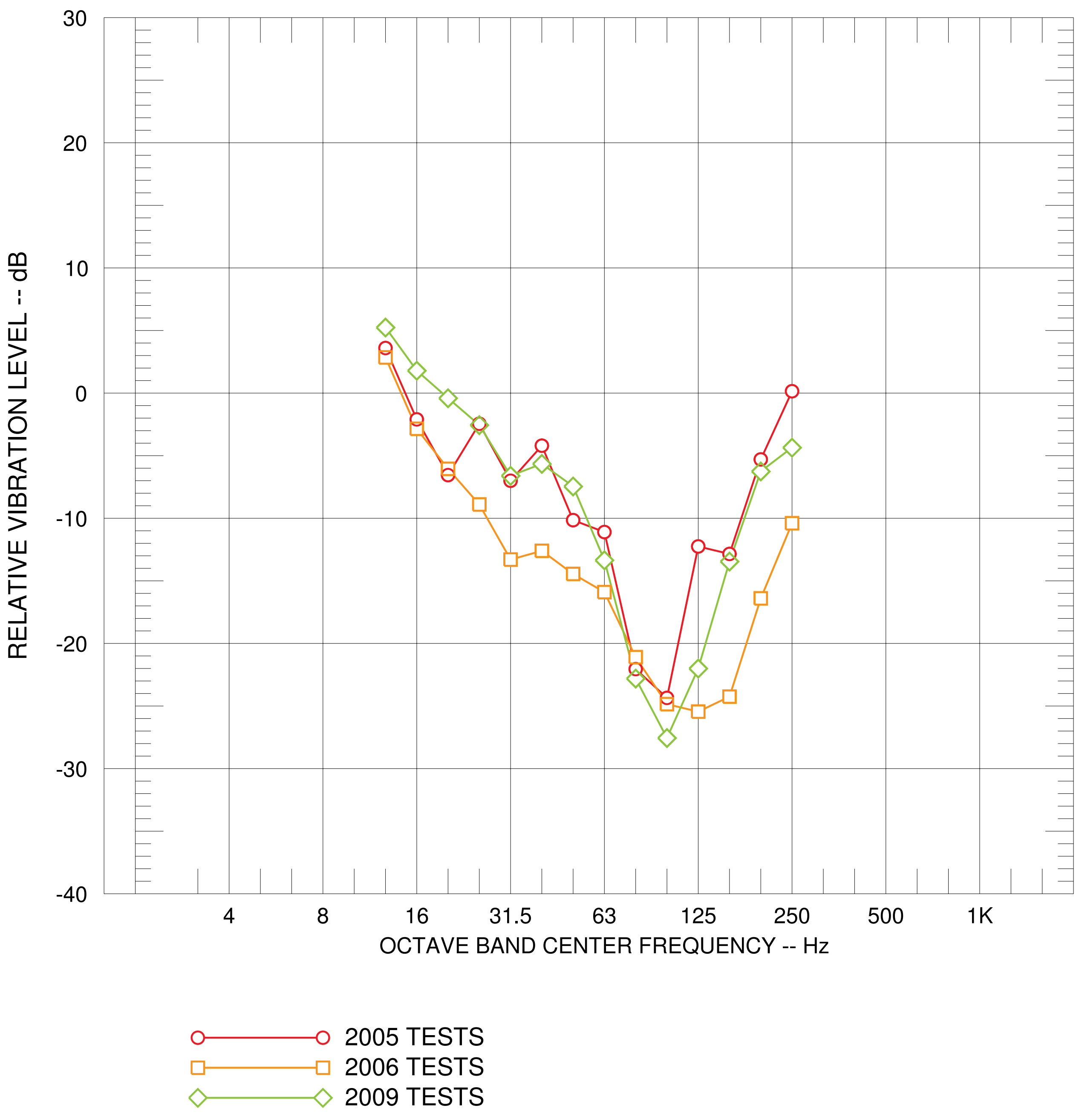

FIGURE 19 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN TDA SITE #4 RE CONTROL SITE #1 - 50 FT EAST OF TRACK CENTERLINE

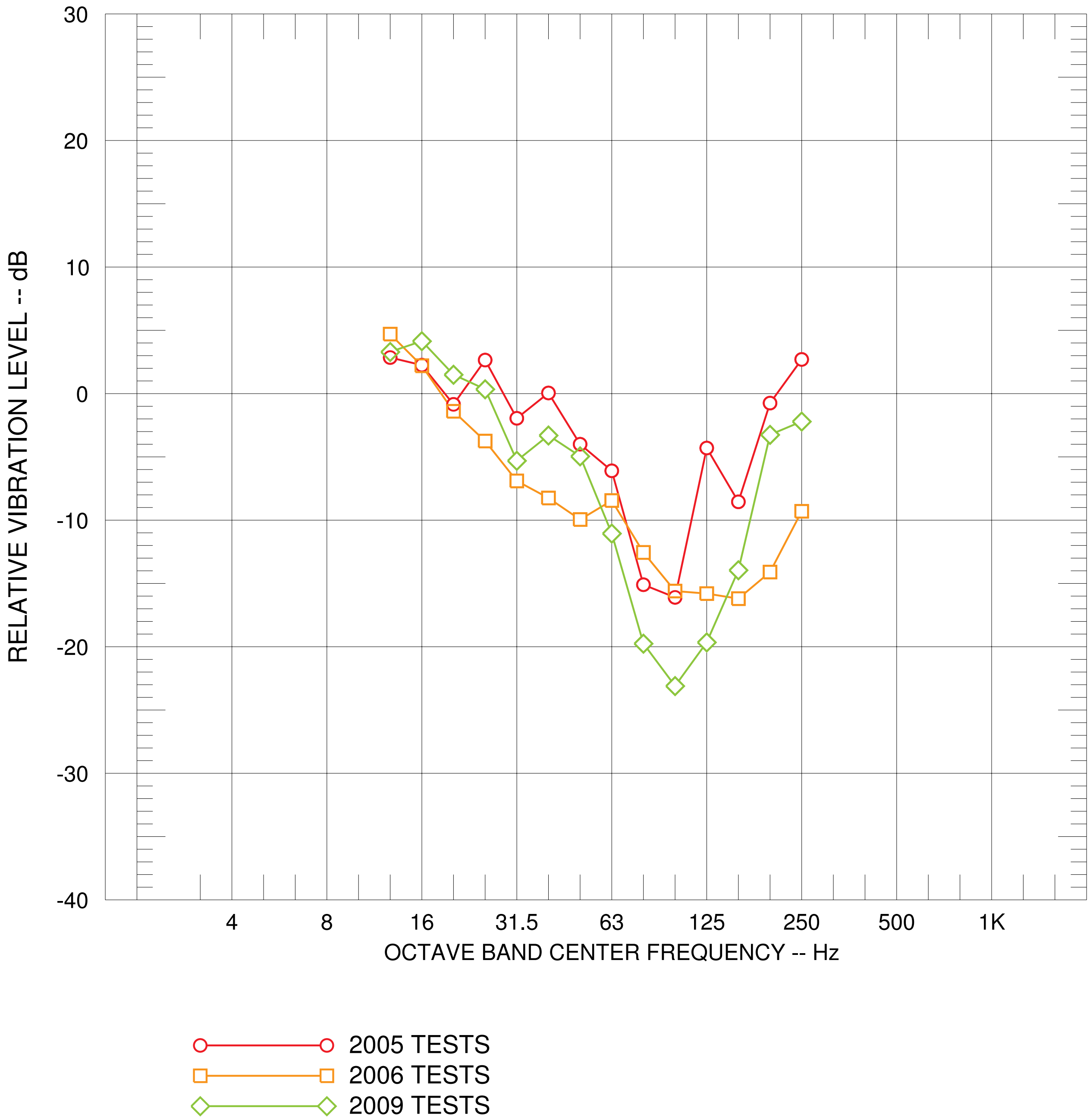

FIGURE 20 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN TDA SITE #4 RE CONTROL SITE #2 - 50 FT EAST OF TRACK CENTERLINE

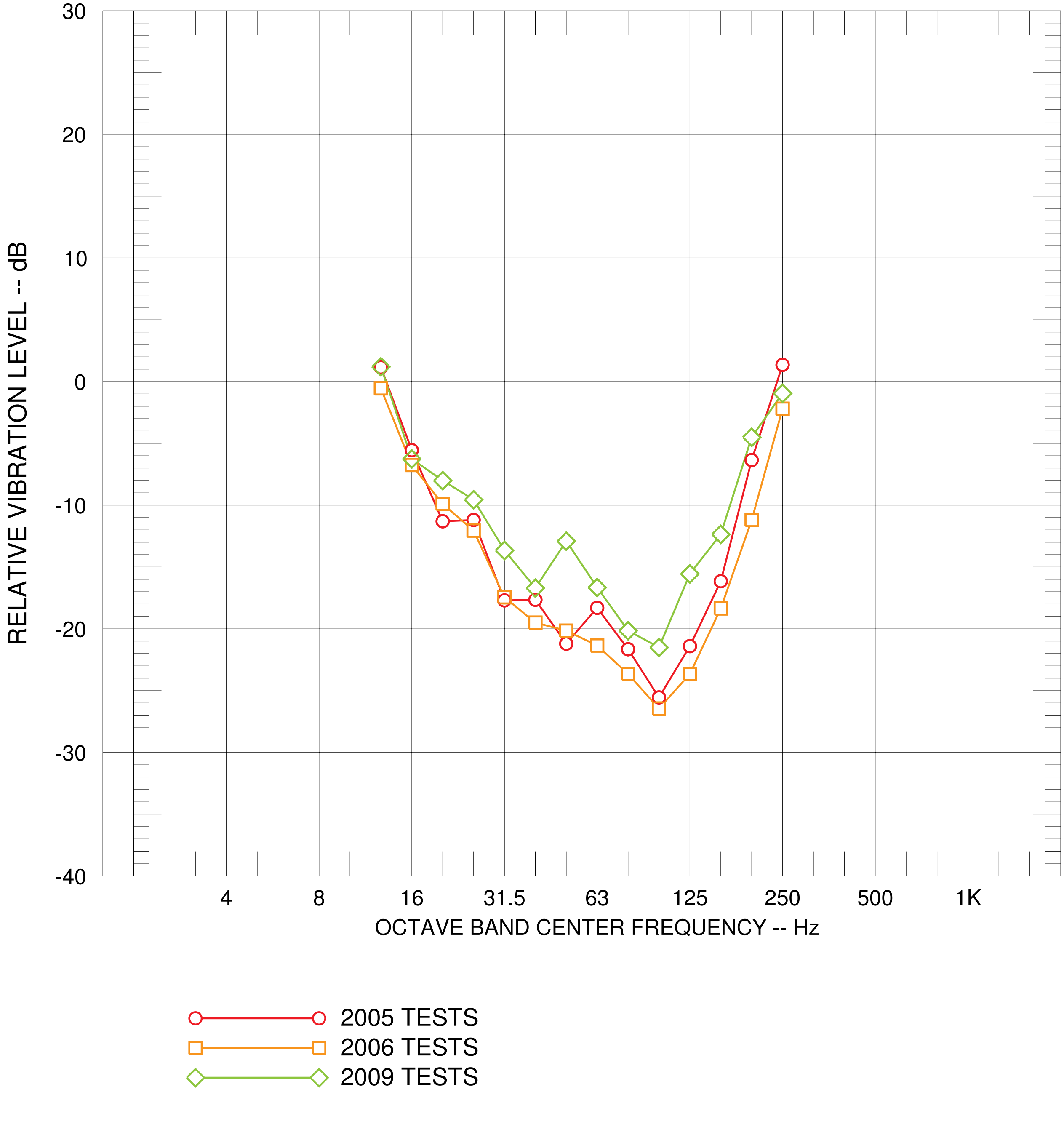

FIGURE 21 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN TDA SITE #4 RE CONTROL SITE #1 - 50 FT WEST OF TRACK CENTERLINE

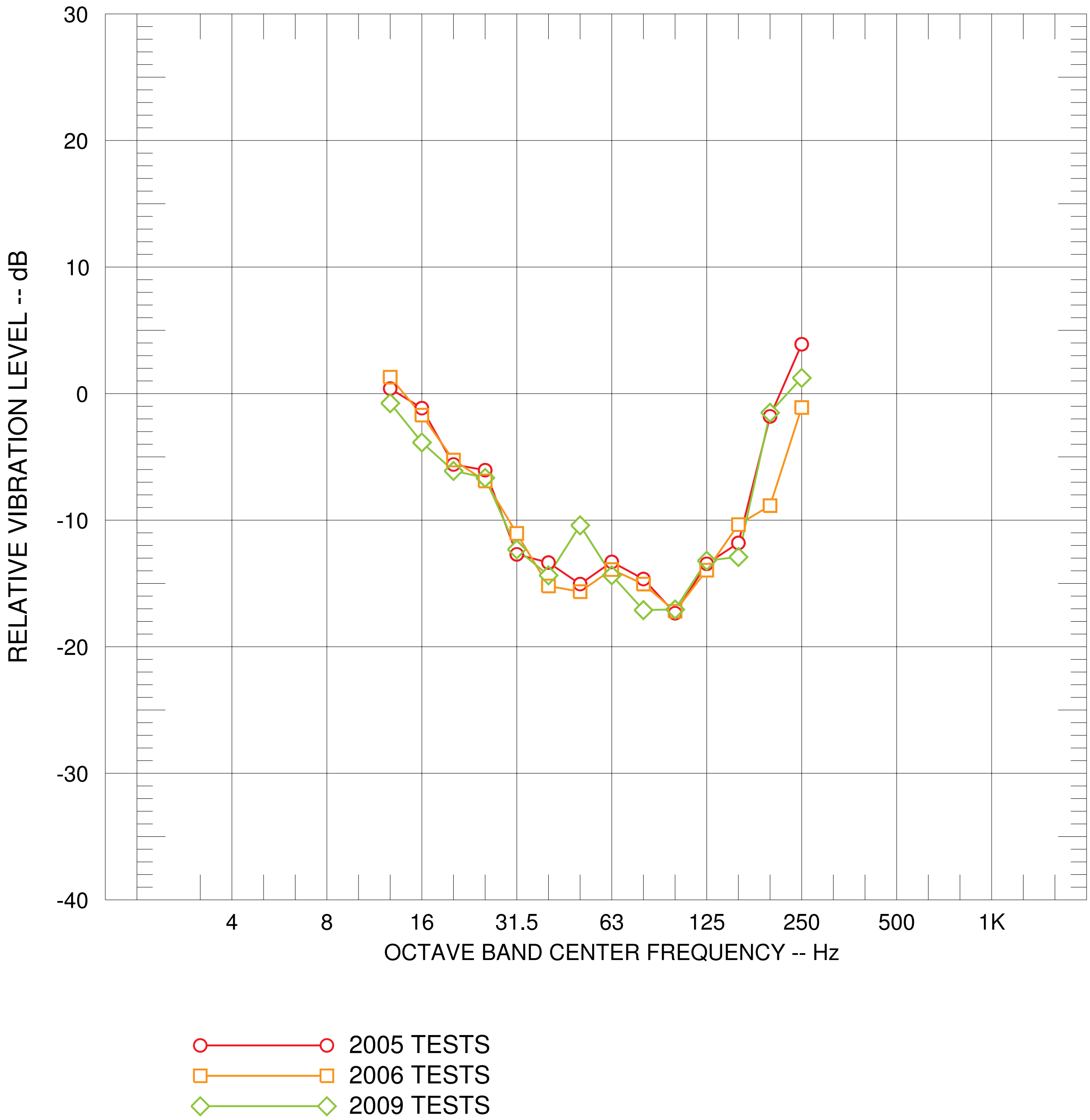

FIGURE 22 AVERAGE ATTENUATION OF TDA UNDERLAYMENT - TWO-CAR TEST TRAIN TDA SITE #4 RE CONTROL SITE #2 - 50 FT WEST OF TRACK CENTERLINE

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May 26, 2009

Chris Adams
HNTB Corporation
VTA FRR Office
1909 Milmont Drive
Milpitas, CA 95035

Subject: Peer Review of TDA Vibration Tests at VTA

Reference: HMMH Project No. 303580

Dear Mr. Adams:

This letter summarizes a peer review carried out by Harris Miller Miller & Hanson Inc. (HMMH) related to field tests recently conducted at the Santa Clara Valley Transportation Authority (VTA). The primary objective of the tests was to document the vibration reduction performance of TDA (tire derived aggregate, i.e. shredded tire) underlayments installed at several locations on the VTA Vasona Light Rail Transit (LRT) line. The tests were conducted by Wilson, Ihrig & Associates, Inc. (WIA) and their results were provided in a draft report dated May 2009 and titled "Evaluation of Tire Derived Aggregate as Installed Beneath Ballast and Tie Light Rail Track." Supplementary data on TDA vibration performance over time were also provided in a WIA letter report dated May 22, 2009.

VTA requested the peer review in response to concerns by the U.S. Federal Transit Administration (FTA) about the acceptability of TDA as a vibration mitigation treatment for rail transit projects. To assist VTA in addressing this issue, HMMH reviewed the WIA reports under subcontract to HNTB Corporation. Our peer review is presented below, including a summary of the WIA reports along with our evaluation, conclusions and recommendations.

SUMMARY OF WIA REPORTS

The WIA reports present the results of a third set of field tests performed in April 2009 to determine the vibration attenuating and damping properties of TDA as installed beneath ballast and tie rail transit track with continuous welded rail (CWR) and concrete ties on the VTA Vasona LRT line. The first series of tests was performed in March and May of 2005 and the second series of tests was performed in August 2006 using similar methodology for all of the tests. The objective of the third set of tests was to evaluate the performance of the TDA underlayment after approximately three and one-half years of revenue service operations.

Test data were obtained at three sites adjacent to sections with TDA underlayment and at two control sites with standard ballast and tie track, for comparison purposes. The TDA sections were underlain with 12 inches of Type A TDA (nominally 3 inch size shreds or chips wrapped with filter fabric) with 12 inches of sub-ballast above that and 12 inches of ballast above the sub-ballast to the base of the ties. The primary vibration source consisted of two articulated VTA Kinkisharyo low-floor light rail vehicles which operated at three speeds to assess the vibration attenuation of the installed TDA sections with respect to the control sections. At each tests site, ground surface vibration was measured using vibration velocity transducers at 6-8 positions typically located at distances of 25 or 50 feet from the track centerline. In addition to wayside ground-borne vibration data, rail strain, rail deflection and track elevation data were obtained with the assistance of other consultants.

The vibration reduction, or insertion loss, provided by the TDA underlayment was obtained by calculating the arithmetic difference between the vibration measured at appropriate distances at each of the TDA sites and the corresponding control section sites. Based on surface impact tests conducted during the 2005 test series, this method assumed that soil conditions are similar at all measurement locations with the exception of one position for which corrections were made. Due to the large number of data samples, most samples were averaged to allow manageable comparisons between the test and control section data, and a number of inconsistent samples were excluded in this process.

The 2009 results for the three TDA sites were found to be consistent with the results obtained in 2005 and 2006 but not all that consistent with each other, with attenuations varying by up to 10 dB or more from site to site. The report suggests that reasons for this variation include limited signal-to-noise ratio in the measurements at the low and high frequencies, flanking vibration transmission at one of the tests sections that is fairly short (130 feet) and site-specific vibration propagation characteristics. However, when the 2009 results for the three sites are averaged, the insertion loss was found to be similar to the 2005 and 2006 results with some slight variations in the range of 25 to 80 Hz due to more favorable results obtained at a fourth TDA site that was included only in the 2005 tests.

The overall conclusions of the WIA reports are that the TDA underlayment is effective at reducing ground-borne vibration at frequencies above 16 Hz, with performance superior to that of a ballast mat but inferior to that of a floating slab trackbed where reduction of very low frequency vibration is necessary. Furthermore, the report concludes that, based on a comparison of the 2009 test data with the data from 2005 and 2006, there have been no significant changes in vibration attenuation, rail strain, rail deflection and track elevation since the inception of revenue service operations.

EVALUATION

Overall, our review suggests that the TDA tests were conducted in a thorough and professional manner. Our primary concern is the wide variation in TDA vibration reduction performance results from site to site. While installation-specific differences in TDA performance cannot be entirely ruled out, it is more likely that, over the frequency range of most interest for this treatment (about 20 Hz to 160 Hz), these variations are primarily due to location-specific ground vibration propagation conditions that may not always be consistent with the results of the general surface impact tests conducted at each site. Despite these variations, however, the test results clearly show that the TDA underlayment provides significant vibration reduction at frequencies above 16 Hz. Furthermore, the data provided in the supplementary letter report do not indicate any deterioration of the performance of the TDA underlayment over time within the range of experimental accuracy.

CONCLUSIONS AND RECOMMENDATIONS

Based on our peer review, we believe that the results in the WIA reports support their conclusion that the TDA installations at VTA are effective in reducing ground-borne vibration. Furthermore, within the range of experimental accuracy, the test results do not indicate degradation of vibration reduction performance or significant changes in rail strain, rail deflection or track elevation after approximately three and one-half years of revenue service operations.

While the average TDA attenuations and design curve suggested by WIA seem reasonable, there is some uncertainty with regard to the actual vibration reduction performance of this treatment given the wide variation in the results from site to site. Thus, for future tests we would recommend more precise measurements at only the most optimal locations. These should include surface impact tests such that the site-specific corrections can be applied at every measurement position. We believe that this approach would yield more consistent results with fewer judgment calls required.

This completes our peer review. Please do not hesitate to contact me if you have any questions, comments or concerns.

Sincerely yours,

HARRIS MILLER MILLER & HANSON INC.

David A. Towers

David A. Towers, P.E.

Principal Engineer

hmmh