Report No. CDOT-2005-21
Final Report

EVALUATION OF THE FHWA TRAFFIC NOISE MODEL (TNM)FOR HIGHWAY TRAFFIC NOISE PREDICTION IN THE STATE OF COLORADO

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November 2006

COLORADO DEPARTMENT OF TRANSPORTATION
RESEARCH BRANCH

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16. Abstract

The Federal Highway Administration's Traffic Noise Model (TNM) versions 2.1 and 2.5 were analyzed to determine their functionality and accuracy in Colorado. First, predicted levels were compared to noise levels measured at 42 locations at 13 sites throughout Colorado. In general, TNM predicted within ± 2 dB of the measured noise levels. Second, each of TNM's input parameters was varied through its useful range. The results for the Hard Soil ground type, barrier insertion loss, flow control, and parallel barriers do not completely agree with known acoustical principles and should be studied further. Finally, TNM results were compared to those of the German RLS90, Nordik Statens Planverk, and STAMINA noise models. TNM exhibits a faster decay rate than all of the other models, and predicts higher insertion loss than the other models for low height barriers.

Implementation:

The findings of this report have been incorporated into the Traffic Noise Model User's Guide for CDOT Projects. The Users Guide will be distributed to CDOT staff and consultants.

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EVALUATION OF THE FHWA TRAFFIC NOISE MODEL (TNM) FOR HIGHWAY TRAFFIC NOISE PREDICTION IN THE STATE OF COLORADO

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Sponsored by the
Colorado Department of Transportation
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Federal Highway Administration

November 2006

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EXECUTIVE SUMMARY

In 2002, CDOT undertook this study in an effort to better understand the complexities of the Federal Highway Administration's new Traffic Noise Model (TNM). The research involved three analyses. First, noise levels predicted using TNM were compared to noise levels measured in various locations across the State. Second, each of TNM's input parameters was varied across its useful range, and the resulting changes in predicted noise level were analyzed. Third, noise levels predicted using TNM were compared to those predicted by other internationally recognized noise models. The overall goal of the study was to develop a Colorado-specific TNM Users Guide, where the use of the Guide will result in accurate and consistent noise analyses on CDOT projects.

For the comparison of measurements to predictions, noise levels were measured at 42 locations at 13 sites across the State of Colorado. During the measurements, traffic and terrain data was collected which was used to create models of each measurement site using STAMINA 2.0, TNM 2.1, and TNM 2.5. The models were used to predict noise levels at each measurement location. On an average and statistical basis, the accuracy is comparable among all three models. STAMINA 2.0 and TNM 2.1 achieved an average absolute error of 2.0 dB, while TNM 2.5 achieved an average absolute error of 1.9 dB. TNM 2.5's maximum overprediction was 5.0 dB and its maximum underprediction was 4.4 dB. STAMINA predicted within 3 dB of measured levels at 34 sites (81% of total). TNM 2.1 predicted within 3 dB of measured levels at 33 sites (79% of total). TNM 2.5 predicted within 3 dB of measured levels at 35 sites (83% of total). Despite the overall comparability of the models, there were significant differences in the results at some sites. In some cases all three models over predict or under predict in the same manner. At other sites one model overpredicted while the other(s) underpredicted. There is no clear trend, e.g. where one model consistently overpredicts or underpredicts versus another.

Each of TNM's input parameters was varied across its usable range, and the effect on predicted noise levels at both close and distant receptors was analyzed. The results for most of the parameters tested were in agreement with published acoustic principles. The results for the following input parameters were *not* in complete agreement with published acoustic principles (note - it is beyond the scope of this study to determine why TNM results differ from other

published data; the differences are pointed out only to guide users and recommend future research; no error on TNM's part is explicitly implied):

- Ground Type: Using a default ground type of Hard Soil versus Lawn results in an increase of 7 dB for a receptor located 300 feet from the road. This is a greater increase than that predicted by other models and by theoretical equations. Therefore, users should exercise care in the selection of default ground type.
- Heavy Trucks and Barriers: The insertion loss of a barrier should decrease when the heavy truck percentage increases. This is because some of the acoustic energy from trucks is emitted from the engine and stack, which are elevated, while all of that from cars comes from the tires/roadway surface. TNM predictions conducted as part of this study showed no change in barrier insertion loss due to increasing truck percentage. This should be investigated further.
- There appears to be a problem with TNM's flow control routine for receptors located more than 500 feet from the road. The increase in noise levels due to a flow control device should drop off with increasing distance from the road. This is what the TNM results exhibit up to about 500 feet. Then, the effect of flow control begins to increase. This should be investigated further, and users should avoid modeling flow control devices for receptors located more than 500 feet from the road.
- There is very little difference in the predicted level from TNM when modeling a barrier as a wall verses a berm. Studies have shown that berms generally provide an extra 1–3 dBA of attenuation (FHWA-EP-00-005/DOT-VNTSC-FHWA-00-01, titled FHWA Highway Noise Barrier Design Handbook, Final Report, February 2000). This should be investigated further.
- TNM's parallel barrier routine provided results that were not in agreement with measurements taken along 6th Avenue in Denver. The mirror source method was employed using TNM and provided better results. Parallel barrier analyses should be conducted carefully, and results compared to those achieved using the mirror source method.

- The routine that predicts the location of noise level contours in TNM is cumbersome, and does not agree with predictions at individual locations. It should not be used to determine impacts on CDOT projects.

When TNM predictions were compared to those of the German RLS 90 model, the Nordic Statens Planverk 48 model, and STAMINA, the following items of note were observed (note - there is no implication herein that TNM is in error, only that there are differences between TNM and other models):

- Regarding decay rate, TNM 2.5 exhibits a faster decay rate than all of the other models at distances greater than 300 feet from the road. FHWA should be queried as to why this is the case.
- The results of ground type analyses vary significantly between the models, and TNM was within range of the others. However, TNM analysis results showed what appears to be an anomaly at receptors 400 to 600 feet from the road when using Hard Soil (predicted values 2 dB higher). FHWA should be queried as to why this is the case.
- TNM predicts a greater insertion loss for low height barriers (e.g. 3 feet) than the other models, and higher than that observed in the field. Therefore, users should exercise caution when modeling such barriers with TNM.

Implementation Statement

The findings of this report have been incorporated into the CDOT TNM Users Guide (Version 1). The Users Guide will be distributed to CDOT staff and consultant noise analysts. Note that only TNM 2.5 findings were used in the recommendations.

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1.0 INTRODUCTION

As of May 2, 2005, any traffic noise analysis required per 23 CFR, Part 772.17(a) Traffic Noise Prediction, must use the FHWA Traffic Noise Model (FHWA TNM, or simply TNM) which is described in "FHWA Traffic Noise Model" Report No. FHWA-PD-96-010, including Revision No. 1, dated April 2004, or any other model determined by the FHWA to be consistent with the methodology of TNM. As of this writing, the most current version of TNM is version 2.5. TNM contains all new algorithms and a new user interface, and is much more complex than the model in use to date: Standard Method in Noise Analysis (STAMINA v2.0).

It is imperative that CDOT conduct accurate noise studies so that mitigation decisions are made in a consistent manner from project to project, region to region, and analyst to analyst. CDOT uses a combination of internal staff and consultants to conduct its noise studies. The level of noise modeling expertise varies, as does familiarity with TNM (which has been used by other states since the release of Version 1.0 in 1998). Given the sophistication of the model, the variation in user expertise, and the complexities of Colorado terrain and conditions, it was determined that research was necessary in order to develop a CDOT TNM Users Guide.

The research involved three analyses. First, noise levels predicted using TNM were compared to noise levels measured in various locations across the State. Second, each of TNM's input parameters was varied across its useful range, and the resulting changes in predicted noise level were analyzed. Third, noise levels predicted using TNM were compared to those predicted by other internationally recognized noise models. The remainder of this report is organized as follows:

- Section 2 Validation of TNM Using Measured Noise Levels
- Section 3 Analysis of specific TNM Input Parameters
- Section 4 Comparison of TNM to Other Roadway Noise Models
- Section 5 Review of FHWA's Phase 1 TNM Validation
- Section 6 Conclusions and Recommendations
- Section 7 References
- Appendix A Traffic Noise Model User's Guide for CDOT Projects

2.0 VALIDATION OF TNM USING MEASURED NOISE LEVELS

TNM was “validated” by comparing predicted noise levels to those measured at 42 individual locations contained in the 13 sites shown in Figure 2-0. A list of the sites and a description of the measurement locations are provided in Table 2-1. The sites were selected to achieve a reasonable geographic representation of the State of Colorado, a representation of different CDOT Regions, include different types of roads, and encompass varying topography and elevation. Some preference was given to sites where accurate topographical data could be readily obtained (specifically, scaled mapping with at least 2-foot elevation contours), and to sites where good-quality noise and traffic data was available from previous CDOT studies.

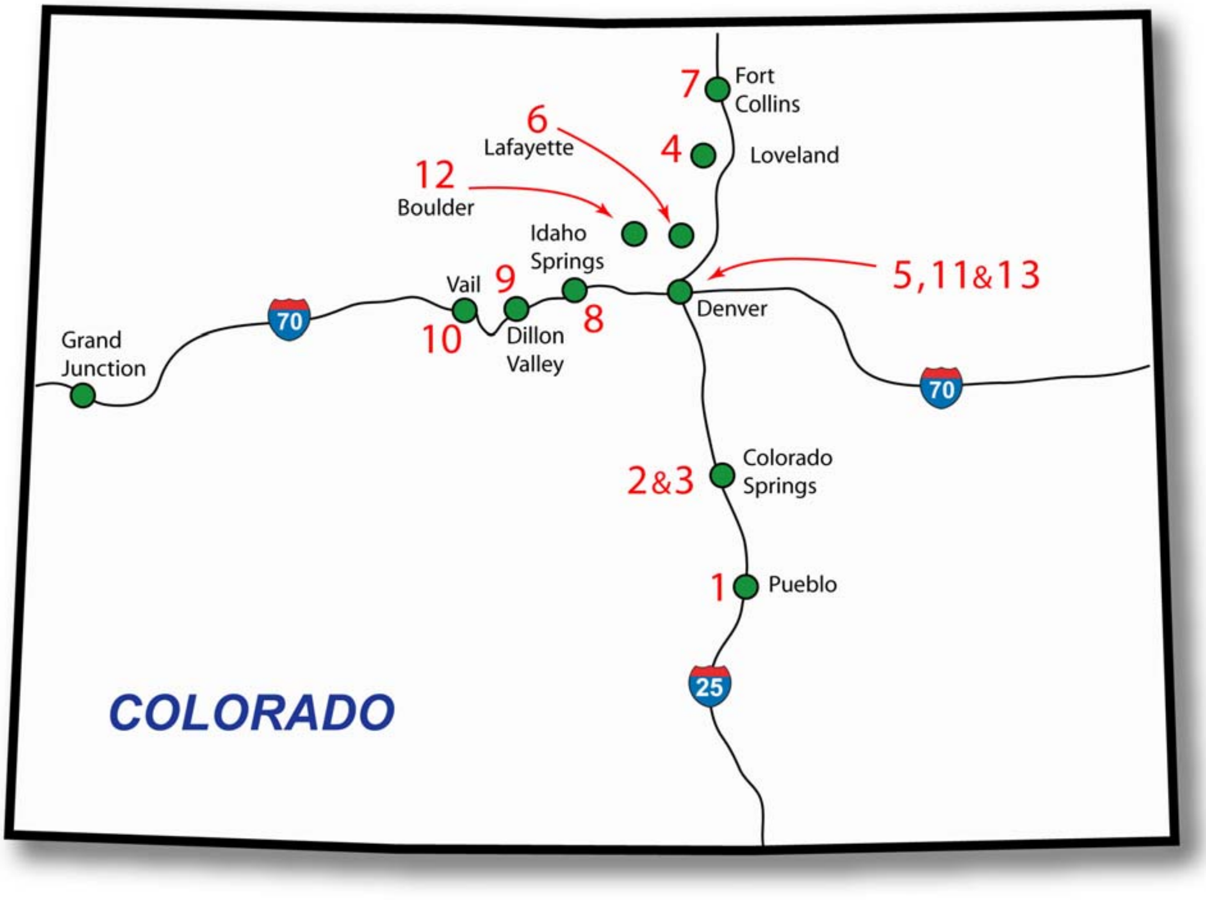


Figure 2-0: General Location of Noise Analysis Sites

Table 2-1: Noise Analysis Sites

Site No.	*Roadway – City*	*General Site Description*	*CDOT Region*	*County*
1	I-25 – Pueblo	West side of I-25, between 24th and 29th Streets	2	Pueblo
2	Powers Blvd. – Colorado Springs	Carefree Circle Area	2	El Paso
3	I-25 – Colorado Springs	East side of I-25 south of Baptist Road	2	El Paso
4	SH 402 – Loveland	Between US 287 and I-25	4	Larimer
5	6th Avenue – Lakewood	Wadsworth Area	6	Denver
6	US 287 – Lafayette	Both sides of US 287 near Beacon Hill neighborhood	4	Boulder
7	US 287 – Fort Collins	Both sides of US 287 near Shields	4	Larimer
8	I-70 – Idaho Springs	North side of I-70 between Exists 239 and 241	1	Clear Creek
9	I-70 – Dillon Valley	Dillon Valley East neighborhood (south side of I-70)	1	Summit
10	I-70 – Vail	North Side of I-70 on east end of town	3	Eagle
11	C-470 – Littleton	Near the C-470 and I-25 interchange	6	Douglas
12	US 36 – Boulder	Between Baseline Road and Foothills Parkway	4	Boulder
13	US 36 - Westminster	Between W 80th Avenue and Federal	6	Adams

2.1 Detailed Site Descriptions

Site 1 – I-25 in Pueblo (See Figure 2-1)

This site is located along the west side of I-25 in Pueblo between 24th and 29th Streets. Measurements were conducted in the residential neighborhood at the two locations shown in the figure. Notable acoustic features of the measurement locations include:

- Minor shielding by houses;
- Propagation of noise over grassy detention basins;
- Three-foot tall safety barrier along west side of I-25; and
- Traffic speeds and volumes were moderate, with some merging traffic.

Site 2 – Powers Boulevard in Colorado Springs (See Figure 2-2)

This site is located along the west side of Powers Boulevard in Colorado Springs between Carefree Circle South and Carefree Circle North. Measurements were conducted in the residential neighborhood at the two locations shown in the figure. Notable acoustic features of the measurement locations include:

- Significant shielding by houses;
- Propagation of noise over grassy terrain; and
- Moderate traffic speeds and volumes, with some stop-and-go due to the traffic light to the north.

Site 3 – I-25 in Colorado Springs (See Figure 2-3)

This site is located along the east side of I-25 in Colorado Springs, south of Baptist Road. Measurements were conducted in this residential neighborhood at the two locations shown in the figure. Notable acoustic features of the measurement locations include:

- Propagation over relatively flat, open, and grassy terrain; and
- High traffic speeds and volumes.

Site 4 – SH-402 in Loveland (See Figures 2-4a and 2-4b)

This site is located along both sides of SH 402 between US 287 and I-25. Measurements were conducted in this rural area at the four locations shown in the figures. Notable acoustic features of the measurement locations include:

- Flat terrain with few obstructions; and
- Moderate speeds (50 mph) and low volumes.

Site 5 – 6th Avenue in Lakewood (See Figure 2-5)

This site is located along the south side of US 6 (6th Avenue) in Lakewood, just east of the Wadsworth interchange. Measurements were conducted here to provide data to test TNM's parallel barrier analysis routine. There is a 12.2-foot tall concrete noise wall running continuously along both sides of 6th Avenue as well as a safety barrier along the centerline. Measurements were conducted at a control location (M1), where there is no noise wall along the south side of the road, and at two locations in the residential neighborhood behind the south wall (M2 and M3). Notable acoustic features of the measurement locations include:

- Urban setting with significant roadways surrounding area;
- High traffic speeds (65 mph) and high traffic volumes; and
- Barrier reflections from noise wall and safety barrier.

Site 6 – US 287 in Lafayette (See Figures 2-6a and 2-6b)

This site is located along both sides of US 287 in Lafayette between Baseline Road and Arapahoe Road. The measurements along the west side of US 287 were conducted to provide data to test TNM's ability to model reflections (hence they are labeled 1R ... 4R in Figure 2-6a). The measurements on the east side of US 287 were conducted to provide data to test TNM's barrier insertion loss prediction accuracy (hence they are labeled 1IL ... 4IL in Figure 2-6b). Traffic speed and volume at this site are moderate to high. Notable acoustic features of the measurement locations include:

- Shielding of some receptors by a noise wall and a row of houses; and
- Barrier reflections from noise wall.

Site 7 – US 287 in Fort Collins (See Figure 2-7)

This site is located along the north side of US 287 in Fort Collins, east of Shields. Measurements were conducted at the one location shown in the figure. Notable acoustic features of the measurement locations include:

- Stop-and-go traffic due to the proximity of the traffic light at Shields;
- Propagation of noise over flat terrain; and
- Low traffic speeds and moderate volumes.

Site 8 – I-70 in Idaho Springs (See Figures 2-8a, 2-8b, and 2-8c)

Measurements were conducted at three locations along the north side of I-70 in Idaho Springs between Exits 239 and 241. Notable acoustic features of the measurement locations include:

- M1: Shielding by numerous structures, significant elevation drop between measurement and highway;
- M2: Shielding by edge of highway "bench", as well as shielding from nearby building;
- M3: propagation over river; and
- Moderate traffic speeds (50 mph) as site is within town with merging traffic.

Site 9 – I-70 in Dillon Valley (See Figure 2-9)

This site is located along the south side of I-70 in the Dillon Valley residential area east of the Dillon/Silverthorne interchange. Measurements were conducted in this residential neighborhood at the three locations shown in the figure. Notable acoustic features of the measurement locations include:

- M1: A control measurement located east of the existing noise wall with direct line of sight to I-70;
- M2 and M3: Located significantly below I-70 and located behind 8-foot tall noise wall;
- I-70, which is located above the elevation of the apartment units;
- M3: Shielded by apartment buildings; and
- Varying speeds among vehicle type from 40 to 75 mph, and somewhat low volumes.

Site 10 – I-70 in Vail (See Figure 2-10)

This site is located along the north side of I-70 in Vail, just west of the East Vail exit. Measurements were conducted at the seven locations shown in the figure around and behind the noise mitigation berm that CDOT constructed in this area. Notable acoustic features of the measurement locations include:

- Noise mitigation berm;
- Land slopes up in elevation to the north; and
- High speeds, but low volumes.

Site 11 – C-470 in Littleton (See Figures 2-11a and 2-11b)

This site is located near the intersection of C-470 with I-25. Measurements were conducted at the two locations shown in the figure. Notable acoustic features of the measurement locations include:

- Levels at M1 being influenced by I-25 and the ramp leading from C-470 East to I-25 South in addition to C-470; An edge of pavement barrier is formed by the ramp;
- M2: Located below C-470 with an edge of pavement barrier formed by the highway; and
- Moderate traffic volumes with high speeds.

Site 12 – US-36 in Boulder (See Figure 2-12)

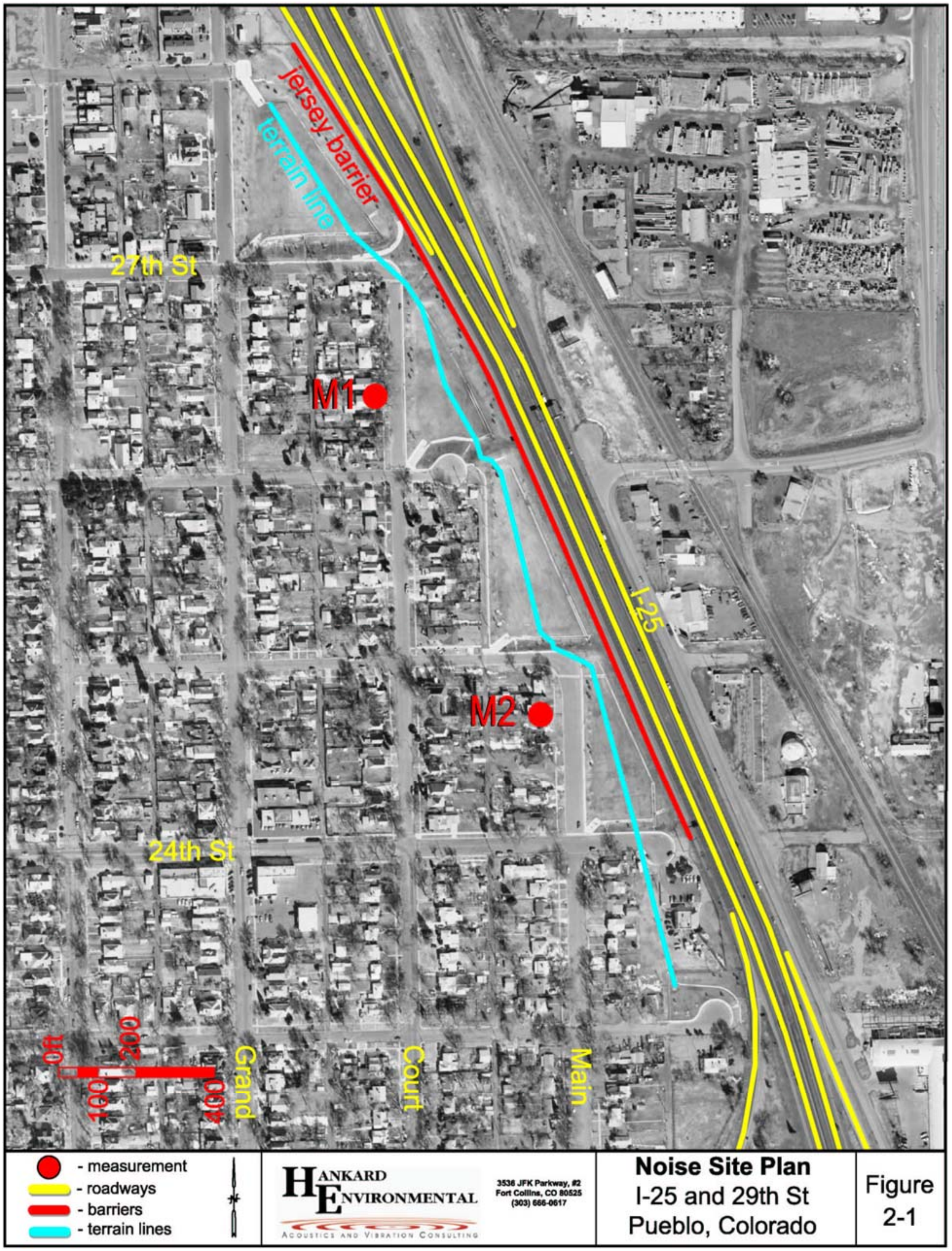
This site is located along US 36 in Boulder, between Baseline Road and Foothills Parkway. Measurements were conducted at the two locations shown in the figure as part of a larger study of the US-36 corridor. This site represents locations that are very close to a highway with no acoustic barriers in place. Notable acoustic features of the measurement locations include:

- M19: Located to the North of US-36 near Apache Road; No barriers or features between the location and the highway;
- M20: Located to the South of US-36 near Moorehead Avenue; There are no barriers between the location and the highway; and
- Very high traffic volumes.

Site 13 – US-36 in Westminster (See Figure 2-13)

Located along US-36 in Westminster, between W 80th Avenue and Federal Boulevard. Measurements were conducted at the two locations shown in the figure as part of a larger study of the US-36 corridor. In contrast to Site 12, this site represents locations that are close to a highway but have noise walls in place. Notable acoustic features of the measurement locations include:

- M7: Located to the northeast of the C-470 and Federal Boulevard intersection; A 15-foot tall double-sided wooden noise wall shields it;
- M8: Located to the southeast of the C-470 and W 80th Avenue intersection; A 15-foot tall masonry noise wall shields it; and
- Very high traffic volumes.



Noise Site Plan
I-25 and 29th St
Pueblo, Colorado

Figure
2-1

● - measurement
🟨 - roadways
🟥 - barriers
🟦 - terrain lines

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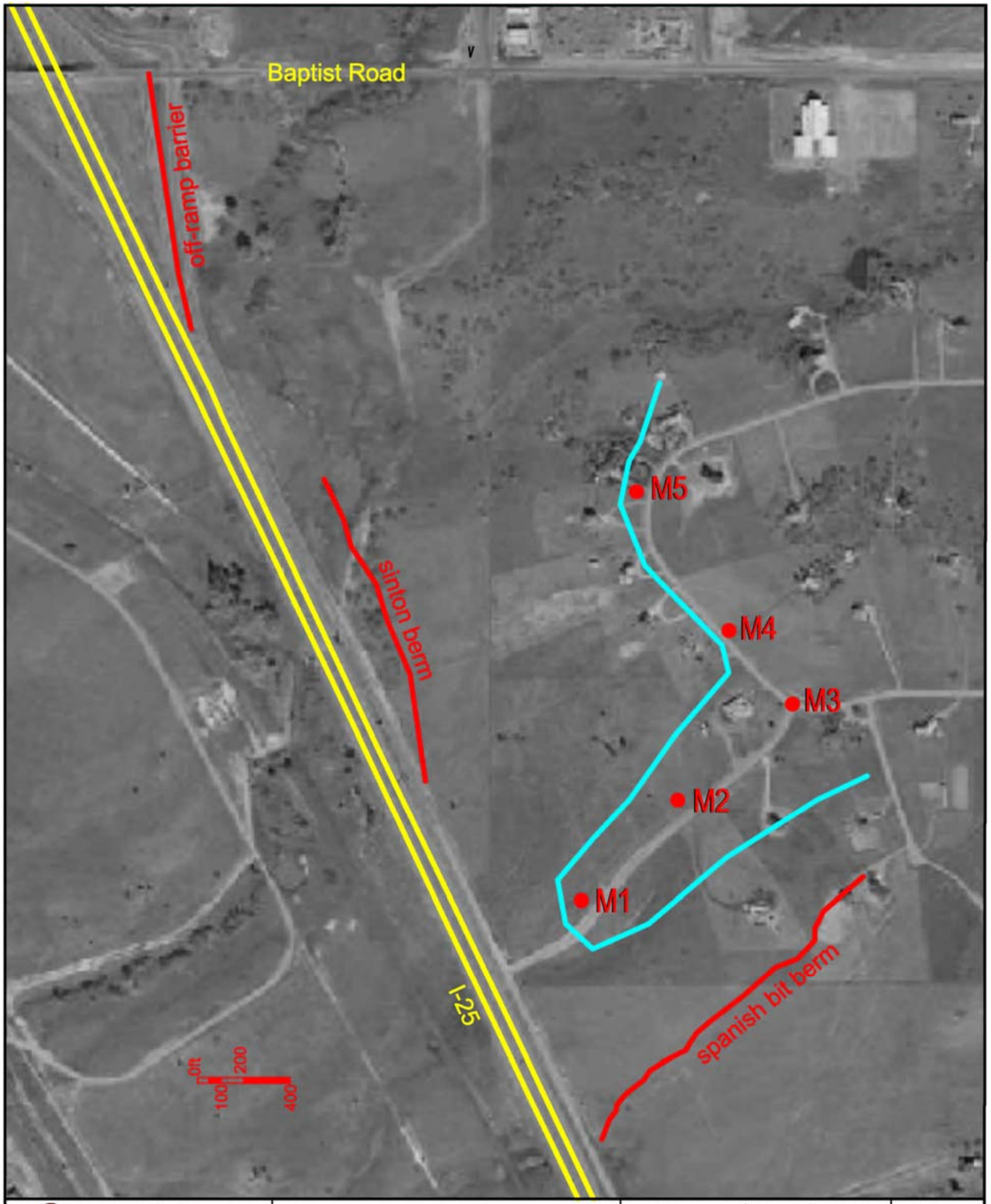
Noise Site Plan
Powers Boulevard
Colorado Springs, CO

Figure 2-2



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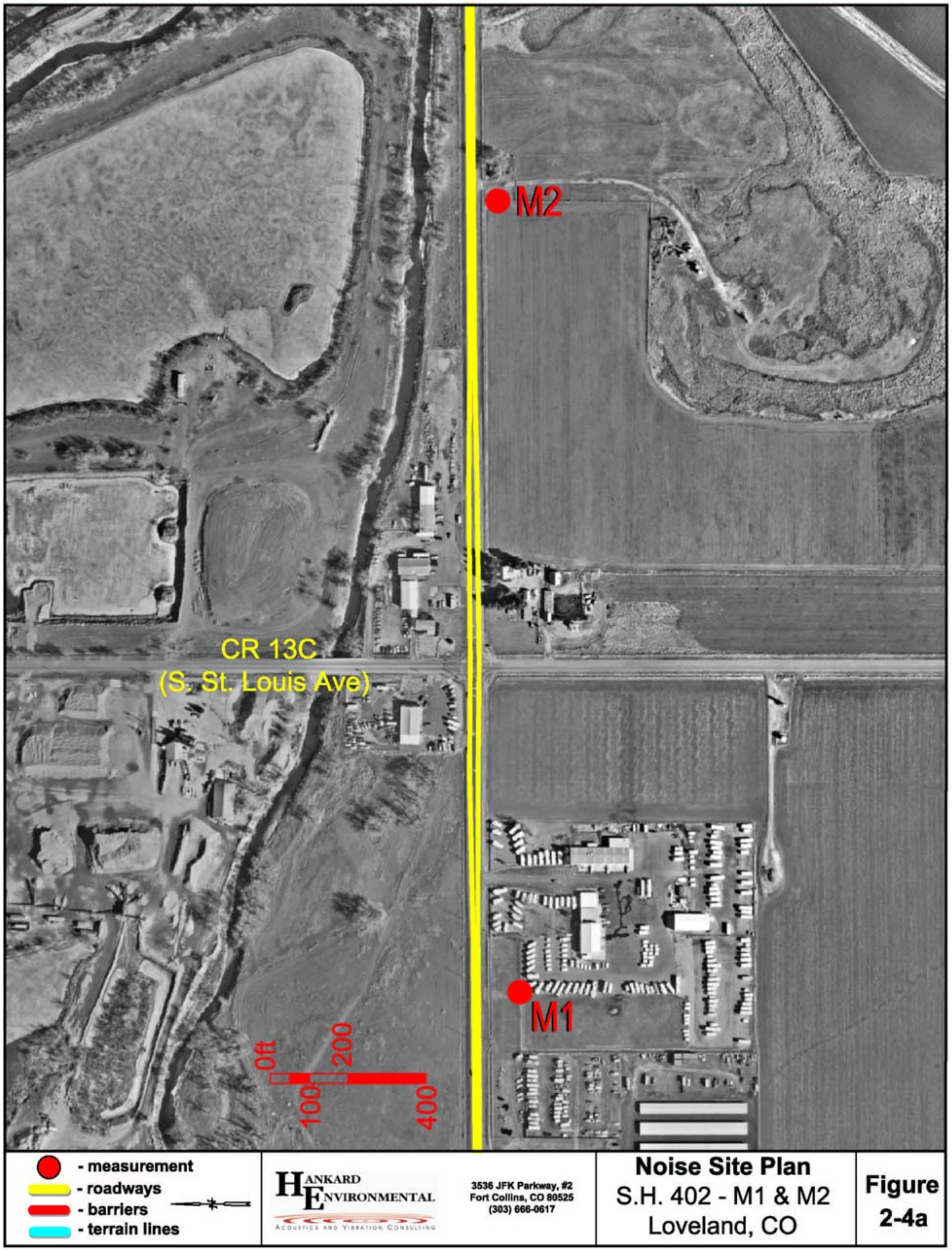
Noise Site Plan
I-25 and Baptist Rd
Colorado Springs, CO

Figure 2-3



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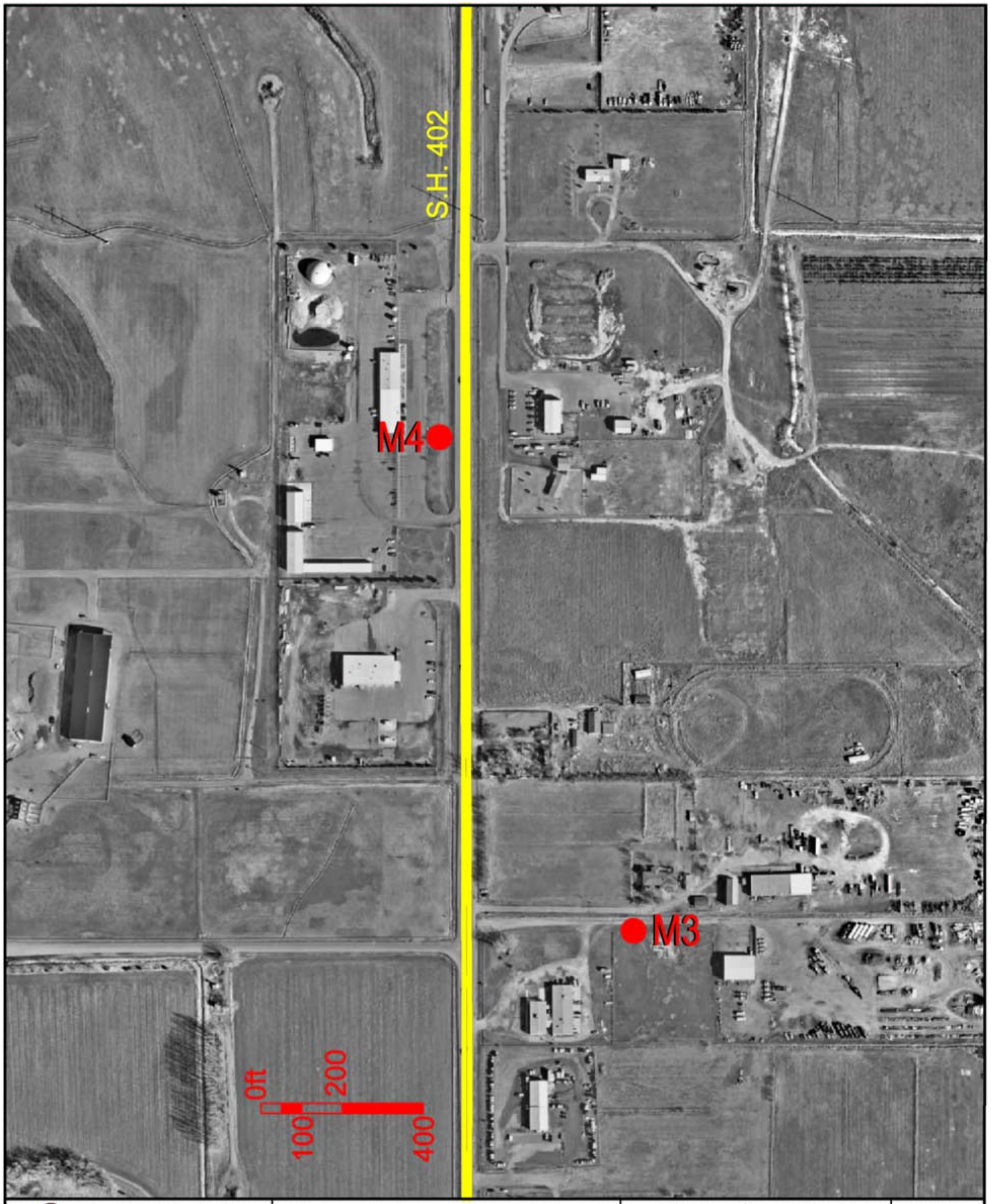
Noise Site Plan
S.H. 402 - M1 & M2
Loveland, CO

Figure 2-4a



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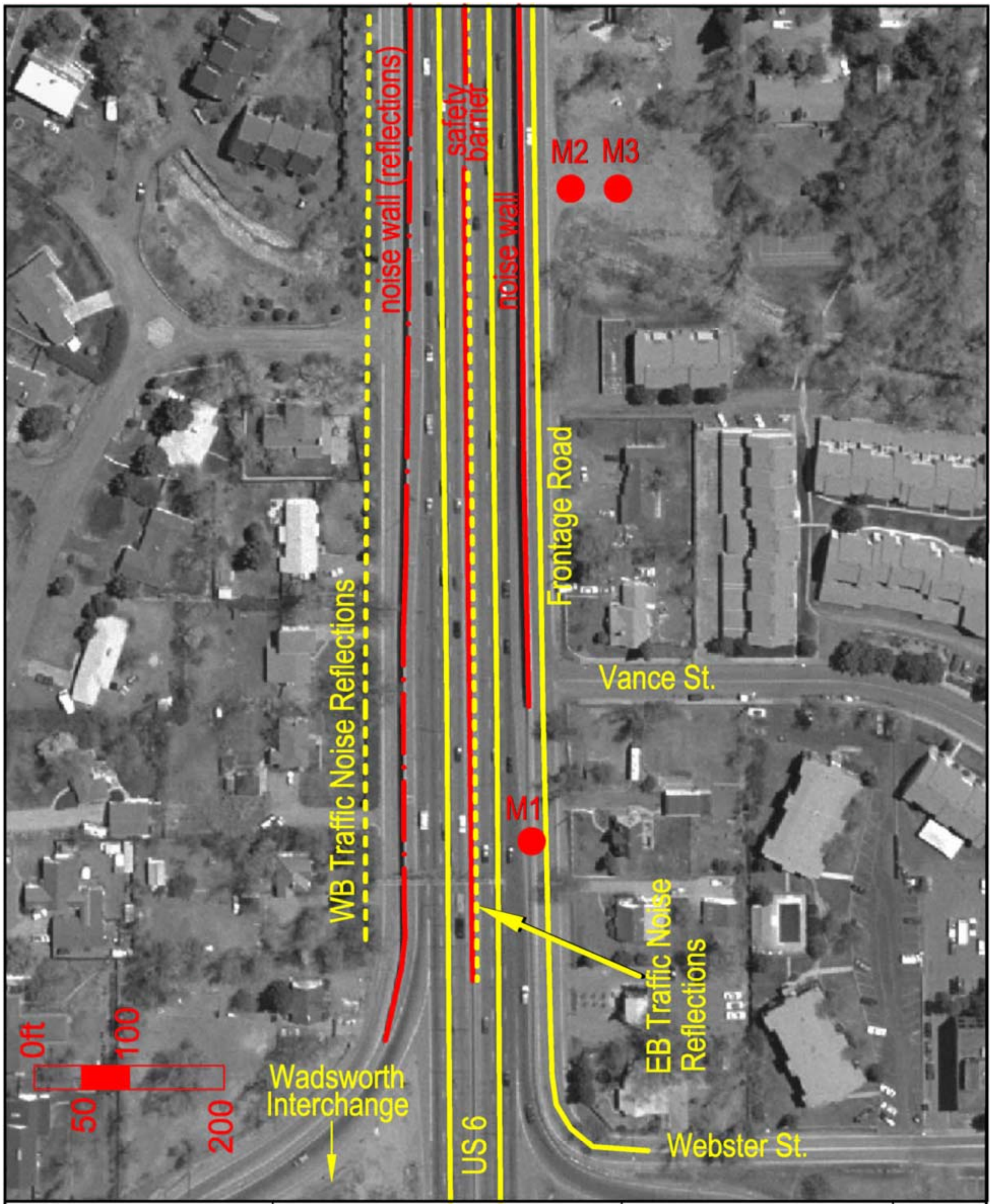
Noise Site Plan
S.H. 402 - M3 & M4
Loveland, CO

Figure 2-4b



● - measurement
🟨 - roadways
🟥 - barriers
🟨 - reflected noise

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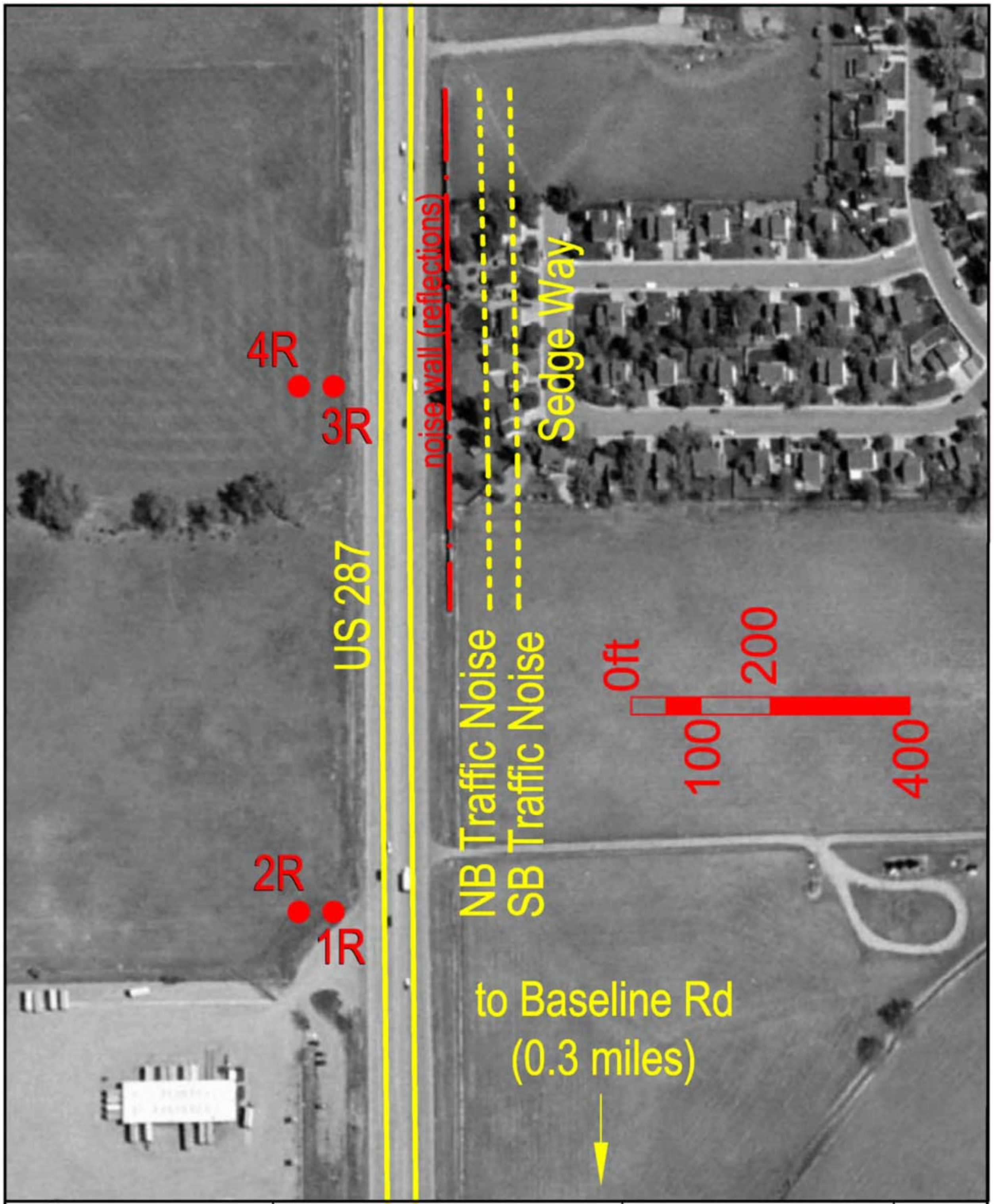
Noise Site Plan
US 6 & Wadsworth
Lakewood, Colorado

Figure 2-5



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Noise Site Plan
US 287
Lafayette, Colorado

Figure 2-6a

● - measurement
🟨 - roadways
🟥 - barriers
🟦 - terrain lines

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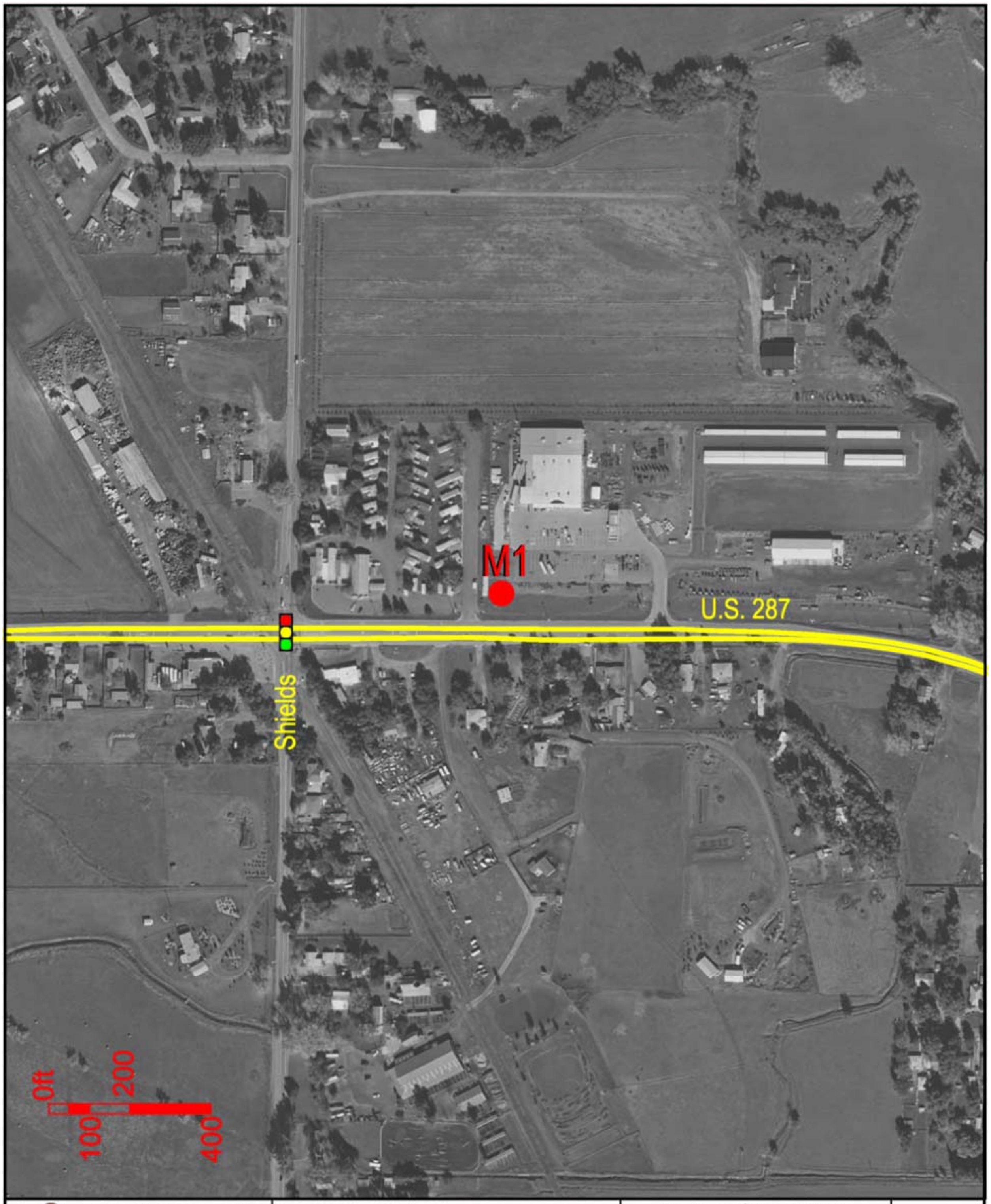
Noise Site Plan
US 287
Lafayette, Colorado

Figure 2-6b



● - measurement
🟨 - roadways
🟥 - barriers
🟦 - terrain lines

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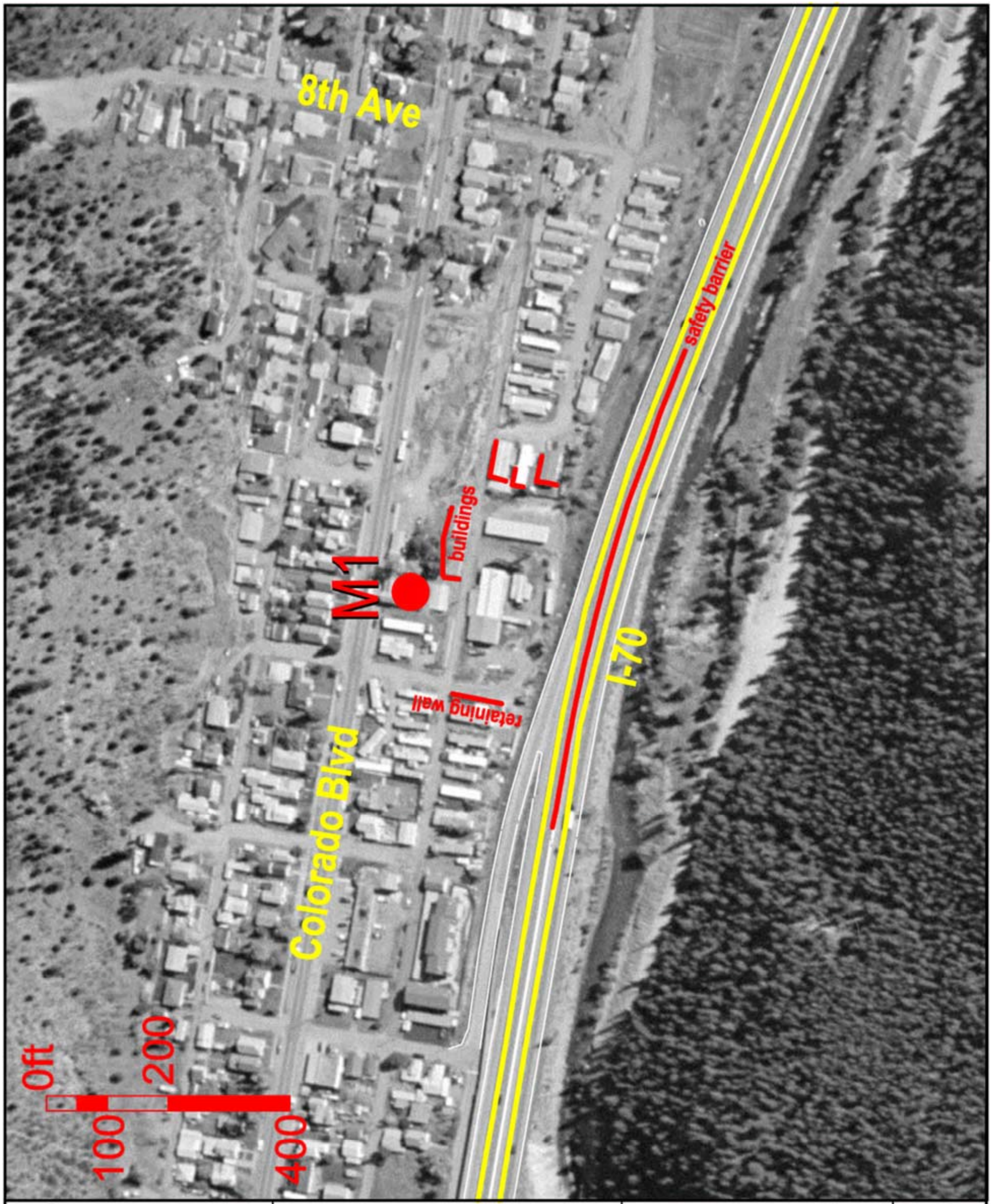
Noise Site Plan
US 287 and Shields
LaPorte, CO

Figure 2-7



● - measurement
🟨 - roadways
🟥 - barriers
🟦 - terrain lines

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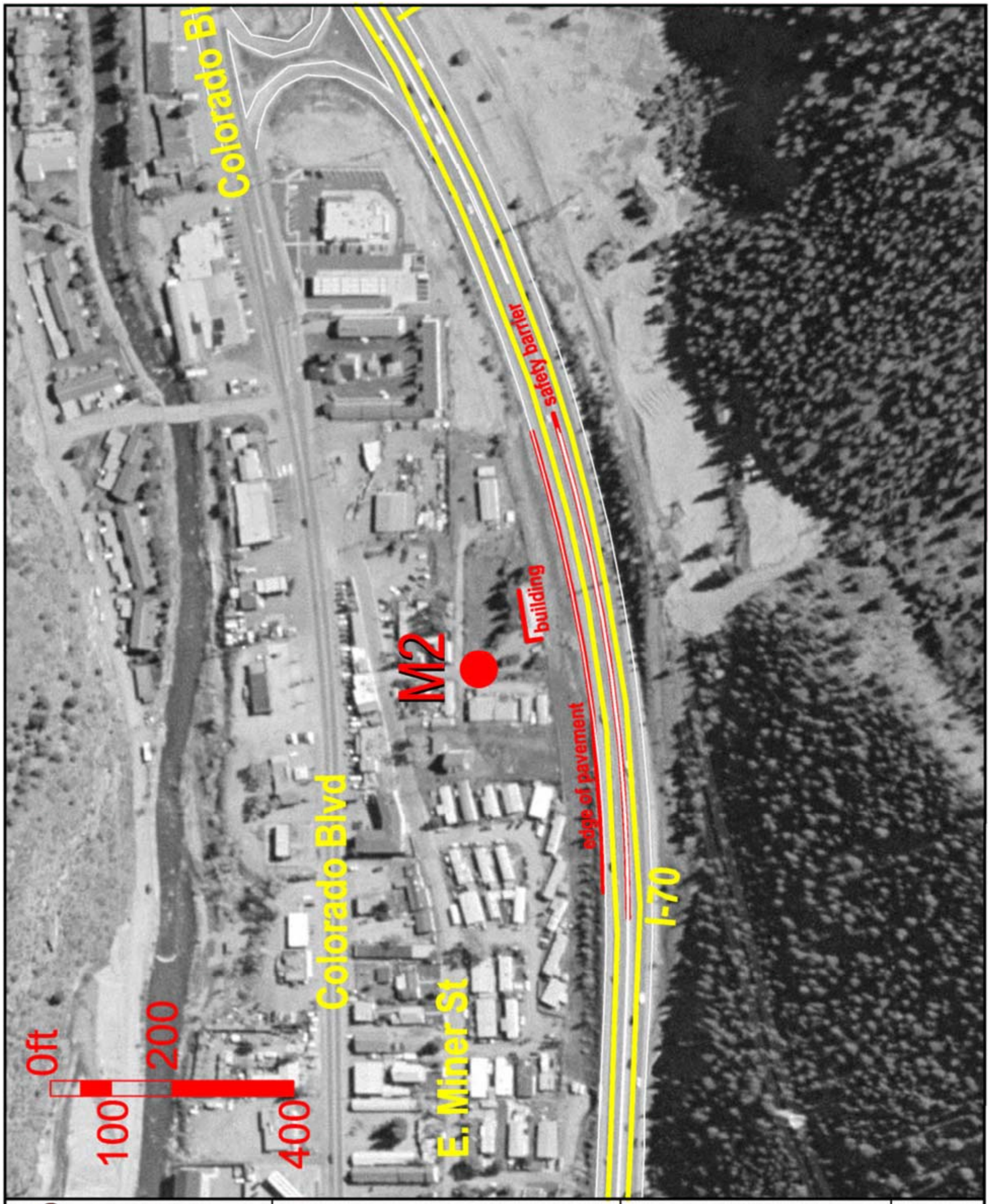
Noise Site Plan
I-70 - M1
Idaho Springs, Colorado

Figure 2-8a



● - measurement
🟨 - roadways
🟥 - barriers
🟦 - terrain lines

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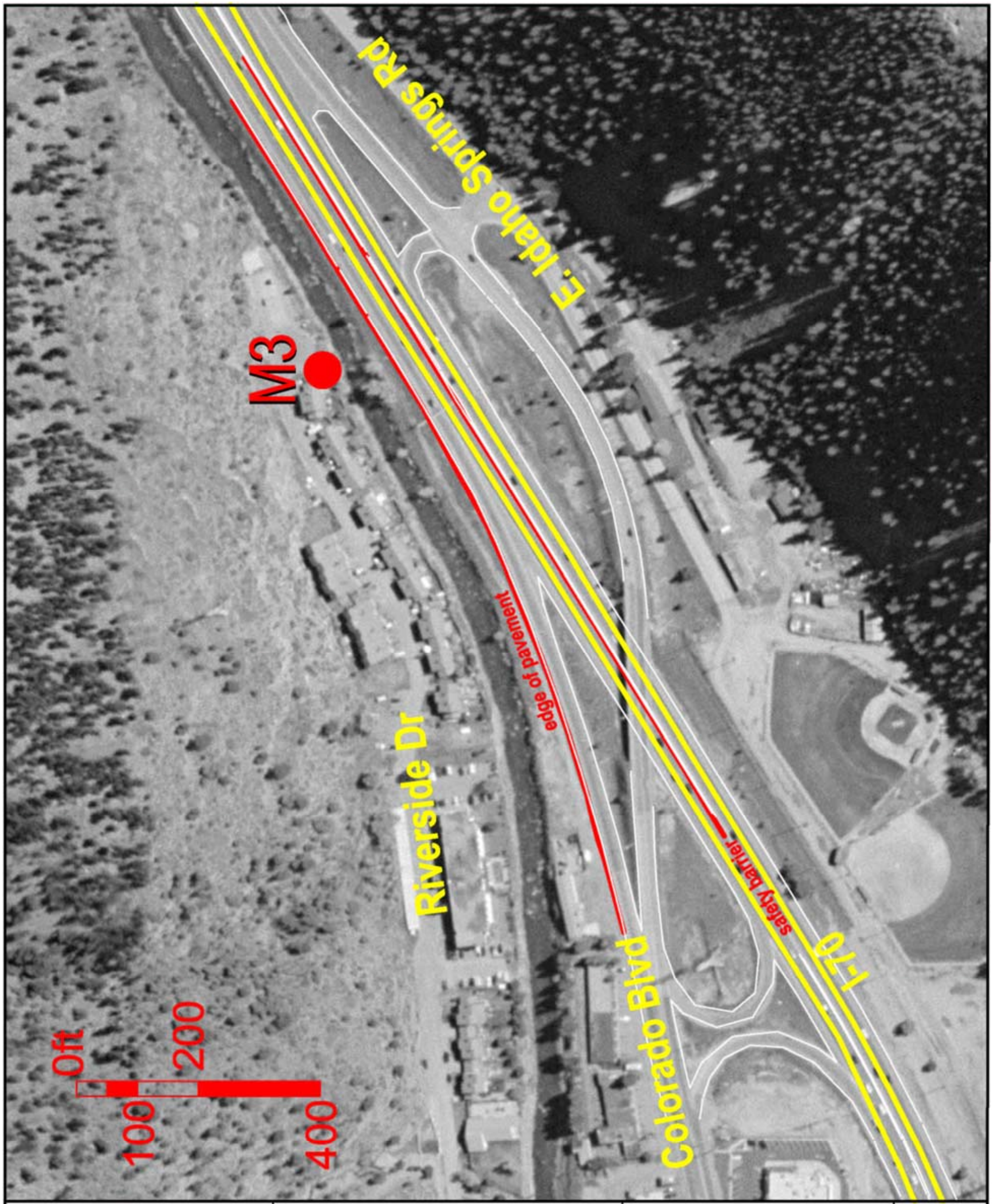
Noise Site Plan
I-70 - M2
Idaho Springs, Colorado

Figure 2-8b



● - measurement
🟨 - roadways
🟥 - barriers
🟦 - terrain lines

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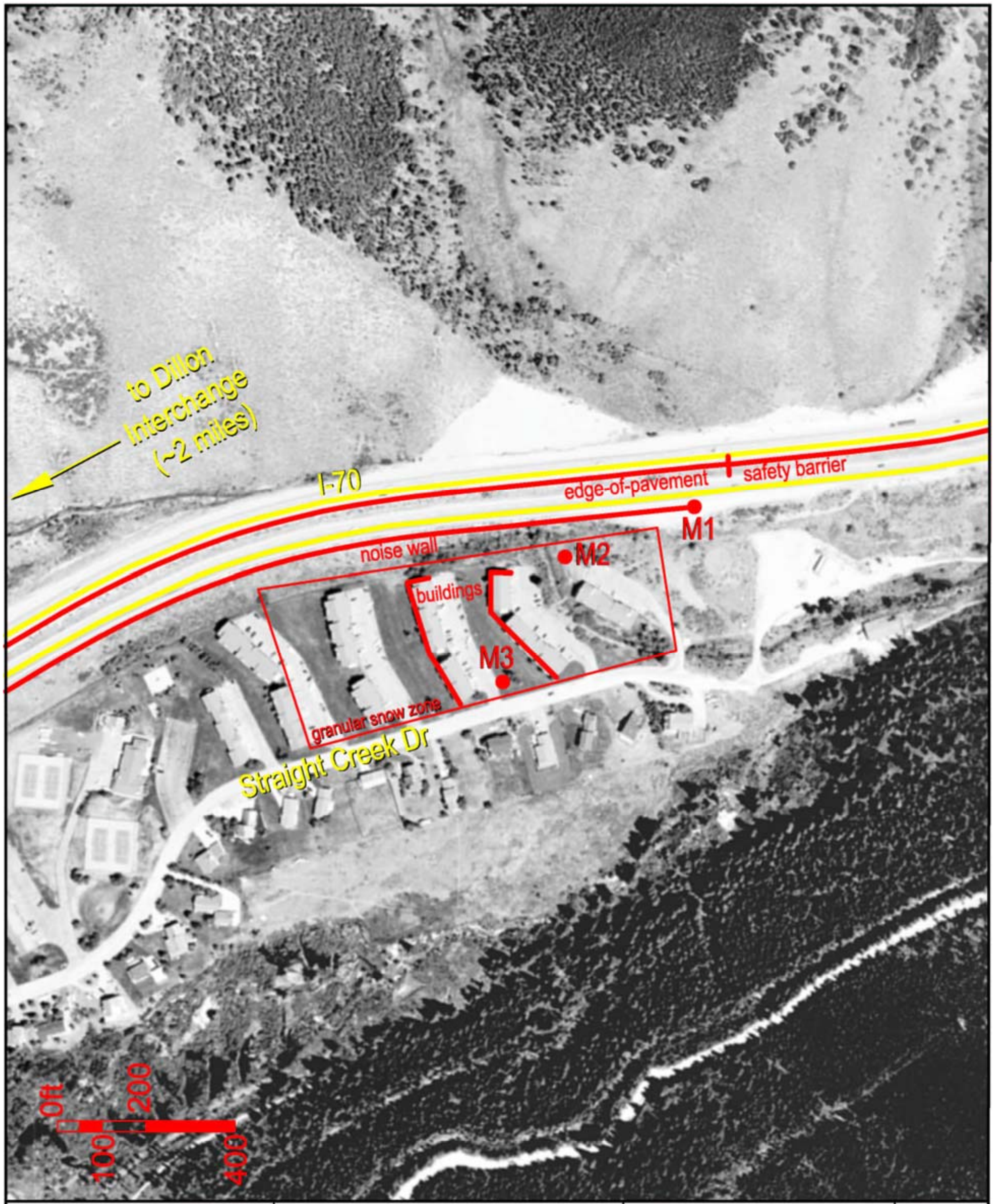
Noise Site Plan
I-70 - M3
Idaho Springs, Colorado

Figure 2-8c



● - measurement
🟨 - roadways
🟥 - barriers
🟩 - ground zone

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Noise Site Plan
I-70
Dillon, Colorado

Figure 2-9

● - measurement
- roadways
- barriers
- terrain lines

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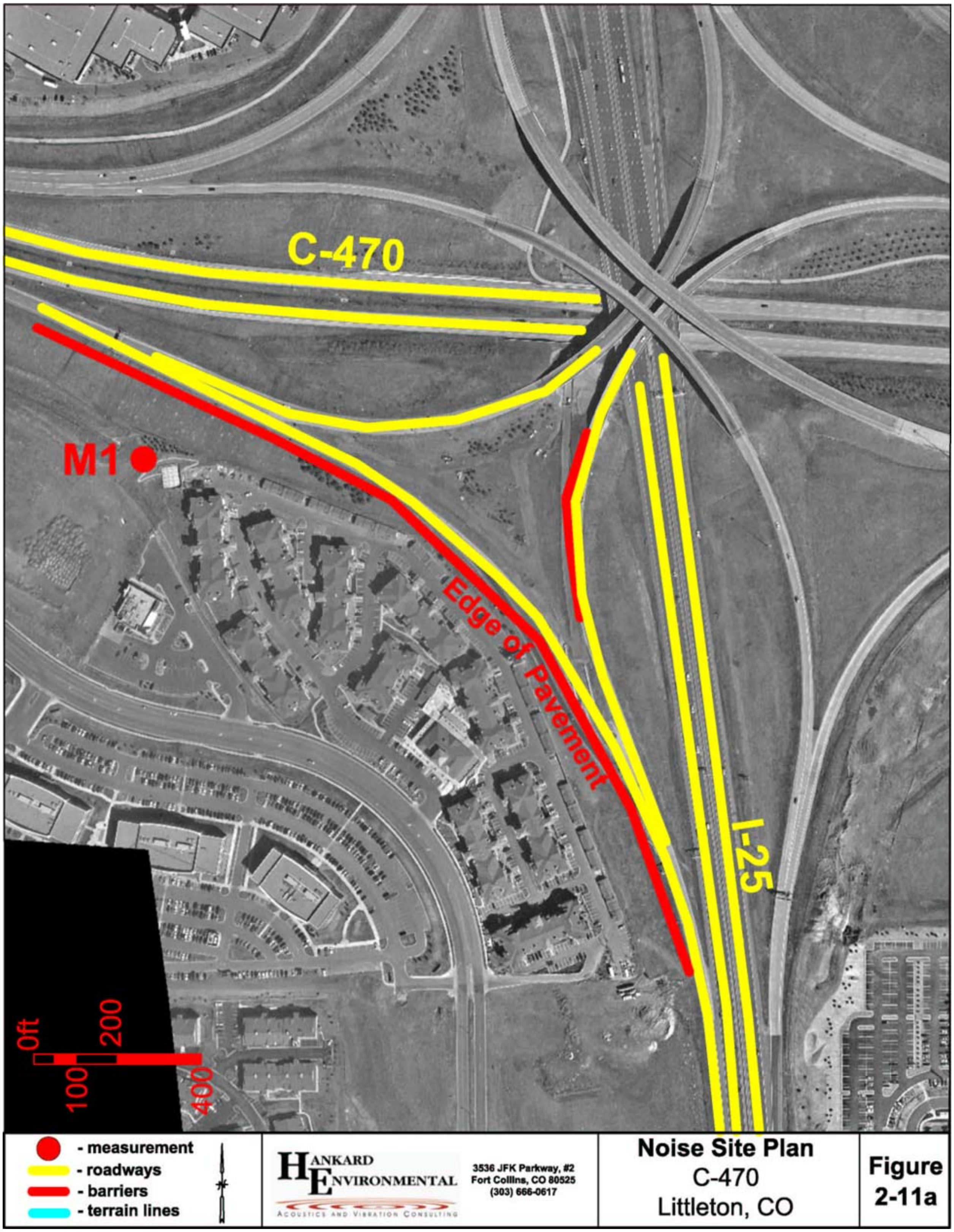
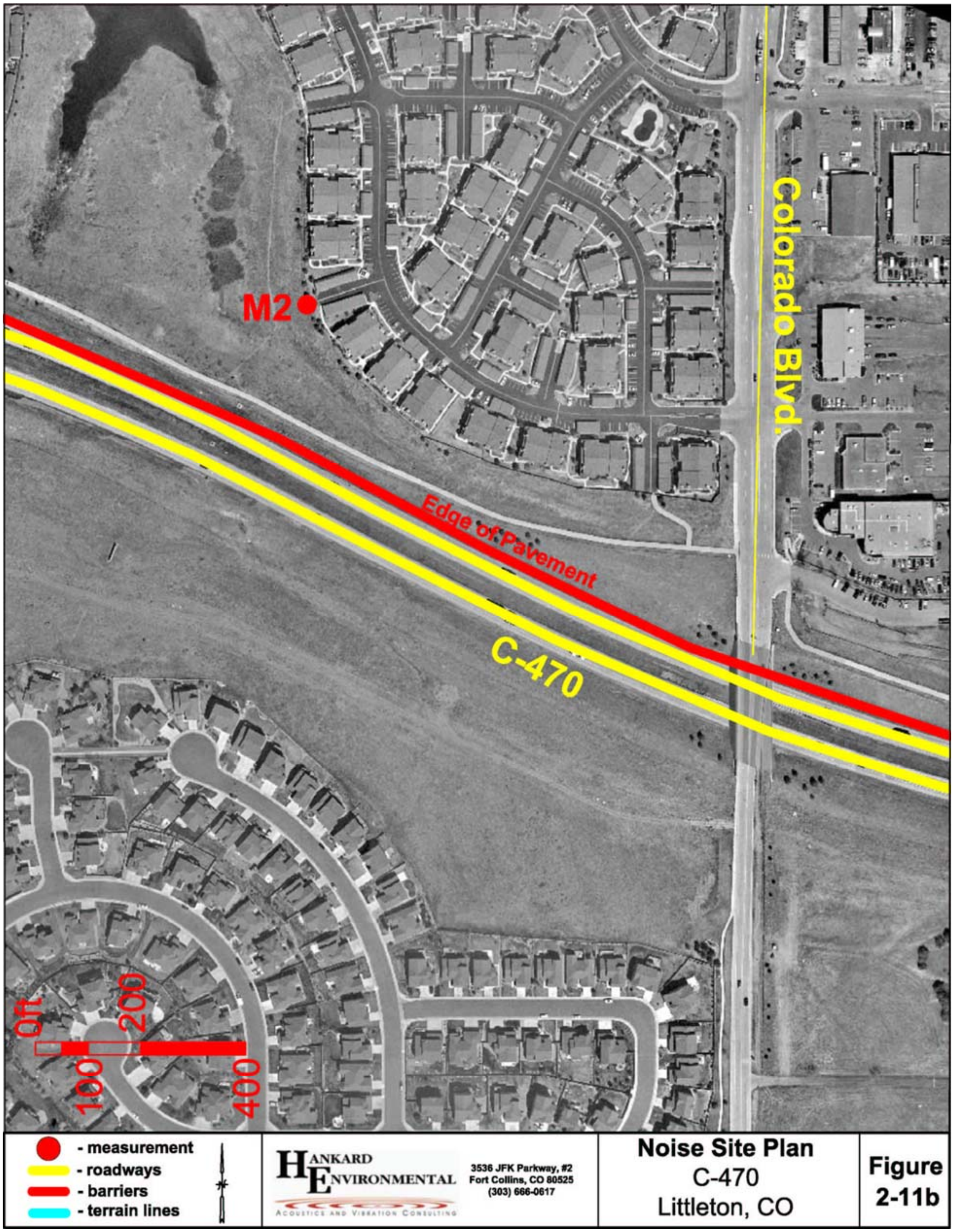
Noise Site Plan
I-70
Vail, CO

Figure
2-10



Noise Site Plan
C-470
Littleton, CO

Figure 2-11a



Noise Site Plan
C-470
Littleton, CO

Figure 2-11b

● - measurement
🟨 - roadways
🟥 - barriers
🟦 - terrain lines

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Noise Site Plan
US-36
Boulder, CO

Figure 2-12

● - measurement
🟨 - roadways
🟥 - barriers
🟦 - terrain lines

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Noise Site Plan
US-36
Westminster, CO

Figure 2-13

2.2 Measured Noise Levels, Traffic Conditions, and Meteorology

Noise levels were measured at each site either as part of this study directly or as part of previous CDOT-sponsored projects. This section describes the measurement equipment used, the measurement procedures that were followed, and the measured noise levels.

2.2.1 Measurement Equipment

Noise levels were measured using the sound level meters listed in Table 2-2, all of which are owned and maintained by Hankard Environmental Inc. Each meter meets American National Standards Institute (ANSI) Type I specifications. All meters were operated within two years of their most recent factory calibration, and were field calibrated before and re-checked after each measurement using either a Bruel & Kjaer Model 4230 or Larson Davis Model CAL200 calibrator. The Larson Davis 824 is a one-third-octave band meter, and the Norsonics 114 is an octave band meter. Thus, this data is available at the locations where these meters were used, but is not discussed herein (TNM results were analyzed on an A-weighted overall spectrum basis only).

Table 2-2: Noise Measurement Equipment

Make	*Model*	*ANSI Rating*
Larson Davis	820	Type I
Larson Davis	824	Type I
Metrosonics	dB 604	Type I
Norsonics	114	Type I

Wind speed, direction, temperature, and relative humidity were monitored on-site during the noise measurements using an RM Young model 0511103 wind speed and direction sensor and a Vaisala HMP45A temperature and humidity probe. The sensors were connected to a Campbell Scientific Model CR510 data logger. Traffic volumes and speeds were monitored on each roadway of interest during the noise measurements. Traffic volumes were either counted in the field manually, or were obtained from a review of videotapes of the traffic stream. Speeds were measured using an Amtech Sports Model 8500 radar gun, and/or driving the roadways of interest either directly before or after the measurements.

2.2.2 Measurement Procedures

The general noise measurement procedure used at all of the sites consisted of first visually surveying the site to find locations that would suit the purpose of the measurements. Measurements at Sites 1 – 4, 7 – 8, and 11–13 were conducted as part of previous projects where the impact of proposed roadway improvements was being analyzed. The purpose of these measurements was to see how accurately the STAMINA or TNM models were predicting noise levels at the receptors of interest. To that end, measurements were typically taken in the yards of residences adjacent to the roadway under study. The measurements at the remaining sites (5, 6, 9, and 10) were conducted explicitly for this study. The measurements along 6th Avenue were taken around the existing noise walls there, as this site was used to test the accuracy of TNM's parallel barrier analysis algorithm. The measurements along US 287 in Lafayette were taken behind, in front of, and away from the existing noise wall there, as this site was used to test TNM's barrier reflection modeling accuracy and barrier analysis routine. The measurements at Dillon Valley and Vail were taken behind the existing walls and berms at each of these sites, respectively, and were used to assess the model's noise barrier insertion loss prediction accuracy.

Noise meters were placed at each measurement location, with the microphone located five feet above the ground. The meters were field calibrated before and after each measurement, and configured to measure and record the A-weighted Leq. Fifteen-minute Leq's were measured at the Sites 1 – 4, 7- 8, and 11-13 (previous studies), while 5-minute Leq's were measured at the remaining sites. All of the noise meters were time-synchronized to each other, and to the meteorological data logger and video camera. Traffic volumes were counted for the exact duration of the noise measurement. All "semis" and other trucks with three or more axles were counted as "heavy trucks". All light trucks, such as two-axle delivery vehicles, were counted as "medium trucks". All other vehicles were counted as "automobiles". The "bus" and "motorcycle" TNM vehicle type inputs were not used in this study. Buses were categorized as either medium or heavy trucks, depending on their size, and motorcycles were categorized as automobiles. The traffic volumes, which covered various time periods, were all adjusted to equate to hourly volumes when used in TNM predictions. The average traffic speed on each roadway of interest was estimated from watching the fluctuating digital read-out of the radar gun, or estimated from driving.

2.2.3 Measurement Results

The measured noise levels are shown in Table 2-3, along with the date, time, day of the week of the measurement, and the distance from the measurement to the center of the roadway of interest. The measured traffic volumes and speeds are shown in Table 2-4. The measured meteorological data are shown in Table 2-5.

Table 2-3: Measured Noise Levels

Site	*Measurement Number*	*Date*	*Time (military)*	*Day of Week*	*Distance to Center of Roadway (feet)*	*Leq (dBA)*
Site 1 I-25 Pueblo	1	8-4-03	9:15-9:45	Monday	350	63.4
	2	8-4-03	9:15-9:45	Monday	290	62.7
Site 2 Powers Blvd. Co. Springs.	1	9-24-02	10:45-11:15	Tuesday	430	53.2
	2	9-24-02	10:45-11:15	Tuesday	185	50.8
Site 3 I-25 Co. Springs.	1	6-25-01	10:00-11:00	Monday	540	60.8
	2	6-25-01	10:00-11:00	Monday	1000	55.0
	3	6-25-01	10:00-11:00	Monday	1730	52.6
	4	6-25-01	10:00-11:00	Monday	1610	52.8
	5	6-25-01	10:00-11:00	Monday	1510	53.3
Site 4 SH 402 Loveland	1	12-17-02	8:45-9:45	Tuesday	110	64.9
	2	12-17-02	8:45-9:45	Tuesday	70	67.1
	3	12-17-02	8:45-9:45	Tuesday	410	57.5
	4	12-17-02	8:45-9:45	Tuesday	60	71.1
Site 5 6th Avenue Lakewood	1	11-8-03	11:00-11:30	Saturday	65	84.4
	2	11-8-03	11:00-11:30	Saturday	110	61.0
	3	11-8-03	11:00-11:30	Saturday	160	62.0
Site 6 US 287 Lafayette	1R	9-8-03	17:00-18:00	Monday	50	71.8
	2R	9-8-03	17:00-18:00	Monday	100	66.6
	3R	9-8-03	17:00-18:00	Monday	50	73.1
	4R	9-8-03	17:00-18:00	Monday	100	67.9
	1IL	9-9-03	10:15-11:25	Tuesday	135	62.9
	2IL	9-9-03	10:15-11:25	Tuesday	250	57.5
	3IL	9-9-03	10:15-11:25	Tuesday	135	56.2
	4IL	9-9-03	10:15-11:25	Tuesday	250	50.0
	5IL	9-9-03	10:15-11:25	Tuesday	250	50.3
Site 7 US 287 La Porte	1	9-26-00	9:00-10:00	Tuesday	100	64.2

Site	*Measurement Number*	*Date*	*Time (military)*	*Day of Week*	*Distance to Center of Roadway (feet)*	*Leq (dBA)*
Site 8 I-70 Idaho Springs	1	10/13/99	15:13-15:43	Wednesday	300	62.5
	2	10/13/99	12:20-13:20	Wednesday	215	61.5
	3	9/22/99	15:36-16:21	Wednesday	160	65.7
Site 9 I-70 Dillon Valley	1	12/18/03	12:15-13:20	Thursday	90	74.8
	2	12/18/03	12:15-13:20	Thursday	170	56.6
	3	12/18/03	12:15-13:20	Thursday	440	51.5
Site 10 I-70 Vail	1	9/26/03	9:15-9:45	Friday	70	78.0
	2	9/26/03	9:15-9:45	Friday	230	58.2
	3	9/26/03	9:15-9:45	Friday	295	56.0
	4	9/26/03	9:15-9:45	Friday	415	57.2
	5	9/26/03	10:15-10:45	Friday	70	78.5
	6	9/26/03	10:15-10:45	Friday	230	55.8
	7	9/26/03	10:15-10:45	Friday	300	59.0
	8	9/26/03	10:15-10:45	Friday	430	59.7
Site 11 C-470 Littleton	1	11/17/03	11:15-11:45	Monday	430	62.4
	2	11/17/03	10:00-10:30	Monday	325	66.5
Site 12 US-36 Boulder	1	5/4/04	17:30–18:00	Tuesday	195	67.4
	2	5/4/04	17:30-18:00	Tuesday	130	72.5
Site 13 US-36 Westminster	1	5/19/04	17:30-18:00	Wednesday	180	66.4
	2	5/19/04	17:30-18:00	Wednesday	200	64.2

Table 2-4: Measured Traffic Volumes and Speeds[1]

Site	*Measurement Number*	*Direction*	*Automobiles (veh/hour)*	*Med. Trucks (veh/hour)*	*Hvy. Trucks (veh/hour)*	*Speed (mph)*
Site 1 - I-25 Pueblo	All	Northbound	1812	52	78	55
		Southbound	1704	56	74	55
Site 2 - Powers Blvd. Co. Springs	All	Northbound	1260	36	50	50
		Southbound	1116	34	46	50
Site 3 I-25 Co. Springs	All	Northbound	1593	105	147	75
		Southbound	1963	101	140	75
Site 4 - SH 402 Loveland	All	Eastbound	324	15	50	50
		Westbound	304	20	46	50
Site 5 - 6th Avenue Lakewood	All	Eastbound	3162	126	66	65
		Westbound	3026	80	32	65
Site 6 - US 287 Lafayette	1R – 4R	Northbound	1507	26	11	53
	1R – 4R	Southbound	1553	17	3	53
	1IL – 2IL	Northbound	577	41	25	53
	1IL – 2IL	Southbound	618	28	32	53
Site 7 - US 287 La Porte	All	Eastbound	365	9	45	39
		Westbound	255	11	44	39
Site 8 - I-70 Idaho Springs	1	Eastbound	1268	86	90	65
		Westbound	846	58	68	65
	2	Eastbound	905	70	89	65
		Westbound	612	87	60	65
	3	Eastbound	633	55	116	65
		Westbound	999	43	61	65
Site 9 - I-70 Dillon Valley	All	Eastbound	735	27	71	50-65
		Westbound	693	19	35	40-65
Site 10 - I-70 Vail	1 – 4	Eastbound	496	38	74	65
		Westbound	424	44	50	65
	5 – 8	Eastbound	586	44	84	65
		Westbound	672	52	42	65
Site 11 - C-470 Littleton	1	Eastbound	1908	68	132	65
		Westbound	1770	66	48	65
	2	Eastbound	2558	68	66	65
		Westbound	2028	54	74	65
Site 12 - US-36 Boulder	All	Eastbound	1788	2	2	62
		Westbound	2564	22	12	62
Site 13 - US-36 Westminster	All	Eastbound	3864	110	78	65
		Westbound	5516	36	62	65

[1] See Table 2-3 for measurement date and times

Table 2-5: Measured Meteorological Conditions[1]

Site	*Measurement Number*	*Temperature (deg. F)*	*Relative Humidity (%)*	*Average Wind Speed (mph)*	*Wind Direction (relative)[1]*
Site 1 – I-25 Pueblo	All	77	n/a	1	n/a
Site 2 – Powers Blvd. Co. Springs	All	70	21	6	Crosswind
Site 3 – I-25 Co. Springs	All	52	n/a	13	Upwind
Site 4 – SH 402 Loveland	All	40	52	4	Crosswind
Site 5 – 6th Avenue Lakewood	All	44	50	2	Light/Variable
Site 6 – US 287 Lafayette	1R-4R	81	25	4	Crosswind
	1IL-5IL	66	58	3	Crosswind
Site 7 – US 287 La Porte	All	n/a	n/a	2	Crosswind
Site 8 – I-70 Idaho Springs	All	70	n/a	5	Crosswind
Site 9 – I-70 Dillon Valley	All	38	30	3	Cross/Upwind
Site 10 – I-70 Vail	M1-M4	49	39	1	Light/Variable
	M5-M8	59	34	1	Light/Variable
Site 11 – C-470 Littleton	M1	n/a	n/a	4	Crosswind
	M2	n/a	n/a	4	Crosswind
Site 12 – US-36 Boulder	M19	76	25	2	Downwind
	M20	76	25	2	Upwind
Site 13 – US-36 Westminster	All	78	29	3	Variable

[1] See Table 2-3 for measurement date and times

2.3 Noise Prediction Methods, Input Data, and Site Details

Noise levels were predicted at each measurement location using STAMINA 2.0, TNM 2.1, and TNM 2.5. Section 2.3.1 describes the modeling input data common to all sites, such as "pavement type", which was set to "average" per current Federal Highway Administration guidelines. Section 2.3.2 describes the modeling input data specific to each site, such as barriers and terrain lines features.

2.3.1 Modeling Input Data Common to All Sites

All STAMINA models utilized Colorado specific Reference Energy Mean Emission Levels (REMELs). In STAMINA, terrain lines were modeled as zero-height barriers, as STAMINA makes no distinction between barrier types such as walls or berms. For STAMINA, except in a few specified instances, ground absorption (alpha) values were set to 0.5. Table 2-6 lists the TNM parameters and their settings that are common for all 13 sites.

Table 2-6: Modeling Parameters Common to All Sites

Parameter	*TNM Menu*	*TNM Submenu*	*Setting*
Units	Setup	General	English
Traffic Entry Type	Setup	General	1 Hour L_{eq}
Relative Humidity	Setup	General	50%
Temperature	Setup	General	68 deg F
Default Ground Type	Setup	General	Lawn
User Defined Vehicles	Input	User Defined Vehicles	None
Pavement Type	Input	Roadways	Average
(Receiver) Height Above Ground	Input	Receiver	4.92 feet

2.3.2 Site Specific Modeling Data

Site 1 – I-25 in Pueblo

- Detention basins modeled with terrain line in TNM
- Centerline Jersey barriers removed from TNM models due to conflict with pavement
- No shielding by houses modeled, as view is relatively direct
- Roadway width set so that both directions overlap one another

Site 2 – Powers Boulevard in Colorado Springs

- Tightly-spaced houses were modeled as a 15-foot tall fixed-height noise wall
- Topography of open field modeled as terrain line in TNM
- Northbound pavement width set to 35 feet, southbound width expanded to the point of overlapping with the northbound pavement

Site 3 – I-25 in Colorado Springs

- Landforms modeled as berms
- Roadway width at 25 feet per direction
- Additional roadway with zero traffic added to overlap both directions of I-25

Site 4 – SH-402 in Loveland

- Eastbound pavement set to 36-foot width
- Westbound pavement widened to overlapping with eastbound

Site 5 – 6th Avenue in Lakewood

- Southern noise wall modeled as barrier. Safety barrier removed.
- Reflection from northern wall modeled as a mirror source with 70% of total 6th Avenue traffic
- Safety barrier reflection of eastbound traffic modeled as roadway with 50% of traffic
- Roadway width at 40 feet per direction
- Center roadway with zero traffic added to overlap both directions of 6th Avenue in TNM
- Receptor M1 given zero alpha in STAMINA

Site 6 – US 287 in Lafayette

- Traffic noise reflections modeled as mirror source for 1R and 2R
- Noise wall modeled as fixed barrier
- Row of houses accounted for in STAMINA with a 3 dB “shielding factor”
- Row of houses modeled by using “building row” option in TNM
- Northbound pavement width at 40 feet
- Southbound pavement width increased until overlapping with northbound US 287

Site 7 – US 287 in Fort Collins

- Pavement width set at 28 feet to ensure overlapping

Site 8 – I-70 in Idaho Springs

- Buildings modeled as fixed height barriers and edge of pavement modeled as barrier
- Safety barriers removed from TNM model to avoid conflict with pavement
- Eastbound pavement width set to 32 feet
- Westbound pavement width increased until overlapping with eastbound

Site 9 – I-70 in Dillon Valley

- Noise wall and safety barrier modeled as fixed barriers
- Ground zone to south of noise wall modeled as “granular snow” in TNM
- Roadway width at 35 feet per direction
- Roadway with zero traffic set to overlap both directions of I-70

Site 10 – I-70 in Vail

- Landform modeled as 0-height barrier in STAMINA, as terrain line in TNM
- Ground zone to north of berm modeled as “field grass” in TNM
- Roadway width at 35 feet per direction
- Roadway with zero traffic set to overlap both directions of I-70
- “Field grass” ground zone placed over overlapping pavement to simulate median

Site 11 – C-470 in Littleton

- Pavement width set to 36 feet
- Roadway with zero traffic set to overlap both directions of C-470
- “Field grass” ground zone placed over zero traffic road to simulate median
- Edge of pavement barriers modeled as zero height walls

Site 12 – US-36 in Boulder

- Pavement width in both directions increased to 28 feet to ensure overlapping

Site 13 – US-36 in Westminster

- Walls modeled as fixed height barriers
- Pavement widths set to 48 feet
- Roadway with zero traffic set to overlap both directions of US 36

2.4 Summary of Model Comparison Results

Table 2-7 shows the measured noise levels, the predicted noise levels using each model, and the resulting accuracy of each model at each of the 42 analysis locations (accuracy being defined as the predicted noise level minus the measured level). Table 2-8 shows some statistical values for the entire data set. A few notes regarding the results are as follows:

- The average of the absolute value of the error from all of the measurements is comparable among all three models, with both STAMINA 2.0 and TNM 2.1 showing an average absolute error of 2.0 dB, and TNM 2.5 showing an average absolute error of 1.9 dB.

- Overall, STAMINA predicted 0.6 dB lower than TNM. The STAMINA results have an average error of –0.3 dB, while TNM 2.1 showed an average error of 1.4 dB and TNM 2.5 showed an average error of 0.3 dB.

- STAMINA's maximum over prediction is 3.8 dB and its maximum under prediction is 6.2 dB, while TNM 2.1 and 2.5 showed maximum over/under predictions of 5.3/3.5 dB and 5.0/4.4 dB, respectively.

- STAMINA predicted within 3 dB of measured levels at 34 sites (81% of total). TNM 2.1 predicted within 3 dB of measured levels at 33 sites (79% of total). TNM 2.5 predicted within 3 dB of measured levels at 35 sites (83% of total). The models are all comparable on this basis.

- The difference between the levels predicted by TNM 2.5 and STAMINA 2.0 varies as much a 5 dB at any one site. One consequence of this is that sites that are predicted to be "impacted" by noise by one model may not be using another (and vice versa). At some sites all three models over predict or under predict in the same manner. At other sites one model may over predict while the other(s) under predict. There is no clear trend, e.g. where one model consistently over predicts or under predicts versus another.

- At some sites, the difference in the predicted levels between TNM 2.1 and TNM 2.5 was as much as 3 to 6 dB, indicating significant changes between these two versions of the model.

- Explanations for the discrepancy at each site where the difference between measured and predicted (TNM 2.5) noise levels are 3 dB or greater are as follows:

    - 6th Avenue: This is an extremely complicated site, consisting of existing noise walls, parallel barrier reflections, and undulating terrain. It is likely that some of the reflected energy was not accounted for by the model.
    - Lafayette: This site is relatively flat and free of reflections. One possibility for the measured levels being 3 to 5 dB lower than predicted is the fact that average traffic speeds may not have been as high as those used in the model due to the stop lights to the north and south. Also, there was a light crosswind the day of the measurements that may have had an effect.
    - Idaho Springs: TNM was generating errors when the 3-foot tall median barriers were modeled. These were removed from the model in order to generate results. The barrier is likely providing approximately 1 dB of noise reduction.
    - Dillon Valley: TNM appears to be overpredicting the noise reduction being provided by the existing noise wall.

Table 2-7: Predicted and Measured Noise Levels (Leq, dBA)

				STAMINA 2.0		*TNM 2.1*		*TNM 2.5*	
Site No.	*Site Name*	*Meas No.*	*Measured Level (dBA)*	*Predicted Level (dBA)*	*Pred. – Meas. (dBA)*	*Predicted Level (dBA)*	*Pred. – Meas. (dBA)*	*Predicted Level (dBA)*	*Pred. – Meas. (dBA)*
01	Pueblo	M1	63.4	61.6	-1.8	65.0	1.6	64.1	0.7
		M2	62.7	62.5	-0.2	64.7	2.0	63.5	0.8
02	Powers	M1	53.2	54.7	1.5	55.6	2.4	54.4	1.2
		M2	50.8	52.7	1.9	53.3	2.5	52.4	1.6
03	Baptist	M1	60.8	62.7	1.9	65.1	4.3	61.6	0.8
		M2	55.0	57.5	2.5	58.2	3.2	53.3	-1.7
		M3	52.6	54.0	1.4	56.5	3.9	51.5	-1.1
		M4	52.8	54.6	1.8	56.7	3.9	50.2	-2.6
		M5	53.3	55.1	1.8	56.2	2.9	50.4	-2.9
04	SH 402	M1	64.9	63.9	-1.0	66.5	1.6	66.3	1.4
		M2	67.1	69.0	1.9	69.3	2.2	68.9	1.8
		M3	57.5	55.2	-2.3	56.7	-0.8	55.4	-2.1
		M4	71.1	69.3	-1.8	70.1	-1.0	69.2	-1.9
05	6th Ave.	M1	84.4	78.2	-6.2	83.2	-1.2	80.9	-3.5
		M2	65.1	65.5	0.4	65.6	0.5	64.9	-0.2
		M3	62.0	64.6	2.6	64.2	2.2	64.0	2.0
06a	Lafayette	M1r	71.8	68.2	-3.6	70.4	-1.4	71.3	-0.5
		M2r	66.6	65.2	-1.4	66	-0.6	68.9	2.3
		M3r	73.1	69.0	-4.1	71.4	-1.7	71.7	-1.4
		M4r	68.0	66.0	-2.0	66.7	-1.3	69.2	1.2
06b	Lafayette	M1il	62.9	64.8	1.9	66.4	3.5	67.8	4.9
		M2il	57.5	60.2	2.7	60.5	3.0	62.3	4.8
		M3il	56.2	59.6	3.4	59.6	3.4	59.7	3.5
		M4il	50.0	53.8	3.8	52.6	2.6	53.9	3.9
		M5il	50.3	53.8	3.5	52.3	2.0	53.3	3.0
07	LaPorte	M1	64.2	62.5	-1.7	64.3	0.1	64.1	-0.1
08	Idaho Spgs.	M1	62.5	60.6	-1.9	63.6	1.1	63.1	0.6
		M2	61.5	63.0	1.5	66	4.5	63.8	2.3
		M3	65.7	66.1	0.4	71	5.3	70.7	5.0
09	Dillon Valley	M1	74.8	73.0	-1.8	77.7	2.9	75.4	0.6
		M2	56.6	53.7	-2.9	56	-0.6	54.0	-2.6
		M3	51.5	48.3	-3.2	48	-3.5	47.1	-4.4
10	Vail	M1	78.0	73.8	-4.2	78	0.0	75.1	-2.9
		M2	55.8	56.1	0.3	57.8	2.0	55.8	0.0
		M3	56.0	56.7	0.7	57.4	1.4	55.3	-0.7
		M4	57.2	57.3	0.1	58.4	1.2	56.7	-0.5

Table 2-7: Predicted and Measured Noise Levels (Leq, dBA)

				STAMINA 2.0		*TNM 2.1*		*TNM 2.5*	
Site No.	*Site Name*	*Meas No.*	*Measured Level (dBA)*	*Predicted Level (dBA)*	*Pred. – Meas. (dBA)*	*Predicted Level (dBA)*	*Pred. – Meas. (dBA)*	*Predicted Level (dBA)*	*Pred. – Meas. (dBA)*
11	C470	M1	62.4	61.2	-1.2	62.7	0.3	60.1	-2.3
		M2	66.5	64.8	-1.7	66.2	-0.3	66.0	-0.5
12	US36 West	M19	67.4	65.7	-1.7	69.5	2.1	70.2	2.8
		M20	72.5	72.0	-0.5	73.3	0.8	73.7	1.2
13	US36 East	M7	66.4	64.2	-2.2	67.1	0.7	66.4	0.0
		M8	64.2	62.1	-2.1	64.9	0.7	62.7	-1.5

Table 2-8: Statistical Calculations of Predicted and Measured Noise Levels

	STAMINA 2.0 (dBA)	*TNM 2.1 (dBA)*	*TNM 2.5 (dBA)*
Average Error	-0.3	1.4	0.3
Average Absolute Error	2.0	2.0	1.9
Maximum Over prediction	3.8	5.3	5.0
Maximum Under prediction	-6.2	-3.5	-4.4
Standard Deviation	2.4	1.9	2.4
95% Confidence Bandwidth	0.7	0.6	0.7

2.5 Paired t-test Statistical Analysis

In general, the t-test compares the means of sample or population data points at a specified critical alpha-value (α) or level of significance. The critical values of α are standard values that the analyst specifies. These specified critical values are commonly used in statistical quality control tables (e.g. 0.01, 0.025, 0.05, 0.10) depending on the level of risk or error that the analyst wants to take. The paired t-test as applied in this analysis is a special case of t-test statistical procedure that uses the difference between the results of two methods of measurements as the random variable. The paired t-test statistical technique tests the null hypothesis (designated by H_o) that there is no difference (difference=0) between the two measurement methods as evidenced by the results of comparing the calculated α-values with the specified critical value.

If the paired t-test procedure is generating α-values that are less than the selected critical value, it will be concluded that the sets of data being compared are SIGNIFICANTLY DIFFERENT. Otherwise, these two data sets will be considered NOT SIGNIFICANTLY DIFFERENT and the measurement methods that generated the data sets are considered STATISTICALLY EQUIVALENT. In this statistical analysis, the paired t-test (two-tailed test) is used with the assumption that the data points were generated using identical testing conditions for each pair of observation. The critical α-value of 0.05 is selected in this analysis. For more information on paired t-test procedure, refer to any standard applied statistics book.

2.5.1 Paired t-test Analysis Conclusions

STAMINA 2.0 The mean difference of the paired observations (predicted – measured) is NOT SIGNIFICANTLY DIFFERENT from zero value at the specified level of significance as determined by the paired t-test calculation. The calculated paired t-test α-value of 0.39 is greater than 0.05 as shown in Table 2.9 – Paired t-test Analysis. Therefore, the STAMINA 2.0 prediction model is statistically comparable or equivalent to the method that performs the actual noise level measurements.

TNM 2.1 The mean difference of the paired observations (predicted – measured) is SIGNIFICANTLY DIFFERENT from zero value at the specified level of significance as determined by the paired t-test calculation. The calculated paired t-test value of 0.000036 is less than the selected significance level of 0.05 as shown in Table 2.9 – Paired t-test Analysis. Therefore, the TNM 2.1 prediction model is SIGNIFICANTLY DIFFERENT from the method that generated the actual measured values.

TNM 2.5 The mean difference of the paired observations (predicted – measured) is NOT SIGNIFICANTLY DIFFERENT from zero value at the specified level of significance as determined by the paired t-test calculation. The calculated paired t-test α-value of 0.40 is greater than 0.05 as shown in Table 2.9 – Paired t-test Analysis. Therefore, the TNM 2.5 prediction model is statistically comparable or equivalent to the method that generated the actual measured values.

TNM 2.5 and STAMINA 2.0 are relatively better models than TNM 2.1 based on the results of the analyses using the paired t-test assuming the actual measured values are the correct true values. Individual statistical comparisons of the three prediction models using the paired t-test as shown in Table 2.10 – Individual Method Comparisons indicate that TNM 2.5 and STAMINA 2.0 are not significantly different and should be statistically equivalent models. TNM 2.1 is significantly different from either TNM 2.5 or STAMINA 2.0 version.

Table 2-9: Paired t-test Analysis

STATISTIC		**STAMINA 2.0**		**TNM 2.1**		**TNM 2.5**	
	Measured Level (dBA)	*Predicted Level (dBA)*	*Predicted - Measured (dBA)*	*Predicted Level (dBA)*	*Measured Level (dBA)*	*Predicted Level (dBA)*	*Predicted - Measured (dBA)*
Sample Size	42	42	42	42	42	42	42
Mean Value	62.3	62.0	-0.3	63.7	1.4	62.6	0.3
Std. Dev.	8.0	6.6	2.4	7.5	1.9	8.1	2.3
Variance	63.9	43.3	5.7	56.1	3.8	65.1	5.5
Calculated t-test α-value			0.39		0.000036		0.40
Significance			No Sig. Diff.		**Sig. Diff.**		No Sig. Diff.
Calculated t-value			-0.816917		4.66401625		0.82748633
Calculated t-value Comments			OK < 2.045(from t-table)		Not OK > 2.045(from t-table)		OK < 2.045(from t-table)

Table 2-10: Individual Method Comparisons

	A	**B**	**C**			
	STAMINA 2.0	**TNM 2.1**	**TNM 2.5**	Method Predicted Level Difference		
Sample No.	*Predicted Level (dBA)*	*Predicted Level (dBA)*	*Predicted Level (dBA)*	**A-B**	**A-C**	**B-C**
1	61.6	65.0	64.1	-3.4	-2.5	0.9
2	62.5	64.7	63.5	-2.2	-1.0	1.2
3	54.7	55.6	54.4	-0.9	0.3	1.2
4	52.7	53.3	52.4	-0.6	0.3	0.9
5	62.7	65.1	61.6	-2.4	1.1	3.5
6	57.5	58.2	53.3	-0.7	4.2	4.9
7	54.0	56.5	51.5	-2.5	2.5	5.0
8	54.6	56.7	50.2	-2.1	4.4	6.5
9	55.1	56.2	50.4	-1.1	4.7	5.8
10	63.9	66.5	66.3	-2.6	-2.4	0.2
11	69.0	69.3	68.9	-0.3	0.1	0.4
12	55.2	56.7	55.4	-1.5	-0.2	1.3
13	69.3	70.1	69.2	-0.8	0.1	0.9
14	78.2	83.2	80.9	-5.0	-2.7	2.3
15	65.5	65.6	64.9	-0.1	0.6	0.7
16	64.6	64.2	64.0	0.4	0.6	0.2
17	68.2	70.4	71.3	-2.2	-3.1	-0.9
18	65.2	66.0	68.9	-0.8	-3.7	-2.9
19	69.0	71.4	71.7	-2.4	-2.7	-0.3
20	66.0	66.7	69.2	-0.7	-3.2	-2.5
21	64.8	66.4	67.8	-1.6	-3.0	-1.4
22	60.2	60.5	62.3	-0.3	-2.1	-1.8

23	59.6	59.6	59.7	0.0	-0.1	-0.1
24	53.8	52.6	53.9	1.2	-0.1	-1.3
25	53.8	52.3	53.3	1.5	0.5	-1.0
26	62.5	64.3	64.1	-1.8	-1.6	0.2
27	60.6	63.6	63.1	-3.0	-2.5	0.5
28	63.0	66.0	63.8	-3.0	-0.8	2.2
29	66.1	71.0	70.7	-4.9	-4.6	0.3
30	73.0	77.7	75.4	-4.7	-2.4	2.3
31	53.7	56.0	54.0	-2.3	-0.3	2.0
32	48.3	48.0	47.1	0.3	1.2	0.9
33	73.8	78.0	75.1	-4.2	-1.3	2.9
34	56.1	57.8	55.8	-1.7	0.3	2.0
35	56.7	57.4	55.3	-0.7	1.4	2.1
36	57.3	58.4	56.7	-1.1	0.6	1.7
37	61.2	62.7	60.1	-1.5	1.1	2.6
38	64.8	66.2	66.0	-1.4	-1.2	0.2
39	65.7	69.5	70.2	-3.8	-4.5	-0.7
40	72.0	73.3	73.7	-1.3	-1.7	-0.4
41	64.2	67.1	66.4	-2.9	-2.2	0.7
42	62.1	64.9	62.7	-2.8	-0.6	2.2
Method Predicted Level Difference Label				A-B	A-C	B-C
t-test α-value				8.4E-09	0.07037	0.00144
Significance				Sig. Diff.	No Sig. Diff.	Sig. Diff.

3.0 ANALYSIS OF SPECIFIC TNM INPUT PARAMETERS

The sensitivity of each TNM input parameter was tested using either models of sites from the validation analysis (refer to Section 2) or "generic" models constructed specifically for the test at hand. All analyses in this section were conducted using TNM 2.5 only.

3.1 Relative Humidity

TNM's relative humidity parameter was cycled from 0 to 100% using a simple model consisting of one 10,000-foot long roadway, "lawn" ground type, with no barriers, terrain lines, building rows, etc. The FHWA default setting for RH is 50%; however Colorado is typically drier than this. TNM predicts 0.5 dB lower using 20% vs. 50% for a receptor 200 ft. from road, and 1.0 dB lower using 20% vs. 50% for a receptor 500 ft. from road. This is consistent with results published in the Technical Noise Supplement, CalTrans/Rudy Hendriks, 1998, and Noise Control for Buildings and Manufacturing Plants, BBN/Layman Miller, 1981.

3.2 Temperature

TNM's temperature parameter was cycled from 30 to 90 degrees F using a simple model consisting of one 10,000-foot long roadway, "lawn" ground type, with no barriers, terrain lines, building rows, etc. The FHWA default setting for temperature is 68 degrees F, which is a reasonable assumption for Colorado. Figure 3-1 shows that TNM's predicted noise level changes less than 1 dB when the temperature is varied across the 30 to 90 degree F range for a receptor located 300 feet from the road. This is consistent with results published in the Technical Noise Supplement, CalTrans/Rudy Hendriks, 1998, and Noise Control for Buildings and Manufacturing Plants, BBN/Layman Miller, 1981.

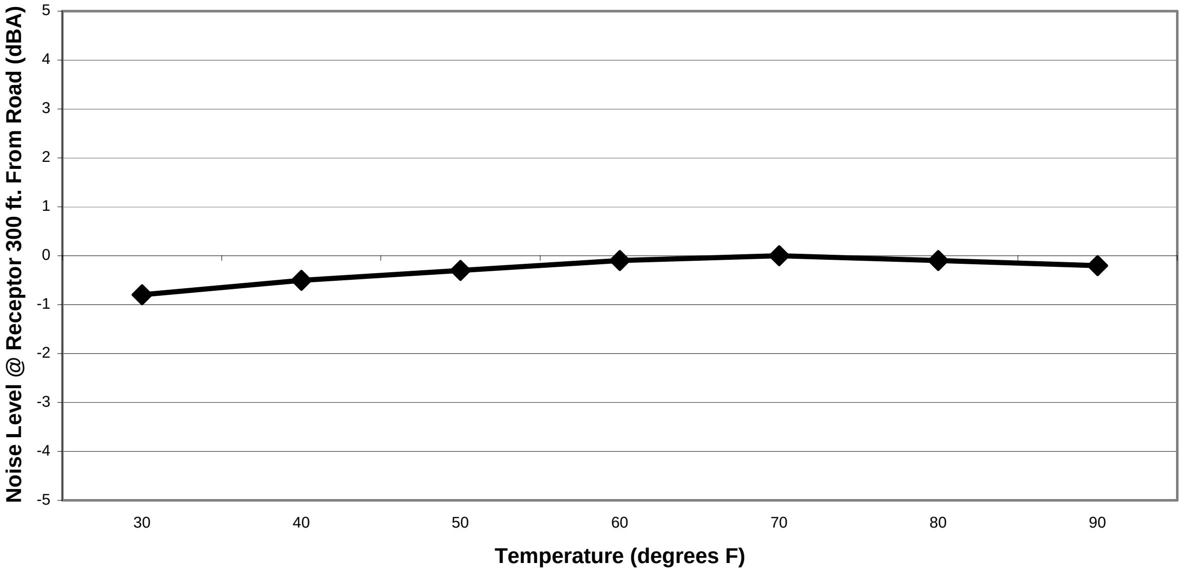


Figure 3-1: TNM Noise Levels versus Temperature

3.3 Default Ground Type

A TNM model consisting of one 10,000-foot long roadway, and no barriers, terrain lines, building rows, etc., was used to predict noise levels at receptors located 100, 200, …, 1,000 feet from the road for each of TNM's default ground types. Figure 3-2 shows the results, which are consistent with the results of studies by others. That is, higher noise levels are predicted for the harder surfaces, and that the effect is more pronounced at the more distant receptor locations. There is little change in the TNM output between Loose Soil, Lawn, Field Grass, or Snow, regardless of distance from the road. There is a 7 dB increase in levels when using Hard Soil versus Lawn for a receptor located 300 feet from the road. This is a significant difference, and therefore care should be taken when determining which of these ground types to use.

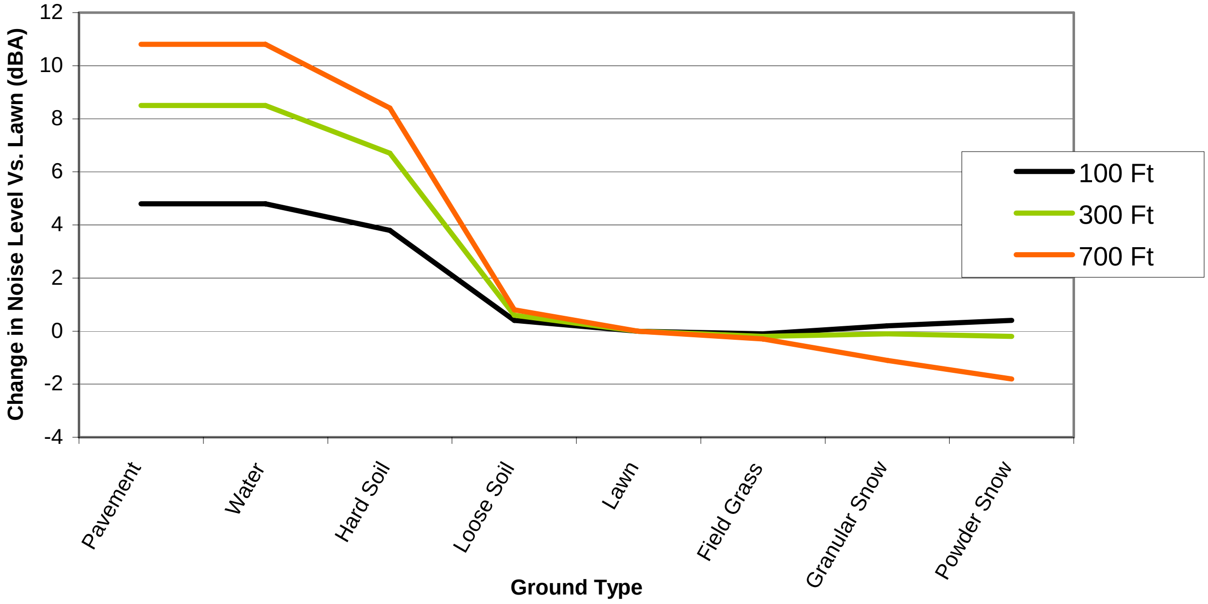


Figure 3-2: TNM Noise Levels versus Default Ground Type

3.4 Pavement Width

Pavement width affects two acoustic phenomena. First, it defines how much acoustically reflective ground there is under the source. Second, it defines where the edge of the road is, which can act as a barrier for receptors that are lower in elevation than the road.

An initial test was conducted using the Lafayette Site model (refer to Section 2), which consists of two parallel roads, separated by 40 feet, with no barriers, terrain lines, building rows, etc., and the site is modeled as being perfectly flat. The default ground type was set to pavement, and the pavement width of the roads was varied from 24 to 75 feet. There was no change in the predicted levels. This is the expected result, because the default ground type is pavement, thus widening the pavement at a flat site really does not change anything.

The effect of ground type on sound propagation is not completely understood in the acoustics community, which is evidenced by the fact that different international models treat it differently. German algorithms ignore it. Nordik and International Standards Association (ISO) 9613, Propagation of Sound Outdoors, break ground effects into those from the ground near the source, receptor, and in between. In the ISO model, noise levels increase when soft terrain is replaced by hard terrain (which is what happens when pavement width is widened over Lawn in TNM), and the effect is more pronounced for closer receptors than for more distant receptors. This is presumably due to the fact that at closer receptors the additional pavement constitutes a higher percentage of the ground area between the road and the receptor.

Using the simple TNM model described above the pavement width was varied 24 to 72 feet (with the default ground type set to Lawn). The predicted levels increase as the pavement width is increased, as expected because hard ground is being superimposed over soft ground. Also, the effect is more pronounced at receptors located 300 feet from the road than those located between 500 and 1,000 feet for the road, which agrees with the ISO 9613 results.

3.5 Pavement Type

TNM contains REMELs for four pavement types: Dense Graded Asphaltic Concrete (DGAC), Portland Cement Concrete (PCC), Open Graded Asphaltic Concrete (OGAC), and "average" (which is derived from DGAC and PCC data). The following changes in predicted noise levels were observed for a receiver located 300 feet from a long, straight roadway when changing the pavement type from "average" to each of the other settings:

- PCC is 2 dB louder than "average"
- DGAC is 1 dB quieter than "average"
- OGAC is 2 dB quieter than "average"

3.6 Roadway on Structure

TNM has the option to define a road segment as being "on structure." Any road segment designated as such will not act as a barrier between any receptors and any other roads in the model. Road on structure behavior was evaluated using the eastern end of the Idaho Springs model (refer to Figure 2-13). Edge of Pavement barriers were removed and 5 receptors were placed along the row of buildings on the north bank of Clear Creek. The I-70 East on-ramp overpass, which shields the receptors from parts of I-70, was used as the roadway on structure.

The model was first run with no overpass in place, then with the overpass in place but not on structure, and finally with the overpass on structure. The results are shown in Table 3-1. Adding the overpass reduced noise levels by 0.7 dB at the closest receptors, and had no effect on the further receptors. Placing the overpass on structure resulted in the same levels as if the structure were not present. In summary, this feature of TNM acts in a predictable and reasonable fashion.

Table 3-1: Road on Structure Analysis Results

	R1 (dBA)	*R2 (dBA)*	*R3 (dBA)*	*R4 (dBA)*	*R5 (dBA)*
No Overpass Present	67.6	69.0	69.8	70.1	70.8
Overpass Not On Structure	66.9	68.7	69.7	70.1	70.8
Overpass On Structure	67.6	69.0	69.8	70.1	70.8

3.7 Vehicle Percentages

The Lafayette model was used to test the effects of increasing the percentage of TNM's non-automobile vehicle types: medium trucks, heavy trucks, busses, and motorcycles. Referring to Figure 2-6b, noise levels were predicted at Locations 1IL and 2IL (which have open exposure to the roadway) and 3IL and 5IL (which are protected by a noise wall). The predicted noise levels are shown in Tables 3-2 through 3-5, below. Each vehicle type was tested separately. The following trends are apparent in the data:

- Medium trucks: 0.1 dB increase per percent increase
- Heavy trucks: 0.2 to 0.3 dB increase per percent increase
- Motorcycles: 0.2 dB increase per percent increase
- Buses: 0.1 dB increase per percent increase
- For heavy trucks, the increases are slightly more pronounced at the more distant receptor locations. Presumably this is because heavy trucks have a significant level of emissions at a height of 12 feet (compared to 0 feet for autos and 5 feet for medium trucks), and sound originating from a higher elevation would be less affected by ground absorption.
- The presence of barriers did not affect the results. This is disconcerting for heavy trucks. Because of the greater source height, it is expected that noise levels behind a barrier would increase as the truck percentage increased. This was not observed here and should be investigated further.

Table 3-2: Leq versus Heavy Truck Percentage (dBA)

% of Traffic	*1%*	*3%*	*5%*	*8%*	*12%*	*15%*
M1	66.8	67.4	68.0	68.7	69.6	70.2
M2	61.2	61.8	62.5	63.3	64.3	64.9
M3	55.1	55.8	56.4	57.2	58.1	58.7
M5	54.0	54.7	55.3	56.2	57.1	57.8
Average	59.3	59.9	60.6	61.4	62.3	62.9

Table 3-3: Leq versus Medium Truck Percentage (dBA)

% of Traffic	*1%*	*3%*	*5%*	*8%*	*12%*	*15%*
M1	67.2	67.4	67.7	68.1	68.6	69.0
M2	61.7	61.9	62.2	62.6	63.1	63.4
M3	55.5	55.8	56.1	56.5	57.1	57.5
M5	54.5	54.8	55.0	55.5	56.0	56.3
Average	59.7	60.0	60.3	60.7	61.2	61.6

Table 3-4: Leq versus Motorcycle Percentage (dBA)

% of Traffic	*0%*	*1%*	*2%*	*3%*
M1	67.8	67.9	68.1	68.3
M2	62.2	62.4	62.6	62.8
M3	56.2	56.4	56.7	57
M5	55.1	55.3	55.6	55.8
Average	60.3	60.5	60.8	61.0

Table 3-5: Leq versus Bus Percentage (dBA)

% of Traffic	*0%*	*1%*	*2%*	*3%*
M1	67.8	67.9	68.0	68.1
M2	62.2	62.3	62.5	62.6
M3	56.2	56.3	56.4	56.5
M5	55.1	55.2	55.3	55.4
Average	60.3	60.4	60.6	60.7

3.8 Truck Speed

The Vail model was used to test the effect of varying heavy truck speed. The traffic used was hand counted at the Vail site and contains approximately 10% heavy trucks. All traffic was set to 75 mph for the initial run, and heavy truck speeds were reduced to 70 and 65 mph in subsequent runs. As shown in Table 3-6, lowering trucks speeds by 5 mph reduced the predicted levels by 0.3 to 0.5 dBA at all receptors. Lowering truck speeds by 10 mph reduced noise levels by 0.5 to 0.9 dBA. The receptor least affected by terrain and at the greatest distance from the roadway showed the highest sensitivity to the speed variations.

Table 3-6: Leq versus Truck Speed

Receptor	Trucks @ 75 mph	Trucks @ 70 mph	ΔLeq (dBA)		Trucks @ 75 mph	Trucks @ 65 mph	ΔLeq (dBA)
M1	76.9	76.6	-0.3		76.9	76.4	-0.5
M2	57.1	56.8	-0.3		57.1	56.6	-0.5
M3	56.6	56.3	-0.3		56.6	56.1	-0.5
M4	58.2	57.7	-0.5		58.2	57.3	-0.9

3.9 Flow Control

A simple model was created to study the traffic flow feature of TNM. The model included three end-to-end roadways in a straight line. The middle roadway had traffic signal flow control applied to it at varying percentages of traffic affected. Three lines of receptors were modeled leading away from the middle roadway perpendicularly; the first at the end of the middle roadway (where acceleration is complete), the second at the center of the middle roadway (where acceleration is in progress) and the third at the start of the middle roadway (where acceleration begins). The receptors were spaced at distances of 100, 250, 500, 750 and 1000 feet from the center of the roadway.

Traffic was first set to 1500 autos with no other vehicle types. Traffic affected by flow control was set to 0%, 50%, and 100%. Traffic was then modified to include 5% medium trucks and 5% heavy trucks. The same flow control values were used again. The predicted levels at all receptors for each traffic condition are shown in Figures 3-3 and 3-4. The following conclusions were drawn from the results:

- Using the traffic control feature of TNM increased predicted levels by 0.5 to 2.9 dBA
- The greatest increases are near the start of the acceleration segment (as expected)
- The increase in noise levels is proportional to % trucks and to % of traffic affected (as expected)
- The effect of flow control on distant (greater than 500 feet) receptors is disconcerting. One would expect very little change in noise levels at distant receptors, because the contribution of the flow control roadway segment to overall noise levels decreases as one move away from the roadway. This should be investigated further.

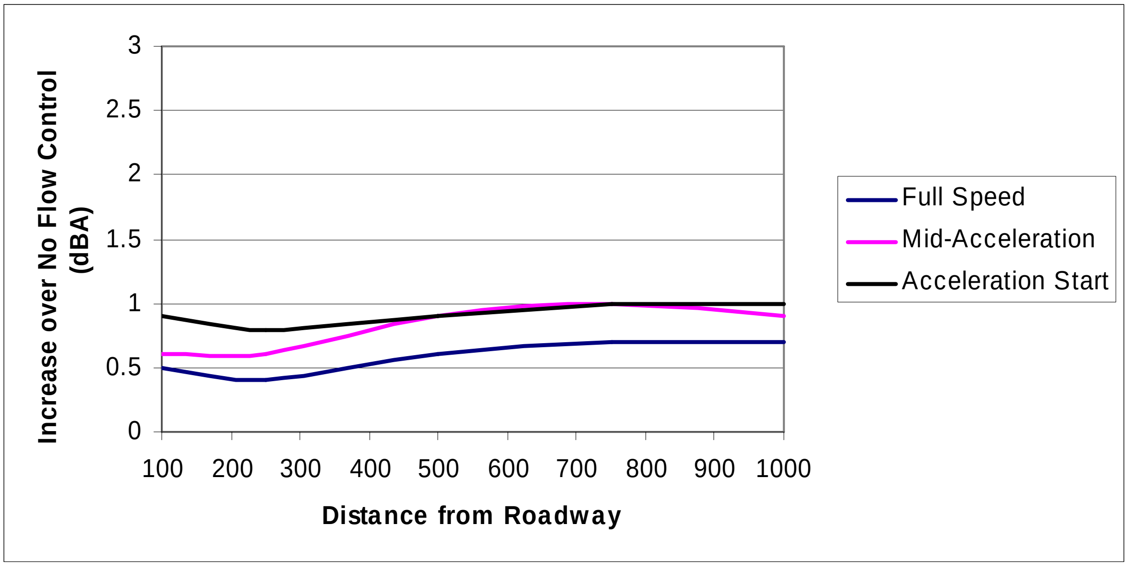


Figure 3-3: Increase in Noise Levels with Flow Control (50% controlled, no trucks)

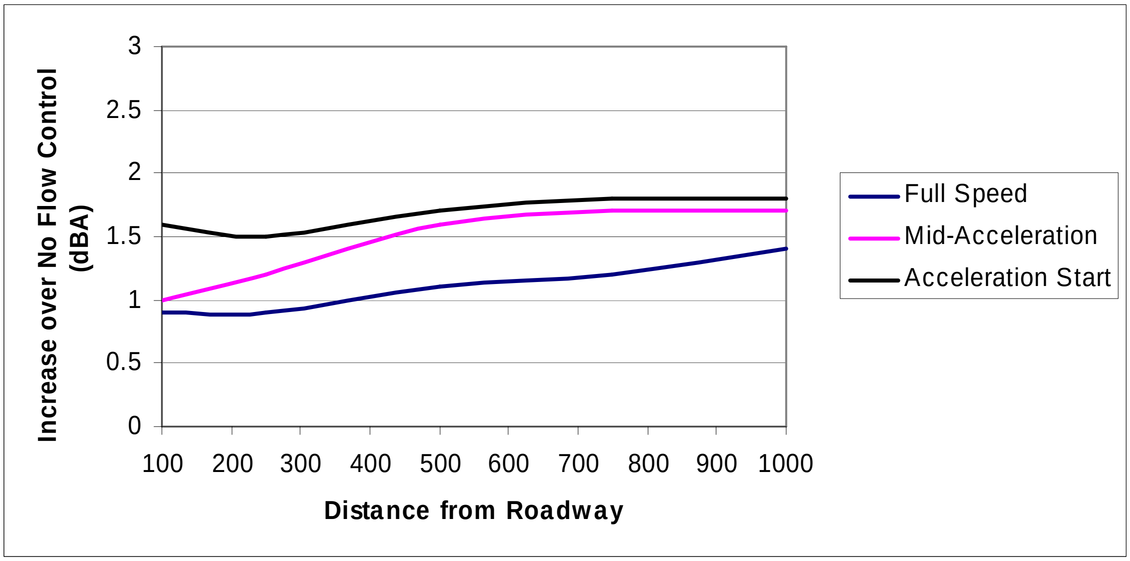


Figure 3-4: Increase in Noise Levels with Flow Control (100% controlled, no trucks)

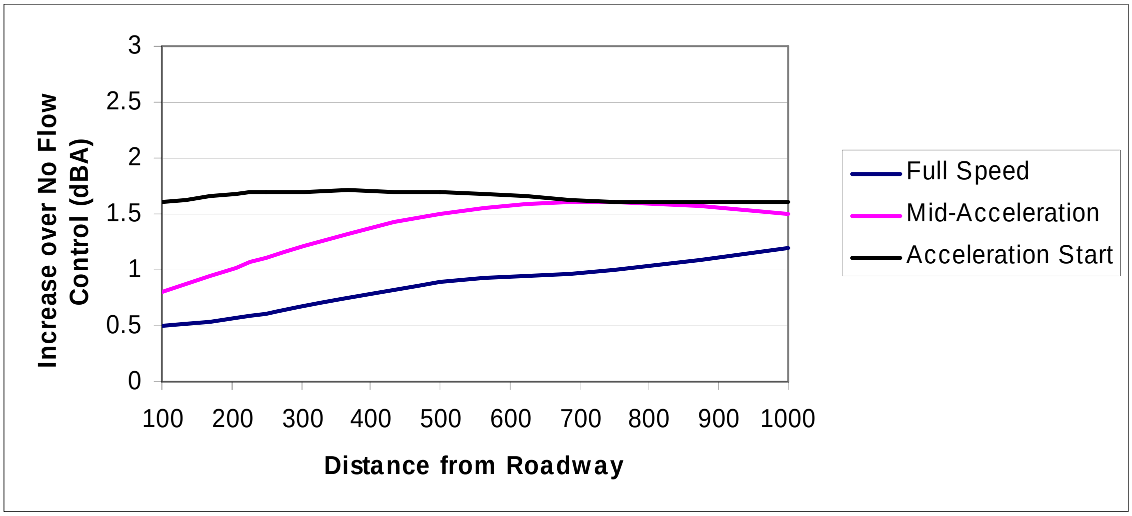


Figure 3-5: Increase in Noise Levels with Flow Control (50% controlled, 10% trucks)

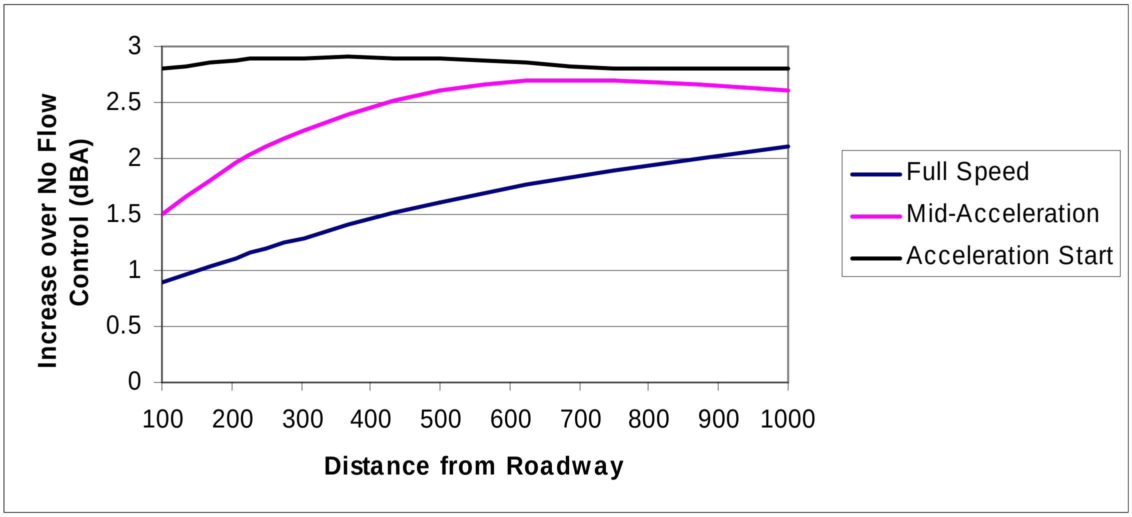


Figure 3-6: Increase in Noise Levels with Flow Control (100% controlled, 10% trucks)

3.10 Barrier Insertion Loss with Multiple Receptors

A simple experiment was executed to determine if there is any difference in the barrier insertion loss predicted for a group of receptors when a) predicting each individually in separate runs, or b) all together. Two receptors were modeled behind a wall using the Lafayette model, first together, then each separately. The results were identical, as expected.

3.11 Barrier On Structure

Similar to roadways, barriers can be designated as "on structure" in TNM. Once a barrier has been designated "on structure," the user must indicate within TNM which road segments will be shielded by the segments of the barrier. To test the effects of placing a barrier (and, assuming, an accompanying roadway) on structure, a model was constructed with two parallel roadways (northbound and southbound), a barrier, and a single receptor, as shown in Figure 3-7. The northbound roadway and the barrier were elevated 15 feet. Traffic consisting of 1500 autos, 75 medium trucks, and 75 heavy trucks at 60 mph was placed on each roadway, and several permutations of the northbound roadway and barrier configurations were run. Table 3-7 shows all of the Leq's predicted at the receptor and a matrix of which road and barrier configurations were used to achieve those results.

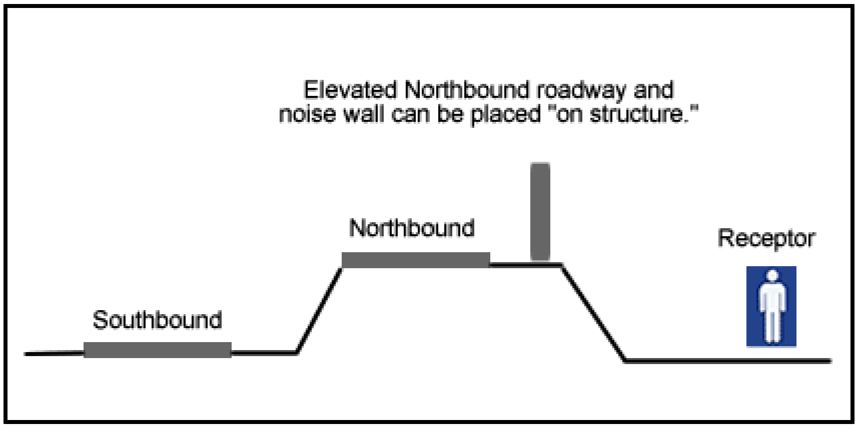


Figure 3-7: Barrier on Structure Analysis Configuration

Table 3-7: Results of Barrier on Structure Analysis

		Barrier Settings			
Leq (dBA)	*Northbound On Structure*	*In Place*	*On Structure*	*Shielding NB*	*Shielding SB*
69.7	X				
66.1	X	X	X	X	
52.1	X	X		X	X
51.0	X	X	X	X	X

The results follow a general, expected trend for the most part. Designating a barrier as a shield for a roadway causes a reduction in levels at shielded receptors. The only issue is that the last two scenarios in Table 3-7 are functionally equivalent. In both, the model is being instructed to shield both roadways, and the location and the elevation of the top of the barrier are the same. The scenarios under which this feature will be needed should be very limited in Colorado. The main one is having a major surface road near or under a barriered interstate.

3.12 Berms

Berms can be modeled in TNM by designating a barrier as such, or by using terrain lines. For this analysis, a 15-foot tall barrier was placed parallel to and 100 feet from the center of the roadway in the generic model, and the slope of the berm was varied. Table 3-8 compares the noise reductions predicted by TNM for a 15-foot tall fixed height noise wall and a 15-foot tall berm with a 3:1 slope. The results are nearly identical. Table 3-9 shows the insertion loss predicted for various berm slopes. Slope has very little effect (~0.1 dB). Table 3-10 compares the insertion loss of a berm with 3:1 slopes to that of a berm modeled using both 3 and 5 terrain lines. Slightly higher insertion loss was predicted using 5 terrain lines versus 3.

Table 3-8: Fixed Height Wall vs. 3:1 Berm

	Distance From Roadway (feet)								
	200	*300*	*400*	*500*	*600*	*700*	*800*	*900*	*1000*
No Barrier	71.5	68	64.8	62	59.9	57.9	56.2	54.8	53.6
15' Fixed Height Wall	61.5	60.7	59.3	57.7	56.2	54.9	53.7	52.6	51.6
Insertion Loss	10.0	7.3	5.5	4.3	3.7	3.0	2.5	2.2	2.0
15' 3:1 Berm	61.4	60.6	59.1	57.5	56.1	54.8	53.7	52.6	51.7
Insertion Loss	10.1	7.4	5.7	4.5	3.8	3.1	2.5	2.2	1.9
Berm IL - Wall IL	0.1	0.1	0.2	0.2	0.1	0.1	0.0	0.0	-0.1

Table 3-9: Effect of Berm Slope

	Distance From Roadway (feet)								
	200	*300*	*400*	*500*	*600*	*700*	*800*	*900*	*1000*
15' 3:1 Berm	61.4	60.6	59.1	57.5	56.1	54.8	53.7	52.6	51.7
Insertion Loss	10.1	7.4	5.7	4.5	3.8	3.1	2.5	2.2	1.9
15' 2:1 Berm	61.5	60.7	59.1	57.5	56.1	54.8	53.6	52.6	51.6
Insertion Loss	10.0	7.3	5.7	4.5	3.8	3.1	2.6	2.2	2.0
2:1 IL - 3:1 IL	-0.1	-0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.1
15' 1:1 Berm	61.7	60.7	59.1	57.5	56.1	54.8	53.6	52.6	51.6
Insertion Loss	9.8	7.3	5.7	4.5	3.8	3.1	2.6	2.2	2.0
1:1 IL - 3:1 IL	-0.3	-0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.1

Table 3-10: 3:1 Berm vs. Berm Approximation Using Terrain Lines (dBA)

	Distance From Roadway (feet)								
	200	*300*	*400*	*500*	*600*	*700*	*800*	*900*	*1000*
15' 3:1 Berm	61.4	60.6	59.1	57.5	56.1	54.8	53.7	52.6	51.7
Insertion Loss	10.1	7.4	5.7	4.5	3.8	3.1	2.5	2.2	1.9
3 Terrain Line 3:1 Berm	61.4	60.6	59.1	57.5	56.1	54.8	53.7	52.6	51.6
Insertion Loss	10.1	7.4	5.7	4.5	3.8	3.1	2.5	2.2	2.0
5 Terrain Line "Rounded Berm"	60.3	60.1	58.8	57.3	55.9	54.7	53.6	52.6	51.6
Insertion Loss	11.2	7.9	6.0	4.7	4.0	3.2	2.6	2.2	2.0

3.13 Barrier Reflections

TNM models reflections in two ways. First, increasing the NRC on a noise wall's highway side increases its insertion loss. The effect is minimal, as expected. For a 20-foot wall, the noise reduction increases by 0.4 dB when the NRC of the wall is increased from 0 to 0.8. Second, TNM utilizes reflections in its Parallel Barrier routine, as described in Section 3.15.

TNM does *not*, presently, handle the issue of noise reflecting off of a wall and reaching receptors on the opposite side of the highway (the side *not* being shielded by the wall). This scenario can be modeled using the mirror source method. This is accomplished by placing a roadway in the model to represent the reflected noise energy. As shown in Figure 2-5, the mirror road is placed on the opposite side of the wall from which the reflections are being addressed. The distance from the wall to the mirror road is the same as that from the wall to the actual road. A mirror source test was conducted using the 6th Avenue Site model. The addition of the mirror source increased predicted noise levels by 0.2 to 1.6 dB. This is a reasonable result, given the fact that an infinitely tall, infinitely long, perfectly reflecting wall would increase levels by 3 dB. TNM accurately predicts that the effect of reflections will be greater at further receptors, where the ratio of the distances between the actual and mirror roads is closer to unity.

3.14 Barrier Placement

A barrier works best when placed as close to the source as possible. A wall was modeled in TNM at three distances from the center of the road, and predictions made at various distances from the road. The results are shown in Figure 3-8, and are consistent with expectations.

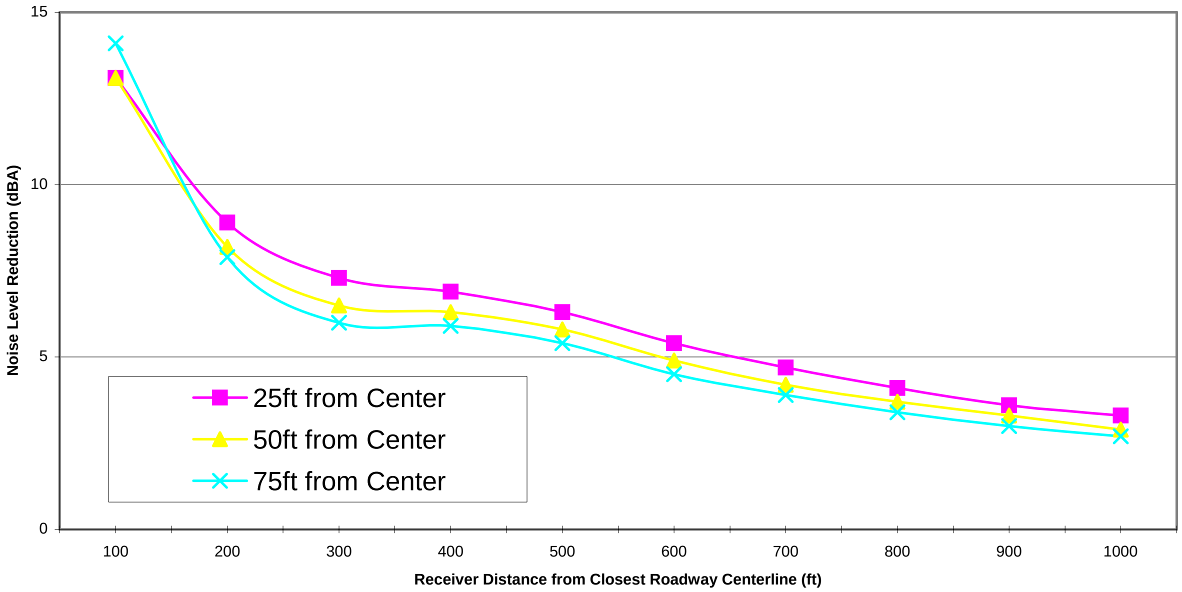


Figure 3- 8: Effect of Placing Barrier Close To Road

3.15 Parallel Barriers

TNM has a parallel barrier analysis tool, which computes the degradation of barrier insertion loss due to the presence of another barrier on the opposite side of a roadway. The analysis is conducted by drawing a cross-section of a set of barriers and roads and defining analysis points. TNM then computes the additional noise levels that can be expected at those points as a result of barrier reflections.

The parallel barrier feature was tested using the 6th Avenue model, which features walls along both the north and south sides of the highway. Three measurements were taken along the south side of 6th Avenue. M2 and M3 were located behind the southern noise wall. M1 was not located behind a wall, and acted as a control point (refer to Figure 2-5).

First, a noise model was developed that included US 6, the three measurement locations as receptors, and both noise walls, but did not include any consideration for reflections. Next, a separate parallel barrier analysis was conducted for the cross-section where the measurements (M2 and M3) were taken. Table 3-11 shows the results.

Table 3-11: Results of Parallel Barrier Analysis

Receptor	Distance from 6th Ave	Both Barriers Present	P. Barrier Analysis Result	Predicted + PB Analysis	Measured Levels	Difference
M1	65	80.7	N/A	80.7	84.4	-3.7
M2	110	64.0	3.6	68.3	65.1	3.2
M3	155	62.9	4.3	66.5	62.0	4.5

There is under prediction at M1, which was expected as this site was receiving noise reflections from the northern wall during the measurements and this was not accounted for in the model. Note that FHWA does say that the parallel barrier analysis tool could be used for predicting single wall reflections by using a short second wall, but this has not been validated by FHWA at the time of this report. The model significantly over predicted for M2 and M3 when including the results from the parallel barrier analysis.

The TNM manual states that a roadway width to wall height ratio between 10:1 and 20:1 the degradation should be between 0 and 3 dB, and if this ratio is less than 10:1 the degradation should be 3 dB or greater. This model represented a ratio of almost exactly 10:1, thus the degradation should have been around 3 dB. One location had a degradation of 3.6 dB and the other had a degradation of 4.3 dB.

The same situation was modeled using a simulated mirror source to represent the reflected energy. This is a method that has been in use in the industry for years, and can be applied using any model. A “mirror” roadway is created and located on the opposite side of the reflection wall. Using this method the measured and predicted noise levels agreed to within 1.5 dB

3.16 Building Rows

A building row was added to the generic model, and it was found that noise levels were reduced by approximately 2 dB for a 25-foot tall building row with 40% coverage, and 4 dB for 80% coverage. These are reasonable results.

3.17 Ground Zones

Using the generic model described above, with the default ground type set to Lawn, a Pavement Ground Zone was added adjacent to the roadway. The width of the ground zone was varied from 25 feet to 200 feet. The results are shown in Figure 3-9. The influence of the ground zone decays as one moves out from the road, beyond the ground zone, but then begins to become more significant again beyond 600 feet. The reason for this should be investigated further.

3.18 Tree Zones

Using the generic model described above, a Tree Zone was added alongside the roadway consisting of 40-foot tall trees. The width of the zone was varied from 25 feet to 200 feet. The results are shown in Figure 3-10 and are consistent with acoustic theory.

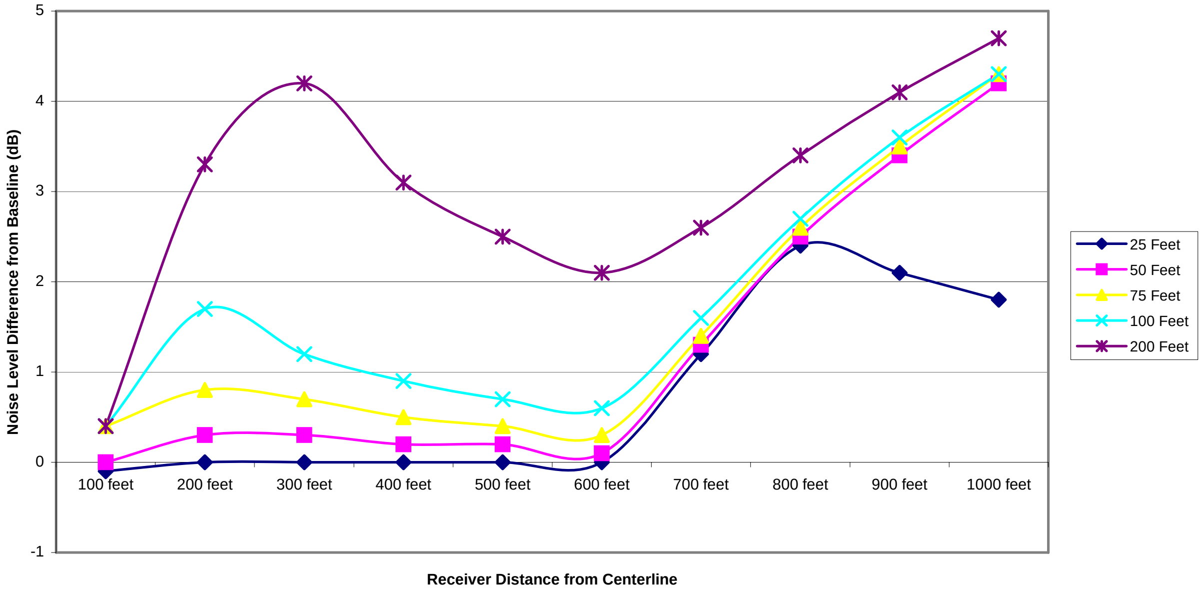


Figure 3-9: Effect of Pavement Ground Zone

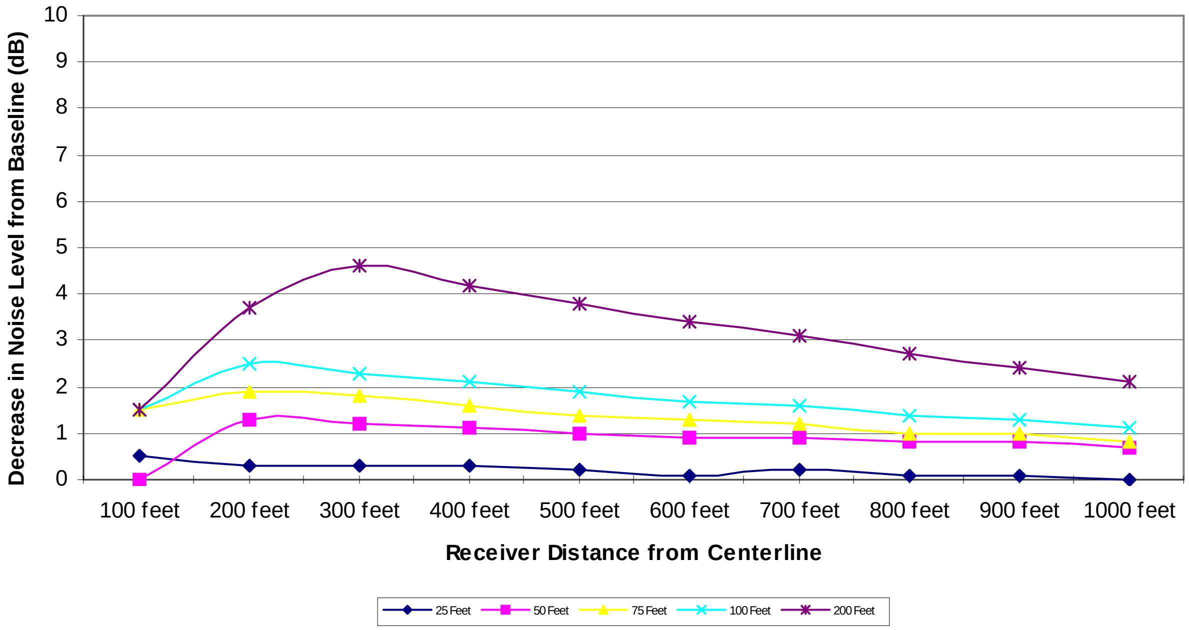


Figure 3-10: Effect of 40 Ft. Tall Tree Zone of Various Widths

3.19 Contours

TNM provides a utility that calculates and displays sound level contours in a pre-defined area. The Lafayette model was used to test this tool. A line of receptors at 50-foot intervals was placed leading away from the roadway perpendicularly. The model was run and the approximate distances to where the sound level dropped to 70, 65, and 60 dBA were determined by interpolating. A contour area was then drawn around the receptors and a zero height barrier was placed between them and the roadway (TNM requires a barrier design in order to conduct a contour analysis, and the TNM manual suggests using a zero height barrier in cases where no real barrier is present). The TNM contour tool was used to calculate contours at 70, 65 and 60 dBA. The distances from the road to the contours were then calculated, and are compared to those determined from the predictions at individual locations in Table 3-12.

Table 3-12: Noise Contour Locations for Both Point and Contour Routine Predictions

Noise Level (dBA)	*Distance (feet) to:*	
	Contour	*Receptors*
70	62	58
65	116	158
60	220	255

There is a somewhat significant difference between the distances to the contours calculated using point predictions and when using the contour tool. This should be investigated further. Also, it should be noted that the authors have found TNM’s contour routine is difficult to use, specifically that using it often causes runs to “crash”. The contour routine should be used for general planning purposes only. It should not be used to determine impacts on CDOT projects. Impact should be determined by predicting noise levels at individual receiver locations.

3.20 Flow Control

In general, flow control devices increase noise levels due to the acceleration away from the stopping point. However, usually only one segment of a road will be effected by the flow control device. As one move away from the road, the contribution of the flow controlled segment becomes less significant, because the distance to other segments that are not flow controlled becomes similar to that to the controlled segment. This is exactly what the TNM results exhibit up to about 500 feet. Then, the effect of flow control begins to increase beyond 500 feet. This should be investigated further. Users should avoid modeling flow control devices for receptors located more than 500 feet from the road.

4.0 COMPARISON OF TNM TO OTHER ROADWAY NOISE MODELS

TNM 2.1 and 2.5 results were compared to those of STAMINA 2.0 with Colorado REMEL's, STAMINA 2.0 with FHWA REMEL's, the German RLS-90 standard, the Nordic Statens Planverk 48 standard, and STAMINA 2.0 with FHWA REMEL's. STAMINA 2.0 w/CDOT REMELs was implemented using a software implementation of FHWA's Highway Traffic Noise Model (Report No. FHWA-RD-77-108) provided by the Minnesota DOT. RLS 90, Planverk 48, and STAMINA 2.0 with FHWA REMEL's were each implemented using the SoundPLAN software program. In the following discussions the models will be referred to as TNM 2.1, TNM 2.5, STAMINA 2.0/CDOT, STAMINA 2.0/FHWA, RLS 90, Planverk 48, and FHWA-RD-77-108.

4.1 Decay Rate

A simple model, upon which all other test models were based, was constructed to compare basic decay rates between the standards. As shown in Figure 4-1, the model consisted of two parallel 5,000 foot long roadways with a line of ten receptors extending perpendicular from 100 to 1,000 feet. The two roadways (northbound and southbound) are separated by 60 feet at their centers, and have a width of 34 feet each. Traffic in each direction consisted of 2250 autos at 60 mph, and 125 medium trucks and 125 heavy trucks at 50 mph. Default ground type in each model was set to: Lawn in TNM 2.1 and 2.5, 0.5 alpha in STAMINA 2.0/CDOT and /FHWA, and 0.5 in SoundPLAN for RLS 90, Planverk 48, and FHWA-RD-77-108. Following the FHWA recommendation for modeling multiple roadways, the TNM 2.1 model contained a third roadway placed in the center of the other two. The width of this roadway was set such that the center road overlapped the other roads by approximately one foot. No traffic was placed on the third road. This additional roadway was covered with a "field grass" ground zone to simulate a grassy median. Referring to Figure 4-2, sound level decay with distance is linear between 100 and 1000 feet for each standard except TNM 2.5. Excluding the TNM models, all results were within 2.8 dBA of each other at 300 feet, and within 5.9 dBA of each other at 1000 feet. TNM 2.1 showed appreciably higher decay through the whole range of distances, and TNM 2.5 showed significant increase in the *rate* of decay beyond 300 feet with respect to the other models.

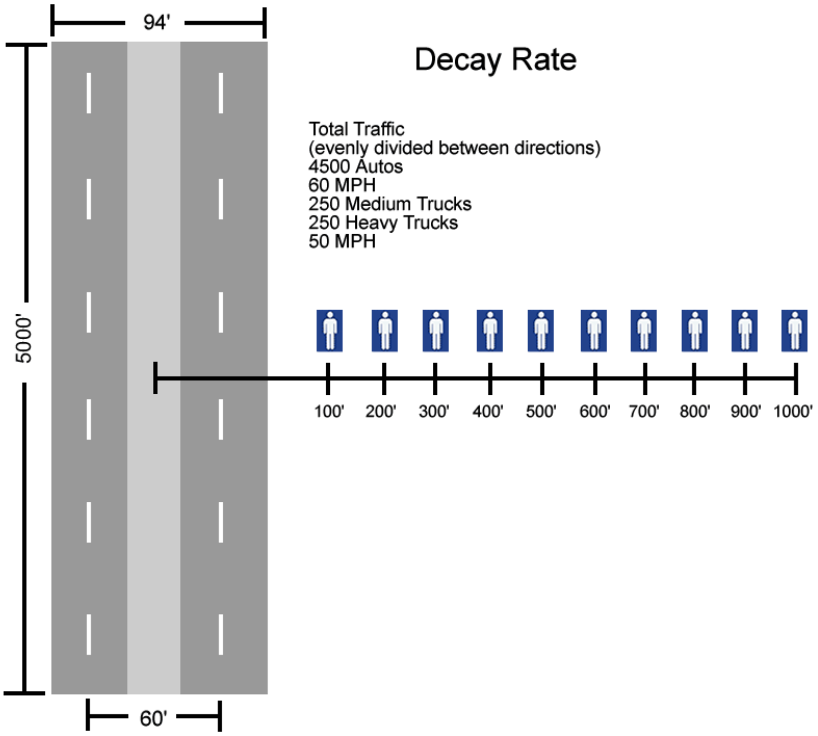


Figure 4-1: Diagram of Base Model Layout

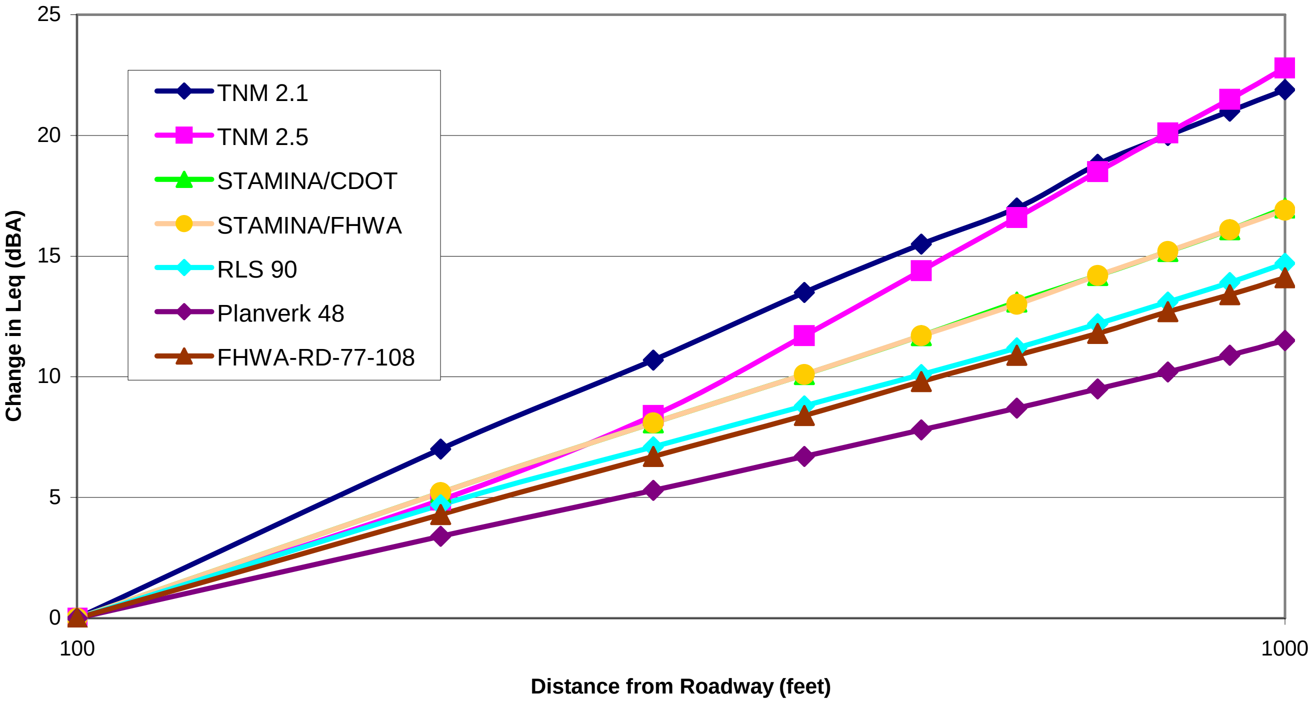


Figure 4-2: Sound Level Decay with Distance for Different Standards

4.2 Ground Type

An analysis was conducted where the ground absorption setting for each model was varied through its range from “soft” to “hard”, with the exception of RLS 90 which has no such input parameter. In TNM, the ground types “Lawn,” “Hard Soil,” and “Pavement” were used. In STAMINA alpha values of 0.0 and 0.5 were used, and in SoundPLAN ground type coefficients of 0, 0.5, and 1.0 were used. Figure 4-3 shows the resulting effect on predicted noise levels for each model, and for receptors of varying distance from the road. STAMINA exhibits the lowest sensitivity to ground absorption input, varying only 2 to 7 dBA over the 1,000 foot analysis distance. The response of Planverk 48 to ground type was similar in character to STAMINA and FHWA-RD-77-108, though at much higher values (range of 3 to 11 dBA over 1,000 feet). TNM 2.1 followed a less uniform curve, and at still higher values than Planverk 48. TNM 2.5 showed the least sensitivity to ground type for receptors between 100 and 300 feet from the road (0.7 to 3.6 dBA), but produced differences that increased with distance from 400 to 1000 feet (5.3 to 10.7 dBA).

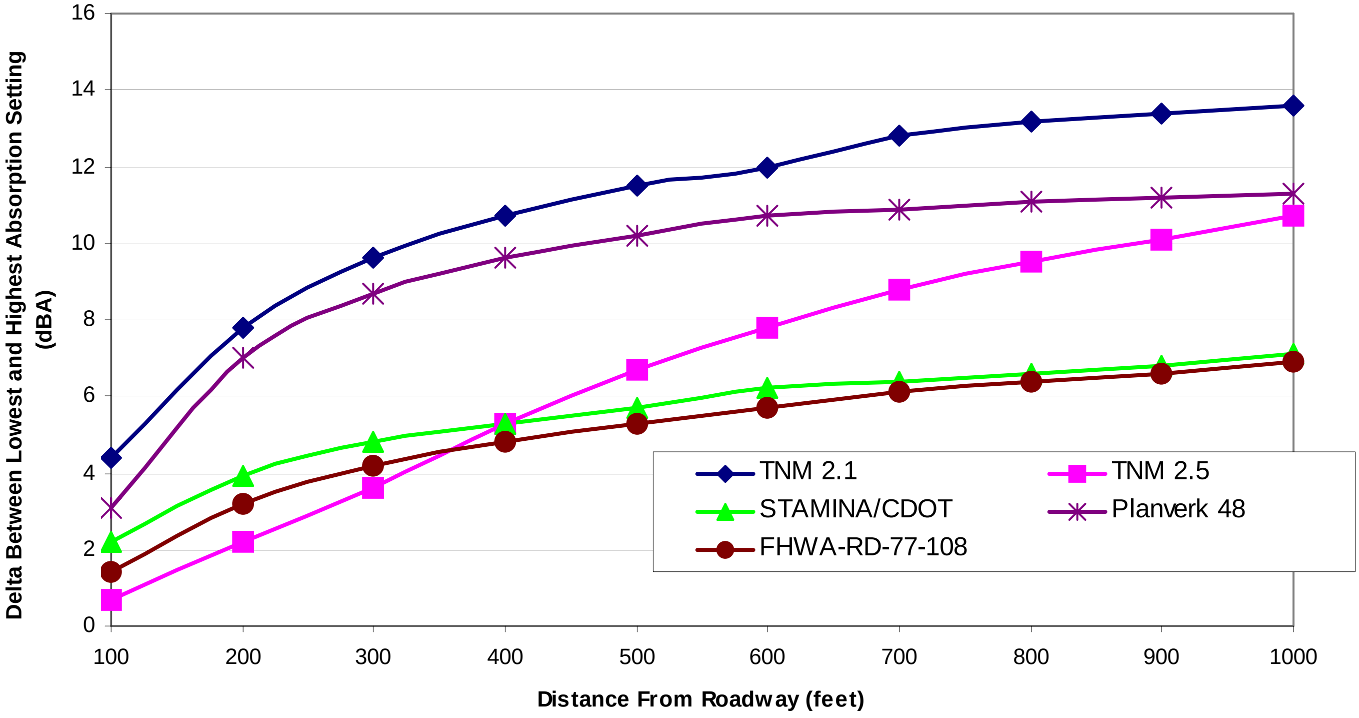


Figure 4-3: Effect of Ground Type Setting On Each Model

Figure 4-4 shows the noise level predicted by each model for each of its available ground type options over a receptor distance of 100 to 1,000 feet. Note that all of the models show a logarithmic decay in level with distance with the exception of TNM. The TNM results show an anomaly in the output for Hard Soil ground type in both versions 2.1 and 2.5. This should be investigated further.

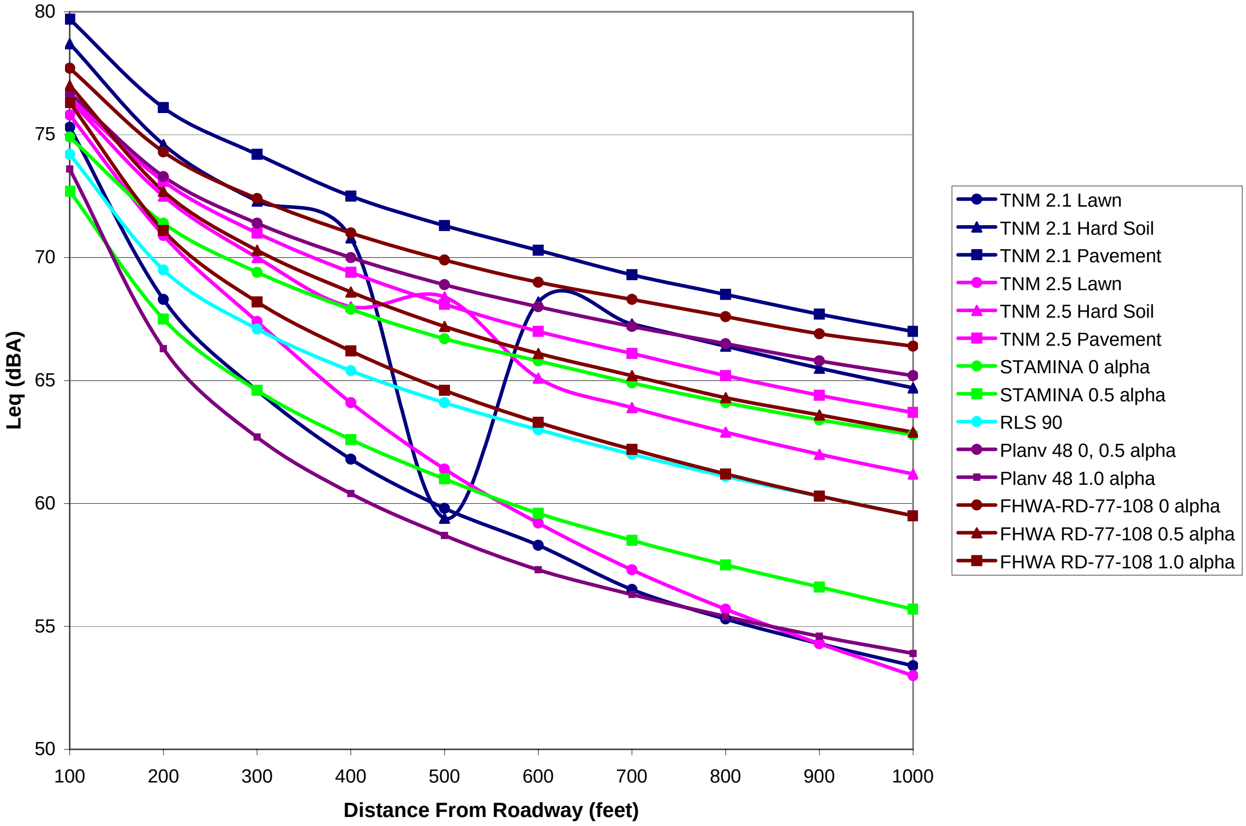


Figure 4-4: Noise Level versus Ground Type

4.3 Barrier Insertion Loss

A 1,000-foot long barrier was placed at a distance of 50 feet from the center of the roadway closest to the receptors (refer to Figure 4-1). The model was run with fixed barrier heights of 20, 12, and 3 feet, and the results were compared to the no-barrier scenario to calculate insertion loss. From Figure 4-5, the results for the 20-foot tall barrier are uniform with distance, and all models are in relatively close agreement. TNM 2.1, 2.5, and STAMINA/CDOT are in very close agreement with each other, but predict 2 dB more insertion loss than RLS 90, Planverk 48, or FHWA-RD-77-108. From Figure 4-6, the results for the 12 foot barrier are similar to that of the 20 foot one. However, TNM 2.5 is starting to show results that deviate from the other models (TNM predicts higher insertion loss). From Figure 4-7, TNM 2.5 and Planverk 48 predict relatively high insertion loss for a three-foot tall barrier (greater than has been observed in the field). The other models predict 1 to 3 dB of reduction, which is in line with results observed in the field. In summary, TNM predicted among the highest insertion losses for all wall scenarios, and its predicted insertion loss for a three foot tall barrier is greater than that measured in the field.

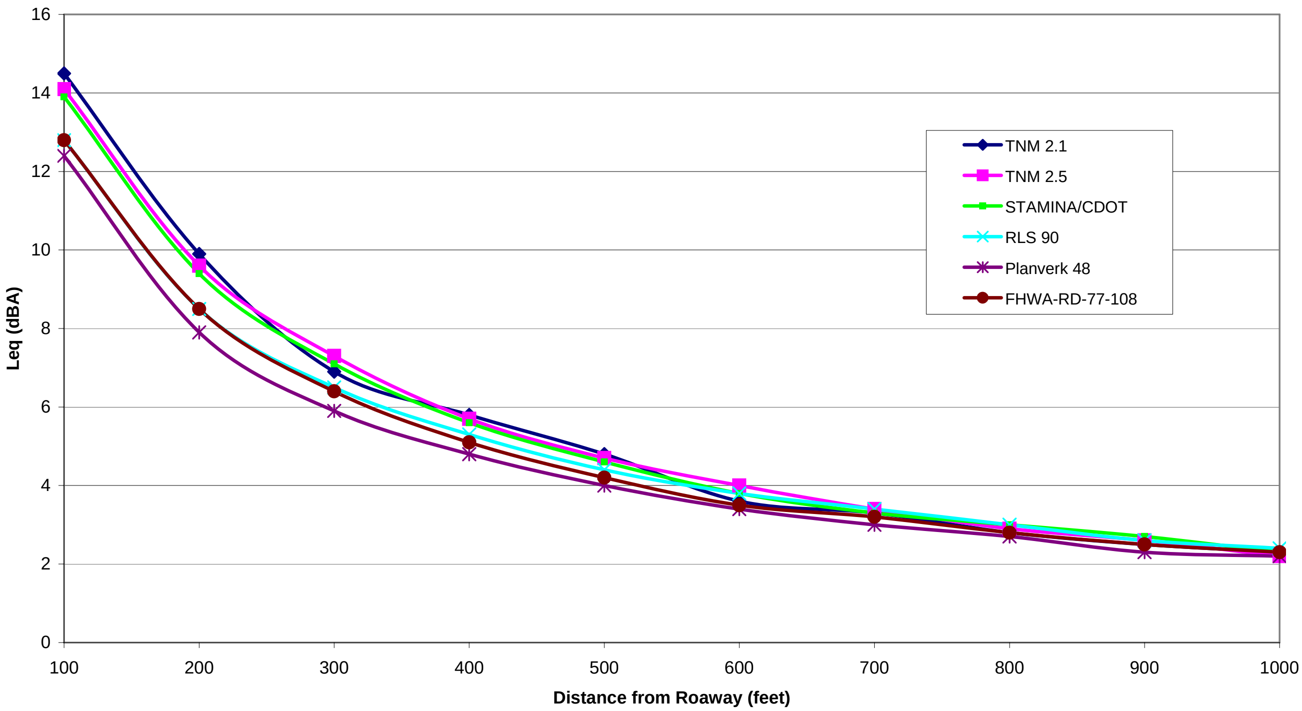


Figure 4-5: Insertion Loss for A 20-foot Tall Barrier

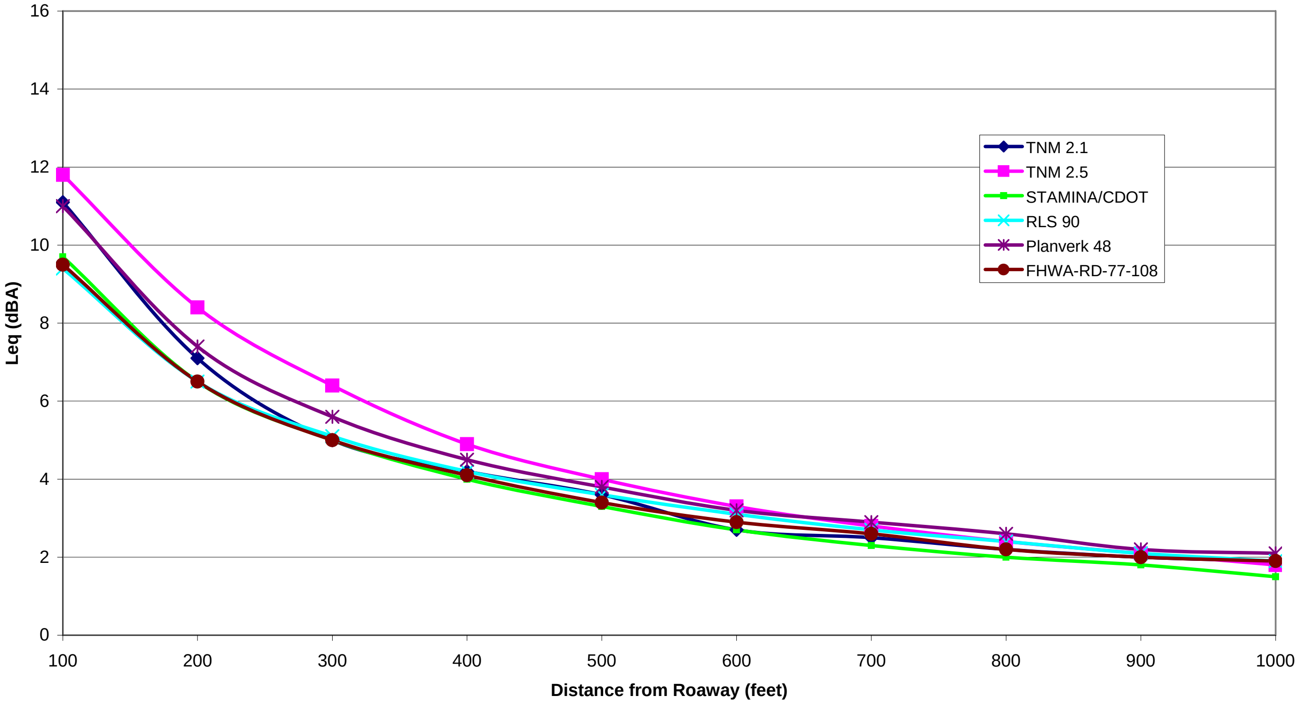


Figure 4-6: Insertion Loss for A 12-foot Tall Barrier

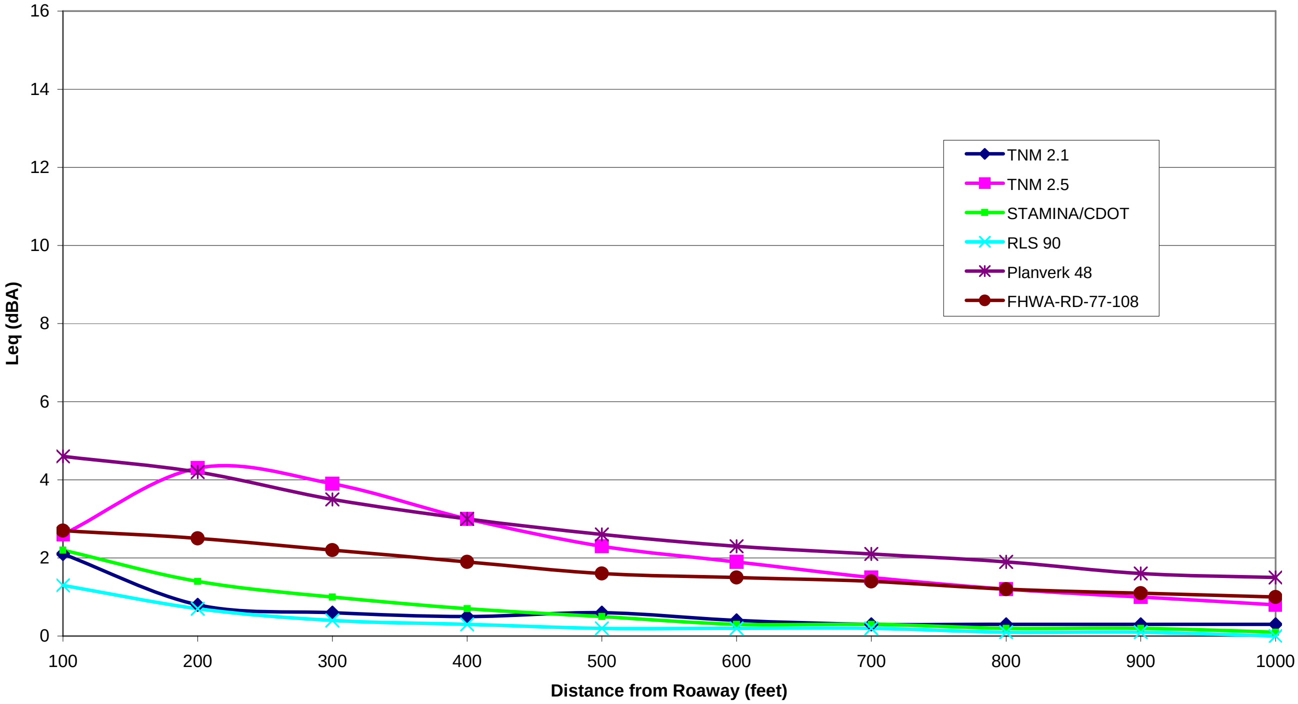


Figure 4-7: Insertion Loss for a 3-foot Tall Barrier

4.4 Terrain Lines

Two analyses were conducted to investigate the effect of placing terrain lines in the model. Referring to Figure 4-8, one receiver was placed a certain distance from the highway (explained more below) and at an elevation 50 feet higher than the road. In the first analysis, a single terrain line was placed parallel to the road and at the elevation of the receiver (50 feet). This effectively creates a barrier. In the second analysis, a single terrain line was placed parallel to the road and at the elevation of the road (0 feet). This creates a valley, and forces sound to propagate through the air versus along the ground. Both analyses were conducted for receptor distances of 300, 500, and 800 feet from the centerline of the roadway. The terrain lines were offset from the center of the road by a distance equal to ½ of that between the road and receptor. In STAMINA, this was accomplished with a 0-height barrier. Terrain lines were used in the other models.

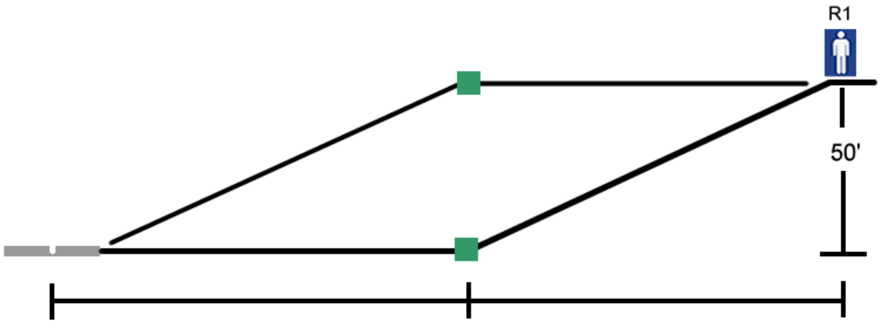


Figure 4-8: Layout for Terrain Line Analysis

The reduction in noise levels due to the addition of the higher terrain line that is acting as a barrier is shown in Figure 4-9. The results vary between the models by as much as 10 dB, but they all have the same pattern with distance. FHWA-RD-77-108 showed the greatest sensitivity, with reductions of 17 dBA at 300 feet and 15 dBA at 800 feet. Least sensitive was STAMINA, with reductions of 8.7 dBA at 300 feet and 4.0 dBA at 800 feet. TNM 2.5 was within the range of the other models.

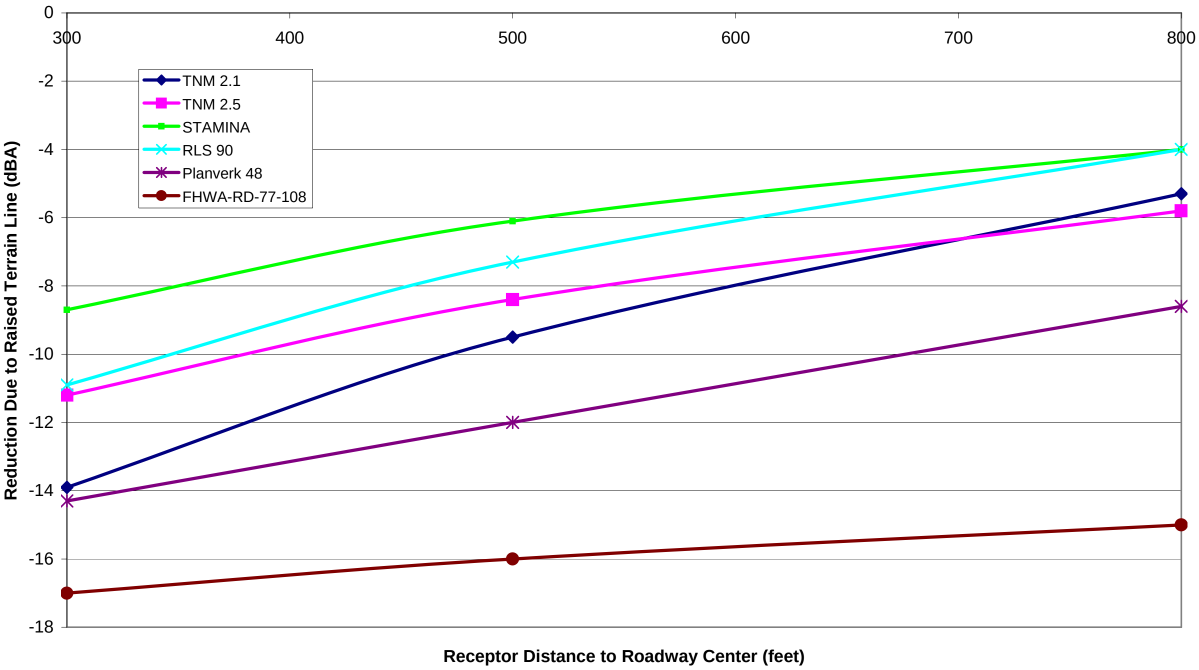


Figure 4-9: Results of Shielding Terrain Line Analysis

The noise level changes for the insertion of the lower terrain line that is forming a valley are shown in Figure 4-10. The valley produces little change in STAMINA, which is expected given the fact that the model does not define a ground plane. The TNM 2.5 and Nordik results are similar, and are reasonable given the nature of outdoor sound propagation. RLS-90 showed an essentially opposite trend, with a sound level change of –1.3 dBA at 300 feet, increasing to a difference of +3.3 dBA at 800 feet.

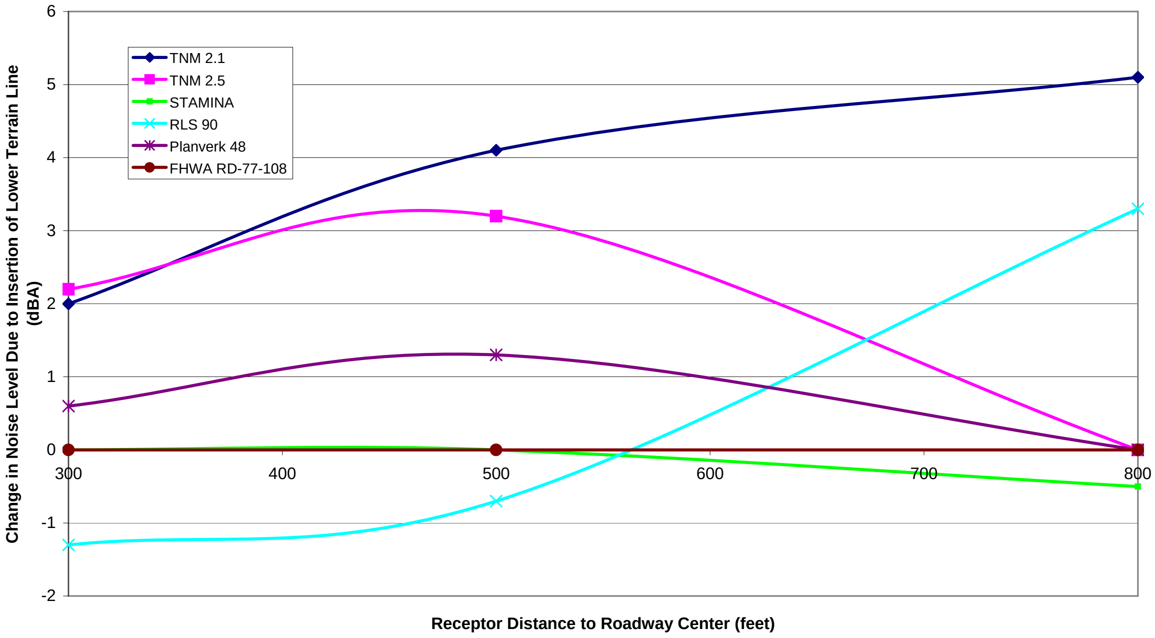


Figure 4-10: Results of Valley Terrain Line Analysis

4.5 Receptor Height

The height of the receptors in the decay rate model was increased first to 10 feet and then to 20 feet. Increasing the receptor height had the least effect in the Planverk 48, RLS 90 and STAMINA models. TNM, version 2.1 in particular, showed the greatest sensitivity to receptor height. In all models, the difference between 10-foot and 20-foot receptor height was minimal.

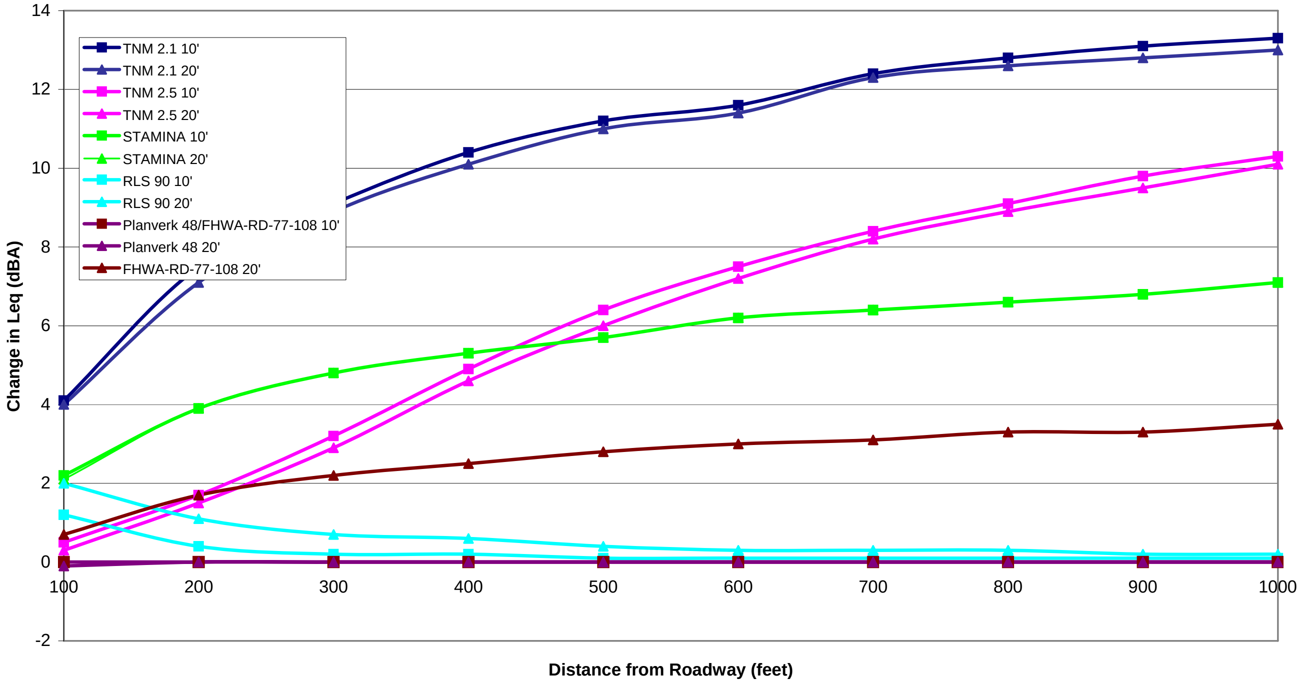


Figure 4-11: Difference in Leq Due to Increased Receptor Height

4.6 Edge of Pavement Barrier

An analysis was conducted to determine the effect on noise levels of the case where receptors are lower in elevation than the road. In this case, the edge of the road closest to the receptors forms a barrier. In TNM, the edge of pavement is automatically defined by the roadway placement and width and the model automatically defines a pavement ground plane out to that location. In the STAMINA and SoundPlan models, a zero foot tall barrier was placed along the roadway at the same elevation as the road. Receptors were placed along the road as shown in Figure 4-1, but their elevation was set to –20 feet.

The results are shown in Figure 4-12, and are generally in line with expectations. That is, close to the road, the edge of pavement acts as a barrier and noise levels are reduced. At greater distances, the edge of pavement has less of a barrier effect, but now the sound is propagating through the air which tends to increase noise levels.

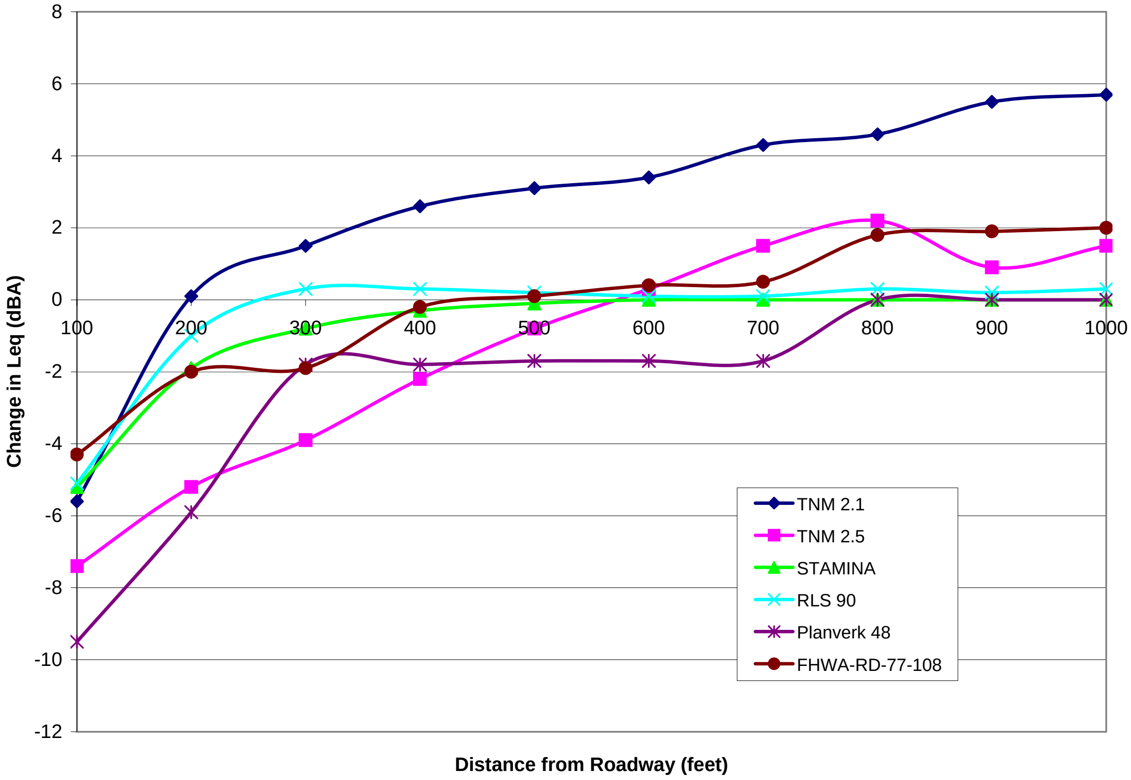


Figure 4-12: Difference in Leq due to Lowering Receptors 20’

5.0 REVIEW OF FHWA'S PHASE 1 EVALUATION

The report entitled *TNM Version 2.5 Addendum to Validation of FHWA's Traffic Noise Model: Phase 1* (July 2004, Final Report) was reviewed. FHWA conducted a series of noise measurements at 17 sites. Accompanying traffic, terrain, and weather data were also collected. TNM 2.5 was used to predict noise levels at each measurement location, and the predicted levels were compared to the measured levels. The Phase 1 study was initially conducted using TNM 2.0. TNM 2.0 was shown to over-predict noise levels by an average of 2.6 dBA. In TNM 2.5, FHWA modified the method used to correct REMELs to a free-field condition, and the over-prediction was reduced to 0.5 dBA. It should be noted, however, that this is the *average* over-prediction. As shown in Figure 5-1, there are still a number of sites in FHWA's study where 5 dB of over- and under-prediction occur.

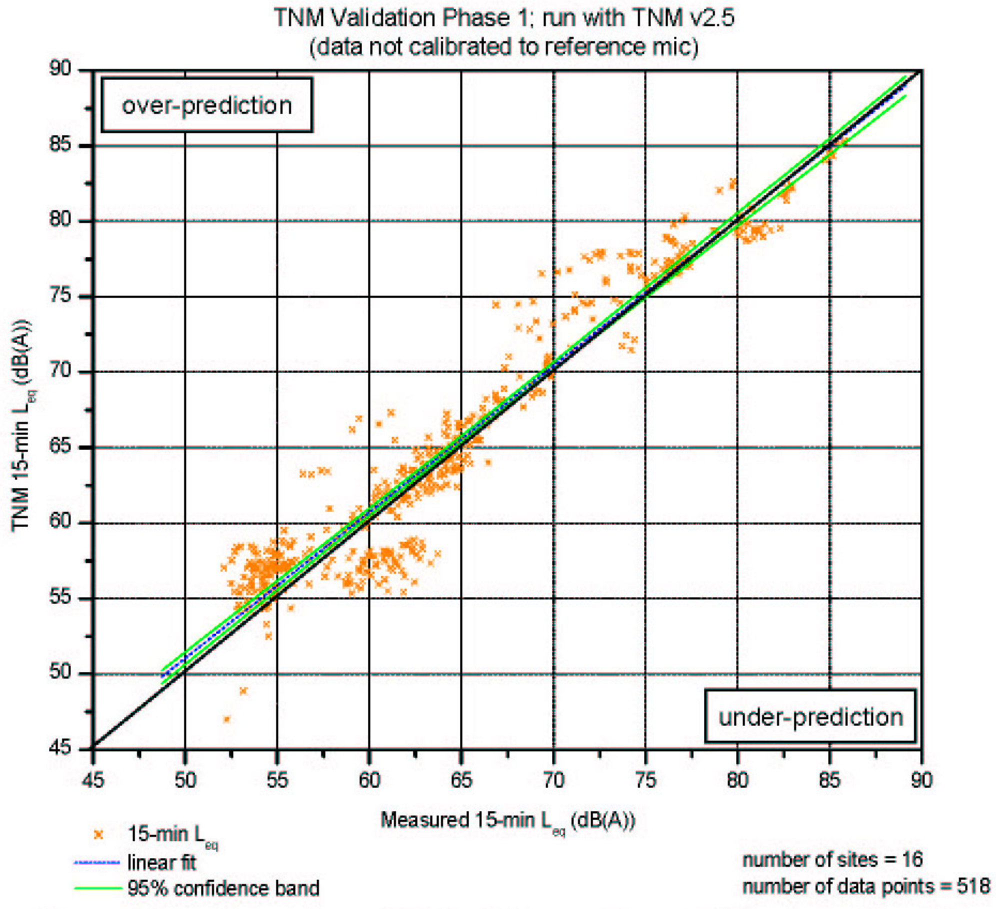


Figure 5-1: TNM Phase 1 Validation Results – Uncalibrated (Source: FHWA)

The FHWA Phase 1 report concludes that there may be “site biases”, such as pavement type, that causes some of the discrepancy between measured and predicted results. To account for this, FHWA compared the predicted noise level at each site to the level measured close to the roadway (i.e. 50 feet). The discrepancy between these values was used as a correction factor to adjust levels predicted at further distances. This “calibration” process improved the average difference to 0.2 dBA. However, as shown in Figure 5-2, there are still sites where measured and predicted results differ by as much as 3 to 5 dBA.

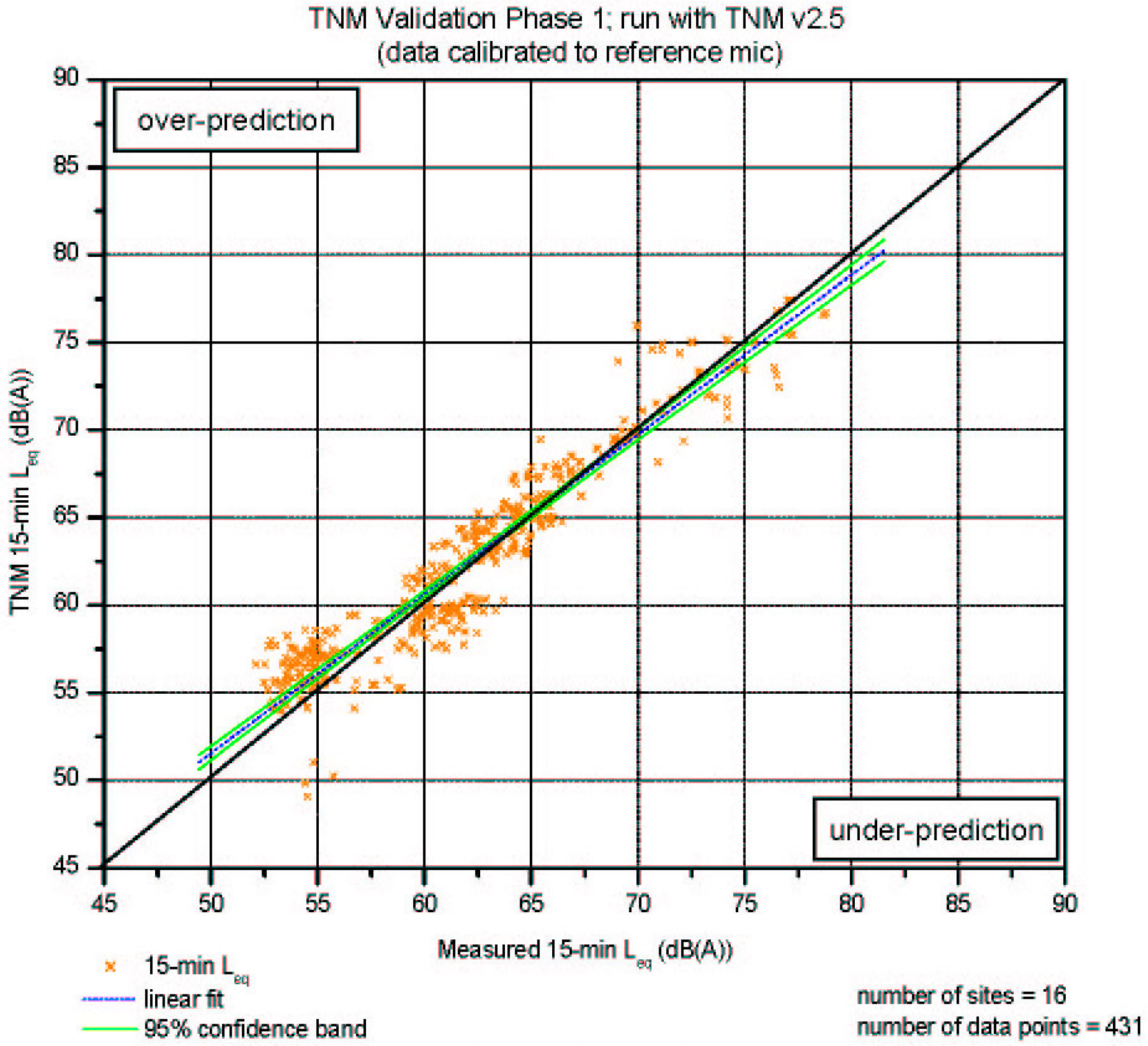
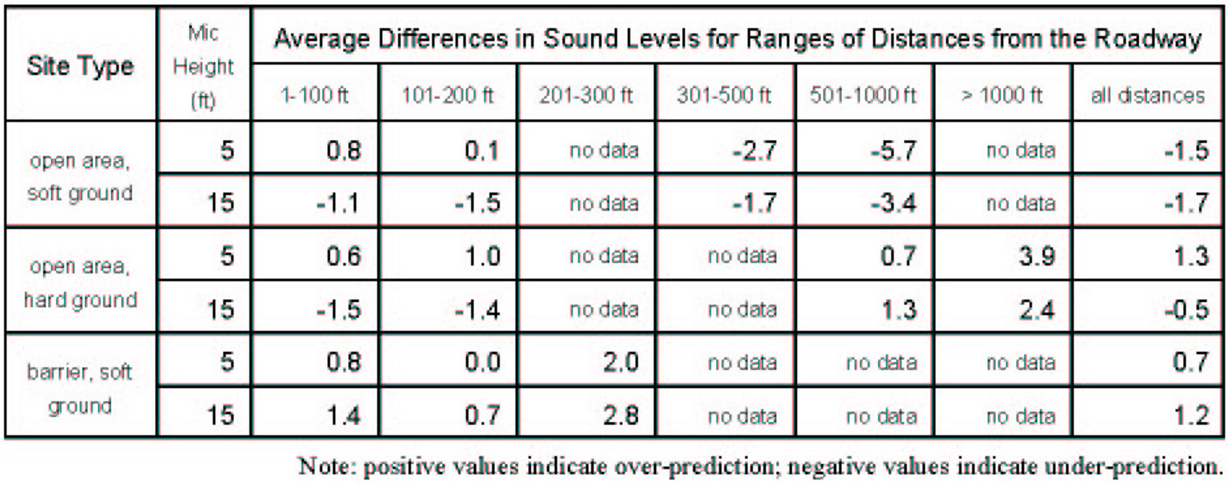


Figure 5-2: TNM Phase 1 Validation Results – Calibrated (Source: FHWA)

Finally, Table 7 of FHWA's Phase 1 Validation Study, which is shown below as Table 5-1, shows that TNM is under-predicting noise levels by an average of 2 to 3 dB at distances of 300 to 500 feet from the road, and under predicting by 2 to 6 dB at distances between 500 and 1,000 feet from the roadway. This is of concern to the Colorado Department of Transportation, as many of its highways are carrying traffic volumes sufficient to cause noise impact at these distances.

Table 5-1: Average Difference (TNM Minus Measured) as a Function of Distance and Height (Source: FHWA)



Site Type	Mic Height (ft)	Average Differences in Sound Levels for Ranges of Distances from the Roadway						
		1-100 ft	101-200 ft	201-300 ft	301-500 ft	501-1000 ft	> 1000 ft	all distances
open area, soft ground	5	0.8	0.1	no data	-2.7	-5.7	no data	-1.5
	15	-1.1	-1.5	no data	-1.7	-3.4	no data	-1.7
open area, hard ground	5	0.6	1.0	no data	no data	0.7	3.9	1.3
	15	-1.5	-1.4	no data	no data	1.3	2.4	-0.5
barrier, soft ground	5	0.8	0.0	2.0	no data	no data	no data	0.7
	15	1.4	0.7	2.8	no data	no data	no data	1.2

Note: positive values indicate over-prediction; negative values indicate under-prediction.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The comparison of predicted noise levels to measured levels shows that TNM 2.5 is accurate to within approximately 2 dB on an average and statistical basis. Interestingly, STAMINA 2.0 achieved similar results. STAMINA predicted within 3 dB of measured levels at 34 sites (81% of total). TNM 2.5 predicted within 3 dB of measured levels at 35 sites (83% of total). Closer inspection of the results at individual measurement locations shows that discrepancies between measured and predicted noise levels vary from –5 to 5 dB. All of this is consistent with the results of FHWA's Phase 1 Validation Study, where a similar comparison of measured and predicted levels was made. There is no clear trend in the discrepancies between measured and prediction values in either of the CDOT or FHWA studies. Statistical analysis showed no difference between STAMINA and TNM 2.5.

The analysis of each of TNM's input parameters yielded results that were mainly in agreement with documented acoustic principles and the results of studies by others. That was not the case with the following:

- Ground Type: Using a default ground type of Hard Soil versus Lawn results in an increase of 7 dB for a receptor located 300 feet from the road. This is a greater increase than that predicted by previous models and theoretical equations. Therefore, users should exercise care in the selection of default ground type.
- Heavy Trucks and Barriers: The insertion loss of a barrier should decrease when the heavy truck percentage increases. This is because TNM assigns more acoustic energy to the upper subsource height for heavy trucks, and the upper subsource height for heavy trucks is greater than that for automobiles and medium trucks. Therefore, increasing the heavy truck percentage increases the amount of energy emitted up high, which will be attenuated less by a barrier. TNM predictions conducted as part of this study showed no change in barrier insertion loss due to increasing truck percentage. This should be investigated further.

- There appears to be a problem with TNM's flow control routine for receptors located more than 500 feet from the road. In general, flow control devices increase noise levels due to the acceleration away from the stopping point. However, usually only one segment of a road will be effected by the flow control device. As one move away from the road, the contribution of the flow controlled road segment becomes less significant, because the distance to other road segments that are not flow controlled becomes similar to that to the controlled segment. This is exactly what the TNM results exhibit up to about 500 feet. Then, the effect of flow control begins to increase beyond 500 feet. This should be investigated further. Users should avoid modeling flow control devices for receptors located more than 500 feet from the road.
- There is very little difference in the results when modeling a barrier as a wall verses a berm. This is in contrast to earlier FHWA findings and the published results of other studies. This should be investigated further.
- The parallel barrier routine provided results that were not in agreement with the measurements taken in Denver. The mirror source method provided better results and should be used instead.
- The routine that predicts the location of noise level contours in TNM is cumbersome, error-prone, and does not agree with predictions at individual locations. It should not be used to determine impacts on CDOT projects.
- Based on FHWA's TNM 2.5 validation study results, the model is under predicting noise levels by more than 2 dB at distances greater than 300 feet from the roadway. This must be kept in mind when conducting analyses on CDOT projects.

When TNM predictions were compared to those of the German RLS 90 model, the Nordic Statens Planverk 48 model, and STAMINA, the following items of note were observed:

- Regarding decay rate, TNM 2.5 exhibits a faster decay rate than all of the other models at distances greater than 300 feet from the road. FHWA should be queried as to why this is the case.
- The results of ground type analyses vary significantly between the models, and TNM was within range of the others. However, the TNM analysis results should an anomaly at receptors 400 to 600 feet from the road when using Hard Soil.
- TNM predicts a greater insertion loss for low height barriers (i.e. 3 feet) than the other models, and higher than that observed in the field. Therefore, users should exercise caution when modeling such barriers with TNM.
- For the two terrain line analyses conducted, TNM prediction trends were reasonable and within range of the other models.

7.0 REFERENCES

TNM Manuals

- TNM 1.0 (January 1998): FHWA Traffic Noise Model Users Guide
- TNM 1.0 (February 1998): FHWA Traffic Noise Model Technical Manual *Note: These are the only comprehensive manuals for TNM and are a must for any analyst*

- TNM 1.1 (Sep. 2000): FHWA Traffic Noise Model Users Guide Addendum
- TNM 2.0 (May 2002): FHWA Traffic Noise Model Users Guide Addendum
- TNM 2.5 (April 2004): FHWA Traffic Noise Model Users Guide Addendum *Note: These are addendums only and discuss only changes to the model with each revision*

Related FHWA Documents

- Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model, Report No. FHWA-PD-94-093, 1995
- Phase 1 Validation, U.S. Department of Transportation Research and Special Programs Administration, John A. Volpe National Transportation Systems Center Acoustics Facility, DTS-34
- Measurement of Highway-Related Noise, Report No. FHWA-PD-96-046, 1996

CDOT Guidelines

- Noise Analysis and Abatement Guidelines, Colorado Department of Transportation, December 2002

Traffic Noise Model User's Guide

for

Colorado DOT Projects

The Colorado Department of Transportation
Research Branch and Environmental Programs

November 2006

Revisions

Revision	Date	By	Revised
1	7/15/04	Hankard Environmental	Initial Internal Release
2	12/31/04	Hankard Environmental	2nd Internal Release
3	7/7/05	Hankard Environmental	3rd Internal Release
4	12/31/05	Hankard Environmental	4th Internal Release
5	10/31/06	Hankard Environmental	Final Release

Table of Contents

1.0 Introduction

Welcome to the Colorado Department of Transportation TNM Users Guide. The Users Guide provides recommendations on the application of the Traffic Noise Model (TNM) on Colorado Department of Transportation (CDOT) projects. The goals of the Users Guide are that its implementation will result in reasonably accurate assessments of existing and future traffic noise levels along Colorado highways, that it will streamline the modeling process to a point where it is commensurate with the level of expertise of CDOT and consultant staff, and that analyses will be relatively consistent from project to project and user to user.

The CDOT TNM Users Guide does not provide information regarding every aspect of the model, such as how to open and close files, navigate the menus, etc. For these features, refer to the documentation provided by the Federal Highway Administration (FHWA), as well as the other references listed in Section 6. Also, in the absence of Colorado-specific information, FHWA policies should be followed. FHWA policies regarding TNM can be found in the model's technical manual, as well as in the FHWA FAQ's posted on the TNM website.

The Users Guide covers the following topics:

- **Building TNM Models (Section 2)**
  Guidelines are provided for each of TNM's input variables. Some of these variables are fixed by FHWA or CDOT policy. Others require judgment based on the site and the project.

- **Using TNM Models (Section 3)**
  General information is provided regarding the prediction of noise levels and noise impact, the analysis of barrier noise reduction, reflections, parallel barriers, predicting the location of noise level contours, and outputting TNM tables.

- **Validating TNM Models (Section 4)**
  Recommendations are provided regarding the necessity for and the procedure for validating TNM models on individual projects, including noise measurements, traffic measurements, and desired accuracies.

- **Documenting TNM Analyses (Section 5)**
  There are a number of ways to describe the results of TNM output. This section helps a user understand what types of data need to be documented.

- **References (Section 6)**

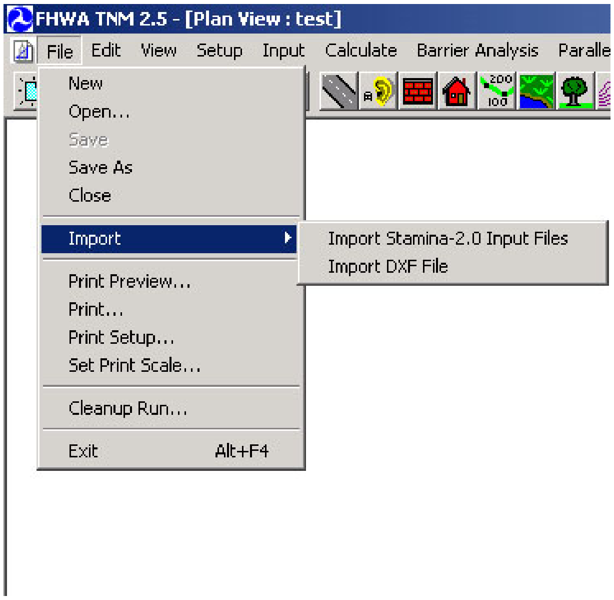
- **Appendices**
    - Appendix A – Entering Roadways into TNM: Additional detail is provided regarding modeling roadways, as this is one of the more involved and important aspects of TNM.
    - Appendix B – Modeling Barrier Reflections in TNM: A procedure is described for modeling reflections, which TNM does not handle directly.

2.0 Building TNM Models

This section provides guidelines for using the File, Edit, View, Setup and Input menus.

2.1 *File* Pull-down Menu

Save As – Most TNM analyses will require multiple model runs. Typically, the model of existing conditions will be duplicated, and changes made to it to reflect proposed roadway alternatives and projected traffic conditions. Also, larger projects may need to be broken into smaller geographical areas, such as individual neighborhoods. It is useful at the beginning of a project to think about these factors and determine a logical file naming strategy. TNM 2.5 run names are NOT limited to eight (8) characters. However, when the combination of the file path and file name becomes too long the model will not open. When one creates a TNM model, the software creates a folder corresponding to the name of the model. Inside the folder it places two files: objects.dat and objects.idx. These same files, with these same names, are placed in ALL TNM run folders. Therefore, it is very important to transfer models within the folder. Note: You must use the “Save As” command *before* you make changes to your existing model. If you make changes to a model, then try to save it as a new model, you will first be required to either save the changes to your original model, or cancel and lose your changes.



Import STAMINA Files - This will be a very useful feature to many users during the transitional period between STAMINA and TNM. Note that the import routine will create a terminal error when it tries to import certain formats, such as user entered emission factors. Also, the file name in the header of the STAMINA file may need to be shortened to avoid locking up TNM. Be sure to ALWAYS check “Import Shielding Factors”.

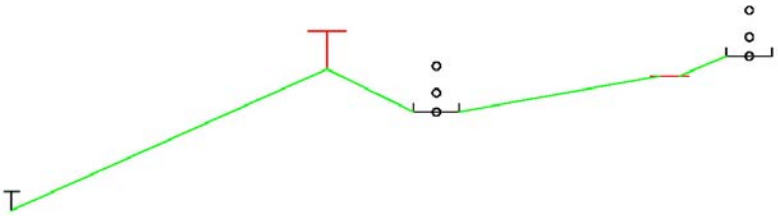
DXF Files – Most CAD programs, such as AutoCAD and Microstation, can export a Drawing Exchange Format (DXF) file. Importing DXF files can be a convenient and accurate method of building TNM models. To use this feature, first model all roadways, terrain lines, barriers, etc. in CAD. Turn off all layers and information that is not going to be imported, and save the CAD file as a DXF file. Import the DXF file into TNM, and assign each entity appropriately. Be sure that units are consistent between the CAD and TNM.

Printing Figures and Tables – Users have somewhat limited control over printing TNM graphics and tables. More control over scale and appearance is available in CAD, GIS, and spreadsheet programs. Additional printing information is provided in Section 5.0, Documenting TNM Analyses.

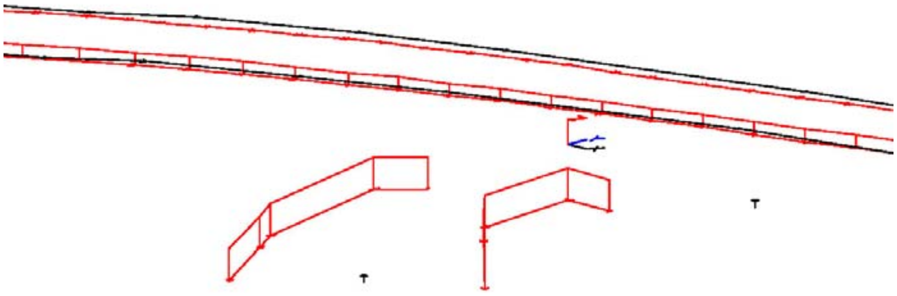
2.2 *Edit* Pull-down Menu

Currently, there is no specific guidance related to this menu for CDOT projects. Refer to FHWA's TNM Users Manual for more information.

2.3 *View* Pull-down Menu



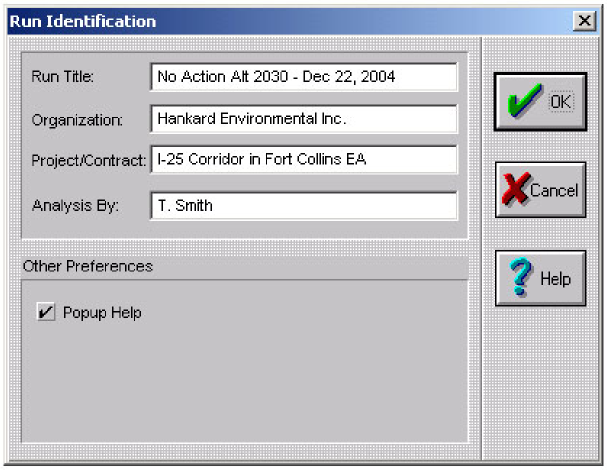
Skew Section – This is a very useful feature for checking the relative elevation of receptors, barriers, terrain lines, and roadways. Note that at least one full segment of a feature (roadway, barrier, terrain line) must be in the view window in order to be included in the skew section. Also, it is best to turn the Snap feature "on", select the receiver (only one at a time) of interest, turn snap "off", then place the second point of the sew section so that the desired roadways, barriers, and terrain lines are included.



Perspective View – This feature is used to display the entire model in a three dimensional manner. The model can be rotated about any axis to see the relationship between roadways, barriers, receptors, etc. Barrier and building heights are also visible.

2.4 *Setup* Pull-down Menu

Run Identification - TNM is a relatively complex model, and multiple runs will be created on any given project. Because the review of technical work will, in some cases, take place by electronically transferring TNM models, it is very important to properly identify each run.



Run Identification

Run Title: No Action Alt 2030 - Dec 22, 2004

Organization: Hankard Environmental Inc.

Project/Contract: I-25 Corridor in Fort Collins EA

Analysis By: T. Smith

Other Preferences

☑ Popup Help

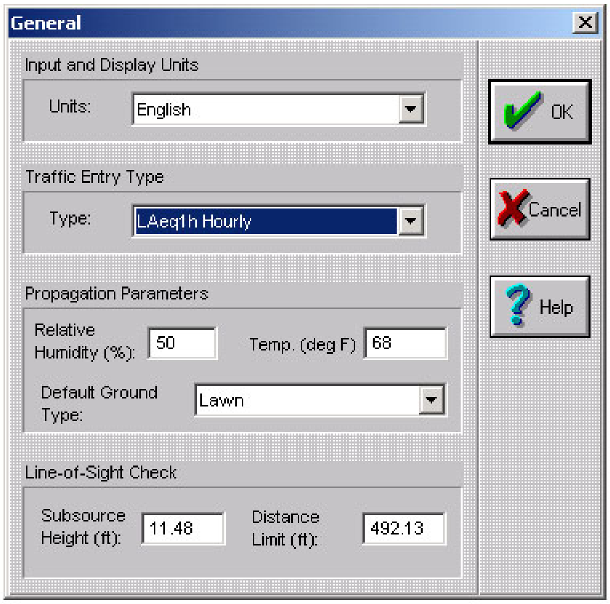
Run Title This should include the Alternative that is being analyzed (e.g. No Action), the year of the design/traffic data used in the analysis, and the date that the model was run.

Organization Enter in the name of the company or agency actually doing the analysis. This will help future reviewers to know where to go with questions.

Project/Contract This should match the official title of the project (e.g.: I-25 Corridor in Fort Collins EA)

Analysis By Include the name or names of those who conducted the analysis.

General – This input dialog box is very important, as it outlines the units, type of analysis, and the overall propagation parameters.



Input and Display Units

Units: English

Traffic Entry Type

Type: LAeq1h Hourly

Propagation Parameters

Relative Humidity (%): 50

Temp. (deg F): 68

Default Ground Type: Lawn

Line-of-Sight Check

Subsource Height (ft): 11.48

Distance Limit (ft): 492.13

Units This should correspond to the units being used by the project, which in Colorado is usually "English". This is very important when importing DXF objects from CAD.

Traffic Entry Type All CDOT noise analyses are to be conducted using the A weighted, one-hour equivalent sound level (Leq). The 24-hour day-night level (DNL) is used on Federal Transit Administration (FTA) projects and on Housing and Urban Development (HUD) projects.

Relative Humidity and Temperature While Colorado typically has a lower RH than the FHWA-default value of 50%, the effect on predicted levels is minimal. The FHWA-default temperature of 68^{o}F is a reasonable representation of typical Colorado conditions. See table below for more information. Note that TNM does not have the capability to model the effect of thermal inversions, which are common in Colorado and can have a significant effect on sound propagation. Other values of temperature and relative humidity can be used when necessary, but this must be substantiated and approved by CDOT and FHWA.

Default Ground Type See CDOT Guidance in *Default Ground Type Information Table* below.

Line-of-Sight Check This feature of TNM is a tool that can be used in the design of barriers. However, on CDOT projects the design goal is noise reduction, not necessarily complete blockage of line of sight.

Relative Humidity Information Table

Acoustic Phenomenon	Noise levels decrease with distance due, in part, to molecular absorption. The rate of absorption is controlled by a complex relationship between humidity, and temperature. In general, very dry air (20% relative humidity) absorbs more sound than moist air. There is little difference in the absorption rate between 30% and 100% RH.
Effect on TNM Predicted Noise Levels	**Minor** Decrease of 0.5 dB using 20% vs. 50% for receptor 200 ft. from road Decrease of 1.0 dB using 20% vs. 50% for receptor 500 ft. from road
FHWA Mandate	Use 50% unless substantiated otherwise
Colorado Specific Aspect	Colorado experiences an *average* relative humidity of approximately 50%, but humidity levels during the daytime are frequently 20% or lower. Overall, Colorado has a drier climate than that of many other states.
CDOT Guidance	Use 50% for Analysis of Alternatives Use measured RH for Analysis of Validation Model, if available

Temperature (molecular absorption) Information Table

Acoustic Phenomenon	Noise levels decrease with distance due, in part, to molecular absorption. The rate of absorption is controlled by a complex relationship between humidity, and temperature. Absorption is lowest at approximate 70ºF. Slightly greater absorption is achieved at higher and lower temperatures.
Effect on TNM Predicted Noise Levels	**Minor** Difference of 0 to 0.5 dB over a range of 30 to 90ºF at a receptor located 200 ft. from a road; difference of 0.5 to 1.0 dB for a receptor located 500 ft. from a road.
FHWA Mandate	Use 68ºF unless substantiated otherwise
Colorado Specific Aspect	68ºF is a typical Colorado temperature.
CDOT Guidance	Use 68ºF for Analysis of Alternatives Use measured temperature for Validation analysis, if available

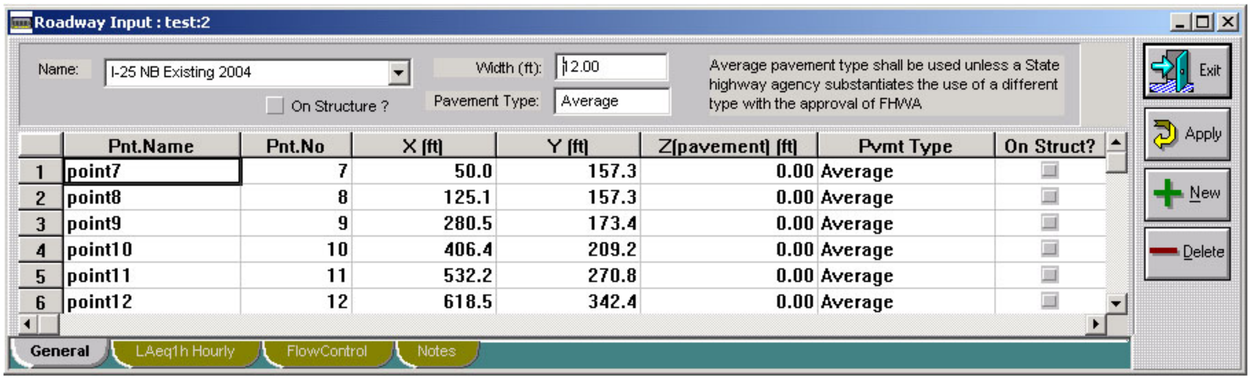
Default Ground Type Information Table

Acoustic Phenomenon	As sound waves propagate away from a source they interact with the ground. The porosity of the surface of the ground and the height of the sound wave above the ground both affect the rate at which sound levels will decay with distance. Noise levels decrease most rapidly when traveling low over soft ground such as grass, less rapidly over hard soil, and also less rapidly when they travel high above the ground (i.e. when the source and/or receiver are elevated).
Effect on TNM Predicted Noise Levels	**Major** Increase of 7 dB using pavement vs. lawn at a receptor located 200 ft. from the road, and an increase of 10 dB using pavement vs. lawn at receptor located 500 ft. from the road.
FHWA Mandate	None
Colorado Specific Aspect	While no data could be found explicitly, Colorado may have a higher tendency to exhibit hard soil conditions due to the lack of moisture.
CDOT Guidelines	TNM predictions are within a few tenths of a dB (i.e. relatively insignificant) when using Field Grass, Lawn, and Loose Soil. Use Lawn if any of these three are applicable. TNM exhibits an anomaly for Hard Soil for receptors between 400 and 600 feet from the roadway. Do not use Hard Soil as a default ground type. Model Hard Soil areas with a Ground Zone, as discussed in Section 2.5, and use with caution if receptors are between 400 and 600 feet from road. Model distinct areas of pavement, water, and hard soil as Ground Zones (refer to Section 2.5). Snow should only be modeled for validation studies where snow was present (which should be avoided in the first place).

2.5 *Input Data* Pull-down Menu

User Defined Vehicles – Emission levels define how much noise energy is produced by one vehicle traveling at a reference speed. TNM contains default emission factors for five vehicle types: autos, medium trucks, heavy trucks, buses, and motorcycles. Both FHWA and CDOT require the use of the default TNM noise emission factors at this time. Therefore, User Defined Vehicles types should NOT be used. FHWA REMELs are described in the report entitled *Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model*, Report No. FHWA-PD-94-093, 1995.

Roadways (General tab) – All roadways within a project study area that carry a significant amount of traffic should be modeled. The following provides information regarding each of TNM's roadway input parameters. Refer to Appendix A for additional, important information regarding roadways.



Name: I-25 NB Existing 2004

☐ On Structure ?

Width (ft): 12.00

Pavement Type: Average

Average pavement type shall be used unless a State highway agency substantiates the use of a different type with the approval of FHWA

	Pnt.Name	Pnt.No	X [ft]	Y [ft]	Z[pavement] [ft]	Pvmt Type	On Struct?
1	point7	7	50.0	157.3	0.00	Average	☐
2	point8	8	125.1	157.3	0.00	Average	☐
3	point9	9	280.5	173.4	0.00	Average	☐
4	point10	10	406.4	209.2	0.00	Average	☐
5	point11	11	532.2	270.8	0.00	Average	☐
6	point12	12	618.5	342.4	0.00	Average	☐

Name This should include information such as the roadway's name, direction, and condition (e.g.: I-25 Southbound Existing 2004).

Length Roadways should extend beyond all of the receivers located within the project's study area by a distance of at least four times that from the roadway to the receptors located at the edge of the study area. For example, roadways should extend 800 feet beyond a receptor located 200 feet from the road, and 2,000 feet beyond a receptor located 500 feet from the road.

Width There are a number of issues related to TNM's pavement width feature and as a result this parameter must be chosen carefully. See Pavement Width - Ground Type and Pavement Width - Edge of Pavement Barrier tables below, as well as Appendix A.

Pavement Type At his time, FHWA requires the use of "average" pavement type for all impact analyses. Other pavement types can be considered for validation purposes, provided sufficient justification exists and is documented. For more information refer to the Pavement Type table below.

On Structure When an elevated roadway intervenes between a receiver and another roadway, it acts as a barrier if it is elevated on fill. If it is on structure, sound can pass under the elevated roadway and it no longer acts as an effective barrier. See Roadway On Structure table below.

Pavement Width Information Table (as it relates to ground type)

Acoustic Phenomenon	A wider pavement results in higher predicted levels, because there is more acoustically hard ground near the source (assuming that the default ground type is acoustically soft). The effect is more pronounced for closer receivers, where the change in pavement width affects a higher percentage of the total ground area between the road and receptor.
Effect on TNM Predicted Noise Levels	**Major** Increasing the pavement width from 24 to 72 feet increases the noise level by 6 dB at a receptor located 300 feet from the center of the road, and 4 dB for a receptor located 700 feet from the road.
FHWA Mandate	No mandate.
Colorado Specific Aspect	None.
CDOT Guidelines	See procedures for modeling roadways in Appendix A.

Pavement Width Information Table (as it relates to edge of pavement)

Acoustic Phenomenon	The width of the pavement determines where the edge of the pavement is in space. For receivers that are located below the elevation of the highway, the edge of pavement acts as a barrier. A wider pavement deck typically results in a more significant break in the roadway-receiver line of sight, and therefore results in lower noise levels at the receiver.
Effect on TNM Predicted Noise Levels	Difficult to discern, because the edge of pavement effect cannot be isolated from the ground type effect.
FHWA Mandate	None.
Colorado Specific Aspect	Colorado has a significant amount of relief in the terrain. In many cases receptors are located below the elevation of the highway. Thus the placement of the edge of pavement must be modeled accurately.
CDOT Guidelines	See procedures for modeling roadways in Appendix A.

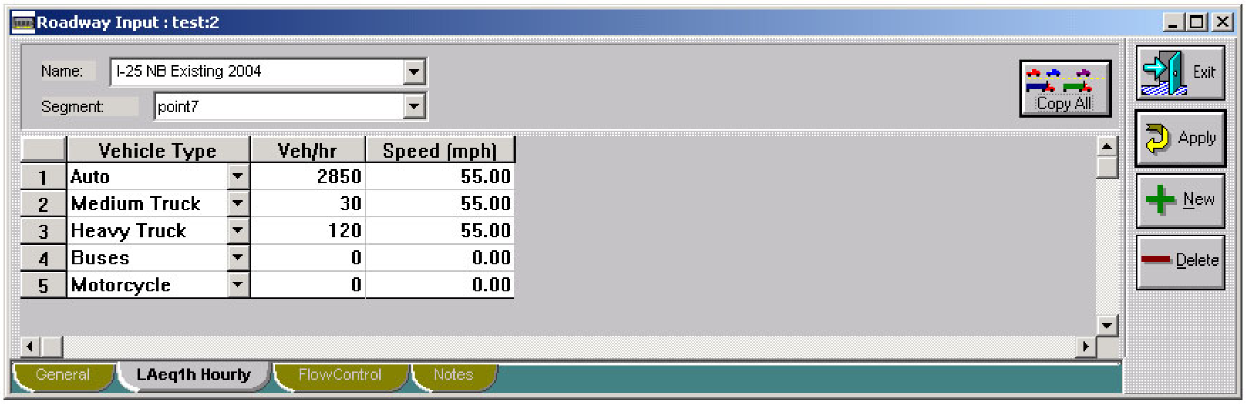
Pavement Type Information Table

Acoustic Phenomenon	Much of the noise from traffic is generated by the interaction between tires and the roadway surface. The physical properties of the pavement surface determine, in part, how much noise is produced. Surface texture is particularly important.
Effect on TNM Predicted Noise Levels	The following changes in TNM’s output are produced at a receptor located 300 feet from a road when the pavement type is changed from Average to each of the other built-in settings: • PCC is 2 dB louder • DGAC is 1 dB quieter • OGAC is 2 dB quieter
FHWA Mandate	Use “average” pavement type for impact analyses.
Colorado Specific Aspect	Colorado has a mix of pavement types in use today. The noise reduction properties of certain pavements, such as SMA, are currently being studied. Many factors go in to the decision of which pavement type to use on a given project, including safety, durability, and cost.
CDOT Guidelines	Use “average” pavement type for impact analyses. Other pavement types can be used for validation analyses, provided that sufficient evidence exists and is documented.

Roadway on Structure Information Table

Acoustic Phenomenon	When one roadway intervenes between a receiver and another roadway, it acts as a barrier if it is elevated on fill. If it is on structure, sound can pass under and it no longer acts as an effective barrier.
Effect on TNM Predicted Noise Levels	A model was created with an overpass blocking approximately one half of a highway that runs directly in front of receivers. Placing the overpass “on structure” resulted in as much as a 0.7 dB increase in noise levels at the closest receptors.
FHWA Mandate	None.
Colorado Specific Aspect	None.
CDOT Guidelines	The On Structure feature should be employed when receptors are located within approximately 500 feet of a road that is elevated on structure (i.e. piers), and there is a significant roadway located either under or behind it such that sound energy can travel under the on-structure road and reach the receptors. Small overpass sections of road with no receivers nearby do not need to be modeled using the On Structure parameter. Note that this feature does NOT apply to roads that are elevated on fill.

Roadways (LAeq1h Hourly tab) – This is where traffic volumes and speeds are input for each vehicle type. Traffic conditions are modeled in TNM using three parameters: hourly traffic volume, average traffic speed, and average traffic mix (five vehicle types). The proper selection of these parameters is very important to the overall integrity of the noise impact analysis. Typically, only the number of Automobiles, Medium Trucks, and Heavy Trucks are readily available. For some projects, the number of Buses may also be available, and rarely, if ever, is the number of motorcycles available. When not available, buses and motorcycle volumes and speeds should be set to zero. For information regarding how each vehicle type is classified, refer to the FHWA TNM User's Manual (Reference 1, Section 8.3.4).



Roadway Input : test:2

Name: I-25 NB Existing 2004

Segment: point7

	Vehicle Type	Veh/hr	Speed [mph]
1	Auto	2850	55.00
2	Medium Truck	30	55.00
3	Heavy Truck	120	55.00
4	Buses	0	0.00
5	Motorcycle	0	0.00

Name This carries over from the input under the General tab.

Veh/hr Use projected "loudest hour" traffic volumes for all impact and mitigation analyses, and actual counted volumes for validation analyses. The "loudest hour" will depend on the results of traffic studies conducted for the project. If the projected peak hour traffic volumes have a Level of Service (LOS) of A, B, or C, then these volumes represent the loudest hour. If the projected volumes have a LOS of D, E, or F, then the volumes will need to be scaled back to LOS C/D to represent the loudest hour. Specify volumes for Buses and Motorcycles only when such information is specifically available and particularly relevant to the project. See Traffic Volume, Mix, and Speed tables below.

Speed Use posted speed for all impact and mitigation analyses. Use actual speeds when conducting validation analyses. The use of speeds other than posted speeds for impact and mitigation analyses must be justified and documented, and will be reviewed on a case-by-case basis. Speeds should be rounded to the nearest one mile per hour.

Copy All THIS IS IMPORTANT - When one enters traffic volumes and speeds directly into TNM this data is only applied to the segment that is highlighted. One must select Copy All to copy the volumes and speeds to the other segments of the roadway. This is done automatically when importing from STAMINA.

Traffic Volume Information Table

Acoustic Phenomenon	Noise levels increase with increasing traffic volume, provided that slowing does not occur due to congestion. The combination of high speeds and high volumes that occurs just before and just after periods of congestion is termed the “loudest hour”, and corresponds to Level of Service (LOS) C/D traffic conditions.
Effect on TNM Predicted Noise Levels	Noise levels increase 3 dB for each doubling of traffic volume.
FHWA Mandate	None
Colorado Specific Aspect	None
CDOT Guidelines	Use projected volumes if they represent LOS A, B, or C conditions. When projected traffic volumes are LOS D, E, or F, use LOS C/D volumes.

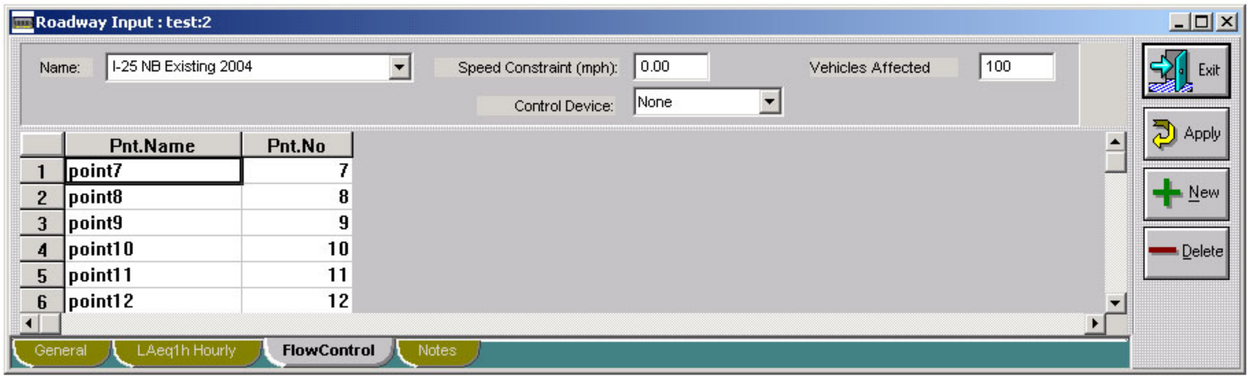
Vehicle Mix (i.e. Truck Percentages) Information Table

Acoustic Phenomenon	Medium trucks, heavy trucks, and buses produce more noise per vehicle than cars due to their larger engine power and the larger number and size of their tires. Also, trucks emit significant energy from their engines and exhausts, which are located higher above the road than tire/roadway noise (which is the dominant noise source from automobiles). Motorcycles are louder than automobiles, particularly during acceleration. TNM assumes properly muffled vehicles.
Effect on TNM Predicted Noise Levels	Medium Trucks: Increase of 0.1 dB per % increase in medium truck volume. Typical range of medium truck percentage is 1 to 10%, which corresponds to a change in levels of 1 dB. Heavy Trucks: Increase of 0.3 dB per % increase in heavy truck volume. Typical range of heavy truck percentage is 1 to 10%, which corresponds to a change in levels of 3 dB. Buses: Same as medium trucks. Not likely significant unless there is special case (i.e. gaming area, transit center). Motorcycles: Increase of 0.2 dB per % increase in motorcycle volume. Not likely significant unless there is special case (i.e. tourist area).
FHWA Mandate	None
Colorado Specific Aspect	None
CDOT Guidelines	Particular attention should be paid to the number of heavy trucks used in an analysis, as this has the greatest impact on predicted levels. Motorcycles and buses need only be modeled under special circumstances (otherwise their volume and speed should be set to zero).

Traffic Speed Information Table

Acoustic Phenomenon	Noise levels increase with increasing speed. The combination of high speeds and high volumes that occurs just before and just after periods of congestion is termed the “loudest hour”, and corresponds to Level of Service C/D conditions.
Effect on TNM Predicted Noise Levels	Cars: ~1 dB increase for every 5 mph increase in speed between 45 and 75 mph Medium Trucks: ~0.6 dB increase for every 5 mph increase in speed between 45 and 75 mph Heavy Trucks: ~0.6 dB increase for every 5 mph increase in speed between 45 and 75 mph
FHWA Mandate	None
Colorado Specific Aspect	None
CDOT Guidelines	Use actual speeds when conducting validation analyses. Use posted speed for predicting existing and future loudest hour noise levels. The use of speeds other than posted speeds must be justified and documented, and will be reviewed on a case-by-case basis. Speeds should be rounded to the nearest one mile per hour. Keep in mind that when modeling the LOS C/D condition speeds are generally tempered somewhat due to the high volume.

Roadways (Flow Control tab) – The Flow Control feature in TNM is used to characterize the impact of acceleration away from signalized intersections, stop signs, tollbooths, and on ramps. Its use requires knowledge of what percent of traffic will be affected by the control device (on average), and results are dependent on site geometry and truck percentage. The Flow Control feature adds approximately 1 to 2 dB to the noise emitted by the controlled roadway segment. Levels are louder near the beginning of the flow control segment. On CDOT projects use this feature only when residences are located within 500 feet of an intersection, at least 50% of mainline traffic is affected by the control device, and the predicted future noise levels with no flow control are greater than 60 dBA.

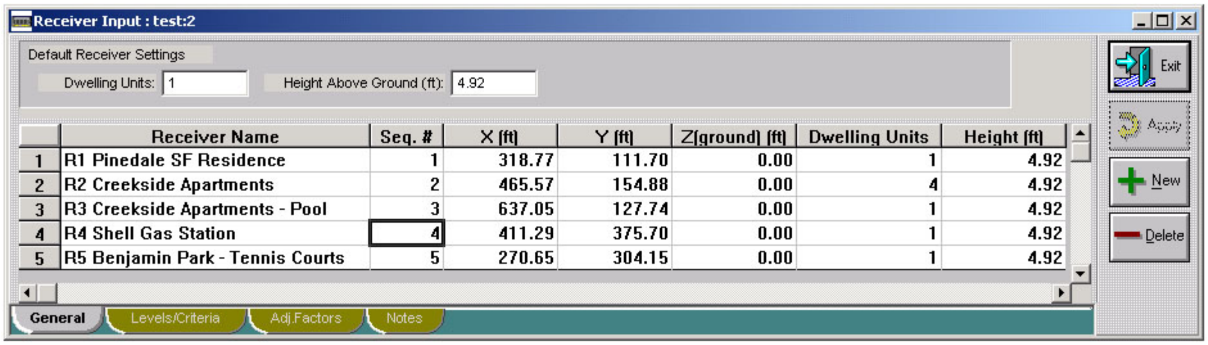


Name: I-25 NB Existing 2004
Speed Constraint (mph): 0.00
Vehicles Affected 100
Control Device: None

	Pnt.Name	Pnt.No
1	point7	7
2	point8	8
3	point9	9
4	point10	10
5	point11	11
6	point12	12

Receivers (General tab) – Noise impact must be assessed at each residence and business located within a project's study area. Generally, the study area extends 500 feet out from either side of the roadway(s) under study, and 500 feet beyond the limits of construction in each direction. For major interstates with six lanes or more, it may be necessary to include receivers out to a distance of 800 feet from the road. The appropriate distance for a project can be determined by modeling a simple straight line road with the project-specific LOS C/D traffic volumes, no barriers, and "lawn" ground type. **It should be noted that predictions at receptors located more than 500 feet from the road are more prone to error and should be reviewed carefully.**

For smaller projects, such as interchange studies, a receptor point should be placed at each residence and business located within the study area. For larger projects, such as corridor studies, it is often prudent to predict only at representative locations (i.e. the closest receptor(s) to the roadway under study in each neighborhood). However, each and every receiver within a project study area must be represented by a receptor point directly or by reference to another one nearby.



Default Receiver Settings

Dwelling Units: 1

Height Above Ground (ft): 4.92

	Receiver Name	Seq. #	X [ft]	Y [ft]	Z[ground] [ft]	Dwelling Units	Height [ft]
1	R1 Pinedale SF Residence	1	318.77	111.70	0.00	1	4.92
2	R2 Creekside Apartments	2	465.57	154.88	0.00	4	4.92
3	R3 Creekside Apartments - Pool	3	637.05	127.74	0.00	1	4.92
4	R4 Shell Gas Station	4	411.29	375.70	0.00	1	4.92
5	R5 Benjamin Park - Tennis Courts	5	270.65	304.15	0.00	1	4.92

Receiver Name The receiver name should include a unique number of some type, as well as a description (i.e.: neighborhood, front-row, pool area, house number and street, etc).

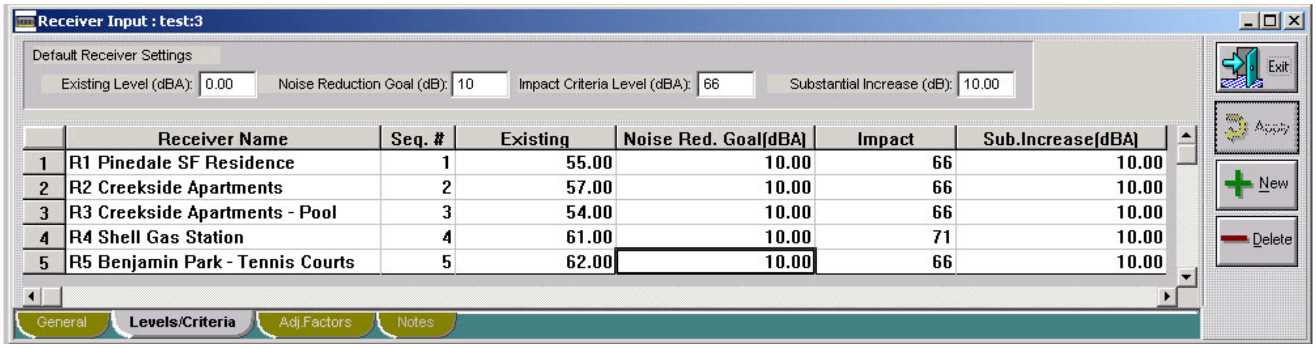
X and Y Coordinates The receptor location should represent the active outdoor use area, such as a patio. It is often not practical to know the exact usage of each property on a larger project, in which case place the receptor location at the façade of the building facing the primary roadway under study.

Z (ground) Coordinate Enter the ground elevation of the receiver. For 2nd story receivers (and above), also enter the *ground* elevation (not the elevation of the floor on which the receiver is located).

Dwelling Units Enter the number of dwelling units (e.g. apartments) that each receiver location represents. It is recommended that the default value for this be left at "1".

Height Above Ground This represents the height above of the ground of the ear of a typical person, which is 5 feet (TNM automatically enters 4.92 feet, but one need not be this specific). For 2nd floor receivers (and above) enter the height of the receiver above the *ground* (not the height above the floor on which the receiver is located).

Receivers (LevelsCriteria tab) – The purpose of these inputs are to define the existing noise level, reduction goal, impact criterion, and what is to be considered a substantial increase for each receptor. Actual values for these parameters can be entered if one chooses to have TNM conduct these computations. Alternatively, these calculations can be conducted separate from TNM in a spreadsheet. Refer to Section 5.0, which discusses how to format TNM output for CDOT projects.



Receiver Input : test:3

Default Receiver Settings

Existing Level (dBA): 0.00
Noise Reduction Goal (dB): 10
Impact Criteria Level (dBA): 66
Substantial Increase (dB): 10.00

	Receiver Name	Seq. #	Existing	Noise Red. Goal(dBA)	Impact	Sub.Increase(dBA)
1	R1 Pinedale SF Residence	1	55.00	10.00	66	10.00
2	R2 Creekside Apartments	2	57.00	10.00	66	10.00
3	R3 Creekside Apartments - Pool	3	54.00	10.00	66	10.00
4	R4 Shell Gas Station	4	61.00	10.00	71	10.00
5	R5 Benjamin Park - Tennis Courts	5	62.00	10.00	66	10.00

Receiver Name Carries over (see General tab).

Existing Level If using TNM to calculate noise level increases (versus a spreadsheet), enter existing loudest hour noise levels.

Noise Reduction Goal The noise reduction goal for CDOT projects is 10 dBA (desired) and 5 dBA (minimum for at least one receiver) for a barrier to be considered feasible.

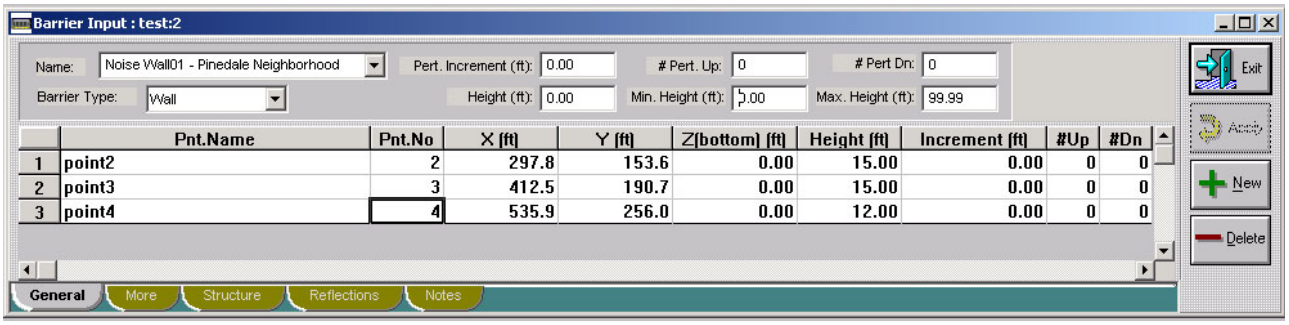
Impact Level For CDOT projects: 66 dBA for Category B (e.g. residential) and 71 dBA for Category C (e.g. commercial).

Substantial Increase 10 dBA for CDOT projects.

Receivers (Adj. Factors tab) – This input is for manually adjusting the predicted traffic noise level from a roadway segment to a receiver to account for phenomenon not otherwise modeled by TNM (such as atmospheric conditions, reflections, etc.) It should only be used when the expected effect on predicted levels is 3 dB or more, per FHWA guidance. The use of adjustment factors must be clearly documented and validated, and should only be used if the phenomenon in question cannot be modeled easily or accurately in some other manner. This parameter should not be used for adding in background noise levels (if necessary, this must be done outside of TNM). See FHWA policy for more information on the use of adjustment factors (Reference 1, Appendix A).

Barriers (General tab) – The Barrier input controls both wall and berm parameters. The following is a list of general TNM barrier considerations on CDOT projects. This is followed by information regarding each TNM barrier input parameter.

- Barriers work best when placed close to either the source or receiver. CDOT strongly prefers to locate barriers within its Right-of-Way (ROW). Issues such as safety, drainage, utilities, and maintenance should be considered when locating a noise barrier. In many cases, the barrier should be located on the edge of the Clear Zone.
- The edge of pavement is automatically modeled as a terrain line in TNM
- Privacy fences are generally not modeled as barriers, as they do not provide sufficient noise reduction, and are not always maintained well (refer to CDOT Noise Guidelines 2002)
- Model single, large buildings as a barrier
- Model rows of buildings as a Building Row (see below)



Name: Noise Wall01 - Pinedale Neighborhood
Pert. Increment (ft): 0.00
Pert. Up: 0
Pert Dn: 0
Barrier Type: Wall
Height (ft): 0.00
Min. Height (ft): 5.00
Max. Height (ft): 99.99

	Pnt.Name	Pnt.No	X (ft)	Y (ft)	Z(bottom) (ft)	Height (ft)	Increment (ft)	#Up	#Dn
1	point2	2	297.8	153.6	0.00	15.00	0.00	0	0
2	point3	3	412.5	190.7	0.00	15.00	0.00	0	0
3	point4	4	535.9	256.0	0.00	12.00	0.00	0	0

Name The name of the barrier needs to be independent of other barriers and could include a unique number, type of barrier, or specific location within the project area.

Barrier Type TNM can model both solid, vertical walls and earthen berms. TNM predicts an additional 0.2 dB of reduction for a berm with 3:1 slopes versus a wall of the same height. Steeper sloped berms act almost exactly like walls in TNM. When modeling berms, ensure that there is enough room to accommodate the required slopes. The model will produce an error when any barrier overlaps a road.

X and Y Coordinates Place points every 100 to 200 feet along a barrier (closer near the end). Note that TNM will generate an error when barriers are placed on top of or within inches of a roadway.

Z (bottom) This is the ground level of the noise barrier. This information should be acquired from the applicable existing or future elevation design data. Ensure that the ground elevations under the barrier are accurate to within 2 feet for planning studies, and to within 1 foot for final design.

Height This is the height of a barrier above "Z (bottom)", or the ground level.

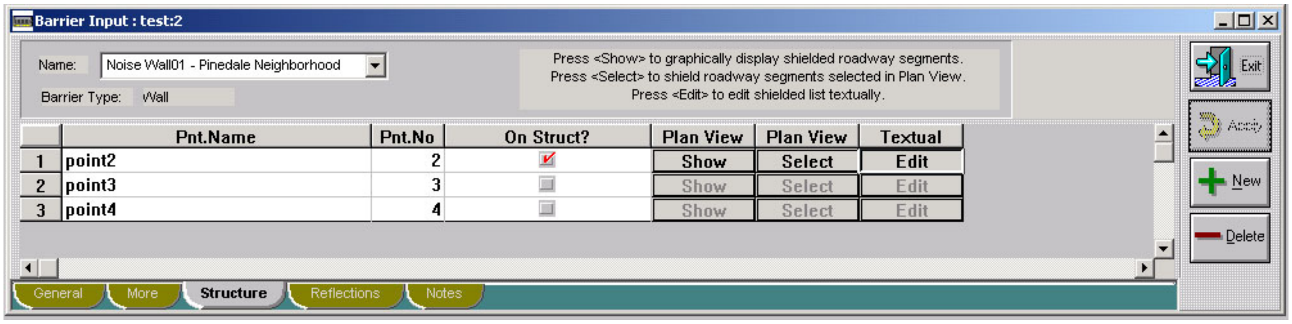
<u>Increment Up and Down</u> The increment (feet) and number of perturbations entered here control how barrier height can be analyzed using the "Barrier Analysis" function, as described in Section 3.2. For example, for a barrier with a height of 10 feet, a 2-foot increment, an up perturbation of 2 and a down perturbation of 1, the user will be able to see the reduction provided by the following wall heights (feet): 8, 10, 12, and 14. If zero is entered as the number of perturbations, the barrier height is fixed.

Barrier Information Table

Acoustic Phenomenon	Any solid barrier that protrudes into the line of sight between a source and receptor causes the sound wave to diffract around the barrier and thus lose intensity. The greater the protrusion the greater the noise reduction. Barriers effectively reduce noise for receptors located within 300 feet of the barrier. Some reduction is provided out to 500 feet. Very little to no real reduction is provided beyond 500 feet.
Effect on TNM Predicted Noise Levels	TNM predicts that a 15-foot tall wall provides 9 dB of reduction for receptors located within 200 feet of the barrier, and 5 dB of reduction for receptors 400 feet from the barrier. TNM predicts that berms will provide only about 0.2 dB of additional reduction versus a same-height wall. Caution: TNM predicts higher noise reductions for barrier than STAMINA and other international roadway noise models. The effect is most pronounced for short barriers, such as 3-foot tall Type 7 safety rail. TNM predicts 2 to 3 dB more reduction for these barriers than the other models, and more than is thought to realistically occur. TNM predicts approximately 1 to 2 dB more reduction for 10 to 20 foot tall barriers.
FHWA Mandate	Do not model berms with a flat top (i.e. the "Top Width" must be set to zero)
Colorado Specific Aspect	None
CDOT Guidelines	Use caution when using TNM to model short barriers, such as Type 7 safety rail. CDOT's 2002 Noise Abatement Guidelines state that a proposed barrier should achieve at least 5 dB (and preferably 10 dB) of noise reduction at front row receptors, and that end receptors should receive at least 5 dB of reduction. Given TNM's propensity to over-predict barrier insertion loss, users are advised to design barriers to meet the higher end of the 5 to 10 dB range wherever possible.

Barriers (More tab) – Entering cost data is optional. For berms, enter slope information as appropriate. CDOT generally requires a 3:1 slope. Do not model flat-topped berms in TNM (set "Top Width" to 0 feet), per FHWA (Reference 5).

Barriers (Structure tab) – The purpose of the Structure tab is to allow a user to model a barrier such that it shields one roadway or roadway segment but not any others from a receptor's vantage point. This would be required, for example, for a barrier that shields an elevated roadway, but not a second one at ground level. This feature should only be applied in extreme cases, and measurements should be taken to validate its accuracy if possible.

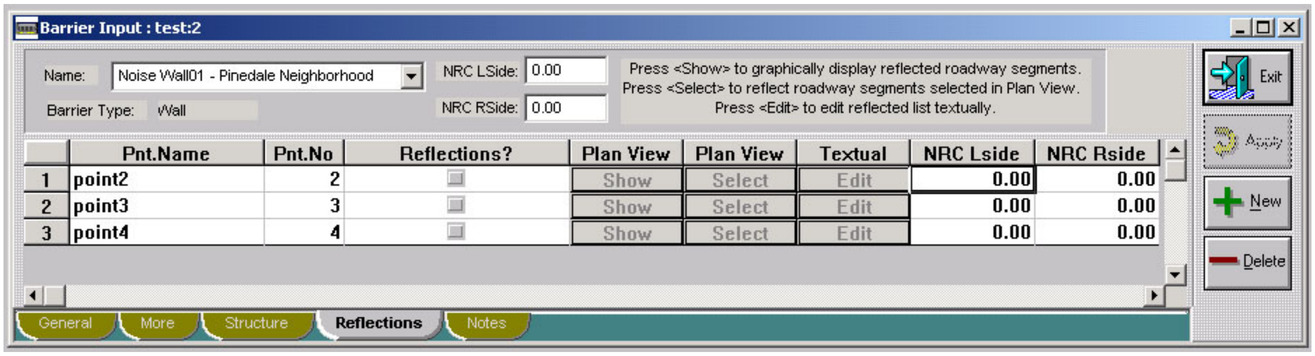


Name: Noise Wall01 - Pinedale Neighborhood
Barrier Type: Wall

Press <Show> to graphically display shielded roadway segments.
Press <Select> to shield roadway segments selected in Plan View.
Press <Edit> to edit shielded list textually.

	Pnt.Name	Pnt.No	On Struct?	Plan View	Plan View	Textual
1	point2	2	☑	Show	Select	Edit
2	point3	3	☐	Show	Select	Edit
3	point4	4	☐	Show	Select	Edit

Barriers (Reflections tab) – The reflective qualities of a barrier affect a) how much noise reduction it provides to the receptors located behind it, and b) how much noise is reflected to the receptors located across from it (on the other side of the roadway). The reflective properties of a barrier are gauged by its Noise Reduction Coefficient. An NRC of 0 represents a perfectly reflective surface, and an NRC of 1 represents a perfectly absorptive one. This feature of TNM currently has limited capability. TNM utilizes the NRC values in parallel barrier calculations, as described in Section 3.3. TNM does not presently have the direct capability to predict the increase in noise levels due to reflection of noise off of walls. There is a work-around available using the parallel barrier module (refer to FHWA FAQ's). The preferred method on CDOT projects is to use the Mirror Source Method, as described in Appendix B.

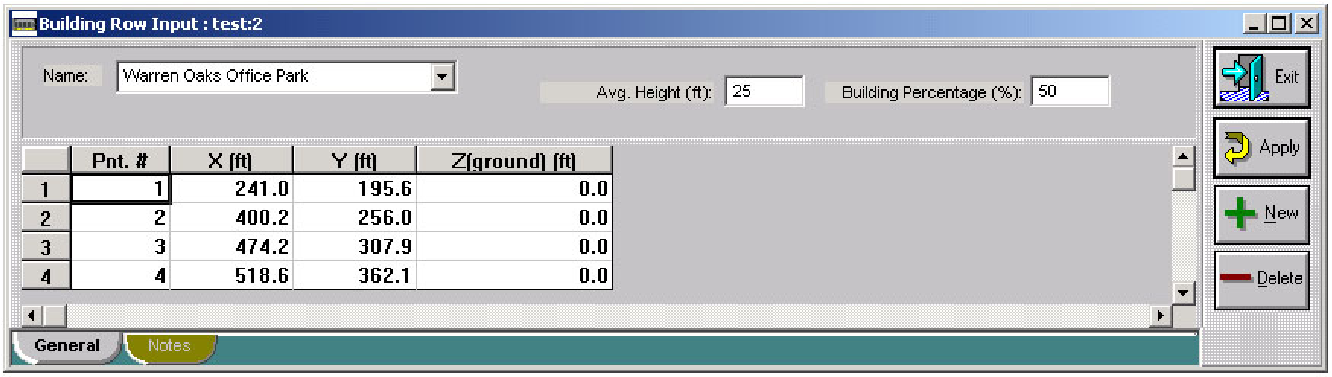


Name: Noise Wall01 - Pinedale Neighborhood
Barrier Type: Wall
NRC LSide: 0.00
NRC RSide: 0.00

Press <Show> to graphically display reflected roadway segments.
Press <Select> to reflect roadway segments selected in Plan View.
Press <Edit> to edit reflected list textually.

	Pnt.Name	Pnt.No	Reflections?	Plan View	Plan View	Textual	NRC Lside	NRC Rside
1	point2	2	☐	Show	Select	Edit	0.00	0.00
2	point3	3	☐	Show	Select	Edit	0.00	0.00
3	point4	4	☐	Show	Select	Edit	0.00	0.00

Building Rows – Building Rows are used to model the shielding effect of buildings that interrupt the line of sight from a receptor to a roadway. In the calculations, TNM applies an average reduction based on the height of the row and the spacing density of the buildings. The model does not know where the gaps between the buildings actually exist. Model rows of homes in a neighborhood and strips of commercial buildings. Model large, single buildings as barriers.



Building Row Input : test:2

Name: Warren Oaks Office Park

Avg. Height (ft): 25

Building Percentage (%): 50

	Pnt. #	X (ft)	Y (ft)	Z(ground) (ft)
1	1	241.0	195.6	0.0
2	2	400.2	256.0	0.0
3	3	474.2	307.9	0.0
4	4	518.6	362.1	0.0

<u>Name</u> The name of the building row should be independent of other building rows and should include the name or location of the buildings.

<u>Avg. Height</u> Use actual height of buildings if known, otherwise approximate using 10 feet per story. See table below for more information.

<u>Building Percentage</u> This should represent the percentage of the line of sight that the buildings block. For example, 50-foot wide houses on 100-foot wide lots would block 50% of the line of sight. Model buildings as barriers if this is greater than about 80%. Spacing accuracy should be at least ±20%. See table below for more information.

<u>Z (ground)</u> This is the ground level of the building row, which along with the height sets the top of the barrier. It should be accurate to within 2 feet for planning studies and 1 foot for final design.

Building Rows Information Table

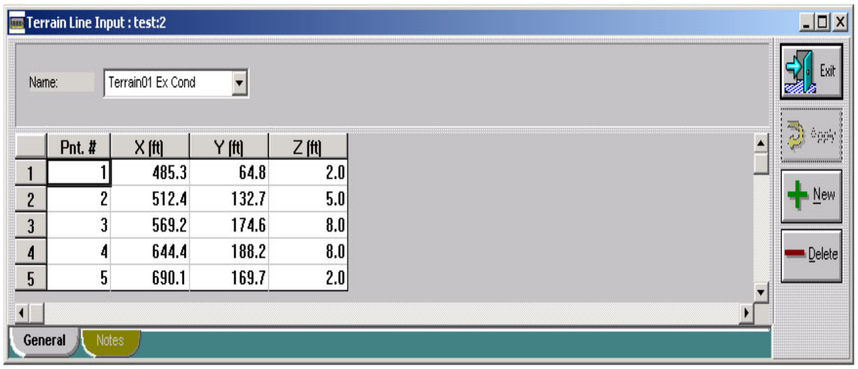
Acoustic Phenomenon	Rows of buildings located between a roadway and a receiver act as a barrier. Noise reduction increases with increasing building height and with increased building density (i.e. closer spacing of buildings).
Effect on TNM Predicted Noise Levels	Height: Reduction increases by 0.5 dB between a height of 25 feet (typical house) and 40 feet % Coverage: Going from 20% to 80% increases reduction from 2 to 4 dB
FHWA Mandate	None
Colorado Specific Aspect	None
CDOT Guidelines	Use 15 feet for one story house with pitched roof, 25 feet for two stories, and add 10 feet per story thereafter. Use a Building Percentage of 40% if not known. Model single, large buildings as a fixed-height barrier.

Terrain Lines – Major changes in ground elevation, such as hills, valleys, cliffs, and berms, should be defined using Terrain Lines, particularly those that block the line of sight between a receptor and a roadway.

<u>Name</u> The name of the terrain line should be independent of other terrain lines and barriers.

<u>X and Y Coordinates</u> Model a point every 100 to 200 feet, or more for severely undulating terrain.

<u>Z Coordinate</u> The ground elevation should be accurate to within 2 feet for planning studies and 1 foot for final design.



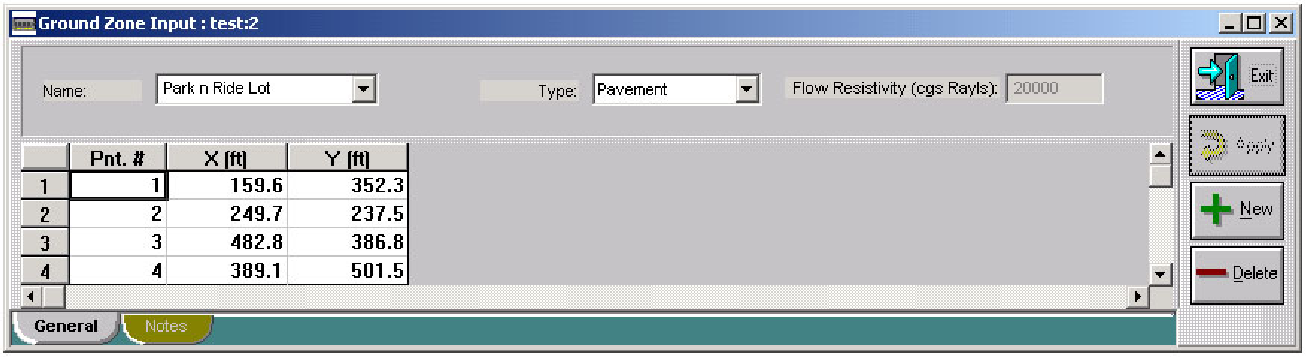
Name: Terrain01 Ex Cond

	Pnt. #	X [ft]	Y [ft]	Z [ft]
1	1	485.3	64.8	2.0
2	2	512.4	132.7	5.0
3	3	569.2	174.6	8.0
4	4	644.4	188.2	8.0
5	5	690.1	169.7	2.0

Terrain Lines Information Table

Acoustic Phenomenon	Terrain lines tell TNM where the ground is, which affects sound propagation in a number of ways. When terrain lines break line of sight between a road and a receptor, noise levels are reduced because the sound waves are forced to diffract over the protrusion. When terrain forms a valley between a road and a receptor, noise levels increase because ground absorption no longer takes place.
Effect on TNM Predicted Noise Levels	**Major** Terrain lines that form barriers reduce predicted levels by as much as 10 dB. Those that form valleys increase noise levels by as much as 3 dB.
FHWA Mandate	None
Colorado Specific Aspect	The undulation in the ground (i.e. elevation changes) at sites in Colorado can be significant.
CDOT Guidelines	Only model relatively significant variations in terrain. Typically, only zero to three terrain lines should be used in any given situation. The most important terrain features to model are those that break line of sight between a road and a receptor. Also, model the ground when it falls away from the line of sight from road to receptor by more than 10 feet. Note that TNM automatically defines the ground plane at the edge of pavement.

Ground Zones – These are used to represent large areas that have a different ground type than the default ground type (refer to Section 2.4). Each ground zone has a defined Flow Resistivity, which affects sound propagation. Apply ground zones on CDOT projects as outlined below.



Name: Park n Ride Lot

Type: Pavement

Flow Resistivity (cgs Rayls): 20000

	Pnt. #	X [ft]	Y [ft]
1	1	159.6	352.3
2	2	249.7	237.5
3	3	482.8	386.8
4	4	389.1	501.5

Name Should indicate the location and type of ground zone.

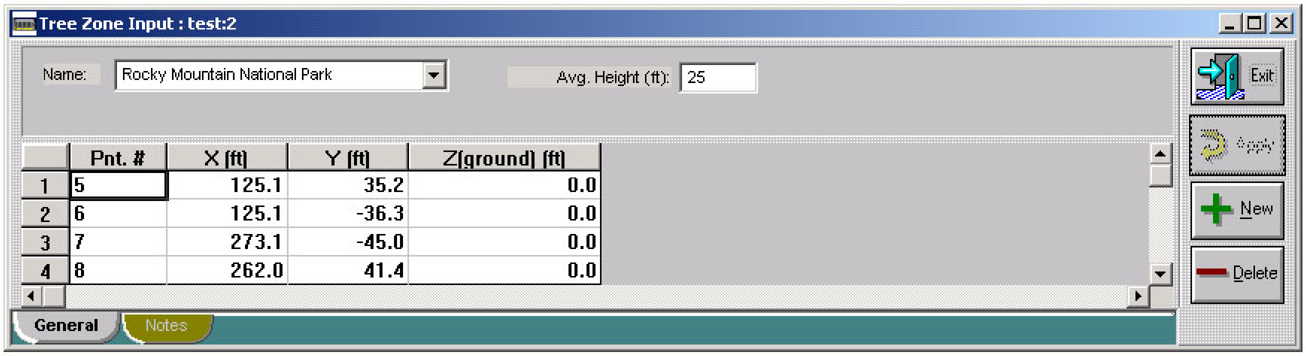
Type Model only pavement, water, or hard soil ground zones as there is little change in the model output between Lawn (assumed default) and Loose Soil and Field Grass. Do not use custom flow resistivities without consent from CDOT. See table below for more information.

X and Y Coordinates Coordinates should outline the ground zone to be modeled and should not overlap or align with roadways, terrain lines, or barriers. Typically this does not need to be accurate to more than plus or minus 5 to 10 feet.

Ground Zones Information Table

Acoustic Phenomenon	As sound waves propagate out from a source they interact with the ground. Depending on the porosity and permeability of the ground, sound waves that strike the ground are changed in intensity and phase. These waves interact with direct waves at the receptor and cause a decrease in overall levels compared to those that would occur for direct propagation only. This phenomenon is distance dependent. Noise levels decrease most rapidly when traveling over soft ground such as grass, less rapidly over hard soil, and even less rapidly when traveling over pavement or water.
Effect on TNM Predicted Noise Levels (vs. Lawn)	Hard Soil: 0.5 to 2.5 dB reduction for 75 to 200 foot wide swath Pavement/Water: 1 to 4 dB reduction for 75 to 200 foot wide swath
FHWA Mandate	None
Colorado Specific Aspect	While no data could be found explicitly, Colorado may have a higher tendency to exhibit hard soil conditions due to the lack of moisture.
CDOT Guidelines	Only model pavement, water, and hard soil ground zones. Only model areas that are at least 75 feet wide. Do not model ground zones for receivers located more than 500 feet from the road.

Tree Zones – These are used to represent large, dense, and coniferous tree areas that block the line of sight from receptors to roadways. See table below for guidance.



Tree Zone Input : test:2

Name: Rocky Mountain National Park

Avg. Height (ft): 25

	Pnt. #	X [ft]	Y [ft]	Z[ground] [ft]
1	5	125.1	35.2	0.0
2	6	125.1	-36.3	0.0
3	7	273.1	-45.0	0.0
4	8	262.0	41.4	0.0

Name Independent of other tree zones.

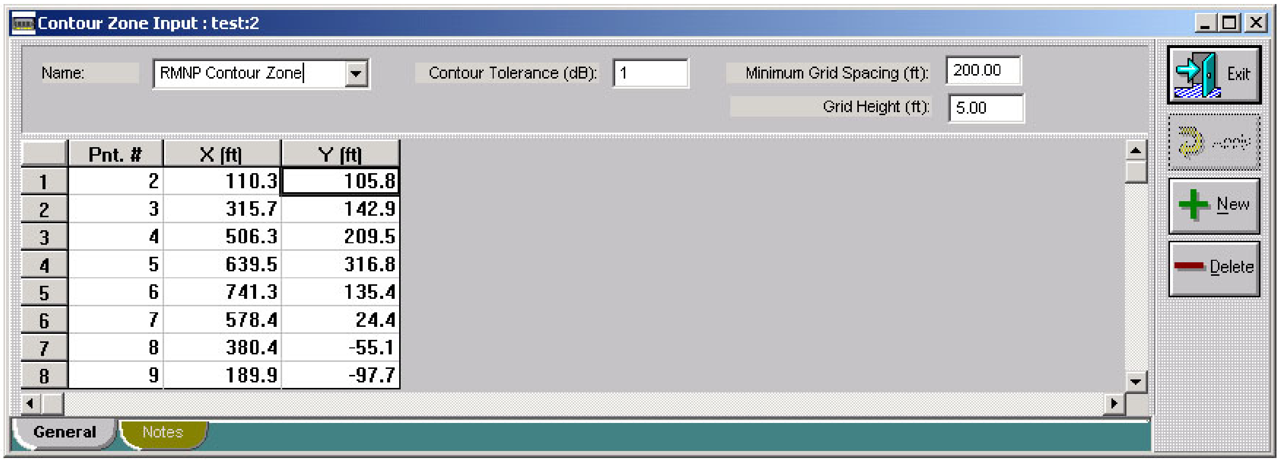
Avg. Height Recommended to limit modeling to trees that are at least 15 feet tall.

X, Y and Z Coordinates Coordinates should outline the tree zone to be modeled, which should be at least 50 feet thick. Tree Zones do not affect the ground zone.

Tree Zones Information Table

Acoustic Phenomenon	Sounds waves that are forced to pass through dense, thick vegetation are scattered, and thus lose intensity.
Effect on TNM Predicted Noise Levels	Reduction of 1 dB for a 50 foot deep tree zone Reduction of 4 dB for a 200 foot deep tree zone
FHWA Mandate	None
Colorado Specific Aspect	This is not a significant issue in Colorado due to the sparse nature of the State's vegetation. Generally not a concern in urban and suburban areas.
CDOT Guidelines	Only model a tree zone if the vegetation is coniferous, the forest is at least 50 feet wide, the trees are at least 15 feet tall, and the vegetation is dense.

Contour Zones – TNM's contouring routine should not be used to determine impact on CDOT projects. It may be used for general planning purposes if desired. It should be noted that some users have experienced difficulty when using TNM's contouring routine. Consult FHWA FAQ's for more information as well as Reference 11, which includes recommendations regarding minimum grid spacing and contour tolerance. When contours are required on CDOT projects, conduct predictions at individual locations and interpolate the results using engineering judgment. Always proceed with caution when using this feature.



Name: RMNP Contour Zone

Contour Tolerance (dB): 1

Minimum Grid Spacing (ft): 200.00

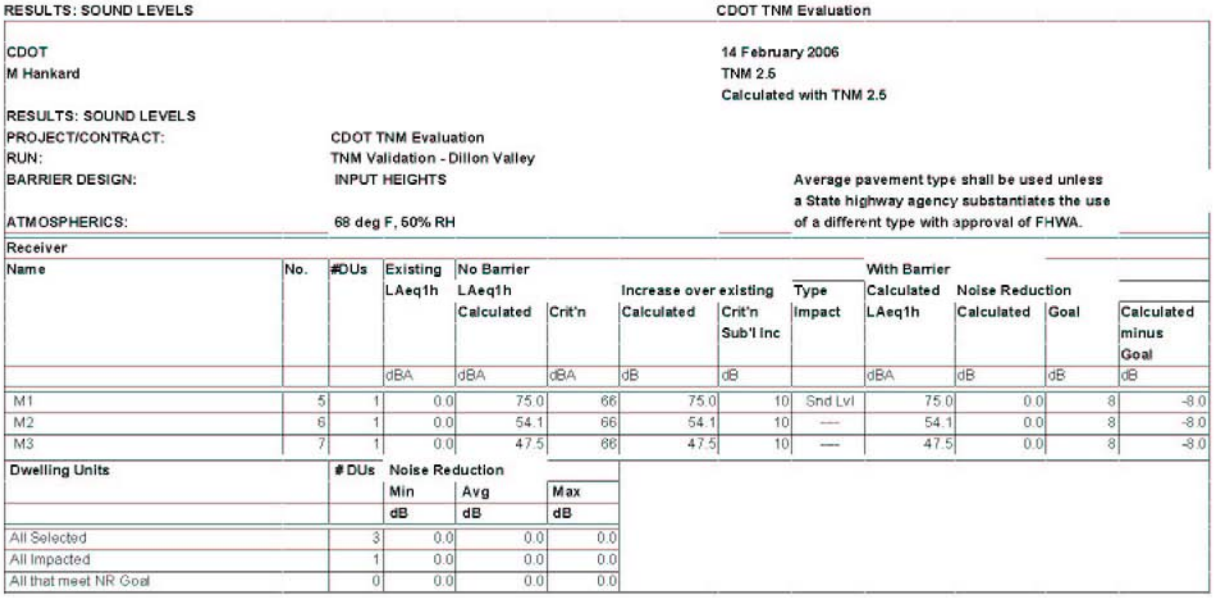
Grid Height (ft): 5.00

	Pnt. #	X (ft)	Y (ft)
1	2	110.3	105.8
2	3	315.7	142.9
3	4	506.3	209.5
4	5	639.5	316.8
5	6	741.3	135.4
6	7	578.4	24.4
7	8	380.4	-55.1
8	9	189.9	-97.7

3.0 Using TNM Models

3.1 Assessing Noise Impact

Assessing noise impact on CDOT projects requires the prediction of noise levels at all residences and businesses located within a project's study area for both existing and design-year conditions, and comparison of the predicted levels to CDOT criteria. Once the models have been constructed as discussed above, TNM is run by selecting "Calculate", ""Current Run", "All Receivers". Predicted levels can be viewed in the "Sound Levels" table under the Tables, Sound Level Results pull-down menu.



RESULTS: SOUND LEVELS CDOT TNM Evaluation

CDOT 14 February 2006
M Hankard TNM 2.5
Calculated with TNM 2.5

RESULTS: SOUND LEVELS
PROJECT/CONTRACT: CDOT TNM Evaluation
RUN: TNM Validation - Dillon Valley
BARRIER DESIGN: INPUT HEIGHTS
ATMOSPHERICS: 68 deg F, 60% RH

Average pavement type shall be used unless a State highway agency substantiates the use of a different type with approval of FHWA.

Receiver												
Name	No.	#DUs	Existing LAeq1h	No Barrier LAeq1h		Increase over existing		Type Impact	With Barrier Calculated LAeq1h	Noise Reduction		
				Calculated	Crit'n	Calculated	Crit'n Sub'l Inc			Calculated	Goal	Calculated minus Goal
			dBA	dBA	dBA	dB	dB		dBA	dB	dB	dB
M1	5	1	0.0	75.0	66	75.0	10	Snd Lvl	75.0	0.0	8	-8.0
M2	6	1	0.0	54.1	66	54.1	10	----	54.1	0.0	8	-8.0
M3	7	1	0.0	47.5	66	47.5	10	----	47.5	0.0	8	-8.0

Dwelling Units	# DUs	Noise Reduction		
		Min	Avg	Max
		dB	dB	dB
All Selected	3	0.0	0.0	0.0
All Impacted	1	0.0	0.0	0.0
All that meet NR Goal	0	0.0	0.0	0.0

3.2 Barrier Analysis

The Barrier Analysis feature of TNM is used to predict the insertion loss (i.e. noise reduction) of a proposed barrier. The following steps should be taken when analyzing barriers using TNM:

- Model proposed barriers longer than will ultimately be necessary, as they can be shortened to the appropriate length using the Barrier Analysis tool.
- Enter a height, increment, and number of up and down perturbations sufficient to cover the expected height range of the barrier.
- Once the model is constructed and has been run, select the barrier to be analyzed, along with all receptors of interest. Select "Barrier Analysis", "New", then save it by selecting "Remember As" and give it an appropriate name.
- The barrier length and height can then be adjusted with TNM's Barrier Analysis feature so that it is predicted to provide between 5 and 10 dBA of noise reduction at front row receptors. First, adjust the height of the entire barrier until the desired reduction is

achieved. Then shorten the length of the barrier based on project constraints, or until the predicted noise reduction at the end receptors is approximately 5 to 7 dBA.

- Note that TNM predicts higher noise reduction for a given barrier than does STAMINA or other international models. Therefore, it is advised that barriers be designed with TNM so that they are predicted to achieve closer to 10 dB of reduction than 5 dB.

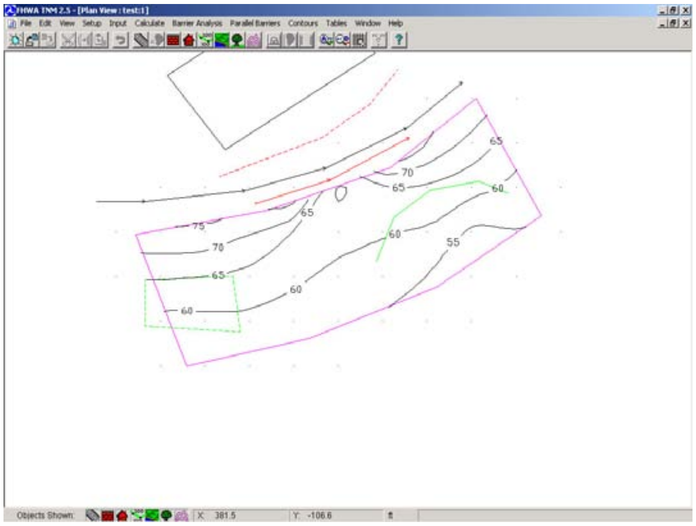
CDOT policy also requires the calculation of the barriers cost-benefit in terms of "cost per dB of reduction per benefited receptor". This can, theoretically, be calculated within TNM. However, it is recommended that it be calculated outside of TNM using a separate spreadsheet program. This is because the data comes from a variety of sources. Cost is calculated by multiplying CDOT's current noise barrier unit cost ($30/square foot) by the exposed area of the barrier (square feet). The noise reduction is calculated using TNM. The number of benefited receptors is the number of receptors that are predicted to receive at least 3 dB of reduction by the barrier.

3.3 *Parallel Barriers Pull-down Menu*

The parallel barrier analysis tool is used to predict how much degradation of noise reduction is occurring due to sound reflecting between parallel barriers. FHWA states that this analysis should be conducted whenever the ratio of the separation of the two walls to the height of the walls is 20:1 or less. FHWA reports that at a ratio of 10:1, a degradation in noise reduction of as much as 3 dBA can occur.

3.4 *Contours* Pull-down Menu

Do NOT use TNM's Contouring routine to predict noise impact on CDOT projects. Contours may be produced for showing the general location of setbacks for future development, or for other planning purposes. The TNM contouring routine has been shown to produce irregular shapes when modeling anything but a simple, relatively flat site with no barriers (Reference 10). If it is used, the grid spacing should be set to no more than 10 feet, the contour interval to no more than 1 dB, and terrain lines and barriers should be avoided.



A sample output of TNM's contour routine is shown at right. The output is only useful if the location of the contours can be determined in relation to other features on the ground. As can be seen, the use of these contour results is somewhat limited unless an aerial of the project or other site graphics are included. When trying to convey noise contour information, it is recommended that the pertinent contour results (i.e. CDOT's NAC for Category B and C receptors) be shown in a figure atop an aerial photograph or other descriptive graphic of the project.

3.5 *Tables* Pull-down Menu

The Tables function allows the user to view and/or print both input data and calculation results. The format of the tables is fixed. Refer to Section 5.0 for analysis documentation guidelines.

4.0 Noise Model Validation Using TNM

Some level of TNM validation should be undertaken on each project. There are three levels of validation to consider:

1. Validate Model Using Results From Other, Similar Projects
   Compare prediction results to previous CDOT projects with validated results for which the geometry, traffic conditions, etc. are relatively equivalent, or can be reasonably and accurately scaled. This is suitable only for very small projects where noise impact and/or mitigation are unlikely.

2. Validate Model Using Short-Term Noise Measurements
   Compare TNM predicted noise levels to short-term (i.e. one hour) measurement results. Conduct measurements and predictions as described below. This is applicable to medium-sized projects such as interchange improvements and small corridors.

3. Validate Model Using Short-Term And Long-Term Noise Measurements
   Compare TNM predicted noise levels to short-term (i.e. one hour) measurement results, and long-term (i.e. 24-hour) measurement results. Conduct measurements and predictions as described below. This is applicable to large corridor projects, and projects where significant mitigation is likely.

Validation Measurements

The following provides some highlights regarding measurement requirements for most CDOT projects. More detailed measurement information can be found in the references.

- Equipment: Use ANSI Type II or Type I sound level meters with integrating capability (to calculate averages (L_{eq})). Use "A" weighting and "slow" time response. Meters should be field calibrated prior to each measurement, and the calibration should be checked after the measurements.
- Short-Term Measurements: For cases where the measurement is taken close to road and noise levels are greater than 60 dBA: 15 minutes minimum, 30 desired. For cases where noise levels are less than 60 dBA, and/or where traffic volumes are low: 30 minutes minimum, 60 minutes desired.
- Long-Term Measurements: Long-term measurements provide a clear understanding of the loudest-hour noise level that repeats from day to day. Therefore, 3 to 4 days of data is required at a minimum, and one week of data is desired. Measurements should be conducted in 15-minute or one-hour intervals. This type of information may be required only for large corridor projects.
- Number of Measurement Locations: Take at least one measurement at each major residential area within the project study area. Conduct additional measurements within a given residential area where noise levels could differ, such as where the topography changes. The number of measurement locations varies from 2 to 4 for an interchange project, to 10 to 20 for a corridor project.

- Other Noise Sources: Whereas the purpose of the measurements is for TNM validation purposes, and given the fact than TNM can only predict noise from roadway traffic, the impact of noise from other sources must be minimized or the measurement is not valid. Other sources of noise could include trains, aircraft, lawn mowers, building ventilation systems, etc.
- Traffic Counts: Traffic volumes on each roadway of interest during the short-term noise measurements must be counted. Counts should be separated into automobiles, medium trucks, and heavy trucks. On low volume roads, counts can sometimes be conducted manually. On higher volumes roads, counts can be obtained by using a traffic counter, or by videotaping traffic. Counts should be converted to hourly values for use in TNM. For long-term measurements, traffic conditions should be sampled during at least one one-hour period.
- Traffic Speeds: Speeds on each roadway of interest must be determined using a radar gun or by driving the road a number of times to determine typical speeds. Trucks sometimes travel more slowly than automobiles.
- Weather Conditions: Wind speed, wind direction, temperature and relative humidity should be measured. Handheld systems like Kestrel are perfectly adequate, as are systems such as Davis and Campbell Scientific.

TNM Validation Predictions

The TNM model of the measurement site should reflect how the entire project is to be modeled. Thus, do not model more features in the measured condition than you will for the existing and future conditions.

- Gather site data such as pictures, aerial photographs, elevation contours, and land use line work.
- Model site geometry using TNM, constructing the most accurate representation of the site as possible, given the data input parameters discussed in Section 2.0.
- Enter the measured hourly traffic volumes and average speeds.

TNM-Measurement Validation

- Compare measured and predicted noise levels.
- Differences should be within 3 dBA.
- If not, re-examine site and make any plausible modeling changes (re-count traffic, enter additional barriers, evaluate for TNM anomalies, etc.)
- If errors continue to be greater than 3 dBA and there is a rational reason for such a discrepancy, then these need to be clearly documented and accounted for in the model using adjustment factors or other means.

5.0 Documenting TNM Analyses

Each stage of the TNM analysis should be documented both electronically and in a hardcopy form. The use of the TNM formatted output is not *required* (i.e. printing of tables and figures directly from TNM). Document the following items:

Validation Analyses

- List of measurement equipment, factory calibration status of equipment, and results of field calibrations
- Table of measured traffic volumes and speeds, and a description of how they were determined
- Table of measured and predicted noise levels and differences
- Plan view of site showing measurement locations and acoustically relevant features, such as barriers and roadways
- TNM files (all *.idx files used in report should be included in electronic format (e.g. CD) with the report or otherwise electronically submitted to the CDOT Noise Specialist)

Impact Assessments

- List of roadways and other features modeled for each area under study
- Table of traffic volumes and speeds for each condition modeled
- Table of existing and future noise levels, and increase in noise levels
- Plan views showing prediction locations and acoustically relevant features
- TNM files (all *.idx files used in report should be included in electronic format (e.g. CD) with the report or otherwise electronically submitted to the CDOT Noise Specialist)

Barrier Analyses

- Existing and future noise levels without mitigation
- Noise reductions at all receptors in the area under study (either by direct prediction or through representation - refer to Section 2.5 regarding receiver placement)
- Overall average noise level reduction for all benefited receptors (those receiving at least 3 dBA of reduction)
- Cost-benefit of barrier ($/# of benefited receivers/average noise reduction)
- Figures as needed to describe the barrier analyzed

- TNM files (all *.idx files used in report should be included in electronic format (e.g. CD) with the report or otherwise electronically submitted to the CDOT Noise Specialist)

Noise Contour Analysis

Noise contours are useful to CDOT and planning agencies to show how far back from a roadway development should be held in order to keep noise levels below CDOT's Noise Abatement Criteria. The following documentation should be provided:

- Design-year noise levels contours for Category B and C shown over aerial or other descriptive project mapping
- A brief explanation of the modeling methodology used to determine the location of the noise contour
- TNM files (all *.idx files used in report should be included in electronic format (e.g. CD) with the report or otherwise electronically submitted to the CDOT Noise Specialist

6.0 References

TNM Manuals

1. TNM 1.0 (January 1998): FHWA Traffic Noise Model Users Guide
2. TNM 1.0 (February 1998): FHWA Traffic Noise Model Technical Manual

The following are addendums only, and discuss only changes to the model with each revision

3. TNM 1.1 (Sep. 2000): FHWA Traffic Noise Model Users Guide Addendum
4. TNM 2.0 (May 2002): FHWA Traffic Noise Model Users Guide Addendum
5. TNM 2.5 (April 2004): FHWA Traffic Noise Model Users Guide Addendum

FHWA and Other Documents

6. *Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model*, Report No. FHWA-PD-94-093, 1995
7. *Phase 1 Validation*, U.S. Department of Transportation Research and Special Programs Administration, John A. Volpe National Transportation Systems Center Acoustics Facility, DTS-34
8. *TNM Version 2.5 Addendum to Validation of FHWA's Traffic Noise Model (TNM): Phase 1*, U.S. Department of Transportation Research and Special Programs Administration, John A. Volpe National Transportation Systems Center Acoustics Facility, DTS-34
9. *Measurement of Highway-Related Noise*, Report No. FHWA-PD-96-046, 1996
10. *TNM FAQs With Guidelines*, Volpe Center Acoustics Facility
11. Representing Highway Noise Exposures II – Return of the Contourtionist, *2005 TRB 84th Annual Meeting, Michael Staiano*

CDOT Guidelines

12. *Noise Analysis and Abatement Guidelines,* Colorado Department of Transportation, December 2002

Appendix A – Entering Roadways into TNM

Which Roadways to Model

- Always model interstates, expressways, and major/principal arterials
- Model any other roadways that carry significant amounts of traffic (typically a peak hour volume of 1,000 vehicles or greater)
- Local or other minor roadways generally will not need to be modeled

How Many Lanes to Model Individually

- Model each road with a minimum of one TNM roadway per direction of travel (e.g. northbound and southbound)
- Model additional lanes as individual roadways only when there are three or more lanes per direction, there are receivers within 400 feet of the centerline of the entire facility, and the traffic distribution per lane is known with some certainty
- Model additional lanes as individual roadways when special circumstances exist such as high occupancy vehicle lanes, truck lanes, etc.

Length and Width

- Modeled roadways should extend beyond each receptor by at least four times their distance from the roadway. For example, a roadway should extend 1,000 feet past a receptor that is located 250 from the center of the road.
- TNM automatically defines the ground plane along the edge of pavement, which is defined by the placement (alignment), elevation, and width of the roadway
- For projects where receptors are located below the elevation of the roadway it is particularly important that the edge of pavement closest to the receptors be accurately placed in space (which, as noted above, is the result of the roadway's alignment, elevation, and width)
- If a roadway has different amounts of pavement on either side of its centerline (e.g. due to inside and outside shoulder widths being different), accurately model the outside shoulder (i.e. that closest to receptors) and disregard inside shoulder variation. For roadways with paved medians, model a roadway in that location with zero traffic, ensuring that it is wide enough so that no default ground is inserted in the median.

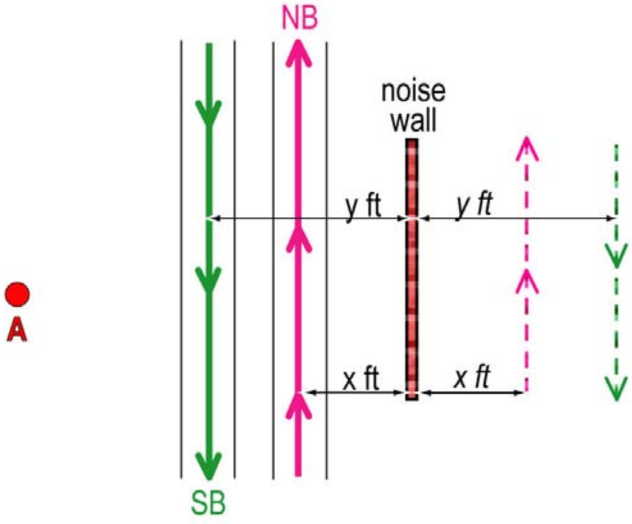
Median Barriers

- FHWA FAQ's advise that median barriers (e.g. Type 7 solid rail "Jersey Barriers" or a berm) should be modeled, but use care when doing so.

Appendix B – Modeling Barrier Reflections Using the Mirror Source Method

Presently, TNM cannot directly model the amount of noise that reflects off of a highway noise barrier and reaches receivers on the opposite side of the highway. There is a work-around available using TNM's parallel barrier routine. As described more fully in Volpe Center's TNM FAQs with Guidelines, some TNM users have simulated single barrier reflections, by making one of the parallel barriers very small (i.e.: 0.3 meters, 1 ft.). Use the results from this parallel barrier calculation and apply it as an adjustment factor. This process has not been validated.

A second work-around, and that which is recommended for use on CDOT projects, is to apply the Mirror Source method. Referring to the figure below, consider a site that has one main north-south running roadway and a 15-foot tall reflective noise wall located on the east side of the road. Noise will reflect off of this wall and increase noise levels at the receptors located on the west side of the road ("A"). To model this condition, a "mirror source", i.e. a second roadway, is placed on the east side of the wall. This distance from the mirror source to the wall is the same as the distance from the actual roadway to the wall ("x" and "y"). One mirror roadway should be placed for each actual roadway modeled. Thus, in the example shown in Figure B1, a mirror northbound roadway is modeled as is a mirror southbound roadway. Note that when using the mirror source method the wall itself is not modeled.



Traffic volumes and speeds on the mirror roadway(s) should match the actual roadway(s) unless the Noise Reduction Coefficient (NRC) of the wall material is known. The NRC is a measure of the absorptive (opposite of reflective) quality of a material. A perfectly absorptive wall has an NRC of 1.0, and a perfectly reflective wall has an NRC of 0.0. Thus, for example, if the wall material has a published NRC of 0.5, traffic volumes on the mirror roadway could be reduced by 50%.

The predicted increase in noise levels at receivers located opposite a reflective wall will increase by anywhere from a few tenths of a dB to 2 dB. The theoretical maximum increase from the doubling in strength of a line source is 3 dB, which would occur when a receiver is located opposite an infinitely long, infinitely tall, perfectly reflective wall. The increase is more pronounced at more distant receptors, where the ratio of the distance between the actual and mirror roadways approaches one.