6. MITIGATION OPTIONS

6.1 TRAIN NOISE

Because no noise impacts from train operations are predicted no mitigation is required.

6.2 AUDIBLE WARNINGS

Because no noise impacts from audible warnings (bells and horns) are predicted no mitigation is required.

6.3 TRANSIT POWER SUBSTATIONS

Noise impacts are predicted for sensitive receiver near potential TPSS site A-1,. Noise impacts at A-1 can be eliminated by specifying a noise limit of 44 dBA at 50 ft from any part of this TPSS units.

6.4 TRAIN VIBRATION

A number of different approaches have been used by rail transit systems to reduce the levels of groundborne vibration. These measures range from very simple approaches such as stiffening the floors at the receivers to the very expensive such as placing the entire track system on a concrete slab that is supported by springs (a floating slab) or constructing a building so that the entire building is supported by rubber or coil springs. The most common vibration mitigation measures used on light rail systems consist of placing some sort of resilient layer between the track and the soil. Some approaches for installing standard vibration mitigation measures with embedded track are:

- **High-resilience boot:** A common embedded track system is to place the rails in a rubber “boot”, position the rails, and then pour concrete around the boot. The rubber boot provides electrical isolation of the rails and provides enough resilience that movement of the rail during operations and movement resulting from thermal expansion and contraction does not cause the concrete to crack. In the standard configuration, the rail boot results in a fairly stiff track system. It is sometimes feasible to reduce the track stiffness by using a thicker and softer material for the boot. However, it is unlikely that a softer boot would provide sufficient vibration isolation except for segments where the predicted vibration levels exceed the impact threshold only at frequencies of 60 Hz and higher. Alternative approaches to increase the resilience of embedded track include using poured materials (e.g., Icoset) and the equivalent of booted track using three separate pieces to enclose the track instead of a single “boot”.
- **Resilient direct fixation track fasteners:** Direct fixation track fasteners are used to attach rails directly to a concrete slab. They are standard on the subways and aerial structures of most modern rail transit systems. The stiffness of a standard direct

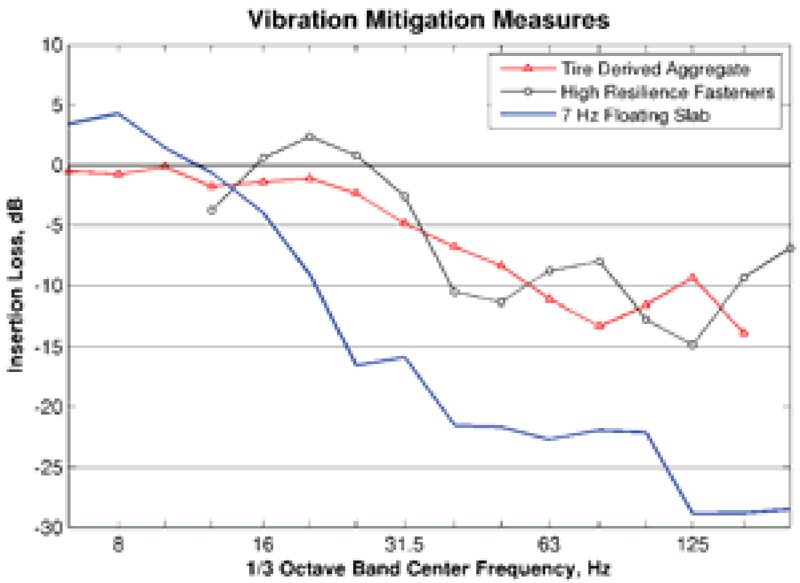
fixation track fastener is around 150k lb/in. Reducing the stiffness to around 110k lb/in will increase the cost by a small amount. Going to a high-resilience direct fixation track fastener (stiffness less than 60k lb/in) will cost approximately twice as much as a standard direct fixation fastener. To use high-resilience direct fixation fasteners with embedded track, the track would be constructed on top of a concrete slab and then concrete panels would be placed between and next to the rails. The design is similar to a typical rail/roadway grade crossing.

- **Ballast mat:** Ballast mats are designed to be placed under ballast and tie track. However, some embedded track designs have used ballast mat under a concrete slab as a vibration mitigation measure. In essence, the ballast mat is used to create a floating slab. This approach has the advantage of putting a continuous layer under the concrete slab, which reduces the potential for litter and other fouling material to get under the slab and short circuit the vibration isolation provided by the resilient layer.
- **Tire Derived Aggregate (shredded tires):** This approach consists of building the track on top of a layer of tire derived aggregate (TDA). This is an innovative approach for recycling old automobile tires. Although this approach has not been used for embedded track, it has been successfully used by light rail systems in Denver and San Jose to reduce vibration from sections of ballast and tie track. A 12 inch layer of TDA was used for both the Denver and San Jose installations and all indications are that those designs are functioning as intended.
- **Floating slab track:** A floating slab consists of a concrete slab supported by elastomer or steel-coil springs. For embedded track the rails would be embedded in the spring-supported slab using the same basic design as use for standard embedded track. The frequency range at which a floating slab is effective depends on the thickness of the slab and the stiffness of the springs. Most North American floating slab systems use rubber pads that are 12 to 18 inches in diameters supporting a concrete slab that is 12 to 24 inches thick. Floating slabs are very effective at reducing vibration levels; however, they are also very expensive.
- **Alternative approaches:** A number of alternative approaches have been proposed that may have applicability under specific circumstances. One example is underground barriers, something that several different Japanese rail systems have investigated recently. The basic concept is to use variations of an open trench or, when the propagation is through soft soils, a solid wall. Other examples include increasing the thickness of the concrete under the track, specifying straighter rail, and, when the track will traverse sections of very soft soil, building the track on top of pile systems.

Figure 30 shows the measured vibration attenuation of a tire derived aggregate system in San Jose and high resilience fasteners in Boston. One factor to note is that these systems all have the potential to amplify vibration at frequencies near their resonance frequency. This could be an issue if floating slabs are used to attenuate vibration for an embedded track section that will carry both street traffic and light rail vehicles. If vehicular traffic will be operating on the same guideway as the light rail vehicles, the floating slab would be likely to amplify the vibration from vehicular traffic. This is because vibration from buses, trucks and other pneumatic tire vehicles tends to peak in the 10 to 20 Hz range.

FIGURE 30: PERFORMANCE OF DIFFERENT VIBRATION MITIGATION MEASURES

The figure shows the floating slab attenuation curve is the average of several measurements. The curves for TDA and high resilience fasteners are based on measurements in San Jose (TDA) and Boston (high-resilience fasteners).



The predicted vibration impacts are either the second floor rooms of motels or mobile home parks with mobile homes located very close to Main Street. For all of the vibration impacts, the predicted levels exceed the applicable impact threshold by less than 2 decibels. The recommended strategies to minimize vibration impacts include:

- Second Floor Rooms of Motels: The motels appear to be relatively lightweight construction, which means that the floors of second floor rooms are likely to be relatively flexible. The recommended approach for vibration mitigation is to stiffen the floors of any second floor motel rooms where vibration impact is predicted. Stiffening floors will reduce the amplification caused by floor resonances. The same procedures used to stiffen bouncy floors or sagging floors can be used to reduce the amplification of groundborne vibration. One approach for stiffening floors is “sistering” of the floor joists by nailing new lumber to the sides of the existing floor joists. Another approach is to add a lally column under the middle of the floor span. Because it is not clear which of the second floor rooms will amplify the groundborne vibration, it is reasonable to wait until light rail vehicles are operating on the Central

Mesa LRT Extension before making a final decision on which floors need to be stiffened.

- Mobile Home Parks: For the mobile home parks, vibration impacts can be eliminated by ensuring that the mobile homes are at least 60 feet away from the centerline of the near track.

The details of the recommended vibration mitigation strategies are summarized in Table 24. The specific mitigation measures to be implemented will be determined in the Final EA.

TABLE 24: SUMMARY OF VIBRATION MITIGATION

Clusters	Location	Closest Cross Streets	Side of Track[a]	# of Impacted Units[b]	Recommended Mitigation[c]
FTA Category 2 Land Uses					
2	American Executive Inn	Longmore and Brooks	WB	1	Stiffen the floor of the affected unit[c]
6	Motel Rawls	Standage and Stewart	WB	3	Stiffen the floors of the affected units[c]
8	Mesa Gardens Mobile Home Park	Beverly and Extension	WB	1	Move the mobile home to 60 ft from the closest track.
12	Apache West Mobile Village	Beverly and Extension	EB	1	Move the mobile home to 60 ft from the closest track.
16A	Mesa Royale Trailer Park	Extension and Date	WB	1	Move the mobile home to 60 ft from the closest track.
16B	Motel 6	Extension and Date	WB	2	Stiffen the floors of the affected units[c]

Notes:
a. Side of the tracks indicates the track for which mitigation is recommended. WB = Westbound tracks, EB = Eastbound tracks.
b. # of impacted units is a count of number of dwelling units that would be impacted by train vibration before mitigation. For example, if impacts are predicted at American Executive Inn then the units that are within the impact distance from the tracks and where people sleep are counted. Rooms that are farther from the tracks are unlikely to be affected by vibration and are not included in the count.
c. Because the predictions are designed to be conservative (on the high side) and because the predicted levels exceed the applicable FTA impact threshold by a small amount, it is likely that the actual vibration levels will be lower than predicted. A reasonable approach for the motel rooms is to wait until the light rail vehicles are operating before taking steps to stiffen the floors of the units where impact is predicted.

6.5 CONSTRUCTION NOISE

Listed below are some typical approaches to reducing noise levels associated with the construction phase of major projects. Requiring the contractor to employ these methods should leave the contractor with enough flexibility to perform the work without undue financial or logistical burdens while protecting adjacent noise sensitive receptors from excessive construction noise levels.

- Avoid nighttime construction unless a variance is issued by the City. This is a requirement of the Mesa noise ordinance.

- Use specialty equipment with enclosed engines and/or high-performance mufflers.
- Locate equipment and staging areas as far from noise-sensitive receptors as possible.
- Limit unnecessary idling of equipment.
- Install temporary noise barriers. This approach can be particularly effective for stationary noise sources such as compressors and generators.
- Reroute construction related truck traffic away from local residential streets.
- Avoid impact pile driving where possible. Where geological conditions permit, the use of drilled piles or a vibratory pile driver is generally quieter.

Specific measures to be employed to mitigate construction noise impacts would be developed by the contractor and presented in the form of a Noise Control Plan.

6.6 CONSTRUCTION VIBRATION

Construction related vibration activities are unlikely to exceed the impact thresholds shown in Table 23. However, the following precautionary vibration mitigation strategies are recommended to minimize the potential for damage to any structures in the corridor:

1. Pre-Construction Survey: The survey should include inspection of building foundations and taking photographs of pre-existing conditions. The survey can be limited to the first row of buildings along Main Street. The only exception is if an important and potentially fragile historic resource is located within approximately 200 ft of Main Street, in which case it should be included in the survey.
2. Vibration Limits: The FTA guidance manual (Ref. 1) suggests vibration limits in terms of peak particle velocity (PPV) ranging from 0.12 in/sec for “buildings extremely susceptible to vibration damage” to 0.5 in/sec for “Reinforced-concrete, steel or timber” buildings. The contract specifications should limit construction vibration to a maximum of 0.5 in/sec for all buildings in the corridor. Should the pre-construction survey identify any buildings that are particularly sensitive to vibration, the vibration limit at these structures should be limited to 0.12 in/sec.
3. Vibration Monitoring: The contractor should be required to monitor vibration at any buildings where the lower vibration limit is applicable and at any location where complaints about vibration are received from building occupants.
4. Alternative Construction Procedures: If high-vibration construction activities would be performed close to structures, it may be necessary for the contractor to use an alternative procedure that produces lower vibration levels. Examples include the use of vibratory compaction or hoerams next to sensitive buildings.

Alternative procedures include use of non-vibratory compaction in limited areas and a concrete saw in place of a hoeram to breakup pavement.

7. REFERENCES

1. Federal Transit Administration Office of Planning and Environment (FTA0. 2006. Transit Noise and Vibration Impact Assessment. Document FTA-VA-90-1003-06, May 2006.

APPENDIX A: FUNDAMENTALS OF NOISE AND VIBRATION

A.1 NOISE FUNDAMENTALS

Sound is mechanical energy transmitted by pressure waves in a compressible medium such as air. Noise is generally defined as unwanted or excessive sound. Sound can vary in intensity by over one million times within the range of human hearing. Therefore, a logarithmic scale, known as the decibel scale (dB), is used to quantify sound intensity and compress the scale to a more convenient range.

Sound is characterized by both its amplitude and frequency (or pitch). The human ear does not hear all frequencies equally. In particular, the ear deemphasizes low and very high frequencies. To better approximate the sensitivity of human hearing, the A-weighted decibel scale has been developed. A-weighted decibels are abbreviated as "dBA". On this scale, the human range of hearing extends from approximately 3 dBA to around 140 dBA. As a point of reference, Figure A-1 includes examples of A-weighted sound levels from common indoor and outdoor sounds.

Using the decibel scale, sound levels from two or more sources cannot be directly added together to determine the overall sound level. Rather, the combination of two sounds at the same level yields an increase of 3 dB. The smallest recognizable change in sound level is approximately 1 dB. A 3-dB increase in the A-Weighted sound level is generally considered perceptible, whereas a 5-dB increase is readily perceptible. A 10-dB increase is judged by most people as an approximate doubling of the perceived loudness.

The two primary factors that reduce levels of environmental sounds are increasing the distance between the sound source and the receiver and having intervening obstacles such as walls, buildings, or terrain features that block the direct path between the sound source and the receiver. Factors that act to make environmental sounds louder include moving the sound source closer to the receiver, sound enhancements caused by reflections, and focusing caused by various meteorological conditions.

Following are brief definitions of the measures of environmental noise used in this study:

Maximum Sound Level (Lmax): Lmax is the maximum sound level that occurs during an event such as a train passing. For this analysis Lmax is defined as the maximum sound level using the slow setting on a standard sound level meter.

Equivalent Sound Level (Leq): Environment sound fluctuates constantly. The equivalent sound level (Leq) is the most common means of characterizing community noise. Leq represents a constant sound that, over a specified period of time, has the same sound energy as the time-varying sound. Leq is used by FTA to evaluate noise impacts at institutional land uses, such as schools, churches, and libraries, from proposed transit projects.

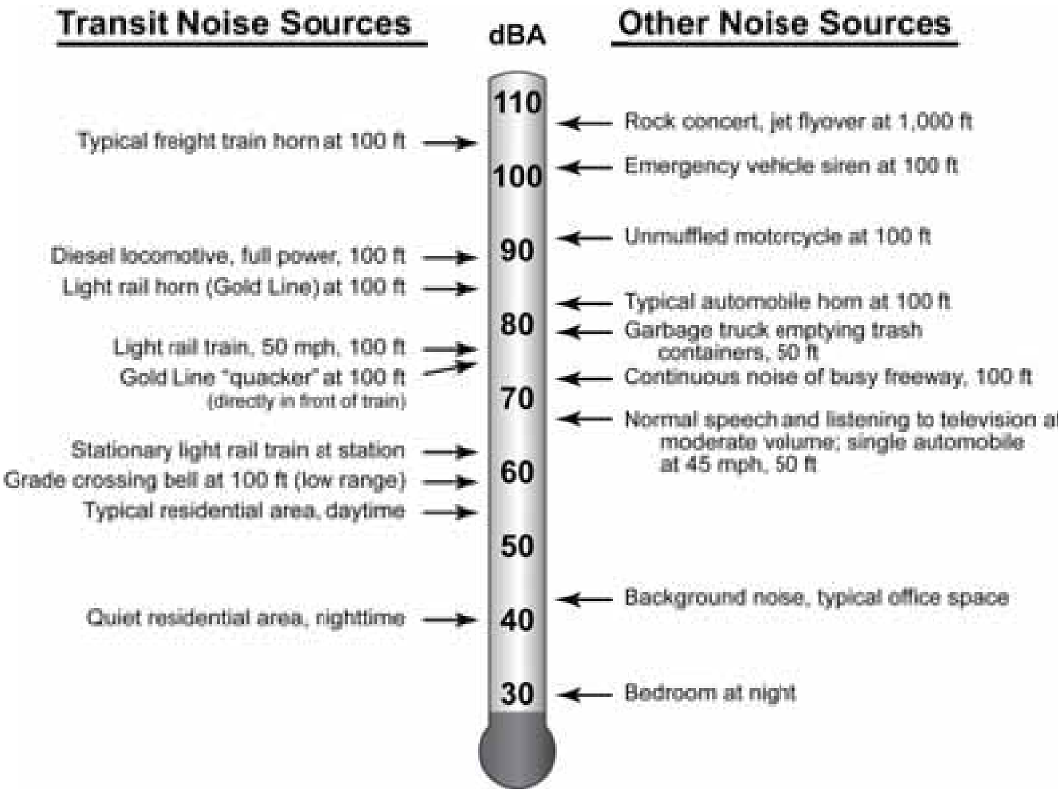
Day-Night Sound Level (Ldn)*:* Ldn is basically a 24-hour Leq with an adjustment to reflect the greater sensitivity of most people to nighttime noise. The adjustment is a 10 dB penalty for all sound that occurs between the hours of 10:00 PM to 7:00 AM. The effect of the penalty is that, when calculating Ldn, any event that occurs during the nighttime is equivalent to ten occurrences of the same event during the daytime. Ldn is the most common measure of total community noise over a 24-hour period and is used by FTA to evaluate residential noise impacts from proposed transit projects.

LXX*:* This is the percent of time a sound level is exceeded during the measurement period. For example, the L99 is the sound level exceeded 99 percent of the measurement period. For a 1-hour period, L99 is the sound level exceeded for all except 36 seconds of the hour. L1 represents typical maximum sound levels, L33 is approximately equal to Leq when free-flowing traffic is the dominant noise source, L50 is the median sound level, and L99 is close to the minimum sound level.

Sound Exposure Level (SEL)*:* SEL is a measure of the acoustic energy of an event such as a train passing. In essence, the acoustic energy of the event is compressed into a 1-second period. SEL increases as the sound level of the event increases and as the duration of the event increases. It is often used as an intermediate value in calculating overall metrics such as Leq and Ldn.

Sound Transmission Class (STC): STC ratings are used to compare the sound insulating effectiveness of different types of noise barriers, including windows, walls, etc. Although the amount of attenuation varies with frequency, the STC rating provides a rough estimate of the transmission loss from a particular window or wall.

FIGURE A-1: TYPICAL OUTDOOR AND INDOOR NOISE LEVELS



A.2 VIBRATION FUNDAMENTALS

One potential community impact from the proposed project is vibration that is transmitted from the tracks through the ground to adjacent houses. This is referred to as groundborne vibration. When evaluating human response, groundborne vibration is usually expressed in terms of decibels using the root mean square (RMS) vibration velocity. RMS is defined as the average of the squared amplitude of the vibration signal. To avoid confusion with sound decibels, the abbreviation VdB is used for vibration decibels. All vibration decibels in this report use a decibel reference of 1 micro-inch/second (μin/sec.).* The potential adverse impacts of rail transit groundborne vibration are as follows:

Perceptible Building Vibration: This is when building occupants feel the vibration of the floor or other building surfaces. Experience has shown that the threshold of human perception is around 65 VdB and that vibration that exceeds 75 to 80 VdB may be intrusive and annoying to building occupants.

Rattle: The building vibration can cause rattling of items on shelves and hanging on walls, and various different rattle and buzzing noises from windows and doors.

* One μin/sec= 10^{-6} in/sec.

Reradiated Noise: The vibration of room surfaces radiates sound waves that may be audible to humans. This is referred to as *groundborne noise*. When audible groundborne noise occurs, it sounds like a low-frequency rumble. For a surface rail system such as the proposed build alternatives, the groundborne noise is usually masked by the normal airborne noise radiated from the transit vehicle and the rails.

Damage to Building Structures: Although it is conceivable that vibration from a light rail system could cause damage to fragile buildings, the vibration from rail transit systems is usually one to two orders of magnitude below the most restrictive thresholds for preventing building damage. Hence the vibration impact criteria focus on human annoyance, which occurs at much lower amplitudes than does building damage.

Vibration is an oscillatory motion that can be described in terms of the displacement, velocity, or acceleration of the motion. The response of humans to vibration is very complex. However, the general consensus is that for the vibration frequencies generated by passenger trains, human response is best approximated by the vibration velocity level. Therefore, vibration velocity has been used in this study to describe train-generated vibration levels.

When evaluating human response, groundborne vibration is usually expressed in terms of decibels using the root mean square (RMS) vibration velocity. RMS is defined as the average of the squared amplitude of the vibration signal. To avoid confusion with sound decibels, the abbreviation VdB is used for vibration decibels. All vibration decibels in this report use a decibel reference of 1 μin/sec.

Figure A-2 shows typical vibration levels from rail and non-rail sources as well as the human and structure response to such levels.

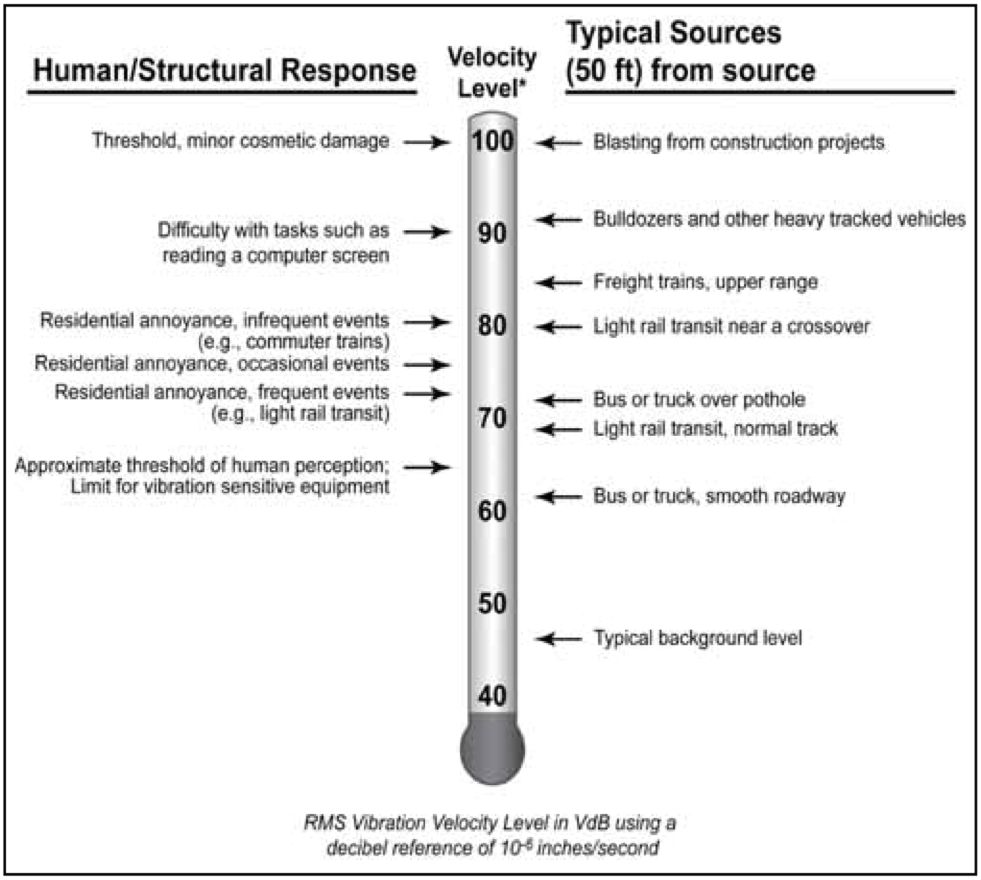
Although there has been relatively little research into human and building response to groundborne vibration, there is substantial experience with vibration from rail systems. In general, the collective experience indicates that:

It is rare that groundborne vibration from transit systems results in building damage, even minor cosmetic damage. The primary consideration therefore is whether vibration will be intrusive to building occupants or will interfere with interior activities or machinery.

The threshold for human perception is approximately 65 VdB. Vibration levels in the range of 70 to 75 VdB are often noticeable but acceptable. Beyond 80 VdB, vibration levels are often considered unacceptable.

For human annoyance, there is a relationship between the number of daily events and the degree of annoyance caused by groundborne vibration. The FTA Guidance Manual includes an 8 VdB higher impact threshold if there are fewer than 30 events per day and a 3 VdB higher threshold if there are fewer than 70 events per day.

FIGURE A-2: TYPICAL VIBRATION LEVELS



Often it is necessary to determine the contribution at different frequencies when evaluating vibration or noise signals. The 1/3-octave band spectrum is the most common procedure used to evaluate frequency components of acoustic signals. The term “octave” has been borrowed from music where it refers to a span of eight notes. The ratio of the highest frequency to the lowest frequency in an octave is 2:1. For a 1/3-octave band spectrum, each octave is divided into three bands where the ratio of the lowest frequency to the highest frequency in each 1/3-octave band is $2^{1/3}$:1 (1.26:1). An octave consists of three 1/3 octaves.

The 1/3-octave band spectrum of a signal is obtained by passing the signal through a bank of filters. Each filter excludes all components except those that are between the upper and lower range of one 1/3-octave band. Refer FTA Guidance Manual (Ref. 1).

APPENDIX B: VIBRATION MEASUREMENT RESULTS

B.3 DETAILED RESULTS FROM VIBRATION PROPAGATION TESTS

This appendix presents the best fit coefficients for each vibration propagation site described in Section 2.2.2. Vibration propagation tests were performed at the following four locations along the proposed project corridor:

- V1 - East Valley Institute of Technology (EVIT) located on the south side of the LRT alignment at Main Street and Longmore Street
- V2 - Epernay Apartment Homes located at 944 West Main Street, Mesa.
- V3 - Mesa Downtown in a pedestrian alleyway between Robson and MacDonald.
- V4 - Mesa Arts Center: The Mesa Arts Center located on Main Street and Center Street

The four measurement sites are shown in Figure B-1 through Figure B-4.

FIGURE B-1: VIBRATION PROPAGATION SITE V1

FIGURE B-2: VIBRATION PROPAGATION SITE V2

FIGURE B-3: VIBRATION PROPAGATION SITE V3

FIGURE B-4: VIBRATION PROPAGATION SITE V4 IN FRONT OF MESA CENTER

The line source transfer mobility coefficients for best fit curves, A, B and C are given in Table B-1 through Table B-4 and based on the relationship.

$$TM = A + B*\log(d) + C*\log(d)^2$$

where:

TM = Transfer Mobility in dB re 1 (µin/sec)/(lb/ft$^{1/2}$)

d = distance in feet

The predicted vibration based on the best-fit coefficients at distances of 25, 50, 75, 100 and 150 ft is shown in Figure B-5 through Figure B-7.

TABLE B-1: LINE SOURCE TRANSFER MOBILITY COEFFICIENTS, SITE V1

Frequency (Hz)	A	B	C
5	50.0	-28.9	0.0
6.3	49.7	-29.6	0.0
8	55.3	-32.4	0.0
10	30.5	-18.4	0.0
12.5	22.5	-11.6	0.0
16	41.7	-16.1	0.0
20	-16.2	68.5	-25.4
25	-31.9	88.8	-30.3
31.5	-0.9	49.5	-19.0
40	83.9	-31.0	0.0
50	72.3	-25.1	0.0
63	83.8	-31.5	0.0
80	72.6	-28.0	0.0
100	85.3	-37.7	0.0
125	-66.9	126.4	-44.5
160	-18.3	65.2	-28.2

TABLE B-2: LINE SOURCE TRANSFER MOBILITY COEFFICIENTS, SITE V2

Frequency (Hz)	A	B	C
5	12.2	-6.4	0.0
6.3	10.6	-7.2	0.0
8	15.1	-10.4	0.0
10	31.5	-19.4	0.0
12.5	39.2	-20.3	0.0
16	54.1	-26.1	0.0
20	53.3	-21.1	0.0
25	35.8	-5.3	0.0
31.5	52.6	-13.2	0.0
40	-7.7	57.4	-20.0
50	20.5	27.1	-12.4
63	-10.6	62.9	-23.0
80	2.5	50.1	-20.8
100	-67.4	140.6	-50.6
125	-30.0	97.4	-40.6
160	34.3	14.1	-17.3
200	67.3	-39.2	0.0
250	52.5	-34.2	0.0
315	33.1	-25.8	0.0

TABLE B-3: LINE SOURCE TRANSFER MOBILITY COEFFICIENTS, SITE V3

Frequency (Hz)	A	B	C
5	24.1	-11.5	0.0
6.3	5.0	-3.3	0.0
8	7.4	-4.4	0.0
10	36.9	-20.5	0.0
12.5	42.1	-18.7	0.0
16	29.8	-5.4	0.0
20	39.2	-6.8	0.0
25	44.6	-8.2	0.0
31.5	81.6	-42.2	7.4
40	38.4	7.1	-6.6
50	15.6	35.9	-15.5
63	7.4	51.2	-21.5
80	23.4	33.9	-18.9
100	10.4	45.8	-23.3
125	38.8	14.0	-15.7
160	21.8	26.1	-20.0
200	90.4	-51.7	0.0
250	103.4	-64.4	0.0
315	89.8	-59.9	0.0

TABLE B-4: LINE SOURCE TRANSFER MOBILITY COEFFICIENTS, SITE V4

Frequency (Hz)	A	B	C
5	14.7	-6.3	0.0
6.3	19.9	-10.4	0.0
8	25.0	-14.5	0.0
10	31.0	-16.9	0.0
12.5	41.9	-19.9	0.0
16	50.2	-19.5	0.0
20	48.2	-11.0	0.0
25	62.7	-16.3	0.0
31.5	67.3	-19.0	0.0
40	71.4	-21.4	0.0
50	-1.8	60.8	-23.8
63	27.8	29.1	-16.3
80	71.1	-19.6	-4.1
100	84.1	-36.2	0.0
125	-47.6	110.8	-41.6
160	78.9	-38.3	0.0
200	43.0	-19.5	0.0
250	19.6	-8.9	0.0
315	15.6	-10.3	0.0

B.4 COMPARISON OF PREDICTED VIBRATION SPECTRA

FIGURE B-5: COMPARISON OF PREDICTED VIBRATION AT 33 MPH FOR ALL FOUR MEASUREMENT SITES

(Curves do not include adjustments for floor amplification or a safety factor)

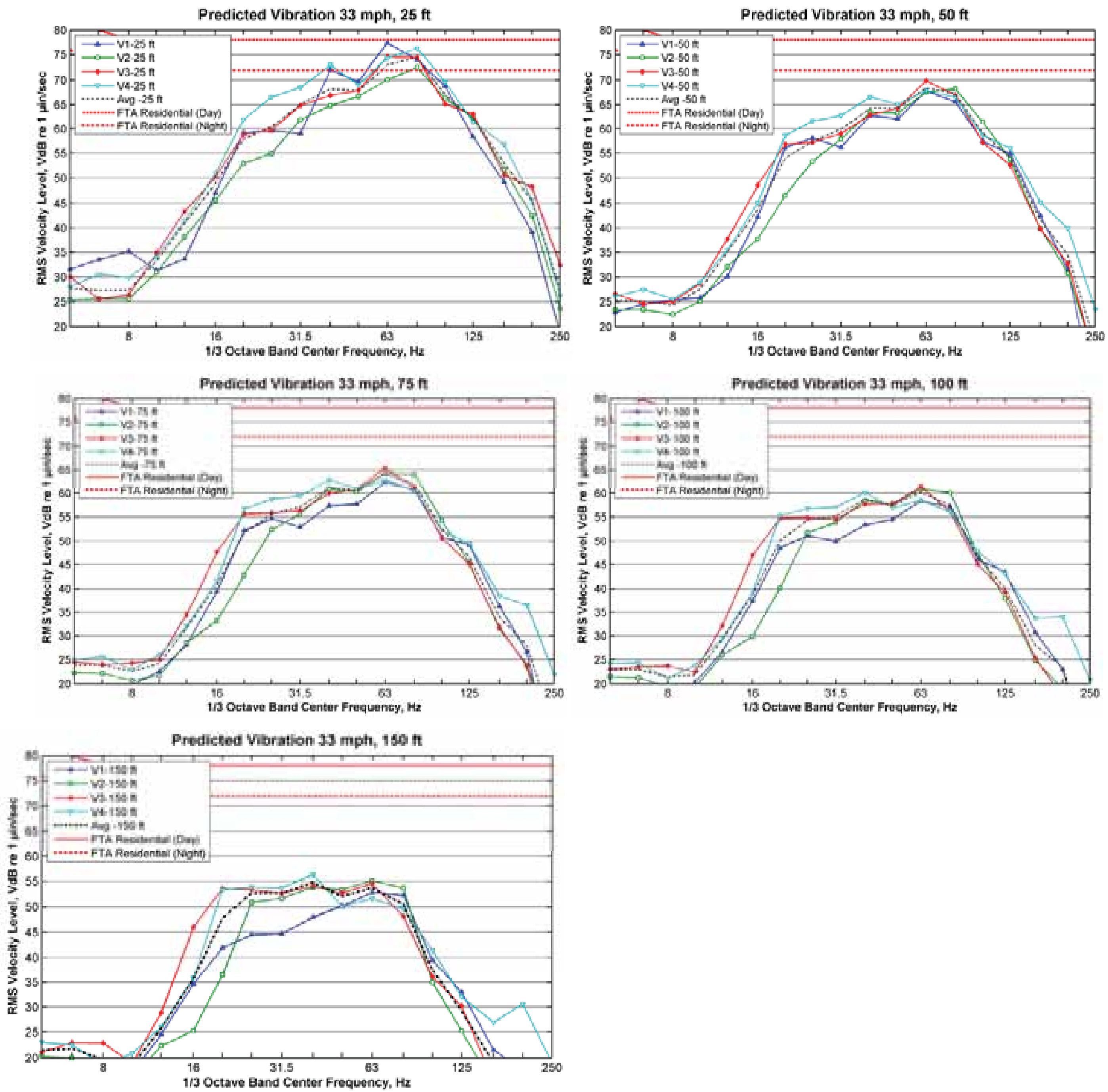


FIGURE B-6: COMPARISON OF PREDICTED VIBRATION AT 29 MPH FOR ALL FOUR MEASUREMENT SITES

(Curves do not include adjustments for floor amplification or a safety factor)

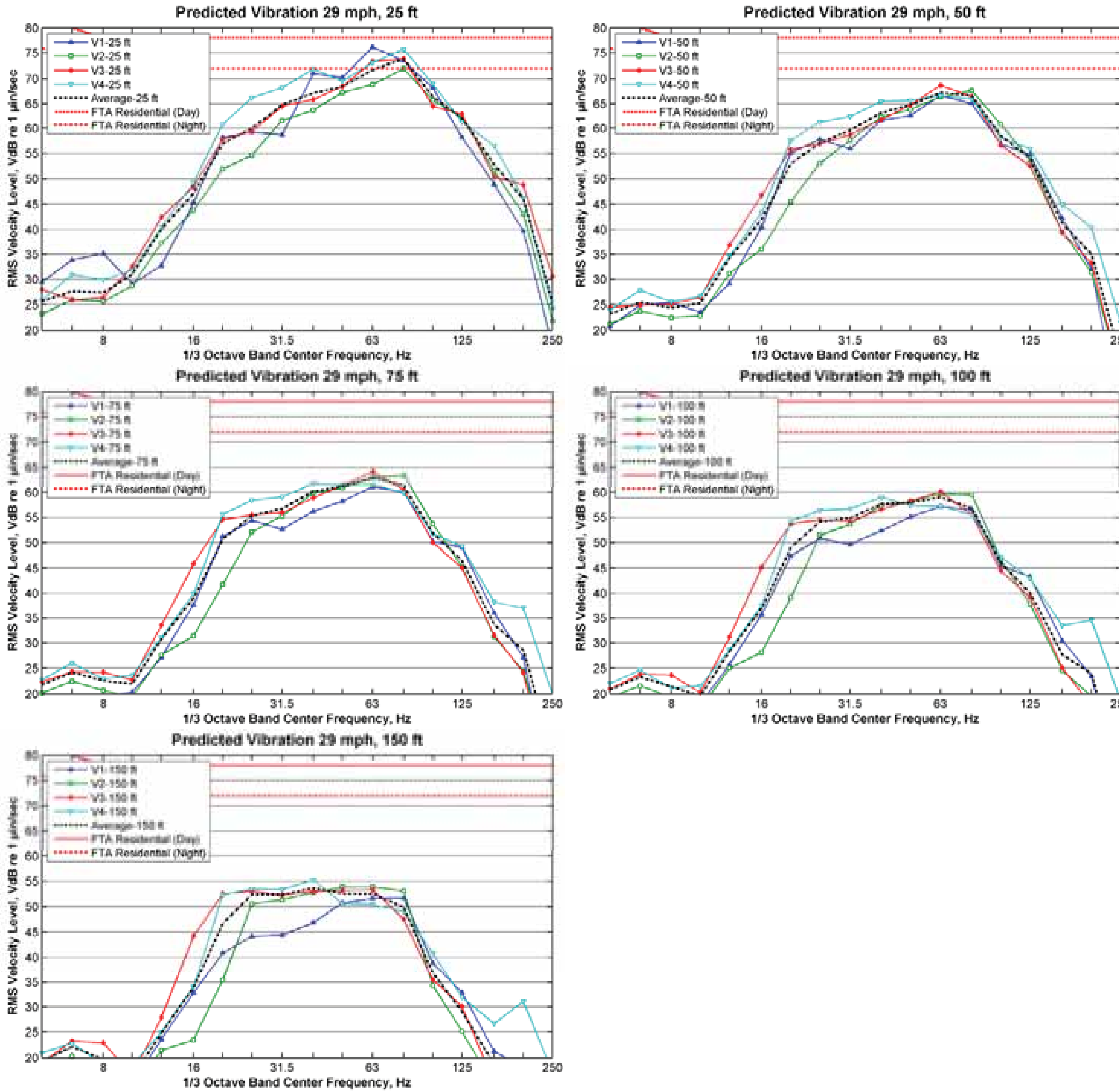
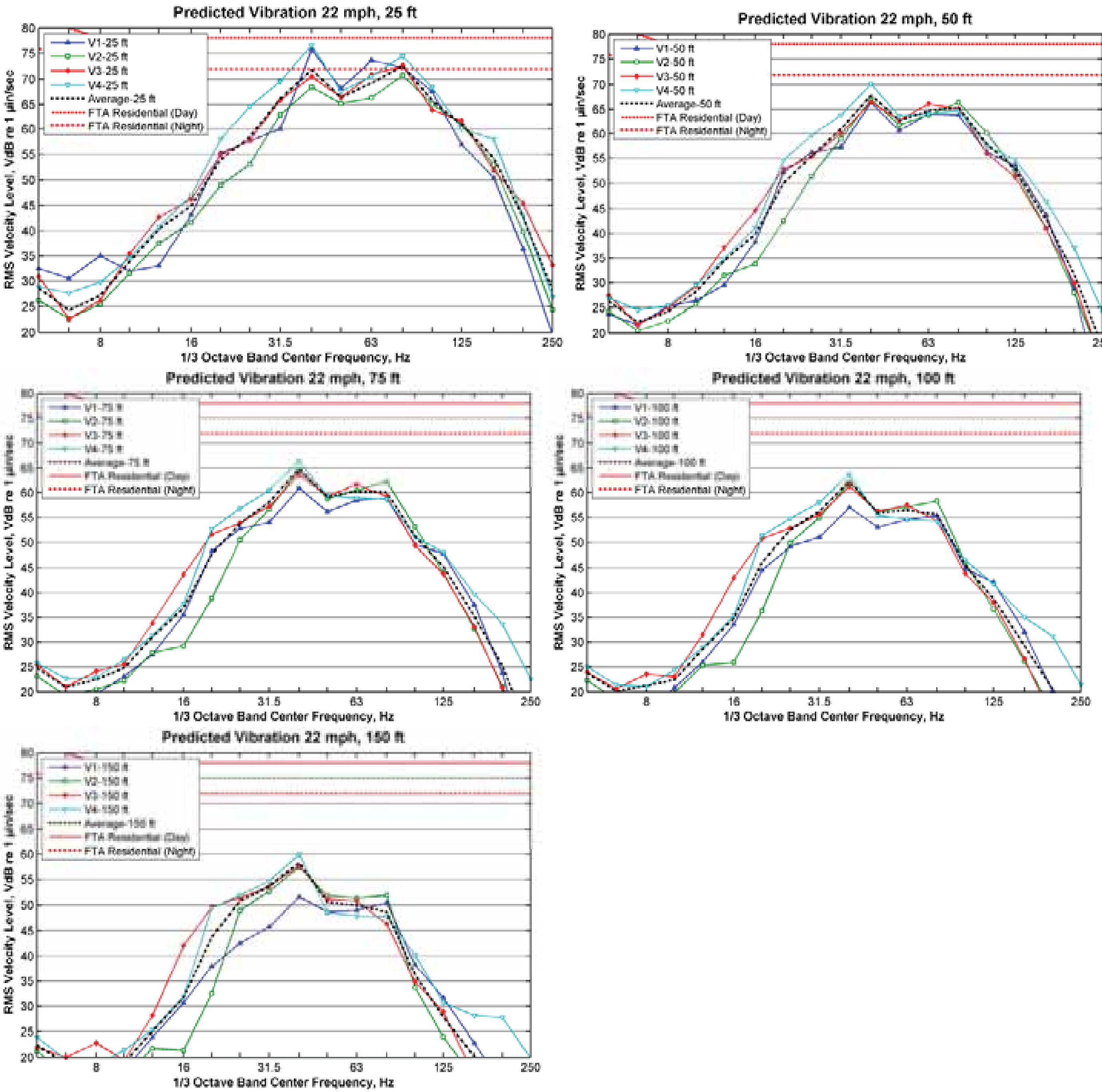


FIGURE B-7: COMPARISON OF PREDICTED VIBRATION AT 22 MPH FOR ALL FOUR MEASUREMENT SITES

(Curves do not include adjustments for floor amplification or a safety factor)



APPENDIX C: FORCE DENSITY MEASUREMENTS

The force density levels were developed from measurements taken at 5552 East Washington Street in Phoenix along the existing METRO Starter Line. Test train vibrations were measured north of the track at distances of 50 to 200 ft from the centerline of the near track. Vibration was measured at controlled train speeds of 5 to 40 mph in increments of 5 mph. Two test train passbys were measured at each speed and all passbys were on the near track. Impact tests were performed using a 45-lb drop weight along the centerline of the near tracks using the same procedure as the vibration propagation tests used for determining the line source transfer mobility.

FIGURE C-1: AERIAL VIEW OF FDL MEASUREMENT LOCATION

C.5 TRANSFER MOBILITY MEASUREMENTS

The impact line for the transfer mobility was located at the centerline of the near track. A series of 20 impacts were conducted at 11 locations along the LRT right-of-way. The impact locations were separated by intervals of 15 ft. Accelerometers were placed at distances of 50, 75, 100, 150, and 200 feet from the impact line. Point source transfer mobilities were calculated from each impact location to each accelerometer. These point source transfer mobilities were combined to produce the line source transfer mobility (LSTM) similar to the procedures described in Section 2.2.1. Figure C-2 shows the impact testing along the centerline of the eastbound (near) track. The LSTM and coherence from these measurements are shown in Figure C-3. Coherence is a measure of the "quality" of the data; a coherence value close to one indicates a strong relationship between the applied force from the impact and the measured vibration at the accelerometer. A coherence value close to zero means that there is little correlation between the impact force and ground vibration.

FIGURE C-2: IMPACT TESTING, EASTBOUND TRACK

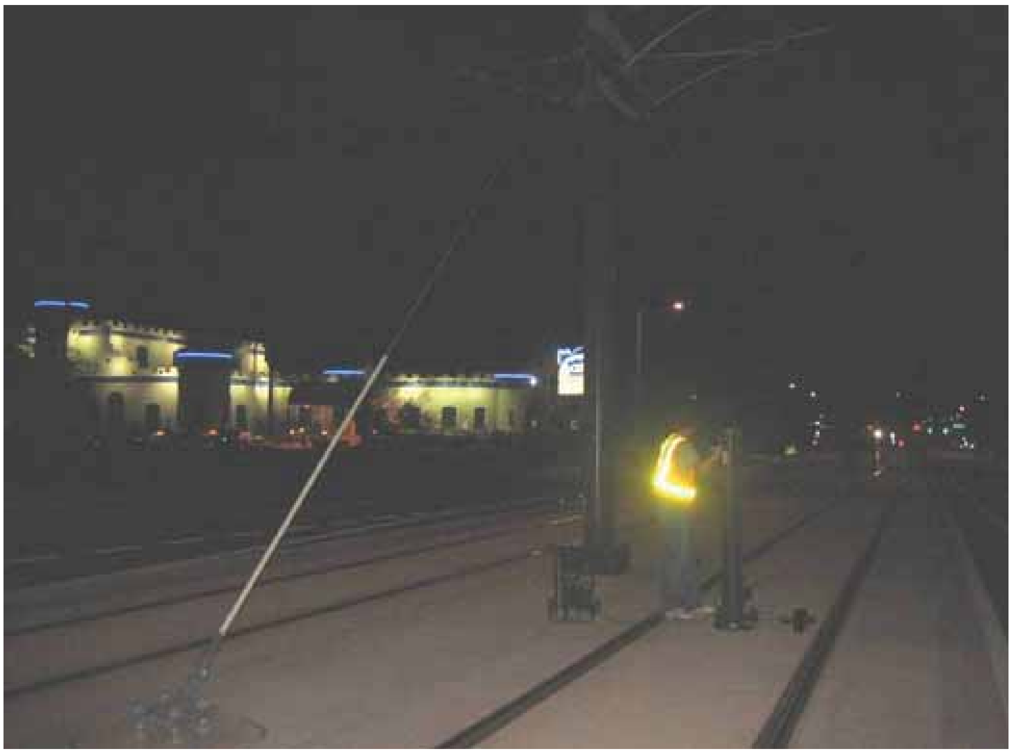
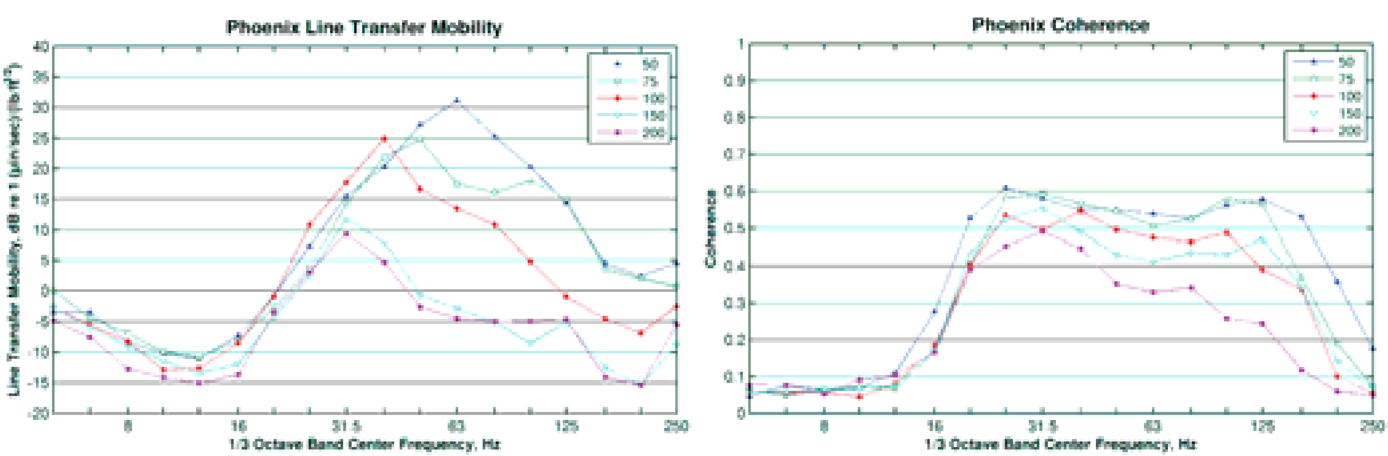


FIGURE C-3: LSTM AND COHERENCE FOR FDL TEST

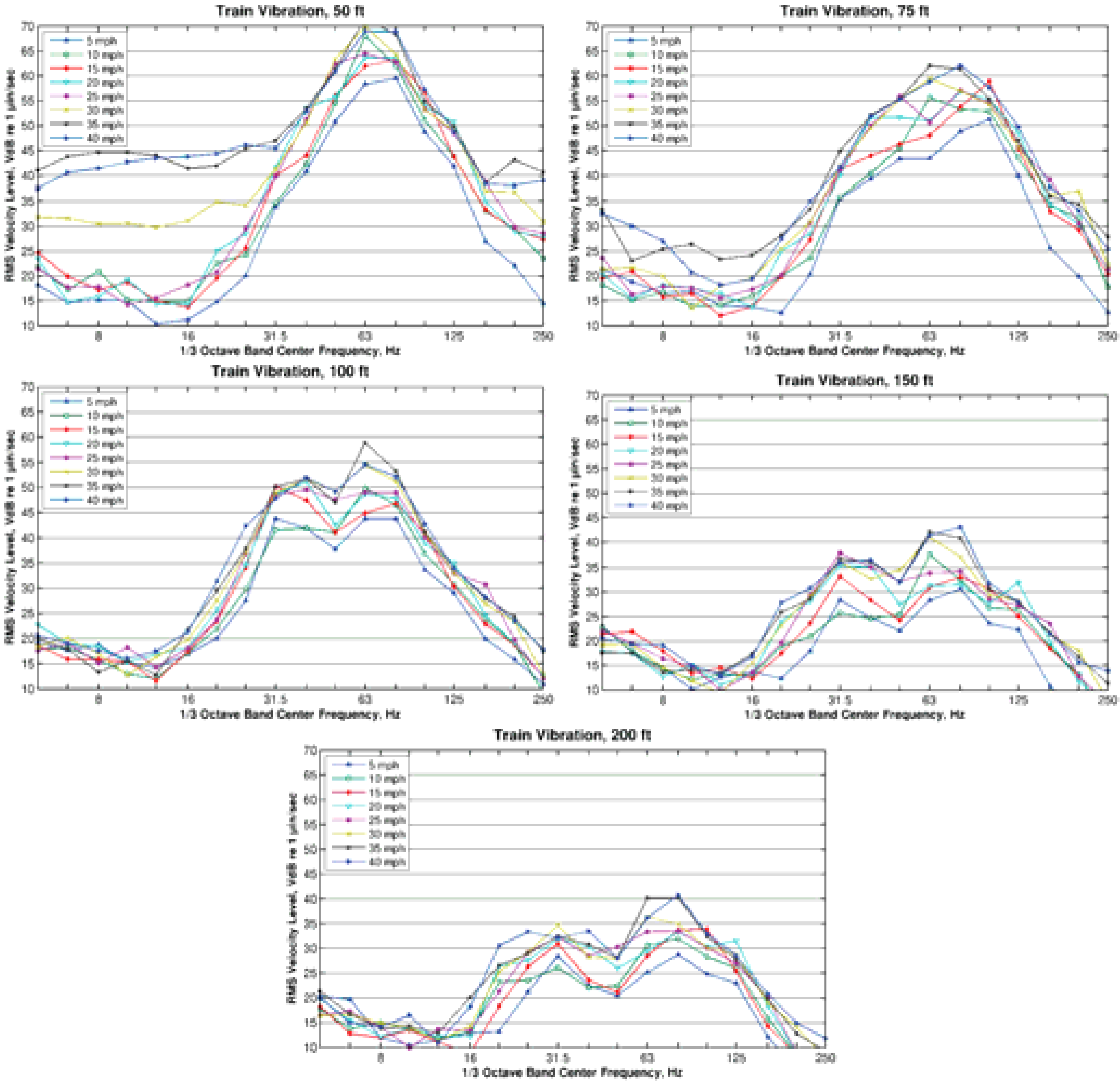


C.6 METRO TRAIN VIBRATION MEASUREMENTS

Train vibration was measured at the same site as the transfer mobility. All test train passbys were performed at controlled speeds on the westbound track. Accelerometers were placed at the same locations as for the transfer mobility tests and two passbys were measured at speeds of 5, 10, 15, 20, 25, 30, 35 and 40 mph each. The test results are shown in Figure C-5. At 50 ft, vibration velocity below 20 Hz was higher for 30, 35 and 40 mph compared to slower train speeds. However, at measurement distances greater than 50 ft speed effects were not noticed at low frequencies. The low frequency speed effects at 50 ft are not fully understood but are most likely from near-field effects.

FIGURE C-4: TEST TRAIN PASSBY FOR FDL MEASUREMENT

FIGURE C-5: MEASURED TEST TRAIN VIBRATION



C.7 FORCE DENSITY CALCULATIONS

The force density level (FDL) was calculated by subtracting the measured line source transfer mobility from the measured train vibration. Force density levels for each speed are shown in Figure C-6 and Figure C-7. The key observations are:

- FDL energy peaks between 60 and 80 Hz for all measured speeds and distances, except the 50 ft measurement at high speeds. As discussed before the unusual behavior at 50 ft for higher speeds is attributed to near-field effects.
- For a given speed, the force density curves converge at all measurement positions.

The average FDL of METRO LRV at different speeds is shown in Figure C-8. The key observations from Figure C-8 are:

- The FDL energy is concentrated between 50 and 125 Hz for most train speeds and the low frequencies do not have any significant peak.
- At 63 Hz, the FDL for 30, 35 and 40 mph is at least 5 decibels higher than at slower speeds.
- FDL peaks at 80 Hz for 35 and 40 mph that are at least 5 decibels higher than at slower speeds.

FIGURE C-6: FORCE DENSITY LEVEL OF METRO STARTER LINE, 5 TO 30 MPH

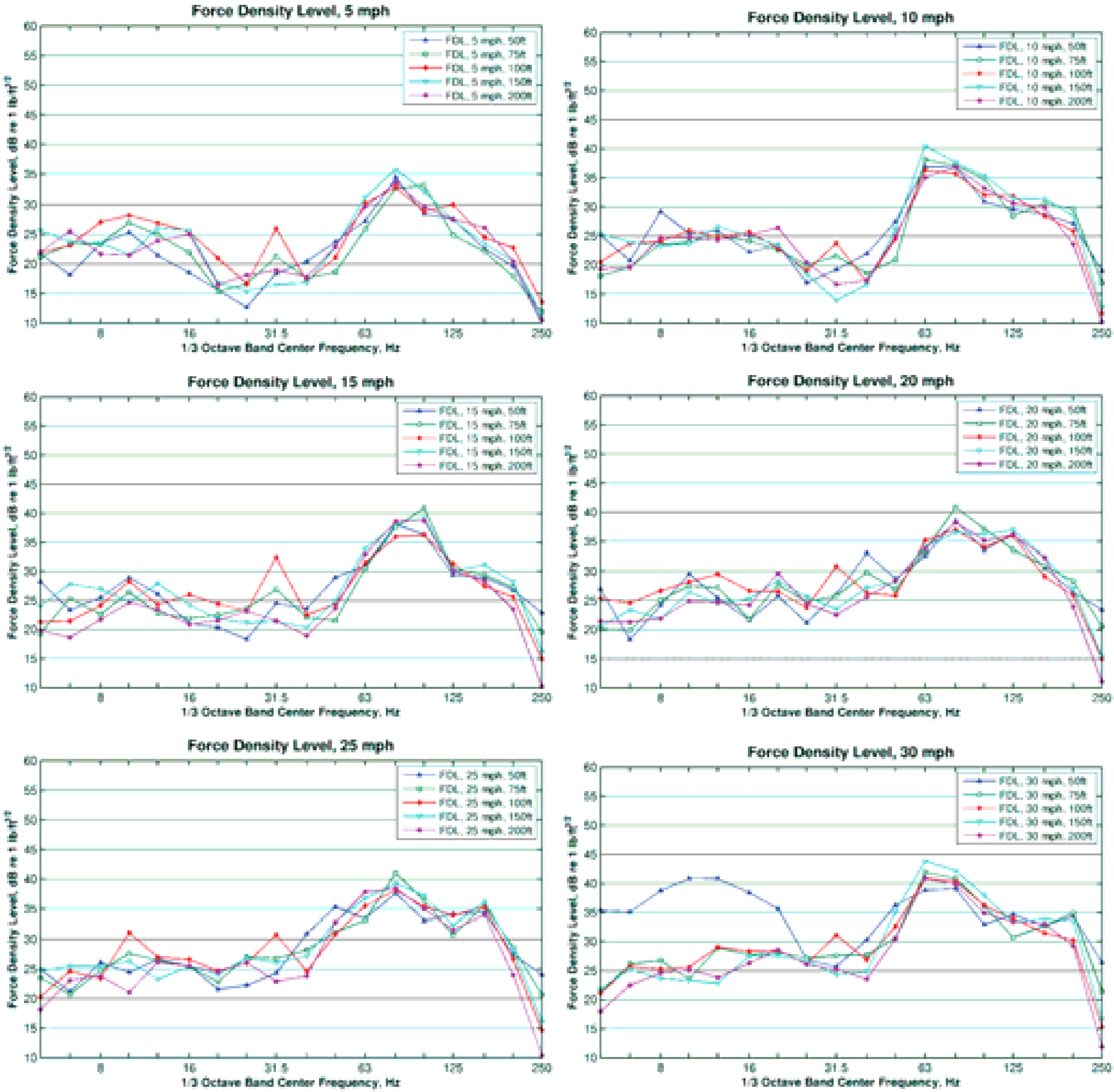


FIGURE C-7: FORCE DENSITY LEVEL OF METRO STARTER LINE, 35 AND 40 MPH

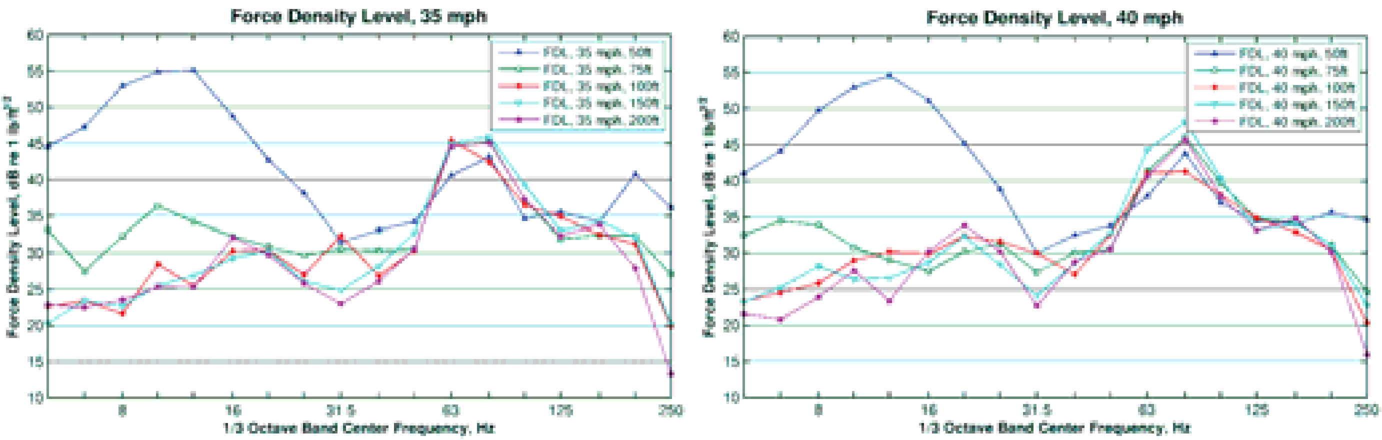
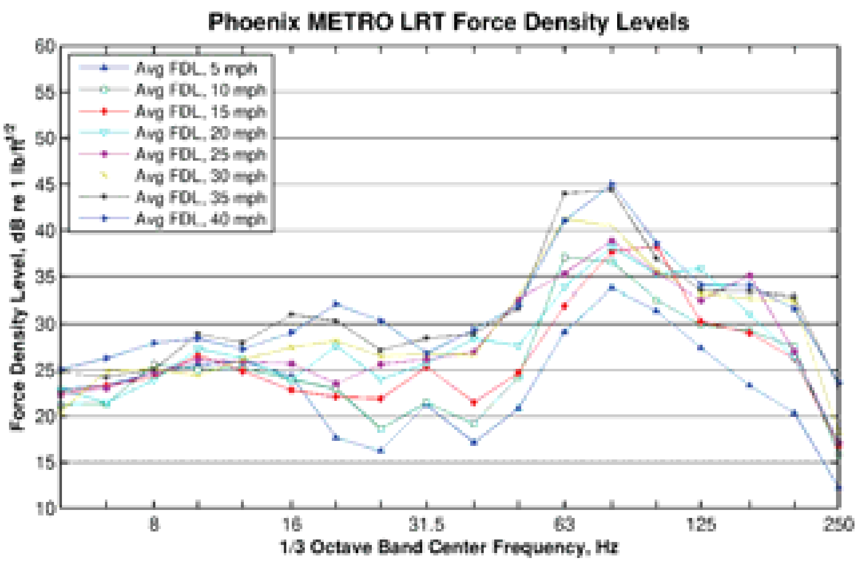


FIGURE C-8: METRO LRV FORCE DENSITY LEVELS VERSUS SPEED



APPENDIX D: METRO LRV NOISE MEASUREMENT RESULTS

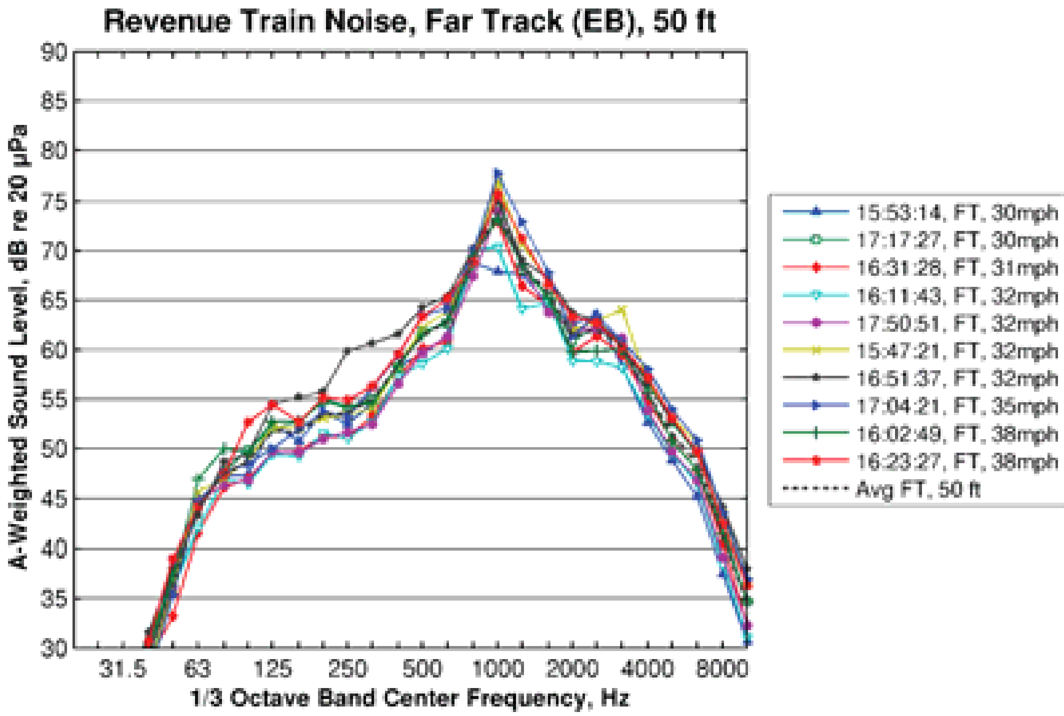
This appendix describes the light rail noise measurements performed at the same site as train vibration. Noise from revenue service trains of the METRO Starter Line and the test train were measured. All noise measurements were performed at the same time as vibration for the same train passbys. The following sections present the results from revenue service and test train measurement.

D.8 LRV NOISE MEASUREMENTS: METRO REVENUE SERVICE

Noise measurements of the revenue service train passbys were performed at 50 and 100 ft from the centerline of the near track. Train speeds of the revenue trains were measured using a radar gun and the speeds ranged over 28 and 38 mph. The noise measurement site is shown in Figure D-1. Microphone positions Mic 1 and Mic 2 were used for the revenue train noise measurement locations. The results of the revenue train noise measurements are presented in Figure D-2 through Figure D-4. The plots in Figure D-2 show that there was a significant difference in the noise levels between the NT and FT trains at the 50 ft measurement position. The reasons for this variation are unknown.

FIGURE D-1: AERIAL VIEW OF MICROPHONE LOCATIONS FOR LRT NOISE MEASUREMENTS

FIGURE D-2: MEASURED REVENUE TRAIN PASSBY NOISE, 50 FT



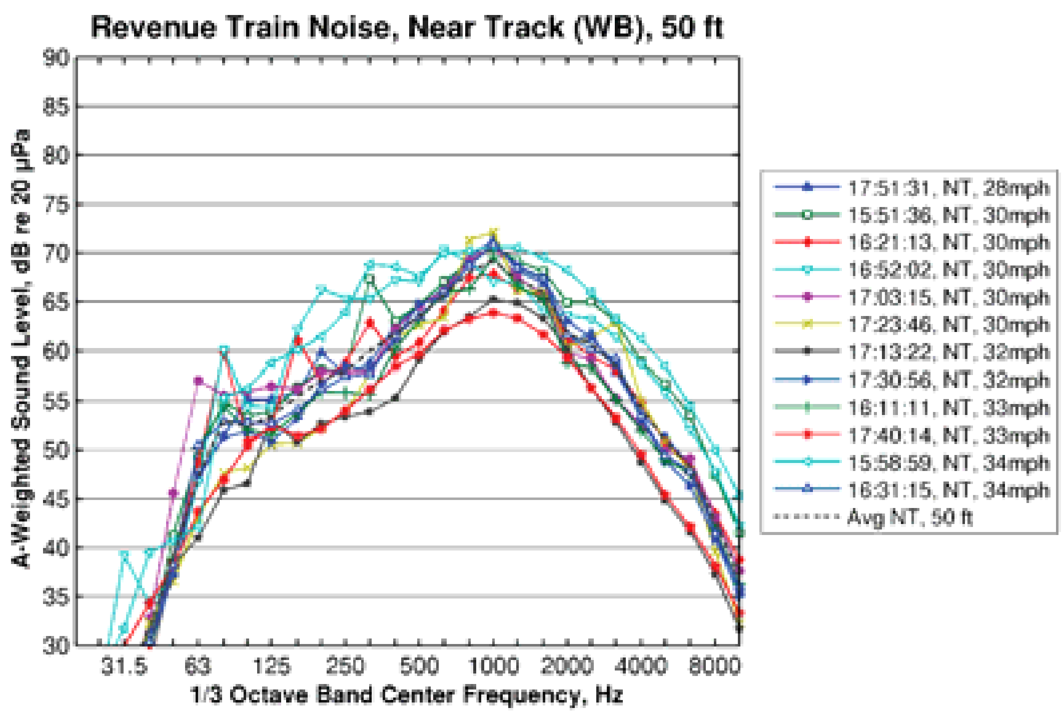
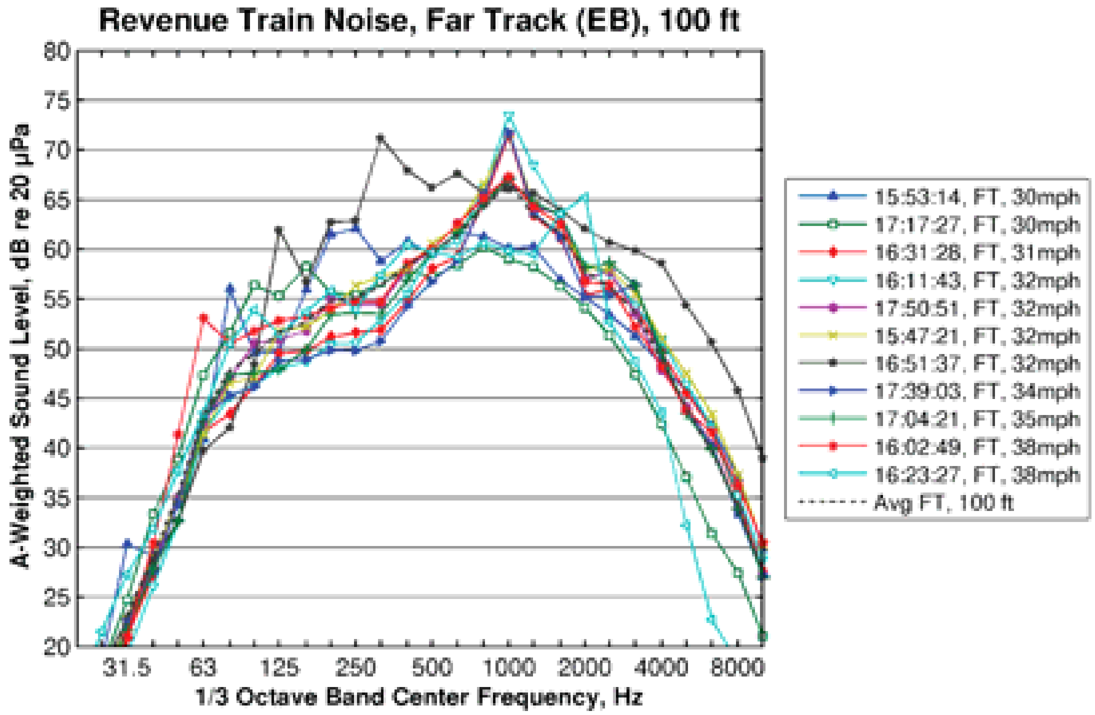


FIGURE D-3: MEASURED REVENUE TRAIN PASSBY NOISE, 100 FT



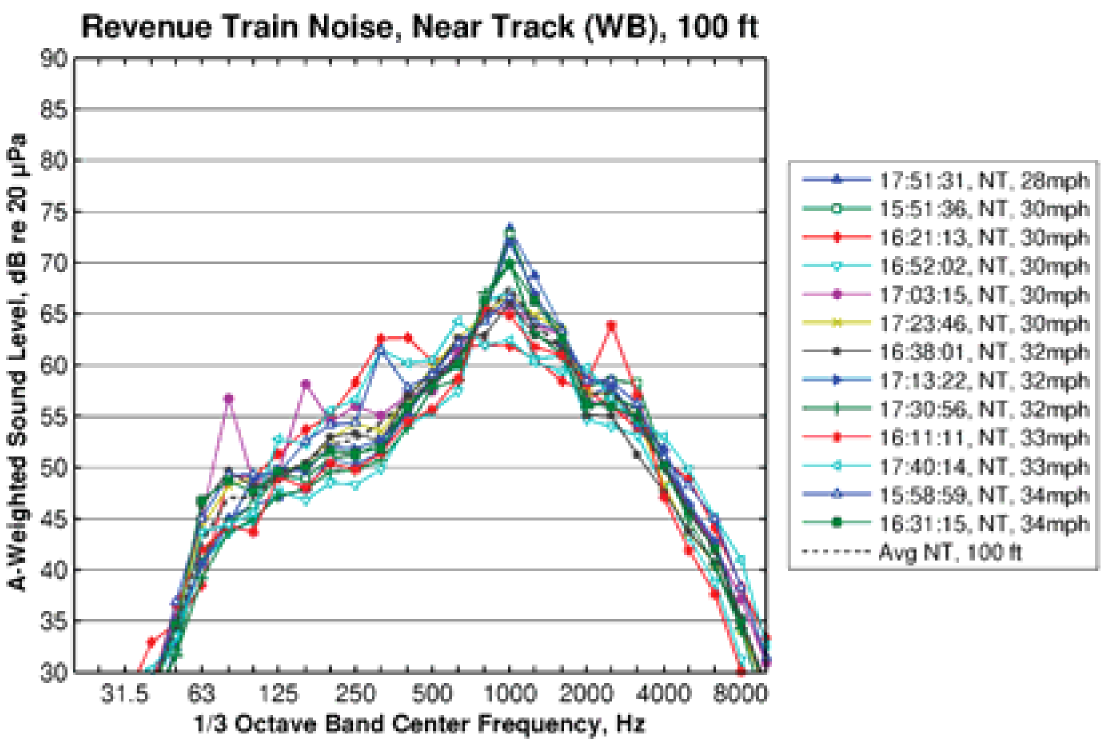
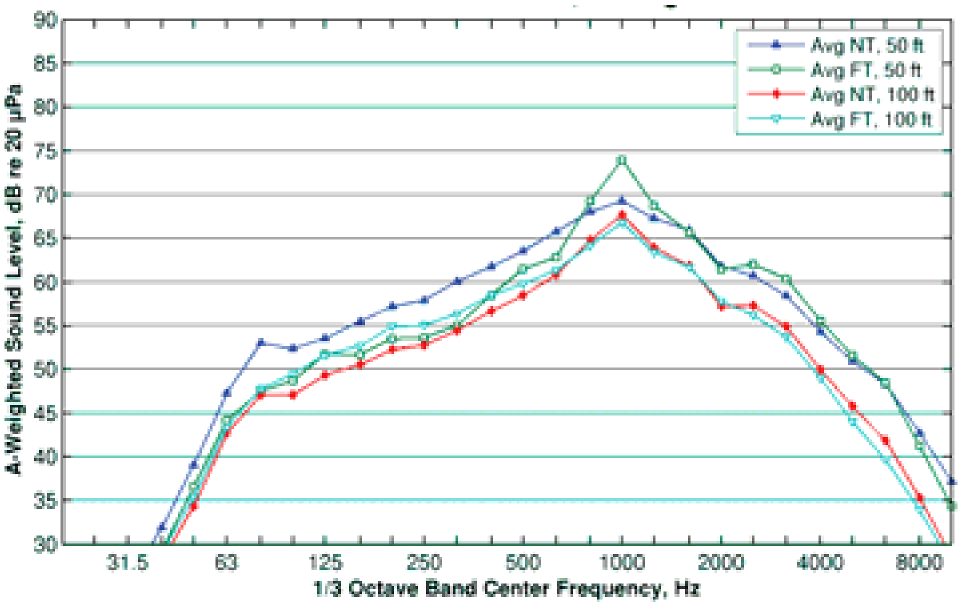


FIGURE D-4: MEASURED AVERAGE REVENUE TRAIN NOISE



D.9 LRV NOISE MEASUREMENTS: TEST TRAIN

Noise measurements of train passbys were performed at controlled speeds after revenue hours. These measurements were made at the same location as the revenue train measurements at distances of 50, 100 and 200 ft from the near track. All train passbys in both inbound and outbound directions were performed in the near track. Noise measurements were performed at speeds of 5 mph to 40 mph, in increments of 5 mph. A summary of the test train measurements is shown in Table D-1 and Table D-2. The results in Table D-1 show that at 50 ft, events 13 and 14 show a maximum noise level of 76.9 and 77.1 dBA, respectively. This data was particularly clean and agreed well with the best fit curves for noise at various speeds. The reference noise level of 77 dBA at 50 ft for train speeds of 35 mph was derived from these tests.

TABLE D-1: SUMMARY OF NOISE MEASUREMENTS OF ALL TEST TRAIN PASSBYS

Event[a]	Train Speed (mph)	Duration (sec)	50 feet			100 feet			200 feet		
			SEL	Leq	Lmax	SEL	Leq	Lmax	SEL	Leq	Lmax
1	5	24.0	72.7	67.8	69.4	66.8	60	61.6	63.7	52.6	54.1
4	10	30.9	76.1	64.0	65.4	74.1	62.4	63.7	69.1	54.3	55.5
5	15	33.7	79.2	75.9	78.1	73.9	64.8	67.0	69.9	56.2	58.5
6	15	37.6	78.1	66.4	67.7	73.7	61.4	62.7	69.8	55.6	56.8
7	20	41.7	79.9	75.7	77.1	75.0	66.7	69.5	71.2	58.1	60
8	20	28.1	79.4	70.0	71.7	74.8	64.0	64.9	71.1	57.8	59.2
9	25	24.9	80.1	72.2	73.7	76.0	67.8	70.3	71.2	59.1	60.4
10	25	33.1	80.5	71.0	72.2	75.9	65.7	67.0	71.5	58.9	60.2
11	30	31.7	81.6	73.5	74.6	77.4	69.0	71.2	72.6	61.2	62.8
12	30	28.1	82.0	73.7	75.0	77.7	68.2	69.3	73.6	61.6	62.8
13	35	23.1	83.4	75.7	76.9	79.0	70.6	72.5	74.5	63.3	64.7
14	35	24.0	83.4	76.2	77.2	79.0	70.5	72.0	74.4	63.7	64.9
15	40	19.5	84.8	78.0	79.6	80.1	72.5	74.3	74.5	64.6	66.1
16	40	16.6	84.8	78.3	79.4	80.2	72.7	74.2	75.6	65.9	67.4

Notes:
a. Events 2 and 3 excluded due to high background noise from a truck and SUV passbys.

TABLE D-2: AVERAGE TEST TRAIN NOISE

Train Speed	50 feet			100 feet			200 feet		
	SEL	Leq	Lmax	SEL	Leq	Lmax	SEL	Leq	Lmax
5	72.7	67.8	69.4	66.8	60.0	61.6	63.7	52.6	54.1
10	76.1	64.0	65.4	74.1	62.4	63.7	69.1	54.3	55.5
15	78.7	71.2	72.9	73.8	63.1	64.9	69.9	55.9	57.7
20	79.7	72.9	74.4	74.9	65.4	67.2	71.2	58.0	59.6
25	80.3	71.6	73.0	76.0	66.8	68.7	71.4	59.0	60.3
30	81.8	73.6	74.8	77.6	68.6	70.3	73.1	61.4	62.8
35	83.4	76.0	77.1	79.0	70.6	72.3	74.5	63.5	64.8
40	84.8	78.2	79.5	80.2	72.6	74.3	75.1	65.3	66.8

APPENDIX E: CLUSTER LOCATIONS

The following figures show the locations of each of the clusters of sensitive receptors that were used for the noise and vibration impact assessment.

FIGURE E-1: CLUSTERS SHEET 1

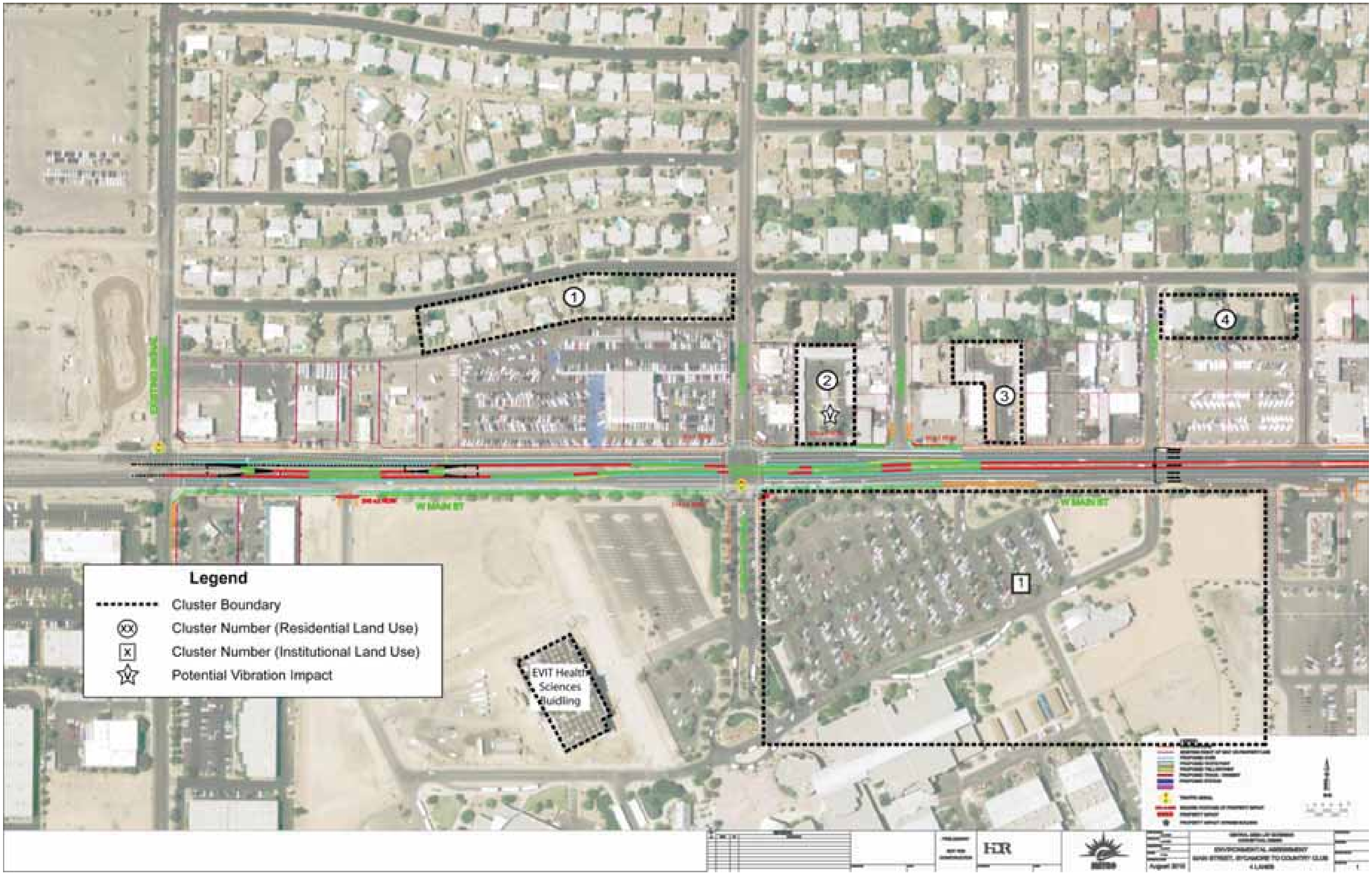


FIGURE E-2: CLUSTERS SHEET 2

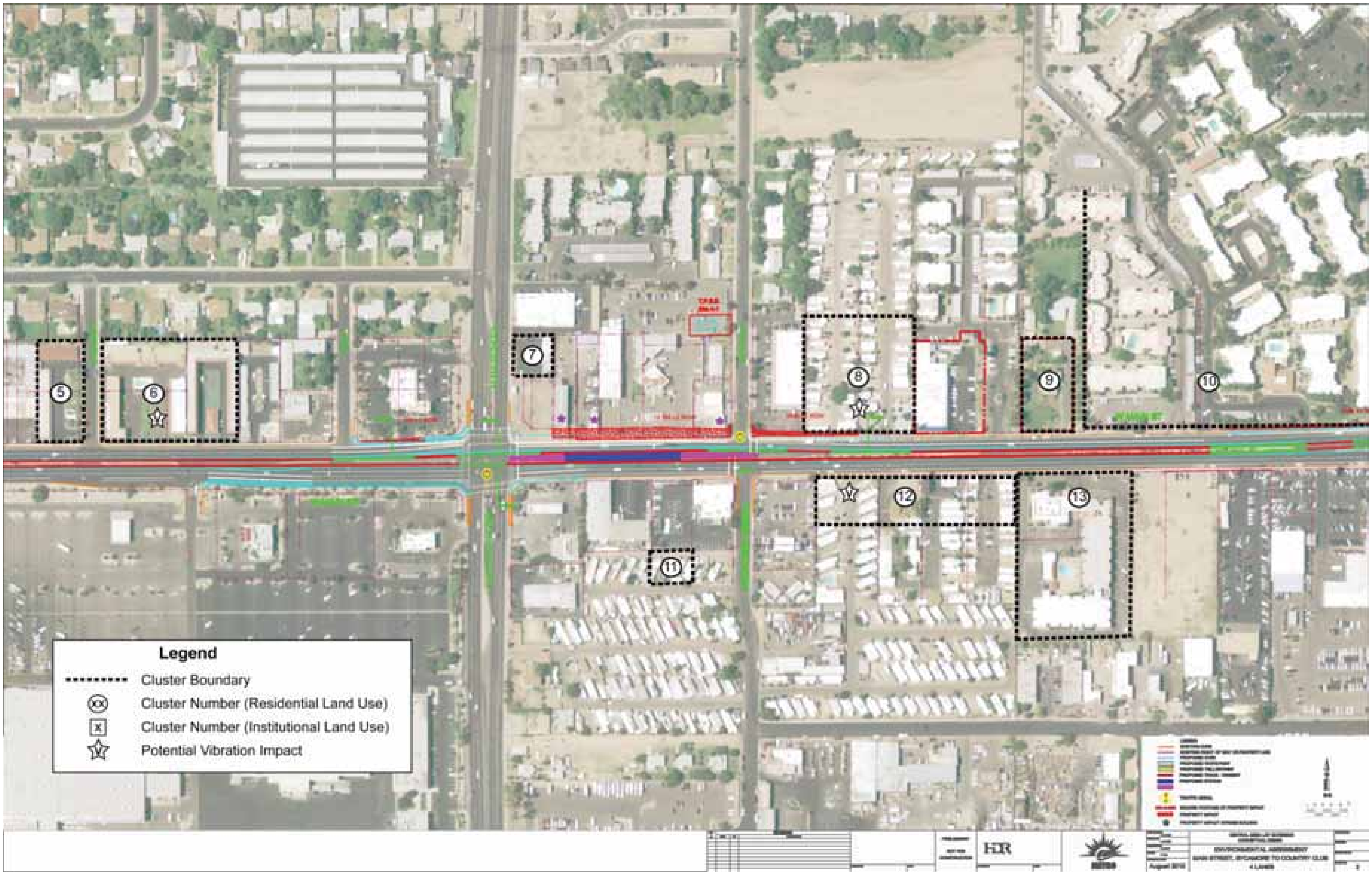


FIGURE E-3: CLUSTERS SHEET 3

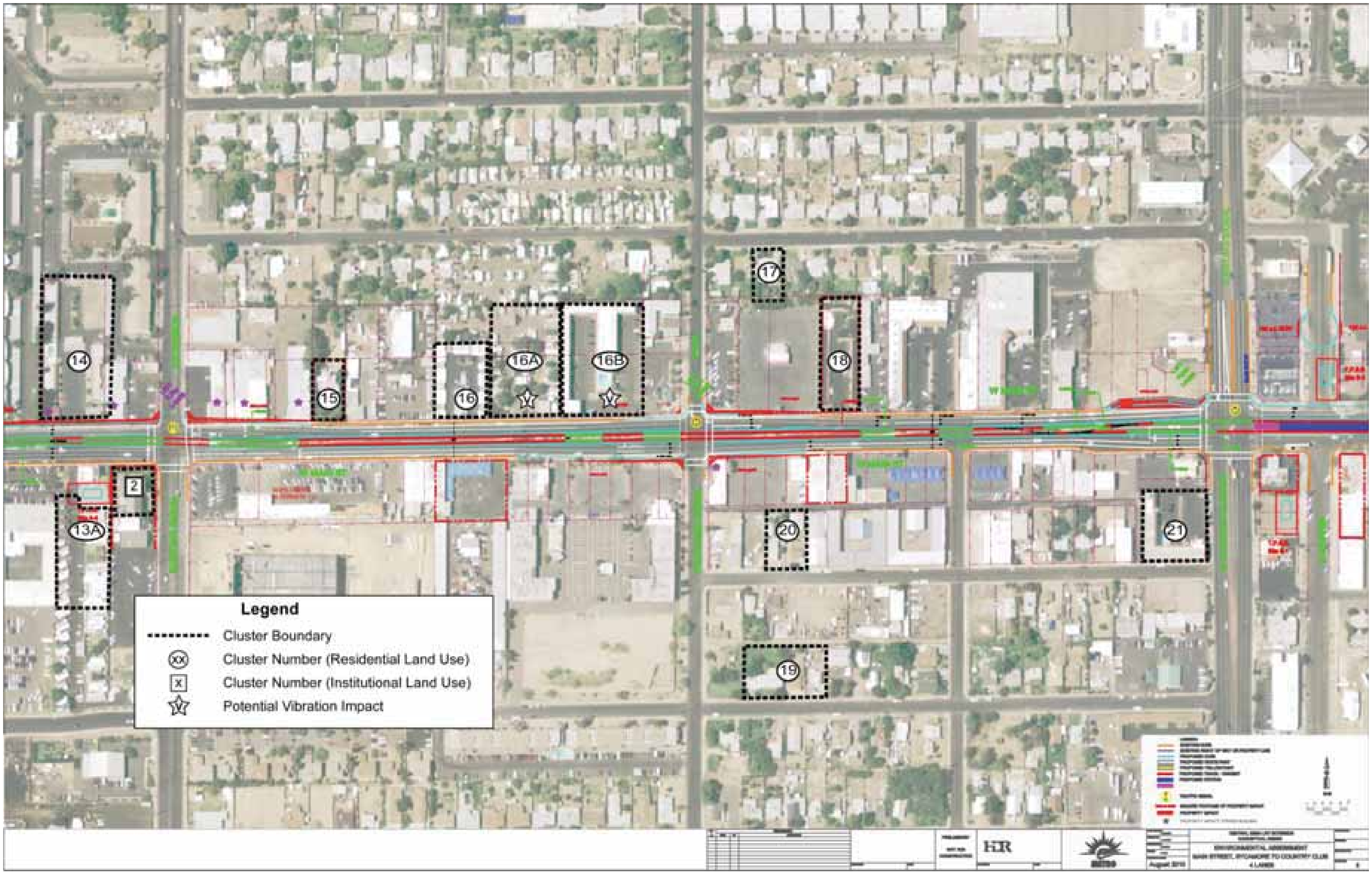


FIGURE E-4: CLUSTERS SHEET 4, 2-LANE ALTERNATIVE

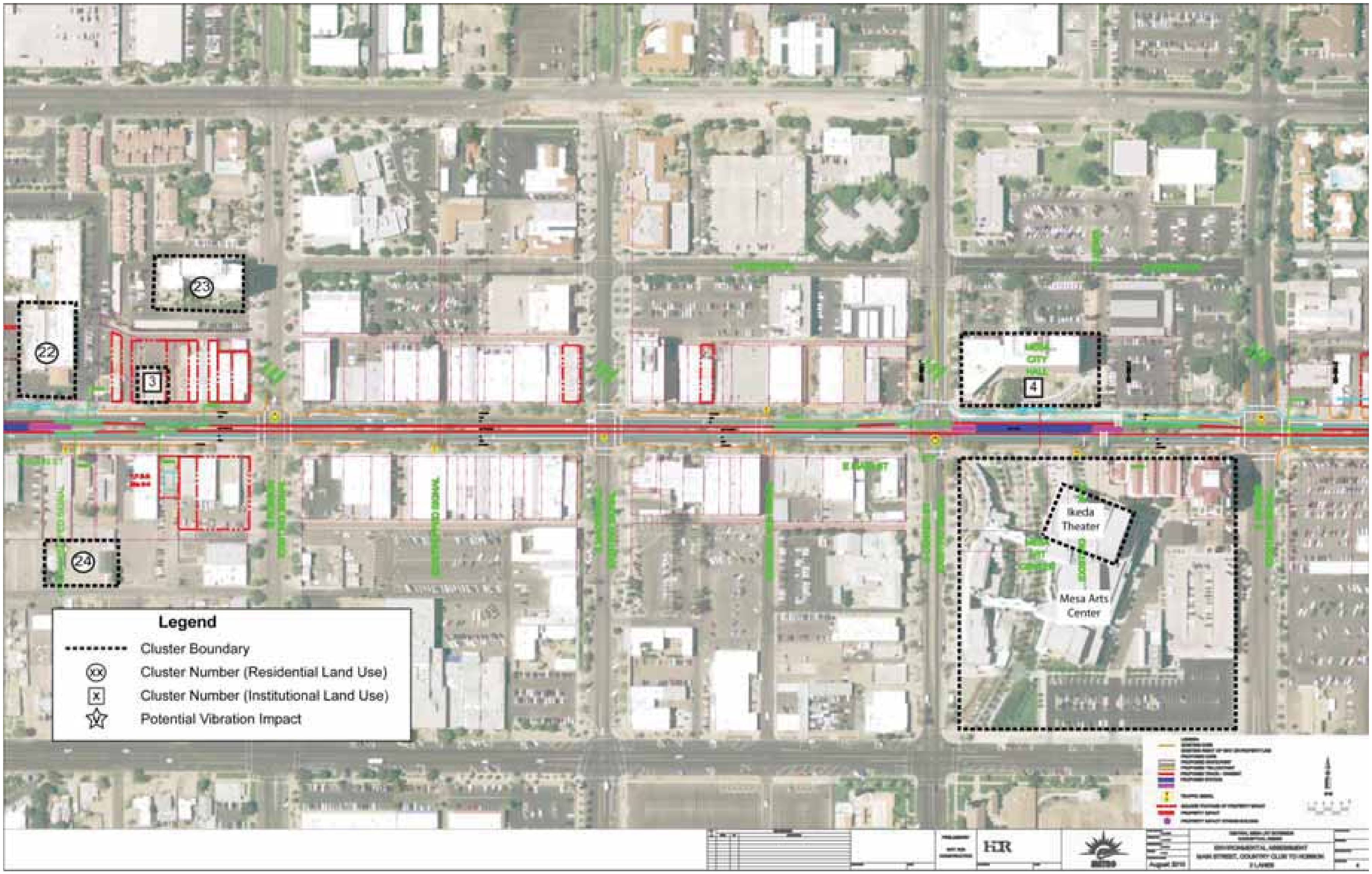


FIGURE E-5: CLUSTERS SHEET 5, 2-LANE ALTERNATIVE

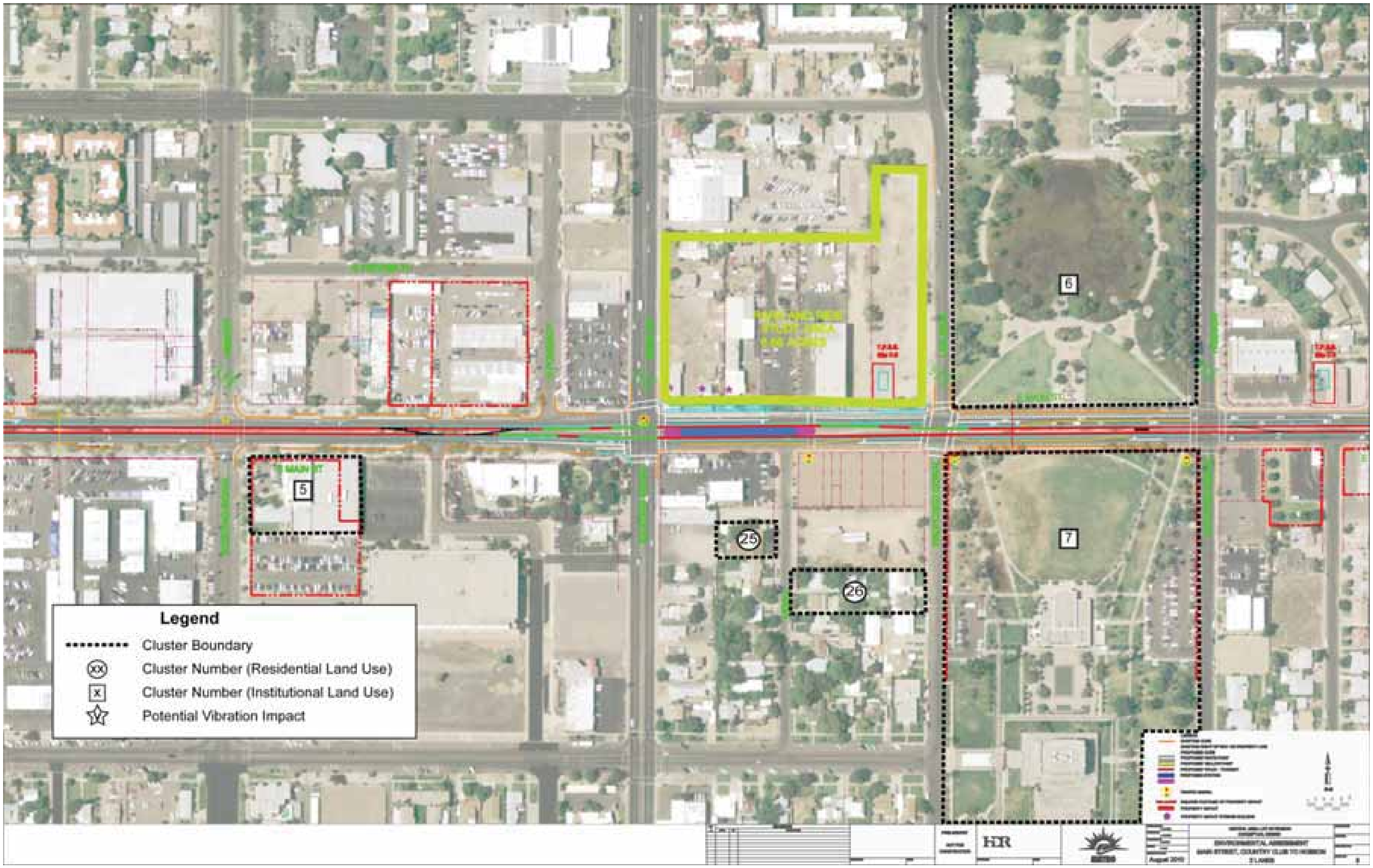


FIGURE E-6: CLUSTERS SHEET 4, 4-LANE ALTERNATIVE

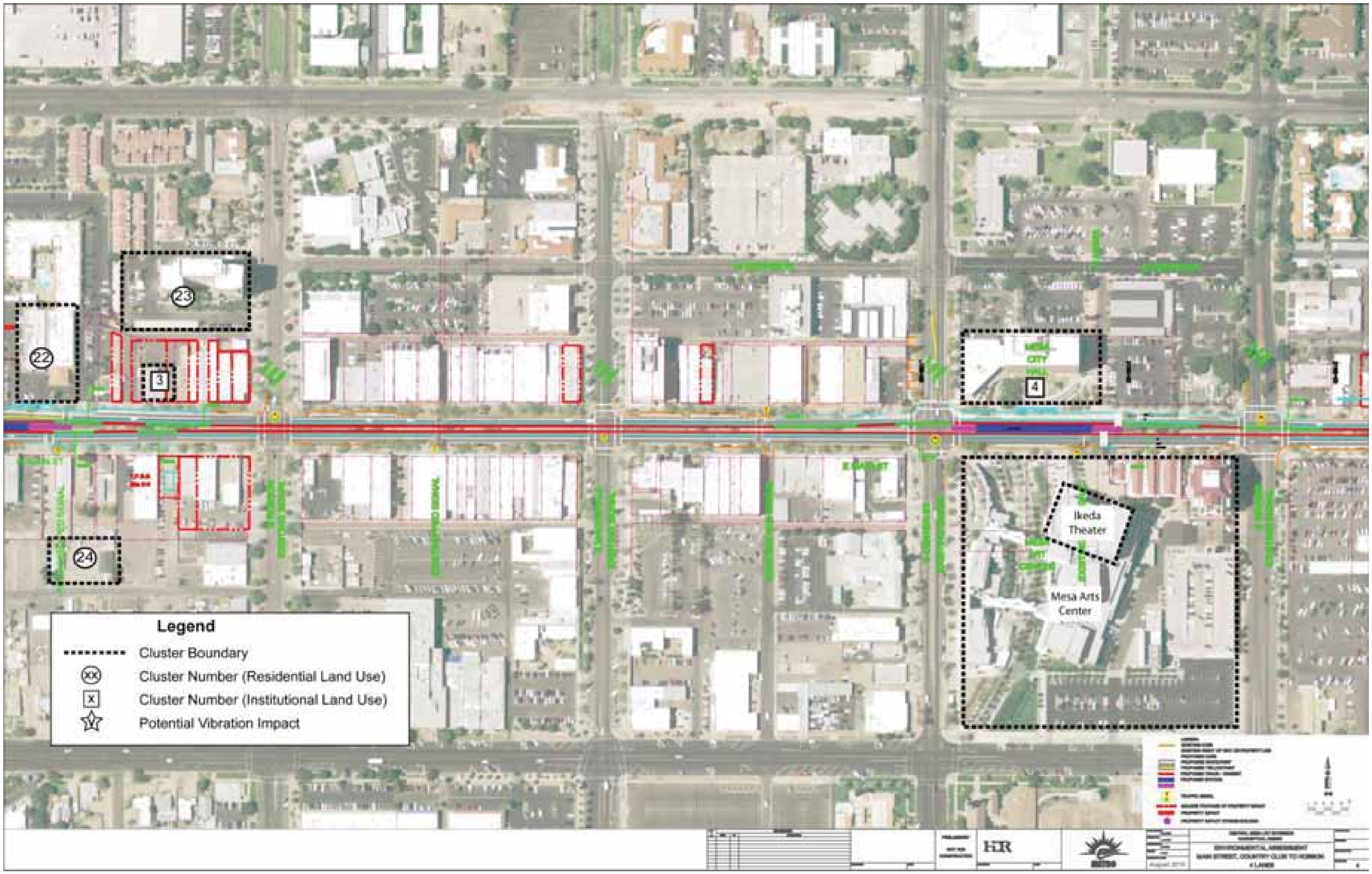
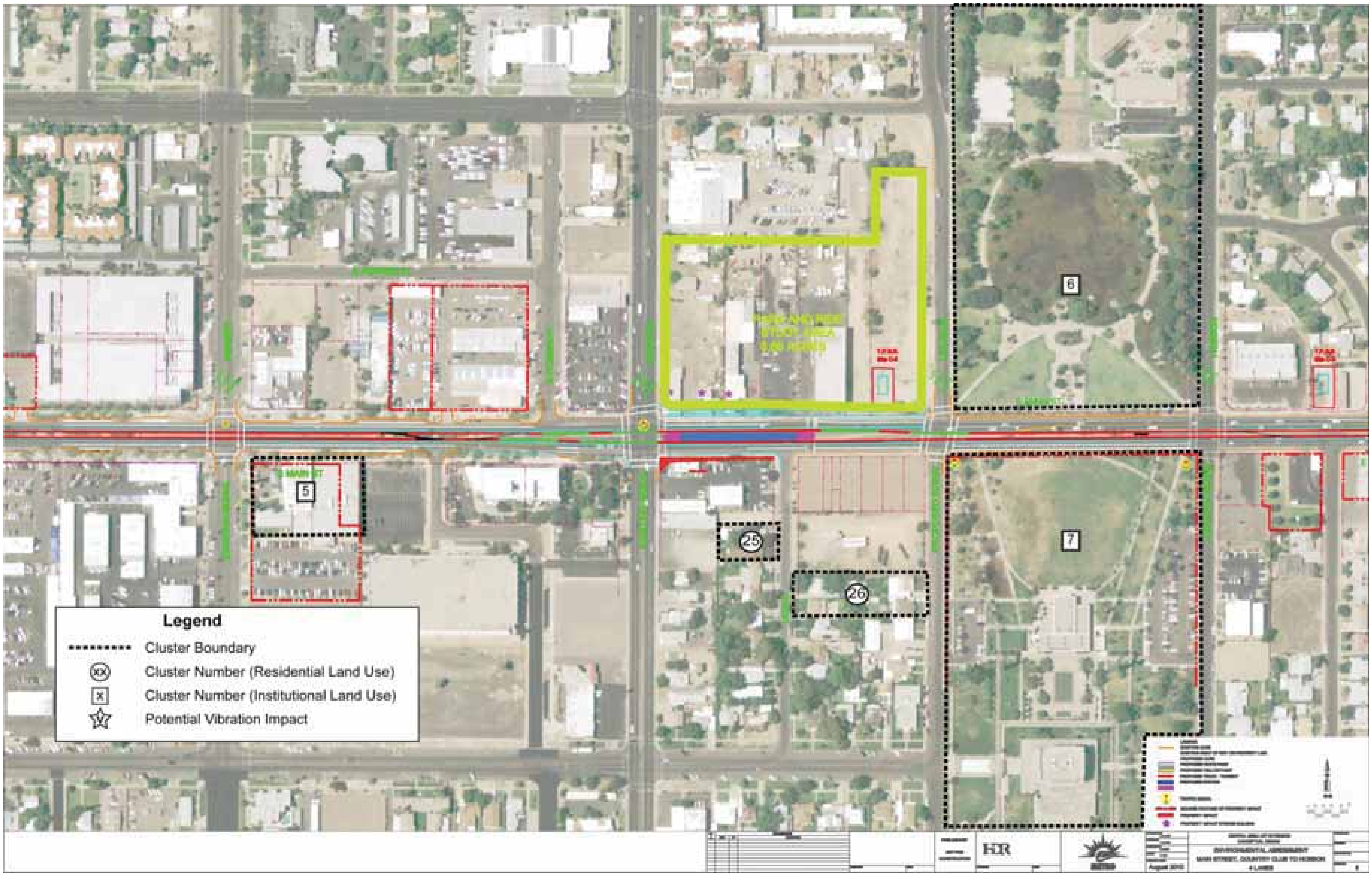


FIGURE E-7: CLUSTERS SHEET 5, 4-LANE ALTERNATIVE



APPENDIX F: DRAFT NOISE MEASUREMENT REPORT FOR CENTRAL MESA LRT EXTENSION

The details of the noise measurements are documented in a separate noise measurement report that is attached to this report. The results of the four long-term (24-hour) measurements are shown in Figure F-1 and tabulated in Table F-1. All three long-tem measurement sites were along Main Street. It is noteworthy that sites LT1 and LT3 showed comparable hourly noise levels and that the levels at LT2 were consistently 5 to 6 decibels lower over the entire measurement period. Because of the greater distance between the microphone and Main Street at LT4, measured hourly noise levels at LT4 was approximately 10 decibels lower than at LT1 and LT3.

FIGURE F-1: SUMMARY OF HOURLY LEQ OF LONG TERM NOISE MEASUREMENTS

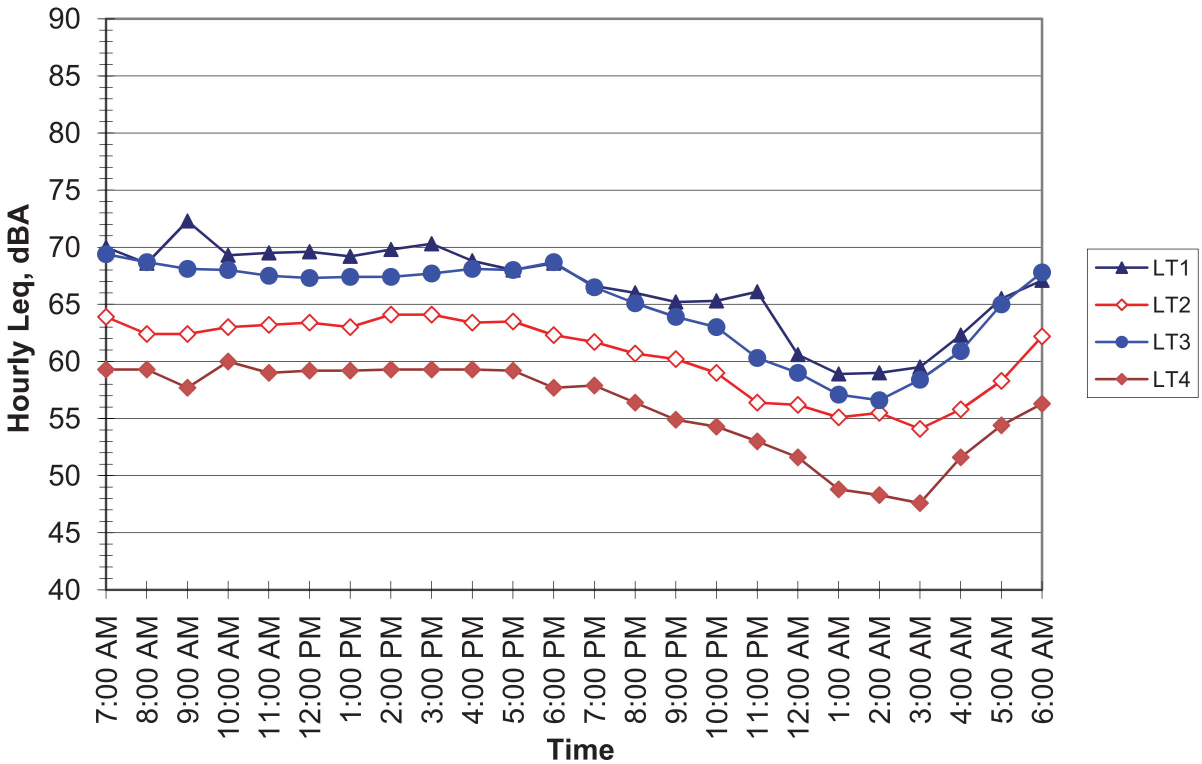


TABLE F-1: RESULTS OF MEASURED HOURLY LEQ AT LONG-TERM NOISE MEASUREMENT SITES

Start Hour	LT1	LT2	LT3	LT4
7:00 AM	70.0	63.9	69.4	59.3
8:00 AM	68.6	62.4	68.7	59.3
9:00 AM	72.3	62.4	68.1	57.7
10:00 AM	69.3	63.0	68.0	60.0
11:00 AM	69.5	63.2	67.5	59.0
12:00 PM	69.6	63.4	67.3	59.2
1:00 PM	69.2	63.0	67.4	59.2
2:00 PM	69.8	64.1	67.4	59.3
3:00 PM	70.3	64.1	67.7	59.3
4:00 PM	68.8	63.4	68.1	59.3
5:00 PM	68.0	63.5	68.0	59.2
6:00 PM	68.6	62.3	68.7	57.7
7:00 PM	66.6	61.7	66.5	57.9
8:00 PM	66.0	60.7	65.1	56.4
9:00 PM	65.2	60.2	63.9	54.9
10:00 PM	65.3	59.0	63.0	54.3
11:00 PM	66.1[a]	56.4	60.3	53.0
12:00 AM	60.6	56.2	59.0	51.6
1:00 AM	58.9	55.1	57.1	48.8
2:00 AM	59.0	55.5	56.6	48.3
3:00 AM	59.5	54.1	58.4	47.6
4:00 AM	62.3	55.8	60.9	51.6
5:00 AM	65.5	58.3	65.0	54.4
6:00 AM	67.1	62.2	67.8	56.3
Leq(day)	69.1	62.9	67.6	58.7
Leq(night)	63.8	57.7	62.5	52.7
Leq(24)	67.8	61.6	66.3	57.3
Ldn	71.5	65.3	70.1	60.6

Notes:

a. This is the adjusted Leq after removing the unusual noise peak during this hour.