Noise and Vibration Analysis Technical Report (Final)

for the

Denver – West Corridor Light Rail Transit Project

Final Design Assessment

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Introduction

As part of the Final Design for the Denver - West Corridor Project, KM Chng Environmental Inc. prepared a detailed noise assessment at the locations where noise barriers were proposed between Knox Court and Oak Street based on the results of the noise analysis contained in the FEIS. This detailed noise assessment included additional 24-hour noise measurements at fourteen locations along the project corridor where noise barriers were proposed, and a reassessment of the noise impacts based on these noise measurement results. A similar noise assessment was prepared for the west end of the project corridor between the Federal Center and the Jefferson County Government Center where noise impacts from changes in the alignment were evaluated. These changes include the single tracking of the alignment between the Federal Center and the Jefferson County Government Center, and the Indiana Street elevated crossing over US 6. Four additional 24-hour noise measurements were obtained along this section of the project corridor. KM Chng also re-evaluated the vibration levels from the LRT operations along these same sections of the West Corridor project area.

The noise and vibration analyses were performed in accordance with the methodology contained in the Federal Transit Administration's (FTA) *Transit Noise and Vibration Impact Assessment*[1].

[1] "Transit Noise and Vibration Impact Assessment", Federal Transit Administration, (FTA-VA-90-1003-06), revised May 2006.

1 NOISE

This chapter includes an introduction to basic noise concepts including noise descriptors, the prediction methodologies and modeling assumptions, the results of the ambient noise monitoring program, and the evaluation of potential impacts along the Denver – West Corridor project area.

1.1 Human Perception of Noise

The characteristics and properties of noise are explained in the following subsections.

1.1.1 Describing Noise

Noise is "unwanted sound" and, by this very definition, the perception of noise is a subjective process. Several factors affect the actual level and quality of sound (or noise) as perceived by the human ear and can generally be described in terms of loudness, pitch (or frequency), and time variation.

Loudness. The loudness, or magnitude, of noise determines its intensity and is measured in decibels (dB). The noise decibel is used to describe a large range of sound levels. For example, ambient noise ranges from 40 decibels from the rustling of leaves to over 80 decibels from a truck passby to over 100 decibels from a rock concert.

Pitch. Pitch describes the character and frequency content of noise. Measured in Hertz (Hz), frequency is typically used to identify the annoying characteristics of noise and thereby identify the proper mitigation to help eliminate or minimize its magnitude. The human ear is typically sensitive to noise frequencies between 20 Hz (low-pitched noise) and 20,000 Hz (high-pitched noise). For example, noise may range from very low-pitched "rumbling" noise from stereo sub-woofers to mid-range traffic noise to very high-pitched whistle noise.

Time Variation. The time variation of some noise sources can be characterized as continuous, such as a building ventilation fan, intermittent, such as for a train passby, or impulsive, like a car backfire.

1.1.2 Description of Noise Levels

Various levels are used to quantify noise from transit sources including a sound's loudness, duration, and tonal character. For example, the A-weighted decibel (dBA) is commonly used to describe the overall noise level. Because the decibel is based on a logarithmic scale, a 10-decibel increase in noise level is generally perceived as a doubling of loudness, while a 3-decibel increase in noise is just barely perceptible to the human ear. The A-weighting is an attempt to take into account the human ear's response to audible frequencies. Typical A-weighted sound levels from transit and other common sources are shown in Figure 1. The following A-weighted noise descriptors are typically used to determine impacts from transit related sources:

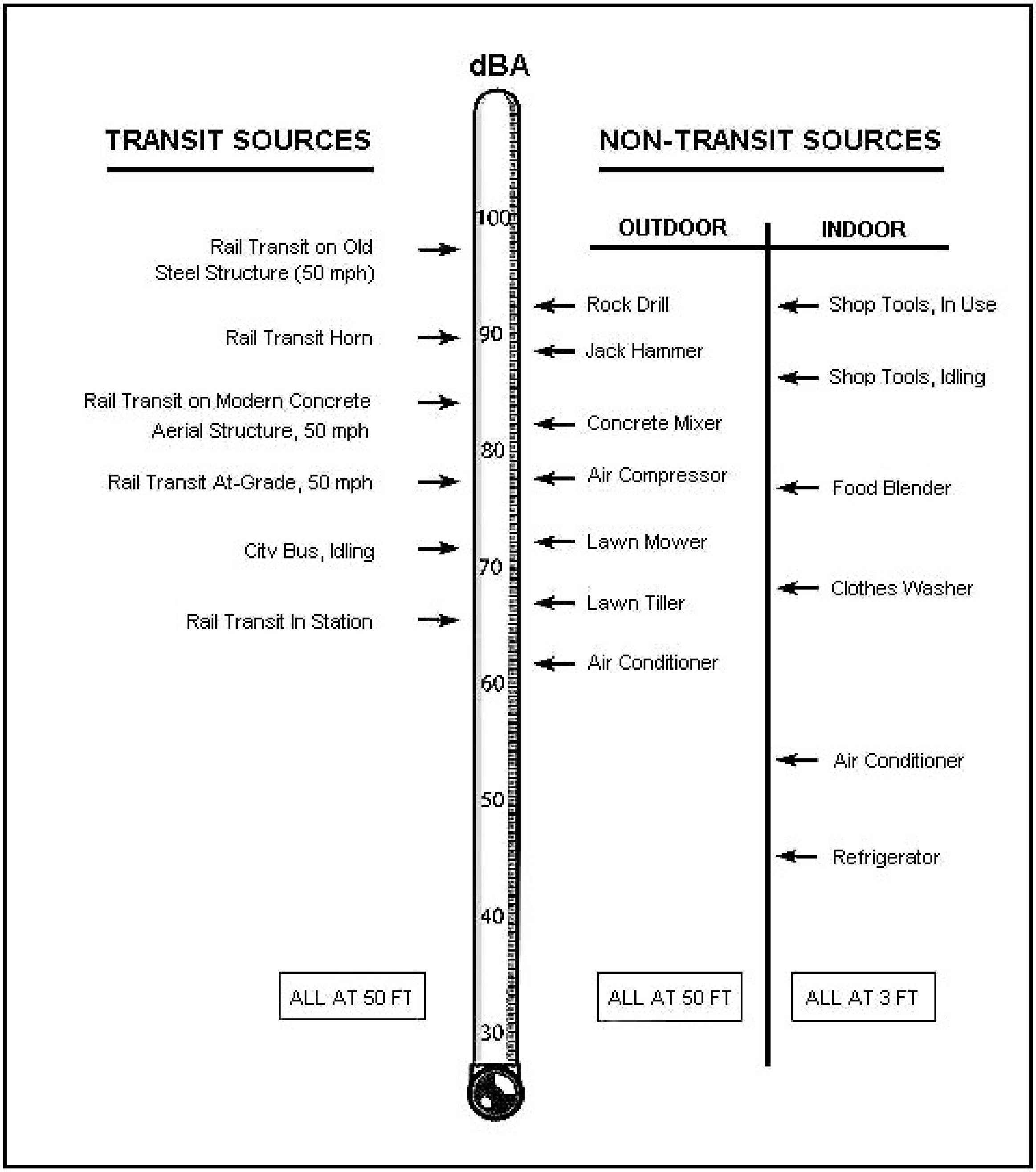


Figure 1: A-Weighted Noise Levels

- L_{MAX} represents the maximum noise level that occurs during an event or train passby and is the noise level actually heard during the event or passby.

- L_{EQ} represents a level of constant noise with the same acoustical energy as the fluctuating noise levels (e.g., highway traffic) observed during a given interval such as one hour. For transit projects the Leq noise level is commonly used to describe levels at non-residential receptors (such as offices, schools, and churches) with primarily daytime uses. L_{EQ}(h) is a noise level averaged over one hour.

- L_{DN}, the day-night noise level, represents the average noise level evaluated over a 24-hour period. A 10-decibel penalty is added to events that occur during the nighttime hours (10:00 PM to 7:00 AM) to account for people's increased sensitivity to noise while they are sleeping. For transit projects the L_{DN} level is commonly used to describe noise at residences.

- SEL is the sound exposure level typically used to predict overall transit source levels. The SEL converts the time period of the Leq to one second allowing for the direct comparison of events or passbys with different time durations.

Unlike the Lmax level, the hourly Leq(h) noise level describes noise over a longer time duration than just a single event. For example, a single LRT vehicle passby at 50 mph has an Lmax noise level of 80 dBA at a distance of 50 feet, but an Leq(h) level of only 54 dBA. This is due to the concept of time averaging whereby the overall average noise level (Leq) during the one-hour period is much less than the short-duration of the single event (Lmax) passby. However, as the number of passby events increases during the hour, the hourly Leq(h) level will increase accordingly, but will not exceed the Lmax single event noise level. The Lmax and the hourly Leq(h) levels are theoretically equivalent for constant noise sources that operate continuously over a one hour period such as a transformers or rooftop ventilation unit.

1.2 Evaluation Criteria

The criteria used to evaluate noise impacts are described in the following subsections.

1.2.1 Operational Noise

Operational criteria are used to assess noise impacts from the project alternatives when they are fully operational. These criteria are, therefore, typically evaluated against the project operations that occur in the design year.

- **FTA Noise Guidelines**

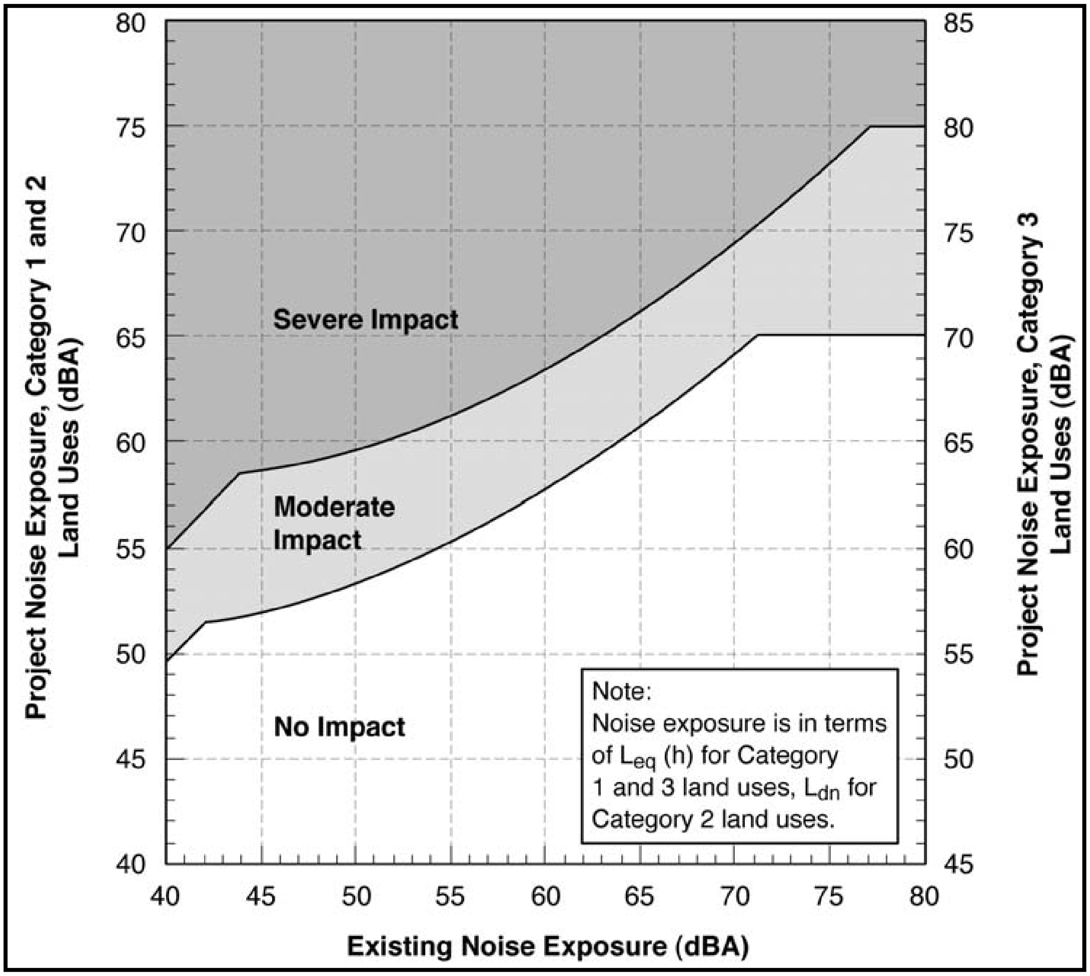
The Federal Transit Administration's *Transit Noise and Vibration Impact Assessment* guidance manual (DOT-95-16, April 1995; revised FTA-VA-90-1003-06, May 2006) presents the basic concepts, methods, and procedures for evaluating the extent and severity of noise impacts from transit projects. Transit noise impacts are assessed based on land use categories and sensitivity to noise from transit sources under the FTA guidelines. The FTA noise impact criteria are defined by two curves that allow increasing project noise levels as existing noise increases up to a point, beyond which impact is determined based on project noise alone. The FTA land use categories and required noise metric are described in Table 1.

Table 1: FTA Land Use Categories and Noise Levels

Land Use Category	Noise Metric (dBA)	Description of Land Use Category
1	Leq(h)	Tracts of land set aside for serenity and quiet, such as outdoor amphitheaters, concert pavilions, and historic landmarks.
2	L_{DN}	Buildings used for sleeping such as residences, hospitals, hotels, and other areas where nighttime sensitivity to noise is of utmost importance.
3	Leq(h)	Institutional land uses with primarily daytime and evening uses such as schools, libraries, and churches where it is important to avoid interference with such activities as speech, meditation and concentration on reading.

Source: Tranist Noise and Vibration Impact Assessment, Federal Transit Administration, Washington, D.C., May 2006.

The FTA noise criteria are delineated into two categories: moderate impact and severe impact. The moderate impact threshold defines areas where the change in noise is noticeable but may not be sufficient to cause a strong, adverse community reaction. The severe impact threshold defines the noise limits above which a significant percentage of the population would be highly annoyed by new noise. The level of impact at any specific site can be established by comparing the predicted project noise level at the site to the existing noise level at the site. The FTA noise impact criteria for all three land use categories are shown in Figure 2.



Source: Transit Noise and Vibration Impact Assessment, Federal Transit Administration, Washington, D.C., May 2006.

Figure 2: FTA Noise Impact Criteria for Transit Projects

1.3 Modeling Methodology and Assumptions

For the noise analysis, a GIS database (in ArcView) was developed from aerial photographs of the project corridor. All first row receptors and any other receptors located within approximately 250 feet of the project corridor were included in the noise analysis. The rail corridor alignment and profile were also input into the GIS database, and ArcView was used to determine the distance from the receptor to both the eastbound and westbound tracks. These distances, operations data, travel speed, and FTA reference source noise levels were input into the computer model to calculate the L_{DN} noise levels from the project at all sensitive residential receptors that were included in the GIS database. A description of the modeling methodologies and the types of noise sources included in the modeling prediction are included in the following sub-sections.

1.3.1 Operations Data

The noise impact assessment from the proposed LRT operations along the project corridor was determined in accordance with FTA guidelines. The information used in the noise modeling analysis included the following:

- FTA reference LRT source noise levels;
- Number of daytime and nighttime LRT operations;
- LRT speed along the corridor;
- Number of LRT vehicles per consist; and
- Track type.

The LRT vehicles proposed for the West Corridor are the same Siemens-Duewag light rail vehicles currently operating on other RTD LRT corridors in Denver. The LRT vehicles will operate in 2 or 3 car consists depending on the peak-hour and off-peak hour demand. The LRT vehicles will travel at a speed of 35 mph between Knox Court and Oak Street due to the residential nature of the neighborhood and the number of stations along this section of the corridor. The LRT vehicles will travel at 40-45 mph west of the Denver Federal Center where the corridor travels along US 6. In addition, the LRT vehicles will operate on continuous welded rail that generates significantly less noise and vibration than jointed track.

LRT daytime (7 AM to 10 PM) and nighttime (10 PM to 7 AM) operations data used in the noise modeling analysis are shown in Table 2. During peak hour periods, the LRT vehicles will operate on 5-minute headways, during off-peak periods the LRT vehicles will operate on 15-minute headways, and during nighttime periods the LRT vehicles will operate on 30-minute headways in each direction. Based on this operations schedule, total LRT operations are expected to be 200 daytime and 56 nighttime operations per day.

Table 2: Summary of LRT Operations Data

Operation Period	Operation Hours	Time Period	Headway	LRT per Hour[1]
Daytime	7 AM – 9 AM	Peak-Hour	5 minutes	12
	9 AM – 4 PM	Off-Peak	15 minutes	4
	4 PM – 7 PM	Peak-Hour	5 minutes	12
	7 PM – 10 PM	Off-Peak	15 minutes	4
Nighttime	10 PM – 11 PM	Off-Peak	15 minutes	4
	11 PM – 2 AM	Nighttime	30 minutes	2
	4:30 AM – 6 AM	Off-Peak	15 minutes	4
	6 AM – 7 AM	Peak-Hour	5 minutes	12

1. LRT trains per hour in each direction.

1.3.2 LRT Reference Noise Levels

The LRT vehicles proposed for the West Corridor project are the Siemens-Duewag light rail vehicles currently operating on other RTD LRT corridors. Noise measurements were obtained during vehicle passbys and were found to be consistent with the reference noise levels contained in the FTA guidance manual. The LRT reference SEL and Lmax noise levels used in the noise modeling analysis are shown in Table 3. For an LRT vehicle traveling at 50 mph at a distance of 50 feet, the Lmax noise level is 80 dBA and the SEL noise level is 82 dBA. The FTA noise model calculations adjust for speed to account for the lower speed along the east end of the corridor (35 mph).

In addition, the LRT vehicles also have warning devices that are sounded as the vehicles enter the stations and at grade crossings. These on-board warning devices consist of a gong, bells, and horn that are used during various degrees of necessity. In general, either the gong or the bells are used when the LRT vehicles enter a station to alert passengers on the platforms of oncoming vehicles. The louder horns are used at grade crossings. However, with the use of quad-gates at grade crossings, the use of the horns is not required except in an emergency. The measured Lmax sound levels obtained by RTD at a distance of 10 feet from the various warning devices is 75 dBA for the gong, 95 dBA for the bells, and 112 dBA for the horn.

Table 3: FTA Reference Noise Source Levels

Noise Source	FTA Reference Noise Level (dBA)	
	Lmax	SEL
LRT vehicles[1]	80	82
Gong[2]	75	78
Bell[2]	95	98
Horn[2]	112	115
LRT Vehicle Idling[3]	70	106

1. FTA Noise level for LRT vehicles at a distance of 50 feet traveling at a speed of 50 mph.
2. RTD measured noise level at a distance of 10 feet.
3. FTA reference Lmax and SEL (for 1-hour period) noise level for LRT vehicle idling.

1.3.3 FTA Noise Calculations

Using the LRT reference source noise levels, the average hourly daytime and nighttime operations, and speed described in the previous sections, the LRT passby hourly Leq(h) noise level at a distance of 50 feet was calculated using the equations shown below from the FTA guidance manual.

$$LeqM_{50}(h) = SEL_{ref} + 10\log(N_{cars}) + 20\log\left(\frac{S}{50}\right) + 10\log(V) + C_{adj} - 10\log(3600) \quad \text{[Equation. 1]}$$

where:

$LeqM_{50}(h)$ = hourly Leq noise level at 50 feet (in dBA) from commuter rail passbys;
SEL_{REF} = reference SEL noise level at 50 feet (in dBA);
N_{CARS} = average consist size (i.e., number of LRT cars per train);
S = train speed (in mph);
V = average hourly commuter rail volumes as follows (in trains/hour):

$$V_D = \left(\frac{\sum_{7AM}^{10PM} number\ of\ trains}{15}\right)$$ [average hourly daytime volume];

$$V_N = \left(\frac{\sum_{10PM}^{7AM} number\ of\ trains}{9}\right)$$ [average hourly nighttime volume];

$$V_{PK} = \sum_{PK-HR} number\ of\ trains$$ [average hourly peak-hour volume];

C_{ADJ}	= adjustment factor applied to track type as follows (in dBA);	
	= +5	for jointed track;
	= +4	for aerial structure with slab track; and,
	= +3	for embedded track on grade.
-10log(3600)	= Leq(h) adjustment factor based on the number of seconds in one hour (in dBA).	

24-Hour L_{DN} Noise Level

At residential receptors identified along the project corridor the 24-hour L_{DN} noise level was used to assess impact against the FTA impact criteria. Using Equation 3, average hourly L_{EQ} noise levels during the daytime (from 7 a.m. to 10 p.m.) and the nighttime (from 10 p.m. to 7 a.m.) periods were used to develop an overall 24-hour L_{DN} noise level.

$$Ldn_{50} = 10\log\left[15 \times 10^{\left(\frac{LeqD_{50}}{10}\right)} + 9 \times 10^{\left(\frac{LeqN_{50}+10}{10}\right)}\right] - 10\log(24) \qquad \text{[Equation 3]}$$

where:

Ldn50	= 24-hour Ldn noise level at 50 feet (in dBA);
LeqD50	= average daytime hourly Leq(h) noise level at 50 feet between 7 a.m. and 10 p.m. (in dBA);
LeqN50	= average nighttime hourly Leq(h) noise level at 50 feet with 10-dBA penalty applied for nighttime events between 10 p.m. and 7 a.m. (in dBA); and,
-10log(24)	= Ldn adjustment factor based on the number of hours in a day (in dBA).

1.4 Existing Conditions

Existing noise levels were measured at representative locations along the project corridor to characterize the existing ambient background noise levels. The scope and the results of the noise measurement program are described in the following subsections.

1.4.1 Background Ambient Noise Measurements

In accordance with FTA noise guidelines, a noise-measurement program was conducted along the West Corridor to (1) establish the existing ambient background levels within the project area and (2) develop project criteria noise limits in accordance with FTA guidelines.

Noise measurements were obtained in June 2006, with additional supplemental noise measurements obtained in September 2006. Noise measurements over a 24-hour period were obtained at a total of 18 locations. Fourteen of these locations were along the east section of the corridor between Knox Court and Oak Street, and four were along the west section of the corridor (three between Union Boulevard and Indiana Street, and one at the Mountainside Estates at the intersection of Colfax Avenue and US 6).

The noise measurements along the east section of the corridor were obtained as part of the final design phase of the project to provide a detailed noise assessment of the noise barriers that were proposed based on the results of the noise analysis contained in the FEIS. A similar noise assessment was prepared for the west end of the project corridor between the Federal Center and the Jefferson County Government Center where noise impacts from changes in the alignment were evaluated. These changes include the single tracking of the alignment between the Federal Center and the Jefferson County Government Center, and the Indiana Street elevated crossing over US 6. As a result of these changes, four additional noise measuremed locations were selected along this section of the project corridor. The location of these 18 measurement sites are shown graphically in the figures contained in Appendix A.

The results of the noise-monitoring program are summarized in Table 4 for each of the 18 measurement locations. These measurements were used to establish the existing background ambient noise levels along the project corridor, and to develop the allowable project noise limits for moderate impact and severe impact using the curves in Figure 2 from the FTA guidance manual. The resulting noise impact criteria are indicated in Table 4 for each measurement site.

The measured L_{DN} noise levels along the east end of the project corridor between Knox Court and Oak Street ranged from 51.4 dBA at measurement location M-14 (at 10575 13th Avenue) to 64.7 dBA at measurement location M-12 (at 10000 13th Place) where the higher measured noise levels are due to the heavy traffic volumes on Kipling Street. In general, the measured L_{DN} noise level at receptor locations near major cross streets with moderate to heavy traffic (M-1 near Knox Court, M-3 near Sheridan Boulevard, and M-12 near Kipling Street) ranged from 60.8 dBA to 64.7 dBA. The measured L_{DN} noise levels at locations between major cross streets ranged from 51.4 dBA at measurement location M-14 to 56.1 dBA at measurement location M-11 depending on the level of local street traffic in the area and the proximity to major cross streets with heavier traffic volumes.

The measured L_{DN} noise levels along the west end of the project corridor along US 6 between Union Boulevard and Indiana Street ranged from 62.8 dBA at measurement location M-15 (at the Van Gordon Street Apartments) to 68.8 dBA at measurement location M-16 (at 13859 West 5th Avenue). The higher measured L_{DN} noise levels at these locations are due to the higher traffic volumes and speeds on US 6 and local street traffic on the adjacent collector roads. Measurement locations M-15 and M-16 are on the south side of US 6 adjacent to the new alignment, while measurement location M-17 is on the north side of US 6.

L_{DN} noise measurements were also obtained at the Mountainside Estates (measurement location M-18) near the interchange of Colfax Avenue and US 6 where the alignment has shifted closer to these residences. The measured L_{DN} noise level at the Mountainside Estates was 58.5 dBA. Although this location is close to US 6, the Mountainside Estates are located below the elevation of the highway, and the terrain provides shielding from the highway traffic noise.

The measured twenty-four hourly Leq(h) noise levels at each of the eighteen measurement locations are shown in the figures in Appendix B. These figures show how the hourly Leq(h) noise levels vary throughout the daytime and nighttime periods, and were used to calculate the L_{DN} noise level. A 10-decibel penalty is added to the hourly Leq(h) noise levels measured during the nighttime hours (10 PM to 7 AM) to account for people's sensitivity to noise during the nighttime period. (This 10-decibel penalty is not shown in the figures in Appendix B). The twenty-four hourly Leq(h) noise levels are then logarithmically averaged to obtain the L_{DN} noise level used in the noise impact assessment.

Table 4: Summary of L_{DN} Noise Measurements and FTA Impact Criteria

Site No.	Location	Measured-L_{DN} Level (dBA)	FTA-Moderate Impact Criterion[1]	FTA-Severe Impact Criterion[1]
East End of Corridor (Knox Court to Oak Street)				
M-1	1095 Knox Court	61.9	59	64
M-2	1227 Quitman Street	54.9	55	61
M-3	1220 Ames Street	60.8	58	63
M-4	1301 Otis Street	59.1	55	61
M-5	7020 13th Avenue	54.9	55	61
M-6	1295 Vance Street	57.0	55	61
M-7	1275 Allison Street	56.0	55	61
M-8	1295 Cody Street	55.9	55	61
M-9	1310 Garrison Street	54.9	55	61
M-10	9348 West 13th Place	52.6	54	60
M-11	1190 Johnson Street	56.1	55	61
M-12	10000 13th Place	64.7	58	64
M-13	10280 13th Place	53.8	55	61
M-14	10575 13th Avenue	51.4	54	60
West End of Corridor (along US 6)				
M-15	453 Van Gordon Street	62.8	60	65
M-16	13859 West 5th Avenue	68.8	63	68
M-17	624 Eldredge Street	68.7	63	68
M-18	Mountainside Estates	58.5	56	62

1. These criteria represent the allowable project noise limits based on the measured exixting noise level.

The measured L_{DN} noise levels along the project corridor were then used to determine the allowable project noise limits from the LRT operations alone. The project noise limits for moderate impact and severe impact were determined using the curves in Figure 2 from the FTA guidance manual. The noise levels from the left side of the figure are used to determine the L_{DN} levels for residential (FTA Category 2) receptors. The FTA noise impact criteria for the West Corridor project are also shown in Table 4. Since the noise impact criteria vary based on the measured L_{DN} noise level, it is possible that two residential receptors with the same predicted project noise level could result in an impact condition at one receptor with the lower measured existing noise level, and a non-impact condition at the second receptor with a higher measured existing noise level.

1.5 Noise Assessment

A detailed noise assessment was prepared for the West Corridor project to determine the potential noise impacts along the project corridor. Using information from the GIS database, and the FTA noise calculation methodology described in Section 1.3.3, L_{DN} noise levels were calculated at all sensitive receptor locations within approximately 250 feet of the project corridor between Knox Court and Oak Street along the east end of the project corridor. A similar noise assessment was prepared for the west end of the project corridor between the Federal Center and the Jefferson County Government Center where noise impacts from changes in the alignment were evaluated. These changes include the single tracking of the alignment between the Federal Center and the Jefferson County Government Center, and the Indiana Street elevated crossing over US 6. In addition, the noise analysis also includes the noise generated by the LRT vehicles traveling over the Dudley/Cody Street track double crossovers, and the use of warning bells as the LRT vehicles enter the station area.

All receptors along the project corridor analysis area were assigned background noise levels based on their proximity to each of the eighteen noise measurement locations. In this way, noise impact criteria were established for each receptor based on the moderate impact and severe impact criteria shown in Table 4. The calculated L_{DN} noise levels from the West Corridor project were then compared to these FTA criteria to determine impact.

1.5.1 Noise Impacts from LRT Operations

A comparison of the predicted L_{DN} noise levels from the LRT operations (with the use of warning bells as the LRT vehicles enter the station area) to the FTA impact criteria established for each of the receptors along the project corridor resulted a total of 50 severe impacts and 168 moderate impacts. Of this total, all 50 severe impacts and 157 of the moderate impacts are located along the east end of the corridor between Knox Court and Oak Street. The remaining 11 moderate impacts are located at the Mountainside Estates at the west end of the project corridor that runs along US Route 6. The severe impacts represent those receptors that are located closest to the project corridor. The project impacts are summarized in Table 5, and the location of the severe and moderate noise impacts are shown in the figures (aerial photographs) contained in Appendix C.

Also contained in Appendix C is a summary table of all the impacted receptors with a specific receptor identification number that corresponds to the identification number shown in the figures. In this way the information contained in the table can be readily correlated with a specific receptor location in the figures. Also contained in the table is the calculated L_{DN} noise level at each of the impacted receptors, the FTA moderate and severe impact criteria levels from Figure 2, the number of decibels above the criteria levels, and the FTA impact designation of each receptor.

Comparing these results with the impact analysis contained in the FEIS indicates that along the east end of the project corridor between Knox Court and Oak Street, the total number and location of the impacted receptors are almost identical. The only specific areas where differences occur are between Raleigh Street and Stuart Street, and between Wolff Street and Zenobia Street where the FEIS identified several moderate noise impacts. However, from the results of the current noise analysis, these receptors were found to be located too far from the project corridor for the noise generated by the LRT operations to exceed the FTA noise impact criteria.

Table 5: Summary of FTA Noise Impacts

Corridor Section	FTA-Severe Impacts	FTA-Moderate Impacts	Total FTA Impacts
Knox Court to Oak Street	50	157	207
Union Boulevard to Jefferson County Government Center (along US 6)	0	11	11
Total Impacts	50	168	218

For the west end of the project corridor between the Federal Center and Jefferson County Government Center where the alignment is now single tracked and the US 6 elevated crossover has been relocated to Indiana Street, this revised noise analysis indicates that noise impacts are not expected to occur along this section of the project corridor. Because of the high background noise levels measured along this section of the project corridor (M-15, M-16, and M-17 in Table 4), the residential receptors located in this area are not impacted by the project. However, because of the lower background noise level measured at the Mountainside Estates, and the shift in the LRT single-track alignment closer to these residences, the results of the noise analysis indicate a total of 11 impacted receptors in this area. These results are similar to those reported in the FEIS.

1.5.2 Noise Impacts from LRT Warning Devices

The LRT vehicles are equipped with several types of warning devices: a gong, a bell, and a horn. RTD's standard operating procedures require the warning bell to be sounded for approximately 5 to 10 seconds (corresponding to a distance traveled of approximately 200 feet) as the LRT vehicles enter the station area. The LRT horns will only be sounded in an emergency condition. Because of the use of quad-gates at the grade crossings, the use of the LRT warning horns at grade crossings is not required. In addition, RTD does not plan to use wayside bells at quad-gated grade crossings. However, PUC has final approval. The use of gongs and bells at the LRT stations was evaluated separately to determine the change in noise levels at receptors located near the stations. Those LRT stations with nearby residences that were included in this analysis are: Knox Court Station, Perry Street Station, Sheridan Station, Lamar Street Station, Wadsworth Station, Garrison Street Station, Oak Street Station, and Red Rock Station.

The measured Lmax sound level from the gong is 75 dBA at a distance of 10 feet, or 61 dBA at a reference distance of 50 feet. This corresponds to an Lmax noise level of 77 dBA for an LRT vehicle at a distance of 50 feet traveling at 35 mph. The FTA noise model was used to calculate the L_{DN} noise contribution from the gong at all receptors located within 200 feet of the stations. The results of this noise analysis indicate that the use of the gong will result in no increase in the total L_{DN} noise levels at those receptors located near the stations. The calculated L_{DN} noise levels from the gong is significantly below the L_{DN} noise levels from the LRT operations (more than 10-dBA) such that the logarithmic sum of the two noise sources results in essentially no increase in noise above that produced by the LRT vehicles alone. As a result, although the gong will be audible above the background noise levels, it does not contribute to the overall calculated L_{DN} noise level from the LRT operations.

The FTA noise model was then used to calculate the L_{DN} noise contribution from the LRT bells at all receptors located within 200 feet of the stations. The measured Lmax sound level from the LRT bells is 95 dBA at 10 feet, or 81 dBA at a reference distance of 50 feet. The results of this noise analysis indicate that the use of the LRT bells while entering a station increases the overall L_{DN} noise levels of the receptors located within 200 feet of the stations by approximately 2 dBA. As a result of this increase in L_{DN} noise level with the LRT bells, four of the previous moderately impacted receptors (without the bells) now become severe impacts, and four previously non-impacted receptors now become moderately impacted. This change in the total number of noise impacts is relatively small because most of the receptors near the stations are already impacted by the project.

Table 6: Summary of Noise Impacts with and without Warning Devices

	Severe Impacts	Moderate Impacts	Total Impacts
LRT Operations without warning devices	46	168	214
LRT Ops with sounding gong at stations	46	168	214
LRT Ops with sounding bells at stations	50	168	218

Table 6 summarizes the results of this analysis. In addition, the table in Appendix D contains the predicted L_{DN} noise levels at the receptor locations near the stations both with and without the LRT warning bells.

1.5.3 Noise Analysis of Bus Operations at LRT Stations

In addition to the noise from the LRT vehicles and warning bells at the station areas, RTD buses will also contribute to the overall project noise levels. Because of the West Corridor LRT project, bus operations along several of the bus routes are expected to increase. For example, bus operations along Sheridan Boulevard are expected to increase from 67 to 121 daily operations; bus operations along Wadsworth Boulevard are expected to increase from 125 to 154 daily bus operations; and the existing buses operating on Kipling Street (39 daily bus operations) will be re-routed onto Oak Street (95 daily bus operations) to provide access to LRT service at Oak Street Station. There is currently no bus service on Oak Street. Bus operations on Knox Court, Lamar Street, and Pierce Street will remain unchanged and were therefore, not included in this noise assessment.

As a result, the noise from bus operations at Sheridan Station, Wadsworth Station, and Oak Street Station are included in this analysis and reflect the additional noise from the incremental increase in bus operations associated with the LRT project, and the noise from the idling buses that stop at the LRT stations. The typical dwell time for the buses at Sheridan Station and Wadsworth Station is 20-seconds, while the dwell time at the Oak Street Station could be up to 3-minutes because there is off-street parking for the buses. If a bus remains at the station for more than 3-minutes, the bus driver is required to shut-off the engine. The typical Lmax noise level for a city bus at a distance of 50 feet traveling at a speed of 35 mph is 80 dBA. For idling buses at a distance of 50 feet, the Lmax noise level is 75 dBA. The bus noise analysis was performed in accordance with FTA procedures.

The bus noise analysis only addresses the noise levels at residential receptors in the immediate vicinity of the LRT stations. This analysis is not meant to be a system wide noise assessment of the entire bus route. The incremental increase in bus operations on Sheridan Boulevard and Wadsworth Boulevard are not expected to result in a significant change in noise levels along these bus routes because of the existing traffic noise along these roads.

Appendix G summarizes the results of the noise analysis of bus operations at Sheridan Station, Wadsworth Station, and Oak Street Station. In general, at the various sensitive receptor locations near the stations, the bus operations result in a 0 to 1-dBA increase in the noise levels generated by the LRT operations alone. However, the bus operations at Sheridan Station will result in a 3-dBA increase in noise level due to the proximity of the receptor to the bus stop.

1.5.4 Noise Mitigation

According to FTA guidelines, all severe impacts should be eliminated and moderate impacts should be eliminated to the extent that it is reasonable and feasible to do so. In order to reduce the number of noise impacts along the project corridor, noise barriers are the recommended noise mitigation. The noise barriers would be located at the edges of the typical 34-foot wide LRT guideway. Because the noise barriers would be located close to the rail corridor, and because the primary noise source from the LRT vehicles is wheel/rail noise, the noise barriers should be at least 6-foot high to provide effective noise mitigation.

The results of the FTA noise modeling analysis indicate that a 6-foot high noise barrier would provide approximately 7-dBA of noise reduction from the near track and 5-dBA of noise reduction from the far track. As a result, the number of noise impacts would be reduced to no severe impacts and 31 moderate impacts. Table 7 summarizes the results of the noise barrier analysis.

Although noise barriers with sound absorption on the interior walls could provide an additional 1-dBA of noise reduction by further reducing the noise from the near track (but no additional noise reduction benefit for the far track), the primary benefit from the sound absorption would be to reduce the reflected noise toward the residents on the opposite side of the rail corridor.

Table 7: Summary Results of the Noise Barrier Analysis

Summary of Project Noise Impacts	Severe Impacts	Moderate Impacts	Total Impacts
Without Mitigation	50	168	218
With 6-ft. High Noise Barrier	0	31	31

From the results of the noise barrier analysis, it is recommended that 6-foot high noise barriers with sound absorptive material on the interior walls be used to reduce the noise impacts along the project corridor. The 6-foot high noise barriers will reduce the noise levels at all of the severe impacted receptors to levels that are below the FTA severe impact criteria. However, the 6-foot high noise barriers will not provide enough noise mitigation to reduce the noise levels to below the FTA moderate impact criteria at all of the severe impact locations. As a result, the remaining moderate noise impacts in Table 7 after mitigation are the remnants from the severe impacted receptors. To reduce most of the remaining impacted receptors to below the FTA moderate impact criteria, an 8-foot high noise barrier would be required at these locations.

Because of the much higher noise levels generated by the LRTs as they travel over the Dudley/Cody Street standard type track crossovers, a 15-foot high noise barrier would have been required at this location to reduce the noise levels of the severe impacted receptors. However, because of the number of additional noise and vibration impacts from the Dudley/Cody Street track crossover, and the height of the noise barrier required to provide the necessary noise mitigation, RTD has decided to install spring loaded rail frogs at this location. The spring loaded rail frogs significantly reduce the noise and vibration levels by reducing the gaps in the rails of a typical track crossover. Standard track crossovers can increase passby noise levels by up to 10-dBA. The use of spring rail frogs can reduce the noise levels by 8 to 10 dBA resulting in noise levels that are similar to or slightly higher than those generated by LRT vehicles traveling on continuous welded rail.

For the noise impacted receptors at the Mountainside Estates, where the LRT alignment will be located above the residences on top of a 20-foot high retained earth structure, the height of the noise barrier can be reduced to 2-feet. In addition, noise barriers on the elevated sections of the project corridor (Wadsworth Boulevard and Kipling Street) could be reduced to a 4-foot height and still provide adequate noise reduction.

Appendix E contains two tables describing the results of the noise barrier analysis. Table E1 describes the location, the recommended height, and the approximate length of each of the proposed noise barriers. Because of the north/south cross streets along the project corridor for local street traffic, the noise barriers are broken into a number of barrier segments rather than several long continuous barriers. The total length of the proposed noise barriers is 27,532 feet (14,245 feet along the west bound track of the project corridor, and 13,287 feet along the east bound track). In addition, Table E2 in Appendix E compares the results of the predicted L_{DN} noise levels with no barrier, and with a 6-foot high noise barrier. The figures in Appendix C show the approximate location of the proposed noise barriers.

The noise impacte mitigation measures described above are based on recommendations pursuant to the FTA guidelines. However, the noise barrier locations will be further modified by the implementation of RTD's policy for *Noise Mitigation Measures for Moderate Impacts.* This policy contains additional screening requirements for noise barriers. The results of implementing this policy will be addressed in a separate technical memorandum.

Noise barriers can be made of any outdoor weather-resistant solid material that meets a minimum sound transmission loss requirement. The normal minimum requirement is a surface density of 4 pounds per square foot. To hold up under wind loads, structural requirements are more stringent. Achieving the maximum possible noise reduction requires careful sealing of gaps between barrier panels and between the barrier and the ground. For this project, pre-cast concrete noise panels with sound absorptive properties are recommended. Two manufacturers of this type of noise barriers are Concrete Solutions, Inc. and The Fanwall Corporation. Typical noise barriers could range from 2-inches to 4-inches thick depending on the structural integrity required of the wall.

2. Vibration

This section introduces some basic ground-borne vibration and ground-borne noise concepts including the prediction methodologies and modeling assumptions, the results of the existing source vibration measurement program, and the evaluation of impacts along the project corridor.

2.1 Human Perception of Vibration

The characteristics and properties used to describe ground-borne vibration and noise are explained in the following subsections.

2.1.1 Describing Vibration

Ground-borne vibration associated with vehicle movements is usually the result of uneven interactions between the wheel and the road or rail surfaces. Examples of such interactions (and subsequent vibrations) include train wheels over a jointed rail, an untrue railcar wheel with "flats", and motor vehicle wheels hitting a pothole or even a manhole cover.

Unlike noise, which travels in air, transit vibration typically travels along the surface of the ground. Depending on the geological properties of the surrounding ground and the type of building structure exposed to transit vibration, vibration propagation may be more or less efficient. Buildings with a solid foundation set in bedrock are "coupled" more efficiently to the surrounding ground and experience relatively higher vibration levels than those buildings located in sandier soil.

Similarly, ground-borne noise results from vibrating room surfaces located near a heavily traveled transit corridor, such as a subway line. Consequently, annoyance resulting from the "rumbling" sound of ground-borne noise is only evaluated indoors and is described using the A-weighted decibel.

2.1.2 Description of Vibration Levels

Vibration induced by vehicle passbys can generally be discussed in terms of displacement, velocity, or acceleration. However, human responses and responses by monitoring instruments and other objects are more accurately described with velocity. Therefore, the vibration velocity level is used to assess vibration impacts.

To describe the human response to vibration, the average vibration amplitude called the root mean square (RMS) amplitude, is used to assess impacts. The RMS velocity is expressed in inches per second (ips) or decibels (VdB). All VdB vibration levels are referenced to 1 µips.

To evaluate the potential for damage to buildings, the peak particle velocity (PPV) is also used to characterize the vibration. Typically expressed in units of ips, PPV represents the maximum instantaneous vibration velocity observed during an event. Typical ground-borne vibration levels from transit and other common sources are shown in Figure 3.

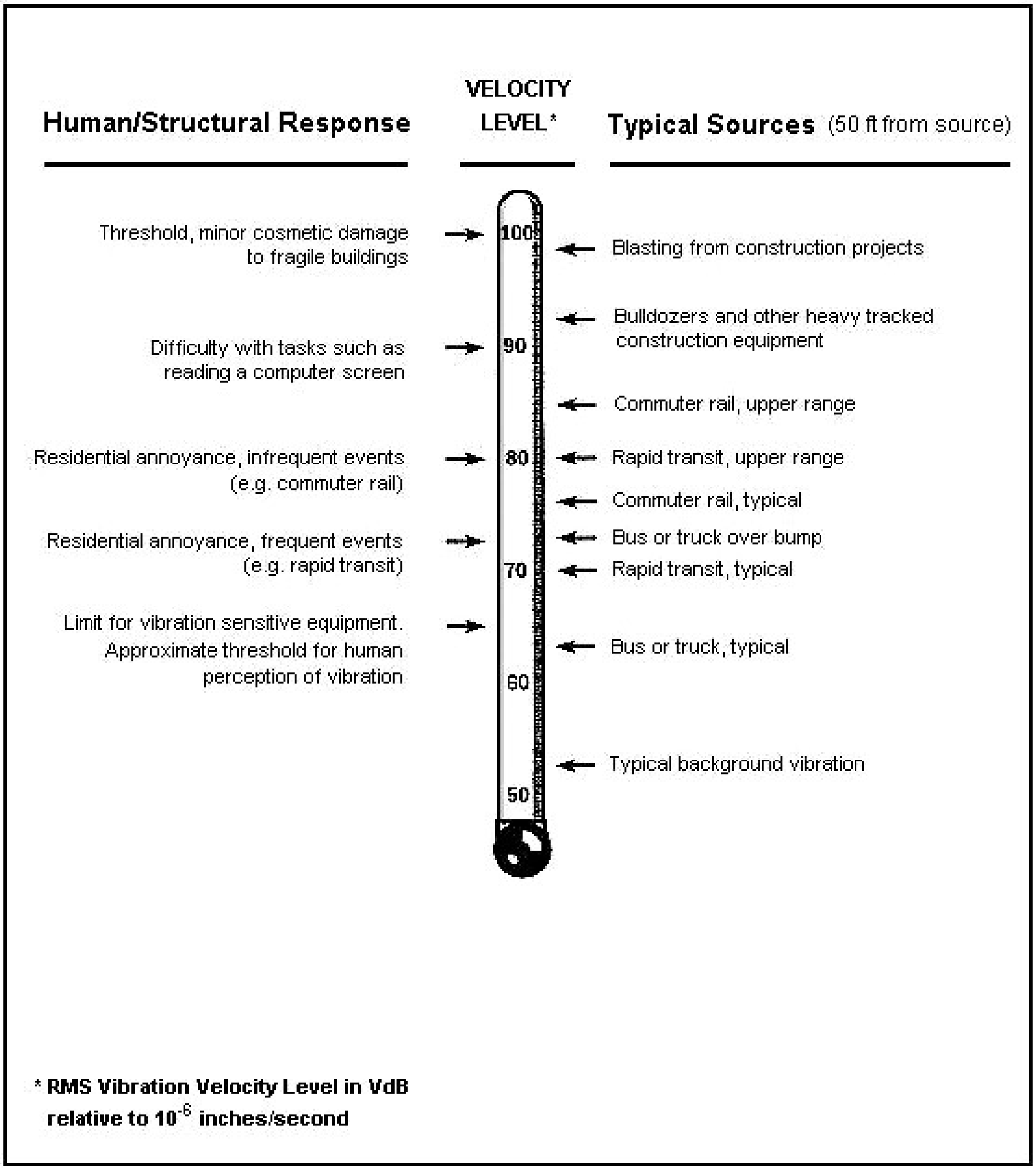


Figure 3: Typical Ground-Borne Vibration Levels

2.2 Evaluation Criteria

As described in the following subsections, the FTA criteria was used to assess annoyance due to vibration and ground borne noise from single event transit operations.

2.2.1 FTA Criteria

The FTA vibration criteria for evaluating ground borne vibration (and noise) impacts from train passbys at nearby sensitive receptors are shown in Table 8. These vibration criteria are related to ground borne vibration levels that are expected to result in human annoyance, and are based on RMS velocity levels expressed in VdB. The FTA's experience with community response to ground borne vibration indicates that when there are only a few train events per day, it would take higher vibration levels to evoke the same community response that would be expected from more frequent events. This is taken into account in the FTA criteria by distinguishing between projects with frequent, occasional, and infrequent events. Frequent events is defined as more than 70 vibration events per day; occasional events is defined as between 30 and 70 vibration events per day; and infrequent events is descried as fewer than 30 vibration events per day. The vibration criteria levels shown in Table 8 are defined in terms of human annoyance for different land use categories such as high sensitivity (Category 1), residential (Category 2), and institutional (Category 3). In general, the vibration threshold of human perceptibility is roughly 65 VdB.

The vibration levels shown in Table 8 are well below the damage criteria levels of approximately 95 to 100 VdB. It is extremely rare for vibration from train operations to cause any sort of building damage, including minor cosmetic damage.

Table 8: FTA Ground-Borne Vibration Impact Criteria for Annoyance (VdB)

Land Use Category	**Ground-Borne Vibration Impact Levels (VdB relative to 1 mico-inch/second)**		
	Frequent Events[1]	Occasional Events[2]	Infrequent Events[3]
1	65 VdB	65 VdB	65 VdB
2	72 VdB	75 VdB	80 VdB
3	75 VdB	78 VdB	83 VdB

1. Frequent events are defined as more than 70 vibration events per day.
2. Occasional events are defined as between 70 and 30 vibration events per day.
3. Infrequent events are defined as fewer than 30 events per day.

2.3 Modeling Methodology and Assumptions

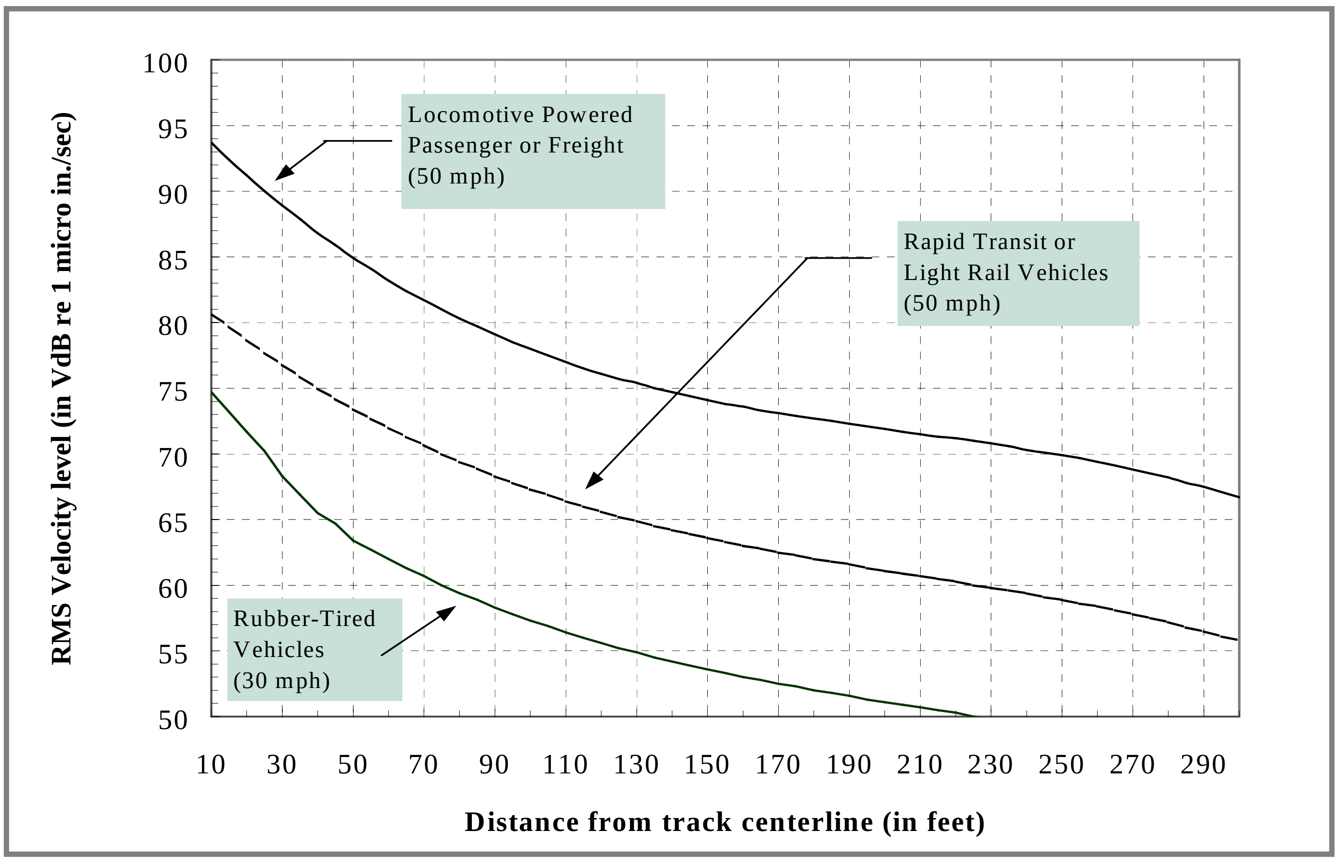
A description of the modeling methodologies and the types of vibration sources included in the modeling prediction are described in the following sub-sections.

2.3.1 Modeling Methodology

Using the FTA's General Assessment methodology, vibration levels from LRT passbys were predicted at receptor locations along the project corridor.

Vibration levels from LRT passbys at sensitive receptors along the project corridor were determined using the FTA guidelines. LRT passbys traveling along continuously welded rail and the Dudley/Cody Street track crossover were included in the modeling analysis.

Reference vibration levels from LRT passbys at 50 mph are based on the FTA ground surface propagation curve shown in Figure 4. Since the total number of LRT passbys along the project corridor exceeds 70 events per day, the FTA impact criterion for residential receptors is 72 VdB from Table 8. For LRT vehicles traveling at 50 mph, the impact distance from Figure 4 is approximately 60 feet. However, since the LRT vehicles along the West Corridor travel at a speed of 35 mph, the impact distance adjusted for speed is approximately 38 feet. In other words, any residential receptor located within 38 feet of the track will receive a vibration level of at least 72 VdB, and will therefore be identified as impacted by the project based on the FTA criteria.



Source: *Transit Noise and Vibration Assessment,* Federal Transit Administration, Washington, D.C., May 2006.

Figure 4: FTA Generalized Ground Surface Vibration Curves

2.4 Vibration Impact Assessment

Using the FTA vibration curve in Figure 4 adjusted for speed, and the distance from each receptor to the nearest track obtained from the GIS database, vibration levels were calculated at all receptors along the project corridor. These calculated vibration levels were then compared to the FTA criterion (72 VdB) to determine impact. Vibration impacts from the Dudley/Cody Street track crossover were also evaluated. LRT vehicles traveling over a track crossover can generate vibration levels that are up to 10-VdB higher than over continuous welded rail. However, RTD's decision to install spring loaded rail frogs at the Dudley/Cody Street track double crossovers has eliminated the vibration impacts at this location.

The results of the vibration impact analysis indicate that there are a total of 12 impacted receptors along the project corridor. All 12 impacted receptors are located along the east end of the project corridor between Knox Court and Oak Street where the residences are relatively close to the rail corridor. There were no vibration impacts predicted along the west end of the project corridor along US 6, where the receptors are located further from the track alignment. For the impacted receptors along the rail corridor, the vibration levels are 1 to 3-VdB above the FTA vibration impact criterion. Appendix F contains a table of the predicted vibration levels at each of the impacted receptors. These impacted receptor locations are shown graphically in the figures in Appendix F.

In addition to the vibration impact assessment at residential receptors, vibration levels were also evaluated at buildings with vibration sensitive equipment. Two such buildings that have been identified are the Denver Federal Center located approximately 430 feet from the nearest LRT track and the Gambro Medical Facility located approximately 75 feet from the nearest LRT track. Applying the FTA's 65-VdB impact criterion for Category 1 receptors (buildings where low ambient vibration is essential for interior equipment operations), the impact distance for LRT vehicles traveling at 35-40 mph is approximately 95 feet. Therefore, the Denver Federal Center is too far away from the LRT corridor to be impacted, while the Gambro Medical Facility could be impacted. However, since we don't know the exact location of the vibration sensitive equipment inside the building or the actual sensitivity of the equipment, it's possible that the coupling losses between the ground and the building foundation (which could be up to 10-VdB depending on the building construction) should be sufficient to reduce the vibration levels inside the building to below the equipment impact specifications.

The number of vibration impacts from this analysis differs from the results in the FEIS where a total of 46 vibration impacts were identified. This difference in the number of impacts is due to the use of different vibration curves than those presented in the FTA guidance manual. For LRT vehicles traveling at 35 mph, the FEIS analysis used an impact distance of 42 feet for ineffective ground vibration propagation characteristics, and 53 feet for effective ground vibration propagation characteristics. However, there is no description in the FEIS of how these vibration curves were developed, and how they were applied on this project.

2.5 Vibration Mitigation

For the 12 vibration impacts identified along the project corridor, ballast mats or shredded rubber tires (such as that used on the Denver T-Rex Project) are recommended as the appropriate mitigation measure. Ballast mats and shredded rubber tires can provide approximately 3 to 10 VdB reduction in vibration levels depending on the frequency of the vibration. For single vibration impacted receptors, the ballast mat should extend for a distance of approximately 100 feet under the tracks directly in front of the impacted receptor.

Appendix A

Noise Measurement Locations

Appendix B

Noise Measurement Results

(Measured Hourly Leq(h) and L_{DN} Noise Levels)

Appendix C

Noise Impact Analysis

Appendix D

Noise Impact Analysis from LRT Gongs and Bells

Appendix E

Noise Barrier Analysis

Appendix F

Vibration Impact Analysis

Appendix G

Bus Noise Analysis at LRT Stations