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Validation of FHWA's Traffic Noise Model® (TNM): Phase 1

U.S. Department of Transportation
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13. ABSTRACT (Maximum 200 words)
The Volpe Center Acoustics Facility, in support of the Federal Highway Administration (FHWA) and the California Department of Transportation (Caltrans), has been conducting a study to quantify and assess the accuracy of FHWA's Traffic Noise Model (TNM) and make recommendations on its use. The TNM Validation Study involves highway noise data collection and TNM modeling for the purpose of data comparison. Phase 1 of the study has been completed. For this phase, over 100 hours of traffic noise data were collected at 17 highway sites around the country. The 17 sites included: open areas next to the highway with acoustically soft ground (e.g., lawn); open areas with acoustically hard ground (e.g., pavement or water); and areas next to the highway with an open area behind a single noise barrier. In comparing the measured sound levels to the TNM-predicted sound levels, several variables were examined, including distance from the roadway, wind conditions, and percentage of heavy trucks. This report discusses the results of Phase 1 of the TNM Validation Study.

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FHWA TNM, validation, noise, highway noise, measurements, modeling, sound levels, noise barrier, distance, height, wind, TNM recommendations

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ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (ha) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

°C=5/9(°F - 32)

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

°F=9/5(°C) + 32

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES	0			1		2			3		4			5	
CENTIMETERS	0	1	2	3	4	5	6	7	8	9	10	11	12	13	

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

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EXECUTIVE SUMMARY

Introduction

The Volpe Center Acoustics Facility (VCAF), in support of the Federal Highway Administration (FHWA) and the California Department of Transportation (Caltrans), has been conducting a study to quantify and assess the accuracy of FHWA's Traffic Noise Model® (TNM) and make recommendations on its use. The TNM Validation Study involves highway noise data collection and TNM modeling for the purpose of data comparison. The number of sites required to do a comprehensive study reflects the incorporation of numerous TNM features, either isolated or grouped with other TNM features. This large task is more manageable divided into multiple phases; in this manner, interim results are available to TNM users.

Phase 1 of the study has been completed. For this phase, over 100 hours of traffic noise data were collected at 17 highway sites around the country. The 17 sites included: open areas next to the highway with acoustically soft ground [e.g., field grass (effective flow resistivity (F) . 150 cgs Rayls) or lawn (F . 300 cgs Rayls)]; open areas with acoustically hard ground [e.g., pavement or water (F . 20,000 cgs Rayls)]; and areas next to the highway with an open area behind a single noise barrier. In comparing the measured sound levels to the TNM-predicted sound levels, several variables were examined, including distance from the roadway, wind conditions, and percentage of heavy trucks. A brief review of the study, including the results, is presented in this section of the report. For more details, please refer to the remainder of the report.

Field Measurements

Phase 1 measurement sites had characteristics of those most commonly modeled by TNM users and were relatively simplistic so as to isolate individual features of TNM. All 17 sites for Phase 1 were either open areas (i.e., free from interfering objects, reflective or absorptive, in the sound propagation path) or featured a noise barrier (wall or berm). Most sites were flat, the exceptions having ground undulations or substantial changes in elevation.

Instrumentation was deployed at each measurement site for capturing acoustical, meteorological, traffic, and site survey data. A-weighted equivalent sound levels in 5-second periods were captured using microphones, spectrum analyzers, sound levels meters, and digital audio tape recorders. One-second time intervals of temperature, relative humidity, wind speed and direction, and ambient atmospheric pressure were captured using automated meteorological stations. Highway traffic was continuously recorded using video cameras. A site survey was completed using a differential global positioning system. Other supporting instrumentation was also deployed. At each measurement site, approximately 6 hours of data were collected.

The types of sites and the locations of the acoustical and meteorological instrumentation are seen in the following table.

Table ES.1. Phase 1 Measurement Sites by Type.

Site Type		Number of Sites	Ranges of Microphone Distances d=dist from roadway bb=dist behind barrier
open area	acoustically soft ground	4	d = 50 to 800 ft (~15 to ~245 m)
	acoustically hard ground	4	d = 50 to 1273 ft (~15 to ~390 m)
noise barrier		9	bb = 50 to 300 ft (~15 to ~90 m)

TNM Modeling

Each measurement site was modeled using TNM. The input objects were taken directly from the site survey map and maps drawn during site scoping and measurements; these include all roadways, receivers, noise barriers, terrain lines, and ground zones. Once a TNM base case was completed for a particular site, a new run was created for each 5-minute data block. This amounted to as many as 70 TNM runs for each measurement site. For each 5-minute period, the corresponding traffic data (scaled from 5 minutes to 1 hour), temperature, and relative humidity were entered. All runs were then calculated, resulting in an hourly, A-weighted, equivalent sound level for each data block.

Data Analysis

After initial processing, the measured and TNM-predicted sound levels were imported into spreadsheets for analysis. For both sets of data, the 5-minute data blocks were logarithmically combined into 15-minute data blocks for final analysis and presentation.

The data sets were also processed in two ways: (1) the TNM-predicted sound levels were calibrated to the measured sound levels using a reference microphone so as to make a direct comparison of measured sound propagation and TNM-predicted sound propagation; and (2) the TNM-predicted sound levels were not calibrated to the measured sound levels so as to add another level of comparison, comparing measurements and predictions with possibly slightly different sound source characteristics. The calibration for the first way of processing was accomplished by applying a calibration value (the difference between a site's measured sound levels at the reference microphone and the TNM-predicted sound levels at the same position) to the predicted sound levels at all other positions. This calibration process eliminates biases due to possible site-specific emission levels.

Since TNM currently calculates sound levels for a windless environment, the data were further processed in two other distinct ways according to the wind speed. The two processing methods were: 1) no data blocks were discarded due to wind conditions (this data set is referred to as the all-wind data); and 2) any data blocks that at any time achieved a "very windy" condition [winds exceeded ~11 mph (5 m/s)] were removed (this data set is referred to as the strong-wind-removed data). The process was assumed to eliminate data subjected to severe refraction and/or possible turbulence; it was also assumed that the removal of data characterized as "very windy" eliminated any data that may have been contaminated by wind noise at the microphone.

For final presentation the data were compared in several ways. First, direct comparisons of TNM-predicted sound levels and measured sound levels were made, then the differences as a function of the following variables were calculated: distance from the roadway, height above the ground, wind speed, wind direction, and percentage of heavy trucks. Additional analysis was performed using alternate TNM runs in order to make recommendations on the use of TNM.

Results

Overall, for the calibrated data, TNM is performing very well. The following graphic shows a direct comparison between TNM-predicted and measured sound levels for the strong-wind-removed data. The TNM-predicted sound levels were calibrated to measured sound levels using a reference microphone. The data are plotted with the horizontal axis being the measured sound levels and the vertical axis being the TNM-predicted sound levels. Each 15-minute data block (15-min L_{eq}) is represented as an orange X, where the number of data points is stated in the lower right corner of the figure. A dashed blue line represents the linear fit and solid green lines show the 95 percent confidence band. A solid black diagonal line symbolizes perfect agreement between TNM-predicted data and measured data. Data points that fall above (to the left of) this line indicate over-prediction and points that fall below (to the right of) this line indicate under-prediction. It should be noted that the uncalibrated results (not shown in this graphic) indicate some over-prediction, but the bias is essentially eliminated after calibrating the TNM-predicted data using a reference microphone.

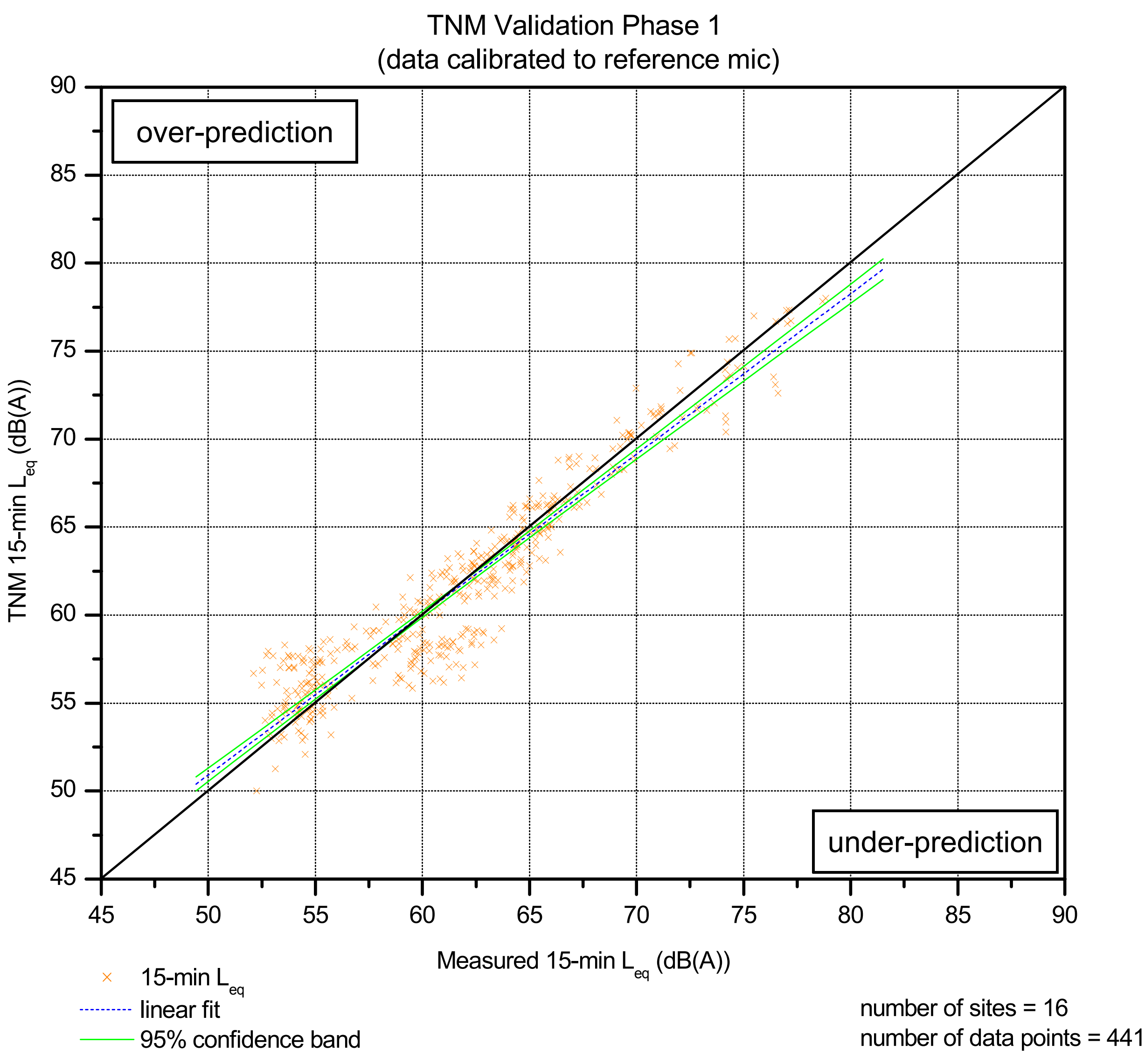

Figure ES.1. Direct Comparison of TNM and Measured Data; All Sites (calibrated); Strong Wind Data Removed. (Note: Data for 16 of the 17 measurement sites are shown in this plot; no data points for Site 04CT remained after eliminating the strong wind data.)

For all data comparisons with the calibrated data, TNM-predicted sound levels are showing good agreement with the measured sound levels for these types of sites: open area, acoustically soft ground sites [out to 800 ft (~245 m) from the roadway]; open area, acoustically hard ground sites [out to 300 ft (~90 m) from the roadway]; and noise barrier sites [out to 300 ft (~90 m) behind the barrier]. The only difference of concern arises for open area, acoustically hard ground sites at far distances. The uncalibrated data (where site bias has not been removed) shows a general over-prediction in the TNM-predicted sound levels.

As for the effects of wind, it is seen that TNM's accuracy is dependent on the wind conditions for noise barrier sites. Also, there seems to be no apparent influence of the percentage of heavy trucks on the performance of TNM, suggesting that TNM implements heavy trucks correctly.

In addition to the above comparisons, results for alternate TNM runs were examined in order to make recommendations on the use of TNM. A summary of the results and recommendations appear in the following tables.

Table ES.2. Summary of Results.

<table>
<tr><th colspan="3">Investigation</th><th>Results</th><th>Comments</th></tr>
<tr><td rowspan="4">Direct comparison of TNM-predicted and measured sound levels</td><td rowspan="2">uncalibrated</td><td>all-wind data</td><td rowspan="2">average 2.6 dB over-prediction</td><td rowspan="2">when calibrating to reference mic, bias is essentially eliminated</td></tr>
<tr><td>strong-wind-removed data</td></tr>
<tr><td rowspan="2">calibrated</td><td>all-wind data</td><td>average 1.0 dB difference from perfect agreement</td><td rowspan="2">good agreement at all types of sites, except for far distances at hard ground sites (some over-prediction, ~ 2.0 dB); TNM propagation algorithms are performing well</td></tr>
<tr><td>strong-wind-removed data</td><td>average 0.5 dB difference from perfect agreement</td></tr>
<tr><td rowspan="5">Differences (calibrated TNM-predicted minus measured) in sound levels as a function of ...</td><td rowspan="2">distance from roadway, height above ground</td><td>all-wind data</td><td rowspan="2">average differences for most sites within 1.5 to 2.0 dB – some exceptions</td><td rowspan="2">far distances [> 300 ft (~90 m)] at hard ground sites show some over-prediction; no strong trends for height above ground</td></tr>
<tr><td>strong-wind-removed data</td></tr>
<tr><td rowspan="2">wind speed, wind direction</td><td>all-wind data</td><td>2.0 dB wind influence at barrier sites</td><td rowspan="2">only conclusive wind influence seen at barrier sites</td></tr>
<tr><td>strong-wind-removed data</td><td>1.0 dB wind influence at barrier sites</td></tr>
<tr><td colspan="2">percentage of heavy trucks (only for strong-wind-removed data)</td><td>no distinct trends</td><td>no apparent influence of % heavy trucks on TNM's performance</td></tr>
</table>

Table ES.3. Recommendations on the Use of TNM.

Topic	Recommendation
Data Calibration	TNM-predicted sound levels should be calibrated to sound levels measured at a site. Refer to example state policies on model calibration [Hendriks 1998] [Lindeman 2001].
Ground Undulations	Substantial ground undulations [$ 5 ft (1.5 m)] should be modeled.
Grass Medians	Grass medians [with widths $ 10 ft (~3 m)] should be modeled using grass ground zones (rather than the median being defined by the default ground type of grass).
Ground Zones	Sites with mixed acoustically soft and hard ground should be modeled with the default ground type being soft ground and the ground zones being hard ground.

Later Phases of the TNM Validation Study

Later phases of the TNM Validation Study will incorporate more site measurements and modeling along with further analysis of the Phase 1 data. Additional measurement sites will incorporate Phase 1-type sites that need further investigation, sites with multiple TNM objects, and sites with less common TNM objects.

Some items discussed in Phase 1 require further investigation. These include: general TNM over-predictions that are seen in the uncalibrated results; TNM's accuracy being dependent on wind conditions at noise barrier sites; the examination of more open area sites with unusual ground surfaces to better evaluate TNM's performance in such situations; and the impact of different TNM-modeling techniques (different user methodologies).

1. INTRODUCTION

Since March 1998, the Federal Highway Administration's (FHWA) Traffic Noise Model® (TNM) has been available for highway traffic noise analysis and barrier design [Anderson 1998]. Prior to its release, the model was assessed for accuracy by comparing TNM computations to: (1) point source measurement data collected by researchers in the 1960s and 70s and another model's results from the 80s; and (2) measurement data collected in two more recent highway traffic noise studies performed by the State of California and by the United States Department of Transportation / Volpe Center Acoustics Facility (Volpe). The agreement between data from measurements, TNM, and an earlier model was found to be quite good in most cases, with the results of the comparisons published in the TNM Technical Manual [Menge 1998]. Since the release, various state departments of transportation, academic researchers, and members of private industry have performed independent comparisons. All of the above comparisons are discussed further in Section 1.1. Though useful, the measurements as a group do not represent a structured study performed with consistent data collection, reduction, and analysis techniques. Further, not all aspects of TNM computations were investigated.

The need for a comprehensive study involving detailed investigations into the accuracy of TNM was identified. In support of the FHWA's Office of Natural Environment and the California Department of Transportation (Caltrans), Volpe is performing multiple sets of paired field measurements and TNM computations, comparing the results for validation of the model. (Please refer to Appendix A for a list of the research team members.) Publications resulting from this validation study are to serve as references for the TNM model.

TNM was originally released as Version 1.0 in 1998. Since then, there have been two additional minor releases (1.0a and 1.0b) and two additional major releases, Version 1.1 in September 2000, and Version 2.0 in June 2002. All TNM upgrades have focused primarily on improving the model's computational run time, updating its DXF import functionality, and including some bug fixes and graphical user interface improvements. Only two small changes were made to the acoustical computations, resulting in, at most, 0.1 to 0.2 dB differences in predicted sound levels compared with the original Version 1.0 release. Therefore, this TNM Validation Study applies to all versions of TNM up to and including Version 2.0. Versions released after 2.0 may have changes made to the acoustics and should be examined for potential differences (stated in the Readme file) before referencing this document.

1.1 Background

The FHWA's Traffic Noise Model (TNM) is a computer software package designed for highway traffic noise prediction and noise barrier design. The model allows for the incorporation of single and parallel barriers with options including barrier type (walls and berms) and absorptive surface characteristics, roadways with options such as traffic flow and pavement type, the design of terrain geometry, rows of buildings, and areas of dense foliage. All of these parameters can be combined to model a highway site, allowing noise prediction for the surrounding areas. Barriers with perturbable height, another feature of the program, allow the user to easily formulate a noise abatement design for the communities in the vicinity of a highway.

TNM computes a predicted noise level through a series of adjustments to a reference sound level. The reference level is the vehicle noise emission level, which refers to the maximum sound level emitted by a vehicle pass-by at a distance of 50 ft (~15 m). These sound levels represent the average emissions according to vehicle type, where more than 6000 vehicle pass-bys were measured [Fleming 1996]. Adjustments are then made to the emission level to account for traffic flow, distance, and shielding. The model integrates state-of-the-art sound propagation and shielding algorithms. These algorithms are based on fairly recent research of sound propagation over ground of different types, atmospheric absorption, and the shielding effects of barriers, berms, buildings, and trees.

In order to validate the sound level predictions computed by TNM prior to Version 1.0's release, comparisons were made to five existing data sets (representing both measured and predicted data). Three of these sets involved point-source geometry, and the remaining two involved in-situ measurements of barrier performance along actual highways. The first comparison was with Embleton's model for reflection from ground of finite impedance [Embleton 1983]. The second comparison was to measurements by Parkin and Scholes over grassland [Parkin 1965], and the third comparison was to measurements of a noise barrier by Scholes, also over grassland [Scholes 1971]. The fourth and fifth comparisons were to measurements of noise barrier performance at two different highway locations by Hendriks and Fleming, respectively [Hendriks 1991] [Fleming 1992]. As stated above, the agreement with data in all of these studies was found to be quite good in most cases.

Since TNM Version 1.0's release, comparisons have also been made independently by state departments of transportation, academic researchers, and members of private industry [Anderson 1999] [Bowlby 2000] [Carpenter 1999] [Harris 2000] [Huybregts 2001] [Romick 1999] [Staiano 2001] [Wayson 2001]. These studies involve sites with acoustically soft and hard ground, many of the soft ground sites with single noise barriers, primarily noise walls as opposed to earth berms. Results have generally shown good agreement with TNM, but a few apparent anomalies have been documented.

Together, all of the discussed studies present an incomplete picture with regard to TNM's accuracy. First, they use different measurement and analysis techniques, allowing for variation in the final sound levels for the measured data. Second, they each use different TNM modeling techniques, also allowing for variation. Third, most of the measurement sites encompass the more typical TNM features (acoustically soft ground and noise walls) but do not include all features in TNM.

The majority of TNM users model sites with acoustically soft ground and barriers; however, sites that include acoustically hard ground, rows of buildings, dense foliage, or other features are also prevalent and are modeled by many users. As TNM users acquaint themselves with the program, some compare their findings with the previous FHWA noise model (Stamina [Barry 1978]) and associated measurements; some users have expressed interest in the results of other TNM studies. Because of the substantial impact TNM will have on the highway noise community as a replacement for Stamina and in light of the Government resources already invested in TNM, a single, cohesive reference (or set of references) which quantifies the accuracy of all components of TNM is necessary.

1.2 Objective of Overall Study

The objective of the study is to quantify and assess the accuracy of FHWA's TNM. For the purpose of comparison to the model, field measurements are performed at various sites around the country. These measurement sites are selected to embody the features available within TNM, with features such as acoustically soft and hard ground, various terrain geometries, various barrier geometries, rows of buildings, and dense foliage. The sites / measurements also incorporate features that may be important to further development of TNM, such as meteorological factors (wind, temperature, etc.). All measurements are performed by Volpe Center staff using a consistent measurement methodology at each site.

In addition to the measurements, TNM modeling of each site is performed. The Volpe Center staff, and other organizations around the country, perform the TNM modeling. In addition, there is a controlled evaluation of the measured / TNM data comparisons by Volpe Center staff. This evaluation includes processing both the measured and TNM-predicted data in specified time intervals and calculating the difference between the two as a function of several variables. With involvement from other organizations, the Volpe Center will examine dissimilarities in TNM modeling techniques and their effects on the sound levels.

A comprehensive study of the accuracy of TNM entails performing sound level measurements and doing TNM modeling at many sites. The number of sites required reflects the incorporation of numerous TNM features, either isolated or grouped with other TNM features. This large task is more manageable divided into multiple phases; in this manner, interim results are available to TNM users. The priority lies in evaluating sites similar to those most commonly modeled by TNM users, the related measurements and modeling composing the first phase of the study. This report addresses the first of multiple phases of the TNM Validation Study.

1.3 Objective of TNM Validation: Phase 1

The objective of Phase 1 of the TNM Validation Study was to assess the accuracy of FHWA's Traffic Noise Model (TNM) for sites that include:

— acoustically soft ground {e.g., field grass [effective flow resistivity (F) . 150 cgs Rayls] or lawn [F . 300 cgs Rayls]} with an open area (i.e., no structures or dense foliage) and various degrees of undulating terrain;

— acoustically soft ground with noise barriers (wall or berm); and

— acoustically hard ground [e.g., pavement or water (F . 20,000 cgs Rayls)] with an open area.

Subsequent phases of the study will include similar sites to expand on the knowledge gained through Phase 1. These phases may also include less commonly modeled TNM features such as dense foliage or rows of buildings and, if needed, future TNM features.

1.4 Report Contents

This document contains: background and objectives of the study (Section 1), measurement sites (Section 2), instrumentation (Section 3), field measurement procedures (Section 4), data reduction and analysis (Section 5), results (Sections 6 through 8), conclusions (Section 9), references (Section 10), research team members and responsibilities (Appendix A), measurement site details (Appendix B), an acoustical instrumentation systems reference (Appendix C), sample data log sheets (Appendix D), request information for the electronic files of the measured sound level data and the TNM input data on a CD ROM (Appendix E), graphs comparing TNM-predicted and measured sound levels where the data for all wind conditions (initial data) are included (Appendix F), and graphs comparing TNM-predicted and measured sound levels where the data under strong wind conditions (refined data) are removed (Appendix G).

The results, including the graphics, are presented in several formats: direct comparisons of TNM-predicted and measured data, average differences (TNM minus measured) and standard deviation as a function of the distance of the receiver from the roadway or noise barrier and height of the receiver above the ground, differences (TNM minus measured) as a function of wind speed and direction, and differences (TNM minus measured) as a function of percentage of heavy trucks. Results using alternative TNM site configurations are also presented for some of the measurement sites, where recommendations on the use of TNM are offered.

2. MEASUREMENT SITES

Phase 1 of the TNM Validation study involved measuring and modeling 17 sites that were both measured and modeled. These sites were selected for the TNM features they exhibited and for the requirements necessary to obtain high quality acoustical data.

2.1 Site Requirements

Phase 1 measurement sites had characteristics of those most commonly modeled by TNM users and were relatively simplistic so as to isolate individual features of TNM. All sites for Phase 1 were either open areas (i.e., free from interfering objects, reflective or absorptive, in the sound propagation path) or featured a noise barrier (wall or berm).

All of the sites encompassed an expansive area free of large reflecting surfaces (other than intended noise barriers), such as parked vehicles, signboards, or buildings within 100 ft (~30 m) of either the highway traffic path or the microphones. The roadways were constructed from dense-graded asphaltic concrete (DGAC), Portland cement concrete (PCC), or open-graded asphaltic concrete (OGAC) (these are the three pavement-type choices within TNM). The roadways were free of extraneous material such as gravel and, in addition, exhibited constant-speed, free-flowing traffic.

The background noise level at each measurement site was low enough to enable the measurement of uncontaminated highway traffic noise levels; the site was not located near known noise sources, such as busy airports, construction sites, rail yards, or other heavily traveled roadways. Good engineering judgement was applied to determine if background noise levels were too high to obtain uncontaminated highway traffic noise data.[1] This judgement was made when choosing a measurement site and also during the measurements when logging potentially intrusive sounds (see Sections 3.4 and 4.2). As will be explained in Section 5.1, the

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[1]It is not feasible to measure background noise levels in a constant-flow highway traffic situation unless an "equivalent" neighborhood is found where the highway traffic noise is not dominant. It is known, however, that a sound source of interest is unaffected by background noise levels that are at least 10 dB lower than the source of interest [ANSI 1998].

intrusive sounds were further examined for potential contamination during the data analysis stage.

There were also site requirements concerning measurement feasibility. For example, receivers needed to be placed at multiple distances from the roadway or behind the noise barrier. These distances ranged from 50 ft (~15 m) to as far back as almost 1300 ft (~400 m), site permitting. The measurement staff required authorization to use the entire site area and physical access to all desired measurement locations. Also, the site and the surrounding area was required to be free of potential sources of electromagnetic interference (e.g., power substations, radio antennae, cell phone repeaters, and high tension lines) that could potentially contaminate the measured acoustical data.

2.2 Selection Process

The Volpe Center Acoustics Facility worked with local organizations in the site selection process in order to expedite the study. The Phase 1 sites were identified by Volpe Center staff in the New England area, Volpe Center staff with help from Harvey Knauer of Environmental Acoustics and Soren Pedersen of Catseye Services for some California sites, and multiple Caltrans personnel for other California sites. All organizations identified sites in conformance with Volpe's requirements. Volpe staff then reviewed the sites and provided final approval after inspection.

The identification process was based upon the requirements put forth in Section 2.1 and a checklist such as the one presented in Appendix D (Figure D.1 shows a blank checklist and Figure D.2 a completed sample checklist). Pertinent site information included the location, site geometry and features, measurement feasibility, and measurement approval from the property owner; sites were selected with all checklist elements in mind. When possible, a site plan was obtained from the property owners or local agencies; these site plans were of sufficient detail to facilitate accurate modeling within TNM. In addition to written details, video imagery of the actual site was collected to assist in the selection process; typically, video imagery showed the actual site and all pertinent surrounding areas.

2.3 Description of Measurement Sites

Phase 1 included 17 measurement sites. In the New England region, there were 4 sites in Massachusetts and 2 sites in Connecticut. On the West Coast, there were 6 sites in southern California and 5 sites in northern California. The types of sites were broken down as follows: 8 of the sites were open area with 4 of them being acoustically soft ground {e.g., field grass [effective flow resistivity (F) . 150 cgs Rayls] or lawn [F . 300 cgs Rayls]} and 4 being acoustically hard ground [e.g., pavement or water (F . 20,000 cgs Rayls)]; 9 of the sites included a barrier, with 7 of them being acoustically soft ground and 2 having a mix of acoustically hard and soft ground. The open area sites were mostly flat, although one had substantial undulations in the terrain. The barrier sites were mostly flat, although some had slight inclines and 2 had substantial drop-offs from the base of the barriers to the measurement areas. The microphone distances from the roadway ranged from 50 ft (~15 m) to approximately 1,300 ft (~400 m). Refer to Table 1 for a summary of each measurement site. Appendix B describes and shows photographs of each measurement site; in addition, TNM plan and profile views are presented.

Table 1. Phase 1, 17 Measurement Sites (see Appendix B for site details).

Site ID*	Location	Site Type								Microphone Distances (ft) d=dist from roadway bb=dist behind barrier
		open area	noise barrier	soft ground	hard ground	mixed ground	flat	with drop-off	undulating	
01MA	Rte 24 Taunton, MA	✓		✓			✓			d = 50, 100, 200
02MA	Rte 2 Acton, MA	✓		✓					✓	d = 50, 200, 400, 600
03MA	Rte 291 Springfield, MA	✓		✓			✓			d = 50, 200, 400, 800
04CT	Rte 84 East Hartford, CT		✓			✓	✓			bb = 56, 125, 200
05CA	Rte 71 Chino Hills, CA		✓	✓			✓			bb = 50, 100, 150
06CA	Rte 15 Wildomar, CA		✓	✓			✓	✓		bb = 55, 100, 200
08CA	Rte 91 Anaheim, CA		✓	✓			✓			bb = 50, 200, 300
09CA	Rte 71 Chino, CA		✓	✓			✓	✓		bb = 55, 100, 200
10CA-berm	Rte 15 Mira Loma, CA		✓	✓			✓			bb = 70, 110
10CA-open	Rte 15 Mira Loma, CA	✓		✓			✓			d = 98, 118, 158
11CA	Rte 237 Sunnyvale, CA		✓			✓	✓			bb = 50, 100, 300
12CA	Rte 680 San Ramon, CA		✓	✓			✓			bb = 50, 100, 200
13CA	Rte 37 Sonoma, CA	✓			✓		✓			d = 50, 900
14CA	Rte 880 Fremont, CA		✓	✓			✓			bb = 50, 100, 150
15CA	Rte 880 Oakland, CA	✓			✓		✓			d = 40, 100, 200, 400
16MA	Rte 90 Wayland, MA	✓			✓		✓			d = 78, 100, 150, 200
17CT	Rte 84 Stafford, CT	✓			✓		✓			d = 60, 1273
totals		8	9	11	4	2	16	2	1	

*Site 07CA is not included in Phase 1 of this study due to insufficient site survey data.

3. INSTRUMENTATION

This section discusses the instrumentation used for acoustics, meteorology, traffic analysis, and site survey, as well as auxiliary instrumentation which is used in the study. For those interested in further information, Appendix C presents detailed technical specifications for the acoustical measurement system.

3.1 Microphone System

The Brüel and Kjær (B&K) Model 4155 and 4189 microphones used in the current study are ½-inch pressure-response electret condenser microphones. Being pre-polarized, the microphone functions as a closed system with regard to humidity, thus eliminating the potential for condensation in high humidity situations. Additionally, B&K Model 2671 preamplifiers and Model WB 1372 power supplies were deployed at each site. A B&K Model 0237 3.5 in (9 cm) foam windscreen was placed atop each microphone to reduce the effects of wind-generated noise at the microphone diaphragm. Such reduction can effectively improve the signal-to-noise (S/N) ratio of sound measurements. (Pictures of the microphone system can be seen in Figure 1.)

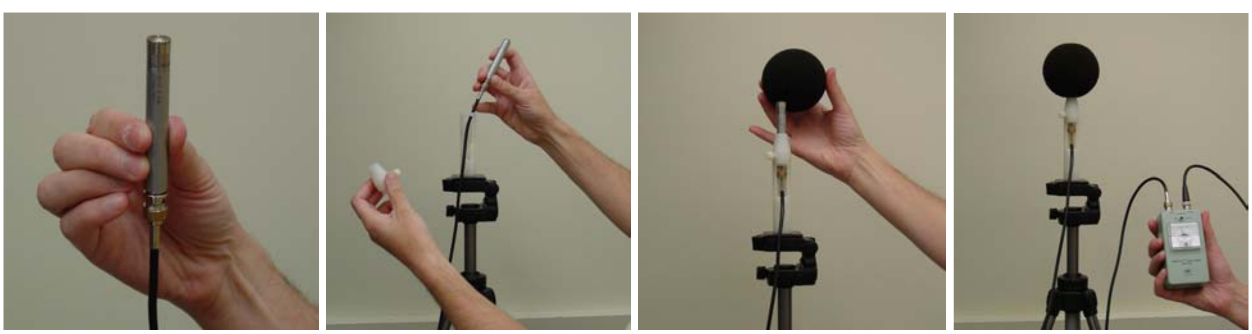


Figure 1. Microphone System.

3.2 Spectrum Analyzer

Up to eight microphone systems were connected via cable to Larson Davis Laboratories (LDL) Model 2900, two-channel, one-third octave-band analyzers (LDL 2900) set up at the acoustic observer's stations (Figure 2). Each channel of an LDL 2900 was configured to continuously measure the A-weighted equivalent sound level in 5-second periods (represented by the symbol L_{Aeq5s}), along with the associated 5-second time-averaged one-third octave-band spectrum. Multiple 5-second averaging periods were combined during analysis to obtain longer time periods. Configured for the 5-second averages, the LDL 2900 (with 4 MB of RAM) is capable of storing up to 36 hours of data. The data in the internal memory of the LDL 2900 were periodically transferred to a floppy disk for later off-line reduction and analysis (see Section 5). Volpe currently maintains four LDL 2900 analyzers, allowing for 8 simultaneous channels of data.

Figure 2. Two Spectrum Analyzers at Acoustic Observer's Station.

3.3 Sound Level Meter and Digital Audio Tape (DAT) Recorder

If necessary, additional microphone systems were deployed at a particular site through the use of LDL Model 820 sound level meters along with Sony Model TCD-D100 digital audio tape (DAT) recorders (Figure 3). The sound level meter was set up to continuously measure the overall A-weighted equivalent sound level in 5-second periods. As with the spectrum analyzer, multiple 5-second averaging periods were combined during analysis. At the end of a measurement day, the LDL 820 data were transferred to a laptop computer. The DAT recorder was also set up to record continuously throughout a measurement day. In "LP" (half-speed) mode, the tape duration is about 4 hours; multiple tapes were used during the day. Once completed, each tape was available for subsequent analysis, using an LDL 2900 to obtain one-third octave-band data.

Figure 3. Sound Level Meter and DAT Recorder Attached to Microphone System.

3.4 Incident Noise Log

It is essential to report sound levels due only to highway traffic noise and not to include levels that may have been contaminated by other noise sources. In order to ensure acoustically "clean" data, any incident noise was logged throughout a measurement day. A customized spreadsheet that implements automated keystroke functions on a Hewlett-Packard (HP) 200 LX palmtop computer (seen on table in Figure 2) was utilized to log the start and stop time and the description of any noise judged to be potentially intrusive to the highway traffic noise measurements (e.g., airplanes, lawn mowers, sirens, etc.). Application of the incident noise spreadsheet data to the overall analysis is discussed in Section 5.

3.5 Meteorological Instrumentation

In addition to the acoustical instrumentation, up to four Qualimetrics Transportable Automated Meteorological Stations (TAMS) were deployed. (Two TAMS units can be seen in Figure 4.) TAMS measured temperature, relative humidity, wind speed and direction, and ambient atmospheric pressure in 1-second time intervals. The data were captured in an HP 200 LX palmtop computer, where files were saved every 2 hours. At the end of a measurement day, the files were transferred to a laptop computer. It is intended that all phases of the validation effort include the collection of meteorological data in sufficient detail to aid in possible future incorporation of such effects into TNM.

Figure 4. Two Meteorological Systems.

3.6 Traffic Analysis Instrumentation

The instrumentation for analyzing the highway traffic included a video camera and an automated traffic detection system. Sony 8-mm or Hi-8 video cameras were deployed to continuously record the traffic; this recording was later processed to determine vehicle traffic counts, categorizations, and speeds. If an overpass was available near the measurement site, the video cameras were placed on the overpass to record all lanes of traffic from above (Figure 5); ideally, one camera for every three single-direction traffic lanes was deployed. When an overpass was not available, the video cameras were placed on the side of the highway at the highest point possible, recording the traffic from an angle. On standard play, each video tape provides up to two hours of recording time; multiple tapes were used for each camera throughout a measurement day.

Figure 5. Video Camera for Highway Traffic Data.

The traffic data were extracted from the video tapes using two methods: 1) manual analysis, including speeds that were determined using fixed reference points of known spacing (this is the only method applied when the recordings were made from the side of the highway as opposed to recordings made from and overpass); and 2) automated analysis using an Autoscope Model 2004 automated traffic detection system. The automated system requires configuration information based on fixed reference points of known spacing and the height of the cameras above the roadway surface.

3.7 Site Survey Instrumentation

A differential global positioning system (dGPS) was used to deliver the coordinates of all important site features; this included the microphone positions, roadway, zones of different ground types, and any substantial ground undulations. This dGPS system includes a base station and a roving unit (Figure 6), the two working together providing a relative, three-dimensional, position accuracy of ~8 in (20 cm) [Fleming 2001].

Figure 6. Differential GPS System: Base Station and Roving Unit.

3.8 Other Instrumentation

Calibration instrumentation was used in the field for establishing and checking the sensitivity of the entire acoustical instrumentation system (i.e., microphone, preamplifier, cables, spectrum analyzer, sound level meter, and DAT). There were three components involved in the calibration procedure: a B&K Model 4231 sound calibrator for absolute level calibration (produces a user-selectable 114 dB sound pressure level at a frequency of 1 kHz), an Ivie IE-20B pink noise generator for relative frequency response calibration, and a ½-inch microphone simulator for evaluation of the instrumentation noise floor and for onsite identification / troubleshooting of electromagnetic interference or other instrumentation problems.

For both technical and safety reasons, hand-held Motorola Radius GP300 FM radios were utilized for communication among all personnel. Also, a single digital watch served as the master clock for time synchronization of all instrumentation.

4. FIELD MEASUREMENT PROCEDURES

The wide variation in site geometries influenced the measurement system setup. Placement of the microphones and meteorological systems depended greatly on the presence of a noise barrier, terrain features, and accessibility. The measurement procedure at each site, however, was essentially the same. All data were collected and analyzed in general conformance with ANSI standards [ANSI 1995 and 1998] and FHWA's procedures [Lee 1996].

4.1 Measurement System Setup

A typical measurement team consisted of: (1) three or four acoustic personnel for instrumentation deployment and for operation of the acoustical and meteorological instrumentation during measurements; and (2) one or two individuals operating the highway traffic analysis instrumentation.

For the acoustical measurements, microphones were placed in a line perpendicular to the roadway at up to four distances from the center of the near travel lane for open area sites or from the center of the noise barrier for barrier sites. Site permitting, one of the positions was at 50 ft (~15 m), one at 200 ft (~60 m), and one at the farthest distance available; others were sometimes placed in between. Meteorological systems were placed at two locations in the microphone line: between the two closest microphone positions and between the two farthest microphone positions. To view example acoustical and meteorological instrumentation arrangements refer to Figure 7 for an open area site plan view, Figure 8 for an open area site profile, and Figure 9 for a barrier site profile. A step-by-step setup procedure follows the illustrations.

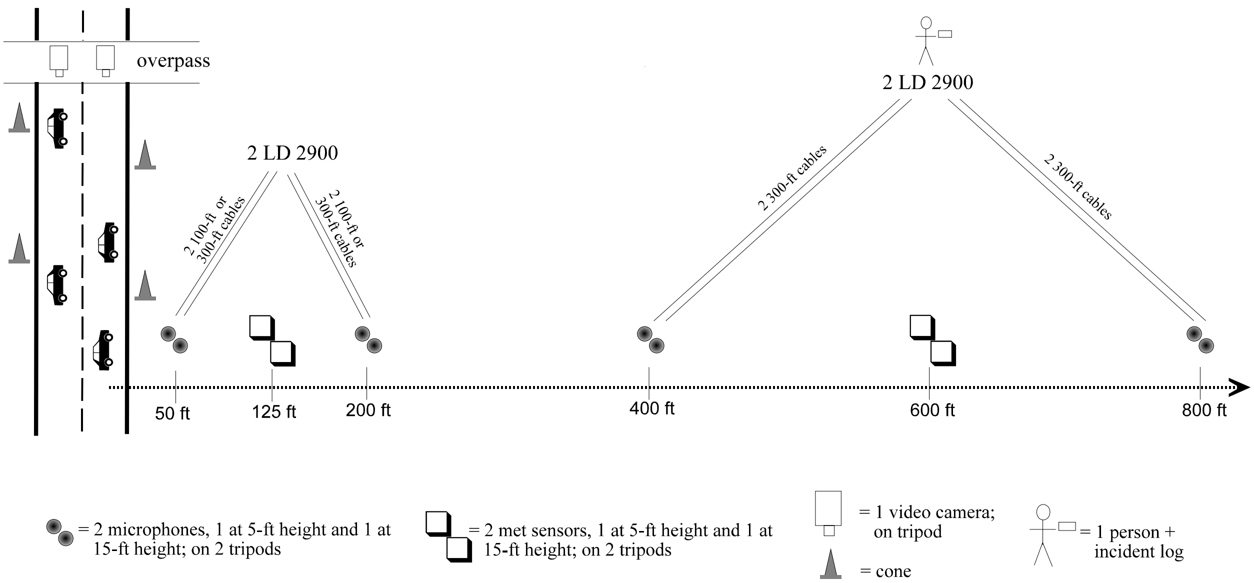


Figure 7. Example Instrumentation Setup for Open Area Site; Plan View.

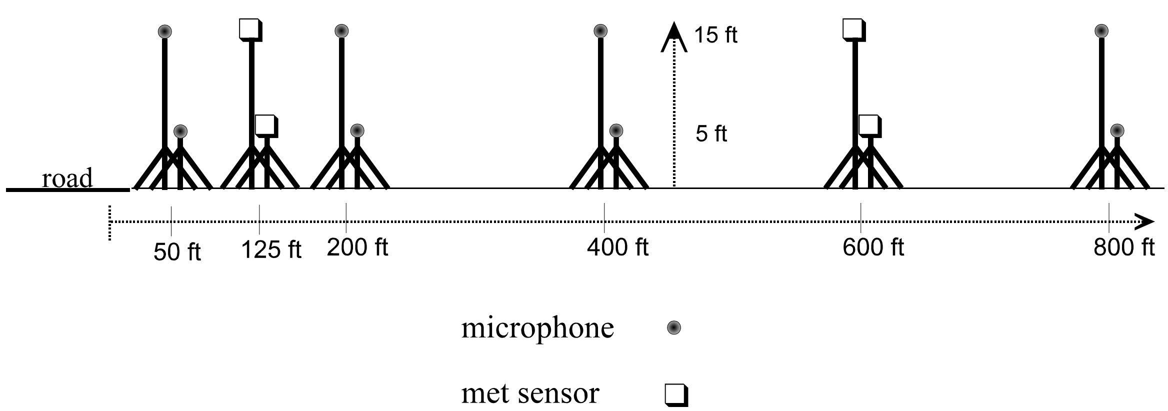


Figure 8. Example Instrumentation Setup for Open Area Site; Profile.

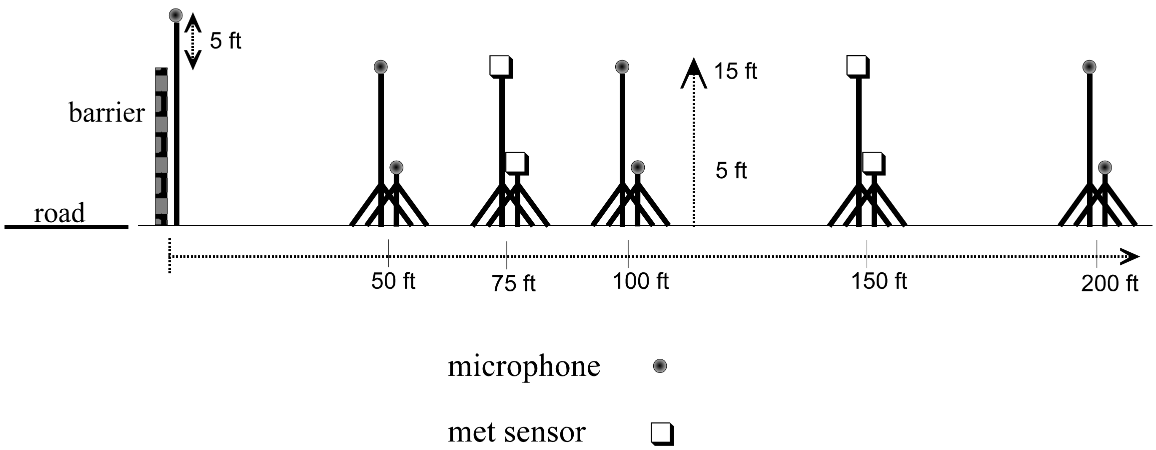


Figure 9. Example Instrumentation Setup for Barrier Site; Profile.

Following is a step-by-step description of the measurement system setup which took place upon arrival at each measurement site:

(1) For each site, microphone positions were predetermined and adjusted in the field as required by physical limitations. Where workable, a short length of rebar was driven into the ground at each position in order to secure tripods and masts.

(2) Each microphone system, including preamplifier and windscreen, was attached to a tripod or a tripod and mast which was positioned at the desired distance from the roadway or barrier. If used, mast arms were adjusted to locate the microphones at the specified heights directly above the local ground surface. Each microphone was oriented for grazing incidence to the expected line-of-sight between the highway traffic and the microphone. Typically, two microphones were deployed at each distance, at heights of 5 and 15 ft (1.5 m and 4.5 m) above the ground. For open area sites, the reference microphone position was at the 50-ft (~15-m) distance, or as close to that distance as possible; if there was an elevation change of more than a few feet from the roadway to

the 50-ft (~15-m) position or if site logistics did not permit two microphones, only one microphone was deployed at a height equivalent to 5 ft (1.5 m) above the roadway elevation. For barrier sites, a single reference microphone was placed at a height of 5 ft (1.5 m) above the top of the barrier or off to the side of the barrier at a height of 5 ft (1.5 m) above the ground; the latter position was used at sites where an open area beyond the end of the barrier (having identical traffic) was available (at Sites 04CT and 10CA-berm).

(3) The spectrum analyzers and, if applicable, the sound level meters and DATs, and acoustic observer were positioned in full view of all microphones but at a sufficient distance [100 ft (~30 m) or more] so as to eliminate the potential for data contamination due to observer activity.

(4) The meteorological stations were positioned at locations between the microphone locations, the positions representative of the meteorological conditions at the nearby microphones. Each meteorological station was placed at a sufficient distance from each microphone location so as to allow personnel to make periodic checks of meteorological system functionality and power supply status without influencing the acoustical measurements. At each position, the meteorological sensors were placed at heights of 5 and 15 ft (1.5 and 4.5 m) directly above the local ground surface.

(5) At least 100 ft (~30 m) of cable was connected between the instrumentation at the microphone location and the observer location (in order to avoid acoustical contamination from observer activity), and all instrumentation was then powered up.

(6) The clocks of all pertinent instrumentation (spectrum analyzers, sound level meters, DAT recorders, meteorological systems, video cameras, etc.) were synchronized.

(7) With all electrical components of the acoustical measurement system connected and activated, a preliminary sound level calibration of the system was performed. The purpose of the preliminary calibration was to ensure that all equipment was operating properly.

(8) The frequency response characteristics of the acoustical measurement system were also determined by measuring and storing 30 seconds of pink noise from a generator inserted at the preamplifier input.

(9) The electronic noise floor of the entire system, absent of the microphone, was then established using a non-transducive (i.e., mechanically passive) capacitive load (a microphone simulator replacing the microphone).

(10) After re-installation of the microphone, a pre-measurement sound level calibration of the system was performed.

(11) The windscreen was then deployed and the preamplifier cable secured to the mast and the leg of the tripod, so as to prevent vibration and audible interference. The measurement mast was then positioned upright, and tripods and/or masts were secured to the rebar anchor to ensure stability. Where use of rebar was not practical, sand bags were attached. (Figure 10 shows the microphone and meteorological system line at one of the measurement sites.)

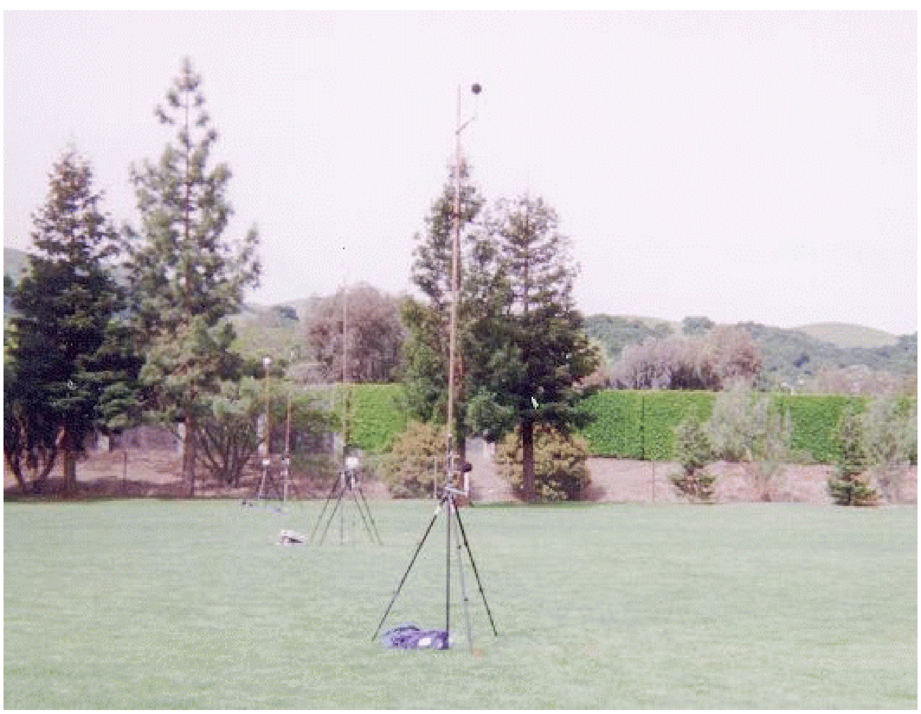


Figure 10. Line of Microphones and Meteorological Systems at Site 12CA.

(12) Each video camera was ideally positioned nearby on an accessible highway overpass or over-the-highway walking bridge and set to record all lanes of traffic in a single-direction. If an overpass or other permanent structure was not available, the video equipment was placed on the side of the highway at the highest point possible (e.g., on a sign or hillside) as to allow a clear image of all applicable traffic lanes. Reference points of known spacing were identified in each camera's view; if fixed, identifiable objects were not available, orange traffic cones were placed in the shoulders of the roadway to serve as the reference points.

(13) Continuous meteorological data collection was then initiated.

(14) Highway traffic sound level measurements with the spectrum analyzers and, where applicable, the sound level meters and DAT recorders were initiated.

(15) Continuous video recordings were initiated.

4.2 Measurements

Once the acquisition of acoustical, meteorological, and traffic data was initiated, the primary function of field personnel was to document any extraordinary acoustical occurrences in the vicinity of the measurement microphones (e.g., potential contamination due to other roadway vehicle pass-bys or aircraft overflights) or the roadway of interest (e.g., excessive congestion or traffic accidents). The incident noise log spreadsheet on the HP 200 LX palmtop computer was used for the documentation. In addition, acoustical system logs and a general site log were filled in; the acoustical system logs were also used during calibration. These paper logs (as seen in Appendix D, Figures D.3, D.4, and D.5) were used to document the locations of all instrumentation and the times and instrumentation settings for an event (calibration, data collection, etc.). All instrumentation operated continuously during two-hour time intervals; for most measurement sites, a total of 6 hours of data was collected.

Throughout measurements, periodic checks were performed on the acoustical and meteorological instrumentation for the following: available battery power, remaining internal memory for devices with internal data storage, and remaining tape in the case of the DAT recorder and video camera. Battery power typically provided at least 12 hours of continuous operation for each instrument except the DAT recorder, which lasted for up to 7 hours on lithium batteries, but was checked at regular intervals after 4 hours of operation. As far as internal memory, although the LDL 2900 is capable of storing 36 hours of 5-second samples (well over the six hours obtained in a typical measurement day), a new data file was initiated every 2 hours in order to facilitate easy transfer to a diskette and to secure the data. If DAT recorders were used, the tapes were replaced once during the 6 hours (1 tape can hold up to 4 hours of data). For reasons of data security and organization, new files were started every 2 hours for the meteorological systems. Also, the tape in the video recorder was replaced every 2 hours; this ensured data security and an image quality necessary for processing with the automated traffic detection system.

4.3 Measurement System Dismantling

Following is a step-by-step description of the system dismantling which took place upon completion of measurements:

(1) A post-measurement sound level calibration of the entire acoustical system was performed and, if present, any drift from the previous calibration was documented.

(2) All instrumentation was powered down and the entire system disconnected and stored.

Prior to data reduction and analysis (see Section 5), the stored sound level data from all spectrum analyzers (and any sound level meters) were transferred to a laptop computer and the LDL binary files converted to comma-delimited ASCII text files. The meteorological data were saved in a comma-delimited ASCII text file. Backup copies of all data files were made daily.

4.4 Surveying Measurement Sites

In addition to performing highway traffic noise measurements, each measurement site was surveyed in order to obtain three-dimensional position information for all important site features.

Differential GPS measurements were usually performed prior to acoustical measurements in order to avoid data contamination due to additional activity; in many cases, the dGPS system was used to locate the desired microphone and meteorological positions, especially when site features interfered with the proper use of a tape measure. The roving unit of the dGPS instrumentation was used to measure a line alongside the roadway, outline the measurement site, measure the microphone line, outline any differing ground type areas, outline any interfering structures / foliage, measure lines along any noise barriers, and measure lines along any substantial ground undulations. Typically, 4 hours were necessary to do a complete survey for a single measurement site.

5. DATA REDUCTION AND ANALYSIS

As previously stated, the objective of the overall TNM Validation Study is to quantify and assess the accuracy of TNM. The final step of the validation process for Phase 1 involved data reduction and analysis, resulting in the determination of TNM's accuracy. After processing the measurement data and performing the associated TNM analysis for each measurement period at each site, the measurement data and TNM predictions were compared. The differences were calculated as functions of several variables.

5.1 Processing of Measured Data

The acoustical data, meteorological data, and incident log data were merged into a spreadsheet file using a computer program, named tnmval.exe (09/11/2000 version), developed by Volpe specifically for this study. In addition to the three data files, an input file is also required to run tnmval.exe; this file contains site information (e.g., site ID, microphone locations, etc.), a specified time block for data output (e.g., 5-minute averages), and the names of the input data files, among other items. For the acoustical data, the input data files can be in either the LDL 2900 spectrum analyzer format or the LDL 820 sound level meter format. Although Phase 1 of this study focused only on the overall sound levels, essential DAT recordings (ones from the reference microphone positions) were processed with the LDL 2900 offline in order to obtain detailed one-third octave-band acoustical data files for the input.

Initially, a 5-minute averaging period was chosen for the data output. Comma-delimited output files were read into a spreadsheet program where each data block time was viewed along with the corresponding 5-minute A-weighted equivalent sound level (L_{Aeq5m}), average wind speed and direction, and average temperature. (The processed 5-minute data blocks for each site can be found in spreadsheet format on the CD ROM referred to in Appendix E.) In addition, 4 different qualifiers were attached to each block:

(1) an indication of the quality of the data according to incident noise ("good" for no incident noise during the 5-minute block; "incident noise" for a block that experienced incident noise, but the noise was found to be nonintrusive; and "bad" for a block in which the

incident noise contaminated the highway traffic noise data – sound levels during the data block with incident noise exceeded the average of the sound levels 30 s before and after of "good" data by 3 dB);

(2) an indication of an overload in the measured data;

(3) an indication of the wind quality ["calm" for speeds never exceeding ~2 mph (1 m/s); "windy" for winds exceeding ~2 mph (1 m/s) any time during the 5-minute block, but did not exceed ~11 mph (5 m/s); and "very windy" for winds exceeding ~11 mph (5 m/s) any time during the block]; and

(4) an indication of the wind direction along the axis perpendicular to the highway ["calm" if the perpendicular wind component never exceeded ~2 mph (1 m/s); "upwind" if that wind component exceeded ~2 mph (1 m/s) and the wind was blowing in the direction from the receiver to the roadway; and "downwind" if that wind component exceeded ~2 mph (1 m/s) and the wind was blowing in the direction from the roadway to the receiver].

The wind qualifications were specified according to current ANSI specifications [ANSI 1998]. The 5-minute data block initially chosen provided a short enough time interval to expose contamination and to adequately represent the wind conditions.

Although 5-minute data blocks were found to be appropriate for the initial analysis of the data, longer data blocks were found to be more appropriate for final analysis and presentation. Fifteen-minute data blocks were selected to represent the final data; a detailed explanation of the time selected is explained in Section 5.4. Combining the 5-minute data blocks into 15-minute data blocks was accomplished by converting the sound levels of three 5-minute data blocks to energy, averaging the acoustical energy of three 5-minute blocks, then converting the average energy to the 15-minute sound level (L_{Aeq15m}). For these 15-minute data blocks, all blocks that had any contamination due to incident noise ("bad") or were overloaded were discarded. For 14 of the 17 sites, the 15-minute blocks were constructed from consecutive 5-minute data blocks.

TNM currently calculates sound levels for a windless environment. Because typical measurement sites can have varying wind conditions, it was useful to determine how well TNM was performing under its self-prescribed wind environment. As such, the data were processed in two distinct ways according to the wind speed, and the resultant data will be displayed and discussed separately. The two processing methods were: 1) no data blocks were discarded due to wind conditions (this data set is referred to as the all-wind data); and 2) any data blocks that at any time achieved a "very windy" condition were removed (this data set is referred to as the strong-wind-removed data). The process was assumed to eliminate data subjected to severe refraction and/or possible turbulence. It was also assumed that the removal of data characterized as "very windy" [winds exceeding ~11 mph (5 m/s)] eliminated any data that may have been contaminated by wind noise at the microphone. Although the highway traffic noise measurements performed during "very windy" conditions were most likely not contaminated by the wind, the possibility existed. Examining the data in both ways (with and without the strong wind) provided a better understanding of which data blocks may have been contaminated and allowed for the maximum number of data points to be analyzed in order to identify trends.

The site survey and traffic data were also processed. In order to obtain a three-dimensional map of a measurement site, key features in the dGPS files were extracted and identified. (The traffic and site survey data for each site can be found in spreadsheet format on the CD ROM referred to in Appendix E.) An example of the processed site survey data is seen in Figure 11. This figure shows the coordinates of the important site features along with the elevations for Site 06CA, which serves as direct input to TNM. (A photograph of Site 06CA appears in Appendix B.)

Also for input to TNM, the video traffic data were analyzed in 5-minute blocks. Using both manual counts and the automated traffic detection system, data extracted from the video tapes supplied vehicle categories, volumes, and speeds for each lane of traffic. The five vehicle categories were: automobiles, medium trucks, heavy trucks, buses, and motorcycles. The number of vehicles for each of these categories was counted, where the 5-minute totals were scaled to vehicles per hour for TNM input. Average speeds were obtained from the automated system and supplemented with the manual data, and were then applied to all present vehicle types for that data block.

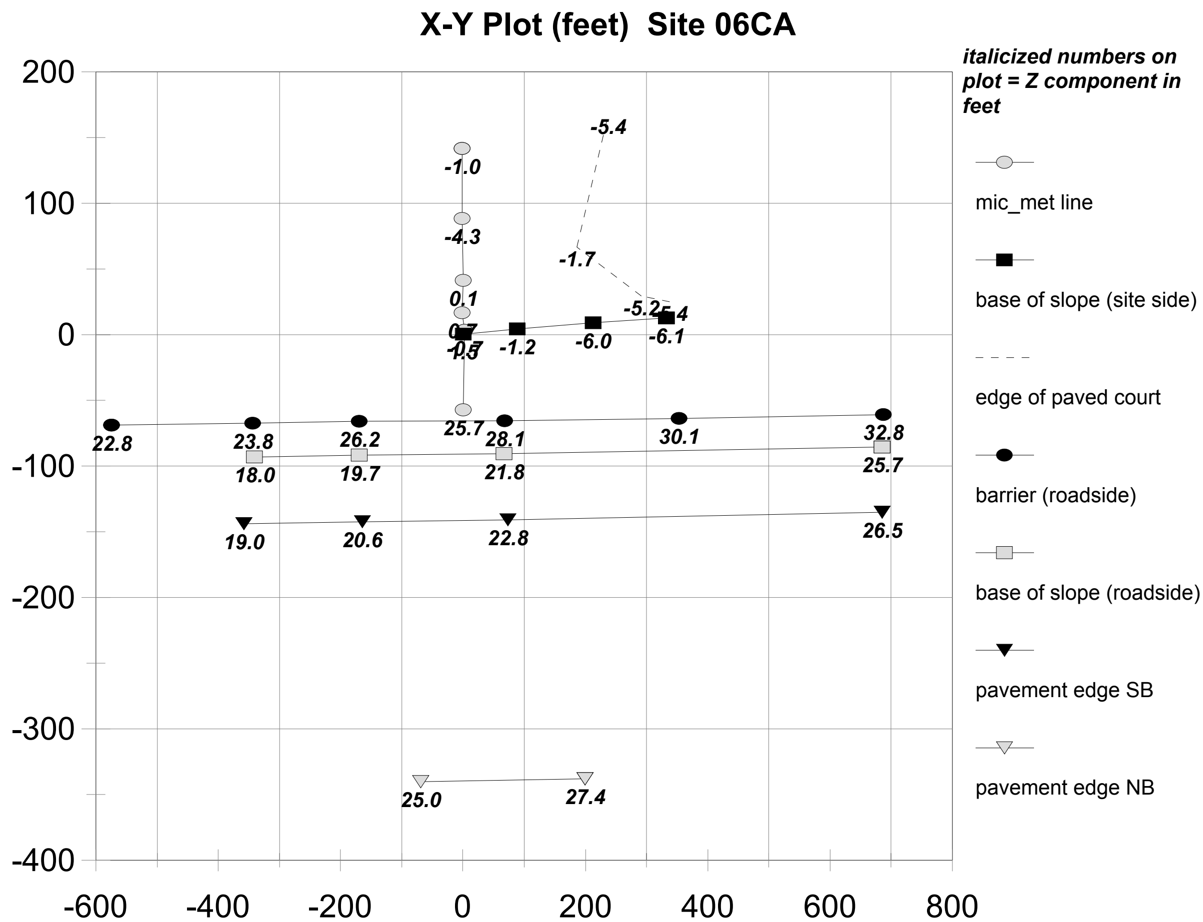


Figure 11. Processed Site Survey Data for Site 06CA.

5.2 TNM Analysis

In setting up a TNM run, the site name was identified and English units were selected. The input objects were taken directly from the site survey map and maps drawn during site scoping and measurements. Each lane for the highway and any paved shoulder or median was entered as a separate roadway, where the average pavement type (the default) was applied. Then each barrier was entered, along with the receivers. Also, any meaningful terrain lines and ground zones were added; good engineering judgement was used to determine the potential impact of these objects on the predicted sound levels, where trivial objects were ignored in order to maintain simplicity.[2] All of this together served as the base case for a particular site. TNM plan views and skew (profile) views for each site are seen in Appendix B, along with descriptions of TNM objects and the version of TNM used for the calculations.

Once a TNM base case was completed for a particular site, a new run was created for each 5-minute data block. This amounted to as many as 70 TNM runs for each measurement site. For each 5-minute period, the corresponding traffic data (scaled from 5 minutes to 1 hour), temperature, and relative humidity were entered. All runs were then calculated, resulting in an hourly, A-weighted, equivalent sound level (L_{Aeq1h}) for each data block. The TNM-predicted sound levels were then imported into the existing spreadsheets for comparison to the measured data. As with the measured acoustical data, the 5-minute data blocks were logarithmically combined into 15-minute data blocks for final presentation.

It should be noted that all input data for the TNM runs was very detailed, more so than would be for typical use of the software. Because of precise measurements, exact site survey information along with traffic data and meteorological data were available for input when creating each TNM run. In comparing TNM-predicted sound levels to measured sound levels, this represents a quantification of TNM's accuracy assuming the best available input data. Other TNM users may not have detailed input for TNM. For example, average daily traffic is often used for the traffic input and the default temperature and humidity are often applied; detailed site plans are sometimes available to users, but sometimes estimations are made of terrain features or object

[2]See Appendix B for site details. In general, ground undulations of 2 ft (0.6 m) or more were included; elevation changes 2 ft (0.6 m) or less were ignored, unless the difference affected the propagation path length over the top of a noise barrier and/or shifted any receiver in or out of the line-of-site of the highway traffic sources; and ground zones with any dimension less than 10 ft (3.0 m) were ignored.

locations. Differences in TNM output related to user methodology needs further investigation, which is planned for Phase 2 of the TNM Validation Study.

5.3 Comparison of Measured Data and TNM Predictions

At this point, the measured and predicted sound levels for a particular site were available in a spreadsheet for further analysis. As a first step, the data sets were processed in two ways: (1) the TNM-predicted sound levels were calibrated to the measured sound levels so as to make a direct comparison of measured sound propagation and TNM-predicted sound propagation; and (2) the TNM-predicted sound levels were not calibrated to the measured sound levels so as to add another level of comparison, comparing measurements and predictions with possibly slightly different sound source characteristics. The TNM database incorporates emission levels averaged over 40 nationwide sites, whereas the measurements included site-specific emissions. Although this report concentrates primarily on the calibrated data (Item 1 above; results seen in Sections 7 and 8), some results are presented for the uncalibrated data (Item 2 above; results seen in Section 6).

The calibration was accomplished using the reference microphone at each site. As a reminder, the reference microphone was located at a distance of 50 ft (~15 m) (or as close to that as possible) from the center line of the near travel lane and 5 ft (1.5 m) above the roadway elevation for an open area site. For a barrier site, it was approximately 5 ft (1.5 m) above the top of the barrier or off to the side of the barrier 5 ft (1.5 m) above the roadway elevation. The difference between the measured sound level at the reference microphone and the predicted sound level at the same position was calculated for each data block (for each 15 minutes for the final analysis). This calibration difference was then applied to the predicted sound levels at all other microphones.

Differences in the calibrated and uncalibrated TNM predictions and measured data were examined as functions of several variables. To start, the differences were calculated as a function of distance from the roadway or barrier and the height of the receiver above the ground. Next, they were calculated as a function of wind, considering both the overall wind speed and the wind direction along the axis perpendicular to the highway. The differences were then calculated as a function of the percentage of heavy trucks. Analyzing this information resulted in the determination of the accuracy of TNM in association with each chosen parameter. It is anticipated that other variables will be incorporated into the comparisons for Phase 2 of the study. In addition to examining the differences between the TNM predictions and measured data, a direct comparison was made between the two sets of data (plots showing TNM vs measured). A further distinction was made by presenting the data in terms of site type (e.g., open area acoustically soft ground, open area acoustically hard ground, and barrier).

The direct comparisons of TNM-predicted sound levels and measured sound levels and the differences as a function of several variables were calculated for two sets of data as described in Section 5.1. Again, the two sets correspond to these two conditions: 1) data for all wind conditions were included (all-wind data; presented in the initial results section, Section7); and 2) data collected during strong wind conditions [greater than ~11 mph (5 m/s)] were eliminated (strong-wind-removed data; presented in the refined results section, Section 8).

5.4 Choosing a Time Interval

Fifteen-minute data blocks were chosen for final data analysis and presentation. Although the initial analysis was in 5-minute data blocks, longer data blocks were found to be more appropriate for data stabilization. An analysis was conducted in order to determine the appropriate length of data block to present the data. Three data block lengths were explored, 15-minute, 30-minute, and 60-minute, where the 5-minute data blocks were logarithmically combined in order to obtain longer data blocks. This study was conducted prior to removal of data measured during high wind speeds.

Figures 12 and 13 show the results of the data block time length study. The vertical axis represents the standard deviation in decibels and the horizontal axis is the length of the data block in minutes. The standard deviation was arithmetically calculated for each set of data, where a set of data refers to all data blocks of a specific time length; the calculations were performed for each length of time for each of six sites.

Figure 12 shows the standard deviation from the average measured sound levels as a function of time block length for each of six sites. For all sites, it can be seen that the data show greater stabilization as the averaging time increases, although no benefit is seen at the 60-minute length. Three of the sites indicate full stabilization at the 15-minute length (i.e., Sites 06CA, 14CA, and 12CA) and two of the sites at the 30-minute length (i.e., Sites 16MA and 17CT); there was no 60-minute data for Site 10CA – the plot shows improvement with longer averaging times, but the stabilization point is unknown for Site 10CA. Figure 13 shows the standard deviation from the average differences in sound levels (TNM minus measured) as a function of time block length for each of the same six sites. For most of the sites, the data are stabilized at the 15-minute length.

It is seen in both figures that Site 10CA's standard deviation values are noticeably higher than the standard deviation values for the other sites. At this particular site, it appears that the wind played a major role in the variation of sound levels; once the strong winds were removed, the variation at the reference microphone dramatically decreased. For more information, please refer to Section 6.2 and Table 3.

The information provided in Figures 12 and 13 indicates that either a 15-minute or 30-minute length data block should be used in the final data analysis and presentation. The 30-minute data block offers the most conservative length in terms of presentation, but severely limits the number of data blocks. Because the 15-minute length offers substantial improvement in stabilization over the 5-minute data blocks (many of the sites indicate full stabilization at the 15-minute length), and an adequate number of data blocks can be obtained for each site, the 15-minute data blocks were applied to the results and will be seen in all data presentation graphics.

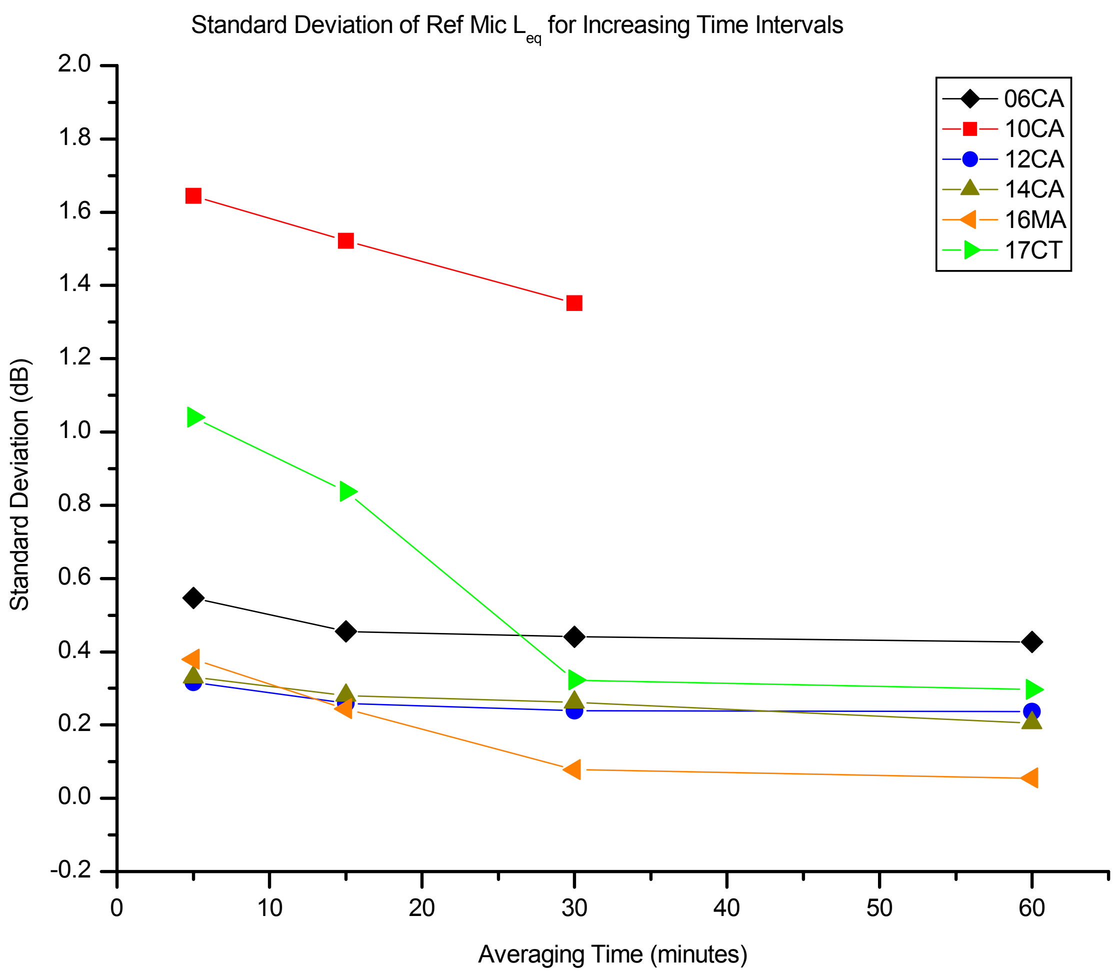


Figure 12. Standard Deviation for 5-, 15-, 30-, and 60-Minute Data Blocks; Measured Data.

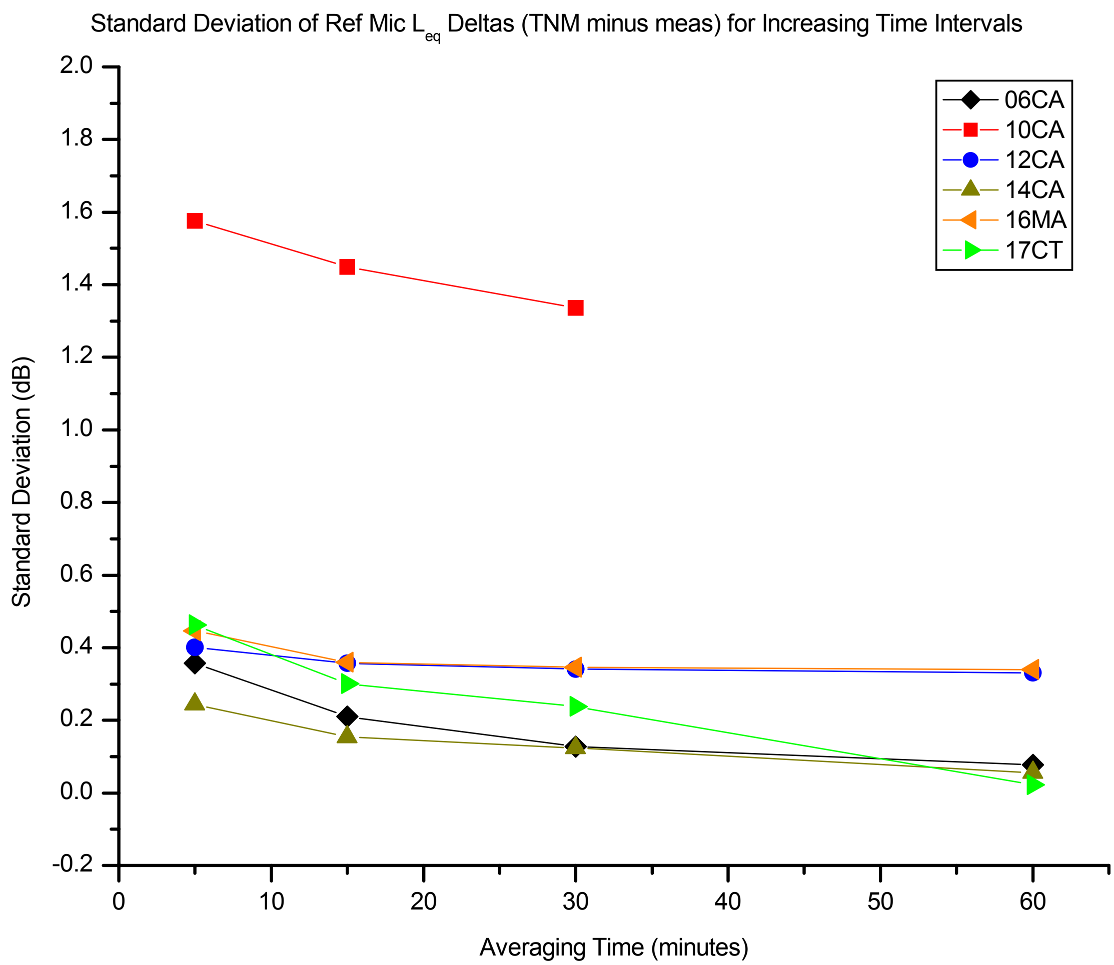


Figure 13. Standard Deviation for 5-, 15-, 30-, and 60-Minute Data Blocks; TNM Minus Measured Data.

6. UNCALIBRATED RESULTS AND DATA CALIBRATION

The results of the TNM Validation Study Phase 1 are presented first for the uncalibrated data. Although the calibrated data results are shown in terms of several variables (in Sections 7 and 8), the results for the uncalibrated data are presented only as a direct comparison between the TNM-predicted sound levels and the measured sound levels. Following the uncalibrated results is a discussion about calibrating the TNM-predicted data to the measured data, including a detailed description of the data calibration process.

For presentation, there are two sets of graphs: 1) the first set is in Appendix F (initial results) and shows results of data captured during all wind conditions (referred to as the all-wind data); and 2) the second set is in Appendix G (refined results) and shows results of data captured during limited wind conditions, where high wind speeds were removed [as described in Section 5.1; data captured during wind speeds exceeding ~11 mph (5 m/s) were removed; this data set is referred to as the strong-wind-removed data]. The uncalibrated and calibrated data are presented in the two appendices.

6.1 Direct Comparison of TNM-Predicted and Measured Sound Levels for the Uncalibrated Data

The first investigation of the results was simply to directly compare the TNM-predicted sound levels to the measured sound levels for the uncalibrated data. The two plots, one for all-wind data and one for the strong-wind-removed data, are presented in Figures F.1 and G.1, respectively. Because none of the data for this comparison included calibrating the TNM-predicted data to the measured data, site specific variables most likely influenced the accuracy of the predicted sound levels.

For a direct comparison (referring to Figures F.1 and G.1), the data are plotted with the horizontal axis being the measured sound levels and the vertical axis being the TNM-predicted sound levels. Each 15-minute data block (15-min L_{eq}) is represented as an orange X, where the number of data points is stated in the lower right corner of the figure. A dashed blue line represents the linear fit and solid green lines show the 95 percent confidence band. A solid black diagonal line symbolizes perfect agreement between TNM-predicted data and measured data. Data points that fall above (to the left of) this line indicate over-prediction and points that fall below (to the right of) this line indicate under-prediction. The text at the top of the figure indicates the type of site for which the data correspond.

In addition to the graphs found in Appendices F and G, Table 2 in this section gives numerical values corresponding to statistical elements of the graphs. In this table, the relation of the linear fit to the line of perfect agreement is examined along with the width of the 95 percent confidence band; values for five variables are stated across the columns. The first two variables concern the linear fit; values for both the average difference and the average of the absolute value of differences are stated. The first variable, the average difference, indicates how well TNM is performing over a broad range of sound levels, combining the over- and under-predictions. The second variable, the absolute value of differences, indicates how well TNM is performing as a function of the amplitude of the over- and under-predictions. This second variable can also indicate the consistency of over- or under-predictions for a range of sound levels. The third, fourth, and fifth variables in the table are the average, maximum, and minimum values of the 95 percent confidence band width, respectively. If all three values are small, and the maximum and minimum values are similar, this indicates that an average of the data shows little variation in amplitude over a broad range of sound levels; as such, a similar data set (sound levels measured and predicted under the same conditions) would provide similar results.

<u>Results</u>

The uncalibrated all-wind data for all sites indicate consistent over-prediction of 2.6 dB. The uncalibrated strong-wind-removed data for all sites also indicate consistent over-prediction of 2.6 dB. The 95 percent confidence band results show a narrower band for the all-wind data than the strong-wind-removed data.

Table 2. Direct Comparison of TNM-Predicted and Measured Data; Uncalibrated Data for All Sites; Statistical Data Corresponding to Figures F.1 (Appendix F) and G.1 (Appendix G).

Data restrictions based on wind speed	Differences of linear fit from perfect agreement (dB)		95% Confidence band width around linear fit (dB)		
	average difference	average of absolute value of differences	average	maximum	minimum
all-wind data	2.6	2.6	0.6	1.1	0.4
strong-wind-removed data	2.6	2.6	0.8	1.4	0.4

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

Discussion

> **The uncalibrated results (for directly comparing TNM-predicted and measured sound levels) indicate by the 2.6 dB offset that either TNM is over-predicting in its vehicle emissions or there are site-specific biases in the measured vehicle emissions (or a combination of both). This is discussed further in Section 6.2. Once the data are calibrated (as described in Section 6.2 and presented in Sections 7 and 8) this positive 2.6 dB offset, which is consistent for sound levels ranging from about 50 to 85 dB(A), is eliminated. In other words, TNM's propagation algorithms are performing quite well.**

The data with and without the wind removed show similar results, with some difference in the widths of the confidence bands. The confidence band widths are narrower for the all-wind data case, most likely because of the increased number of data points – it is more certain that the average of that type of data set would be in that range.

6.2 Data Calibration

After examining uncalibrated results, all data were calibrated to the reference microphone, as was described in Section 5.3. This calibration value (the difference between TNM-predicted sound levels and measured sound levels at the reference microphone; TNM-predicted minus measured) was calculated for each 15-minute data block then applied to all other receivers for that data block (calibration values were subtracted from the TNM-predicted sound levels). Table 3 shows the average calibration values and ranges of calibration values for each measurement site. All calibration values are shown for both the all-wind data and the strong-wind-removed data.

Table 3. Data Calibration Values by Site.

Site ID	Includes Data Measured during All Wind Conditions (all-wind data)		Includes Data Measured during All except Strong Wind Conditions (strong-wind-removed data)	
	average calibration (dB)	calibration range (dB)	average calibration (dB)	calibration range (dB)
01MA	4.6	2.8 to 5.9	3.9	2.8 to 4.5
02MA	6.7	5.6 to 8.0	7.1	7.0 to 7.3
03MA	1.5	1.3 to 2.0	1.5	1.3 to 2.0
04CT	0.3	-0.1 to 0.7	NA	NA
05CA	3.0	2.7 to 3.1	3.0	2.9 to 3.1
06CA	2.2	1.9 to 2.5	2.2	1.9 to 2.4
08CA	1.9	0.4 to 2.6	2.0	0.4 to 2.5
09CA	1.4	0.6 to 1.7	1.2	0.6 to 1.6
10CA-berm	7.2	6.2 to 9.5	6.6	6.2 to 6.9
10CA-open	7.7	6.2 to 9.5	6.5	6.2 to 6.9
11CA	2.6	1.9 to 3.0	1.7	1.2 to 2.5
12CA	2.4	2.1 to 2.8	2.4	2.1 to 2.8
13CA	1.4	0.6 to 2.5	1.7	1.4 to 1.9
14CA	2.4	2.0 to 2.8	2.4	2.0 to 2.6
15CA	5.5	4.2 to 6.0	6.2	6.0 to 6.3
16MA	4.1	3.1 to 4.6	4.4	4.3 to 4.5
17CT	4.2	3.5 to 4.7	4.2	3.5 to 4.7

Table 4 shows the average calibration values according to site type (all sites; open, acoustically soft ground sites; open, acoustically hard ground sites; barrier, acoustically soft ground sties; sites with the reference microphone in an open area; and sites with the reference microphone above the top of the barrier). All calibration values are shown for both the all-wind data and the strong-wind-removed data.

Table 4. Data Calibration Values by Site Type.

Site Type	Includes Data Measured during All Wind Conditions (all-wind data)	Includes Data Measured during All except Strong Wind Conditions (strong-wind-removed data)
	average calibration (dB)	average calibration (dB)
all	3.5	3.6
open area, soft ground	5.1	4.8
open area, hard ground	3.8	4.1
barrier, soft ground	2.6	2.7
ref mic in open	4.3	4.7
ref mic above barrier	2.3	2.1

The average calibration values by site, as listed in Table 3, range from 0.3 dB (Site 04CT) to 7.7 dB (Site 10CA-open) for the data during all wind conditions and 1.2 dB (Site 09CA) to 7.1 dB (Site 02MA) for the strong-wind-removed data; the averages of all the sites, as listed in Table 4, are 3.5 dB and 3.6 dB, respectively. When grouping into site types, it is seen (in Table 4) that the average calibration values are lower for the barrier sites than the open area sites, with the open area, soft ground sites having the highest average calibration values. Also, it is seen that sites where the reference microphone was placed above the top of a noise barrier have average calibrations values lower than sites where the reference microphone was placed in the open. It should be noted that some of the average calibration values increased for the case where the strong wind data were removed; in these cases, the wind may have beneficially influenced the measured sound levels. This is discussed further in Section 8.

Site Variation

It was statistically determined by HMMH and Caltrans [Anderson 1999] that there are ± 2.5 to 3.5 dB site-to-site differences in the TNM emissions; in extreme cases this represents 5.0 to 7.0 dB variability. This variability was calculated prior to controlling for measured site effects (e.g., pavement type). As an example of site effects, it is known that varying sound levels are produced by different pavement types [Fleming 1996] [Reyff 2001]. In general, tire/pavement noise is louder with older pavements and with denser pavements [in general, Portland Cement Concrete (PCC) produces louder sound levels than Dense-Graded Asphalt Concrete (DGAC) which produces louder sound levels than Open-Graded Asphalt Concrete (OGAC)]. All TNM runs were calculated using the "average" pavement option. So there was the potential for TNM to under-predict the sound levels for PCC sites, and to over-predict the sound levels for OGAC sites. Upon examining the calibration values in terms of pavement type, there were no immediately apparent trends; further investigation is planned for later phases of the study.

The pavement type is just one of the variables. Overall, as stated in Anderson 1999, "Because TNM does not account for this inherent variability, comparison of TNM computations with field measurements at a single measurement site might well disagree by this amount (± 2.5 to 3.5 dB), even if TNM's propagation algorithms are precisely correct." This may explain the variability of calibration values.

General Over-Prediction

Regardless of the variation discussed above, all average calibration values in Tables 3 and 4 are positive, indicating that TNM is over-predicting at the reference microphone location. This is the same trend as seen when directly comparing the TNM-predicted sound levels to the measured sound levels (Section 6.1) for all microphone locations. Again, either TNM is over-predicting in its vehicle emissions or there are site-specific biases in the measured vehicle emissions (or a combination of both). Although preliminary investigations have begun, there are no final conclusions as to what is causing the over-prediction; further investigation is planned for later phases of the study.

There is something to note about the traffic input in TNM. In processing 17 sites, it was found that the predicted levels produced by TNM are easily influenced by the speed assigned to the traffic. This is understandable if you look at the plot of the national emission levels as a function of speed for each vehicle type (found in Fleming 1996, Anderson 1998, and Menge 1998). For automobiles, the difference in level between 60 and 65 mph is several decibels; applied to hundreds of vehicles, this would make a substantial difference in predicted sound levels. The emission levels are very sensitive to speed. In the current study, great care was taken to input correct vehicle speeds for each 5-minute period of data; for most of the sites, the speeds were taken from the actual traffic during each 5-minute block. Other TNM users often use average daily traffic data for the roadway input. The potential for error based on vehicle speeds when using average daily traffic would be greater.

<u>Importance of Calibration</u>

The above discussions stress the importance of calibration. Regardless of the reason for over-prediction by TNM, it can be accounted for by taking measurements and applying a calibration value.

> **By calibrating to a reference microphone (within 100 ft from the roadway), more realistic predictions can be calculated at positions farther from the roadway, the location of residences. This calibration eliminates biases due to possible site-specific emission levels or possible over-predictions by TNM.**

In this study, each 15-minute calibration value is applied only to that 15-minute block of data; the single average calibration value presented for each site (in Table 3) was calculated strictly for presentation purposes. The typical TNM user would ultimately need a single site calibration value in order to apply it to a TNM run. In obtaining this calibration value, guidelines must be followed in order for it to be effective (description follows).

The range of calibration values shown in Table 3 reveals the variation one may sometimes encounter when comparing acoustically clean 15-minute blocks of measured and TNM-predicted data. As seen in Table 3, calibration values can vary widely for one site; applying only one of those calibration values would poorly represent the overall site calibration value. This stresses the importance of capturing data for more than just one 15-minute block at one time during the day.

Data Calibration for TNM Users

The approach for calibrating TNM to measured data depends on the state noise policy for the state of the highway project. Although each noise analyst should refer to their state noise policy, the following guidance gives examples of how to best use TNM for highway traffic sound level predictions.

In California, the Department of Transportation (Caltrans) gives specific guidance on calibrating a noise prediction model [Hendriks 1998]. Their calibration process is defined as follows: an adjustment is made to the calculated future noise levels by algebraically adding a calibration constant derived from the difference between measured and calculated noise levels at representative sites. The types of sites to which the calibration process is applied include highway widening projects, design of retrofit noise barriers, or other improvements that do not significantly change highway alignment or profile. Sound levels are measured at representative locations at a site during peak noise hour, in accordance with FHWA's measurement procedures [Lee 1996], and the site is modeled using exact site geometry and traffic input. The difference between measured and predicted sound levels is then calculated and applied to future sound levels, unless it is 1 dB or less; if the difference is 5 dB or greater, the measurements should be investigated. Please refer to the Caltrans document [Hendriks 1998] for further details.

In Florida, the Department of Transportation (FDOT) also gives specific guidance on calibrating a noise prediction model [Lindeman 2001]. FDOT takes a different approach than Caltrans. Field measurements are conducted along all existing or proposed roadway segments or links that may be affected by the resulting highway traffic noise. Sound levels are measured at a representative site during peak noise hour, in accordance with FHWA's measurement procedures [Lee 1996], and the site is modeled using exact site geometry and traffic input. A comparison is made between the predicted and measured sound levels; if the levels are within ± 3 dB of one another, this is considered an indication that the model is within an accepted level of accuracy. If the difference is greater than ± 3 dB, further investigation into the problem is required; this may require adjusting the model (improving modeling techniques) and/or repeated field measurements for verification, investigating until an acceptable difference is reached. Please refer to the FDOT document [Lindeman 2001] for further details.

Whatever the calibration process, it is important to apply good engineering judgement to the modeling and field measurements. Among other items, the placement of the microphone(s), site geometry, surrounding objects, extraneous noise, and highway traffic noise fluctuations must all be considered. Referring specifically to the sound level measurements, it is important to capture multiple samples of an appropriate length when measuring highway traffic sound levels. For highway noise measurements, guidance on the sample period to use and the number of samples to obtain can be found in the noise barrier standard [ANSI 1998] and FHWA's highway noise measurements report [Lee 1996]. Briefly summarizing, it is recommended to capture at least three acoustically clean samples (with six being preferred), where the sample length depends on the traffic flow; very steady traffic flow requires 5-minute acoustical averages and less steady traffic flow (but not sparse traffic) requires 15-minute acoustical averages.

7. INITIAL CALIBRATED RESULTS

The results of the TNM Validation Study Phase 1 are now presented for the initial calibrated data in terms of several variables. For the initial calibrated results, the data were calibrated using a reference microphone, as described in Section 6.2. Also, the data were processed according to Section 5, the case where data collected during all wind conditions (all-wind data) are retained. Strong wind data have not yet been eliminated; the results for data captured during limited wind conditions [data captured during wind speeds exceeding ~11 mph (5 m/s) were removed – referred to as the strong-wind-removed data] are presented in Section 8. Results for the calibrated all-wind data indicate how well TNM is computing sound propagation effects, accounting for such things as ground absorption and diffraction.

First, a direct comparison is made between the TNM-predicted sound levels and the measured sound levels (as was also shown for the uncalibrated data). The remaining results are presented in terms of the difference or delta between the TNM-predicted sound levels and measured sound levels as a function of a specific variable. The variables investigated are distance, height, and wind speed and direction. In addition to presenting all the data from all the sites as a whole, the data are also divided into three categories: open area, acoustically soft ground sites {e.g., field grass [effective flow resistivity (F) . 150 cgs Rayls] or lawn [F . 300 cgs Rayls]}; open area, acoustically hard ground sites [e.g., pavement or water (F . 20,000 cgs Rayls)]; and barrier, acoustically soft ground sites. This is done in order to reveal possible site-specific influences on the results. (Measurements for barrier; acoustically hard ground sites were not performed as part of the Phase 1 study; the barrier, acoustically soft ground sites will be referred to as just barrier sites for the remainder of this section.)

Plot and table descriptions that were detailed in Section 6 will be repeated in this section for convenience.

7.1 Direct Comparison of TNM-Predicted and Measured Sound Levels

The first investigation of the results was simply to directly compare the TNM-predicted sound levels to the measured sound levels, as with the uncalibrated results. For presentation, the set of graphs corresponding to the all-wind data results are seen in Figures F.2 through F.6 in Appendix F.

For a direct comparison, the data are plotted with the horizontal axis being the measured sound levels and the vertical axis being the TNM-predicted sound levels. Each 15-minute data block (15-min L_{eq}) is represented as an orange X, where the number of data points is stated in the lower right corner of the figure. A dashed blue line represents the linear fit and solid green lines show the 95 percent confidence band. A solid black diagonal line symbolizes perfect agreement between TNM-predicted data and measured data. Data points that fall above (to the left of) this line indicate over-prediction and points that fall below (to the right of) this line indicate under-prediction. The text at the top of the figure indicates the type of site for which the data correspond.

In addition to the graphs found in Appendix F, Table 5 in this section gives numerical values corresponding to the statistical elements of the graphs. In this table, the relation of the linear fit to the line of perfect agreement is examined along with the width of the 95 percent confidence band; values for five variables are stated across the columns. The first two variables concern the linear fit; values for both the average difference and the average of the absolute value of differences are stated. The first variable, the average difference, indicates how well TNM is performing over a broad range of sound levels, combining the over- and under-predictions. The second variable, the absolute value of differences, indicates how well TNM is performing as a function of the amplitude of the over- and under-predictions. This second variable can also indicate the consistency of over- or under-predictions for a range of sound levels. The third, fourth, and fifth variables in the table are the average, maximum, and minimum values of the 95 percent confidence band width, respectively. If all three values are small, and the maximum and minimum values are similar, this indicates that an average of the data shows little variation in amplitude over a broad range of sound levels; as such, a similar data set (sound levels measured and predicted under the same conditions) would provide similar results.

Results

The results are now presented for Appendix F (Figures F.2 through F.6) and Table 5, the data set representing all the wind conditions. The initial calibrated data for all sites (Figure F.2 and Table 5) show that TNM is in excellent agreement with the measured sound levels, the average difference being only -0.8 dB. There is only slight under-prediction across all sound levels, the confidence band width being very narrow, an average of 0.5 dB.

Table 5. Direct Comparison of TNM-Predicted and Measured Data; All Wind Data Included; Statistical Data Corresponding to Figures F.2-F.6 (Appendix F).

Site Type	Differences of Linear Fit from Perfect Agreement (dB)		95% Confidence Band Width around Linear Fit (dB)		
	average difference	average of absolute value of differences	average	maximum	minimum
all	-0.8	0.8	0.5	0.8	0.3
open area, soft ground	-0.3	0.3	1.0	1.5	0.6
open area, hard ground	0.6	1.6	0.5	0.9	0.3
near distances	-0.5	0.5	0.7	1.2	0.3
far distances	2.2	2.2	0.5	0.9	0.3
barrier, soft ground	-1.2	1.3	0.6	1.0	0.3

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

The results for the open area, acoustically soft ground sites (Figure F.3 and Table 5) indicate excellent agreement between predicted and measured data, with the average difference being -0.3 dB. There is very slight under-prediction at all sound levels with some variation, the average confidence band width being 1.0 dB, effectively rendering the -0.3 dB average difference statistically insignificant, i.e., there is no statistical difference between the predicted and measured values for the open area, acoustically soft ground sites.

For open area, acoustically hard ground sites, the data are first presented as a group (Figure F.4 and Table 5) then divided into far distance (lower sound levels) and near distance (higher sound levels) data (Figure F.5 and Table 5). As a group, a substantial skew is seen in the linear fit, where the average difference from perfect agreement is 0.6 dB. For near distances, the average difference for the linear fit is only -0.5 dB, with the average confidence band width being 0.7 dB; this indicates excellent agreement. For far distances, the average difference is 2.2 dB, with the average confidence band width being 0.5 dB; this indicates some over-prediction.

Lastly, for barrier sites (Figure F.6 and Table 5), results show good agreement, indicating an average under-prediction of -1.1 dB. The confidence band width is narrow, an average of 0.6 dB, over all sound levels.

Discussion

> **Overall, TNM is performing very well in a direct comparison to all acoustically clean[3] data collected, regardless of the wind condition. The average difference from perfect agreement is less than a decibel. In examining the performance by site type, TNM is performing very well for open area, acoustically soft ground sites; open area, acoustically hard ground sites at near distances; and barrier sites – all within an average of 0.3 to1.2 dB of perfect agreement. The only difference of concern arises for open area, acoustically hard ground sites at far distances [in these cases, beyond 900 ft (~275 m) from the roadway], where TNM is over-predicting an average of 2.2 dB. Please refer to Section 8.1 for a discussion on this over-prediction.**

[3]The highway traffic noise data are not contaminated by other noises. See Sections 3.4 and 5.1 for more details.

7.2 Differences in Sound Levels as a Function of Distance and Height

The second investigation of the results examined the average differences (TNM minus measured) and standard deviation as a function of the distance of the receiver from the roadway or noise barrier and height of the receiver above the ground. It is important to investigate these variables: multiple distances can help determine how far from the road TNM is valid; receiver height above the ground can help validate ground effects (the microphone closer to the ground should be more affected by the ground surface) and can help in examining a noise barrier's shadow zone. For presentation, the set of graphs corresponding to the all-wind data results as a function of distance and height are seen in Figures F.7 through F.12 and Tables F.1 through F.3 in Appendix F.

For these sets of graphs, the data are plotted with the horizontal axis being the distance from either the center of the near travel lane of the roadway or the barrier and the vertical axis being the average difference (TNM minus measured) in sound levels. Also shown vertically is the standard deviation of the data from the average values. A solid black horizontal line at a value of 0 dB for the average difference symbolizes perfect agreement between TNM-predicted data and measured data. Data above this line indicate over-prediction and data below this line indicate under-prediction. The text at the top of the figure indicates the type of site for which the data correspond, with the specific sites listed in the legend. The text also indicates if the data presented are for the 5-ft (1.5-m) height position or the 15-ft (4.5-m) height position. For the tables in Appendix F, values for the average difference in sound levels are presented along with the standard deviation for each microphone location at each site.

In addition to the graphs and tables found in Appendix F, the table in this section, Table 6, gives the values for the average difference in sound levels for each type of site (open area, soft ground; open area, hard ground; and barrier). The averages are given for ranges of distances from the highway or noise barrier; note that only some ranges of distances are covered for each type of site. The data are also divided by the two different heights (5 ft and 15 ft or 1.5 m and 4.5 m), where averages over all distances are given in the right hand column.

Table 6. Average Differences (TNM minus Measured) as a Function of Distance and Height; All Wind Data Included

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	0.1	1.1	no data	-0.1	-1.0	no data	0.3
	15	0.3	-1.6	no data	-0.5	-0.9	no data	-0.8
open area, hard ground	5	0.4	-0.1	no data	2.6	0.7	4.0	0.9
	15	-0.6	-0.4	no data	1.4	1.0	2.8	0.1
barrier, soft ground	5	-0.6	-1.7	-1.3	no data	no data	no data	-1.1
	15	-0.2	-1.1	-0.1	no data	no data	no data	-0.5

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

Results

The results are now presented for Appendix F (Figures F.7 through F.12 and Tables F.1 through F.3) and Table 6, the data set representing all wind conditions. The data for the open area, acoustically soft ground sites at the 5-ft (1.5-m) height location (Figure F.7 and Table F.1) show that the average differences between the TNM-predicted and measured sound levels for each position at each site are within about 2.0 dB, except for Site 02MA, where TNM is over-predicting by 2.7 dB at the 200-ft (~60-m) position and under-predicting by 2.5 dB at the 600-ft (~180-m) position. The average difference of all these sites is 0.3 dB (Table 6) and the standard deviations range from 0.3 to 1.5 dB. For the 15-ft (4.5-m) height locations (Figure F.8 and Table F.1) the average differences for each position at each site are within about 1.5 dB, except for Site 02MA, where TNM is under-predicting by 2.5 dB at the 600-ft (~180-m) position, and Site 10CA-open, where it is under-predicting by 4.1 and 3.7 dB. The average difference for all these sites is -0.8 dB (Table 6) and the standard deviations range from 0.1 to 1.5 dB. In examining the different ranges of distances (in Table 6), it is seen that there is no overall trend in variation as a function of distance; with height, the differences are generally less for the 5-ft (1.5-m) position, except in the 501- to 1000-ft (~150- to ~300-m) range, where the differences are about the same for the 5- and 15-ft (1.5- to 4.5-m) heights.

The data for the open area, acoustically hard ground sites at the 5-ft (1.5-m) height location (Figure F.9 and Table F.2) show that the average differences between the TNM-predicted and measured sound levels for each position at each site range from 0.0 to 4.0 dB, the larger differences generally tending to be at farther distances. The average difference for all these sites is 0.9 dB (Table 6) and the standard deviations range from 0.2 to 0.9 dB. For the 15-ft (4.5-m) height locations (Figure F.10 and Table F.2), the average differences for each position at each site are within 1.5 dB, except for Site 17CT, where TNM is over-predicting by 2.8 dB at the 1273-ft (~390-m) distance. The average difference for all these sites is 0.1 dB (Table 6) and the standard deviations range from 0.0 to 0.8 dB. In examining the different ranges of distances (in Table 6), it is seen that there is a trend in variation as a function of distance; farther distances show greater differences, although the differences in the 301- to 500-ft (~90- to ~150-m) range are larger than the 501- to 1000-ft (~150- to ~300-m) range differences. With height, the differences reveal no trend.

The data for the barrier sites at the 5-ft (1.5-m) height location (Figure F.11 and Table F.3) show that the average differences between the TNM-predicted and measured sound levels for each position at each site are within about 2.0 dB, except for Sites 04CT, 08CA, and 09CA, where TNM is under-predicting by about 2.5 to 4.0 dB at most positions. The average difference for all these sites is -1.1 dB (Table 6) and the standard deviations range from 0.2 to 2.7 dB. For the 15-ft (4.5-m) height locations (Figure F.12 and Table F.3) the average differences for each position at each site are within about 2.0 dB, except for Sites 04CT and 09CA, where TNM is under-predicting by about 2.0 to 4.0 dB at most positions. The average difference for all these sites is -0.5 dB (Table 6) and the standard deviations range from 0.2 to 2.0 dB. In examining the different ranges of distances (in Table 6), it is seen that there are no strong trends in variation as a function of distance or height for these sites, except that there is under-prediction in all cases.

Discussion

> **Where all data are included regardless of wind speed, the results (as a function of distance and height) indicate that the average difference between the TNM-predicted sound levels and the measured data is mostly within 1.5 to 2.0 dB, with several sites' differences being within 1.0 dB. The exceptions are few and occur only at some microphone positions for some sites; discussions regarding these sites will follow. Also, in examining the sites by type, the results do not show any strong trends due to the height of the receiver (microphone) or distance from the roadway, except for the open area, hard ground sites, where the tendency is toward larger differences between TNM-predicted data and measured data at the farther distances [greater than 300 ft (~90 m)].**

For the open area, acoustically soft ground sites 02MA and 10CA-open, some under- and over-predictions are observed. Please refer to the discussion in Section 8.2, after the strong-wind-removed data results are introduced, for further explanation. For the open area, acoustically hard ground sites 15CA and 17CT, the over-predictions seem to be distance dependent (greater with greater distance). For the barrier sites (04CT, 08CA, and 09CA), there are some under-predictions. Again, please refer to the discussion in Section 8.2 for further explanation.

7.3 Differences in Sound Levels as a Function of Wind Speed and Direction

The third investigation of the results for the all-wind data examined the differences (TNM minus measured) as a function of wind speed and direction. It is important to investigate TNM's performance in terms of wind variables since these are not accounted for in the model; under certain conditions, measured sound levels are affected by the wind, influencing the differences between TNM-predicted and measured sound levels. For presentation, the set of graphs corresponding to the all-wind data results as a function of wind speed and direction are seen in Figures F.13 through F.15 in Appendix F.

For these sets of graphs, the data are plotted with the horizontal axis being the wind speed and the vertical axis being the difference (TNM minus measured) in sound levels. Each data point represents a 15-minute data block (15-min L_{eq}) and is further categorized by wind direction. For characterization of wind direction, the wind component perpendicular to the roadway is specified; the three wind direction categories are up, down, and calm. "Up" signifies an upwind condition (wind blowing in the direction from the receiver to the roadway) at a speed greater than or equal to 2.2 mph (1 m/s); "Down" signifies a downwind condition (wind blowing in the direction from the roadway to the receiver) at a speed greater than or equal to 2.2 mph (1 m/s); and "Calm" signifies that the perpendicular wind component is less than 2.2 mph (1 m/s) in either direction. A solid black horizontal line at a value of 0 dB for the difference symbolizes perfect agreement between TNM-predicted data and measured data. Data above this line indicate over-prediction and data below this line indicate under-prediction. The text at the top of the figure indicates the type of site for which the data correspond, with the specific sites listed in the legend. It should be noted that fewer data points are available for this analysis than for that in Section 7.1 (also presenting 15-minute data blocks) because the wind had to be directionally consistent throughout the 15 minutes; otherwise, the data point was discarded.

In addition to the graphs found in Appendix F, Tables 7 through 9 in this section give numerical values corresponding to the graphs. In these tables grouped by site type, averages for the wind speed are presented for each site, along with the corresponding values for the average difference in sound levels categorized by wind direction. Also, overall averages are given at the bottom of each table for all sites combined. For the wind study, results are not presented as a function of microphone height above the ground; investigation is planned for later phases of the study.

<u>Results</u>

The results will now be described in the order they are presented graphically in Appendix F and in tables in this section. The data for the open area, acoustically soft ground sites (Figure F.13 and Table 7) show that, for the data as a group, there is no strong trend indicated. There is one site, however, that gives the indication of over-predictions for upwind conditions and under-predictions for downwind conditions; this is Site 02MA. Although Site 10CA has upwind data, it does not indicate a trend; it is seen that the wind speeds are high at this site – perhaps there are other effects influencing the results. Averages over each wind condition for all open area, soft ground sites show a -0.1-dB under-prediction for upwind conditions, a -0.4-dB under-prediction for downwind conditions, and a 0.4-dB over-prediction for calm conditions.

Table 7. Differences (TNM minus Measured) as a Function of Wind Speed and Direction; Open Area, Soft Ground Sites; All Wind Data Included

Site	Average Wind Speed (mph)	Average Sound Level Difference (dB)		
		for upwind conditions	for downwind conditions	for calm conditions
01MA	6.8	no data	0.7	-0.5
02MA	5.5	1.2	-1.5	0.7
03MA	2.3	no data	no data	0.8
10CA-open	9.4	-1.5	no data	no data
AVERAGES	6.0	-0.1	-0.4	0.4

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

Table 8. Differences (TNM minus Measured) as a Function of Wind Speed and Direction; Open Area, Hard Ground Sites; All Wind Data Included

Site	Average Wind Speed (mph)	Average Sound Level Difference (dB)		
		for upwind conditions	for downwind conditions	for calm conditions
13CA	9.6	-0.8	1.0	0.7
15CA	8.3	no data	0.9	no data
16MA	4.8	no data	-0.6	-1.4
17CT	0.8	no data	no data	3.3
AVERAGES	5.9	-0.8	0.4	0.9

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

The data for the open area, acoustically hard ground sites (Figure F.14 and Table 8) show that, for the data as a group, there is no strong trend indicated. The many downwind data points are showing over- and under-predictions and the two upwind data points (for Site 13CA) are showing under-predictions. Notice that the wind speeds at some of the sites are rather high – perhaps there are other effects influencing the results. Averages over each wind condition for all open area, hard ground sites show a -0.8-dB under-prediction for upwind conditions, a 0.4-dB over-prediction for downwind conditions, and a 0.9-dB over-prediction for calm conditions.

Table 9. Differences (TNM minus Measured) as a Function of Wind Speed and Direction; Barrier, Soft Ground Sites; All Wind Data Included

Site	Average Wind Speed (mph)	Average Sound Level Difference (dB)		
		for upwind conditions	for downwind conditions	for calm conditions
04CT	5.4	-1.8	no data	-2.2
05CA	5.1	0.0	no data	-0.3
06CA	3.2	1.4	no data	-0.2
08CA	5.2	no data	-3.7	-1.0
09CA	2.7	-3.1	-4.9	-3.4
10CA-berm	5.2	0.0	no data	1.8
11CA	7.2	0.4	no data	no data
12CA	2.7	no data	-0.3	-0.8
14CA	3.6	no data	-1.5	-0.1
AVERAGES	4.5	-0.5	-2.6	-0.8
Averages, shifting 09CA by +3 dB	4.5	0.0	-1.8	-0.4

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

The data for the barrier sites (Figure F.15 and Table 9) show that, for the data as a group, there is a trend indicating that upwind conditions may cause over-prediction by TNM and downwind conditions may cause under-prediction by TNM. Sites 06CA and 11CA show over-prediction in upwind conditions. Sites 08CA, 12CA, and 14CA show under-prediction in downwind conditions. Site 09CA, the only site with upwind, downwind, and calm conditions needs to be examined closely.

As stated earlier (referred to in Section 7.2, described in Section 8.2), Site 09CA shows differences offset in the negative direction. If the predicted 09CA data were to be shifted up 3.0 dB as an approximation to account for additive reflections (see Section 8.2), the data set would show the calm data differences being distributed around the zero line, the upwind differences indicating some under- and some over-predictions, and the downwind differences indicating under-predictions. Averages over each wind condition for all barrier sites show a -0.5-dB under-prediction for upwind conditions, a -2.6-dB under-prediction for downwind conditions, and a -0.8-dB under-prediction for calm conditions. Upon shifting the 09CA averages by positive 3.0 dB, the averages over each wind condition would show a perfect agreement for upwind conditions, a -1.8-dB under-prediction for downwind conditions, and a -0.4-dB under-prediction for calm conditions.

Discussion

> **For the data representative of all wind conditions, TNM's accuracy seems to be relatively independent of the wind (affected on average less than 0.5 dB) for the open area, soft ground sites; TNM-predicted sound levels are closer to the measured levels in downwind conditions (increasing the accuracy) because of other over-predictions for the open area, hard ground sites; and TNM's accuracy is dependent on the wind (affected on average up to 2.0 dB) for barrier sites.**

TNM's accuracy for certain cases *should* be dependent on wind conditions since the model calculates sound levels for a windless environment. In general, upwind conditions can lower the measured sound levels at the receiver position and downwind conditions can raise the measured sound levels at the receiver position, the effects being greater with higher wind speeds. Refraction caused by the wind can affect both soft-ground attenuation and barrier insertion loss

[Beranek 1992]. In addition, over hard ground sites, the sound can be channeled in downwind conditions (raising the received sound levels).

In examining the results as a function of wind, the open area, soft ground data overall indicate neutrality for upwind conditions and some under-prediction for downwind conditions. For Site 02MA, however, it is seen that there is some over-prediction for the upwind condition and some under-prediction for the downwind condition (possibly behaving more like a barrier site because of the large ground undulations). With soft ground sites there are some counteracting effects. Under upwind conditions, the sound can be refracted upward, away from the ground and the microphones (hence reducing the sound levels at the microphones) but would then be interacting less with the ground (hence decreasing the soft-ground attenuation and increasing the sound levels at the microphones). This may be why the overall results indicate that the accuracy of TNM for open area, soft ground sites is independent of wind.

In examining the results as a function of wind, the open area, hard ground data overall indicate some under-prediction for upwind conditions and some over-prediction for downwind conditions. Under upwind conditions, the sound can be refracted upward, away from the reflective hard ground and the microphones (hence reducing the sound levels at the microphones). Under downwind conditions, the sound can be refracted downward then reflected upward, channeling the sound (hence raising the sound levels at the microphones, especially over long distances). The results do not readily support this, although some explanation can be offered. For the downwind results, even though Table 8 indicates a 0.4 dB overall over-prediction and not an under-prediction as one would expect, it is important to recall results presented earlier in this section. TNM is tending to over-predict for farther positions at hard ground sites; these over-predictions may overpower the under-predictions from downwind effects, thereby merely lowering the over-predictions. For the upwind results, there are only two data points, under-predicted less than 1.0 dB; no explanation is offered for this. For hard ground sites, results do not indicate that the accuracy of TNM is very affected by the wind, but part of the non-effect is due to general over-prediction at hard ground sites; this is noted for investigation in later phases of the TNM Validation Study.

In examining the results as a function of wind, the barrier data overall indicate some over-prediction for upwind conditions and some under-prediction for downwind conditions. Many of the sites indicate this trend, especially the ones where upwind or downwind data, when compared to calm wind data, show a definite increase or decrease, respectively, from the calm wind results (Sites 06CA, 08CA, 09CA, and 14CA in Figure F.15). Referencing back to the distance and height data (Section 7.2), some of the under-predictions that were seen (Sites 08CA and 09CA) may be due to the wind. At noise barrier sites, under upwind conditions, the sound can be refracted upward, making the barrier more effective (hence reducing the sound levels at the microphones). Under downwind conditions, the sound can be refracted downward behind the barrier, making the barrier less effective (hence raising the sound levels at the microphones). Results from the barrier sites indicate that wind is a factor in TNM's ability to predict precisely accurate results. It is seen, however, that the average wind influence is less than 2.0 dB (less than 3.0 dB without adjusting Site 09CA); this is noted for investigation in later phases of the TNM Validation Study.

7.4 Summary of Initial Calibrated Data Results

(Excerpts from Discussion in each of the subsections of Section 7)

Direct Comparison of TNM-Predicted and Measured Sound Levels. Overall, TNM is performing very well for all acoustically clean (see footnote in Section 7.1) data collected, regardless of the wind condition. The average difference from perfect agreement is less than a decibel. In examining the performance by site type, TNM is performing very well for open area, acoustically soft ground sites; open area, acoustically hard ground sites at near distances; and barrier sites – all within 0.3 to1.2 dB of perfect agreement. The only unfavorable trend arises for open area, acoustically hard ground sites at far distances [in these cases, beyond 900 ft (~275 m) from the roadway], where TNM is over-predicting an average of 2.2 dB.

Differences in Sound Levels as a Function of Distance and Height. Where all data are included regardless of wind speed, the results indicate that the average difference between the TNM-predicted sound levels and the measured data is mostly within 1.5 to 2.0 dB, with several sites' differences being within 1.0 dB. The exceptions are few and occur only at some microphone positions for some sites. Also, in examining the sites by type, the results do not show any strong trends due to the height of the receiver (microphone) or distance from the roadway, except for the open area, hard ground sites, where the tendency is toward larger differences between TNM-predicted data and measured data at the farther distances [greater than 300 ft (~90 m)].

Differences in Sound Levels as a Function of Wind Speed and Direction. For the data representative of all wind conditions, TNM's accuracy seems to be relatively independent of the wind (affected on average less than 0.5 dB) for the open area, soft ground sites; TNM-predicted sound levels are closer to the measured levels in downwind conditions (increasing the accuracy) because of other over-predictions for the open area, hard ground sites; and TNM's accuracy is dependent on the wind (affected on average up to 2.0 dB) for barrier sites.

8. REFINED CALIBRATED RESULTS

The results of the TNM Validation Study Phase 1 are now presented in terms of the same variables that were described in Section 7 (Section 7 results being for the initial calibrated data). This section focuses on refined calibrated results, where the data were calibrated using a reference microphone, as described in Section 6.2. The data were processed according to Section 5.1, the case of data captured during limited wind conditions [data captured during wind speeds exceeding ~11 mph (5 m/s) were removed – referred to as the strong-wind-removed data]. This refinement (from the all-wind data – data captured during all wind conditions were retained) was made to further increase the stability of the data (removing strong wind influences) and to eliminate any possible contamination at the microphone due to wind.

As in Section 7, a direct comparison is made between the TNM-predicted sound levels and the measured sound levels, and the remaining results are presented in terms of the difference or delta between the TNM-predicted sound levels and measured sound levels as a function of these variables: distance, height, wind speed and direction, and additionally, the percentage of heavy trucks. Again, in addition to presenting all the data from all the sites as a whole, the data are also divided into three categories: open area, acoustically soft ground sites {e.g., field grass [effective flow resistivity (F) . 150 cgs Rayls] or lawn [F . 300 cgs Rayls]}; open area, acoustically hard ground sites [e.g., pavement or water (F . 20,000 cgs Rayls)]; and barrier, soft ground sites. This is done in order to reveal possible site-specific influences on the results. (Measurements for barrier; acoustically hard ground sites were not performed as part of this evaluation; the barrier, acoustically soft ground sites will be referred to as just barrier sites for the remainder of this section.)

Plot and table descriptions that were detailed in Sections 6 and 7 will be repeated in this section for convenience.

8.1 Direct Comparison of TNM-Predicted and Measured Sound Levels

The first investigation of the results was simply to directly compare the TNM-predicted sound levels to the measured sound levels, as with the uncalibrated results (Section 6) and the calibrated, all-wind results (Section 7). For presentation, the set of graphs corresponding to the strong-wind-removed data results [data for winds exceeding ~11 mph (5 m/s) were removed] are seen in Figures G.2 through G.6 in Appendix G.

For a direct comparison, the data are plotted with the horizontal axis being the measured sound levels and the vertical axis being the TNM-predicted sound levels. Each 15-minute data block (15-min L_{eq}) is represented as an orange X, where the number of data points is stated in the lower right corner of the figure. A dashed blue line represents the linear fit and solid green lines show the 95 percent confidence band. A solid black diagonal line symbolizes perfect agreement between TNM-predicted data and measured data. Data points that fall above (to the left of) this line indicate over-prediction and points that fall below (to the right of) this line indicate under-prediction. The text at the top of the figure indicates the type of site for which the data correspond.

In addition to the graphs found in Appendix G, Table 10 in this section gives numerical values corresponding to the statistical elements of the graphs. In this table, the relation of the linear fit to the line of perfect agreement is examined along with the width of the 95 percent confidence band; values for five variables are stated across the columns. The first two variables concern the linear fit; values for both the average difference and the average of the absolute value of differences are stated. The first variable, the average difference, indicates how well TNM is performing over a broad range of sound levels, combining the over- and under-predictions. The second variable, the absolute value of differences, indicates how well TNM is performing as a function of the amplitude of the over- and under-predictions. This second variable can also indicate the consistency of over- or under-predictions for a range of sound levels. The third, fourth, and fifth variables in the table are the average, maximum, and minimum values of the

95 percent confidence band width, respectively. If all three values are small, and the maximum and minimum values are similar, this indicates that an average of the data shows little variation in amplitude over a broad range of sound levels; as such, a similar data set (sound levels measured and predicted under the same conditions) would provide similar results.

Results

The results for the data set where the strong wind data were removed will now be described in the order they are presented in Appendix G (Figures G.2 through G.6) and Table 10. The calibrated data for all sites (Figure G.2 and Table 10) show that TNM is in excellent agreement with the measured sound levels, the average difference being only -0.4 dB. There is only very slight over-prediction at the lower sound levels and slight under-prediction at the higher sound levels. The confidence band width is narrow over all sound levels, the average being 0.6 dB.

Table 10. Direct Comparison of TNM-Predicted and Measured Data; Strong Wind Data Removed; Statistical Data Corresponding to Figures G.2-G.6 (Appendix G).

Sites	Differences of Linear Fit from Perfect Agreement (dB)		95% Confidence Band Width around Linear Fit (dB)		
	average difference	average of absolute value of differences	average	maximum	minimum
all	-0.4	0.8	0.6	1.2	0.3
open area, soft ground	0.1	0.2	1.2	1.9	0.7
open area, hard ground	1.2	1.7	0.8	1.2	0.6
near distances	-0.4	0.4	1.8	2.9	1.2
far distances	2.4	2.4	0.7	1.3	0.4
barrier, soft ground	-0.6	0.7	0.7	1.1	0.4

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

The results for the open area, acoustically soft ground sites (Figure G.3 and Table 10) indicate excellent agreement between predicted and measured data, with the average difference being

0.1 dB. There is some variation in the confidence band width, the average being 1.2 dB. Since the confidence band encompasses the perfect agreement line over the range of levels, it can be stated that there is no statistical difference between the measured and modeled results for open area, acoustically soft ground sites.

For open area, acoustically hard ground sites, the data are first presented as a group (Figure G.4 and Table 10) then divided into far distance (lower sound levels) and near distance (higher sound levels) data (Figure G.5 and Table 10). As a group, a substantial skew is seen in the linear fit, where the average difference from perfect agreement is 1.2 dB. Dividing the data into two categories allows a better evaluation of TNM's performance at this type of site. For near distances, the average difference for the linear fit is only -0.4 dB, with the average confidence band width being 1.8 dB; this indicates excellent agreement. For far distances, the average difference is 2.4 dB, with the average confidence band width being 0.7 dB; this indicates some over-prediction.

Lastly, for barrier sites (Figure G.6 and Table 10), results show excellent agreement, indicating a consistent average under-prediction of only -0.6 dB. The confidence band width is narrow, an average of 0.7 dB, over all sound levels.

Discussion

> **Overall, TNM is performing very well in a direct comparison to the measured data, the average difference from perfect agreement being less than half a decibel. In examining the performance by site type, TNM is performing very well for open area, acoustically soft ground sites; open area, acoustically hard ground sites at near distances; and barrier sites – all within 0.1 to 0.6 dB of perfect agreement, some cases showing no statistical difference between the measured and modeled results. The only difference of concern arises for open area, acoustically hard ground sites at far distances [in these cases, beyond 900 ft (~275 m) from the roadway], where TNM is over-predicting an average of 2.4 dB.**

At far distances for open area, acoustically hard ground sites, the measured spectra and predicted spectra were examined to help understand the differences in levels. Spectra for the 900-ft (~275-m) position at site 13CA and the 1273-ft (~390-m) position at site 17CT were observed for both the measured and TNM-predicted data (a special diagnostic tool for TNM allows the extraction of spectra, not just the overall sound levels). Examination of a limited set of data points revealed that the overall sound levels at the far distances were dominated by frequencies between 200 and 2000 Hz. For a majority of the frequencies in this range, TNM under-attenuated the sound, causing the overall sound levels to be higher than the measured sound levels. Since TNM theoretically accounts for the hard ground by reflecting most of the energy, these barely attenuated reflected sound waves also reach the receiver. The sound waves at the measurement site most likely did not achieve this near perfect reflection upon impact with the hard ground; therefore, less energy was reflected at each encounter, and at far distances, the sound levels would be lower than those predicted using near perfect reflection. This will be investigated further in future development of TNM.

The strong-wind-removed data in this section and all-wind data in Section 7.1 show similar results. One of the noticeable differences is that the confidence band widths are narrower for the all-wind cases than the strong-wind-removed cases; this is most likely because of the greater number of data points in the all-wind cases – it is more certain that the average of that type of data set would be in that range.

Another noticeable difference between the two data sets concerns the average difference of the linear fit from perfect agreement. One would expect the linear fit difference to decrease when removing the strong wind data, as this eliminates some of influences of wind on the measured data which are not accounted for by TNM. The linear fit difference does in fact decrease for the following groups: open area, soft ground sites; near distance open area, hard ground sites; and barrier, soft ground sites. The difference from perfect agreement also decreases for all sites as a whole, from -0.8 dB to -0.4 dB. The biggest improvement is for barrier sites (from -1.2 to

-0.6 dB), most likely due to the strong winds, since they would have the largest effect at barrier sites. This is further discussed in Section 8.3.

The only increase in the difference between the linear fit and perfect agreement is for the far distance open area, hard ground sites (from 2.2 dB to 2.4 dB). For the data points that were eliminated due to strong winds, it appears that the influence of the wind on the measured sound levels brought them closer to the TNM-predicted sound levels. Although the wind conditions are discussed in detail in Section 8.3, a brief insight into the linear fit differences for the far distance open area, hard ground sites is explained here. It is known that in downwind conditions (when the wind is blowing in the direction from the roadway to the receiver), one would measure higher sound levels at a receiver (especially noticeable at receivers placed a far distance from the roadway) than for either upwind or calm conditions. Ignoring other variables, TNM should under-predict in strong downwind cases since it does not account for wind. If, however, measurements are taken at far distances over acoustically hard ground (where TNM is over-predicting), this downwind effect would be seen as a decrease in over-prediction. Two of the open, hard ground sites had receivers placed a far distance from the roadway, Site 17CT and Site 13CA. No strong wind data were removed for Site 17CT, but Site 13CA had several strong wind data points removed; the removed data were measured during strong downwind conditions. This explains the small decrease in accuracy when removing the strong wind data points for the far distance open area, hard ground sites. Again, the influences of wind will be further discussed in Section 8.3.

8.2 Differences in Sound Levels as a Function of Distance and Height

The second investigation of the results examined the average differences (TNM minus measured) and standard deviation as a function of the distance of the receiver from the roadway or noise barrier and height of the receiver above the ground. As was stated in Section 7.2 (the all-wind data), it is important to investigate these variables: multiple distances can help determine how far from the road TNM is valid; short and tall heights above the ground can help validate ground effects (the microphone closer to the ground should be more affected by the ground surface) and can help in examining a noise barrier's shadow zone. For presentation, the set of graphs corresponding to the strong-wind-removed data results [data for winds exceeding ~11 mph (5 m/s) were removed] as a function of distance and height are seen in Figures G.7 through G.12 and Tables G.1 through G.3 in Appendix G.

For these sets of graphs, the data are plotted with the horizontal axis being the distance from either the center of the near travel lane of the roadway or the barrier and the vertical axis being the average difference (TNM minus measured) in sound levels. Also shown vertically is the standard deviation of the data from the average values. A solid black horizontal line at a value of 0 dB for the average difference symbolizes perfect agreement between TNM-predicted data and measured data. Data above this line indicate over-prediction and data below this line indicate under-prediction. The text at the top of the figure indicates the type of site for which the data correspond, with the specific sites listed in the legend. The text also indicates if the data presented are for the 5-ft height position or the 15-ft height position. For the tables in Appendix G, values for the average difference in sound levels are presented along with the standard deviation for each microphone location at each site.

In addition to the graphs and tables found in Appendix G, the table in this section, Table 11, gives the values for the average difference in sound levels for each type of site (open area, soft ground; open area, hard ground; and barrier). The averages are given for ranges of distances from the highway or noise barrier; note that only some ranges of distances are covered for each type of site. The data are also divided by the two different heights (5 ft and 15 ft), where averages over all distances are given in the right hand column.

Table 11. Average Differences (TNM minus Measured) as a Function of Distance and Height; Strong Wind Data Removed

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	0.4	1.0	no data	0.0	-0.8	no data	0.4
	15	0.4	-1.3	no data	-0.6	-0.9	no data	-0.7
open area, hard ground	5	0.1	-0.3	no data	no data	0.7	4.0	0.6
	15	-0.7	-1.2	no data	no data	1.3	2.8	0.0
barrier, soft ground	5	-0.3	-1.0	0.8	no data	no data	no data	-0.4
	15	0.2	-0.4	1.9	no data	no data	no data	0.1

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

Results

The results are now presented for Appendix G (Figures G.7 through G.12 and Tables G.1 through G.3) and Table 11, the data set where the strong wind data are removed. The data for the open area, acoustically soft ground sites at the 5-ft (1.5-m) height location (Figure G.7 and Table G.1) show that the average differences between the TNM-predicted and measured sound levels for each position at each site are within about 2.0 dB, except for Site 02MA, where TNM is over-predicting by 2.6 dB at the 200-ft (~60-m) position. The average difference of all these sites is 0.4 dB (Table 11) and the standard deviations range from 0.1 to 0.9 dB. For the 15-ft (4.5-m) height locations (Figure G.8 and Table G.1) the average differences for each position at each site are within about 1.5 dB, except for Site 02MA, where TNM is under-predicting by 2.5 dB at the 600-ft (~180-m) position, and Site 10CA-open, where it is under-predicting by 3.3 and 3.4 dB. The average difference for all these sites is -0.7 dB (Table 11) and the standard deviations range from 0.1 to 0.5 dB. In examining the different ranges of distances (in Table 11), it is seen that there is no overall trend in variation as a function of distance; with height, the true values of the differences for 5 ft (1.5 m) above the ground are always slightly greater than the 15-ft (4.5-m) height differences, but the magnitudes of the differences reveal no trend.

The data for the open area, acoustically hard ground sites at the 5-ft (1.5-m) height location (Figure G.9 and Table G.2) show that the average differences between the TNM-predicted and measured sound levels for each position at each site range from 0.0 to 4.0 dB, the larger differences generally tending to be at farther distances. The average difference for all these sites is 0.6 dB (Table 11) and the standard deviations range from 0.1 to 0.9 dB. For the 15-ft (4.5-m) height locations (Figure G.10 and Table G.2), the average differences for each position at each site are within about 1.5 dB, except for Site 17CT, where TNM is over-predicting by 2.8 dB. The average difference for all these sites is 0.0 dB (Table 11) and the standard deviations range from 0.0 to 0.8 dB. In examining the different ranges of distances (in Table 11), it is seen that there is a trend in variation as a function of distance; at far distances the differences are greater than at the near distances. With height, the differences reveal no trend.

The data for the barrier sites at the 5-ft (1.5-m) height location (Figure G.11 and Table G.3) show that the average differences between the TNM-predicted and measured sound levels for each position at each site are within about 2.0 dB, except for Site 09CA, where it is, in general, under-predicting by 2.3 to 3.6 dB, and Site 11CA, where TNM is over-predicting by 3.1 dB at the 300-ft (~90-m) position. The average difference for all these barrier sites is -0.4 dB (Table 11) and the standard deviations range from 0.0 to 1.4 dB. For the 15-ft (4.5-m) height locations (Figure G.12 and Table G.3), the average differences for each position at each site are within about 2.0 dB, except for Site 09CA, where TNM is generally under-predicting by 3.4 dB at all locations, and Site 10CA-berm, where it its over-predicting by 2.4 dB at the 70-ft (~20-m) position. The average difference for all these sites is 0.1 dB (Table 11) and the standard deviations range from 0.1 to 1.5 dB. In examining the different ranges of distances (in Table 11), it is seen that there are no strong trends in variation as a function of distance or height for these sites, except that there is under-prediction in the 201- to 300-ft (~60- to ~90-m) range and over-prediction in the 301- to 500-ft (~90- to ~150-m) range for both heights.

<u>Discussion</u>

> **Where the strong wind data were removed, the results (as a function of distance and height) indicate that the average difference between the TNM-predicted sound levels and the measured data is mostly within 1.5 to 2.0 dB, with several sites' differences being within 1.0 dB. The exceptions are few and occur only at some microphone positions for some sites; discussions regarding these sites will follow. Also, in examining the sites by type, the results do not show any strong trends due to the height of the receiver (microphone) or distance from the roadway, except for the open area, hard ground sites, where the tendency is toward larger differences between TNM-predicted data and measured data at the farther distances [greater than 500 ft (~150 m)].**

These discussions by site type apply to both the all-wind (Section 7.2) and strong-wind-removed data (this section).

For the open area, acoustically soft ground sites 02MA and 10CA-open, some under- and over-predictions occurred. Site 02MA was the only measurement site in Phase 1 of this validation study to have an undulating ground surface, and it also had a grass median. The site undulations most likely contributed to the difficulty in achieving good predicted results at some of the positions. Section 8.5 will discuss alternate methods for modeling this site, with some differences in the results. Phase 2 of the validation study will incorporate more of the undulating sites to further analyze TNM's performance. Site 10CA-open was the only site in Phase 1 to have a plowed soft dirt ground surface. At this site the 15-ft (4.5-m) positions were under-predicted. The ground was modeled as loose soil (F = 500 cgs Rayls); in addition, other ground types were implemented, but with no improvements. It is known that rough surfaces attenuate sound differently than smooth surfaces [Attenborough 2000] [Chambers 1997]. Because TNM can account only for the ground type and not the surface type, it is likely that the rough surface of plowed soft dirt may have contributed to the differences in the predicted and measured levels. More sites with unusual ground surfaces should be examined to better evaluate TNM's performance in such situations.

For the open area, acoustically hard ground sites 15CA and 17CT, the over-predictions seem to be distance dependent (greater with greater distance). TNM propagates sound over acoustically hard ground in a theoretical sense, where the ground reflections may not properly capture the energy loss experienced in a real outdoor situation. Please refer back to the spectral discussion in Section 8.1 for more details.

For the barrier sites, under- and over-predictions varied depending on the removal of strong winds. Where all wind data were included, Sites 04CT, 08CA, and 09CA all show under-predictions. Where the strong wind data were removed, Site 09CA still shows under-predictions and Sites 10CA-berm and 11CA show some over-predictions. The over-predictions occurred at the closer high microphone position at Site 10CA-berm and the farther low microphone position at Site 11CA; similar locations at other noise barrier sites show good results. There is no immediately apparent reason for the over-predictions at these two sites; further investigation is needed. As for the under-predictions, some are expected at noise barrier sites under certain wind conditions. In downwind situations (wind blowing in the direction from the roadway to the receiver), noise barriers can become less effective as the wind pushes the sound down into the shadow zone (the area behind a noise barrier where the sound is strongly attenuated under calm wind conditions). There will be further discussions of wind in Section 8.3. With Site 09CA, TNM seems to be consistently under-predicting, more so for the all-wind case. Further thought about this site possibly reveals the cause. A 5- to 6-ft (1.5- to 1.8-m) wall surrounded the back of the site, along with a community of relatively dense houses, forming a triangular shape, with the noise barrier being one side of an almost equilateral triangle. It is possible that with the elevated roadway and barrier, the sound could have gotten trapped in this huge "pit," causing the reflected sound levels to be added; in such a case, the measured levels would be consistently higher than the TNM-predicted levels, which the results indicate. Refer to Figures B.8(a) and (b) in Appendix B for a picture and TNM views of Site 09CA.

8.3 Differences in Sound Levels as a Function of Wind Speed and Direction

The third investigation of the results for the strong-wind-removed case examined the differences (TNM minus measured) as a function of wind speed and direction. As was stated in Section 7.3 (the all-wind data), it is important to investigate TNM's performance in terms of wind variables, since these are not accounted for in the model; under certain conditions, measured sound levels are affected by the wind, influencing the differences between TNM-predicted and measured sound levels. For presentation, the set of graphs corresponding to the strong-wind-removed data results [data for winds exceeding ~11 mph (5 m/s) were removed] as a function of wind speed and direction are seen in Figures G.13 through G.15 in Appendix G.

For these sets of graphs, the data are plotted with the horizontal axis being the wind speed and the vertical axis being the difference (TNM minus measured) in sound levels. Each data point represents a 15-minute data block (15-min L_{eq}) and is further categorized by wind direction. For characterization of wind direction, the wind component perpendicular to the roadway is specified; the three wind direction categories are up, down, and calm. "Up" signifies an upwind condition (wind blowing in the direction from the receiver to the roadway) at a speed greater than or equal to 2.2 mph (1 m/s); "Down" signifies a downwind condition (wind blowing in the direction from the roadway to the receiver) at a speed greater than or equal to 2.2 mph (1 m/s); and "Calm" signifies that the perpendicular wind component is less than 2.2 mph (1 m/s) in either direction. A solid black horizontal line at a value of 0 dB for the difference symbolizes perfect agreement between TNM-predicted data and measured data. Data above this line indicate over-prediction and data below this line indicate under-prediction. The text at the top of the figure indicates the type of site for which the data correspond, with the specific sites listed in the legend. It should be noted that fewer data points are available for this analysis than for that in Section 8.1 (also presenting 15-minute data blocks) because the wind had to be directionally consistent throughout the 15 minutes; otherwise, the data point was discarded.

In addition to the graphs found in Appendix G, Tables 12 through 14 in this section give numerical values corresponding to the graphs. In these tables grouped by site type, averages for the wind speed are presented for each site, along with the corresponding values for the average difference in sound levels categorized by wind direction. Also, overall averages are given at the bottom of each table for all sites combined. For the wind study, results are not presented as a function of microphone height above the ground; investigation is planned for later phases of the study.

Results

The results will now be described in the order they are presented graphically in Appendix G and in tables in this section. The data for the open area, acoustically soft ground sites (Figure G.13 and Table 12) show that, for the data as a group, there is no strong trend indicated. There are only two sites that have anything but calm wind conditions in the direction perpendicular to the highway; Site 10CA indicates nothing, and Site 02MA indicates that TNM is under-predicting in downwind conditions. Averages over each wind condition for all open area, soft ground sites show a -1.0-dB under-prediction for upwind conditions, a -1.9-dB under-prediction for downwind conditions, and a 0.3-dB over-prediction for calm conditions.

The data for the open area, acoustically hard ground sites (Figure G.14 and Table 13) show that, for the data as a group, there is no strong trend indicated. There are two sites that have other than calm wind conditions in the direction perpendicular to the highway; Site 15CA indicates that TNM is over-predicting in downwind conditions, and Site 16MA indicates that TNM is under-predicting in downwind conditions. Averages over each wind condition for all open area, hard ground sites show nothing for upwind conditions, a 0.1-dB under-prediction for downwind conditions, and a 1.0-dB over-prediction for calm conditions.

Table 12. Differences (TNM minus Measured) as a Function of Wind Speed and Direction; Open Area, Soft Ground Sites; Strong Wind Data Removed

Site	Average Wind Speed (mph)	Average Sound Level Difference (dB)		
		for upwind conditions	for downwind conditions	for calm conditions
01MA	6.0	no data	no data	-0.6
02MA	2.9	no data	-1.9	0.7
03MA	2.3	no data	no data	0.8
10CA-open	5.8	-1.0	no data	no data
AVERAGES	4.2	-1.0	-1.9	0.3

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

Table 13. Differences (TNM minus Measured) as a Function of Wind Speed and Direction; Open Area, Hard Ground Sites; Strong Wind Data Removed

Site	Average Wind Speed (mph)	Average Sound Level Difference (dB)		
		for upwind conditions	for downwind conditions	for calm conditions
13CA	no data	no data	no data	no data
15CA	6.4	no data	1.3	no data
16MA	3.7	no data	-1.2	-1.3
17CT	0.8	no data	no data	3.3
AVERAGES	3.6	no data	0.1	1.0

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

Table 14. Differences (TNM minus Measured) as a Function of Wind Speed and Direction; Barrier, Soft Ground Sites; Strong Wind Data Removed

Site	Average Wind Speed (mph)	Average Sound Level Difference (dB)		
		for upwind conditions	for downwind conditions	for calm conditions
04CT	no data	no data	no data	no data
05CA	4.7	-0.1	no data	-0.3
06CA	3.0	1.4	no data	-0.2
08CA	2.3	no data	no data	-1.0
09CA	1.8	-2.8	-4.7	-3.2
10CA-berm	4.3	2.0	no data	1.7
11CA	5.2	1.1	no data	no data
12CA	2.7	no data	-0.3	-0.8
14CA	2.9	no data	-0.7	0.1
AVERAGES	3.4	0.3	-1.9	-0.4
Averages, shifting 09CA by +3 dB	3.4	0.9	-0.9	-0.1

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

The data for the barrier sites (Figure G.15 and Table 14) show that, for the data as a group, there is a trend indicating that upwind conditions may cause over-prediction by TNM and downwind conditions may cause under-prediction by TNM. Sites 06CA, 10CA, and 11CA readily show over-prediction in upwind conditions. Site 12CA leans toward under-prediction in downwind conditions. Site 09CA, the only site with upwind, downwind, and calm conditions needs to be examined closely. As stated earlier (in Section 8.2), Site 09CA shows differences offset in the negative direction. If the predicted 09CA data were to be shifted up 3.0 dB as an approximation to account for additive reflections (as suggested in Section 7.3; explained in 8.2), the data set would show the calm data differences being distributed around the zero line, the upwind differences indicating mostly over-predictions, and the downwind differences indicating under-predictions. Averages over each wind condition for all barrier sites show a 0.3-dB over-prediction for upwind conditions, a -1.9-dB under-prediction for downwind conditions, and a -0.4-dB under-prediction for calm conditions. Upon shifting the 09CA averages by positive 3.0 dB, the averages over each wind condition would show a 0.9-dB over-prediction for upwind conditions, a -0.9-dB under-prediction for downwind conditions, and a -0.1-dB under-prediction for calm conditions.

Discussion

> **Where the strong wind data were removed, TNM's accuracy is relatively unaffected by the wind (on average less than 0.5 dB) for the open area, soft ground sites; TNM-predicted sound levels are closer to the measured levels in downwind conditions (increasing the accuracy) because of other over-predictions for the open area, hard ground sites; and TNM's accuracy is dependent on the wind (affected on average up to 1.0 dB) for barrier, soft ground sites.**

As was stated in Section 7.3, TNM's accuracy for certain cases *should* be dependent on the wind since the model calculates sound levels for a windless environment. In general, upwind conditions can lower the measured sound levels at the receiver position, and downwind conditions can raise the measured sound levels at the receiver position, the effects greater with higher wind speeds. Refraction caused by the wind affects both soft-ground attenuation and barrier insertion loss [Beranek 1992]. In addition, over hard ground sites, the sound can be channeled in downwind conditions (raising the received sound levels).

In examining the results as a function of wind, the open area, soft ground data overall indicate under-predictions for both upwind and downwind conditions, more so for the downwind conditions. However, data exist for only one site under upwind conditions and one site for downwind conditions. The site with downwind conditions, Site 02MA, does indicate some influence from wind since the downwind data are vertically offset from the calm wind data; as was stated in Section 7.3, there is the possibly that this site may behave more like a barrier site when it comes to wind effects because of the large ground undulations. Overall, it is difficult to make any firm conclusions about the effects of wind on the accuracy of TNM predictions at open area, soft ground sites, although it seems that TNM's accuracy is relatively independent.

In examining the results as a function of wind, the open area, hard ground data overall indicate neutrality for downwind conditions; no data exist for upwind conditions. Under downwind conditions, the sound can be refracted downward then reflected upward, channeling the sound (hence raising the sound levels at the microphones, especially over long distances). The results do not readily support this, although some explanation can be offered. As was stated in Section 7.3, for the downwind results, even though Table 13 indicates a 0.1 dB overall over-prediction and not an under-prediction as one would expect, it is important to recall results presented earlier in this section. TNM is tending to over-predict for farther positions at hard ground sites; these over-predictions may overpower the under-predictions from downwind effects, thereby merely lowering the over-predictions. For hard ground sites, results do not indicate that the accuracy of TNM is very affected by the wind, but part of the non-effect is due to general over-prediction at hard ground sites; this is noted for investigation in later phases of the TNM Validation Study.

In examining the results as a function of wind, the barrier data overall indicate some over-prediction for upwind conditions and some under-prediction for downwind conditions. Many of the sites indicate this trend, especially the ones where upwind or downwind data, when compared to calm wind data, show a definite increase or decrease, respectively, from the calm wind results (Sites 06CA, 09CA, and 14CA in Figure G.15). At noise barrier sites, under upwind conditions, the sound is being refracted upward, making the barrier more effective (hence reducing the sound levels at the microphones). Under downwind conditions, the sound is being refracted downward behind the barrier, making the barrier less effective (hence raising the sound levels at the microphones). Results from the barrier sites indicate that wind is a factor in TNM's ability to predict precisely accurate results. It is seen, however, that the average wind influence is less than 1.0 dB (less than 2.0 dB without adjusting Site 09CA); this is noted for investigation in later phases of the TNM Validation Study.

Examining the differences between TNM-predicted sound levels and measured sound levels as a function of wind, similar overall results are seen for the all-wind data and the strong-wind-removed data. The only notable difference is the greater influence of wind at barrier sites. The higher wind speeds included in the all-wind data influenced the differences between TNM-predicted and measured data more than the lower wind speeds for the strong-wind-removed data. If one were to assume that the all-wind data were uncontaminated by the high wind speeds, which in most cases was probably true, then results indicate that TNM's accuracy is dependent on the wind environment, where the wind causes differences from measured levels of 2.0 dB or more at higher wind speeds [>11 mph (5 m/s)] and 1.0 dB at lower wind speeds.

8.4 Differences in Sound Levels as a Function of Percentage of Heavy Trucks

The third investigation of the results for the strong-wind-removed case examined the differences (TNM minus measured) as a function of percentage of heavy trucks. This was not investigated for the all-wind data. It is important to investigate TNM's performance in terms of percentage of heavy trucks in order to verify the implementation of this type of vehicle in the model. Heavy trucks are modeled differently from other vehicle types because of the added noise emission source for the truck stack exhaust. At highway speeds, 95 percent of the acoustical energy is apportioned to the tire/pavement interaction noise and 5 percent to the truck stack exhaust noise [Coulson 1996]. There are also other differences from other vehicle types, for example, relative levels in the emission spectra.

Any issues related to the implementation of heavy trucks would be more apparent with a greater percentage. For presentation, the set of graphs corresponding to the strong-wind-removed data results [data for winds exceeding ~11 mph (5 m/s) were removed] as a function of percentage of heavy trucks are seen in Figures G.16 through G.18 in Appendix G.

For these sets of graphs, the data are plotted with the horizontal axis being the percentage of heavy trucks and the vertical axis being the difference (TNM minus measured) in sound levels.

Each data point represents a 15-minute data block (15-min L_{eq}). A solid black horizontal line at a value of 0 dB for the difference symbolizes perfect agreement between TNM-predicted data and measured data. Data above this line indicate over-prediction and data below this line indicate under-prediction. The text at the top of the figure indicates the type of site for which the data correspond, with the specific sites listed in the legend.

Results

The results will now be described in the order they are presented graphically in Appendix G. The data for the open area, acoustically soft ground sites (Figure G.16) show no overall trend; the percentage of heavy trucks ranges from about 2 to 13 percent. Only Site 03MA shows a trend of slightly more over-prediction with a higher percentage of heavy trucks.

The data for the open area, acoustically hard ground sites (Figure G.17) show a slight trend overall, but the trend is most likely influenced by the general over-prediction at far distance hard ground sites. For these sites, the percentage of heavy trucks ranges from about 3 to 18 percent. The data for the barrier sites (Figure G.18) show no overall trend; the percentage of heavy trucks ranges from about 0 to 12 percent. Only Sites 05CA and 08CA show a trend of slightly less over-prediction with a higher percentage of heavy trucks.

Discussion

> **When examining the strong-wind-removed data as a function of the percentage of heavy trucks, it is seen that there are some slight site-specific trends. Also, a slight overall trend is seen for the acoustically hard ground sites; the previously discussed over-predictions (Section 8.2) for far distances at acoustically hard ground sites most likely influenced these results. Overall results show no distinct trends. This indicates no apparent influence of the percentage of heavy trucks on the performance of TNM, suggesting that TNM implements heavy trucks correctly.**

8.5 Some Alternate TNM Runs and Recommendations

All TNM runs for the results described above were modeled according to the standard practice for this study. This standard practice included modeling all substantial terrain features; it also involved choosing the default ground type to be either lawn or field grass, unless the entire site consisted of a different ground type (e.g., pavement). Some other practices were implemented for research purposes, to determine if their effects would be useful or not. The results for a few of the Phase 1 sites, applying the alternate modeling techniques, will be presented in this section, along with recommendations based on these investigations. The strong-wind-removed data [data for winds exceeding ~11 mph (5 m/s) were removed] were used in these investigations.

Undulations versus Flat Terrain

The first investigation involved terrain features. Site 02MA was examined in this case, the only site with an undulating ground surface. See Figures B.2(a) and (b) in Appendix B for site specifics as it was originally modeled; although only one cross section is shown, it should be noted that the actual site consisted of undulations in multiple directions. The elevation of the undulations ranged from +5 to -20 ft (+1.5 to -6.0 m). All terrain lines were removed for the investigation of this case, modeling the site as flat, not undulating.

The investigation of strong-wind-removed results examined the average differences (TNM minus measured) and standard deviation as a function of the distance of the receiver from the roadway and height of the receiver above the ground, as was done in Section 8.2. The results are presented graphically in Figures G.19 and G.20 in Appendix G. These plots include all the open area, soft ground sites. In directly comparing the flat Site 02MA results (Figures G.19 and G.20) to the undulating Site 02MA results (G.7 and G.8), it is seen that flattening the terrain in the TNM run definitely affects the resulting sound levels. At the 5-ft (1.5-m) height (Figures G.19 and G.7), TNM's predictions are improved (on average about 1.5 dB) at 200 ft (~60 m) and impaired (on average about 0.5 dB) at 400 and 600 ft (~120 and ~60 m). At the 15-ft (4.5-m) height (Figures G.20 and G.8), TNM's predictions are improved (on average about 0.5 dB) at

50 ft (~15 m), impaired (on average about 0.5 dB) at 200 ft (~60 m), and are relatively unaffected at 400 and 600 ft (~120 and ~60 m).

> **The results as a whole indicate that this undulating site should not be simplified by flattening it (overall, nothing is gained), and that undulations of this size [+5 to -20 ft (+1.5 to -6.0 m)] cannot be ignored. Of course, more undulating ground sites (and sites with elevation changes) need to be evaluated. Measurements have already been performed at several of these sites in Pennsylvania; analysis for these sites will be part of Phase 2 of the TNM Validation Study.**

Modeling a Grass Median

The second investigation involves grass medians. Through the Volpe's interaction with TNM users, it was found that TNM was calculating counter-intuitive results with grass medians, where the medians were defined solely by the default ground type between roadways. Although the counter-intuitive behavior only appears at certain distances from the roadway, an investigation involving the addition of a grass ground zone to define the median was executed. Sites 01MA and 02MA were examined in this investigation, both sites having grass medians. See Figures B.1(a) and (b) and B.2(a) and (b) in Appendix B for site specifics as they were originally modeled.

For the strong-wind-removed data, results were examined for the average differences (TNM minus measured) and standard deviation as a function of the distance of the receiver from the roadway and height of the receiver above the ground, as was done in Section 8.2. The results are presented graphically in Figures G.21 and G.22 in Appendix G. These plots include all the open area, soft ground sites. In directly comparing the grass ground zone median results (Figures G.21 and G.22) to the default grass median results (G.7 and G.8), it is seen that adding the grass ground zone to represent the median in the TNM runs (instead of allowing the median to be set based on a default ground type of grass) definitely affects the resulting sound levels. For Site 01MA, there is very little effect, but Site 02MA shows differences. For Site 02MA, there is some improvement and some impairment, the greatest improvement closer to the roadway. Because very little is shown here, the results are inconclusive. In Volpe's TNM testing and interactions with TNM users, however, some improvements were seen when adding a grass ground zone to represent the median.

> **It is recommended to add a grass ground zone as the median when the actual site possesses one, unless its width is small [less than 10 ft (~3 m)]; in small-width cases, the roadways in each direction should be extended to just overlap. Further investigation needs to be performed in order to fix this counter-intuitive behavior.**

Hard Ground Zone on Soft or Soft Ground Zone on Hard

The third investigation involved ground zones. Through the Volpe's interaction with TNM users and modeling for this study, it was found that TNM was potentially having difficulty with its predictions when placing a soft ground zone on default hard ground (e.g., a lawn ground zone on default pavement). Since Site 16MA, seen in Figures B.15(a) and (b) in Appendix B, contains mixed ground surfaces, it was used to test placing a soft ground zone on default hard ground; it originally was modeled as a pavement ground zone placed on default field grass. This was done informally, and graphical representation of the results are not presented here. However, cursory results showed that TNM predicts more accurate results when placing the pavement ground zone of default field grass than when placing a field grass ground zone on default pavement. Other TNM users have seen similar results. This too needs further investigation.

> **For now, it is recommended that mixed ground sites be modeled with the default ground type being soft ground and the ground zones being hard ground.**

Discussion and Recommendations

In running alternate TNM configurations of particular sites, it is seen that substantial ground undulations cannot be ignored (i.e., the site cannot be modeled with flat ground), as is expected. For the site examined, the undulations ranged from +5 to -20 ft (+1.5 to -6.0 m); more sites with undulations and changes in elevation will be analyzed in Phase 2 of the study. Investigations involving grass ground zone medians were inconclusive here, but it is recommended to add a grass ground zone as the median when the actual site possesses one, unless its width is small [less than 10 ft (~3 m)]; in small-width cases, the roadways in each direction should be extended to just overlap. Investigations involving ground zones at mixed ground [soft (e.g., field grass) and hard (e.g., pavement)] sites indicate that this type of site should be modeled with the default ground type being soft ground and the ground zones being hard ground.

8.6 Summary of Refined Calibrated Data Results

(Excerpts from Discussions in each of the subsections of Section 8)

Direct Comparison of TNM-Predicted and Measured Sound Levels. Overall, TNM is performing very well, the average difference from perfect agreement being less than half a decibel. In examining the performance by site type, TNM is performing very well for open area, acoustically soft ground sites; open area, acoustically hard ground sites at near distances; and barrier sites – all within 0.1 to 0.6 dB of perfect agreement, some cases showing no statistical difference between the measured and modeled results. The only difference of concern arises for open area, acoustically hard ground sites at far distances [in these cases, beyond 900 ft (~275 m) from the roadway], where TNM is over-predicting an average of 2.4 dB.

Differences in Sound Levels as a Function of Distance and Height. Where the strong wind data were removed, the results indicate that the average difference between the TNM-predicted sound levels and the measured data is mostly within 1.5 to 2.0 dB, with several sites' differences being within 1.0 dB. The exceptions are few and occur only at some microphone positions for some sites. Also, in examining the sites by type, the results do not show any strong trends due to the height of the receiver (microphone) or distance from the roadway, except for the open area, hard ground sites, where the tendency is toward larger differences between TNM-predicted data and measured data at the farther distances [greater than 500 ft (~150 m)].

Differences in Sound Levels as a Function of Wind Speed and Direction. Where the strong wind data were removed, TNM's accuracy is relatively unaffected by the wind (on average less than 0.5 dB) for the open area, soft ground sites; TNM-predicted sound levels are closer to the measured levels in downwind conditions (increasing the accuracy) because of other over-predictions for the open area, hard ground sites; and TNM's accuracy is dependent on the wind (affected on average up to 1.0 dB) for barrier, soft ground sites.

Differences in Sound Levels as a Function of Percentage of Heavy Trucks. When examining the strong-wind-removed data as a function of the percentage of heavy trucks, some slight site-specific trends can be seen. Also, there is a slight overall trend for the acoustically hard ground sites; the previously discussed over-predictions (Section 8.2) for far distances at acoustically hard ground sites most likely influenced these results. Overall results show no distinct trends. This indicates no apparent influence of the percentage of heavy trucks on the performance of TNM, suggesting that TNM implements heavy trucks correctly.

Some Alternate TNM Runs and Recommendations. In running alternate TNM configurations of particular sites, it is seen that substantial ground undulations cannot be ignored (i.e., the site cannot be modeled with flat ground), as is expected. For the site examined, the undulations ranged from +5 to -20 ft (+1.5 to -6.0 m); more sites with undulations and changes in elevation will be analyzed in Phase 2 of the study. Investigations involving grass ground zone medians were inconclusive here, but adding a grass ground zone as the median when the actual site possesses one is recommended, unless its width is small [less than 10 ft (~3 m)]; in small-width cases, the roadways in each direction should just be extended to overlap. Investigations involving ground zones at mixed ground [soft (e.g., field grass) and hard (e.g., pavement)] sites indicate that this type of site should be modeled with the default ground type being soft ground and the ground zones being hard ground.

9. CONCLUSIONS

9.1 Summary of TNM Validation Study, Phase 1

The first phase of the TNM Validation Study has been completed. Phase 1 included measuring and modeling highway traffic noise levels at 17 sites around the United States. These sites consisted of open areas with acoustically soft and hard ground, as well as sites with noise barriers that were protecting schools, parks, and communities. The measurements and modeling were performed with consistent methodology, thus creating a large data set with comparable results.

The TNM-predicted data and measured data were analyzed and examined in terms of several variables in order to highlight any strengths or weaknesses in TNM's calculations. Analysis included calibrating the TNM-predicted data to reference levels measured at the measurement site, although some uncalibrated data were examined – stressing the importance of calibrating. The data were also examined with and without data that included strong winds [all-wind data include data captured during wind speeds greater than ~ 11 mph (5 m/s); strong-wind-removed data do not]. Comparing TNM-predicted sound levels to measured sound levels revealed the following results.

Results

(See Table 15 at the end of Results for a summary in tabular form.)

Direct Comparison of TNM-Predicted and Measured Sound Levels.

Uncalibrated. The uncalibrated results (for directly comparing TNM-predicted and measured sound levels) indicate by the 2.6 dB offset that either TNM is over-predicting in its vehicle emissions or there are site-specific biases in the measured vehicle emissions (or a combination of both). Once the data are calibrated, this positive 2.6 dB offset, which is consistent for sound levels ranging from about 50 to 85 dB(A), is eliminated. In other words, TNM's propagation algorithms are performing quite well. See Recommendations in this section for a note on calibrating to a reference microphone.

Calibrated to Reference Microphone. Overall, TNM is performing very well for the data collected, regardless of the wind condition. The all-wind average difference from perfect agreement is less than 1.0 dB; the strong-wind-removed average difference from perfect agreement is less than 0.5 dB. The all-wind 1.0 dB difference and strong-wind-removed 0.5 dB difference are also seen when examining the performance by site type: TNM is performing very well for open area, acoustically soft ground sites; open area, acoustically hard ground sites at near distances; and barrier sites. The only difference of concern arises for open area, acoustically hard ground sites at far distances [in these cases, beyond 900 ft (~275 m) from the roadway], where TNM is over-predicting an average of 2.2 dB for the all-wind data and 2.4 dB for the strong-wind-removed data. Further data analysis will help in improving TNM's predictions for sound propagation over acoustically hard ground.

Differences in Sound Levels as a Function of Distance and Height. Where all data are included regardless of wind speed, the results indicate that the average difference between the TNM-predicted sound levels and the measured data is mostly within 1.5 to 2.0 dB, with several sites' differences being within 1.0 dB. The exceptions are few and occur only at some microphone positions for some sites. Also, in examining the sites by type, the results do not show any strong trends due to the height of the receiver (microphone) or distance from the roadway, except for the open area, hard ground sites, where the tendency is toward larger differences between TNM-predicted data and measured data at the farther distances, greater than 300 ft (~90 m) for the all-wind data and greater than 500 ft (~150 m) for the strong-wind-removed data. Again, further data analysis will help in improving TNM's predictions for sound propagation over acoustically hard ground.

Differences in Sound Levels as a Function of Wind Speed and Direction. The effect of wind on TNM's accuracy is dependent on the type of site. For open area acoustically soft ground sites, TNM's accuracy is relatively independent of the wind (average differences from measured sound levels being less than 0.5 dB for both the all-wind and strong-wind-removed data). For the hard ground sites, TNM-predicted sound levels are closer to the measured levels in downwind conditions (increasing the accuracy) because of other over-predictions for the open area, hard ground sites. For barrier sites, TNM's accuracy is dependent upon the wind (average differences from measured sound levels being up to 2.0 dB for the all-wind data and 1.0 dB for the strong-wind-removed data). It is anticipated that the wind investigations will provide a better understanding for the planning of a more comprehensive TNM measurement study examining wind effects on sound propagation in the vicinity of highways and for possible implementation into TNM.

Differences in Sound Levels as a Function of Percentage of Heavy Trucks. When examining the strong-wind-removed data as a function of the percentage of heavy trucks, some slight site-specific trends can be seen. Also, there is a slight overall trend for the acoustically hard ground sites; the previously discussed over-predictions for far distances at acoustically hard ground sites most likely influenced these results. Overall results show no distinct trends. This indicates no apparent influence of the percentage of heavy trucks on the performance of TNM, suggesting that TNM implements heavy trucks correctly.

Table 15. Summary of Results.

<table>
<tr><th colspan="3">Investigation</th><th>Results</th><th>Comments</th></tr>
<tr><td rowspan="4">Direct comparison of TNM-predicted and measured sound levels</td><td rowspan="2">uncalibrated</td><td>all-wind data</td><td rowspan="2">average 2.6 dB over-prediction</td><td rowspan="2">when calibrating to reference mic, bias is essentially eliminated</td></tr>
<tr><td>strong-wind-removed data</td></tr>
<tr><td rowspan="2">calibrated</td><td>all-wind data</td><td>average 1.0 dB difference from perfect agreement</td><td rowspan="2">good agreement at all types of sites, except for far distances at hard ground sites (some over-prediction, ~ 2.0 dB); TNM's propagation algorithms are performing well</td></tr>
<tr><td>strong-wind-removed data</td><td>average 0.5 dB difference from perfect agreement</td></tr>
<tr><td rowspan="5">Differences (calibrated TNM-predicted minus measured) in sound levels as a function of ...</td><td rowspan="2">distance from roadway, height above ground</td><td>all-wind data</td><td rowspan="2">average differences for most sites within 1.5 to 2.0 dB – some exceptions</td><td rowspan="2">far distances [> 300 ft (~90 m)] at hard ground sites show some over-prediction; no strong trends for height above ground</td></tr>
<tr><td>strong-wind-removed data</td></tr>
<tr><td rowspan="2">wind speed, wind direction</td><td>all-wind data</td><td>2.0 dB wind influence at barrier sites</td><td rowspan="2">only conclusive wind influence seen at barrier sites</td></tr>
<tr><td>strong-wind-removed data</td><td>1.0 dB wind influence at barrier sites</td></tr>
<tr><td colspan="2">percentage of heavy trucks (only for strong-wind-removed data)</td><td>no distinct trends</td><td>no apparent influence of % heavy trucks on TNM's performance</td></tr>
</table>

Recommendations

(See Table 16 at the end of Recommendations for a summary in tabular form.)

Data Calibration. By calibrating TNM sound levels to a reference microphone (within 100 ft from the roadway), more realistic predictions can be calculated at positions farther from the roadway, the location of residences. This calibration eliminates biases due to possible site-specific emission levels or possible over-predictions by TNM. For highway noise measurements, guidance on the sample period to use and the number of samples to obtain (to get a calibration value) can be found in the noise barrier standard [ANSI 1998] and FHWA's highway noise measurements report [Lee 1996]. To see examples of state policies on calibrating the model, refer to the following documents: Hendriks 1998 and Lindeman 2001.

Some Alternate TNM Runs and Recommendations. In running alternate TNM configurations of particular sites, it is seen that substantial ground undulations cannot be ignored (i.e., the site cannot be modeled with flat ground), as is expected. For the site examined, the undulations ranged from +5 to -20 ft (+1.5 to -6.0 m); more sites with undulations and changes in elevation will be analyzed in Phase 2 of the study. Investigations involving grass ground zone medians were inconclusive here, but adding a grass ground zone as the median when the actual site possesses one is recommended, unless its width is small [less than 10 ft (~3 m)]; in small-width cases, the roadways in each direction should be extended to overlap. Investigations involving ground zones at mixed ground [soft (e.g., field grass) and hard (e.g., pavement)] sites indicate that this type of site should be modeled with the default ground type being soft ground and the ground zones being hard ground.

Table 16. Recommendations on the Use of TNM.

Topic	Recommendation
Data Calibration	TNM-predicted sound levels should be calibrated to sound levels measured at a site. Refer to example state policies on model calibration [Hendriks 1998] [Lindeman 2001].
Ground Undulations	Substantial ground undulations [$ 5 ft (1.5 m)] should be modeled.
Grass Medians	Grass medians [with widths $ 10 ft (~3 m)] should be modeled using grass ground zones (rather than the median being defined by the default ground type of grass).
Ground Zones	Sites with mixed acoustically soft and hard ground should be modeled with the default ground type being soft ground and the ground zones being hard ground.

9.2 Future Work for the TNM Validation Study

Later phases of the TNM Validation Study will incorporate more site measurements and modeling along with further analysis of the Phase 1 data.

The later-phase measurement sites will incorporate Phase 1-type sites that need further investigation, sites with multiple TNM objects, and sites with less common TNM objects. Highway traffic noise measurements have already been performed at five sites in Pennsylvania, including sites with undulating terrain and substantial elevation changes. More measurements are being planned. All new data will be processed in a manner similar to that in Phase 1.

Some issues discussed in Phase 1 require further investigation, possibly supplementing Phase 1 analysis with more measurements and modeling. These include:

General TNM over-predictions are seen in the uncalibrated results. Although these over-predictions were essentially eliminated when calibrating the TNM sound levels to the measured reference microphone sound levels, they should be examined for future TNM improvements.

TNM's accuracy is dependent on wind conditions at noise barrier sites. Further analysis needs to be performed, including examining the wind effects at different heights above the ground. More data need to be collected and analyzed before determining the necessity of adding wind effects to the model.

One of the Phase 1 measurement sites, 10CA-open, contained an unusual ground surface. This site generated unusual results. It is planned that more open area sites with unusual ground surfaces will be examined in later phases of the study to better evaluate TNM's performance in such situations.

Plans for investigating the impact of different TNM-modeling techniques (different user methodologies) are already underway. Phase 1 and possibly Phase 2 sites will be used in this analysis.

10. REFERENCES

Anderson 1999 — Anderson, Grant S., *Hard-Site, Soft-Site Study: Emission Measurements and Propagation Acoustics,* Report No.295700-12 (Prepared for California Department of Transportation by Harris, Miller, Miller, and Hanson, Inc., Burlington, MA, 1999)

Anderson 1998 — Anderson, Grant S., Cynthia S.Y. Lee, Gregg G. Fleming, and Christopher W. Menge, *FHWA Traffic Noise Model, Version 1.0: User's Guide,* Report No.s FHWA-PD-96-009 and DOT-VNTSC-FHWA-98-1 (U.S. Department of Transportation, Volpe National Transportation Systems Center, Acoustics Facility, Cambridge, MA, 1998)

ANSI 1998 — American National Standards Institute and the Acoustical Society of America Standards, *Methods for Determining the Insertion Loss of Outdoor Noise Barriers,* ANSI S12.8-1998 (Acoustical Society of America, New York, New York, 1998)

ANSI 1995 — American National Standards Institute and the Acoustical Society of America Standards, *Measurement of Sound Pressure Levels in Air,* ANSI S1.13-1995 (Acoustical Society of America, New York, New York, 1995)

Attenborough 2000 — Attenborough, Keith and Tim Waters-Fuller, "Effective impedance of rough porous ground surfaces," *J. Acoust. Soc. Am.*, Vol. 108, No. 3, pp. 949-956 (2000)

Barry 1978 — Barry, T.M. and J. Regan, *FHWA Traffic Noise Prediction Model*, Report No. FHWA-RD-77-108 (Federal Highway Administration, Washington, DC, 1978)

Beranek 1992	Beranek, Leo L. and István L. Vér, editors, *Noise and Vibration Control Engineering - Principles and Applications* (John Wiley & Sons, Inc., New York, New York, 1992)
Bowlby 2000	Bowlby, William, "TNM validation work, I-40/I-240, Memphis, TN," Study overview from Bowlby & Associates, Inc. (2000)
Carpenter 1999	Carpenter, Sharon P., "TNM insertion loss study," Presentation at Highway Noise Subcommittee Meeting of Annual Transportation Research Board Conference (January, 1999)
Chambers 1997	Chambers, James P., James M. Sabatier, and Richard Raspet, "Grazing incidence propagation over a soft rough surface," *J. Acoust. Soc. Am.*, Vol. 102, No. 1, pp. 55-59 (1997)
Coulson 1996	Coulson, Robert K., *Vehicle Noise Source Heights and Sub-Source Spectra* (Florida Atlantic University, Boca Raton, Florida, 1996)
Embleton 1983	Embleton, T.F.W., J.E. Piercy, and G.A. Daigle, "Effective flow resistivity of ground surfaces determined by acoustical measurements," *J. Acoust. Soc. Am.*, Vol. 74, No. 4, pp. 1239-1244 (1983)
Fleming 2001	Fleming, G.G., *et al.*, "A differential global positioning system for determining time space position information in support of aircraft noise certification," *Proceedings of 2001 National Technical Meeting*, Institute of Navigation (2001)

Fleming 1996 Fleming, Gregg G., Amanda S. Rapoza, and Cynthia S.Y. Lee, *Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model (FHWA TNM®), Version 1.0*, Report No. FHWA-PD-96-008 and DOT-VNTSC-FHWA-96-2 (U.S. Department of Transportation, Volpe National Transportation Systems Center, Acoustics Facility, Cambridge, MA, 1996)

Fleming 1992 Fleming, Gregg G. and E. Rickley, *Parallel Barrier Effectiveness Under Free-flowing Traffic Conditions*, Report No. FHWA-RD-92-086 and DOT-VNTSC-FHWA-92-1 (Federal Highway Administration, Office of Engineering and Highway Operations Research and Development, Mclean, VA, 1992)

Harris 2000 Harris, R.A., L.F. Cohn, and Susan Knudson, "Evaluation of the Federal Highway Administration's Traffic Noise Model," *Journal of Transportation Engineering*, Vol. 126, pp. 513-520 (2000)

Hendriks 1998 Hendriks, Rudolf W., *Technical Noise Supplement: A Technical Supplement to the Traffic Noise Analysis Protocol* (California Department of Transportation, Division of Environmental Analysis, Sacramento, CA, 1998) – Website URL for document: www.dot.ca.gov/hq/env/noise/index.htm

Hendriks 1991 Hendriks, Rudolf W., *Field Evaluation of Acoustical Performance of Parallel Highway Noise Barriers Along Route 99 in Sacramento, California*, Report No. FHWA/CA/TL-91/01 (California Department of Transportation, Sacramento, CA, 1991)

Huybregts 2001	Huybregts, Cornelius and Stephen Samuels, "Experiences with implementing the American FHWA (TNM) in Australia," *Proceedings of Inter-Noise 2001* (2001)
Lee 1996	Lee, Cynthia S.Y. and Gregg G. Fleming, *Measurement of Highway-Related Noise,* Report No.s FHWA-PD-96-046 and DOT-VNTSC-FHWA-96-5 (U.S. Department of Transportation, Volpe National Transportation Systems Center, Acoustics Facility, Cambridge, MA, 1996)
Lindeman 2001	Lindeman, Winfield M., *Project Development and Environmental Manual (PD & E)*, Part 2, Chapter 17 (Florida Department of Transportation, Tallahassee, FL, 2001) – Website URL for document: www11.myflorida.com/emo/pubs/pdeman/pdeman.htm
Menge 1998	Menge, Christopher W., Christopher F. Rossano, Grant S. Anderson, and Christopher J. Bajdek, *FHWA Traffic Noise Model, Version 1.0: Technical Manual,* Report No.s FHWA-PD-96-010 and DOT-VNTSC-FHWA-98-2 (U.S. Department of Transportation, Volpe National Transportation Systems Center, Acoustics Facility, Cambridge, MA, 1998)
Parkin 1965	Parkin, P.H. and W.E. Scholes, "The horizontal propagation of sound from a jet engine close to the ground, at Hatfield," *J. Sound Vib.*, Vol. 2, No. 4, pp. 353-374 (1965)
Reyff 2001	Reyff, James, *I-80 Davis OGAC Pavement Noise Study,* 3-Year Summary Report (Prepared for California Department of Transportation by Illingworth & Rodkin, Inc., Petaluma, CA, 2001)

Romick 1999 Romick-Allen, Richard K., Susan M. Morgan, Chiang Lin, and Rex Pierce, *Acoustics of Sound Transmission Over Noise Barrier Walls*, Report No. ITRC FR97-4 (Illinois Transportation Research Center, Edwardsville, IL, 1999)

Scholes 1971 Scholes, W.E., A.C. Salvidge, and J.W. Sargent, "Field performance of a noise barrier," *J. Sound Vib.*, Vol. 16, pp. 627-642 (1971)

Staiano 2001 Staiano, Michael A., "TNM validation case - April 2000 measurements of Interstate I-97," Study overview from Staiano Engineering, Inc. (2001)

Wayson 2001 Wayson, Roger L., *et al.*, "Noise barrier measurement, modeling and evaluation at multiple sites in Florida," *Proceedings of Inter-Noise 2001* (2001)

Appendix A:

Research Team Members and Responsibilities

<u>Volpe National Transportation Systems Center, Acoustics Facility</u>:

Gregg Fleming

Division Chief, Environmental Measurement and Modeling; B.S., Electrical Engineering, University of Lowell, MA. Mr. Fleming is responsible for all aspects of the study.

Judith Rochat

Physical Scientist; Ph.D., Acoustics, Pennsylvania State University, University Park, PA. Dr. Rochat is involved with all aspects related to study design, data collection, data reduction, and data analysis.

David Read

Computer Specialist. Mr. Read is involved with aspects related to study design, data collection, data reduction, and data analysis and is also responsible for the acoustical instrumentation, both preparatory and in the field.

Cynthia Lee

Electronics Engineer; B.S., Electrical Engineering, Northeastern University, Boston, MA. Ms. Lee is involved with aspects related to study design, data collection, data reduction, and data analysis.

Christopher Roof

Electronics Engineer; B.S., Electrical Engineering and Music, Boston University, Boston, MA. Mr. Roof provides data collection support.

Amanda Rapoza

Electronics Engineer; B.S., Acoustic Engineering, University of Hartford, West Hartford, CT. Ms. Rapoza provides data collection and data analysis support.

Brian Kim

Environmental Engineer; Ph.D. Candidate, Environmental Engineering, University of Central Florida, Orlando, FL. Mr. Kim provides data collection support.

Clay Reherman

General Engineer; M.S., Manufacturing Engineering, Boston University, Boston, MA. Mr. Reherman provides data analysis support.

Eric Boeker

Physical Scientist; M.S., Acoustics, Pennsylvania State University, University Park, PA. Mr. Boeker provides data collection and data analysis support.

Michael Lau

Computer Engineer; B.S., Computer Systems Engineering, Boston University, Boston, MA. Mr. Lau provides data collection and data analysis support.

Max Gates, John Foulis, Khemerith Veasna, Matt Corbo, Kevin Wright

College students who provide data collection and data analysis support.

Other Organizations:

Bob Armstrong - Federal Highway Administration (FHWA)
Noise Team Leader, Office of Natural Environment. Mr. Armstrong is involved with aspects of study design.

Steve Ronning - FHWA
Noise Specialist, Office of Natural Environment. Mr. Ronning is involved with aspects of study design and data collection support.

Chris Corbisier - FHWA
Civil Engineer, Office of Natural Environment. Mr. Corbisier is involved with aspects of study design and data collection support.

Trevor May - Out of the Box Productions
Environmental and Graphic Designer. Mr. May provides data collection and data analysis support.

Harvey Knauer - Environmental Acoustics
Transportation Noise and Air Quality Engineer. Mr. Knauer provides site selection and data collection support.

Soren Pedersen - Catseye Services
President. Mr. Pedersen provides site selection support.

Bruce Rymer - California Department of Transportation (Caltrans)
Senior Transportation Engineer. Mr. Rymer is involved with aspects of study design and provides data collection support.

Rudy Hendriks - Caltrans

Retired Annuitant. Mr. Hendriks is involved with aspects of study design and provides data collection support.

Keith Jones - Caltrans

Senior Transportation Engineer. Mr. Jones is involved with aspects of study design.

Balachandra Nanjundaiah - Caltrans

Transportation Engineer. Mr. Nanjundaiah provides data collection support.

Jim Andrews - Caltrans

Senior Transportation Engineer. Mr. Andrews provides data collection support.

Lefteris Koumis - Caltrans

Transportation Engineer. Mr. Koumis provides data collection support.

Chris Corwin, Andre Nguyen, Mitch Khalilifia, Dave Buehler - Caltrans

District personnel and contractors who provide data collection support.

Appendix B:
Measurement Site Details

All TNM Validation Phase 1 measurement sites are described here in detail, including site location, microphone positions, and meteorological system positions. All heights of the instrumentation are measured above the ground level, with exceptions noted. In addition to a photograph of each site, the TNM plan and skew views for the model of each site are presented. The following abbreviations are applied in the site descriptions:

DGAC	Dense-graded asphalt concrete
OGAC	Open-graded asphalt concrete
PCC	Portland cement concrete
d	distance from roadway
bb	distance behind barrier

Site ID	01MA	
Location	Taunton, MA; Rte 24; Southbound side; just North of Exit 12, near overpass	
Site Type	open area, flat	
Ground Type	field grass, acoustically soft	
Roadway	4 lanes, DGAC, shoulders, field grass median	
Instrumentation Positions	Microphones d = 50 ft, height = 5 and 15 ft d = 100 ft, height = 5 and 15 ft d = 200 ft, height = 5 and 15 ft	Meteorological Systems d = 75 ft, height = 5 and 15 ft d = 150 ft, height = 5 and 15 ft

Figure B.1(a). Site 01MA: Description and Photograph

Site ID	**01MA - TNM model** (TNM Version 1.1)
Default Ground Type	field grass
Pavement Type	average
TNM objects	roadways, receivers, terrain lines (defining trench: depth = 4 ft)

plan view

skew view

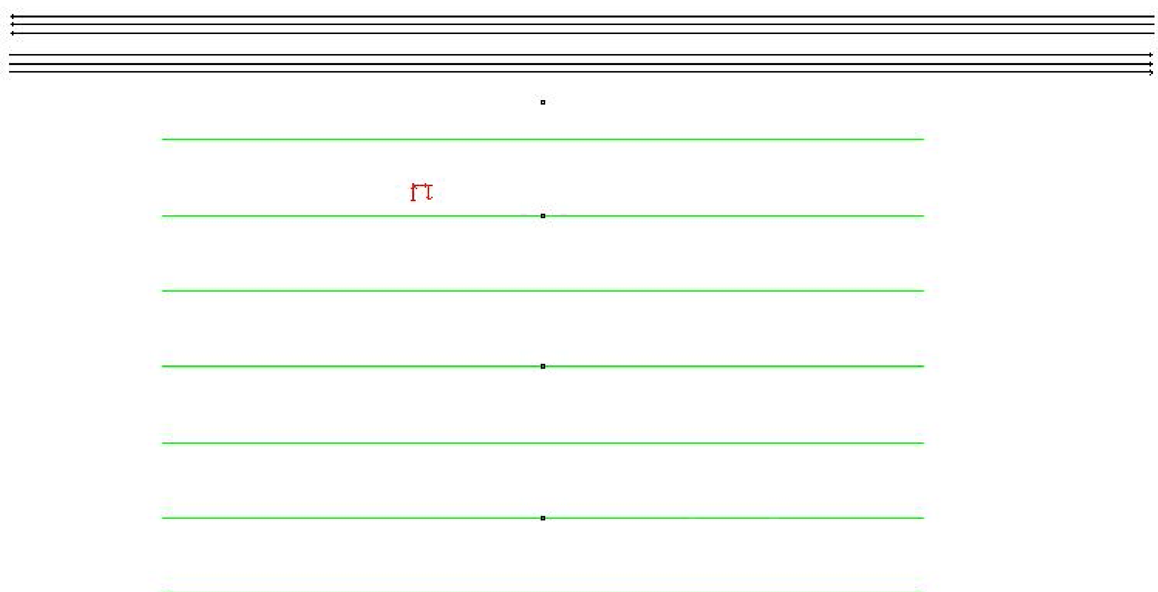
Figure B.1(b). Site 01MA: TNM Model Description, TNM Plan and Skew Views

Site ID	02MA	
Location	Acton, MA; Rte 2; Eastbound side; 1 mile East of Exit 43	
Site Type	open area, undulating	
Ground Type	field grass and alfalfa, acoustically soft	
Roadway	4 lanes, DGAC, shoulders, field grass median	
Instrumentation Positions	Microphones d = 50 ft, height = 5 and 15 ft d = 200 ft, height = 5 and 15 ft d = 400 ft, height = 5 and 15 ft d = 600 ft, height = 5 and 15 ft	Meteorological Systems d = 100 ft, height = 5 and 15 ft d = 500 ft, height = 5 and 15 ft

Figure B.2(a). Site 02MA: Description and Photograph

Site ID	**02MA - TNM model** (TNM Version 1.1)
Default Ground Type	field grass
Pavement Type	average
TNM objects	roadways, receivers, terrain lines (defining undulations: ranging from -20 to +3 ft), barrier (for large boulder)

plan view



skew view

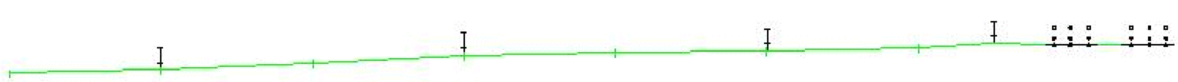


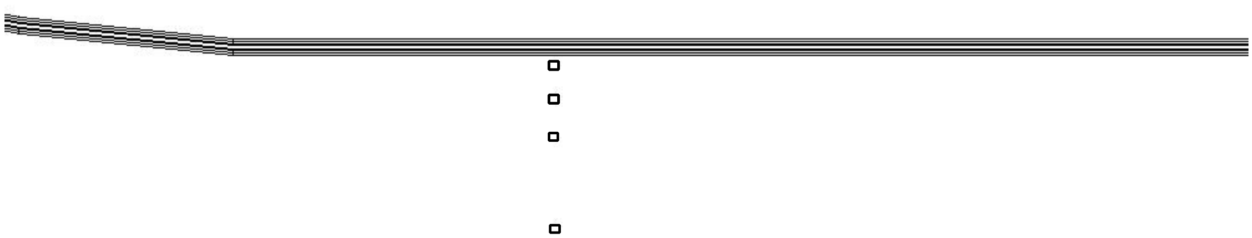
Figure B.2(b). Site 02MA: TNM Model Description, TNM Plan and Skew Views

Site ID	**03MA**	
Location	Springfield, MA; Rte 291; Northbound side; South of Exit 5; Smith & Wesson soccer fields	
Site Type	open area, flat	
Ground Type	lawn, acoustically soft	
Roadway	4 lanes, DGAC, shoulders, hard soil median	
Instrumentation Positions	Microphones d = 50 ft, height = 5 ft above roadway level d = 200 ft, height = 5 and 15 ft d = 400 ft, height = 5 and 15 ft d = 800 ft, height = 5 and 15 ft	Meteorological Systems d = 150 ft, height = 5 and 15 ft d = 600 ft, height = 5 and 15 ft

Figure B.3(a). Site 03MA: Description and Photograph

Site ID	**03MA - TNM model** (TNM Version 1.1)
Default Ground Type	lawn
Pavement Type	average
TNM objects	roadways, receivers, ground zone (hard soil median: width = 14 ft)

plan view



skew view

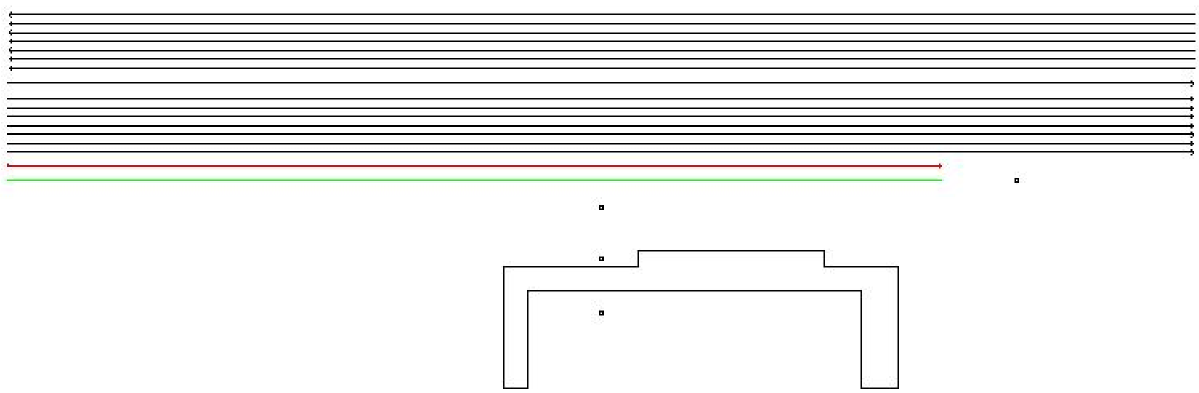
Figure B.3(b). Site 03MA: TNM Model Description, TNM Plan and Skew Views

Site ID	**04CT**	
Location	East Hartford, CT; Rte 84; Northbound side; North of Exit 58; farthest North lawn of Woodcliff Estates	
Site Type	barrier (17.3 ft wood), flat	
Ground Type	lawn and some pavement, mixed acoustically soft and hard	
Roadway	12 lanes, DGAC, shoulders, pavement median	
Instrumentation Positions	Microphones d = 52.5 ft (offset from mic line, no barrier), height = 5 ft bb = 56 ft, height = 5 and 15 ft bb = 125 ft, height = 5 and 15 ft bb = 200 ft, height = 5 and 15 ft	Meteorological Systems bb = 75 ft, height = 5 and 15 ft bb = 175 ft, height = 5 and 15 ft

Figure B.4(a). Site 04CT: Description and Photograph

Site ID	**04CT - TNM model** (TNM Version 1.1)
Default Ground Type	lawn
Pavement Type	average
TNM objects	barrier, roadways, receivers, terrain line (change in elevation of -5 ft from barrier base), ground zone (pavement parking lot: largest width = 55 ft, largest length ~ 530 ft)

plan view



skew view

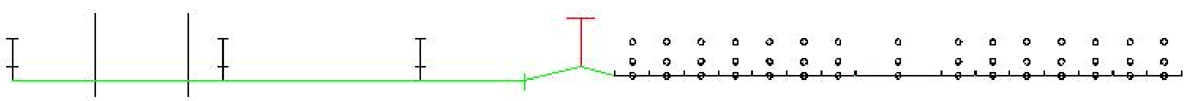


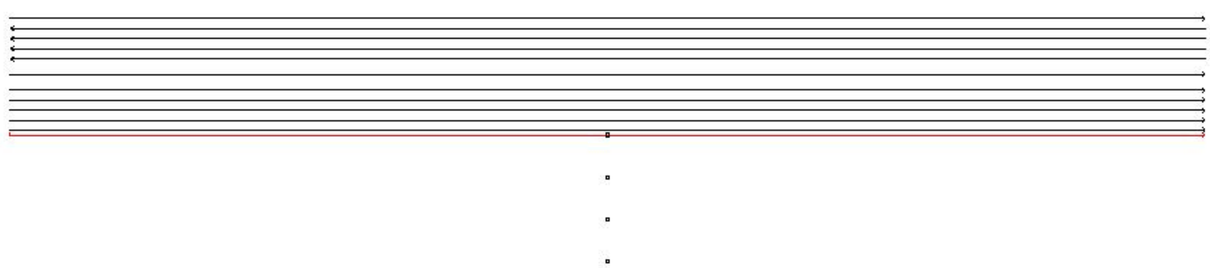
Figure B.4(b). Site 04CT: TNM Model Description, TNM Plan and Skew Views

Site ID	05CA	
Location	Chino Hills, CA; Rte 71; Southbound side; just North of Central Ave/Soquel Cyn Pkwy Exit; near intersection of Los Serranos and Pomona Ricon	
Site Type	barrier (15 ft concrete block), flat	
Ground Type	field grass, acoustically soft	
Roadway	8 lanes, PCC, shoulders, pavement median	
Instrumentation Positions	Microphones bb = 0 ft, height = 3.5 ft above barrier bb = 50 ft, height = 5 and 15 ft bb = 100 ft, height = 5 and 15 ft bb = 150 ft, height = 5 and 15 ft	Meteorological Systems bb = 75 ft, height = 5 and 15 ft bb = 125 ft, height = 5 and 15 ft

Figure B.5(a). Site 05CA: Description and Photograph

Site ID	**05CA - TNM model** (TNM Version 1.1)
Default Ground Type	field grass
Pavement Type	average
TNM objects	barrier, roadways, receivers

plan view



skew view

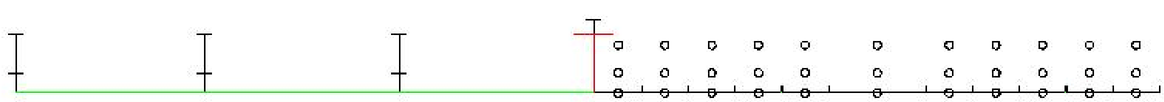


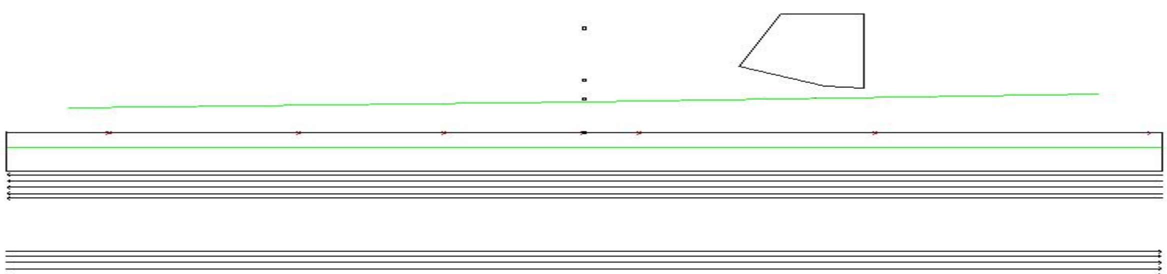
Figure B.5(b). Site 05CA: TNM Model Description, TNM Plan and Skew Views

Site ID	**06CA**	
Location	Wildomar, CA; Rte 15; Southbound side; South of Baxter Exit; playing fields of Donald Graham Elementary School	
Site Type	barrier (ave 12.5 ft: 5 ft berm, 7.5 ft concrete block wall), flat, with 27 ft drop-off from barrier	
Ground Type	lawn, acoustically soft	
Roadway	6 lanes, DGAC, shoulders, grass median	
Instrumentation Positions	Microphones bb = 0 ft, height = 5 ft above barrier bb = 55 ft, height = 5 and 15 ft bb = 100 ft, height = 5 and 15 ft bb = 200 ft, height = 5 and 15 ft	Meteorological Systems bb = 75 ft, height = 5 and 15 ft bb = 150 ft, height = 5 and 15 ft

Figure B.6(a). Site 06CA: Description and Photograph

Site ID	**06CA - TNM model** (TNM Version 1.1)
Default Ground Type	lawn
Pavement Type	average
TNM objects	roadways, receivers, barrier, terrain lines (start of change in elevation of +5 ft from roadway level to barrier base; change in elevation of -27 ft from barrier base to mic line), ground zones (hard soil for edge of road: width = 74 ft; pavement for blacktop play area: largest dimension ~ 145 ft)

plan view



skew view

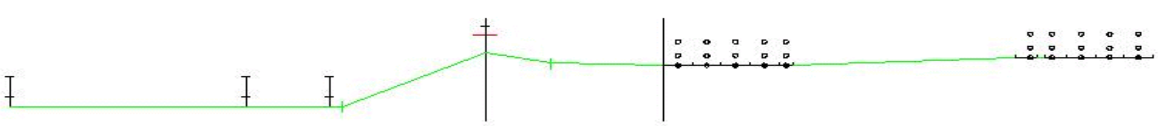


Figure B.6(b). Site 06CA: TNM Model Description, TNM Plan and Skew Views

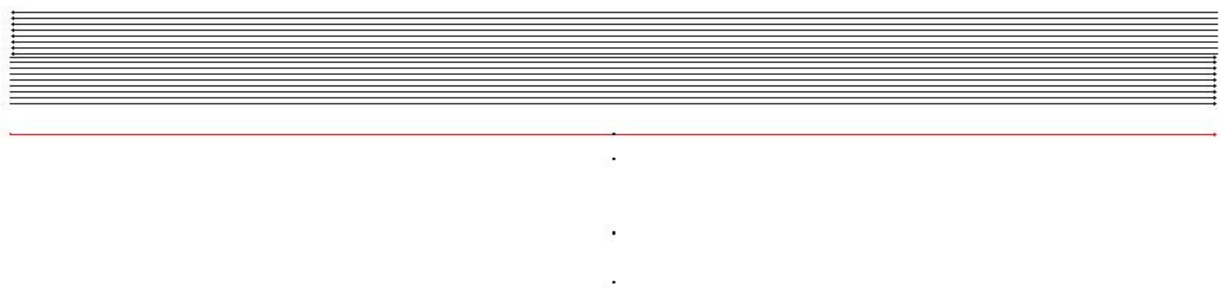
Site ID	**08CA** Measured two microphone lines: one with a single barrier (as shown and described here) and one with parallel barriers (will be analyzed in a later phase of the study).	
Location	Anaheim, CA; Rte 91; Eastbound side; East of Lakeview Exit; playing fields of Peralta Canyon Park	
Site Type	barrier (14.5 ft concrete block), relatively flat	
Ground Type	lawn, acoustically soft	
Roadway	14 lanes, PCC (HOV lanes DGAC), shoulders, pavement median	
Instrumentation Positions	Microphones bb = 0 ft, height = 5 ft above barrier bb = 50 ft, height = 5 and 15 ft bb = 200 ft, height = 5 and 15 ft bb = 300 ft, height = 5 ft	Meteorological Systems bb = 100 ft, height = 5 and 15 ft

Figure B.7(a). Site 08CA: Description and Photograph

Site ID	**08CA - TNM model** (TNM Version 1.1)
Default Ground Type	lawn
Pavement Type	average
TNM objects*	roadways, receivers, barrier

*Since there is a slight incline from the 50-ft mic to the 300-ft mic, this was accounted for in the mic line using the z coordinate of the receivers (potentially important to the sound propagation path length). This incline is not consistent throughout the site and was therefore not modeled elsewhere.

plan view



skew view

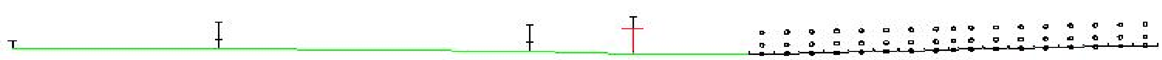


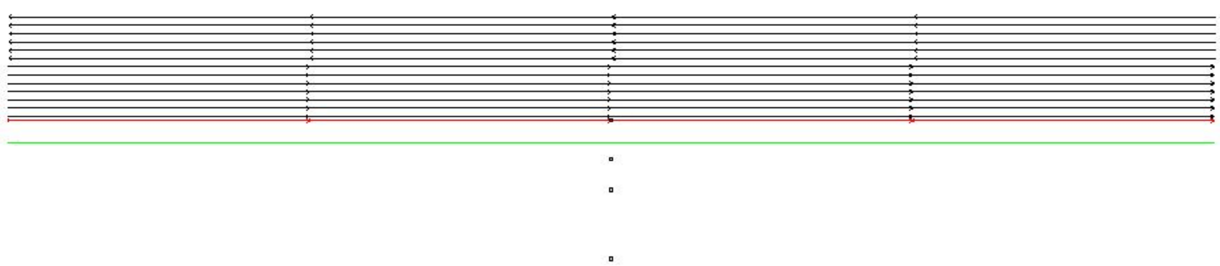
Figure B.7(b). Site 08CA: TNM Model Description, TNM Plan and Skew Views

Site ID	**09CA**	
Location	Chino, CA; Rte 71; Northbound side; North of Edison/Grand Exit; field at end of Alicia St	
Site Type	barrier (15 ft concrete block), flat, with 16 ft drop-off from barrier	
Ground Type	field grass, acoustically soft	
Roadway	10 lanes, PCC, shoulders, pavement median	
Instrumentation Positions	Microphones bb = 0 ft, height = 5 ft above barrier bb = 55 ft, height = 5 and 15 ft bb = 100 ft, height = 5 and 15 ft bb = 200 ft, height = 5 and 15 ft	Meteorological Systems bb = 75 ft, height = 5 and 15 ft bb = 150 ft, height = 5 and 15 ft

Figure B.8(a). Site 09CA: Description and Photograph

Site ID	**09CA - TNM model** (TNM Version 1.1)
Default Ground Type	field grass
Pavement Type	average
TNM objects	roadways, receivers, barrier, terrain line (change in elevation of -16 ft from barrier base to mic line)

plan view



skew view

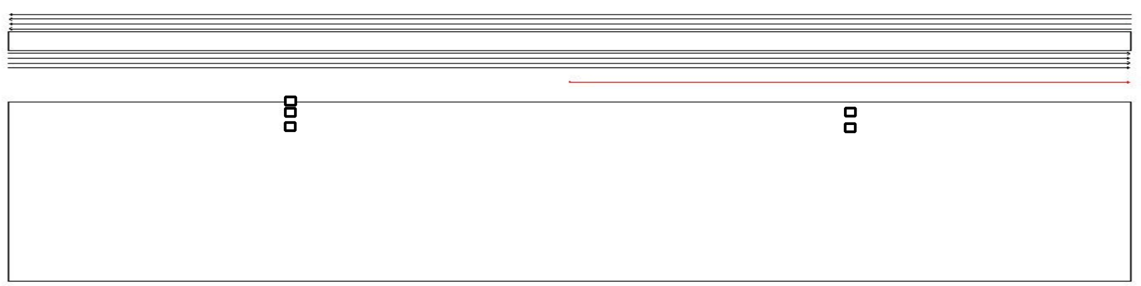
Figure B.8(b). Site 09CA: TNM Model Description, TNM Plan and Skew Views

Site ID	**10CA - berm**	Measured two microphone lines: one with a berm (as shown and described here) and one with an open area (shown next).
Location	Mira Loma, CA; Rte 15; Southbound side; North of Limonite Ave Exit; field just North of Swan Lake Community	
Site Type	barrier (16 ft grass-covered earth berm), flat	
Ground Type	plowed dirt, acoustically soft	
Roadway	6 lanes, PCC, shoulders, hard soil median	
Instrumentation Positions	Microphones d = 98 ft (bb = 50 ft) (in the open area mic line), height = 5 ft bb = 70 ft, height = 5 and 15 ft bb = 110 ft, height = 5 and 15 ft	Meteorological Systems bb = 90 ft, height = 5 and 15 ft

Figure B.9(a). Site 10CA-berm: Description and Photograph

Site ID	**10CA - berm - TNM model** (TNM Version 1.0b)
Default Ground Type	field grass
Pavement Type	average
TNM objects	roadways, receivers, barrier (as berm), ground zones (hard soil for median: width = 48 ft; loose soil for measurement field: width ~ 450 ft)

plan view (berm and open area sites combined)



skew view (just berm)

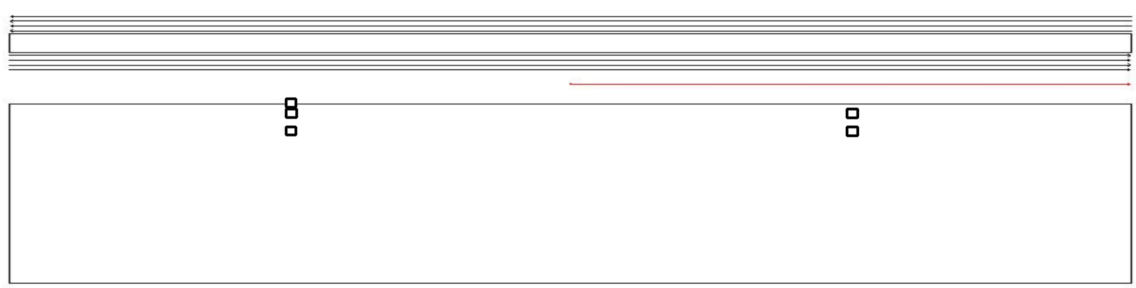
Figure B.9(b). Site 10CA-berm: TNM Model Description, TNM Plan and Skew Views

Site ID	**10CA - open**	Measured two microphone lines: one with a berm (previously shown) and one with an open area (as shown and described here).
Location	Mira Loma, CA; Rte 15; Southbound side; North of Limonite Ave Exit; field just North of Swan Lake Community	
Site Type	open area, flat	
Ground Type	plowed dirt, acoustically soft	
Roadway	6 lanes, PCC, shoulders, hard soil median	
Instrumentation Positions	Microphones d = 98 ft (bb = 50 ft) height = 5 ft d = 118 ft (bb = 70 ft), height = 5 and 15 ft d = 158 ft (bb = 110 ft), height = 5 and 15 ft	Meteorological Systems d = 138 ft (bb = 90 ft), height = 5 and 15 ft

Figure B.10(a). Site 10CA-open: Description and Photograph

Site ID	**10CA- open - TNM model** (TNM Version 1.0b)
Default Ground Type	field grass
Pavement Type	average
TNM objects	roadways, receivers, ground zones (hard soil for median: width = 48 ft; loose soil for measurement field: width ~ 450 ft)

plan view (berm and open area sites combined)



skew view (just open area)

Figure B.10(b). Site 10CA-open: TNM Model Description, TNM Plan and Skew Views

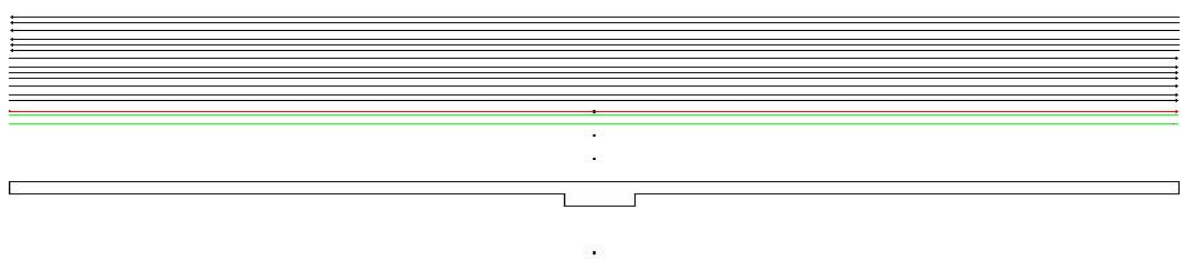
Site ID	**11CA**	
Location	Sunnyvale, CA; Rte 237; Westbound side; just East of E. Carribean Drive Exit; Eastern end of Sunnyvale Baylands County Park	
Site Type	barrier (16 ft wood), relatively flat	
Ground Type	field grass and some pavement, mixed acoustically soft and hard	
Roadway	3 lanes + 2 auxiliary lanes, DGAC, shoulders, buffer zones, pavement median	
Instrumentation Positions	Microphones bb = 0 ft, height = 5 ft above barrier bb = 50 ft, height = 5 and 15 ft bb = 100 ft, height = 5 and 15 ft bb = 300 ft, height = 5 and 15 ft	Meteorological Systems bb = 75 ft, height = 5 and 15 ft bb = 200 ft, height = 5 and 15 ft

Figure B.11(a). Site 11CA: Description and Photograph

Site ID	**11CA - TNM model** (TNM Version 1.1)
Default Ground Type	field grass
Pavement Type	average
TNM objects	roadways, receivers, barrier, terrain lines* (change in elevation of -4 ft from barrier base/roadway level to mic line), ground zone (pavement drive and parking area: largest width = 52 ft)

*Since there is a slight incline from the 50-ft mic to the 300-ft mic, this was accounted for in the mic line using the z coordinate of the receivers (potentially important to the sound propagation path length). When first modeling the site, a terrain line was added to the back of the site, just beyond the 300 ft mic in order to apply the slight incline to the entire area, not just the mic line. It was shown that this additional terrain line did not affect the levels and was therefore removed.

plan view



skew view

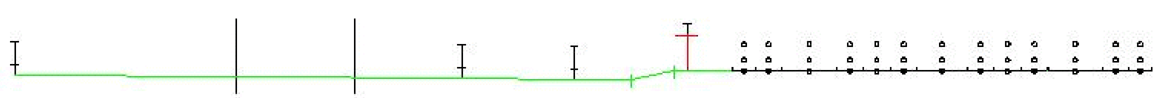


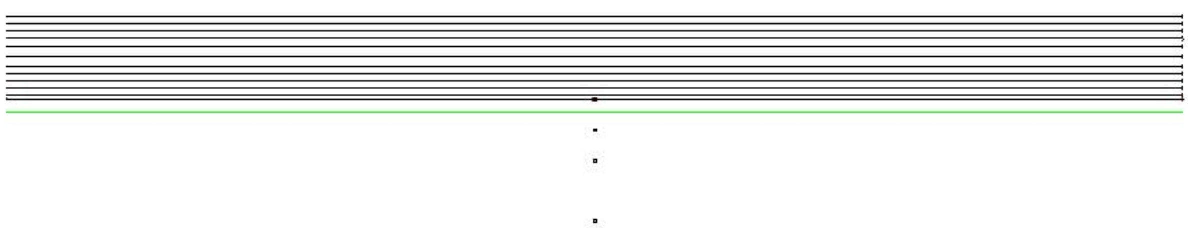
Figure B.11(b). Site 11CA: TNM Model Description, TNM Plan and Skew Views

<table>
<tr><td>Site ID</td><td colspan="2">12CA</td></tr>
<tr><td>Location</td><td colspan="2">San Ramon, CA; Rte 680; Northbound side; South of Bollinger Canyon Exit; Athan Downs Sports Fields (Northern most field)</td></tr>
<tr><td>Site Type</td><td colspan="2">barrier (12 ft concrete block), flat, with 6 ft drop-off from barrier</td></tr>
<tr><td>Ground Type</td><td colspan="2">lawn, acoustically soft</td></tr>
<tr><td>Roadway</td><td colspan="2">8 lanes, PCC, shoulders, pavement median</td></tr>
<tr><td>Instrumentation Positions</td><td>Microphones
bb = 0 ft, height = 4 ft above barrier
bb = 50 ft, height = 5 and 15 ft
bb = 100 ft, height = 5 and 15 ft
bb = 200 ft, height = 5 and 15 ft</td><td>Meteorological Systems
bb = 75 ft, height = 5 and 15 ft
bb = 150 ft, height = 5 and 15 ft</td></tr>
</table>

Figure B.12(a). Site 12CA: Description and Photograph

Site ID	**12CA - TNM model** (TNM Version 1.1)
Default Ground Type	lawn
Pavement Type	average
TNM objects	roadways, receivers, barrier, terrain line (change in elevation of -6 ft from barrier base to mic line), ground zone (pavement for strip next to barrier, not necessary)

plan view



skew view

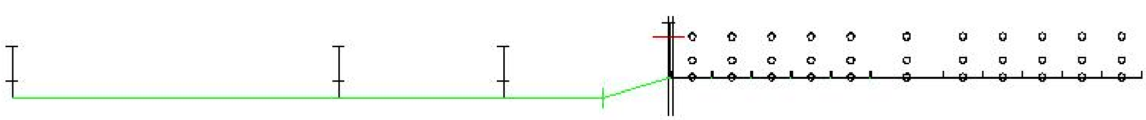


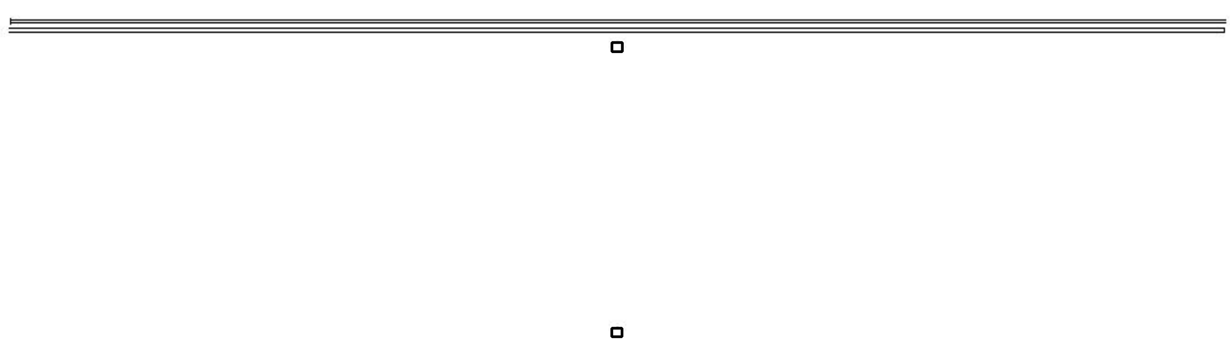
Figure B.12(b). Site 12CA: TNM Model Description, TNM Plan and Skew Views

<table>
<tr><th>Site ID</th><th colspan="2">13CA</th></tr>
<tr><td>Location</td><td colspan="2">Sonoma, CA; Rte 37; Eastbound side; ~0.5 mi East of Rte 121; Tolay Creek Levee, San Pablo Bay National Wildlife Refuge</td></tr>
<tr><td>Site Type</td><td colspan="2">open area, relatively flat</td></tr>
<tr><td>Ground Type</td><td colspan="2">water, acoustically hard</td></tr>
<tr><td>Roadway</td><td colspan="2">2 lanes, OGAC?, shoulders, pavement median</td></tr>
<tr><td>Instrumentation Positions</td><td>Microphones
d =50 ft (offset from mic line), height = 5 and 15 ft
d = 900 ft, height = 5 and 15 ft</td><td>Meteorological Systems
d = 100 ft (offset from mic line), height = 5 and 15 ft
d = 900 ft, height = 5 and 15 ft</td></tr>
</table>

Figure B.13(a). Site 13CA: Description and Photograph

Site ID	**13CA - TNM model** (TNM Version 1.1)
Default Ground Type	water
Pavement Type	average
TNM objects	roadways, receivers

plan view



skew view

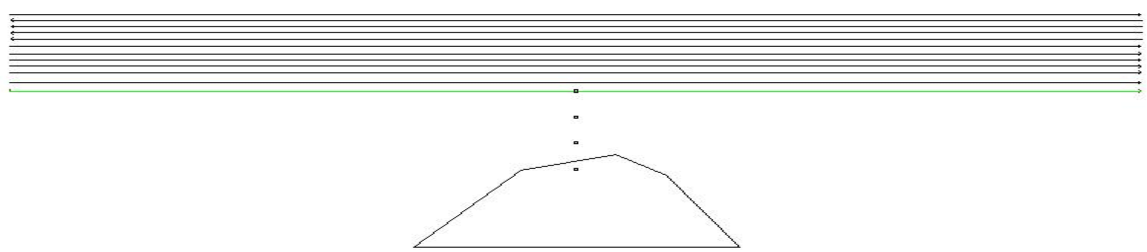
Figure B.13(b). Site 13CA: TNM Model Description, TNM Plan and Skew Views

Site ID	**14CA**	
Location	Fremont, CA; Rte 880; Northbound side; South of Stevenson Blvd Exit; Marshall Park	
Site Type	barrier (16 ft concrete block), flat, with 2 ft drop-off from barrier	
Ground Type	lawn and wood chips, acoustically soft	
Roadway	8 lanes, DGAC, shoulders, pavement median	
Instrumentation Positions	Microphones bb = 0 ft, height = 5 ft above barrier bb = 50 ft, height = 5 and 15 ft bb = 100 ft, height = 5 and 15 ft bb = 150 ft, height = 5 and 15 ft	Meteorological Systems bb = 75 ft, height = 5 and 15 ft bb = 135 ft, height = 5 and 15 ft

Figure B.14(a). Site 14CA: Description and Photograph

Site ID	**14CA - TNM model** (TNM Version 1.1)
Default Ground Type	field grass
Pavement Type	average
TNM objects	roadways, receivers, barrier, terrain line (change in elevation of -2 ft from barrier base to mic line), ground zone (lawn area: largest width ~ 180 ft, largest length ~ 400 ft)

plan view



skew view

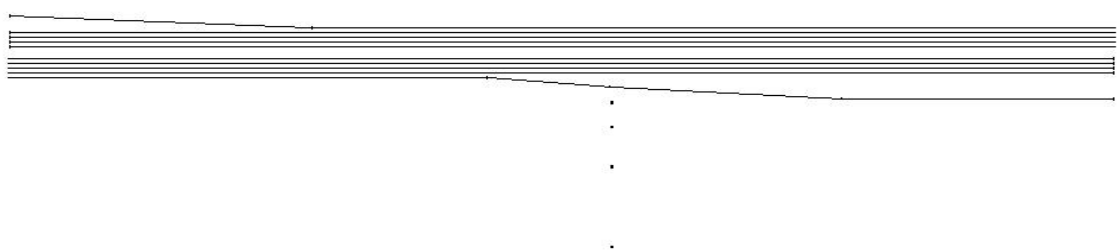
Figure B.14(b). Site 14CA: TNM Model Description, TNM Plan and Skew Views

Site ID	**15CA**	
Location	Oakland, CA; Rte 880; Northbound side; South of 66th Ave Exit; Oakland Stadium Parking Lot C (on South side of stadium)	
Site Type	open area, flat	
Ground Type	pavement, acoustically hard	
Roadway	10 lanes, DGAC, shoulders, pavement median	
Instrumentation Positions	Microphones d = 40 ft, height = 5 and 15 ft d = 100 ft, height = 5 and 15 ft d = 200 ft, height = 5 and 15 ft d = 400 ft, height = 5 and 15 ft	Meteorological Systems d = 105 ft, height = 5 and 15 ft d = 300 ft, height = 5 and 15 ft

Figure B.15(a). Site 15CA: Description and Photograph

Site ID	**15CA - TNM model** (TNM Version 1.1)
Default Ground Type	pavement
Pavement Type	average
TNM objects	roadways, receivers

plan view



skew view

Figure B.15(b). Site 15CA: TNM Model Description, TNM Plan and Skew Views

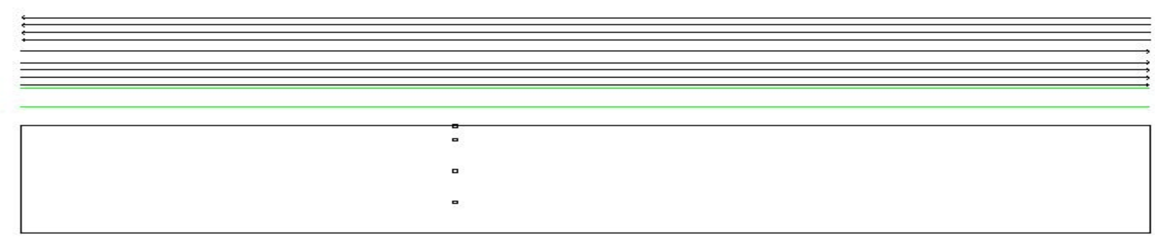
Site ID	**16MA**	
Location	Wayland, MA; Rte 90; Eastbound side; East of Natick Exit (13); Cochituate State Park, farthest parking lot East of boat launch (adjacent to Rte 30 overpass)	
Site Type	open area, flat	
Ground Type	mostly pavement with some lawn, acoustically hard and soft	
Roadway	6 lanes, DGAC, shoulders, pavement median	
Instrumentation Positions	Microphones d = 78 ft, height = 5 and 15 ft d = 100 ft, height = 5 and 15 ft d = 150 ft, height = 5 and 15 ft d = 200 ft, height = 5 and 15 ft	Meteorological Systems d = 90 ft, height = 5 and 15 ft d = 175 ft, height = 5 and 15 ft

Figure B.16(a). Site 16MA: Description and Photograph

Site ID	**16MA - TNM model** (TNM Version 1.1)
Default Ground Type	field grass
Pavement Type	average
TNM objects	roadways*, receivers, terrain lines (defining trench: depth = 4 ft), ground zone (pavement parking lot: width ~ 170 ft)

*Highway traffic noise from farther distances to the West is blocked by a hill and an overpass; in order to concentrate more on a simple hard ground site, these shielding objects were not modeled, and, instead, the roadways were shortened.

plan view



skew view

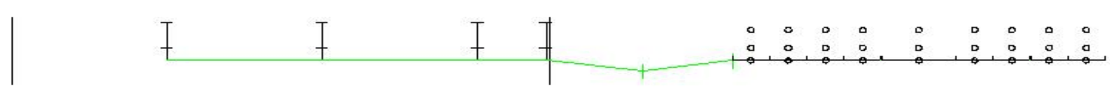


Figure B.16(b). Site 16MA: TNM Model Description, TNM Plan and Skew Views

<table>
<tr><td>Site ID</td><td colspan="2">17CT</td></tr>
<tr><td>Location</td><td colspan="2">Stafford, CT; Rte 84; Eastbound side; just East of Exit 72</td></tr>
<tr><td>Site Type</td><td colspan="2">open, relatively flat</td></tr>
<tr><td>Ground Type</td><td colspan="2">water, acoustically hard</td></tr>
<tr><td>Roadway</td><td colspan="2">6 lanes, DGAC, shoulders, grass median</td></tr>
<tr><td>Instrumentation
Positions</td><td>Microphones
d = 60 ft, height = 5 and 15 ft
d = 1273 ft, height = 5 and 15 ft</td><td>Meteorological Systems
d = 60 ft, height = 5 and 15 ft
d = 1273 ft, height = 5 and 15 ft</td></tr>
</table>

Figure B.17(a). Site 17CT: Description and Photograph

Site ID	**17CT - TNM model** (TNM Version 1.1)
Default Ground Type	pavement
Pavement Type	average
TNM objects	roadways*, receivers, ground zone (field grass median: width = 18 ft)

*Highway traffic noise from farther distances to the South is blocked by a hill and an overpass; in order to concentrate more on a simple hard ground site, these shielding objects were not modeled, and, instead, the roadways were shortened.

plan view

skew view

Figure B.17(b). Site 17CT: TNM Model Description, TNM Plan and Skew Views

Appendix C:

Acoustical Instrumentation Systems Reference

C.1 Instrumentation List

A. B&K Deltatron Microphone System:

Model 4155 or 4189 ½-in Electret Condenser Microphone

Model 2671 Deltatron Preamplifier

Model WB 1372 Deltatron Power Supply

Custom-fabricated BNC to XLR adapters

Custom-fabricated 4-conductor 100 ft (~30 m) or 300 ft (~90 m) shielded XLR microphone cables

B. Spectrum Analyzer (LDL 2900):

LDL Model 2900 Spectrum Analyzer

C. Sound Level Meter (LDL 820):

LDL Model 820 Sound Level Meter

D. Digital Audio Tape (DAT) Recorder:

Sony Model TCD-D100 DAT Recorder

Ancillary:

B&K Model 4231 Sound Calibrator

½-in Microphone Simulator (Dummy Microphone)

Ivie IE-20B Pink Noise Generator

17 Ah Gel-Cell Battery *or* 40 Ah Gel-Cell Battery

Tripod (with extending pole or mast for high positions)

Watch to serve as Master Clock

C.2 Configuration

A. LDL Model 2900 Spectrum Analyzer:

1. Range settings - Normal calibration at 114 dB SPL will automatically set the input range to 120 dB. The range stays at 120 dB for pink noise and is changed to 60 dB for testing the noise floor with the microphone simulator. The input range also changes for data collection (usually to 100 dB for highway traffic noise). All such changes are logged.

2. Data settings - For calibration, the LDL 2900 set-up has the following features: dual channel, linear 20 Hz to 10 kHz weighting on input, and 0.5-second L_{eq}. For data collection, the LDL 2900 set-up has the following features: dual channel, A-weight filter on input, and 5-second L_{eq}.

B. LDL Model 820 Sound Level Meter:

1. Data settings - The LDL 820 set-up has the following features: A-weight filter on input and 5-second L_{eq}.

C. SONY Model TCD-D100 DAT Recorder:

1. Mode - Operate the Sony TCD-D100 in "LP" (half-speed) mode; the sample rate is 32 kHz. In this mode the tape duration is approximately four hours.

2. Range - Calibrate using the 114 dB 1 kHz tone; set the gain at -6 dB VU, allowing a dynamic range of about 40 to 120 dB.

C.3 Operation

A. Set-up:

1. Run microphone cable and connect between B&K Model 2671 Deltatron preamplifier and B&K Model WB 1372 Deltatron power supply. Note: Custom-fabricated BNC-to-XLR adapter cables are required at both ends of the microphone cable.

2. Interconnect equipment per Figures C.1, C.2, and C.3.

3. Set time and date on the LDL 2900 Spectrum Analyzer, LDL 820 Sound Level Meter, and Sony TCD-D100 DAT Recorder per Master Clock.

4. Check instrument settings.

B. Calibration:

1. Remove foam windscreen from microphone.

2. Carefully apply calibrator to microphone.

3. Carefully apply power to calibrator (114 dB setting).

4. Wait ten seconds for system to stabilize.

5. Perform calibration of LDL Model 2900.

6. Perform calibration of the LDL 820 SLM and the Sony TCD-D100 DAT recorder. On the Sony TCD-D100, record the calibration signal for at least 30 seconds; this duration allows an ID marker to be written. A normal calibration will illuminate 8 segments on

the Sony Model TCD-D100 display.

7. After recording the calibration signal, turn off the calibrator and remove it from the microphone.

8. Remove the microphone from the B&K Model 2671 Deltatron preamplifier.

9. Attach the Ivie IE-20B Pink Noise Generator to the B&K Model 2671.

10. Capture and record 30 seconds of the pink noise.

11. Remove the Ivie IE-20B Pink Noise Generator from the B&K Model 2671.

12. Attach the ½-in microphone simulator to the B&K Model 2671.

13. Capture and record 30 seconds of microphone simulator floor.

14. Remove the microphone simulator, and re-install the microphone.

15. Attach the calibrator to the microphone.

16. Apply power to calibrator (114 dB setting).

17. Wait ten seconds for calibrator signal to stabilize.

18. Check calibration level of the LDL Model 2900.

19. Check calibration level of the LDL 820 SLM and record the calibration signal on the

DAT recorder for a minimum of 30 seconds.

20. After recording the calibration signal, turn off the calibrator and remove it from the microphone. Attach the foam windscreen.

21. The acoustical system is ready for initiation of measurements.

C.4 System Performance Limits

System Performance Limits

Component	Mode	Overload Point	Floor (Mic Simulator)
B&K Deltatron Mic System		140 dB SPL	~20 dB(A)
LDL2900 Analyzer	120 dB Range	134 dB SPL	~41 dB
LDL 820 SLM		140 dB SPL	~20 dB
Sony TCD-D100 DAT Recorder	cal -6 dB VU	120 dB SPL	~40 dB

C.5 Power Requirements

B&K Model WB 1372 Deltatron Power Supply:

3 x 9V cells

Typical "life": >> **40 hours** on a set of 9V cells

LDL Model 2900:

12 V (~ 1 A)

Typical "life": **40** hours powered by gel-cell

LDL Model 820:

1 x 9V cell

Typical "life": **20** hours on one 9V cell

SONY Model TCD-D100:

2 x AA cells or 4.3 V

Typical "life": up to **7 hours** on a set of Lithium AA cells, but must be checked regularly

B&K Model 4231 Calibrator:

4 x AA cells

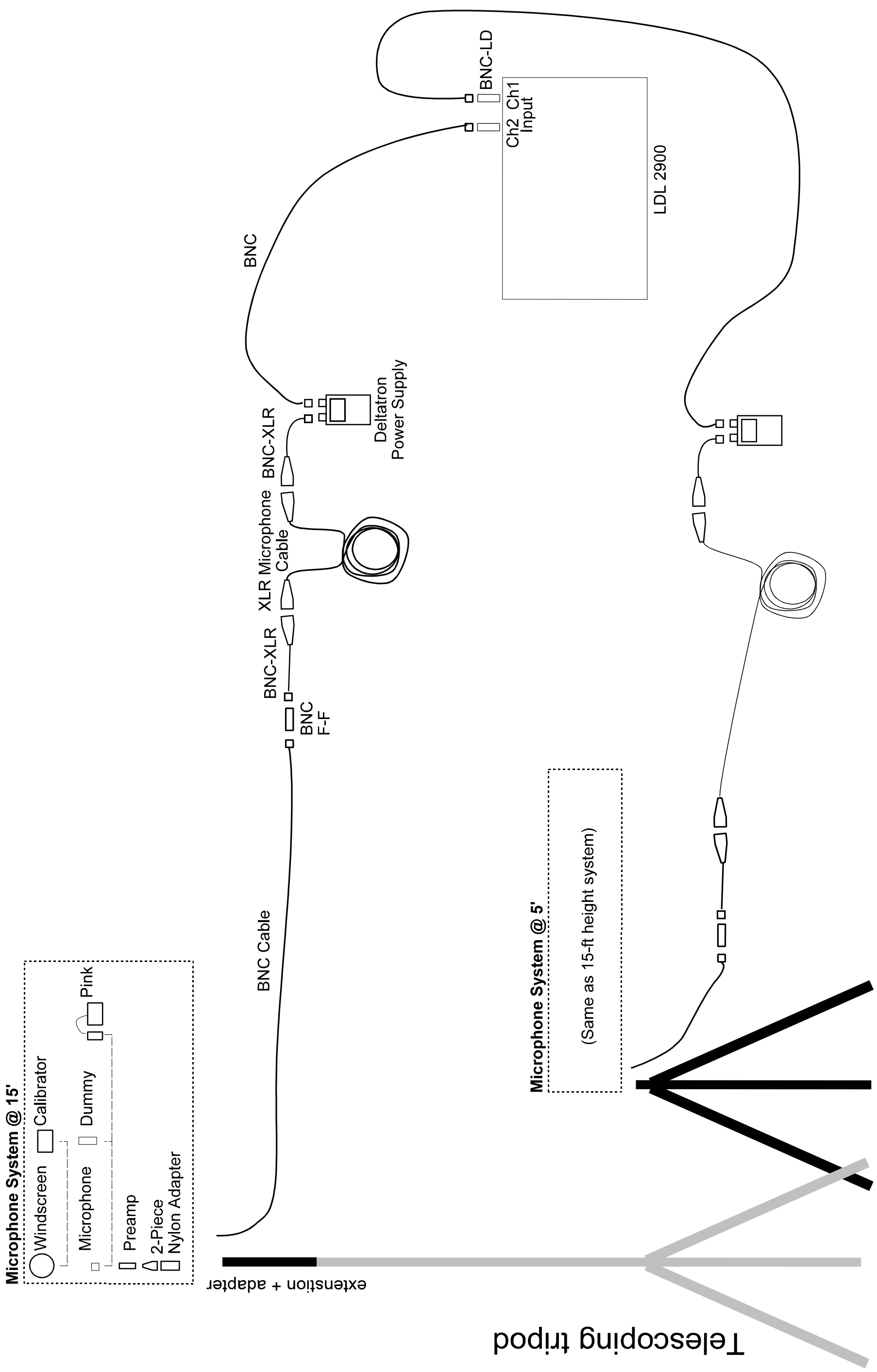


Figure C.1. Instrumentation Diagram for LDL 2900 System

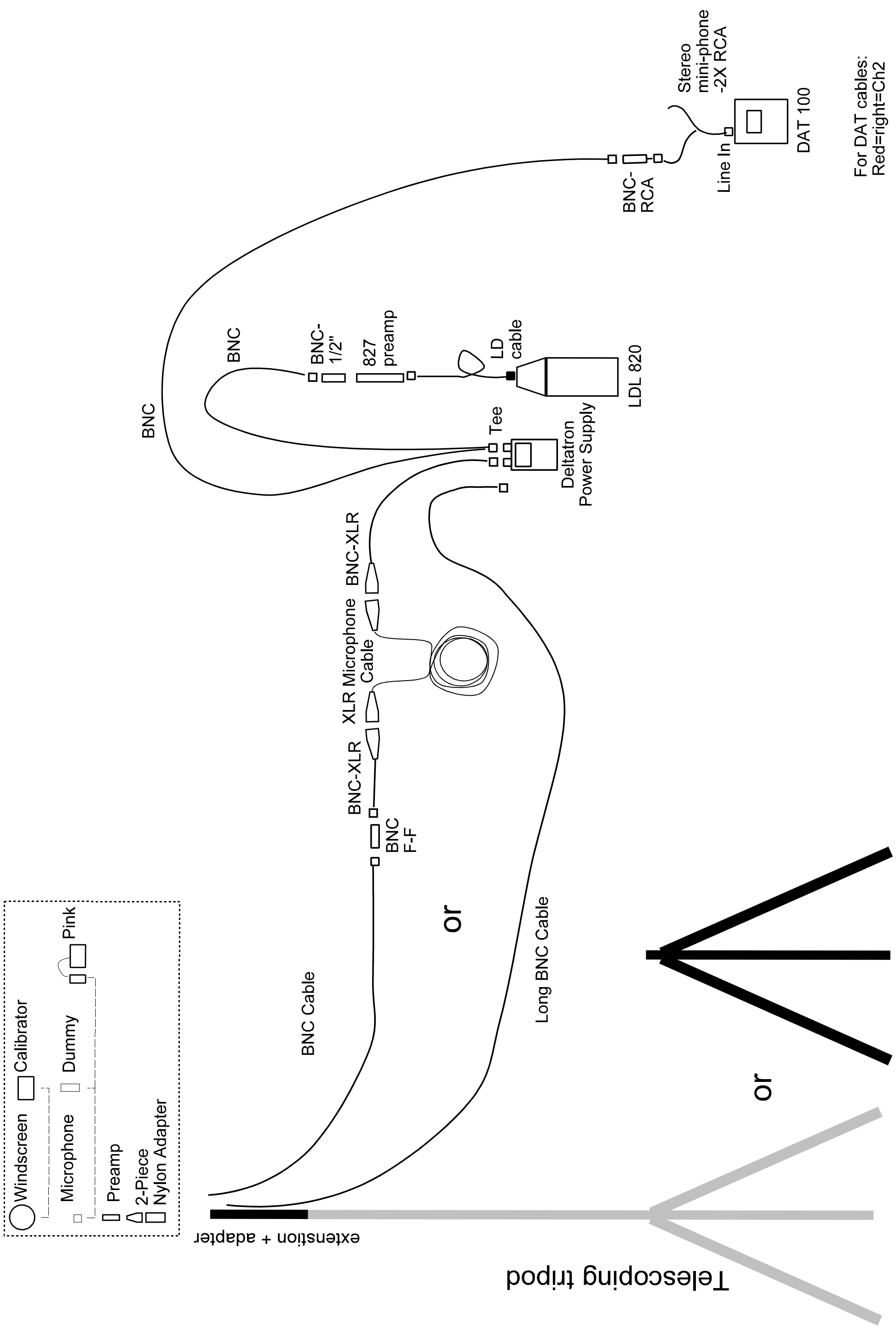


Figure C.2. Instrumentation Diagram for LDL 820 and Sony TCD-D100 System

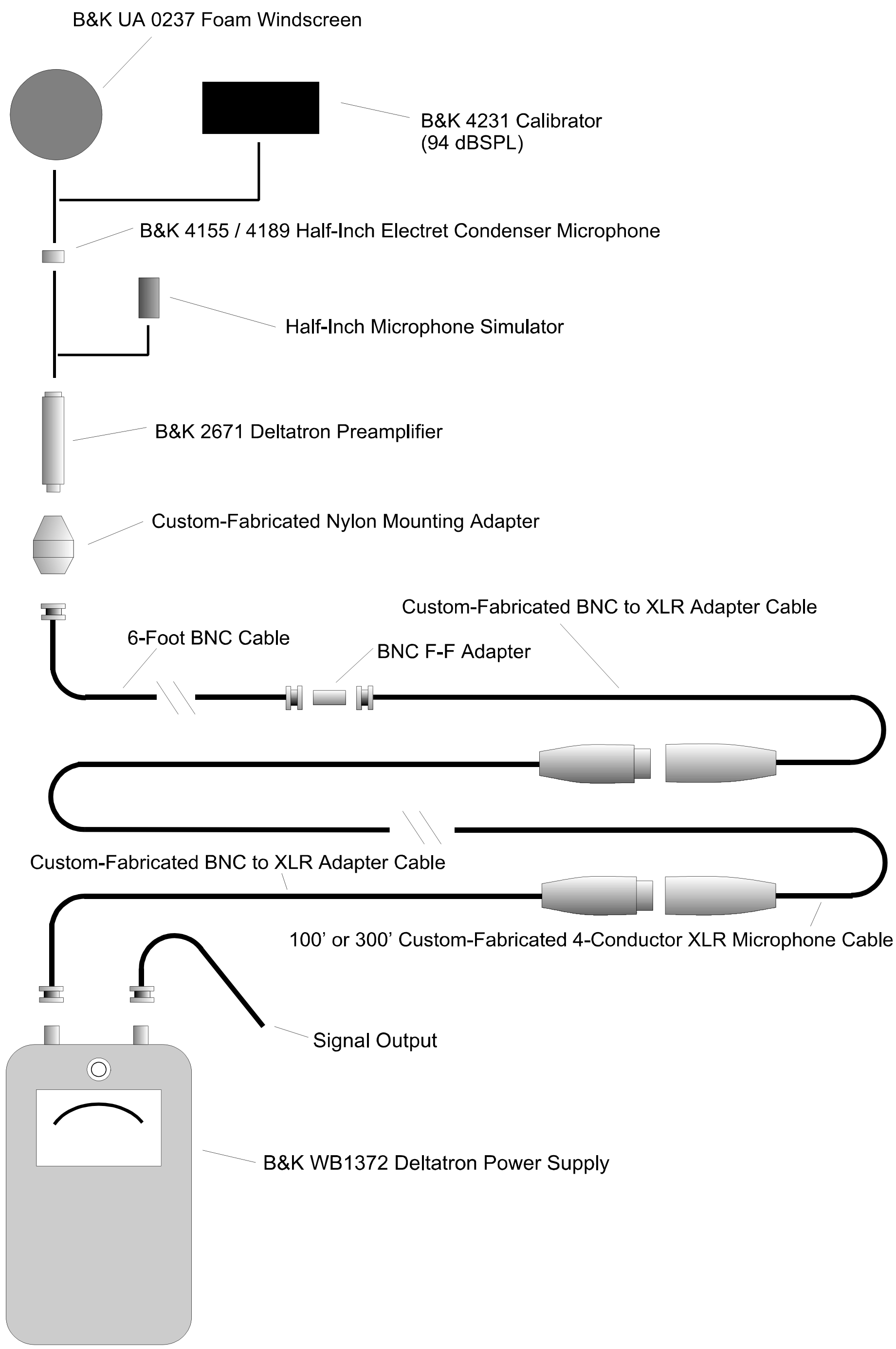


Figure C.3. B&K Deltatron Microphone System

Appendix D:

Sample Data Log Sheets

FHWA TNM Validation Measurement Site Checklist:

Date: __________ Time: ____________ Observer: ______________________________

State: __________ Site#: ____________ Location: ______________________________
(Include distance to nearest landmark/exit/mile marker)

Site Diagram - Plan View *

* Include microphone and observer locations, overpasses for a video camera, and all ground undulations in detail.

Site Diagram - Cross Sectional View

Roadway Description (Constant-flow, level-grade roadways only)								
Name	Direction	Posted Speed (mph)	Pavement Type and Age	# of Lanes	Shoulder and width (ft)?		Median and width (ft)?	
					Yes / No		Yes / No	
					Yes / No		Yes / No	

Barrier Description (Single noise walls only)					
Existing / Proposed ?		Material Type	Offset Distance from Centerline of Near Lane (ft)	Height (ft)	NRC
	(Date?)				
	(Date?)				

Other Considerations								
Max Receiver Distance from Centerline of Near Lane (ft)	Overpass for Video Camera	Ground Undulations (ft)			Nearby Vegetation or Other Ground Zones		Nearby Structures	
		Min	Max	Avg	Description	Distance (ft)	Description	Distance (ft)
	Yes / No							
measured (preferred) or estimated								

Site Ownership/Approval			
State/Public Property		Private Property	
Approval	Contact Information	Approval	Contact Information
Yes / No		Yes / No	

* A site is not considered viable if the site-scoping organization has not arranged for all appropriate approvals.

Other Comments/Observations:

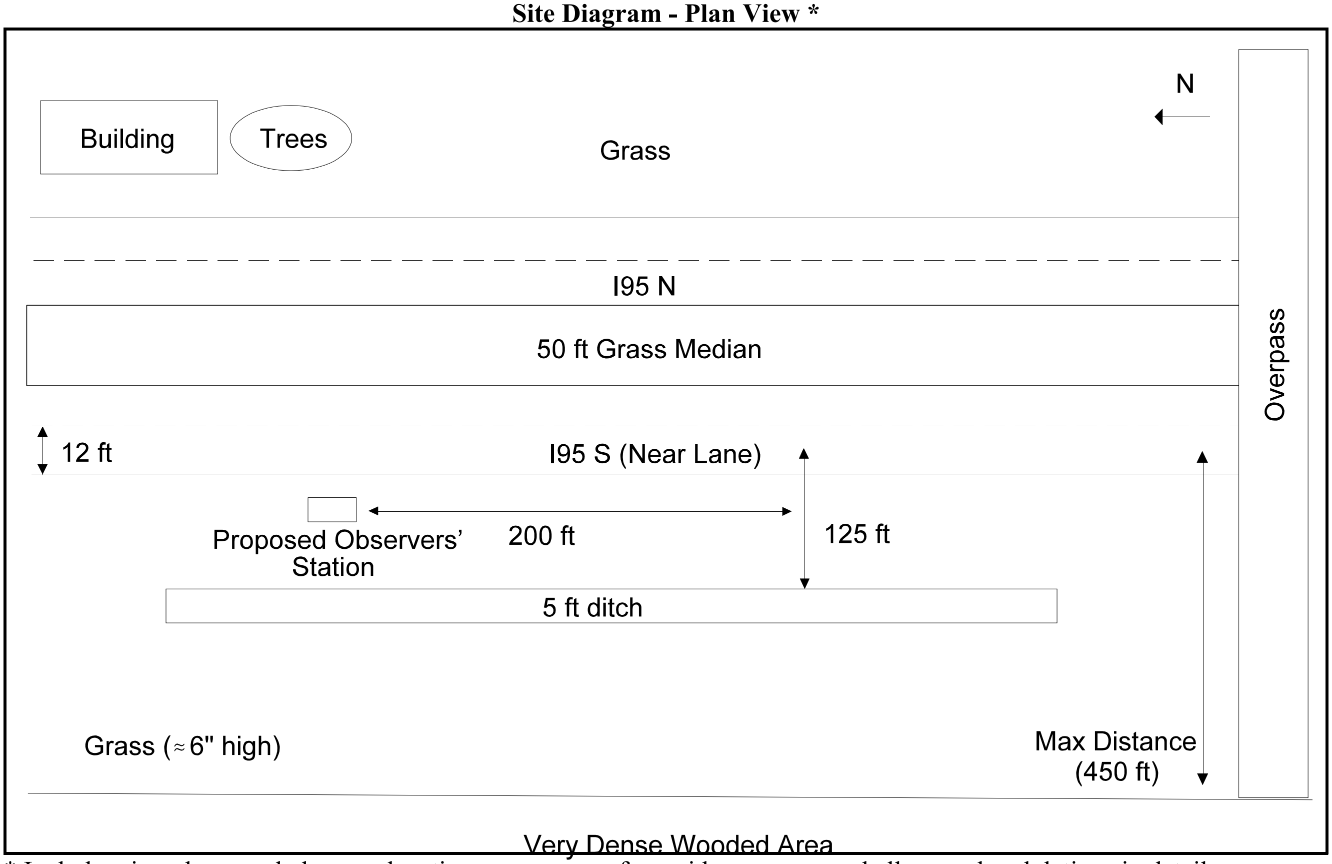
Figure D.1. Blank Site Checklist

FHWA TNM Validation Measurement Site Checklist:

Date: 5/21/99 Time: 08:00 AM Observer: John Smith

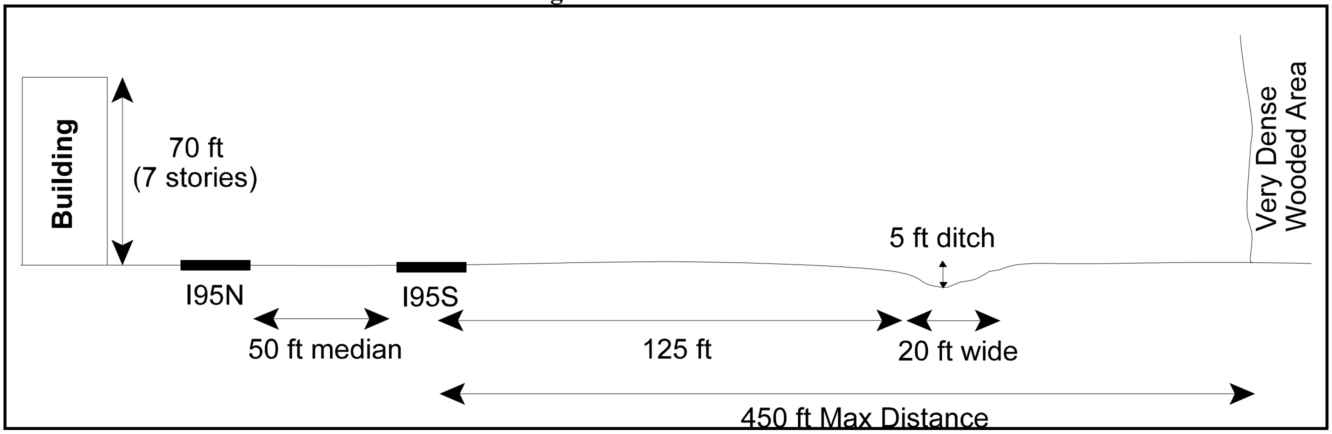
State: MA Site#: 1 Location: I95 S @ 0.25 miles north of junction with Rt. 495
(Include distance to nearest landmark/exit/mile marker)

Site Diagram - Plan View *



* Include microphone and observer locations, overpasses for a video camera, and all ground undulations in detail.

Site Diagram - Cross Sectional View



Roadway Description (Constant-flow, level-grade roadways only)								
Name	Direction	Posted Speed (mph)	Pavement Type and Age	# of Lanes	Shoulder and width (ft)?		Median and width (ft)?	
I95	S	55	DGAC 1990	2	Yes / No	10	Yes / No	50
I95	N	55	DGAC 1990	2	Yes / No	10	Yes / No	50

Barrier Description (Single noise walls only)					
Existing / Proposed ?		Material Type	Offset Distance from Centerline of Near Lane (ft)	Height (ft)	NRC
N/A	(Date?)				
N/A	(Date?)				

Other Considerations								
Max Receiver Distance from Centerline of Near Lane (ft)	Overpass for Video Camera	Ground Undulations (ft)			Nearby Vegetation or Other Ground Zones		Nearby Structures	
		Min	Max	Avg	Description	Distance (ft)	Description	Distance (ft)
450 measured (preferred) or estimated	Yes / No	4	6	5	Dense wooded area	450	N/A	

Site Ownership/Approval			
State/Public Property		Private Property	
Approval	Contact Information	Approval	Contact Information
Yes / No	Mike Paiewonski Mass Hwy Dept. 10 Park Plaza Boston, MA 02116 (617) 973-8244	Yes / No	

* A site is not considered viable if the site-scoping organization has not arranged for all appropriate approvals.

Other Comments/Observations:

Figure D.2. Completed Sample Site Checklist

Traffic Noise Model Validation Study

Acoustical System Log

Date:	State:	Site ID:
Site Location:		
Personnel:		
Microphone System (A-D, S1, S2):	CH 1 – position (ft):	height (ft):
Calibration System (A, B):	CH 2 – position (ft):	height (ft):

Event End T.O.D.	Event Duration	2900 Range	Comments

Figure D.3. LDL 2900 Spectrum Analyzer System Log

Traffic Noise Model Validation Study

Alternate Acoustical System Log

Date:	State:	Site ID:
Site Location:		
Personnel:		
Microphone System (1, 2):	CH 1 – position (ft):	height (ft):
Calibration System (A, B):	CH 2 – position (ft):	height (ft):

Start Time	End Time	DAT ID#	Event ID (cal, pink, etc.)	CH 1 level	CH 2 level	Comments (any instrumentation switch, etc.)

Figure D.4. LDL 820 Sound Level Meter and Sony TCD-D100 DAT Recorder System Log

TNM Validation Study - GENERAL SITE LOG

Date:	State:	Site ID:
Site Location:		
Personnel:		

Instrument Deployment:

Position	Height	Analyzer	SLM	Met	Unit ID	Chan #	Notes
		Check One					

Figure D.5. General Site Log

Appendix E:

Measured Sound Level Data and TNM Input Data

The **TNM Validation: Phase 1 Data CD ROM** is available upon request from the U.S. DOT / Volpe Center. Please phone 617-494-2372 or e-mail support@trafficnoisemodel.org to request a copy. The Federal Highway Administration requires that all results obtained using the data be supplied to the U.S. DOT / Volpe Center or the Federal Highway Administration. (Contact information is found on the Report Documentation Page at the beginning of this report.)

Appendix F:
Comparison of TNM-Predicted and Measured Sound Levels;
All Wind Data Included

Data presented in this appendix include all processed data regardless of the wind conditions.

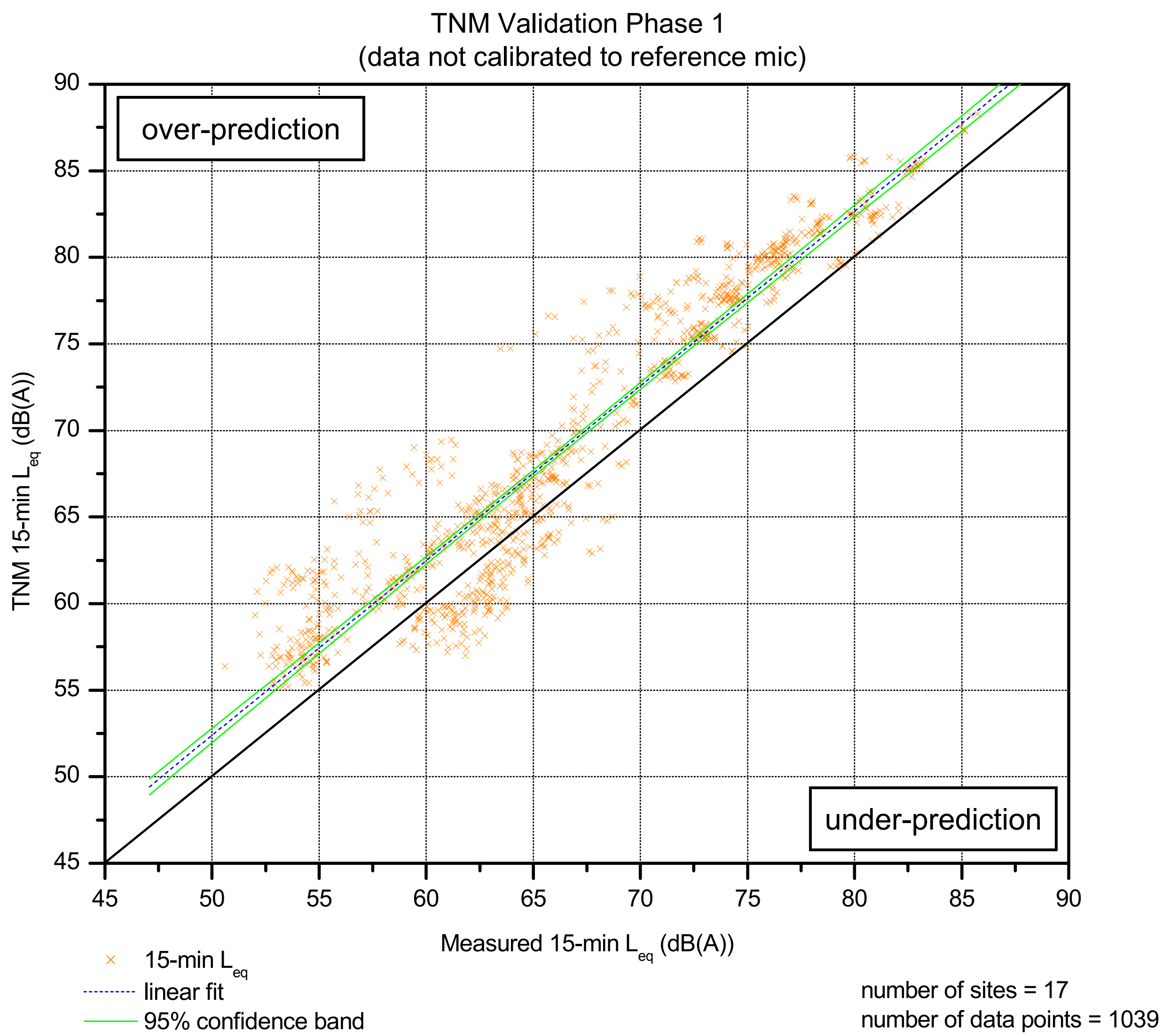


Figure F.1. Direct Comparison of TNM and Measured Data; All Sites (not calibrated); All Wind Data Included.

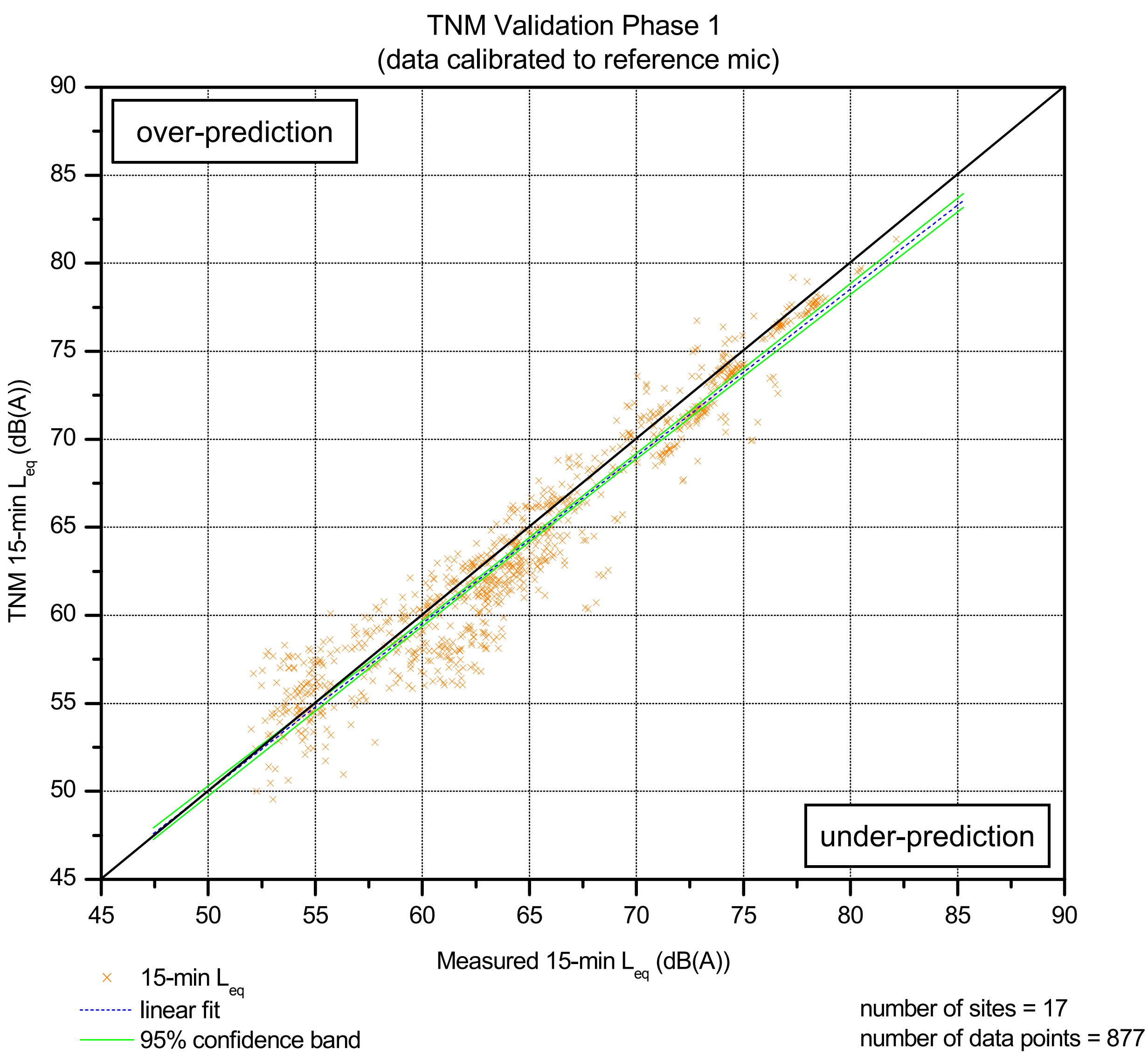


Figure F.2. Direct Comparison of TNM and Measured Data; All Sites (calibrated); All Wind Data Included.

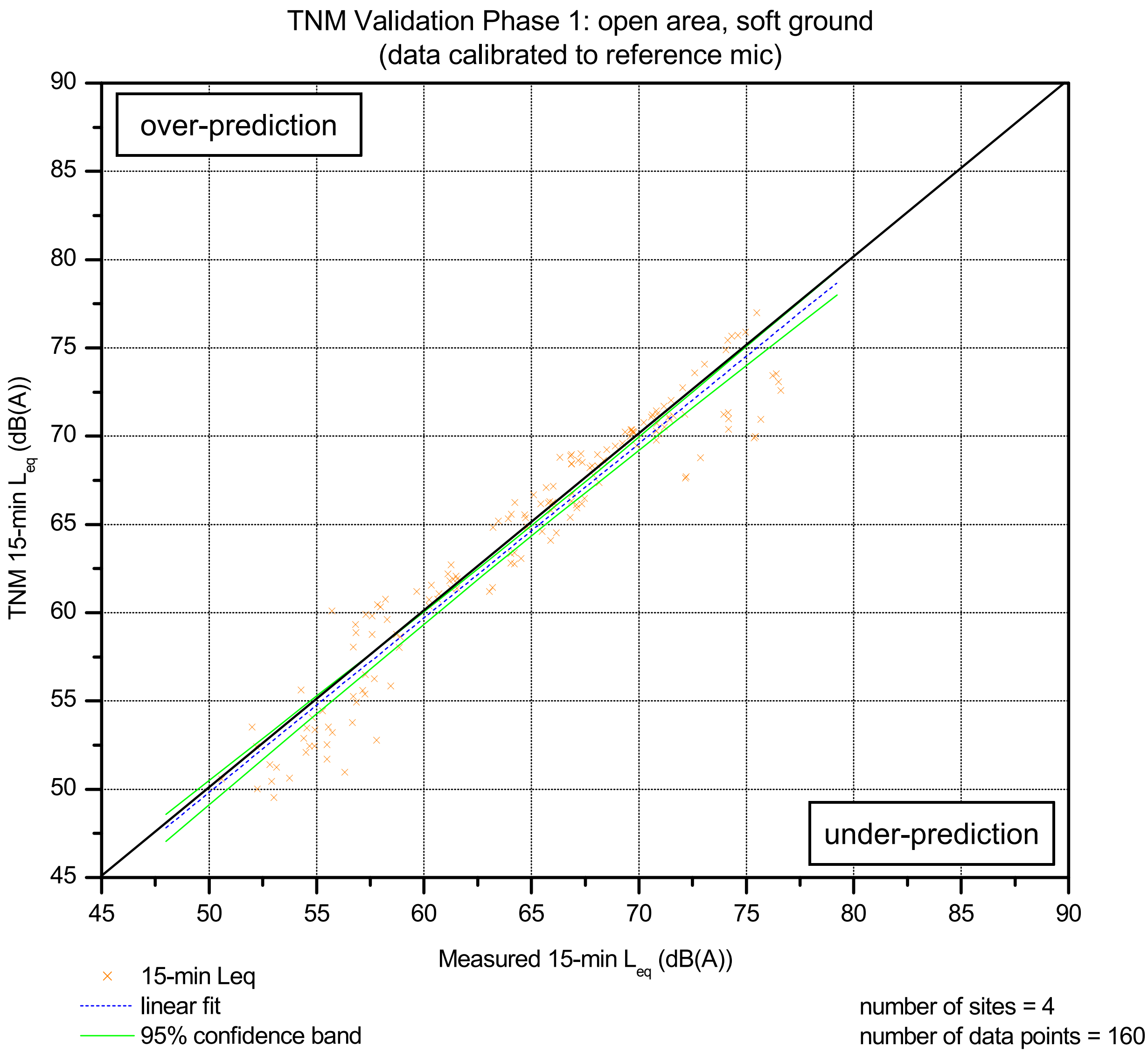


Figure F.3. Direct Comparison of TNM and Measured Data; Open Area, Soft Ground Sites; All Wind Data Included.

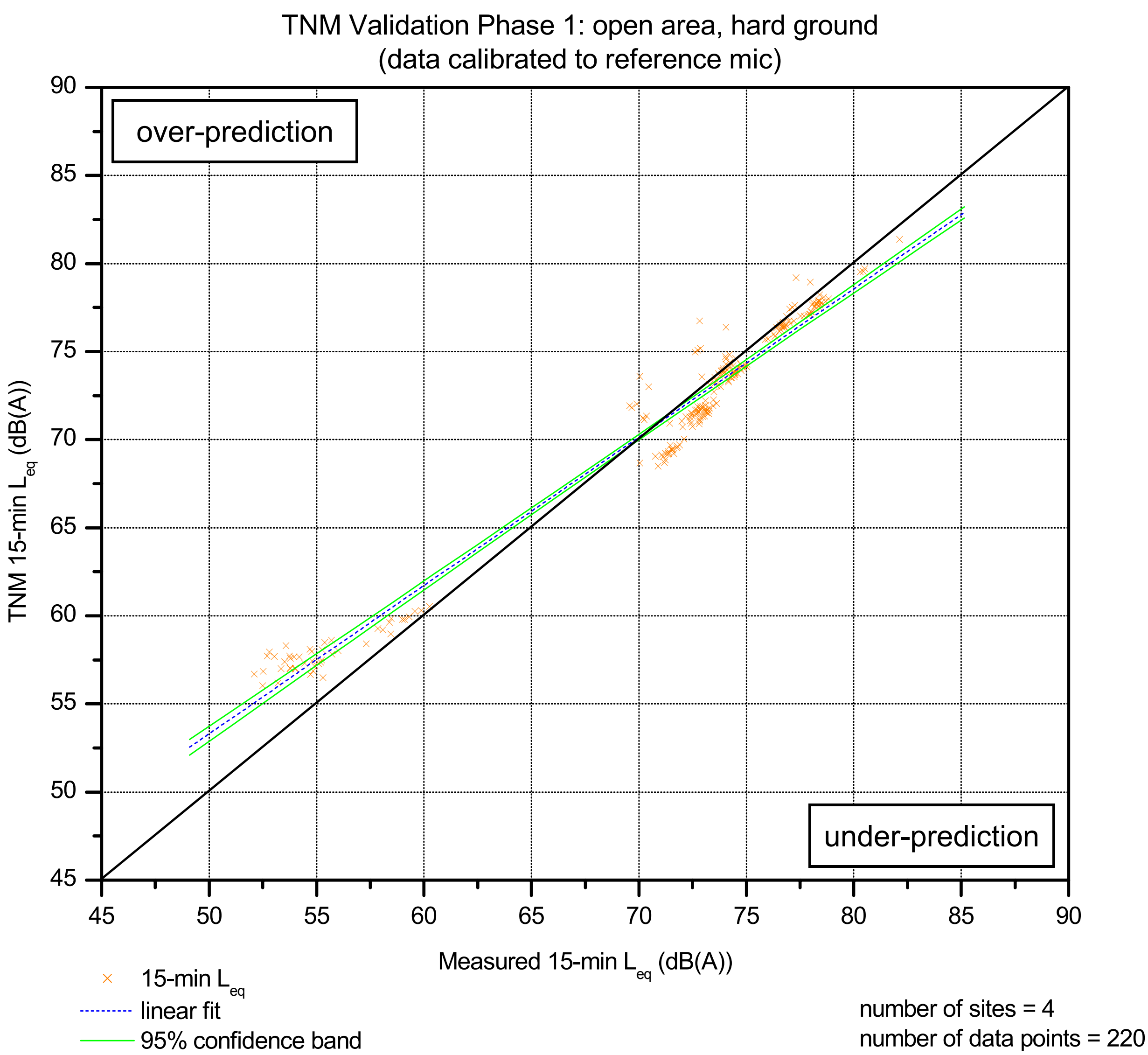
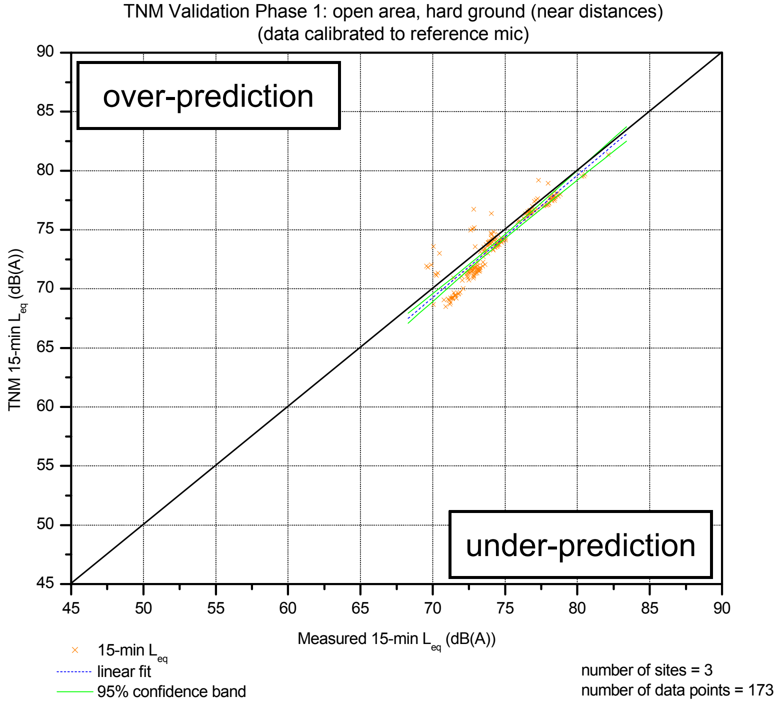


Figure F.4. Direct Comparison of TNM and Measured Data; Open Area, Hard Ground Sites; All Wind Data Included.



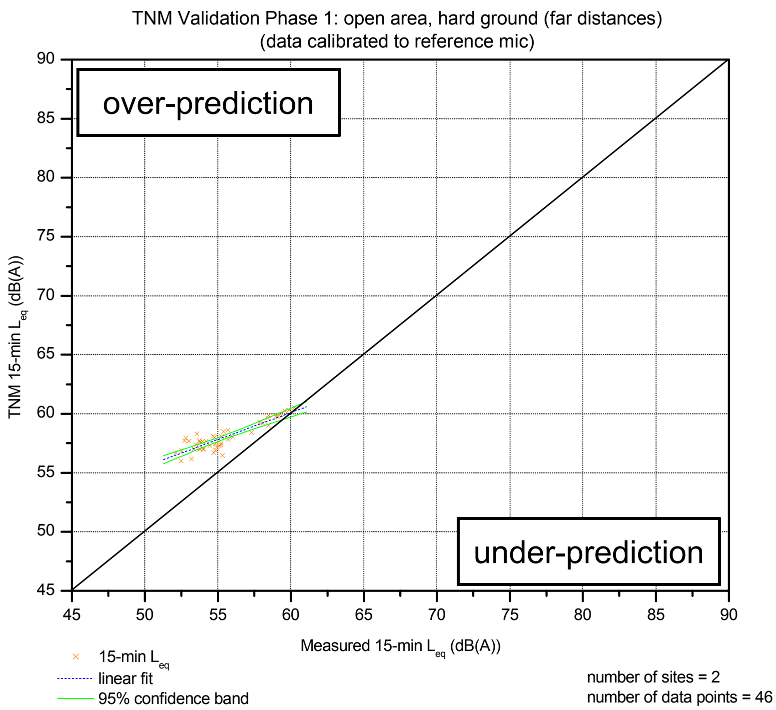


Figure F.5. Direct Comparison of TNM and Measured Data; Open Area, Hard Ground Sites; Separated High and Low Sound Levels; All Wind Data Included.

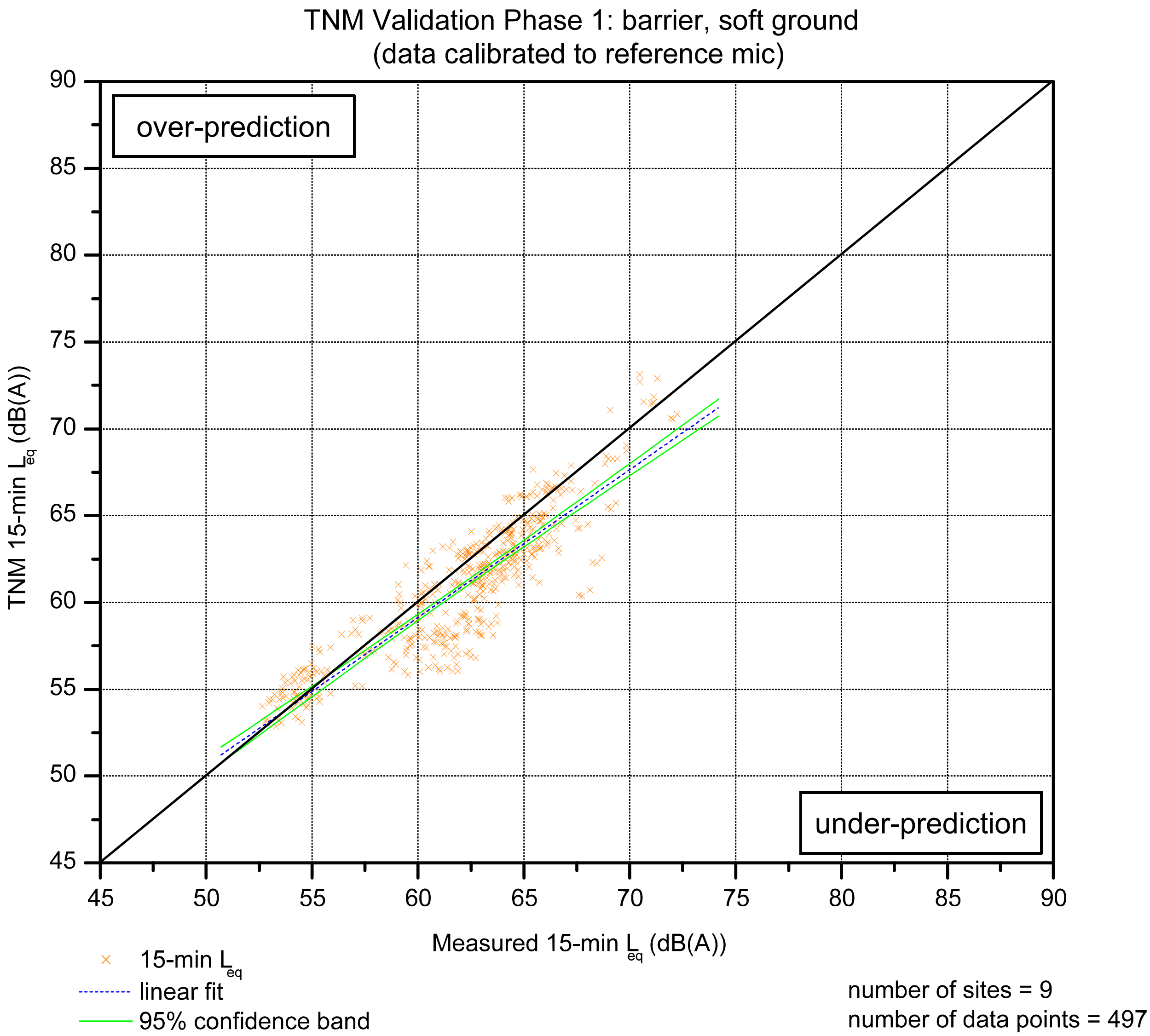


Figure F.6. Direct Comparison of TNM and Measured Data; Barrier, Soft Ground Sites; All Wind Data Included.

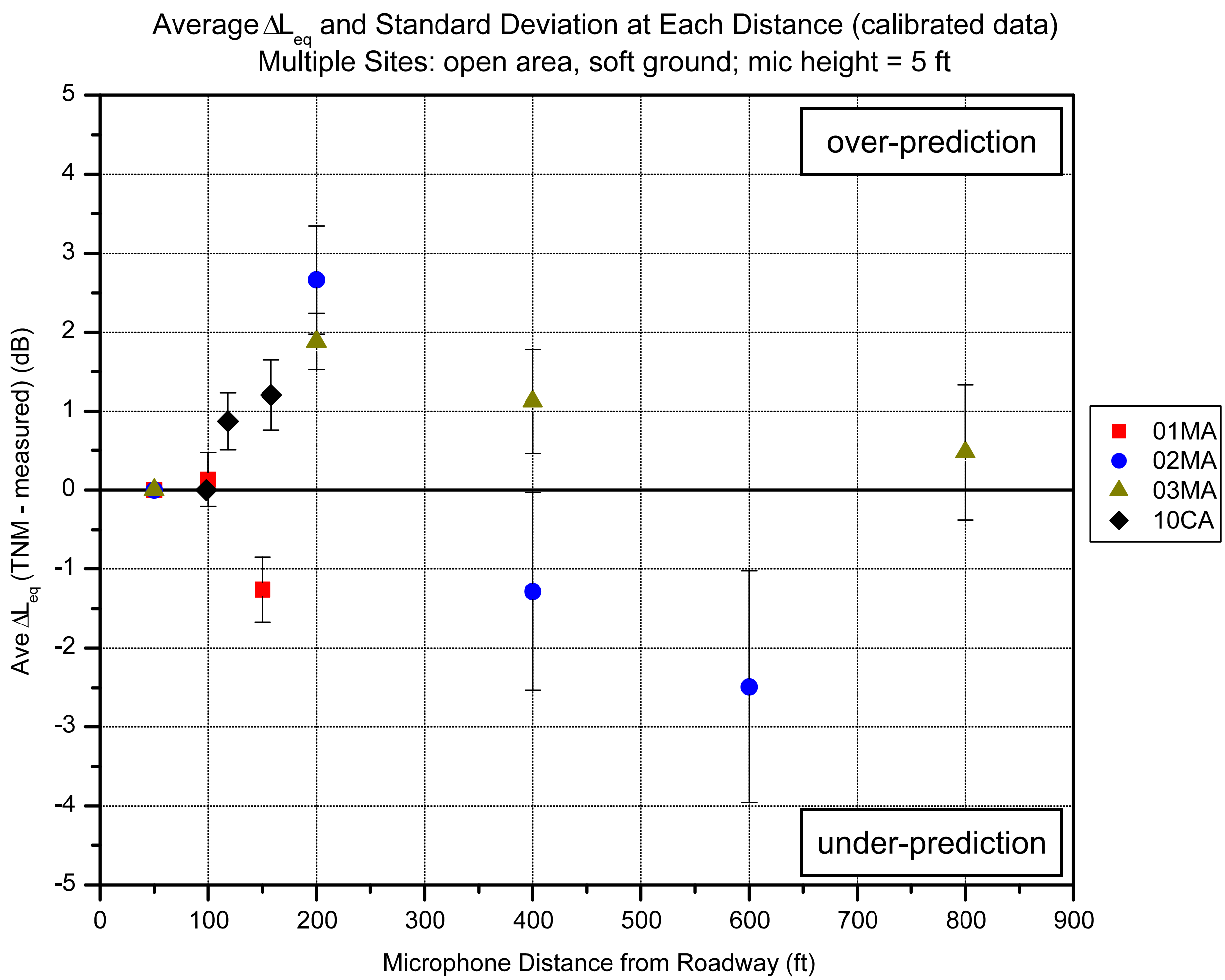


Figure F.7. Average Differences (TNM minus Measured) as a Function of Distance; Open Area, Soft Ground Sites; 5-ft Height; All Wind Data Included.

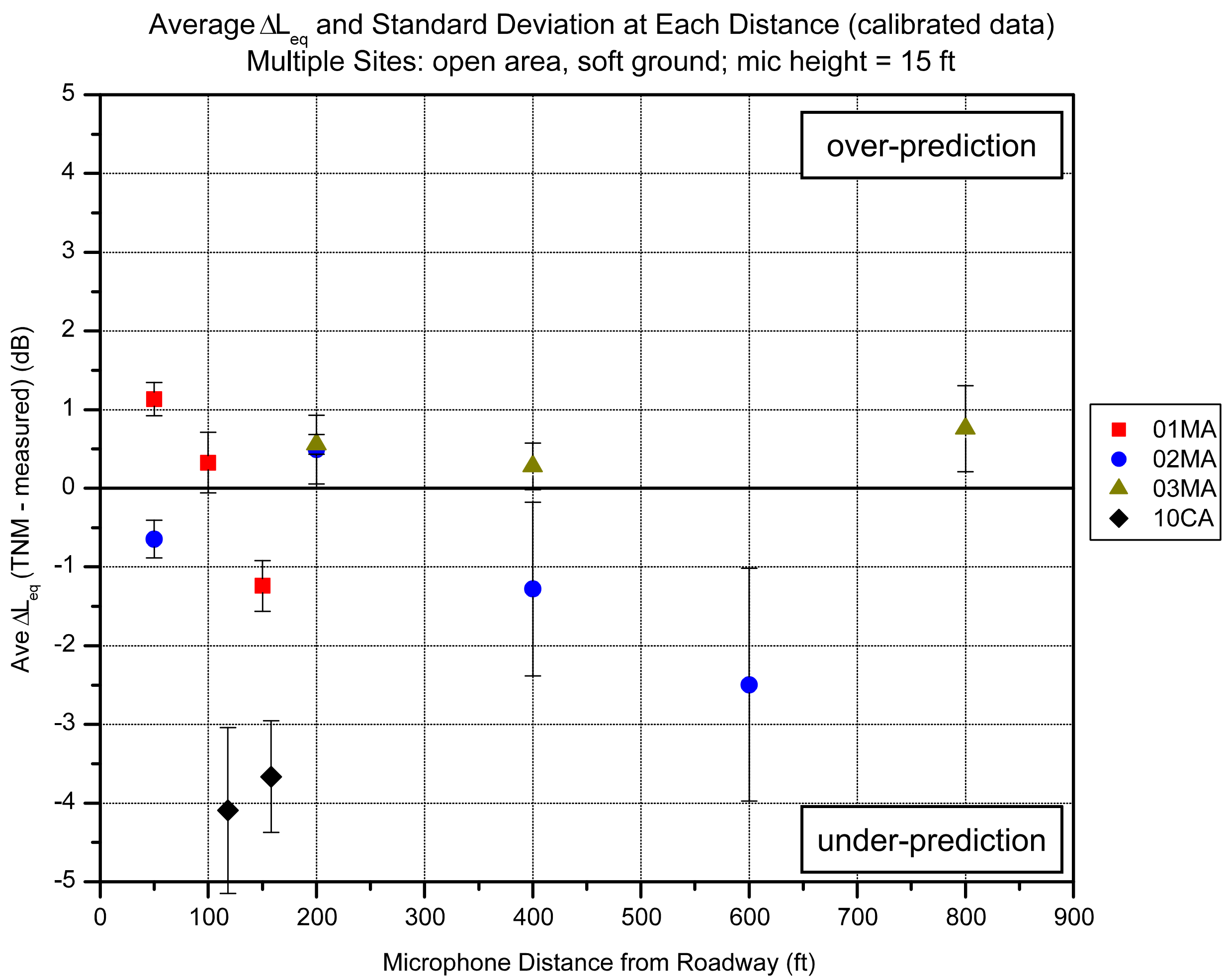


Figure F.8. Average Differences (TNM minus Measured) as a Function of Distance; Open Area, Soft Ground Sites; 15-ft Height; All Wind Data Included.

Table F.1. Average Differences (TNM minus Measured) and Standard Deviations as a Function of Distance and Height; Open Area, Soft Ground Sites; All Wind Data Included

Site ID	Distance From Roadway (ft)	5 ft mic (dB)		15 ft mic (dB)	
		average	stan dev	average	stan dev
01MA	50			1.1	0.2
	100	0.1	0.3	0.3	0.4
	150	-1.3	0.4	-1.2	0.3
02MA	50			-0.6	0.2
	200	2.7	0.7	0.5	0.4
	400	-1.3	1.3	-1.3	1.1
	600	-2.5	1.5	-2.5	1.5
03MA	50				
	200	1.9	0.4	0.6	0.1
	400	1.1	0.7	0.3	0.3
	800	0.5	0.9	0.8	0.5
10CA	98				
	118	0.9	0.4	-4.1	1.1
	158	1.2	0.4	-3.7	0.7

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

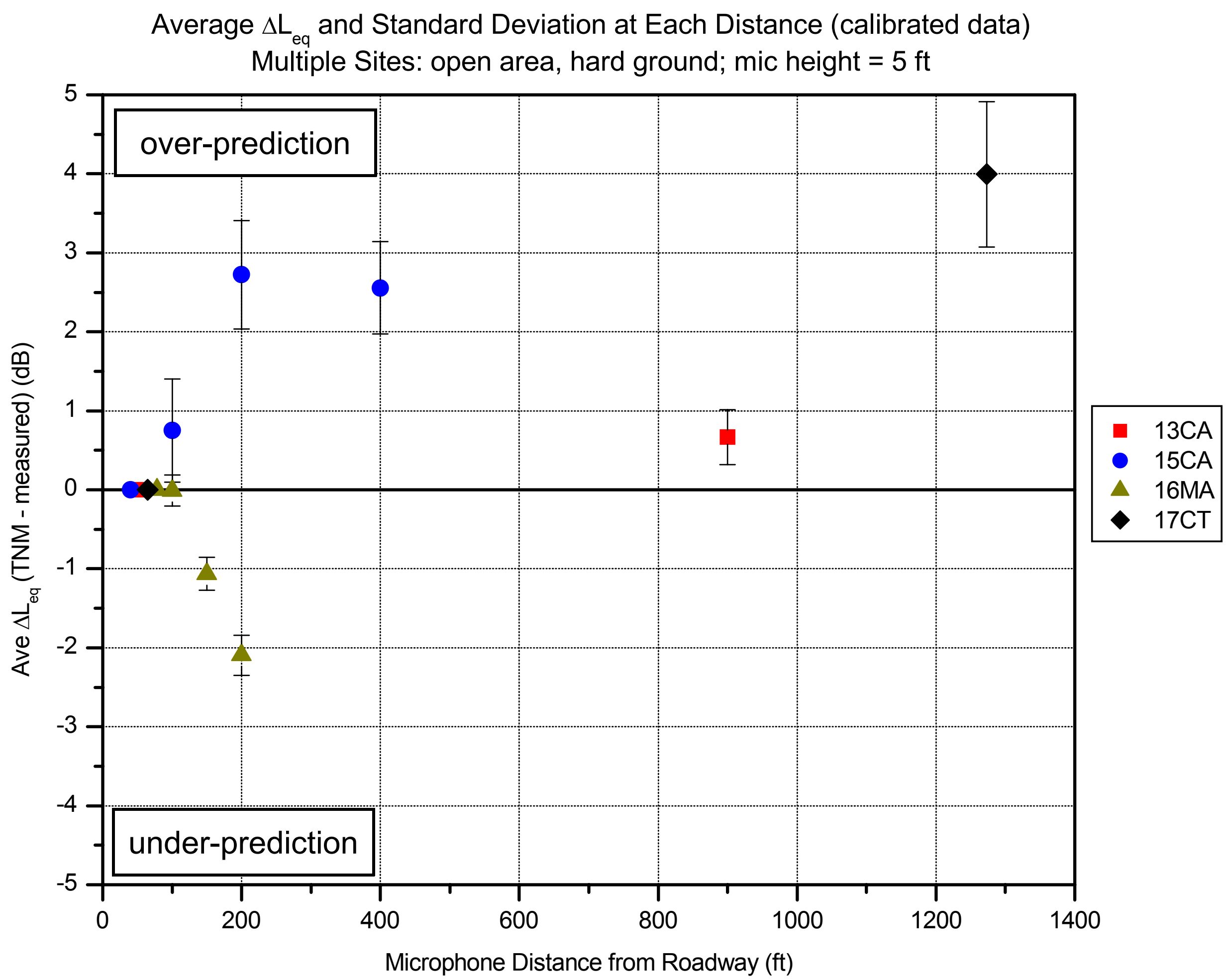


Figure F.9. Average Differences (TNM minus Measured) as a Function of Distance; Open Area, Hard Ground Sites; 5-ft Height; All Wind Data Included.

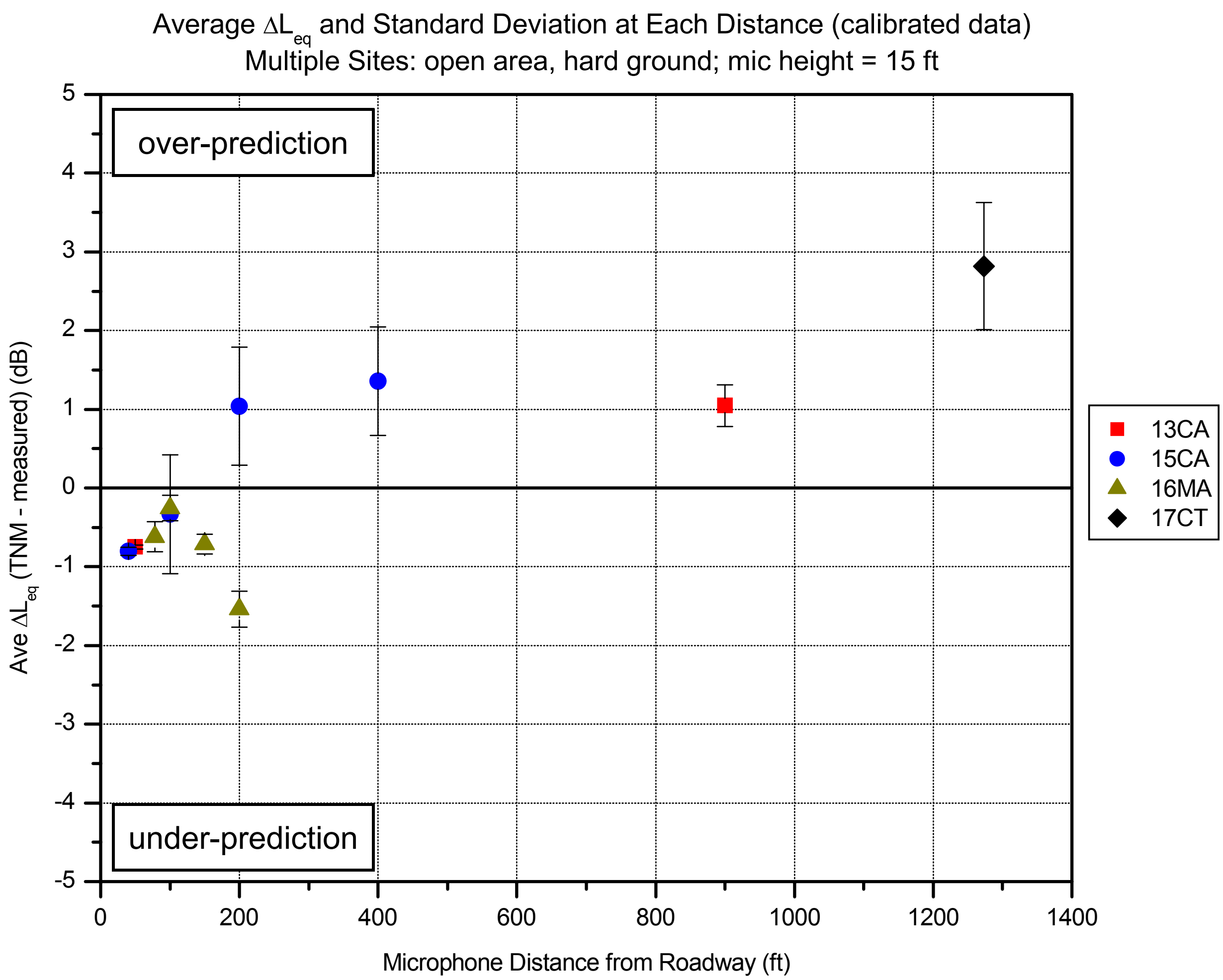


Figure F.10. Average Differences (TNM minus Measured) as a Function of Distance; Open Area, Hard Ground Sites; 15-ft Height; All Wind Data Included.

Table F.2. Average Differences (TNM minus Measured) and Standard Deviations as a Function of Distance and Height; Open Area, Hard Ground Sites; All Wind Data Included

Site ID	Distance From Roadway (ft)	5 ft mic (dB)		15 ft mic (dB)	
		average	stan dev	average	stan dev
13CA	50			-0.7	0.0
	900	0.7	0.3	1.0	0.3
15CA	40			-0.8	0.1
	100	0.8	0.7	-0.3	0.8
	200	2.7	0.7	1.0	0.7
	400	2.6	0.6	1.4	0.7
16MA	78			-0.6	0.2
	100	0.0	0.2	-0.3	0.2
	150	-1.1	0.2	-0.7	0.1
	200	-2.1	0.3	-1.5	0.2
17CT	65				
	1273	4.0	0.9	2.8	0.8

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

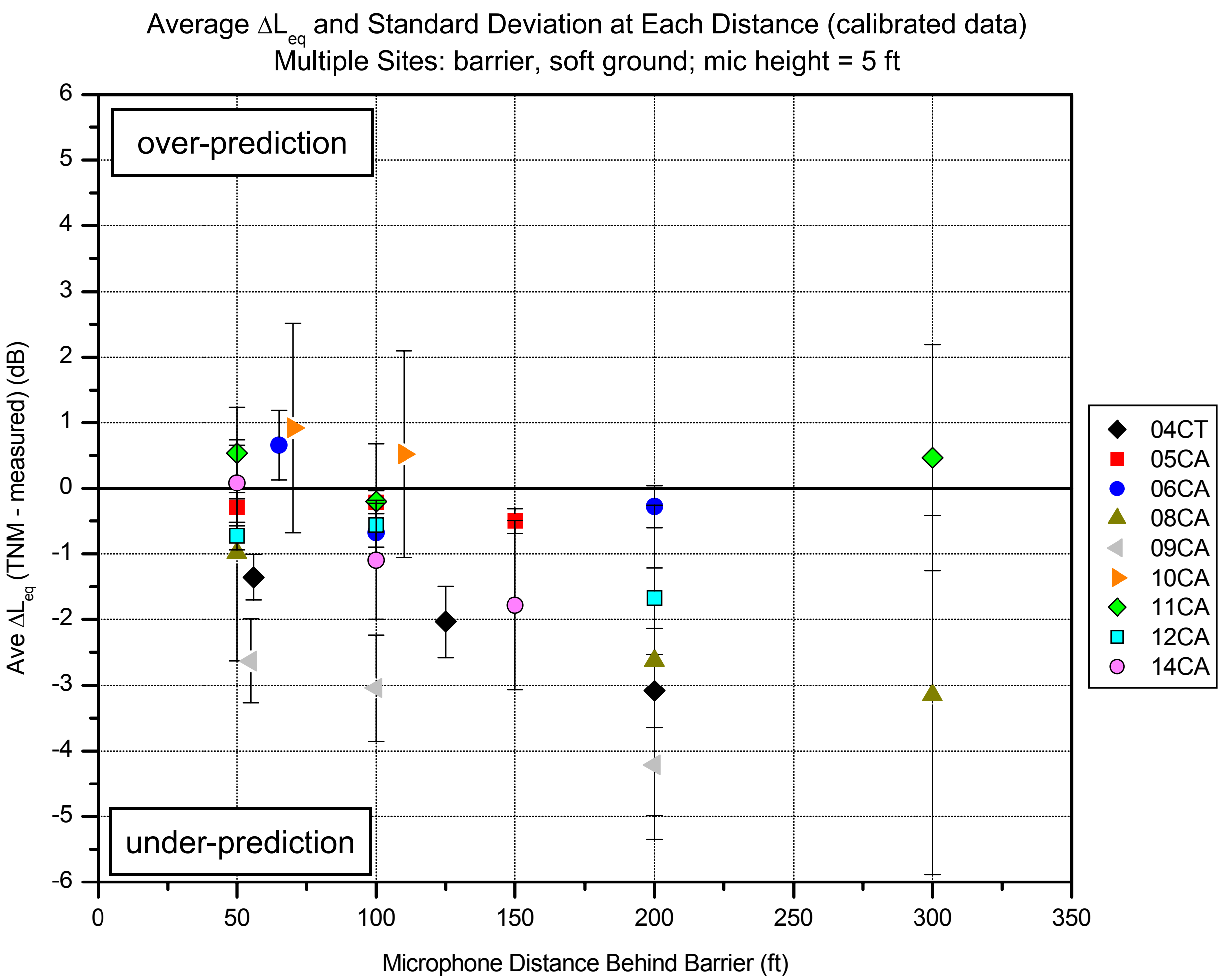


Figure F.11. Average Differences (TNM minus Measured) as a Function of Distance; Barrier, Soft Ground Sites; 5-ft Height; All Wind Data Included.

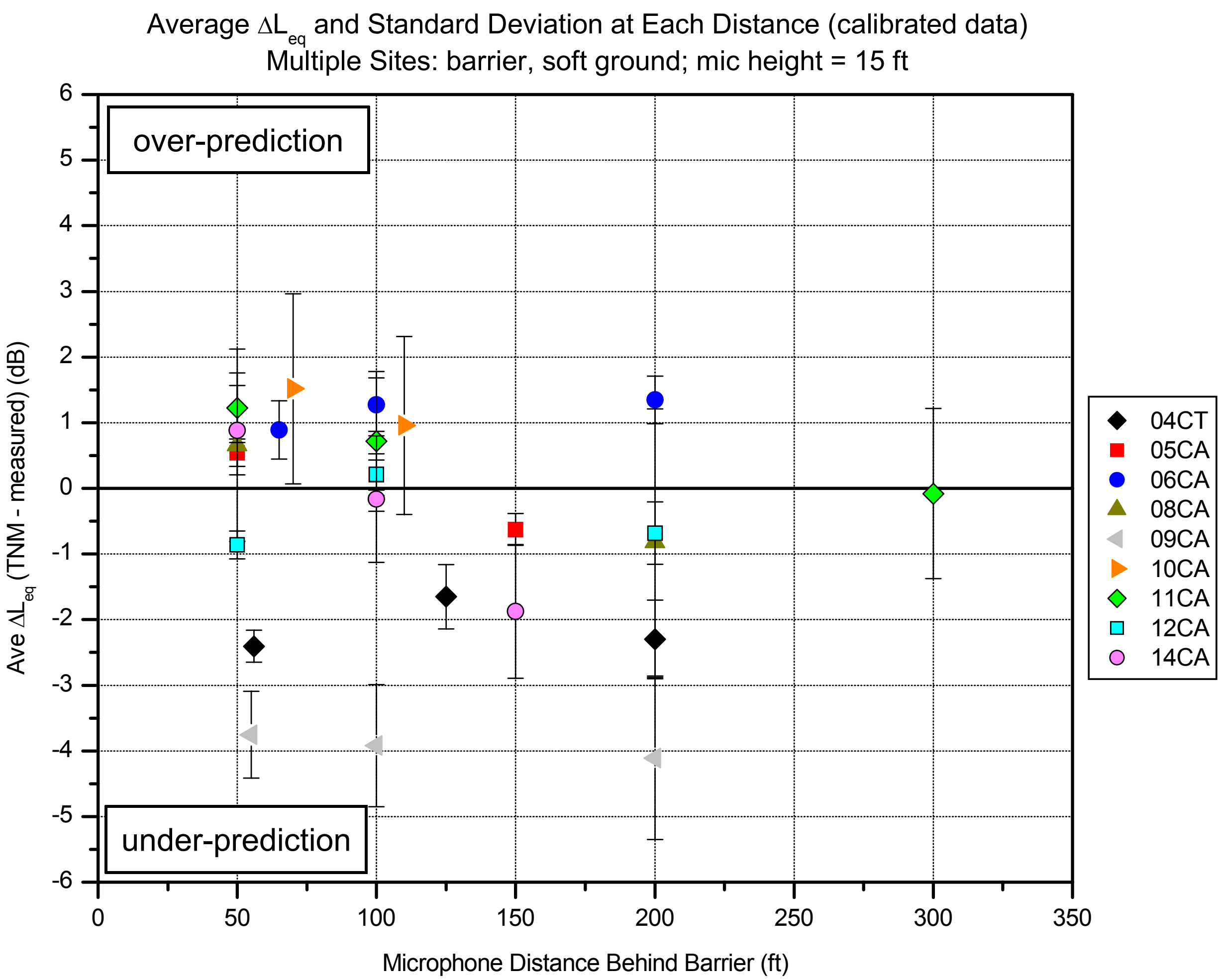
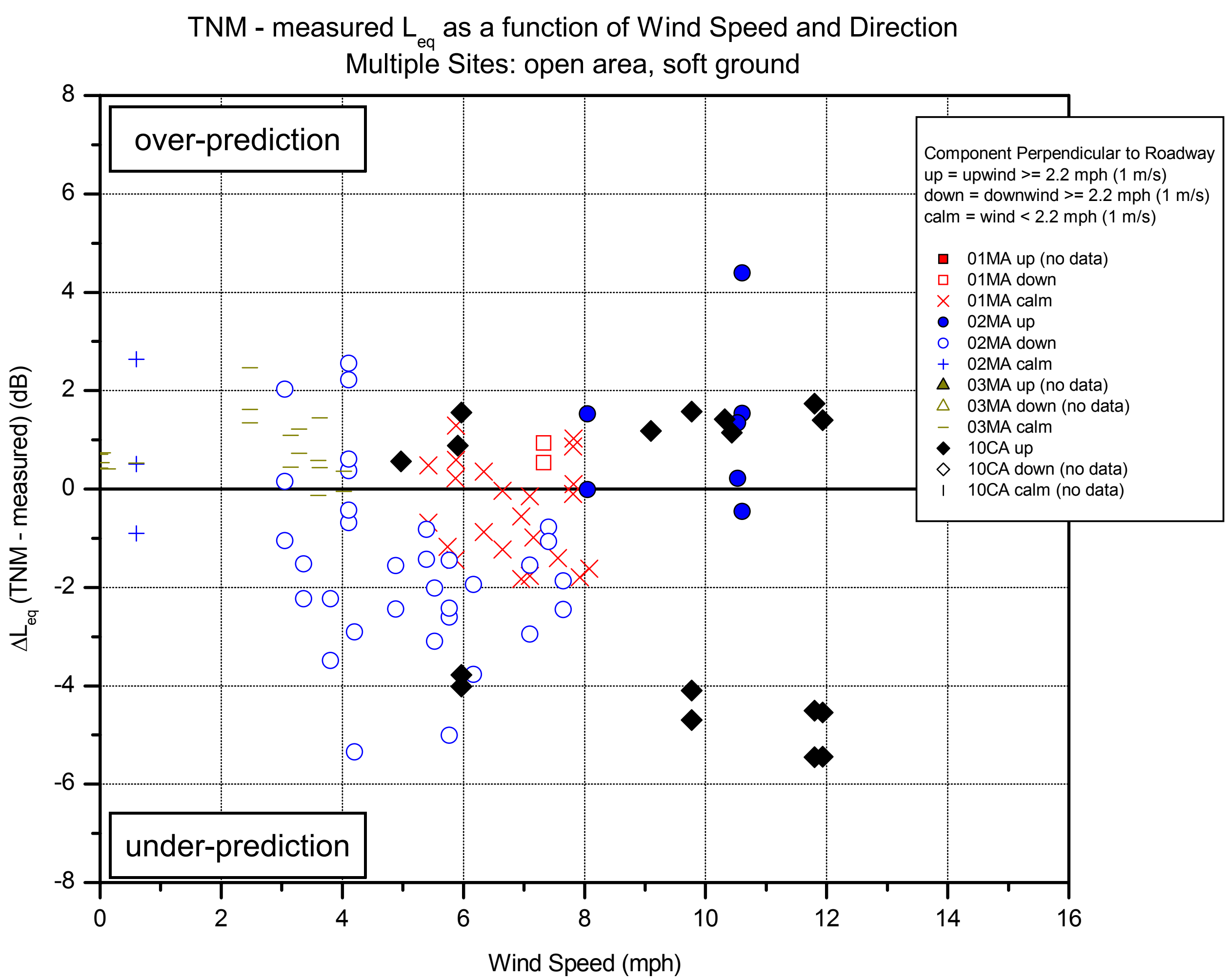


Figure F.12. Average Differences (TNM minus Measured) as a Function of Distance; Barrier, Soft Ground Sites; 15-ft Height; All Wind Data Included.

Table F.3. Average Differences (TNM minus Measured) and Standard Deviations as a Function of Distance and Height; Barrier, Soft Ground Sites; All Wind Data Included

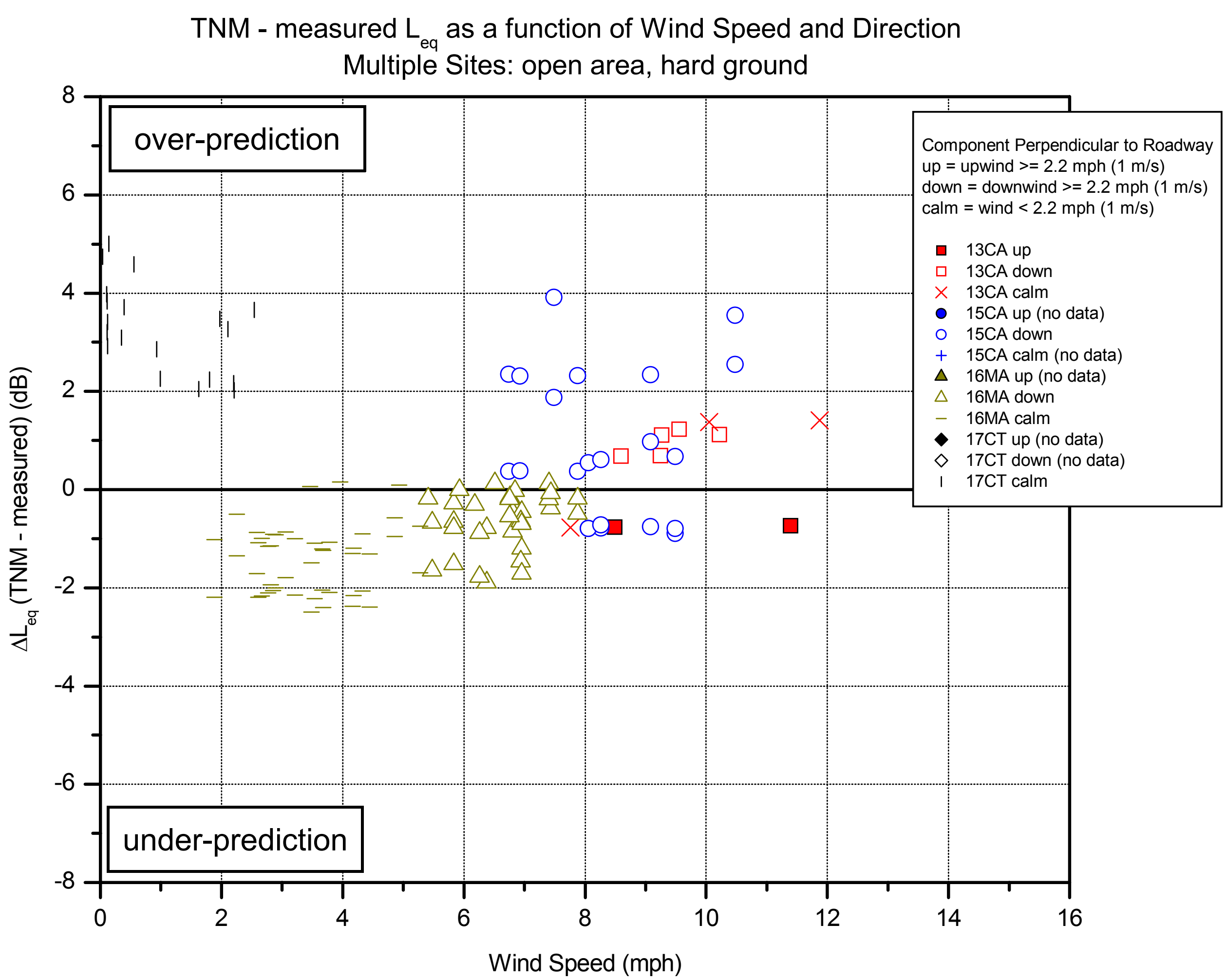
Site ID	Distance Behind Barrier (ft)	5 ft mic (dB)		15 ft mic (dB)	
		average	stan dev	average	stan dev
04CT	56	-1.4	0.3	-2.4	0.2
	125	-2.0	0.5	-1.6	0.5
	200	-3.1	0.6	-2.3	0.6
05CA	50	-0.3	0.2	0.5	0.2
	100	-0.2	0.2	0.2	0.2
	150	-0.5	0.2	-0.6	0.2
06CA	65	0.7	0.5	0.9	0.4
	100	-0.7	0.4	1.3	0.4
	200	-0.3	0.3	1.3	0.4
08CA	50	-1.0	1.6	0.7	1.5
	200	-2.6	2.4	-0.8	2.0
	300	-3.2	2.7		
09CA	55	-2.6	0.6	-3.8	0.7
	100	-3.0	0.8	-3.9	0.9
	200	-4.2	1.1	-4.1	1.2
10CA	70	0.9	1.6	1.5	1.4
	110	0.5	1.6	1.0	1.4
11CA	50	0.5	0.7	1.2	0.5
	100	-0.2	0.9	0.7	1.1
	300	0.5	1.7	-0.1	1.3
12CA	50	-0.7	0.2	-0.9	0.2
	100	-0.6	0.3	0.2	0.3
	200	-1.7	0.5	-0.7	0.5
14CA	50	0.1	0.7	0.9	0.7
	100	-1.1	0.9	-0.2	1.0
	150	-1.8	1.3	-1.9	1.0

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



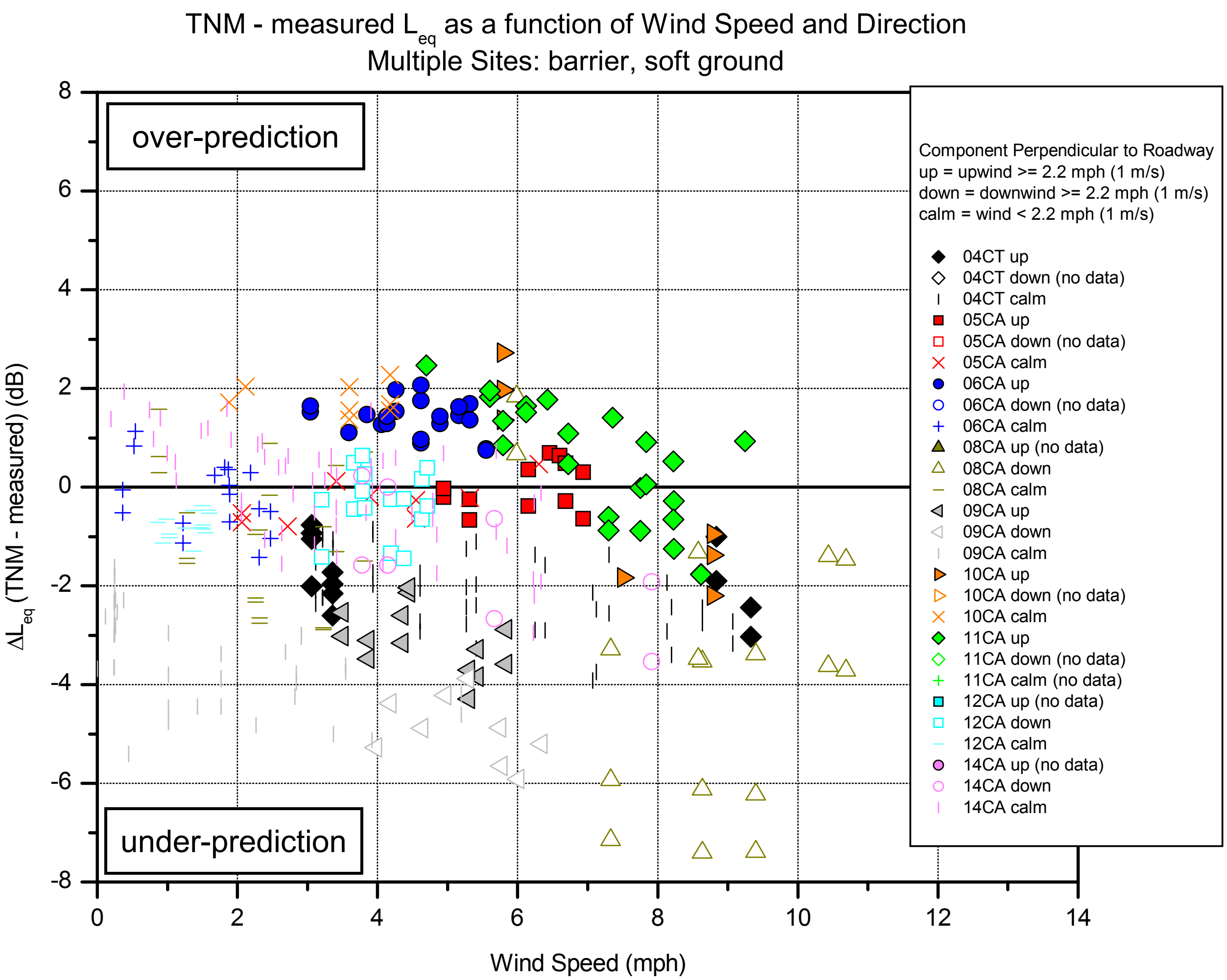
Note: The "Wind Speed" on the horizontal axis represents the overall non-directional wind speed; each data point is further categorized by the wind component perpendicular to the roadway.

Figure F.13. Differences (TNM minus Measured) as a Function of Wind Speed and Direction; Open Area, Soft Ground Sites; All Wind Data Included.



Note: The "Wind Speed" on the horizontal axis represents the overall non-directional wind speed; each data point is further categorized by the wind component perpendicular to the roadway.

Figure F.14. Differences (TNM minus Measured) as a Function of Wind Speed and Direction; Open Area, Hard Ground Sites; All Wind Data Included.



Note: The "Wind Speed" on the horizontal axis represents the overall non-directional wind speed; each data point is further categorized by the wind component perpendicular to the roadway.

Figure F.15. Differences (TNM minus Measured) as a Function of Wind Speed and Direction; Barrier, Soft Ground Sites; All Wind Data Included.

Appendix G:

Comparison of TNM-Predicted and Measured Sound Levels;

Strong Wind Data Removed

Data presented in this appendix include all processed data except where the wind speed exceeded ~11 mph (5 m/s).

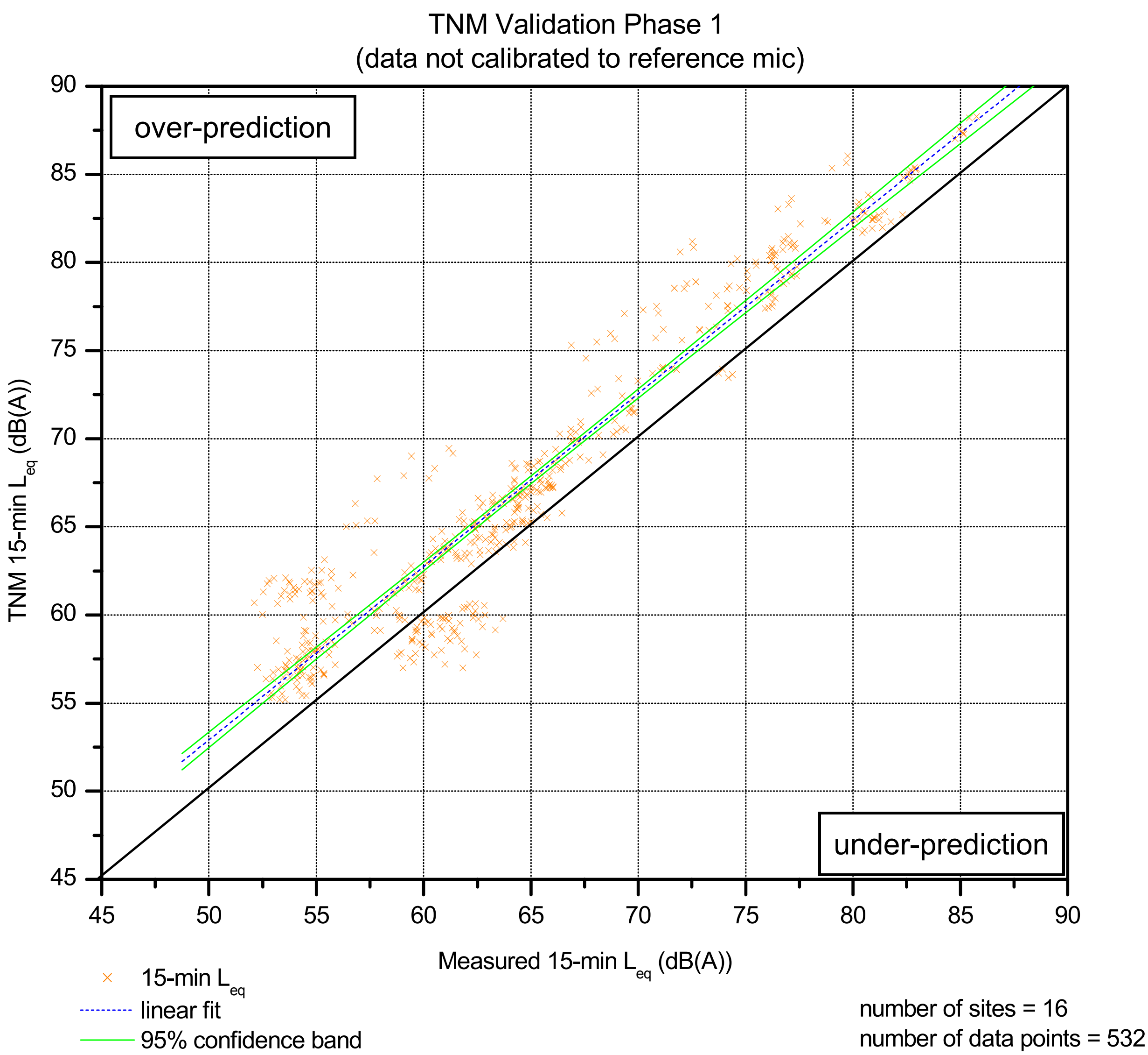


Figure G.1. Direct Comparison of TNM and Measured Data; All Sites (not calibrated); Strong Wind Data Removed.

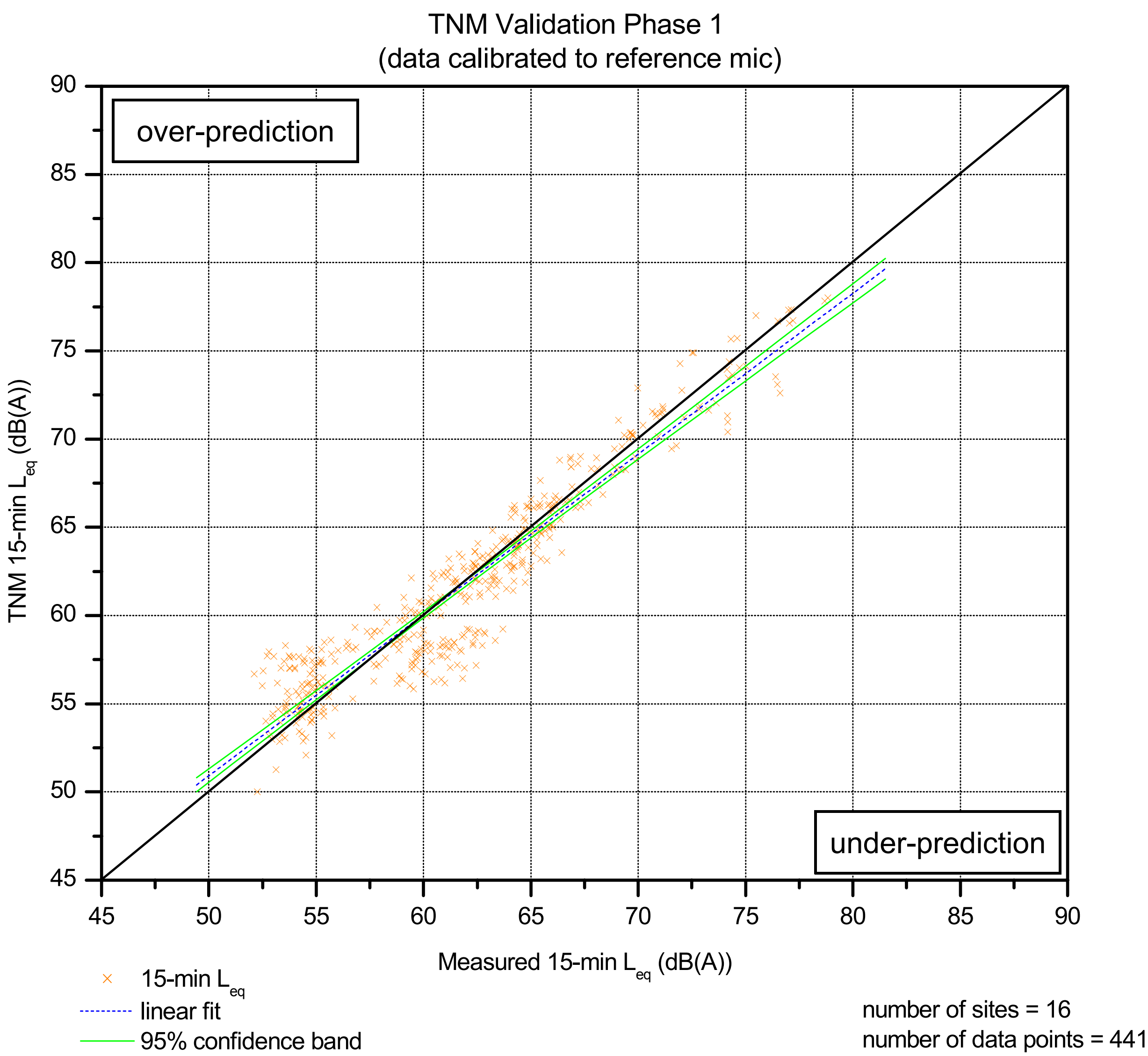


Figure G.2. Direct Comparison of TNM and Measured Data; All Sites (calibrated); Strong Wind Data Removed.

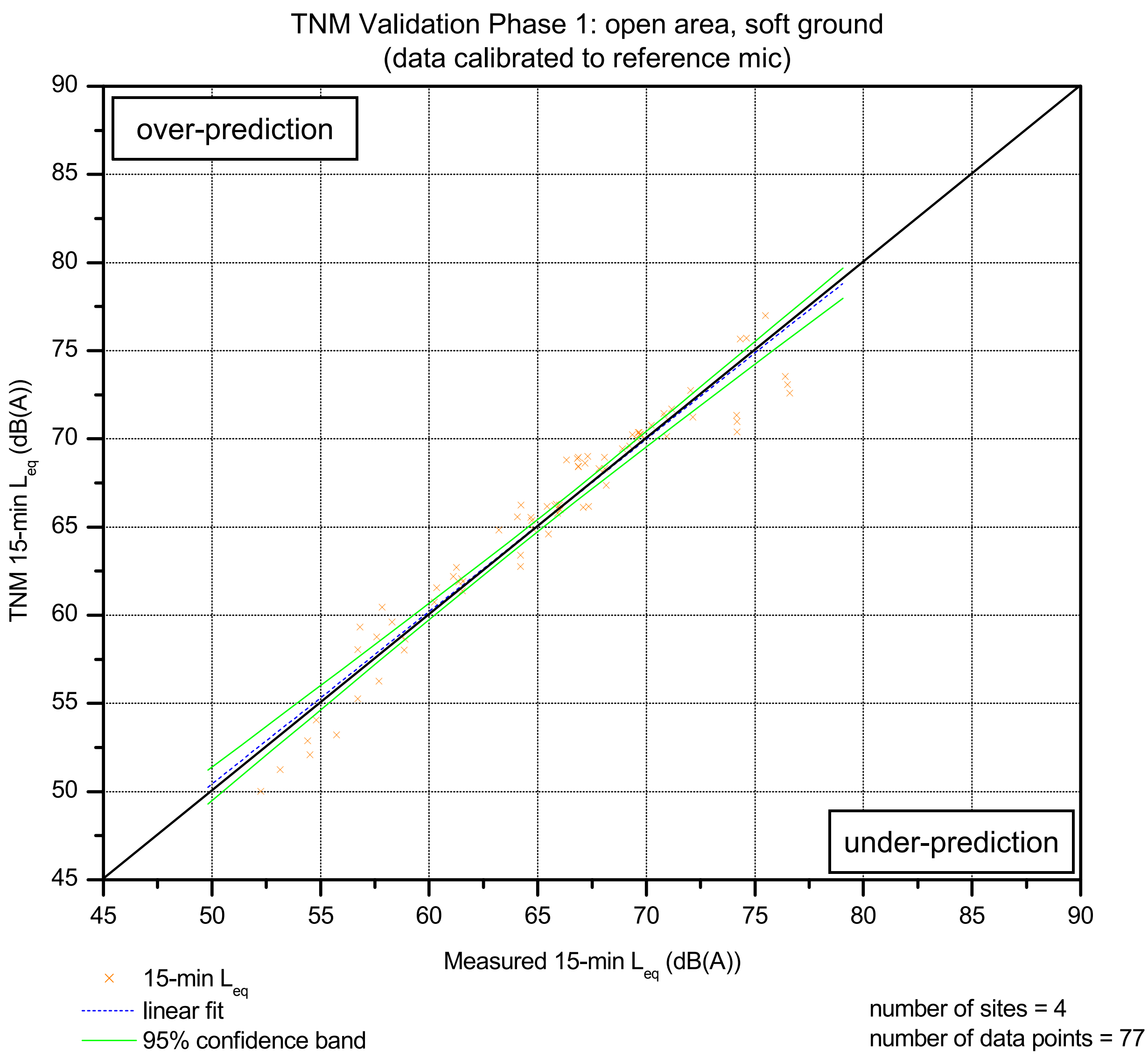


Figure G.3. Direct Comparison of TNM and Measured Data; Open Area, Soft Ground Sites; Strong Wind Data Removed.

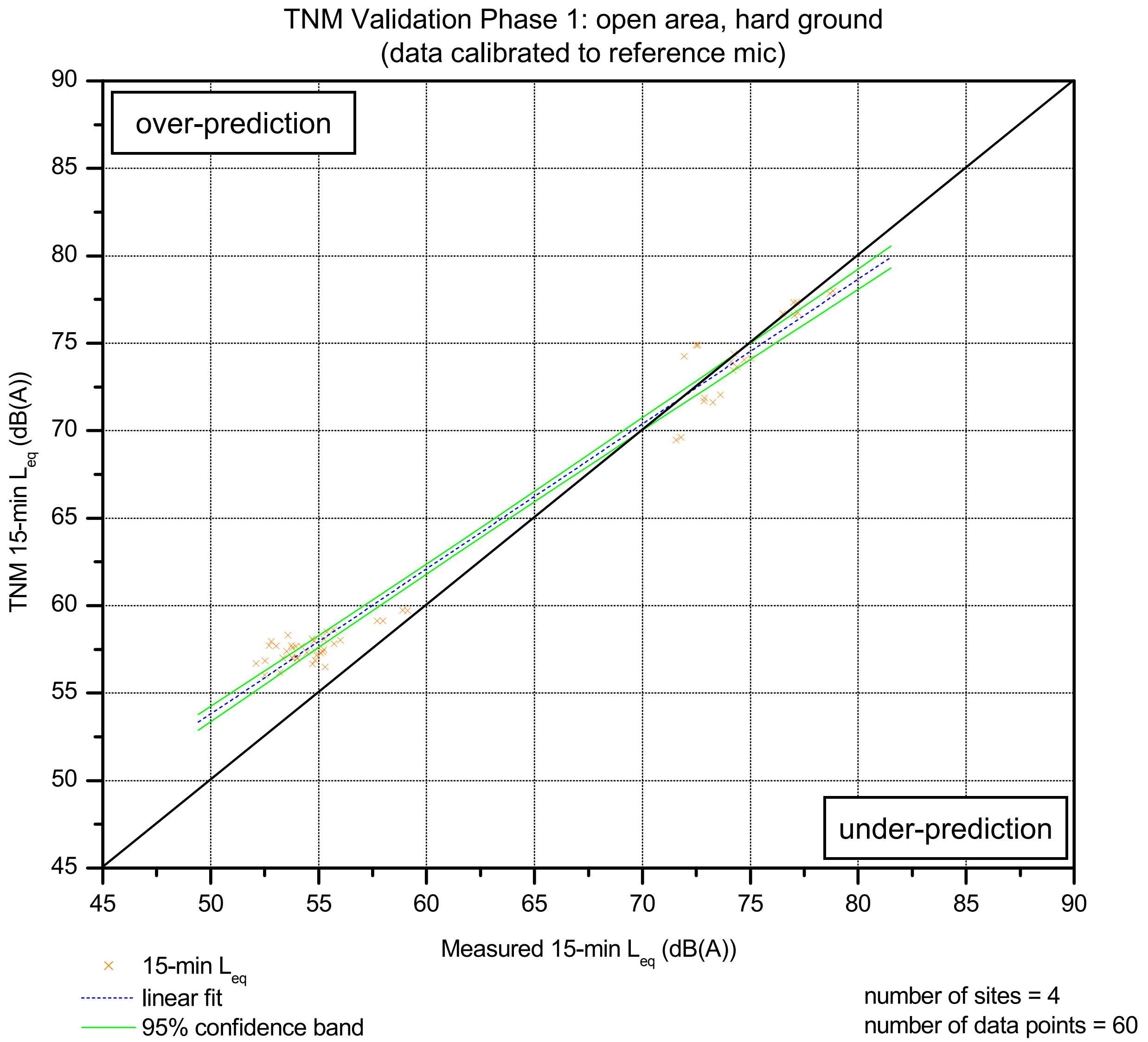
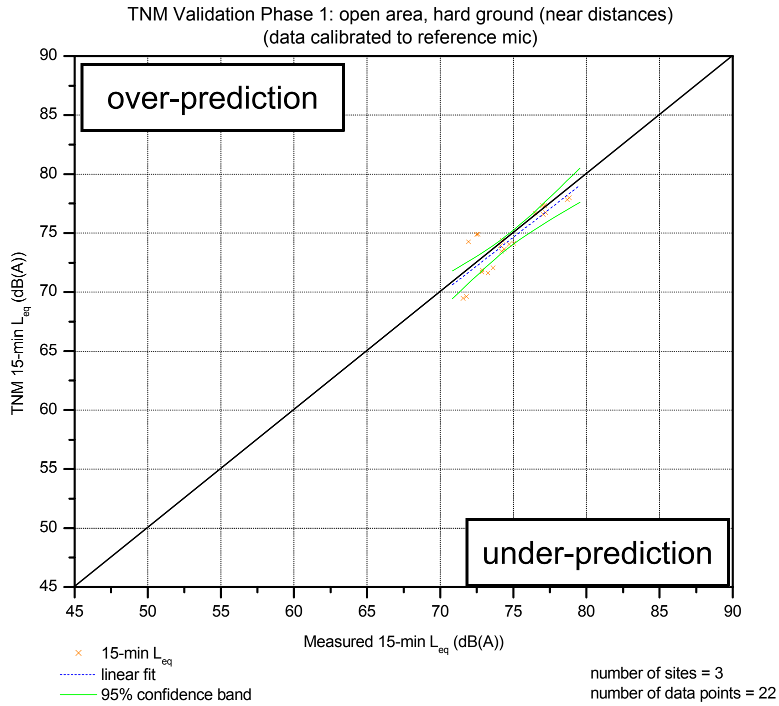


Figure G.4. Direct Comparison of TNM and Measured Data; Open Area, Hard Ground Sites; Strong Wind Data Removed.



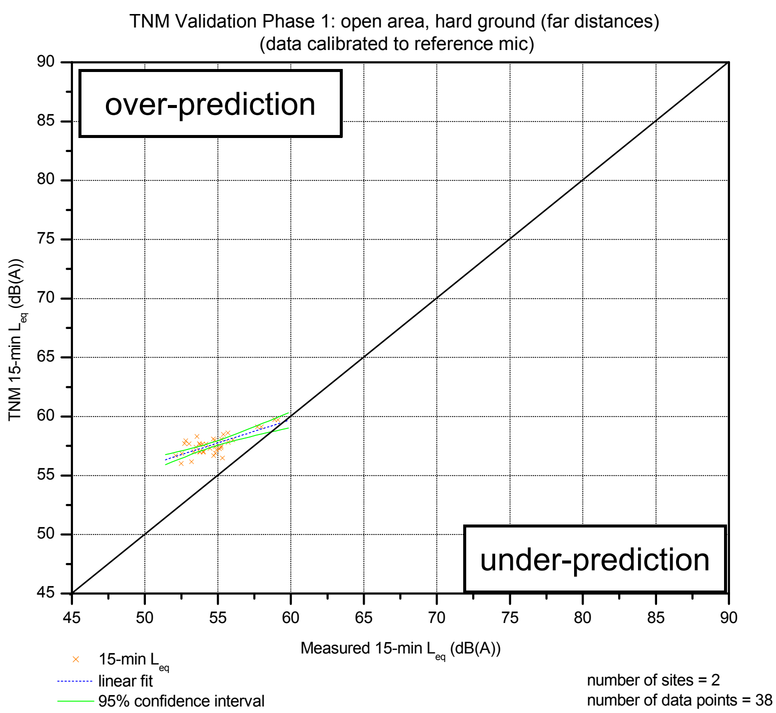


Figure G.5. Direct Comparison of TNM and Measured Data; Open Area, Hard Ground Sites; Separated High and Low Sound Levels; Strong Wind Data Removed.

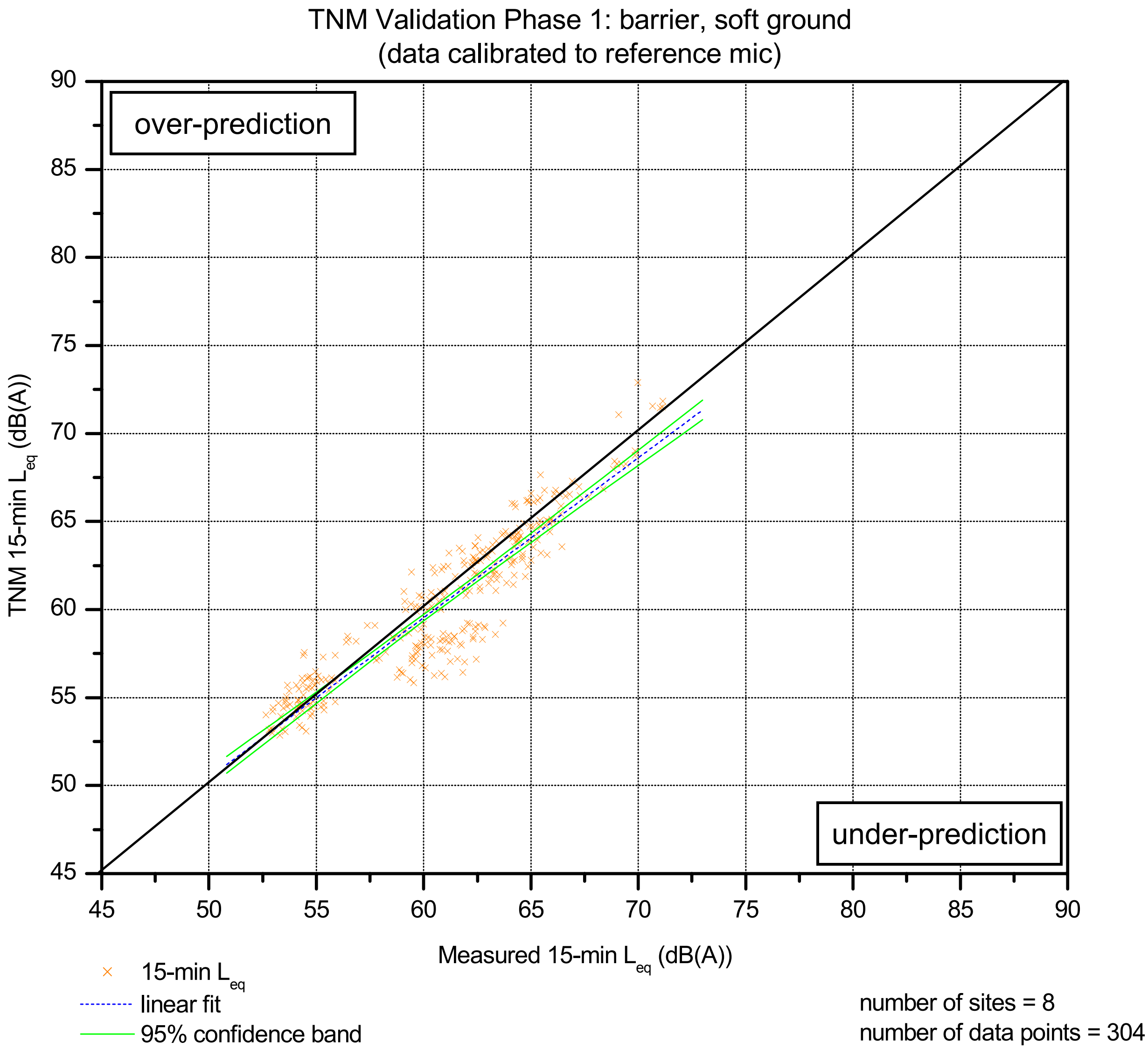


Figure G.6. Direct Comparison of TNM and Measured Data; Barrier, Soft Ground Sites; Strong Wind Data Removed.

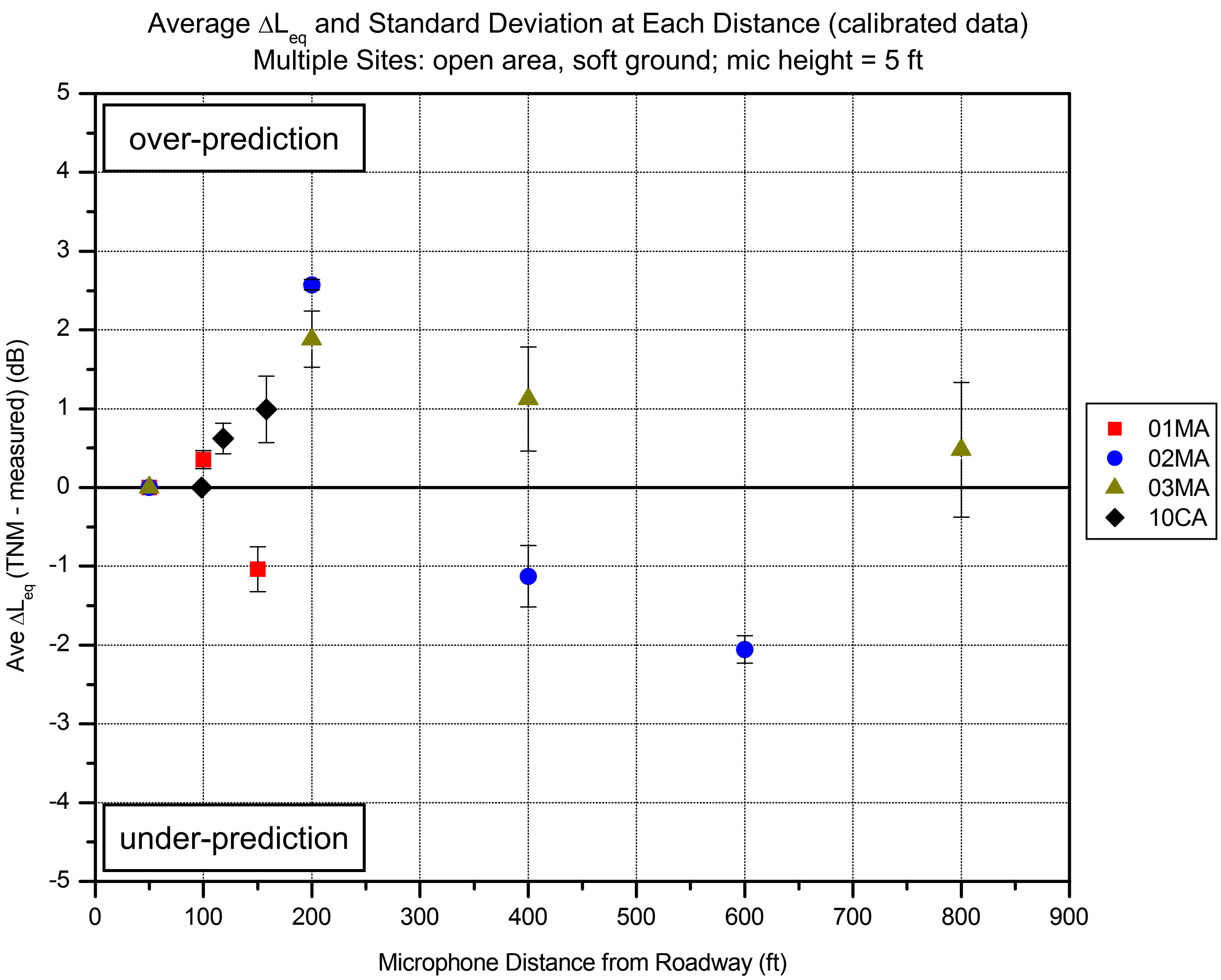


Figure G.7. Average Differences (TNM minus Measured) as a Function of Distance; Open Area, Soft Ground Sites; 5-ft Height; Strong Wind Data Removed.

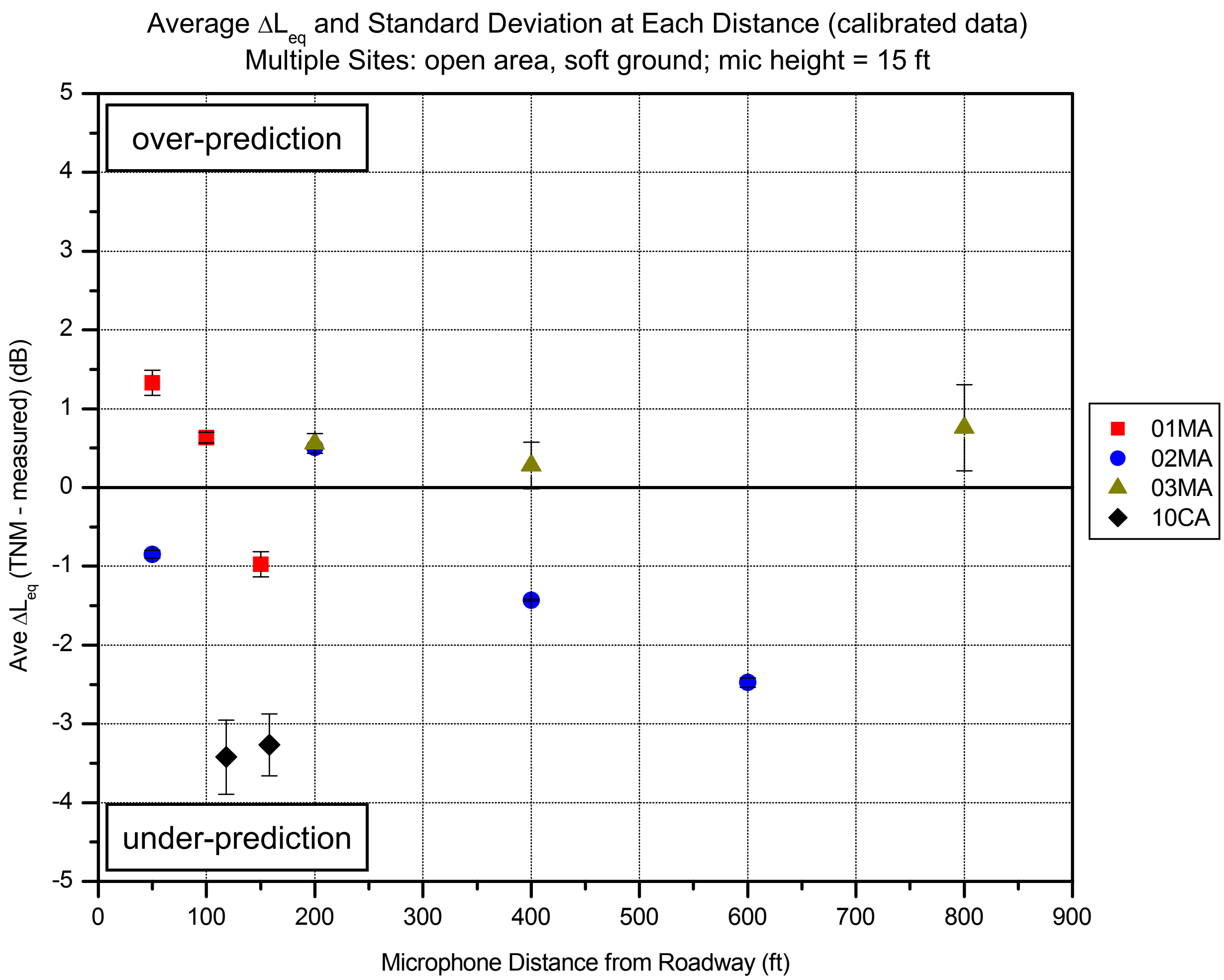


Figure G.8. Average Differences (TNM minus Measured) as a Function of Distance; Open Area, Soft Ground Sites; 15-ft Height; Strong Wind Data Removed.

Table G.1. Average Differences (TNM minus Measured) and Standard Deviations as a Function of Distance and Height; Open Area, Soft Ground Sites; Strong Wind Data Removed

Site ID	Distance From Roadway (ft)	5 ft mic (dB)		15 ft mic (dB)	
		average	stan dev	average	stan dev
01MA	50			1.3	0.2
	100	0.4	0.1	0.6	0.1
	150	-1.0	0.3	-1.0	0.2
02MA	50			-0.8	0.1
	200	2.6	0.1	0.5	0.0
	400	-1.1	0.4	-1.4	0.0
	600	-2.1	0.2	-2.5	0.1
03MA	50				
	200	1.9	0.4	0.6	0.1
	400	1.1	0.7	0.3	0.3
	800	0.5	0.9	0.8	0.5
10CA	98				
	118	0.6	0.2	-3.4	0.5
	158	1.0	0.4	-3.3	0.4

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

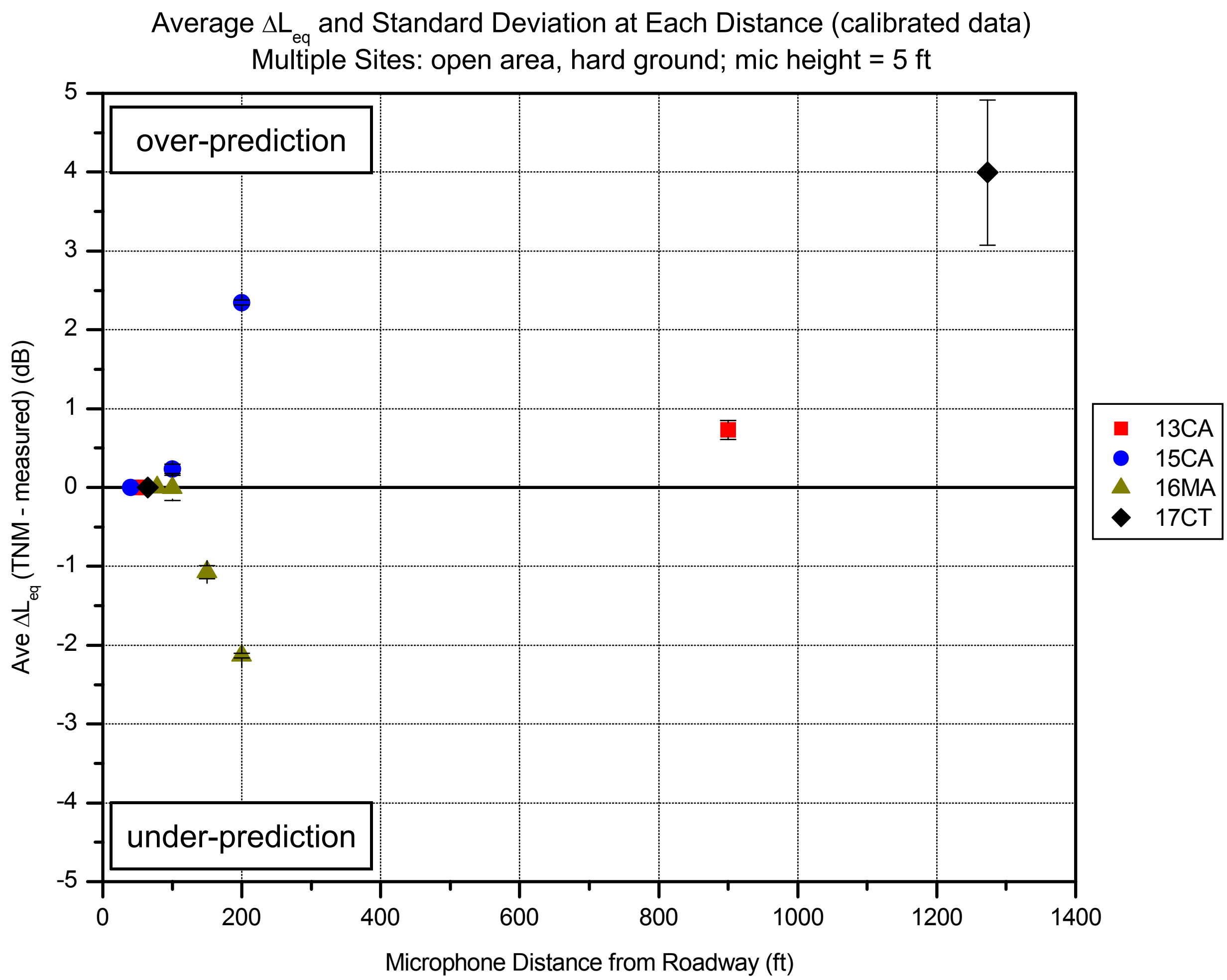


Figure G.9. Average Differences (TNM minus Measured) as a Function of Distance; Open Area, Hard Ground Sites; 5-ft Height; Strong Wind Data Removed.

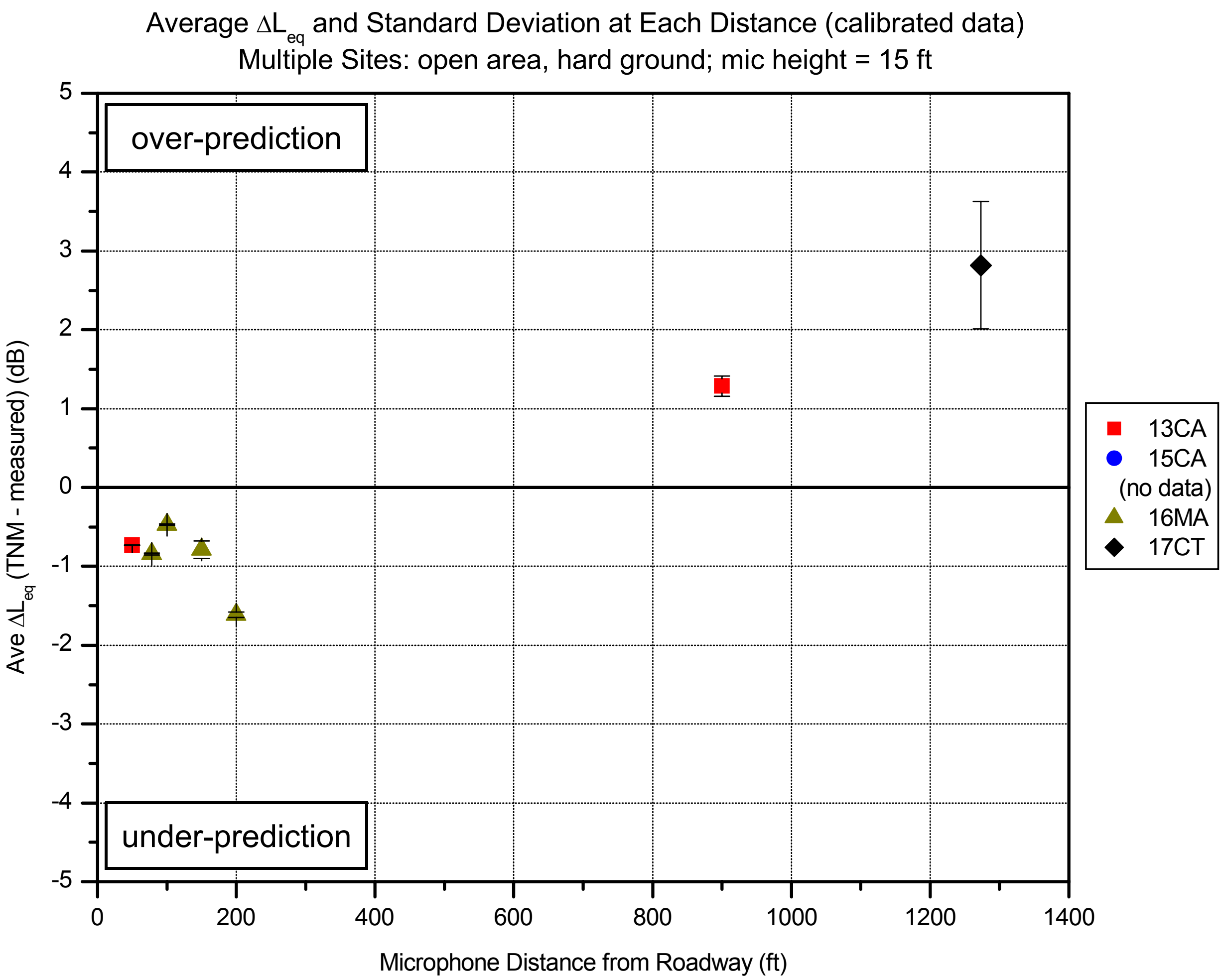


Figure G.10. Average Differences (TNM minus Measured) as a Function of Distance; Open Area, Hard Ground Sites; 15-ft Height; Strong Wind Data Removed.

Table G.2. Average Differences (TNM minus Measured) and Standard Deviations as a Function of Distance and Height; Open Area, Hard Ground Sites; Strong Wind Data Removed

Site ID	Distance From Roadway (ft)	5 ft mic (dB)		15 ft mic (dB)	
		average	stan dev	average	stan dev
13CA	50			-0.7	0.0
	900	0.7	0.1	1.3	0.1
15CA	40				
	100	0.2	0.1		
	200	2.3	0.0		
	400				
16MA	78			-0.8	0.0
	100	0.0	0.2	-0.5	0.0
	150	-1.1	0.1	-0.8	0.1
	200	-2.1	0.0	-1.6	0.0
17CT	65				
	1273	4.0	0.9	2.8	0.8

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

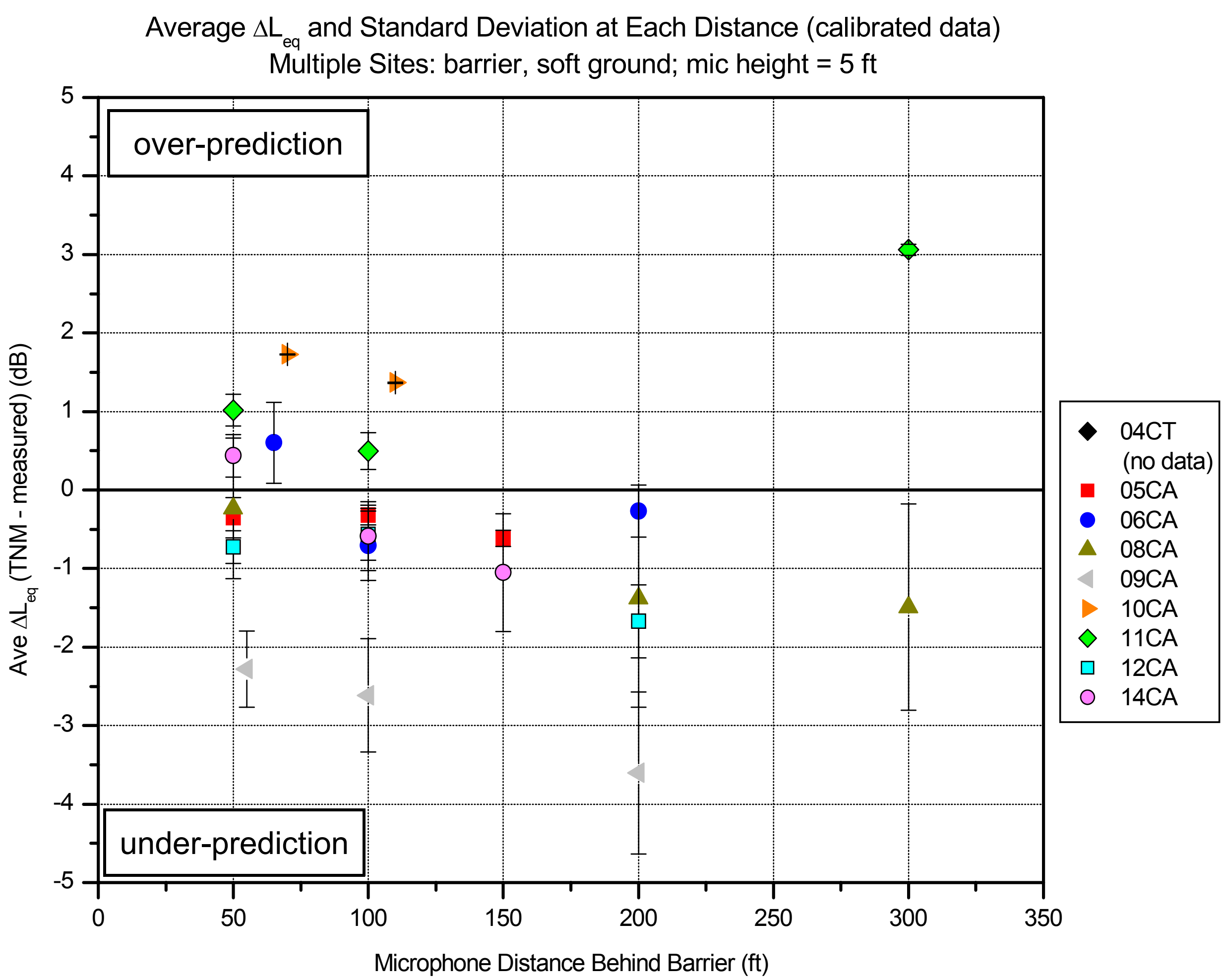


Figure G.11. Average Differences (TNM minus Measured) as a Function of Distance; Barrier, Soft Ground Sites; 5-ft Height; Strong Wind Data Removed.

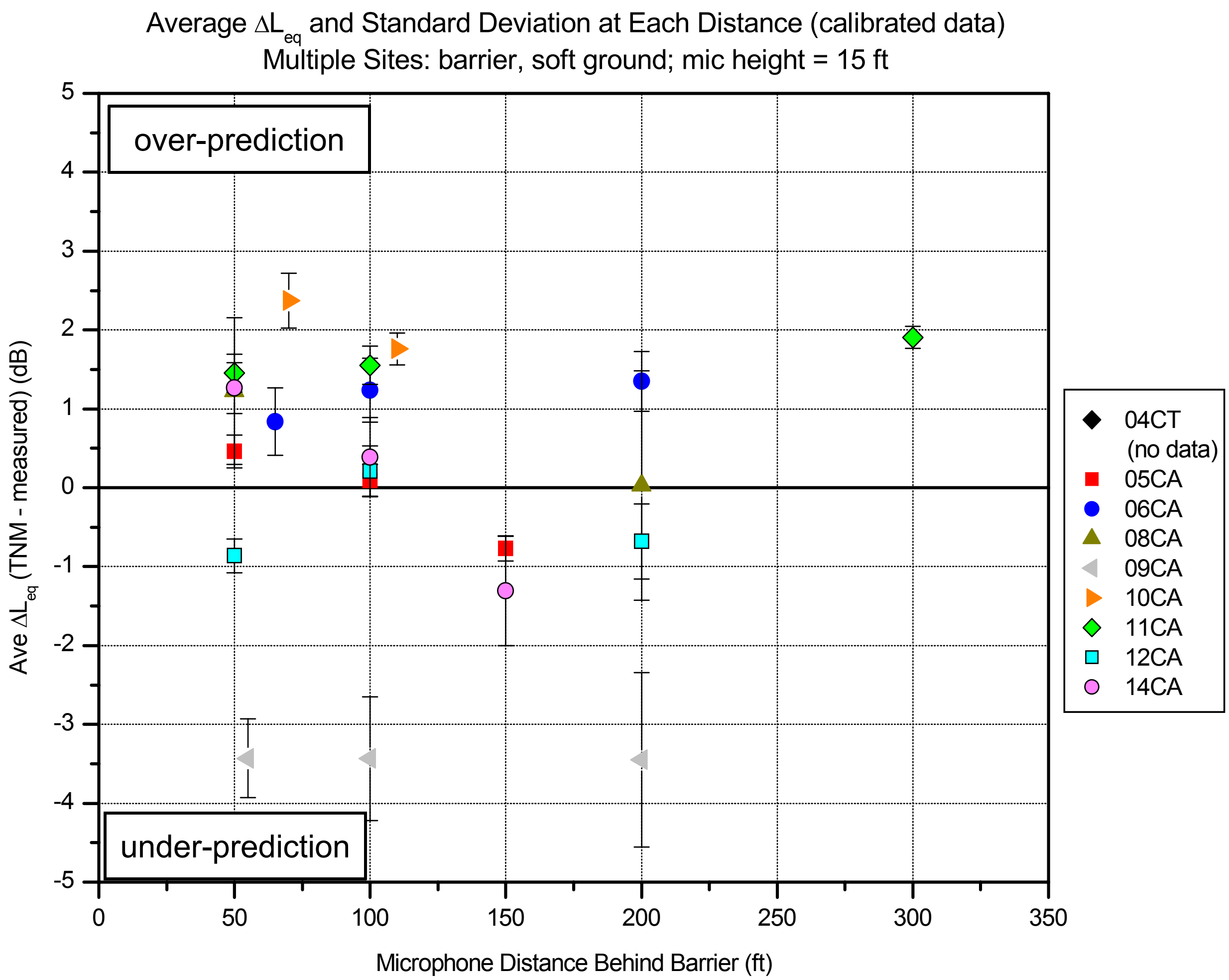
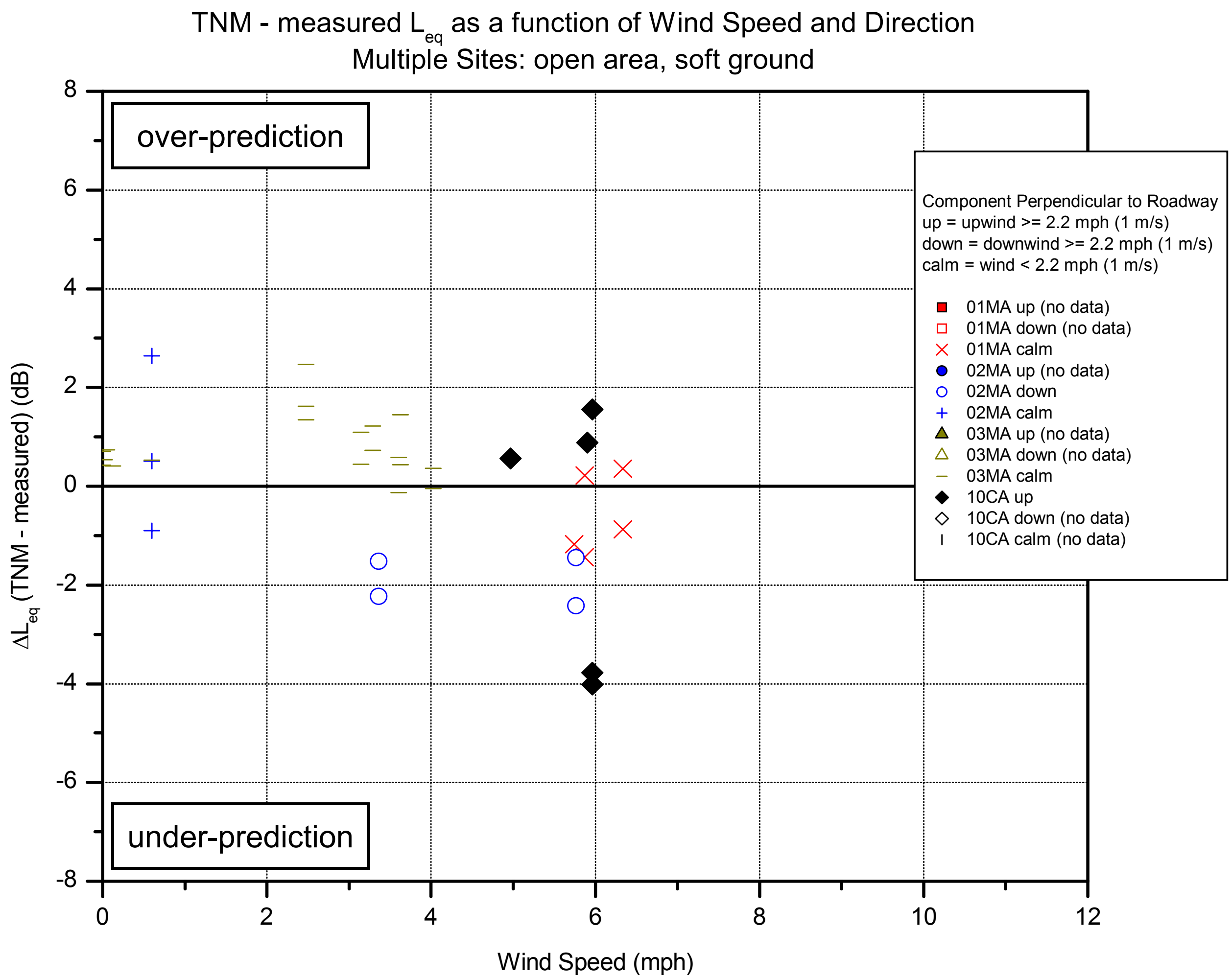


Figure G.12. Average Differences (TNM minus Measured) as a Function of Distance; Barrier, Soft Ground Sites; 15-ft Height; Strong Wind Data Removed.

Table G.3. Average Differences (TNM minus Measured) and Standard Deviations as a Function of Distance and Height; Barrier, Soft Ground Sites; Strong Wind Data Removed

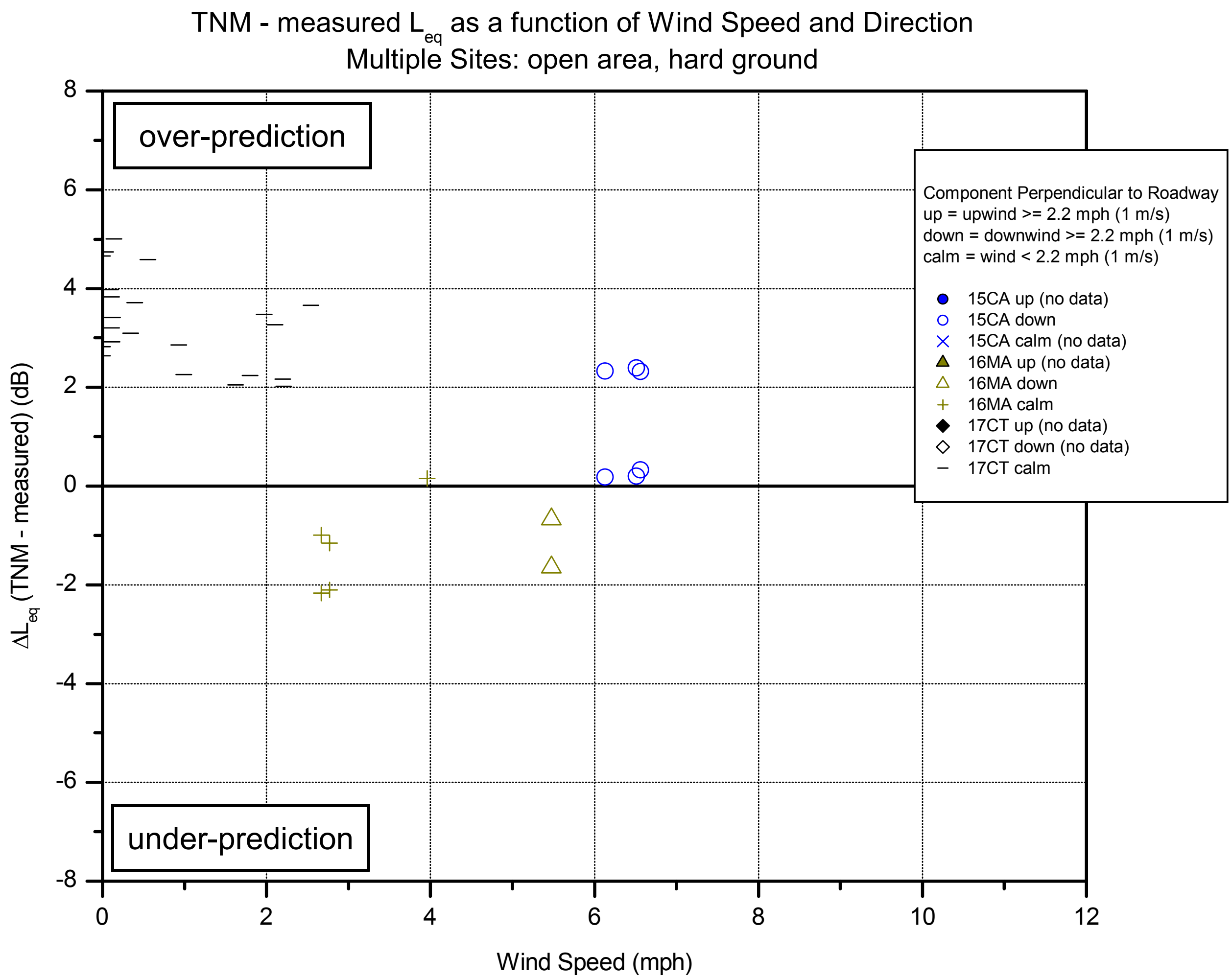
Site ID	Distance Behind Barrier (ft)	5 ft mic (dB)		15 ft mic (dB)	
		average	stan dev	average	stan dev
04CT					
05CA	50	-0.4	0.3	0.5	0.2
	100	-0.3	0.1	0.1	0.2
	150	-0.6	0.1	-0.8	0.2
06CA	65	0.6	0.5	0.8	0.4
	100	-0.7	0.4	1.2	0.4
	200	-0.3	0.3	1.3	0.4
08CA	50	-0.2	0.9	1.2	0.9
	200	-1.4	1.4	0.0	1.5
	300	-1.5	1.3		
09CA	55	-2.3	0.5	-3.4	0.5
	100	-2.6	0.7	-3.4	0.8
	200	-3.6	1.0	-3.4	1.1
10CA	70	1.7	0.0	2.4	0.3
	110	1.4	0.0	1.8	0.2
11CA	50	1.0	0.2	1.5	0.2
	100	0.5	0.2	1.6	0.2
	300	3.1	0.1	1.9	0.1
12CA	50	-0.7	0.2	-0.9	0.2
	100	-0.6	0.3	0.2	0.3
	200	-1.7	0.5	-0.7	0.5
14CA	50	0.4	0.3	1.3	0.3
	100	-0.6	0.4	0.4	0.5
	150	-1.1	0.8	-1.3	0.7

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



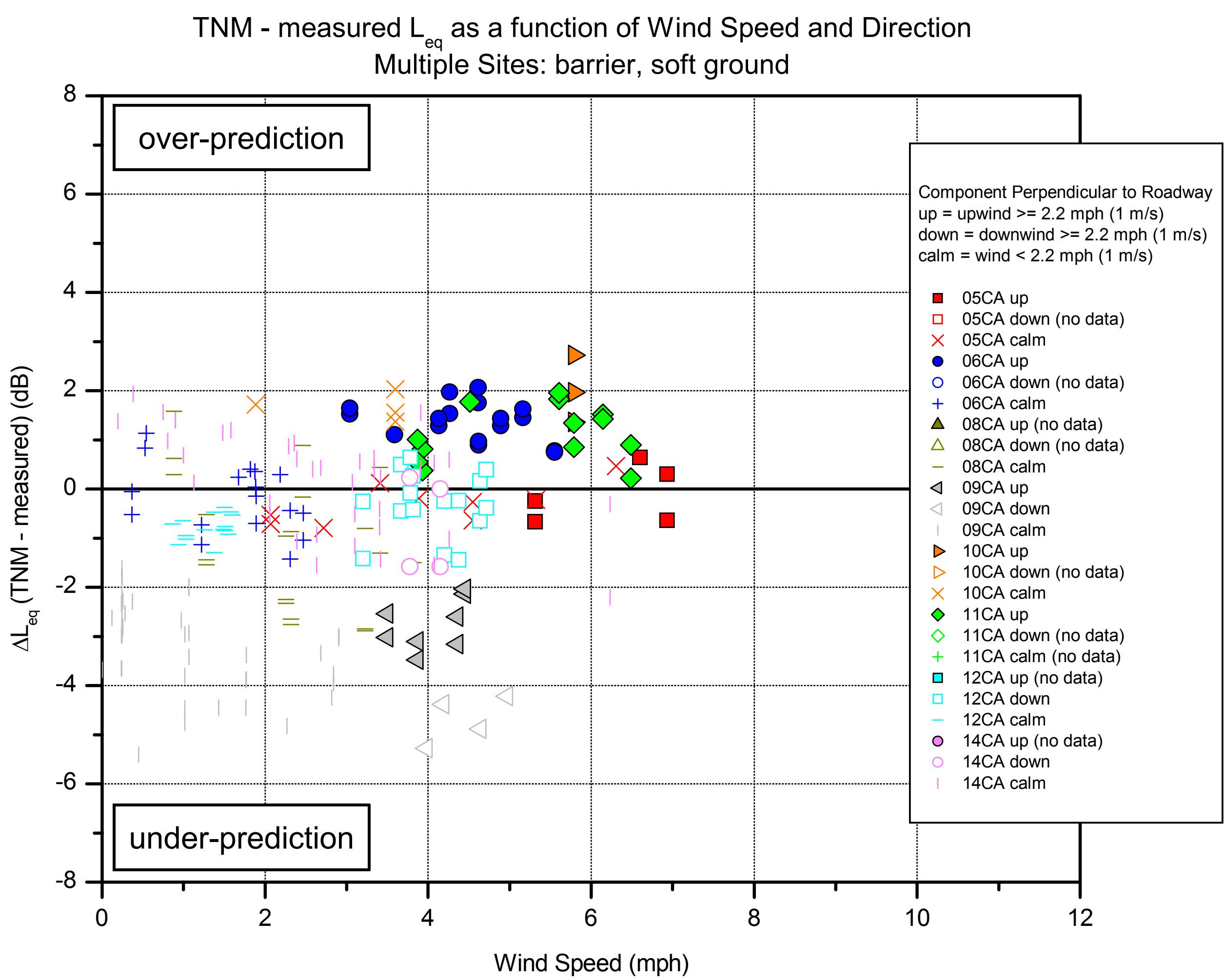
Note: The "Wind Speed" on the horizontal axis represents the overall non-directional wind speed; each data point is further categorized by the wind component perpendicular to the roadway.

Figure G.13. Differences (TNM minus Measured) as a Function of Wind Speed and Direction; Open Area, Soft Ground Sites; Strong Wind Data Removed.



Note: The "Wind Speed" on the horizontal axis represents the overall non-directional wind speed; each data point is further categorized by the wind component perpendicular to the roadway.

Figure G.14. Differences (TNM minus Measured) as a Function of Wind Speed and Direction; Open Area, Hard Ground Sites; Strong Wind Data Removed.



Note: The "Wind Speed" on the horizontal axis represents the overall non-directional wind speed; each data point is further categorized by the wind component perpendicular to the roadway.

Figure G.15. Differences (TNM minus Measured) as a Function of Wind Speed and Direction; Barrier, Soft Ground Sites; Strong Wind Data Removed.

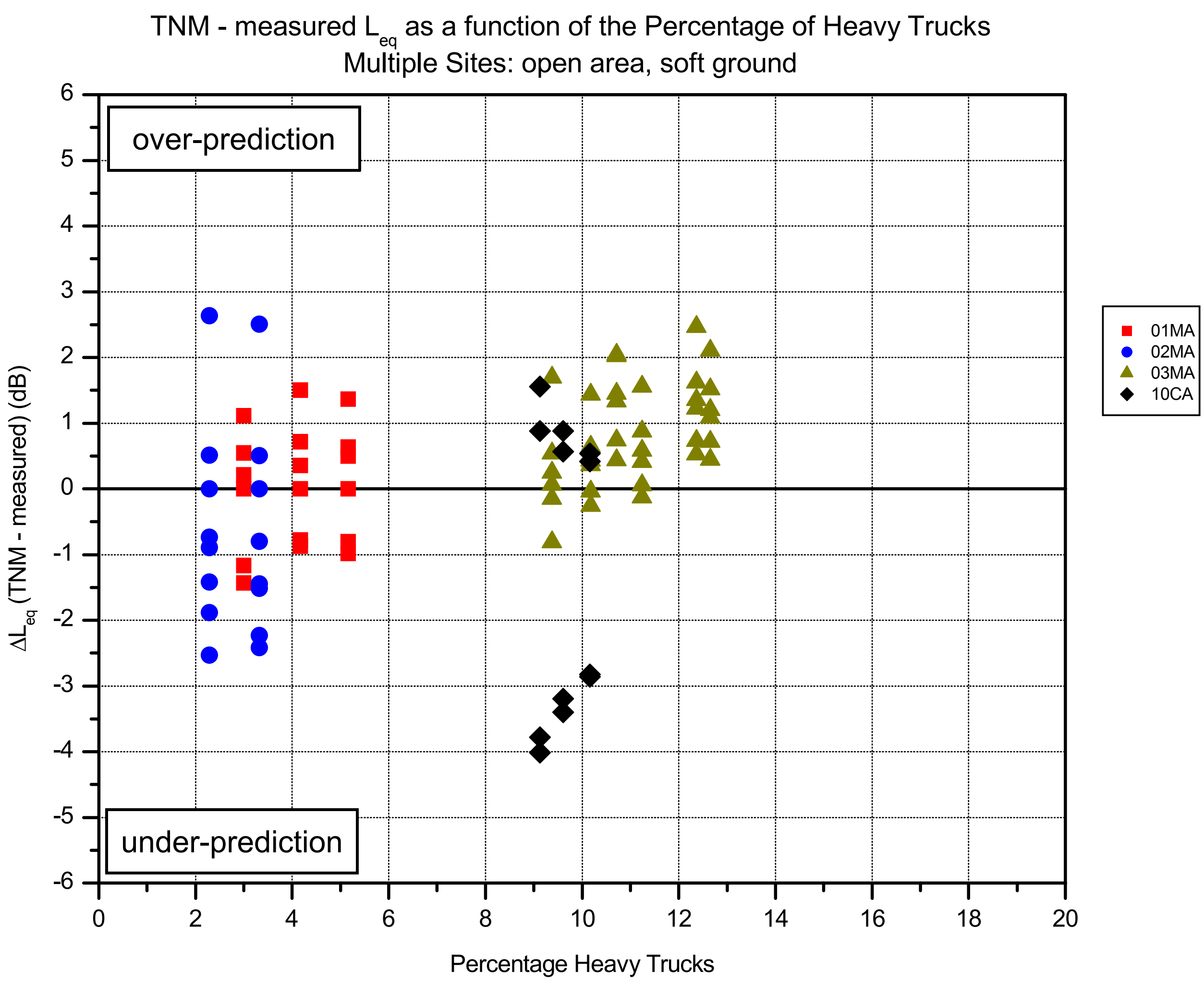


Figure G.16. Differences (TNM minus Measured) as a Function of Percentage of Heavy Trucks; Open Area, Soft Ground Sites; Strong Wind Data Removed.

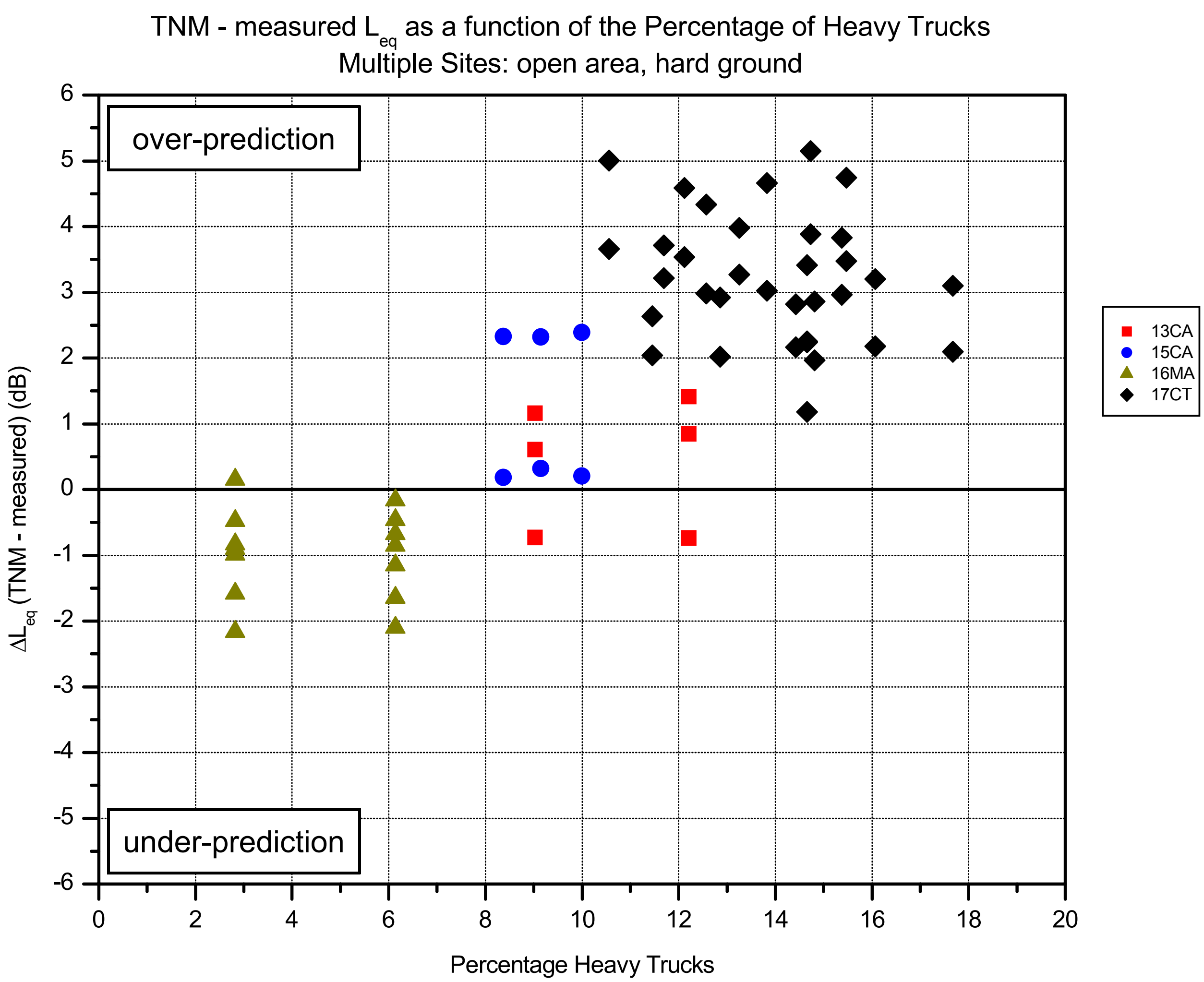


Figure G.17. Differences (TNM minus Measured) as a Function of Percentage of Heavy Trucks; Open Area, Hard Ground Sites; Strong Wind Data Removed.

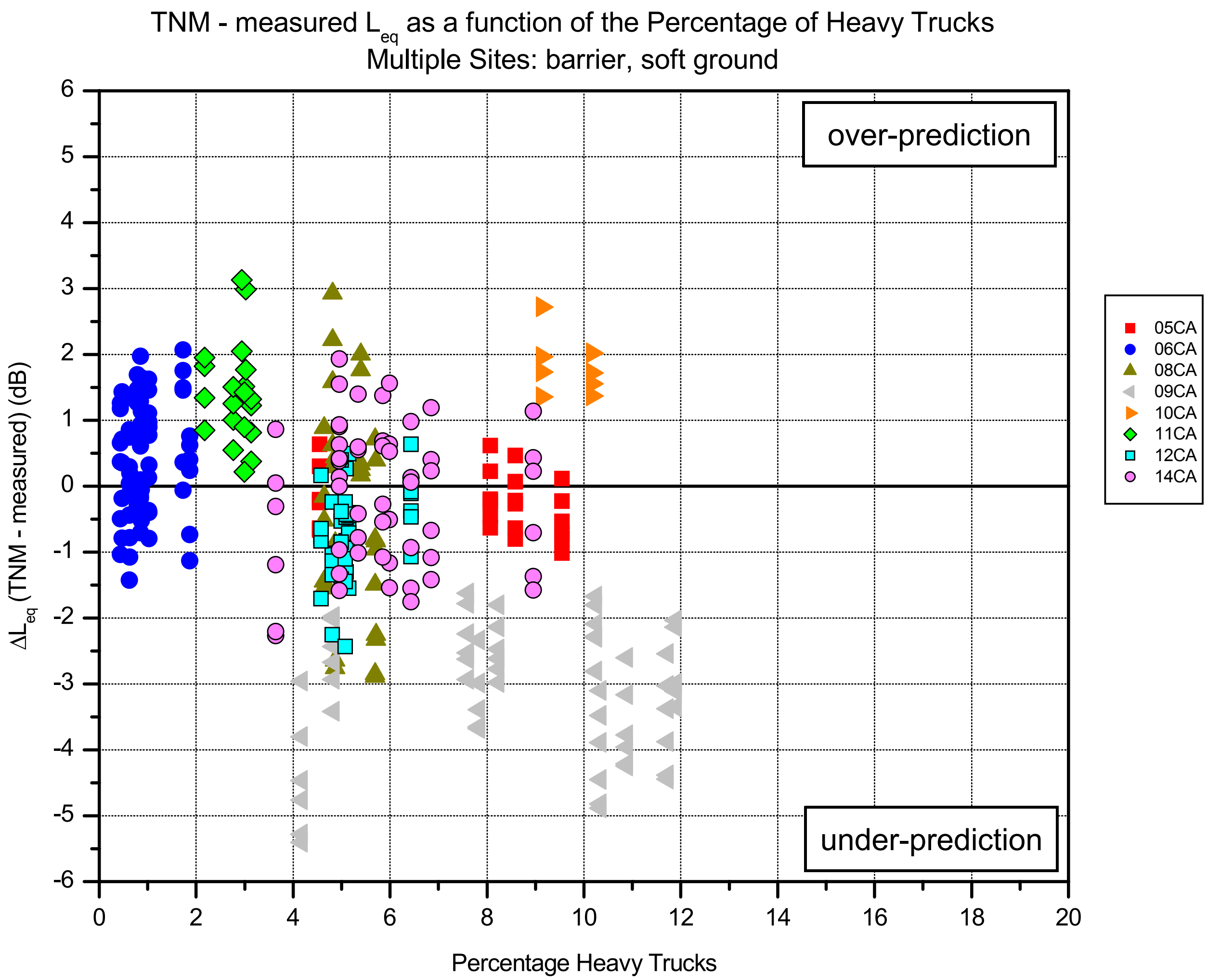


Figure G.18. Differences (TNM minus Measured) as a Function of Percentage of Heavy Trucks; Barrier, Soft Ground Sites; Strong Wind Data Removed.

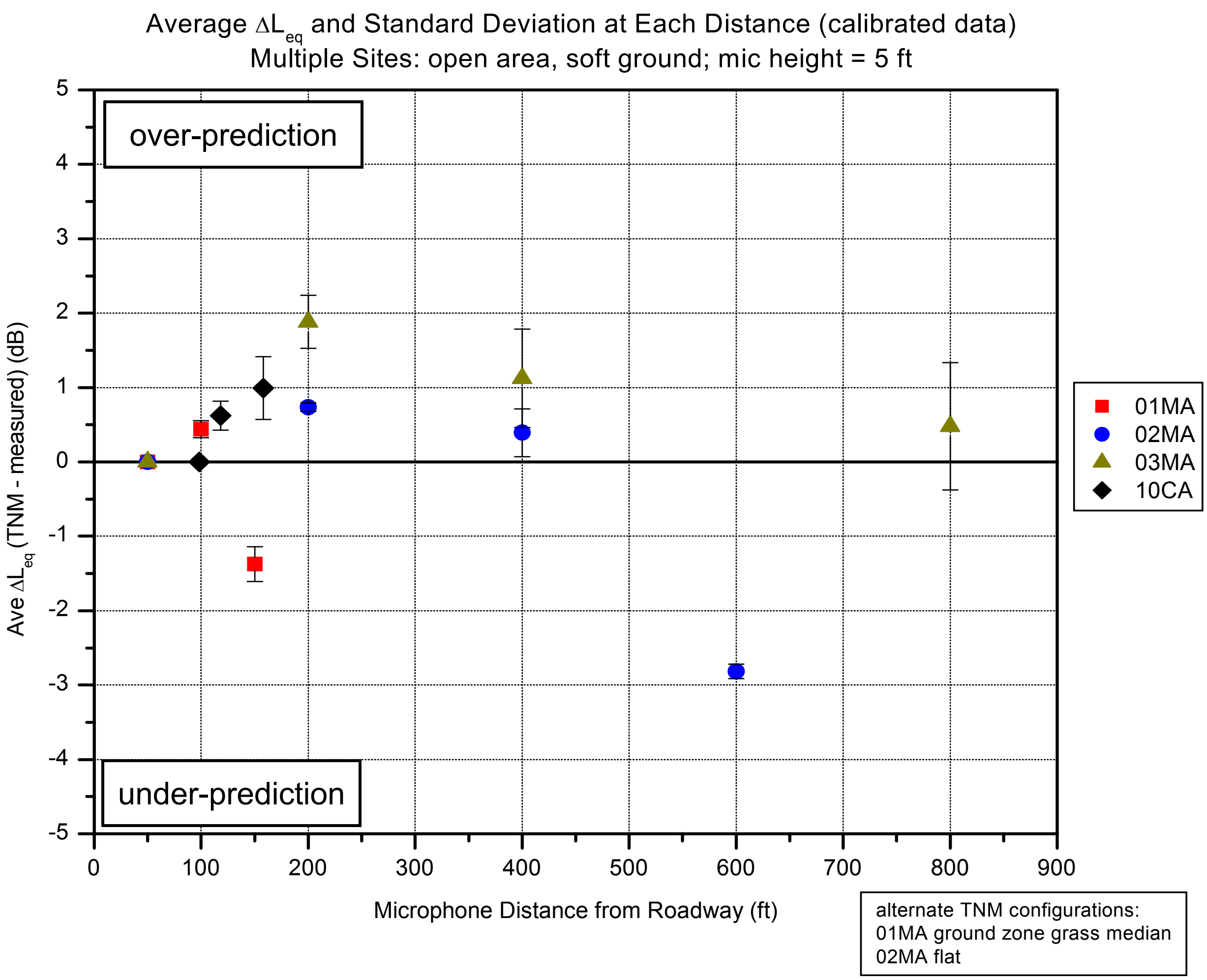


Figure G.19. Average Differences (TNM minus Measured) as a Function of Distance; Open Area, Soft Ground Sites; 5-ft Height; Alternate TNM Configuration 1; Strong Wind Data Removed.

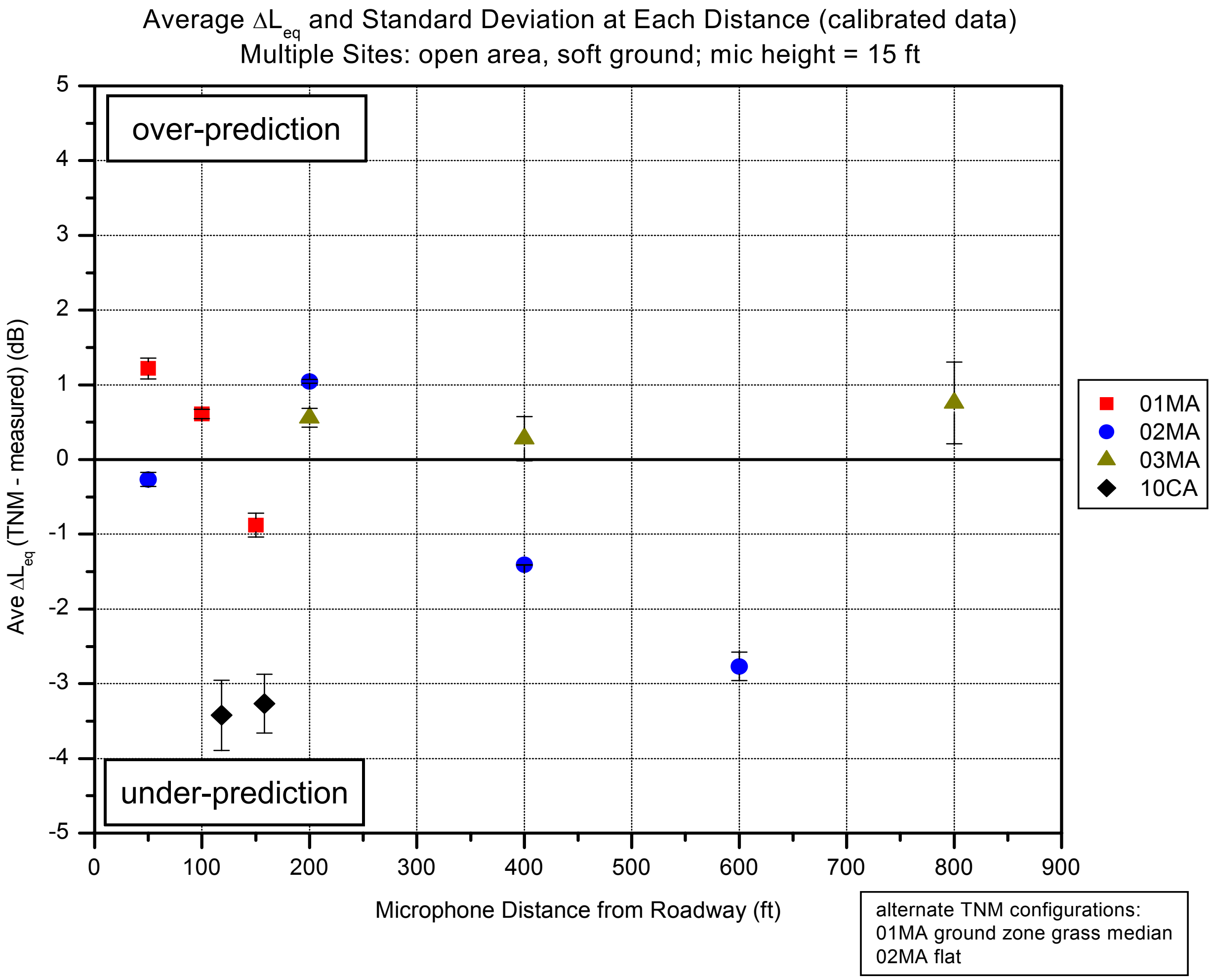


Figure G.20. Average Differences (TNM minus Measured) as a Function of Distance; Open Area, Soft Ground Sites; 15-ft Height; Alternate TNM Configuration 1; Strong Wind Data Removed.

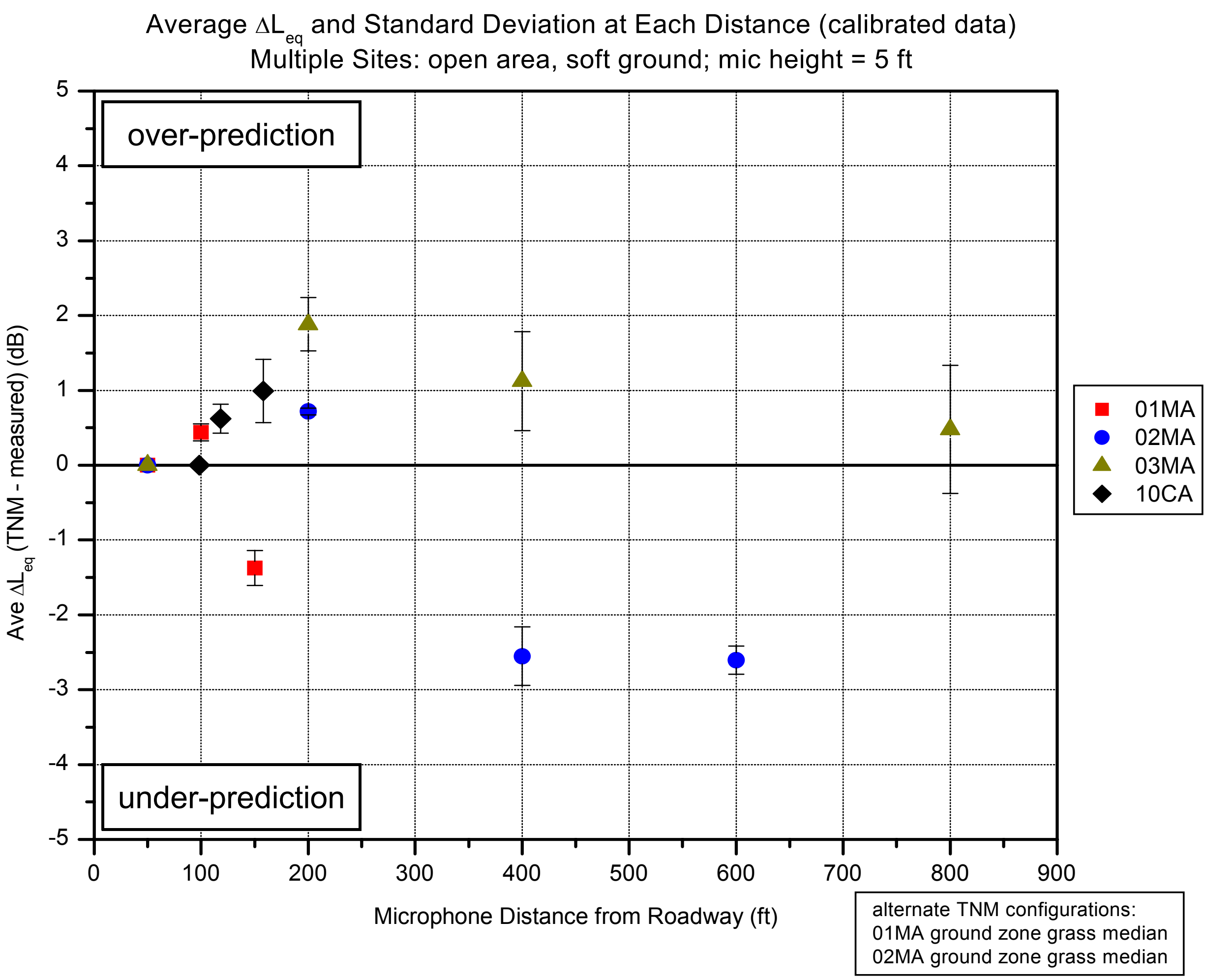


Figure G.21. Average Differences (TNM minus Measured) as a Function of Distance; Open Area, Soft Ground Sites; 5-ft Height; Alternate TNM Configuration 2; Strong Wind Data Removed.

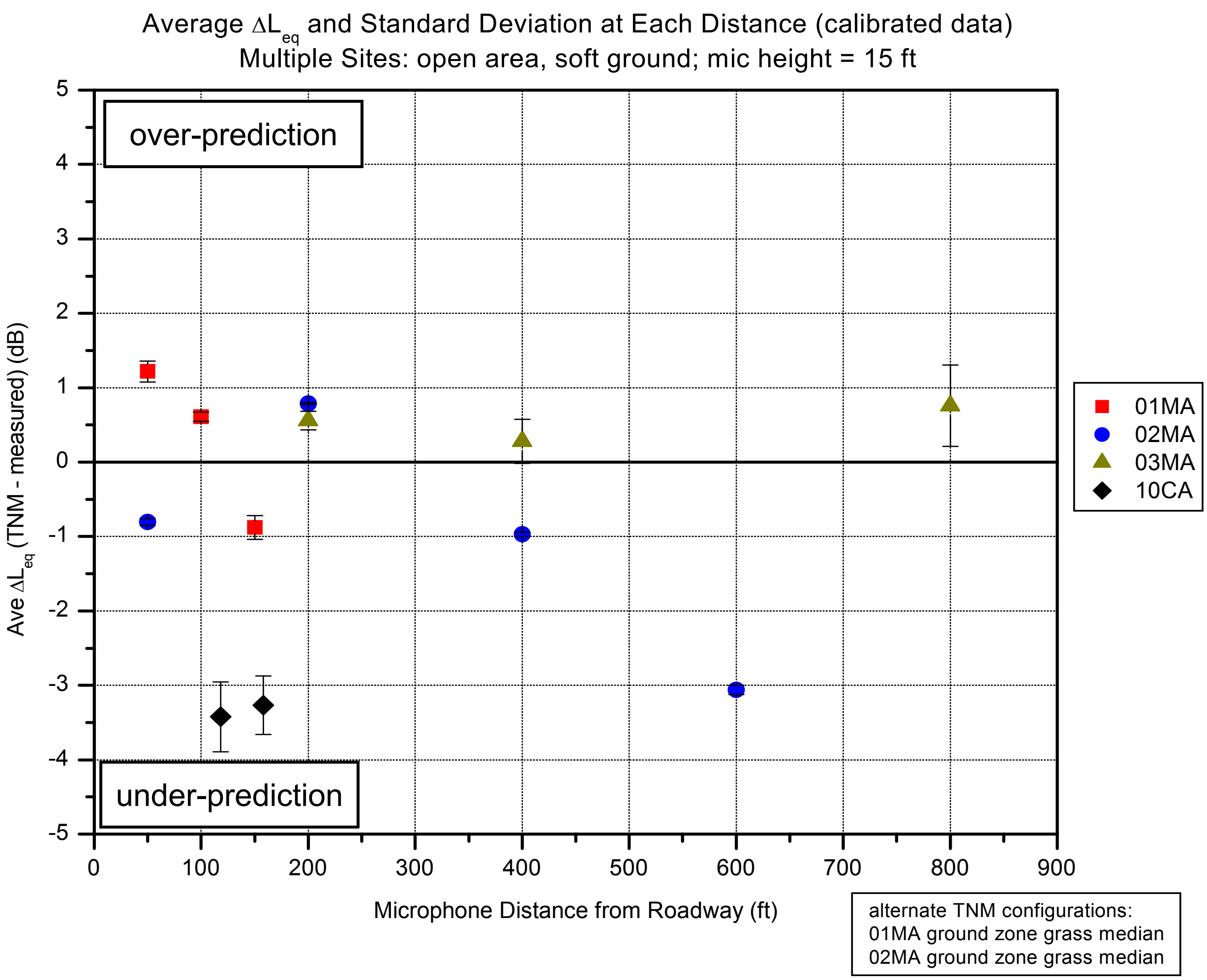


Figure G.22. Average Differences (TNM minus Measured) as a Function of Distance; Open Area, Soft Ground Sites; 15-ft Height; Alternate TNM Configuration 2; Strong Wind Data Removed.

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