DECEMBER 2019

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Federal Highway Administration

VALIDATION REPORT

TRAFFIC NOISE MODEL 3.0

FHWA-HEP-20-011

FEDERAL HIGHWAY ADMINISTRATION

OFFICE OF NATURAL ENVIRONMENT

Washington, D.C.

Notice

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13. ABSTRACT (Maximum 200 words) The Federal Highway Administration (FHWA) with the assistance of the Volpe Center Acoustics Facility conducted a study to quantify the agreement of FHWA's Traffic Noise Model Version 3.0 (TNM 3.0) with measured highway noise data and with predictions from TNM 2.5. For this phase of validation, 281 hours of traffic noise data were collected at 14 highway sites across the country. The 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. Data were compared in aggregate and as a function of several parameters including: TNM version, site, distance, ground type and pavement type. Model results from FHWA's Consistency Test Suite were also compared. The results provide information about the degree and sources of variation between TNM 2.5 and 3.0.			
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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

**SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)*

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Abbreviations

Abbreviation	Term
B&K	Brüel and Kjær (Instrumentation Company)
DAT	Digital Audio Tape
dB	Decibel
dB(A)	A-weighted Decibel
DGAC	Dense Graded Asphalt Concrete
dGPS	Differential Global Positioning System
DOT	Department of Transportation
FHWA	Federal Highway Administration
LDL	Larson Davis Laboratories (Instrumentation Company)
OGAC	Open Graded Asphalt Concrete
PCC	Portland Cement Concrete
RMS	Root Mean Squared
RMSE	Root Mean Squared Error
SLM	Sound Level Meter
SPL	Sound Pressure Level
TNM	Traffic Noise Model
TAMS	Transportable Automated Meteorological Stations
ANSI	American National Standards Institute

Executive Summary

The Federal Highway Administration (FHWA), conducted a validation study to quantify the agreement of FHWA's Traffic Noise Model Version 3.0 (TNM 3.0) with measured highway noise data and also with predictions from TNM 2.5.

The FHWA Traffic Noise Model (TNM), first released in 1998, has been a valuable tool for highway traffic noise analysis and barrier design. Given the utility and impact of TNM, it is necessary to validate the sound level predictions to ensure accuracy. In 2002, the FHWA completed a comprehensive Validation of TNM 2.5. This validation included collection and analysis of traffic noise data at seventeen highway sites around the country (the validation dataset). These sites had characteristics of those most commonly modeled by TNM users: 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.

The most recent version of TNM, version 3.0, includes improved acoustical computations as well as minor changes and updates. These improvements include:

- Bug Fixes
  - One affecting ground impedance averaging (Bug 1)
  - One affecting the selection of highest path points (Bug 2)
- The removal of interpolation/extrapolation at lowest and highest one-third octave bands
- The replacement of horizontal divergence with combined horizontal and vertical divergence
- A change in the manner in which elemental triangles are determined
- Updated computations for Day-night equivalent Level (L_{dn}) and Day-evening-night equivalent level (L_{den})
- Added percentile level computations, L_{10} and L_{50}
- Changes to vehicle speed computations to make them more robust
- The correction of a few coefficients in the reference emission level (REMEL) database
- The standardization of effective flow resistivity (EFR) and noise reduction coefficient (NRC) values

Because of these changes, it is advisable once again to validate the model against the measured validation dataset in order to ascertain the model's accuracy in predicting practical site conditions. This report contains the results of this validation study; leveraging the original validation dataset, to compare and contrast measured data against TNM 3.0 predictions, providing continuity and consistency of analyses. Following the methodology of the TNM 2.5 validation study, TNM 3.0 predictions were generated for all 5-minute time blocks using input files from the TNM 2.5 studies, exported to TNM 3.0 compatible format. Predictions were first generated for all 5-minute time blocks using Average pavement. As an additional analysis set, predictions were also generated with the TNM specific pavement (Dense Graded Asphalt Concrete (DGAC), Open Graded Asphalt Concrete (OGAC), or Portland Cement Concrete (PCC)) that best matched the site. Although other factors are confounded with pavement type, comparing data modeled with specific pavement type against measured data can provide additional insight by accounting for one known deviation between sites as modeled and actual measurements.

Changes in predictions between TNM 2.5 and TNM 3.0 were first examined, as it is important to understand how the model improvements affect results under a variety of conditions, as well as providing historical context. A direct comparison of levels predicted by TNM 2.5 and TNM 3.0 for the measured validation dataset is shown in Figure 1. This figure shows that TNM 3.0 predicts values about 1 dB lower than TNM 2.5. In the figure, the colored circles represent individual 5-minute model computations (color coding is given in the legend); the blue dashed line shows a first-order linear regression between the two datasets; the blue dotted lines indicate the 95-percent prediction interval for any new computations; and the solid black line indicates where all results would fall if both models gave the same predictions for all analyses. Although the statistical parameters (noted in the top left corner of the graphic) indicate good average agreement, individual predictions are somewhat varied between models, since 95-percent of the variation falls within a +/-2.78 dB range.

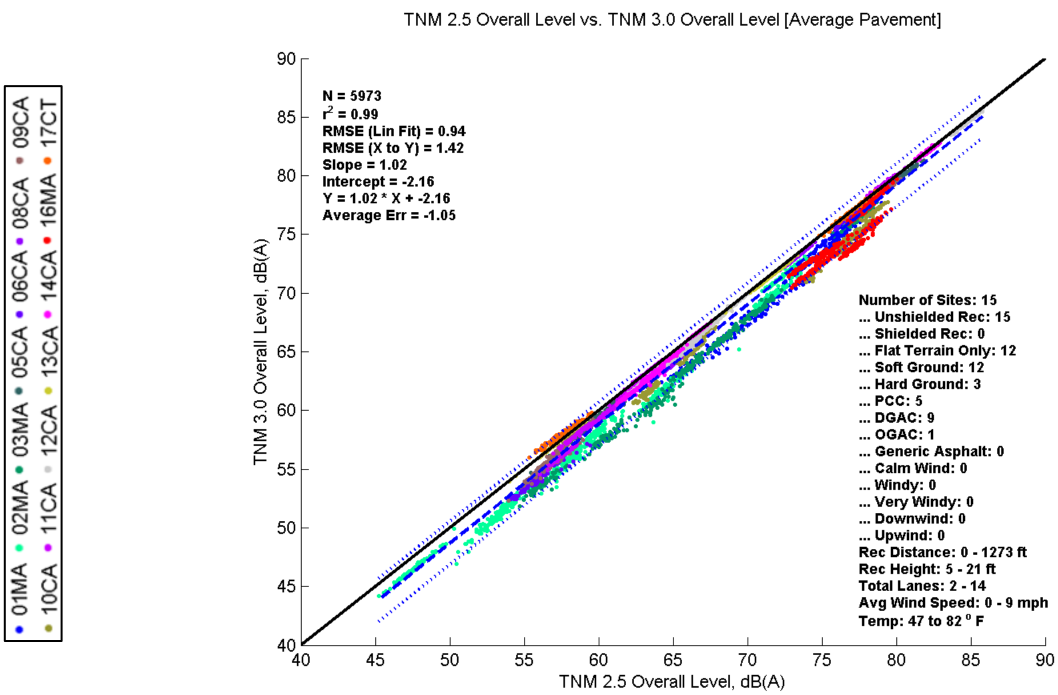

Figure 1: Comparison of Predicted Levels between TNM Version 2.5 and Version 3.0 (Measurement Data)

The variation is due to the combined effects of all changes between TNM 2.5 and 3.0. Further exploration was completed to understand the major contributors to the variation. An analysis of predictions found that the largest differences occurred at sites with multiple ground types, especially at larger source-to-receiver distances, while smaller differences occur at sites where multiple ground impedances are not part of the computations (sites with a single ground type). As a result, it was concluded that the first bug fix accounts for a significant portion of the observed differences between TNM 2.5 and 3.0 for the measured validation dataset.

In addition to reanalyzing the original measured validation dataset, sites that are included in the Consistency Test Suite (CTS) were also used to explore changes in predictions between TNM 2.5 and TNM 3.0. The CTS sites have a large number of receivers and can show how differences in TNM versions change more continuously as a function of distance or location. These sites also provide a greater diversity of acoustically significant structures and traffic flow. These models, however, do not include measurement data. For these model sites, it was found that on average TNM 3.0 predicts values about 2 dB lower than TNM 2.5. Although the statistical parameters indicate good average agreement, individual predictions are somewhat inconsistent between models, since 95-percent of the variation falls within +/- 5.33 dB range. This larger prediction interval is not surprising, as the CTS sites incorporate a greater number TNM's features, and thus a greater number of improvements between TNM 2.5 and TNM 3.0 can potentially affect results.

A research version of TNM (TNM 2.6), which included several bug fixes including the fix to the ground impedance averaging bug but not the remainder of the TNM 3.0 improvements, was utilized to identify causes of variation outside of the bug fixes. The average Root Mean Squared (RMS) difference between TNM 2.6 and 3.0 is small, 0.43 dB, compared to 1.42 dB between TNM 2.5 and 3.0, so, from a sound pressure level perspective, 70% of the variation is due to bug fixes (especially the fix to the ground impedance averaging). Further exploration of the data found that much of the remaining variation was the result of receivers at somewhat extreme locations: 1) large heights (up to 60 ft above ground), 2) large distances (up to 1600 ft from the roadway), and 3) positions near the end of the roadway oriented in a line perpendicular to the roadway. Computations for these receivers were affected by the following TNM 3.0 improvements:

- The replacement of horizontal divergence with combined horizontal and vertical divergence,
- The removal of interpolation/extrapolation at lowest and highest one-third octave bands, and
- A change in the manner in which elemental triangles are determined.

Finally, comparison of the measured validation dataset and model predictions was performed. The initial comparison, shown in Figure 2, includes all data in aggregate and was performed for four model variations: 1) TNM 2.5 with Average pavement (top left), 2) TNM 3.0 with Average pavement (bottom left) 3) TNM 2.5 with specific pavement (top right) and 4) TNM 3.0 with specific pavement (bottom right). The formatting is similar to Figure 1, except in this presentation the levels on the x-axis correspond to measured data instead of a second set of modeled data.

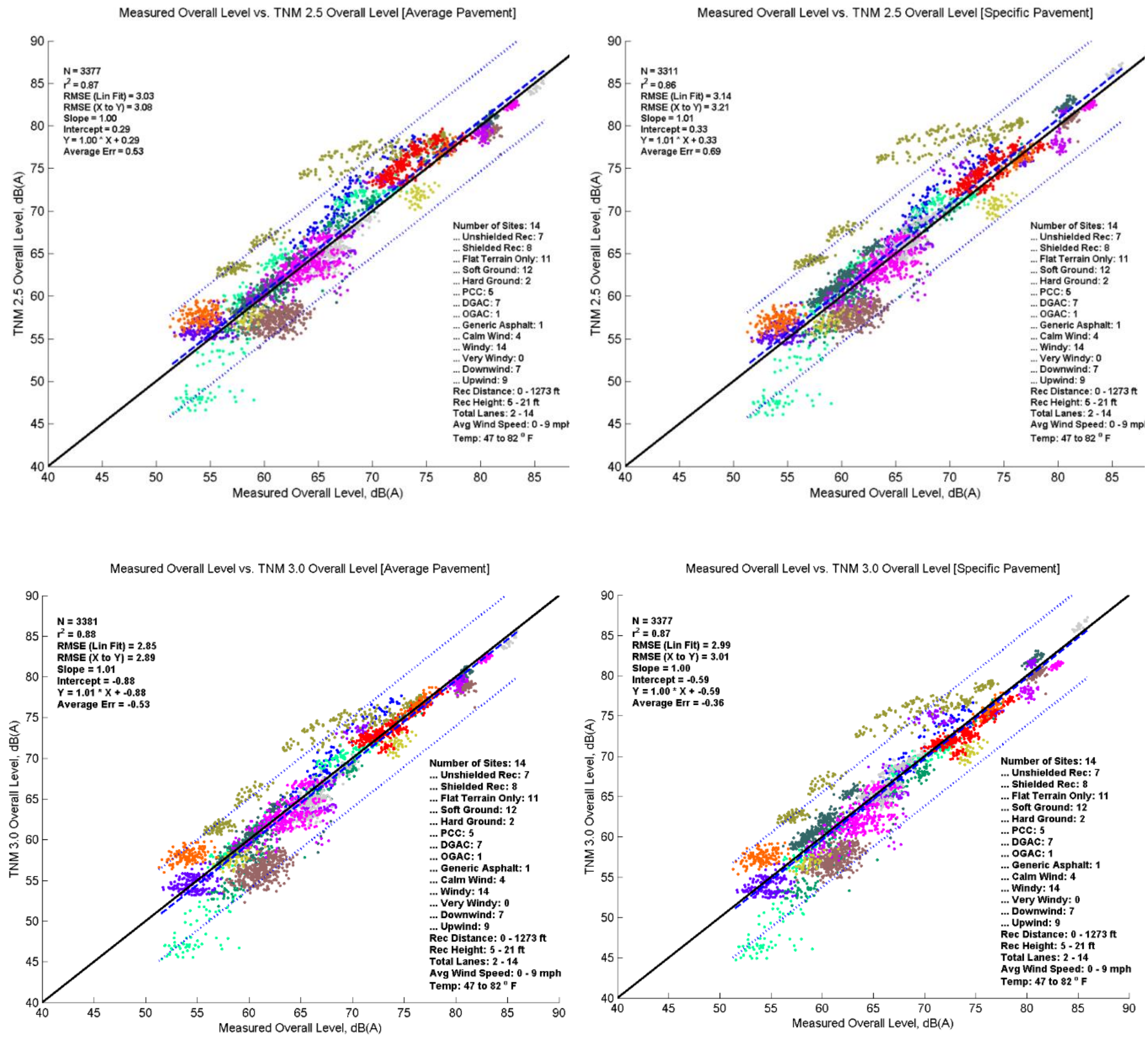

Figure 2: TNM 2.5 and 3.0 Predictions and Measured Results using Average and Specific Pavements for All Data Analyzed

Figure 2 shows that TNM 2.5 (top two graphics) on average over predicts the measured data while TNM 3.0 (bottom two graphics) under predicts the measured data. This trend is consistent over the range of measured sound levels; the offset between the solid black line and dashed regression line is nearly constant. Modeling with specific pavement types does not change the overall picture greatly; the same general trends are visible in both sets of results. Modeled with average pavement, TNM 2.5 on average over predicts these data by 0.53 dB, while TNM 3.0 under predicts these data by -0.53 dB. Modeled with specific pavements, the average error is shifted upward to 0.69 for TNM 2.5 and -0.36 for TNM 3.0; a result of modeling 5 of the 14 sites with PCC pavement. Because PCC typically has much higher sound pressure levels than Average pavement, while DGAC has only slightly lower sound pressure levels than

Average pavement for the same traffic, one would expect an upward shift in these results modeled with specific pavements.

To determine if TNM 3.0 is performing better or worse for a specific type of site, comparisons were also performed for several sub-sets of the data: sites with acoustically hard or soft ground, sites with or without a barrier, receivers at near, medium and far distances, and on a site-by-site basis. These results are summarized as follows:

- Sites with acoustically soft ground: TNM 3.0 and TNM 2.5 have similar magnitudes in average prediction errors. TNM 3.0 on average under predicts soft ground by 0.81 dB with Average pavement and by 0.47 dB with specific pavements. TNM 2.5 on average over predicts soft ground by 0.23 dB with Average pavement and by 0.56 dB with specific pavements.
- Sites with acoustically hard ground: TNM 3.0 has smaller magnitudes in average prediction errors. TNM 3.0 on average over predicts hard ground by 1.11 dB with Average pavement and by 0.25 dB with specific pavements. TNM 2.5 on average over predicts hard ground by 2.29 dB with Average pavement and by 1.4 dB with specific pavements.
- Sites without a barrier (Open sites): TNM 3.0 has smaller magnitudes in average prediction errors. TNM 3.0 on average over predicts open sites by 0.4 dB with Average pavement and under predicts by 0.11 dB with specific pavements. TNM 2.5 on average over predicts open sites by 1.98 dB with Average pavement and by 1.46 dB with specific pavements.
- Sites with a barrier: TNM 3.0 has larger magnitudes in average prediction errors. TNM 3.0 on average under predicts sites with barriers by 1.15 dB with Average pavement and by 0.53 dB with specific pavements. TNM 2.5 on average under predicts sites with barriers by 0.44 dB with Average pavement and over predicts by 0.15 dB with specific pavements.
- Comparisons for Measurements at Similar Distances: Distance effects are especially difficult to analyze in the aggregate because all possible confounding factors tend to show up in each distance category. For example, data for acoustically hard and soft ground, and for sites with and without barriers are present for receivers at most distances. Thus, interactions between distance and ground type, barrier presence, and pavement type may be present at all distances. Even so, it is still useful to consider how each model is performing at various distances.
- Distances less than 125 feet: TNM 3.0 has smaller magnitudes in average prediction errors. TNM 3.0 on average under predicts near distances by 0.17 dB with Average pavement and over predicts by 0.19 dB with specific pavements. TNM 2.5 on average over predicts near distances by 0.78 dB with Average pavement and by 1.15 dB with specific pavements.
- Distances between 125 and 500 feet: TNM 3.0 has larger magnitudes in average prediction errors. TNM 3.0 on average under predicts middle distances by 1.21 dB with Average pavement and over predicts by 1.2 dB with specific pavements. TNM 2.5 on average over predicts middle distances by 0.18 dB with Average pavement and by 0.12 dB with specific pavements.
- Distances greater than 500 feet: TNM 3.0 has larger magnitudes in average prediction errors. TNM 3.0 on average under predicts far distances by 0.78 dB with Average pavement and by 1.37 dB with specific pavements. TNM 2.5 on average over predicts middle distances by 0.03 dB with Average pavement and under predicts by 0.55 dB with specific pavements.
- Site-by-site basis: In general, the trends for individual sites mirror trends for the groupings noted above. TNM 2.5 tends to over predict measured data while TNM 3.0 tends to under

predict measured data; modeling with specific pavements increases overall levels when sites include PCC pavements.

Overall, when predictions were compared to measured data, both TNM 2.5 and TNM 3.0 performed similarly, but not identically. In general, the correlation and variance were not significantly different; however, biases as measured by average errors showed that TNM 2.5 tends to over predict measured data by about 0.5 dB while TNM 3.0 tends to under predict measured data by about 0.5 dB. The differences between the predicted results (TNM 2.5 to TNM 3.0) were generally found to be the result of a correction to the computation of Fresnel ellipses used to account for changes in ground impedance between source and receiver. This primarily affected sites with acoustically soft ground. It should be noted that the Fresnel ellipse correction may also affect the pre-computed sub-source corrections used to project the reference sound level (REMELs) data at 50 feet back to the source; these were derived during TNM's original development. This may explain why TNM 3.0 is predicting about 1 dB lower than TNM 2.5 on average for the measured validation dataset. It is recommended that the sub-source corrections be recomputed using TNM 3.0 and the datasets in this report be compared again to document any improvements obtained.

SECTION I INTRODUCTION

1.1 BACKGROUND

First released in March 1998, the Federal Highway Administration's (FHWA) Traffic Noise Model (TNM) has been a valuable tool for highway traffic noise analysis and barrier design [Anderson 1998]. TNM uses acoustic ray modeling to predict noise adjacent to highways related to vehicle traffic for specific highway design features including barrier type and geometry, vehicle traffic flow, number and geometry of roads, road pavement type, ground type, and terrain geometry [Menge 1998]. The reference sound levels used in the predictions, referred to as the Reference Energy Mean Emission Levels (REMELs), are defined as the maximum sound level emitted by a vehicle pass-by at a distance of 50 feet (15 m). REMELs were derived from emissions of more than 6000 vehicle pass-by measurements that were averaged by vehicle and pavement type [Fleming 1996].

Design features are defined in three-dimensional space as points, line segments, or polygons. Barriers are line segments with shielding qualities. For a typical analysis, TNM automatically increases the height of barriers during computation to "pre-compile" attenuation for different barrier heights[1]. Vehicle traffic flow is defined for each lane of a roadway by a series of line segments that store the number of autos, medium trucks, heavy trucks, buses, and motorcycles as well as their respective constant speeds. TNM automatically determines vehicle acceleration under certain conditions, for example, if users input flow control devices such as stop signs or if road elevation changes are significant. Users may input roadway elevation changes, bridges, and specific pavement types, including Open Graded Asphalt Concrete (OGAC), Dense Graded Asphalt Concrete (DGAC), Portland Cement Concrete (PCC), and Average[2]. A default ground type is assigned to account for the acoustic impedance of the ground and specific zones may be defined by polygons to characterize additional regions, for example, the default ground type may be grass while a nearby parking lot may defined as pavement. Finally, acoustically significant terrain features may also be included. These typically include hills, berms, ditches, etc. and are modeled by one or more series of terrain line segments.
Given the utility and impact of TNM, it is necessary to validate the sound level predictions that the software computes to ensure its accuracy. Prior to the initial release, TNM 1.0 was assessed for accuracy by comparing TNM computations to five datasets:

1. Embleton's model for reflection from ground of finite impedance [Embleton 1983]
2. Measurements made by Parkin and Scholes over grassland [Parkin 1965]
3. Scholes' measurements of a noise barrier over grassland [Scholes 1971]
4. Hendriks' measurements of noise barrier performance at a highway location [Hendriks 1991]
5. Fleming's work measuring noise barrier performance at a highway location [Fleming 1992]

All of these comparisons presented good agreement and the results of these comparisons are reported in the TNM v1.0 Technical Manual [Menge 1998]. After its release, TNM version 1.0 was compared

[1] This allows an engineer to quickly evaluate slight differences in barrier designs.
[2] At the time of this writing, only Average pavement is allowed to be used for FHWA projects. However, the other pavement types may be used for model validation.

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 focused mostly on sites with acoustically soft or hard ground, with or without single noise barriers and exhibited good agreement with TNM 1.0, with a few differences that have been documented in the above references.

Since its initial release, TNM has undergone two minor releases (1.0a and 1.0b) as well as four major releases (1.1, 2.0, 2.5 and now 3.0). Up to version 2.0, TNM upgrades focused primarily on improving the model's computational performance (reducing runtime), updating its AutoCAD import functionality as well as bug fixes and graphical user interface improvements. Only two minor changes in acoustical computations in the earlier versions that would result in, at most, a 0.2 dB difference in predicted sound level were made. Version 2.5 was the first version with major improvements to the acoustics and addressed the following issues: the over-prediction of acoustically hard ground and an anomaly related to diffraction points. These issues were corrected by implementing a more comprehensive methodology to correct the measured emission levels back to the source and correcting the diffraction algorithm parameters. Validation of TNM 2.5 included the analysis of sixteen highway sites around the country. The sixteen 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 [Rochat 2002].

The most recent version of TNM, version 3.0, was developed to improve further upon the acoustics by: replacing the interpolation below 250 Hz and the extrapolation above 5000 Hz with explicitly computed results; fixing anomalies in the impedance averaging and highest path point selection; improving free-field divergence computations; adding single barrier reflections for barriers not between source and receiver; as well as making minor changes including updates to emissions and acceleration computations, metrics and horizontal geometry [Hastings 2015]. Because of these changes, it is advisable once again to validate the model against measured data in order to ascertain the model's accuracy in predicting practical site conditions and to compare how predictions vary between TNM 2.5 and 3.0 as a function of specific parameters, such as receiver height and distance, pavement width, ground type and barrier characteristics.

1.2 Programmatic Differences between TNM 2.5 and TNM 3.0

As mentioned above, several changes were implemented in TNM 3.0 as part of the systematic improvement of the code. These included:

- The standardization of EFR/NRC values
- The correction of a few coefficients in the REMELs database
- Changes to vehicle speed computations
- Updated computations for Day-night equivalent Level (Ldn) and Day-evening-night equivalent level (Lden)
- Added percentile level computations, L10 and L50
- A change in the manner in which elemental triangles are determined

- The replacement of horizontal divergence with combined horizontal and vertical divergence
- The removal of interpolation/extrapolation at lowest and highest one-third octave bands
- Bug Fixes
    - One affecting ground impedance averaging (Bug 1)
    - One affecting the selection of highest path points (Bug 2)

These changes are described in Hastings [2015] and the effect of these changes are discussed in detail in Section 6.1.

1.3 Objectives

The primary objective of this validation study is to quantify and asses the differences between predictions from FHWA's TNM 3.0 and acoustic data measured at practical highway sites. In order to frame these differences within the historical context of TNM development, differences in predictions between TNM 2.5 and TNM 3.0 will also be examined. These comparisons will also highlight how specific changes in the acoustics affect computed results. Finally, next steps that will facilitate improving the model's accuracy based on the findings described in this report will be proposed.

1.4 Contents

Section 1 (this section) covers background and objectives of the study. Section 2 describes the measurement sites. Section 3 describes the modeling of the measurement sites. Section 4 describes the modeling of Consistency Test Suite (CTS) sites. Section 5 discusses data reduction and analysis. Section 6 analyzes differences between TNM 2.5 and 3.0 predictions. Section 7 covers the analysis differences between model predictions and measurements. Section 8 provides a summary of findings. While this document is intended to stand on its own, additional details relevant to Sections 2 through 5 can be found in Rochat [2002] and Bowlby [2014]. Appendices A through I provide additional background information and detailed results.

Section 2 Measurement Sites

The measurement data used in this validation study were originally collected and processed for the TNM 2.5 Validation Study [Rochat 2002]. Sections 2.1 through 2.3 summarize the measurement sites used. For completeness much of the measurement site, instrumentation, measurement procedure and protocol descriptions from the 2002 study are reproduced in Appendices Appendix A: Measurement Site Descriptions through Appendix F: Sample Data Log Sheets.

2.1 Site Requirements

Measurement sites for comparing TNM predictions to measured data were chosen to reflect acoustically soft and hard ground sites with or without a single barrier. These characteristics provide a clear study of the fundamental physics modeled in TNM, namely straight ray propagation with ground reflections and barrier diffractions. In order to isolate these characteristics and obtain accurate measurements, three general requirements were imposed on sites: open areas, little outside noise contamination, and measurement accessibility.

In order to avoid horizontal reflections of noise sources, sites were used that did not contain large vertical surfaces that could reflect sound waves other than the barriers intended for the study. Suitable sites were free of parked vehicles, signboards, or buildings within 100 feet of the highway traffic and the microphones. Additionally, the traffic related noise at these sites was generated by constant speed, free flowing traffic on roadways that were constructed using OGAC, DGAC, or PCC. These roadways were also free of detritus such as gravel.

To avoid contamination from other noise sources, potential measurement sites were far from other observable noise sources, such as airports, construction sites, rail yards or other heavily traveled roadways. These sites were also not located near sources of potential electromagnetic interference, such as power substations, radio antennae, cell phone towers or high-tension lines. Acoustic background levels were required to be at least 10 dB lower than the highway traffic noise in order to minimize measurement contamination.

Finally, areas had to be physically accessible to the measurement staff to place multiple microphones and measurement systems from 50 ft (15 m) to as far as 1300 ft (400 m) from the roadway.

2.2 Site Selection Process

The site requirements were organized into a checklist that was used in the potential measurement site evaluation and selection. Information about each site was recorded: location, site geometry and features, measurement feasibility, and measurement approval from the property owner. When possible, site plans that gave sufficient detail for modeling in TNM were obtained from the property owners or local agencies.

The measurement site selection was completed by Volpe Center staff, with the assistance of Harvey Knauer of Environmental Acoustics, Soren Pedersen of Catseye Services as well as Caltrans personnel for some California sites. All persons involved in the site selection followed the same checklist and methodology to record pertinent information regarding the sites. FHWA reviewed and gave approval on all chosen measurement sites.

2.3 Description of Measurement Sites

Given the criteria previously outlined, 16 measurement sites were chosen in the New England area (01MA, 02MA, 03MA, 16MA, 17CT) and California (05CA, 06CA, 08CA, 09CA, 10CA berm, 10CA open, 11CA, 12CA, 13CA, 14CA, 15CA). Eight of these sites were open area sites, in which four of the sites contained acoustically soft ground (e.g. field grass [effective flow resistivity, σ = 150 cgs Rayls] or lawn [σ = 300 cgs Rayls]) and four of the sites contained acoustically hard ground (e.g. pavement or water [σ = 20,000 cgs Rayls]. The open area sites were all mostly flat, with the exception of one, which had undulations ranging from -20 to +3 feet in its terrain. Eight of the chosen measurement sites were those with barriers, with seven of these sites containing acoustically soft ground and one containing a mix of acoustically soft and hard ground. These barrier sites were also mostly flat, with a few having slight inclines across the terrain and two having substantial (greater than 15 ft) drop-offs from the base of the barriers to the measurement areas. A summary of the sites and more detailed information for each site (descriptions, diagrams, photographs, TNM plans and profile views) can be found in Appendix A: Measurement Site Descriptions.

Table 1: 16 Measurement Sites (see Appendix A for site details)

Site ID	Location	Site Type								Pavement Type	Microphone Distances
		Open area	Noise barrier	Soft ground	Hard ground	Mixed ground	Flat	With drop-off	Undulating		
01MA	Rte 24 Taunton, MA	X		X			X			DGAC	d = 50, 100, 200
02MA	Rte 2 Acton, MA	X		X					X	DGAC	d = 50, 200, 400, 600
03MA	Rte 291 Springfield MA	X		X			X			DGAC	d = 50, 200, 400, 800
05CA	Rte 71 Chino Hills, CA		X	X			X			PCC	bb = 50, 100, 150
06CA	Rte 15 Wildomar, CA		X	X			X	X		DGAC	bb = 55, 100, 200
08CA	Rte 91 Anaheim, CA		X	X			X			PCC	bb = 50, 200, 300
09CA	Rte 71 Chino, CA		X	X			X	X		PCC	bb = 55, 100, 200
10CA-berm	Rte 15 Mira Loma, CA		X	X			X			PCC	bb = 70, 110
10CA-open	Rte 15 Mira Loma, CA	X		X			X			PCC	d = 98, 188, 158
11CA	Rte 237 Sunnyvale, CA		X			X	X			DGAC	bb = 50, 100, 300
12CA	Rte 680 San Ramon, CA		X	X			X			PCC	bb = 50, 100, 200
13CA	Rte 37 Sonoma, CA	X			X		X			OGAC	d = 50, 900
14CA	Rte 880 Fremont, CA		X	X			X			DGAC	bb = 50, 100, 150
15CA	Rte 880 Oakland, CA	X			X		X			DGAC	d = 40, 100, 200, 400
16MA	Rte 90 Wayland, MA	X			X		X			DGAC	d = 78, 100, 150, 200
17CT	Rte 84 Stafford, CT	X			X		X			DGAC	D = 60, 1273
Totals		8	8	11	4	1	15	2	1		

SECTION 3 TNM MODELING OF MEASUREMENT SITES

TNM runs were set up for each site for each 5-minute time block in the acoustic data. English units were used for modeling. Input objects were taken directly from the site survey and maps drawn during site scoping and measurements. Base cases were created where each lane of the highway and any paved shoulder or median was entered as a separate roadway and Average pavement (the default pavement type) was applied. Barriers and receivers were added based on the survey data and microphone locations. Terrain lines and ground zones were also added. Engineering judgement was used to determine the potential impact of these objects on the predicted sound levels. To maintain simplicity, ground undulations of 2 ft (0.6 m) or more were included; and elevation changes 2 ft (0.6 m) or less were ignored, unless it affected the propagation path length over the top of a noise barrier and/or shifted any receiver in or out of the line-of-sight of the highway traffic sources. Ground zones with any dimension less than 10 ft (3.0 m) were also ignored. Once all objects were entered into the model, a version without traffic data was saved as a base case for the site. TNM plan views and skew (profile) views for each site are shown in Appendix A: Measurement Site Descriptions.

Once a TNM base case was completed for a particular site, a new run was created for each 5-minute data block. For each 5-minute period, the corresponding traffic data (scaled from 5 minutes to 1 hour), temperature, and relative humidity were entered. Once traffic and meteorological data were entered, three versions of each run were generated for the current validation study, one to be run using TNM 2.5, one using TNM 2.6[3], and one using TNM 3.0. The versions for TNM 2.5 and 2.6 were identical copies of those used in the previous validation studies. The version for TNM 3.0 was generated by exporting the TNM 2.5 model to a TNM 3.0 compatible format. In some cases, adjustments to the 3.0 models were made to pass TNM 3.0's enhanced error checking. All runs were then calculated, resulting in an hourly, A-weighted, equivalent sound level (LAeq1h) for each data block.

Once models had been developed for all 5-minute time blocks using Average pavement (as in the 2002 study), a new model was developed by replacing the Average pavement with the specific pavement in TNM that best matched the site (DGAC, OGAC, or PCC). Thus, for each site there are two sets of predictions for each 5-minute block, one using Average pavement and one using the most appropriate specific pavement.

It should be noted that all input data erred on the side of excessive detail rather than insufficient detail. In some cases, TNM users may not have as 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. Although detailed site plans may be available to users, estimations of terrain features or object locations are often required. Further investigation is needed to quantify the potential differences in TNM output related to user methodology.

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[3] TNM 2.6 is an unreleased research version based on TNM 2.5. This version has several bug fixes that were also implemented in TNM 3.0.

SECTION 4 TNM MODELING OF CONSISTENCY TEST SUITE SITES

FHWA developed test sites that could be used to evaluate whether or not other software programs could be considered consistent with TNM [Bowlby, Williamson, Bowlby, and Kaliski 2014]. These test sites are henceforth referred to as the Consistency Test Suite (CTS). In contrast to the measurement sites, where there were practical limitations to the number and location of receivers, the CTS sites have a larger number of receivers that allow one to observe how differences in TNM versions change more continuously as a function of distance/location. A limitation to the CTS is that model inputs do not vary over time (only from model-to-model) and therefore results from the CTS do not lend themselves to statistical interpretation of random effects.

Several sets of models were developed in the CTS that were designed to evaluate key parameters or physical effects:

- Set 1: Effect of speed (by vehicle type, pavement type, and default ground)
- Set 2: Distance adjustment for each ground type and each vehicle type as function of pavement width
- Set 3: Effect of roadway width and number of lanes per roadway with and without a median
- Set 3.2: Ground sloping up
- Set 3.3: Ground sloping down (also introduces edge of shoulder shielding)
- Set 3.4: Drop-off of sound level with increasing receiver height above ground for a close-in receiver
- Set 4: Terrain variations: swale in center of median, depressed roadway, elevated roadway, at-grade roadway with terrain line
- Set 5: Building rows, parallel to road
- Set 6: Tree zones, with and without ground zone
- Set 7: Noise barrier: single barrier parallel to road (at-grade, cut, fill); berm vs. wall; single far-side noise barrier reflections; single median barrier
- Set 8: Parallel Barriers, modeled by various numbers of roadways and values of NRC
- Set 9: Roadway segments “on structure”
- Set 10: Barrier segments “on structure”
- Set 11: Roadway segments (both on and off structure) shielded and not shielded by barrier segments “on structure”
- Set 12: Double diffraction (two barriers between the roadway and the receiver)
- Set 13: Multiple diffraction (defaulting to double diffraction) for more than two barriers between the roadway and the receiver
- Set 14: Use of “flow control roadways” (accelerating traffic)
- Case 3.5.1 – Receivers collinear with extended roadway centerline, 50 ft past roadway end, 12-ft wide roadway
- Case 3.5.2 – Repeat case 3.5.1, but with a 24-ft wide roadway

- Case 3.5.3 – Receivers collinear with extended roadway centerline, 200 ft past roadway end, 12-ft wide roadway
- Case 3.5.4 – Repeat case 3.5.3, but with a 24-ft wide roadway
- Case 7.1.1.3.4 – Noise barrier located 100 ft from edge of pavement (EOP)
- Case 7.1.1.4.4 – Noise barrier located 200 ft from EOP
- Case 7.1.1.5.4 – Vertical stack of receivers behind noise barrier
- Case 14.3 – “Flow control roadway” for acceleration on upgrade (start speed 0 mph)
- Case 14.4 – “Flow control roadway” for acceleration on downgrade (start speed 0 mph)
- Case 14.5 – Heavy truck deceleration on an upgrade cruise roadway (start speed 60 mph)

Further details of the CTS models can be found in Bowlby *et al* [2014].

SECTION 5 DATA CULLING AND MATCHING

Measured data were organized in five-minute blocks. In contrast to previous validation studies, these five-minute blocks were not combined into fifteen-minute blocks. Although combining five-minute blocks will reduce the variance, it will not affect parameter estimates for mean values or mean differences. The inclusion of a temporally finer set of data also provides improved resolution into variation due to differences between actual traffic emissions and traffic emissions modeled by the REMELs database developed by Fleming et al [1996]. The main difference when comparing this analysis with previous analysis is that variance and number of samples will be higher for this analysis.

TNM does not account for the effects of high wind speeds nor does it provide predictions for sound sources other than traffic noise[4]. Because measurements during periods of high wind or with non-traffic noise are outside the scope of TNM's present modeling approach, these data were removed from further analysis. This is consistent with previous TNM validation studies and more details can be found in Rochat [2002].

Previous validation work excluded site 04CT. For consistency, this site was excluded from this present work as well.

For measurement sites, each five-minute block, after removal of high wind and noise contaminated blocks, was compared with predictions from TNM 2.5 and TNM 3.0 using models with Average pavement and with the site-specific pavement, e.g. DGAC, OGAC, PCC. In some cases, a particular five-minute block failed to run for a given site/pavement pair. Removing these blocks from all datasets (TNM 2.5 with Average pavement vs. Measurement, TNM 2.5 with specific pavement vs. Measurement, TNM 3.0 with Average pavement vs. Measurement, etc.) would allow for exactly the same comparisons between the groups at the cost of a much more extensive sorting routine and a loss of otherwise good data. For this reason, all matched data blocks were kept for each paired comparison. This does result in the number of samples being slightly different between the different comparisons; however, these differences are small and do not affect the interpretation of the results.

For CTS sites, each one-hour block, as described by the Meta data (e.g. set number, number of lanes, number of barriers, etc.), was matched between the two versions of TNM. In some cases, the Meta data were not sufficient to determine a unique match; that is more than one five-minute block had the same Meta data. These blocks were excluded in order to make sure that only the exact same models were compared.

[4] Ambient noise can be considered during the reporting phase; however, this is limited to a single overall level that is compared to all microphones. It does not allow for different levels at different microphones, nor does it allow for the location of non-traffic noise sources such as aircraft overflights, construction noise, etc.

Section 6 Differences between TNM 3.0 Predictions and TNM 2.5 Predictions

Although the primary purpose of this validation report is to examine the performance of the TNM 3.0 acoustics relative to measured, practical data; for historical context, it is important to first examine how predictions have changed between TNM 2.5 and TNM 3.0.

6.1 Predictions for Measurement Sites

A direct comparison of levels predicted by TNM 2.5 and TNM 3.0 is shown in Figure 3 for all traffic data processed for the measurement sites. In the figure, the colored circles represent individual 5-minute model computations (color coding is given in the legend); the blue dashed line shows the first-order linear regression between the two datasets; the blue dotted lines indicate the 95-percent prediction interval for any new computations[5]; and the solid black line indicates where all results would fall if both models gave the same predictions for all analyses. Note that in the upper left-hand corner of the graph several statistical parameters are presented: the number of samples, the coefficient of determination (r^2), the root mean squared error (RMSE), the regression slope and intercept, the regression equation, and the average difference. In the lower right-hand corner, a metadata summary is provided covering the number of sites, the presence of a barrier, receiver distances and heights, number of roadway lanes, pavement type, and temperature and wind conditions included in the analysis. Each site is presented in a different color in order to help highlight any potential grouping of the data.

In general, the larger the sample size, the higher the confidence for the computation of all parameters. In this report, the maximum number of modeled samples is 5973. When sub-sets are examined, the number of samples will be smaller. The r^2 provides a measure of correlation. The RMSE provides a measure of absolute variation between the two predictions and represents the sample standard deviation. A slope (m) of one indicates that for every 1-dB change in one model's prediction there will be an identical 1-dB change in the other model's prediction. If the slope is less than one, then the model on the y-axis tends to change predictions slower than the model on the x-axis and *vice versa*. If the intercept (b) is zero and the slope is one, then there is perfect agreement between the trends in the two datasets. If the intercept is negative, then the model on the y-axis predicts lower levels than the model on the x-axis for low levels and *vice versa*; however, the average difference provides a measure of the *overall bias* between the two datasets.

The first comparison shows all sixteen sites[6] in Figure 3. These included: 7 unshielded sites, 8 shielded sites, 11 sites with flat terrain, 3 sites with terrain variations, 12 sites with acoustically soft ground, 2

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[5] *The term confidence interval will be reserved for intervals about parameter estimates and prediction intervals will be reserved for intervals about sets of observations. The difference between the size of these intervals is typically proportional to the square root of the number of samples.*

[6] *Site 10CA is two sites, one is open and the other has a berm barrier, thus the total number of shielded and unshielded sites is equal to fifteen rather than fourteen.*

sites with acoustically hard ground, 5 sites with PCC roadway surfaces, 7 sites with DGAC, 1 site with OGAC and 1 site with a generic asphalt roadway surface. Sites include highway widths ranging from 2 – 14 lanes. Receiver heights ranged from 5 to 21 feet above the ground and receiver locations were as far as 1273 feet from the center of the nearest travel lane. Temperatures ranged from 47 to 82 degrees Fahrenheit. Wind speeds ranged from 0 to 9 miles per hour for measurement analysis but are not included in modeling for the current or any previous version of TNM.

In Figure 3 it can be seen that there is a high degree of correlation between the two models, $r^2 = 0.99$ and that both models are equally sensitive to changes in the input parameters, slope = 1.02, but that TNM 3.0 predicts values about 1 dB lower than TNM 2.5. Although the statistical parameters indicate good overall agreement, individual predictions are somewhat varied between models since 95-percent of the variation falls within +/- 2.78 dB[7] range. Consideration is needed to understand the source of this variation.

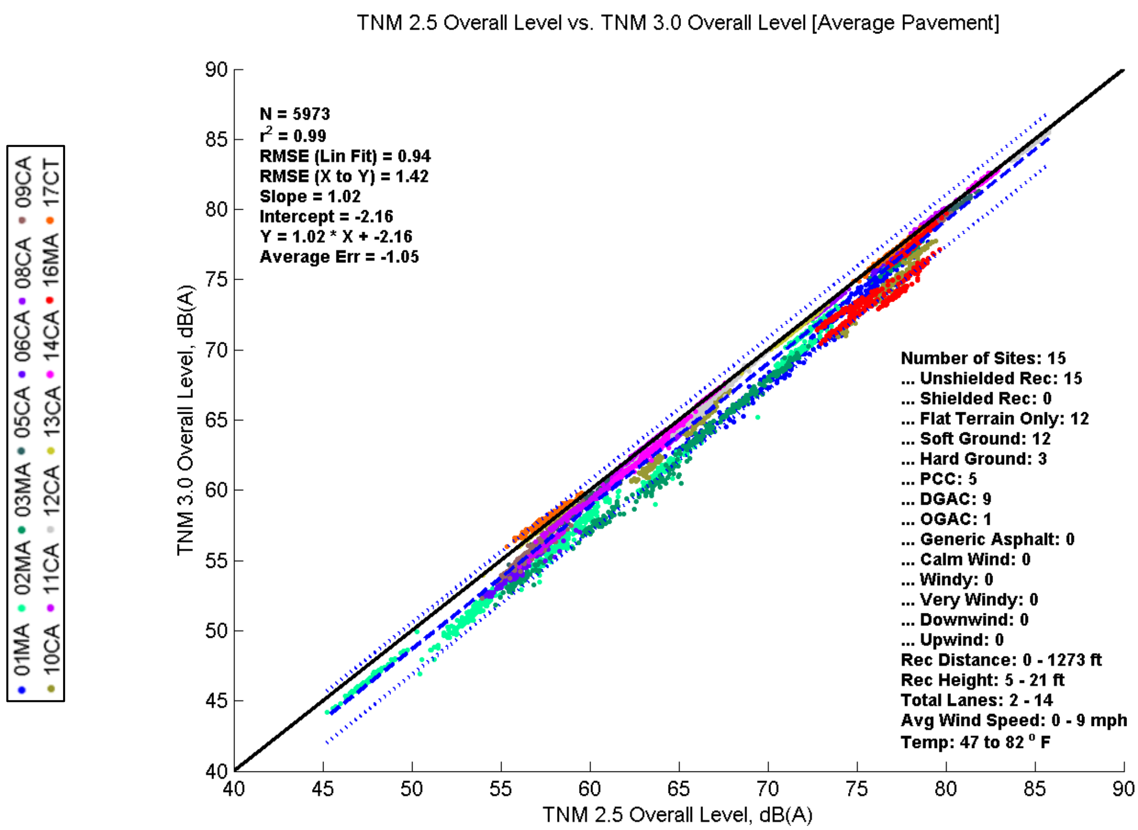


Figure 3: Comparison of Predicted Levels between TNM Version 2.5 and Version 3.0 (Measurement Data)[8]

[7] *PI = 1.42 * 1.96 dB*

[8] *Note, in cases where predictions are compared to other predictions, wind Meta data are not tabulated since they have no bearing on the comparison.*

Programmatic Differences between TNM 2.5 and TNM 3.0

As mentioned in the introduction, several changes were implemented in TNM 3.0 as part of the systematic improvement of the code. These included:

- The standardization of EFR/NRC values
- The correction of a few coefficients in the REMELs database
- Changes to vehicle speed computations
- Updated computations for Day-night equivalent Level (L_{dn}) and Day-evening-night equivalent level (L_{den})
- Added percentile level computations, L_{10} and L_{50}
- A change in the manner in which elemental triangles are determined
- The replacement of horizontal divergence with combined horizontal and vertical divergence
- The removal of interpolation/extrapolation at lowest and highest one-third octave bands
- Bug Fixes
    - One affecting ground impedance averaging (Bug 1)
    - One affecting the selection of highest path points (Bug 2)

These changes are described in full in Hastings [2015] and reviewed in this section.

Standardization of EFR/NRC Values

The standardization of the Effective Flow Resistivity and Noise Reduction Coefficients EFR/NCR conversion table represents a minor change in the conversion between these two measures of acoustic absorption for user selectable NRC values in order to make these conversions consistent with Table 2 in the TNM Technical Manual [Menge, 1998]. (Differences in red text.) It is not expected that these changes will have a significant effect, especially at far distances where low frequencies dominate. For the measurement sites included in this report, user selected NRC values were not included in any models so these changes cannot affect the results discussed in Section 6.

TABLE 2: EFFECTIVE FLOW RESISTIVITY USED FOR VALUES OF NOISE REDUCTION COEFFICIENT (NRC)

	EFR cgs Rayls	
NRC	TNM 3.0	TNM 2.5
0.00	20000	20000
0.05	***5000***	***4250***
0.10	1570	1570
0.15	865	865
0.20	***500***	***555***
0.25	385	385
0.30	300	300
0.35	214	214
0.40	***150***	***165***
0.45	129	129
0.50	102	102
0.55	81	81
0.60	64	64

0.65	50	50
0.70	***40***	***39***
0.75	30	30
0.80	22	22
0.85	16	16
0.90	***10***	***10.4***
0.95	5.5	5.5
1.00	0.1	0.1

REMEL Coefficient Corrections

The correction of four coefficients in the REMELs database are shown in Table 3. (Differences in red text.) Two coefficients were changed for heavy trucks, which have a small effect on the shape of the spectrum, primarily for the higher one-third octave bands. These changes are only applicable for specific pavements. One coefficient was changed for buses, which has a small effect on the shape of the spectrum, primarily for the higher one-third octave bands and applies to all pavement types. One coefficient was also changed for motorcycles, which primarily affects levels at low speeds and does not have a significant effect at highway speeds. For highway traffic with normal variation of speed and vehicle distributions, it is expected that any differences observed from these corrections would be undetectable when averaging across the data for all vehicle types. This is especially true for the measurement site data, where speeds were modeled in 5-minute time blocks, leading to even more variation in traffic data.

TABLE 3: CONSTANTS FOR A-WEIGHTED SOUND-LEVEL EMISSIONS AND 1/3RD-OCTAVE-BAND SPECTRA

Vehicle Type	Pavement Type	Full Throttle	Coefficient	Technical Manual	TNM 3.0
HT	DGAC	NO	H2	-54.9684***55***0	-54.9684***45***0
HT	PCC	NO	G1	-298.5689***55***	-298.5689***60***
BUS	ALL	ALL	J2	-0.282***5570***	-0.282***5557***
MC	ALL	NO	C	56.0***00000***0	56.0***86099***0

Changes to Vehicle Speed Computations

The regression equation used to model heavy truck deceleration was also modified in TNM 3.0 [Hastings 2015, Menge 1998]. The new curve fit is similar in form to the original (and uses the same data), but is valid over a wider range of speeds. This equation is not relevant to the variation between TNM 2.5 and TNM 3.0 for the measurement sites shown in Figure 3.

Updated Computations for Ldn and Lden, Added Metrics L10 and L50

Changes were also made to the methods for computing Ldn and Lden in TNM 3.0. These changes were made to create a more robust and accurate model. In addition, L10 and L50 metrics were added based on the STAMINA model but with further improvements to the computations to match measured data better. Neither of these changes are relevant to the measurement site validation analysis as it relies on $L_{Aeq,1\text{-}hr}$.

Changes in Elemental Triangle Determination

In TNM 2.5 elemental triangles were determined by subdividing the region of a base triangle into 10 degree sub-triangles; however, the last sub-triangle was generally some value less than 10 degrees as it represented the remainder after the greatest integer number of 10 degree triangles had been generated. In some cases, this angle can be less than 1 degree. To avoid exceptionally small elemental triangles, TNM 3.0 determines elemental triangles slightly differently. TNM 3.0 determines the maximum angle that is less than or equal to 10 degrees that results in an integer number of sub-triangles. In this way, each elemental triangle derived from a base triangle has the same subtended angle. Sensitivity studies during the development of TNM 3.0 have shown that this change in methodology does not significantly affect final results.

Horizontal Divergence Changes

The replacement of horizontal divergence with combined horizontal and vertical divergence could produce noticeable differences for cases where the vertical component of distances is a significant portion of the total source-to-receiver distance. This would be most noticeable for receivers close to the roadway with a large change in elevation between the roadway and the receiver, e.g. the top floor of a high-rise very close to a highway in a city.

Removal of Interpolation/Extrapolation at Lowest and Highest One-third Octave Bands

TNM 2.5 and versions prior included an interpolation function for one-third octave bands below 250 Hz and an extrapolation function above 5000 Hz. This was done to reduce processing time, which at the times of TNM's initial development were significantly longer than processing times on today's computers. However, this was at the expense of some accuracy, especially at long distances where low frequencies can dominate the overall level. TNM 3.0 no longer interpolates or extrapolates any one-third octave bands, but rather explicitly computes the values for each band from 50 Hz to 10,000 Hz. This involves more calculations (and thus somewhat longer processing times) but improves accuracy. It is expected that there could be differences between TNM 2.5 and 3.0 at long distances.

Bug Fixes

In addition to the improvements between TNM 2.5 and 3.0, two program bugs were corrected in TNM 3.0.

The first bug in the TNM code in versions 2.5 and earlier affects the ellipse for ground impedance averaging, which is utilized whenever there is more than one ground type covering the area between source and receiver (e.g., roadway and lawn). In this text, this bug is referred to as bug 1. In the original journal article that describes this process [Boulanger, 1997], the equations that define the limits perpendicular and parallel to the path were written as:

$$x_{1,2} = \pm b\sqrt{1 - \frac{(y_m\cos(\theta)-c)^2}{a^2} + \frac{y_m^2\sin^2(\theta)}{b^2}}$$

And

$$y_{1,2} = -\frac{B}{A} \pm \sqrt{\frac{1}{A} - \left(\frac{c\ \sin(\theta)}{Aab}\right)^2}$$

There are two sign errors in these equations, circled in red above. These equations are correctly defined as:

$$x_{1,2} = \pm b\sqrt{1 - \frac{(y_m\cos(\theta)-c)^2}{a^2} - \frac{y_m^2\sin^2(\theta)}{b^2}}$$

And

$$y_{1,2} = +\frac{B}{A} \pm \sqrt{\frac{1}{A} - \left(\frac{c\ \sin(\theta)}{Aab}\right)^2}$$

In TNM 3.0, these equations have been updated to reflect correctly the elliptical geometry.

The second bug was related to a section of code that was intended to catch unrealistic attenuation values during the selection of highest path points when more than two potential highest path points were between the source and receiver. The way this error check was constructed in TNM 2.5 it rejected some valid attenuation levels, which had the potential to affect the highest path point selection process when there were more than two highest path points. Although this had the potential to cause an unexpected pair of highest path points, it did not affect the actual computation of attenuations once the highest path points were selected. The effect of this bug is somewhat ambiguous since highest path points for barriers are based on input heights only, not the current (perturbed height) so, the effect of this bug depends on how users input multiple barrier heights. In general though, there is the potential for different highest path points to be chosen between TNM 2.5 and TNM 3.0 for complex models where more than two highest path points intervene between source and receiver.

The effects of this first bug are described in more detail below. The second bug fix is not relevant for this analysis.

Effects of Bug 1 on Predictions

The effects of bug 1 are illustrated in Figure 4 to Figure 9 and summarized in Table 4 and Table 5. For Figure 4 to Figure 7, TNM 2.5 predictions are compared with 3.0 predictions. For Figure 8 and Figure 9, TNM 2.6 predictions are are compared with TNM 3.0. TNM 2.6 is a research version of TNM based on TNM 2.5, but with the two itemized bugs corrected. Since selecting two highest path points from a list of more than two highest path points is not involved for these sites, the second bug fix is not relevant and only the first bug fix is expected to have any effect on the results.

In Figure 4 to Figure 8, the validation data are grouped by the location of the microphone: magenta for microphones within 100 ft horizontally and less than 15 ft vertically; green for microphones greater than 100 ft horizontally and less than 15 ft vertically; blue for microphones within 100 ft horizontally and at least 15 ft high; and red for microphones greater than 100 ft horizontally and at least 15 ft high. These groupings were selected to help focus on geometrically different Fresnel ellipses. Microphones that are close to the roadway will have shorter ellipses and microphones that are far from the roadway will have longer ellipses. The degree to which the ellipse approximates a circle will depend both on the distance from the roadway and the orientation of the parent ellipsoid, which also depends on the microphone height.

Figure 4 shows a the correlation between predictions from TNM 2.5 and TNM 3.0 for all measured sites. The average differences are shown in the upper left hand corner of the graph for the four different categories (and also repeated in Table 4). It can be seen that in general TNM 3.0 predicts lower levels for all groups, but that the high, near microphones have the smallest difference. The practical conclusion from this is that one should expect better agreement between TNM 2.5 and TNM 3.0 for microphones that are near the roadway and elevated.

Finding a smaller difference between high, near microphones and the others supports the argument that one cause of differences between TNM 2.5 and TNM 3.0 is the correction to Bug 1. However, even the high, near microphones can still be affected by this difference to some degree. One way of avoiding the effects of Bug 1 is to consider sites that have only one, continuous ground type encompassing the area from source to receiver. This can only be done by considering sites with hard ground (as the roadway at the source is always considered hard ground), either pavement or water, for the default ground and with no additional ground zones. In these cases, the acoustic impedance of the ground and the roadways will be the same and any Fresnel ellipse will return the same ground type throughout. Figure 5 shows one such case, Site 13CA.

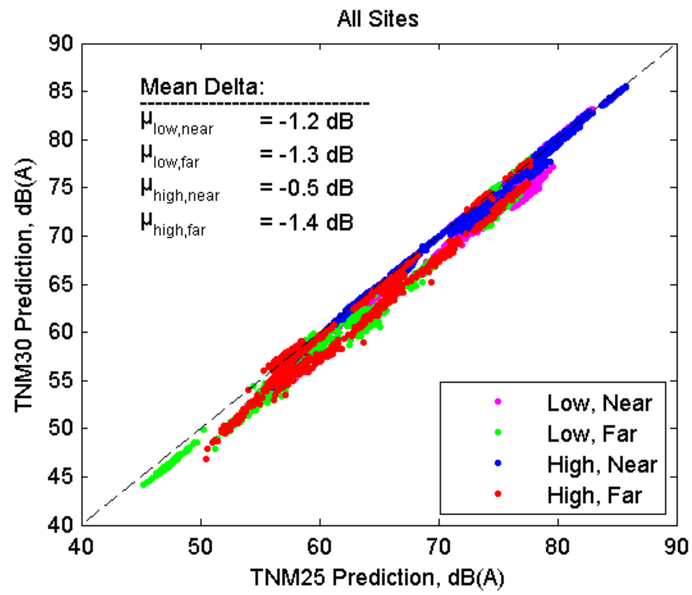


Figure 4: Predictions for Measurement Sites (TNM 2.5 vs. TNM 3.0) – Grouped by Microphone Location, All Sites (Measurement Data)

The correlation between TNM 2.5 and TNM 3.0 is substantially better when evaluating Site 13CA. In fact the average difference is at most 0.2 dB for a given grouping. This is a strong indication that primary contributor to differences between TNM 2.5 and TNM 3.0 for the measurement sites is Bug 1. Further confirmation of this can be seen by considering a case that has a default soft ground type, such as Site 01MA in Figure 6. Here all groups have lower predictions for TNM 3.0 and, as discussed previously, the high, near microphone has the closest agreement between the models.

One nuance of the effect of this difference in models can be seen in Figure 7 for Site 08CA. Although the this is a soft ground site, the level differences lie between the previous two examples discussed. The reason for this is that Site 08CA has a barrier near the roadway. This has the effect of changing the geometry for Fresnel ellipses for microphones beyond the barrier since the barrier creates a new propagation path. Thus the effect of the ellipse difference is diminished in a manner similar to the high, near microphone groupings.

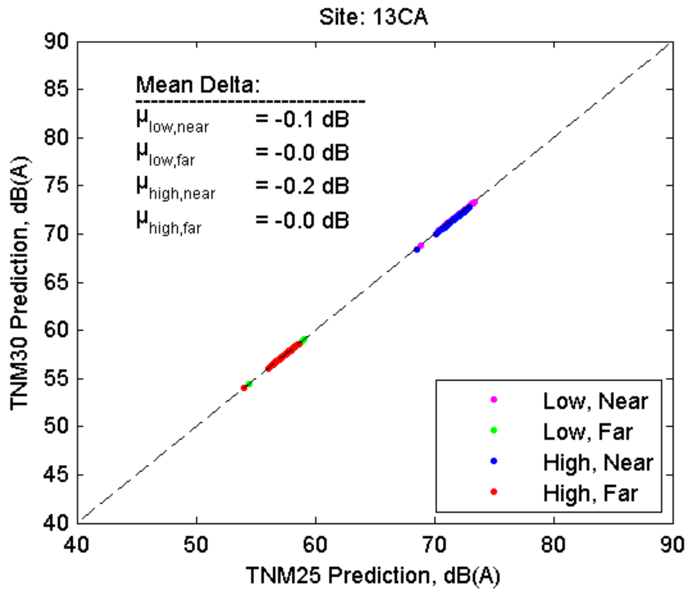


Figure 5: Predictions for Measurement Sites (TNM 2.5 vs. TNM 3.0) – Grouped by Microphone Location, Site 13CA (Default Ground is Acoustically Hard, No Barrier Present) (Measurement Data)

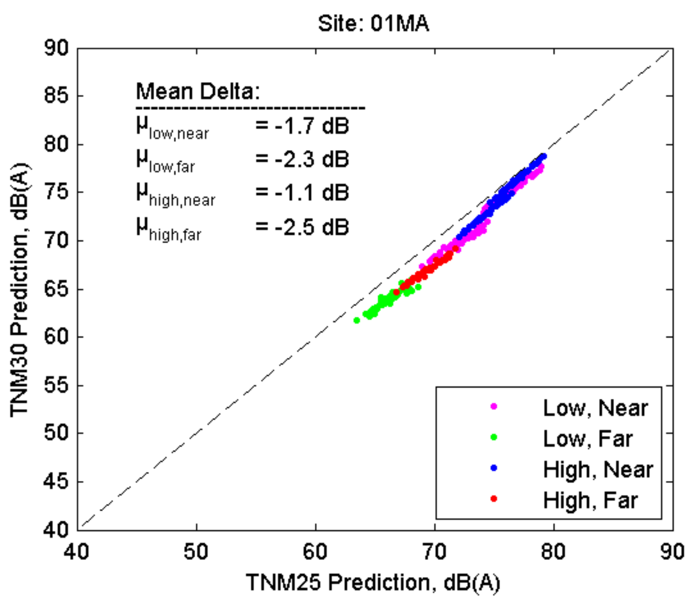


Figure 6: Predictions for Measurement Sites (TNM 2.5 vs. TNM 3.0) – Grouped by Microphone Location, Site 01MA (Default Ground is Acoustically Soft, No Barrier Present) (Measurement Data)

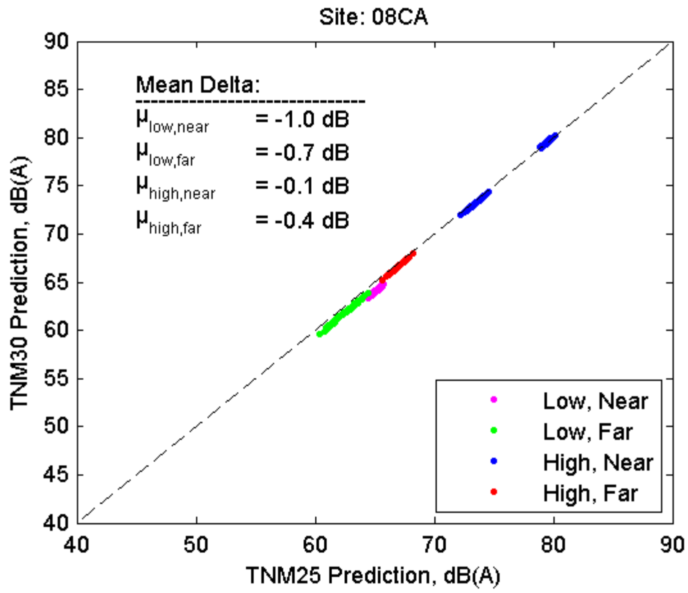


Figure 7: Predictions for Measurement Sites (TNM 2.5 vs. TNM 3.0) – Grouped by Microphone Location, Site 08CA (Ground Type is Acoustically Soft, Barrier Present) (Measurement Data)

Table 4 summarizes the average differences by grouping, ground types (including median and number of lanes) and whether or not a barrier is present. As can be seen, the pattern holds. Sites with only hard ground have negligible differences between the two models. Sites with soft ground have noticeable differences, but these are somewhat mitigated for high, near receivers, and cases where a barrier is present. Note that Site 16MA is not included in this table because it has ground zones and would further complicate the analysis.

TABLE 4: AVERAGE DIFFERENCES BETWEEN TNM 2.5 AND TNM 3.0 PREDICTIONS FOR MEASUREMENT SITES – GROUPED BY MICROPHONE LOCATION AND SITE (MICROPHONE LOCATION - NEAR: <100 FT. HORIZONTAL, LOW: <15 FT. VERTICAL)

Delta 25 vs 30									
Site	Terrain	Lanes	Median	Ground	Low Near	Low Far	High Near	High Far	Avg
13CA	flat	2	pavement	hard	-0.1	0.0	-0.2	0.0	-0.1
17CT	flat	6	pavement	hard	0.0	0.2	NA	0.6	0.3
15CA	flat	10	pavement	hard	0.3	0.2	0.2	0.2	0.2
				Avg Hard	0.1	0.1	0.0	0.3	0.1
01MA	flat	4	field grass	soft	-1.7	-2.3	-1.1	-2.5	-2.9
02MA	flat	4	field grass	soft	-1.9	-1.7	-0.9	-2.4	-1.7
06CA	berm+wall	6	lawn	soft	-1.4	-1.7	-1.5	-1.4	-1.5
03MA	flat	4	hard soil	soft	-1	-2.7	NA	-2.5	-2.1
10CA	berm	6	hard soil	soft	-2.2	-2.2	-1.2	-1.7	-1.8
11CA	wall	5	pavement	soft	-0.8	-1.4	0	-0.6	-0.7
05CA	wall	8	pavement	soft	-0.7	-0.7	-0.3	-0.5	-0.6
12CA	wall	8	pavement	soft	-0.6	-0.6	-0.2	-0.4	-0.45
14CA	wall	8	pavement	soft	-0.8	-0.7	-0.1	-0.5	-0.5
09CA	berm+wall	10	pavement	soft	-1.4	-1.2	-0.5	-0.9	-1
08CA	wall	14	pavement	soft	-1	-0.7	-0.1	-0.4	-0.6
				Avg Soft	-1.4	-1.5	-0.6	-1.3	-1.2

While these results give strong evidence that the difference in ellipse computations is the driving factor of differences between TNM 2.5 and TNM 3.0 predictions for the measurement sites, further evidence can be found by modifying TNM 2.5 to remove this difference with 3.0. To this end, TNM 2.6 was created by making the same code corrections for the two bugs identified. Since the second bug is not relevant for the measurement site cases, only the change to the ellipse computation will have any affect on the results.

The results of rerunning the analyses using TNM 2.6 are shown in Figure 8 and Table 5. Here the magnitude of the average errors for the different geometrical groupings range from 0.4 to 0.8 dB compared to 0.5 to 1.4 dB in TNM 2.5. These differences can be reasonably attributed to numerical precision in the different stages of data and computations between the two different implementations. Figure 3 is replicated using TNM 2.6 in Figure 9. Note the significant improvement in agreement between TNM 3.0 and TNM 2.6 compared to the agreement between TNM 3.0 and 2.5. Additional examples can be found in Appendix G: Comparison of Modeled Results for TNM 2.5, 2.6, and 3.0.

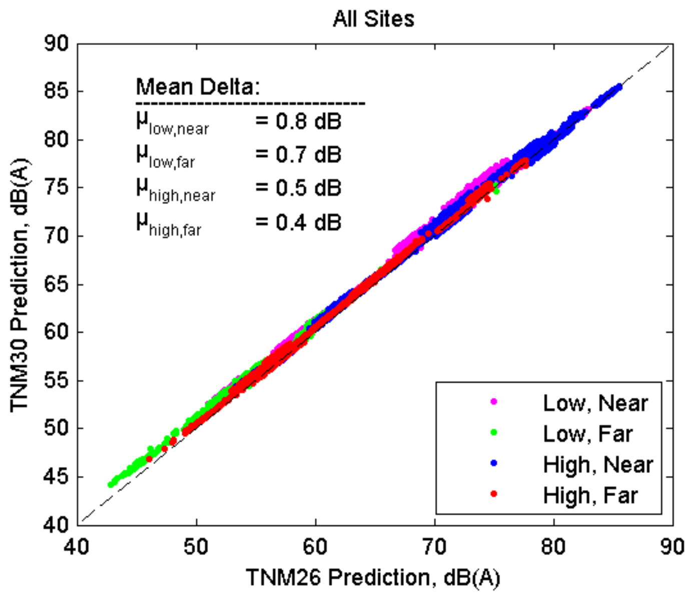


Figure 8: Predictions for Measurement Sites (TNM 2.6 vs. TNM 3.0) – Grouped by Microphone Location, All Sites (Measurement Data)

TABLE 5: AVERAGE DIFFERENCES BETWEEN TNM 2.6 AND TNM 3.0 PREDICTIONS FOR MEASUREMENT SITES – GROUPED BY MICROPHONE LOCATION AND SITE

Delta 26 vs 30									
Site	Terrain	Lanes	Median	Ground	Low Near	Low Far	High Near	High Far	Avg
13CA	flat	2	pavement	hard	0.0	0.0	-0.1	0.0	0.0
17CT	flat	6	pavement	hard	0.2	0.1	NA	0.0	0.1
15CA	flat	10	pavement	hard	0.3	0.2	0.2	0.2	0.2
				Avg Hard	0.2	0.1	0.1	0.1	0.1

01MA	flat	4	field grass	soft	1.5	0.6	1.2	0.8	1
02MA	flat	4	field grass	soft	1.7	1	1	0.4	1
06CA	berm+wall	6	lawn	soft	1.3	1.3	0.9	0.9	1.1
03MA	flat	4	hard soil	soft	1.7	0.8	NA	0.5	1
10CA	berm	6	hard soil	soft	1	1	0.9	0.8	0.9
11CA	wall	5	pavement	soft	1.3	1.3	1.1	1	1.2
05CA	wall	8	pavement	soft	0.5	0.7	0.2	0.4	0.5
12CA	wall	8	pavement	soft	0.5	0.6	0.2	0.4	0.4
14CA	wall	8	pavement	soft	0.8	0.8	0.5	0.5	0.7
09CA	berm+wall	10	pavement	soft	0.4	0.7	0	0.2	0.3
08CA	wall	14	pavement	soft	0.9	0.9	0.6	0.5	0.7
				Avg Soft	1	0.8	0.6	0.5	0.7

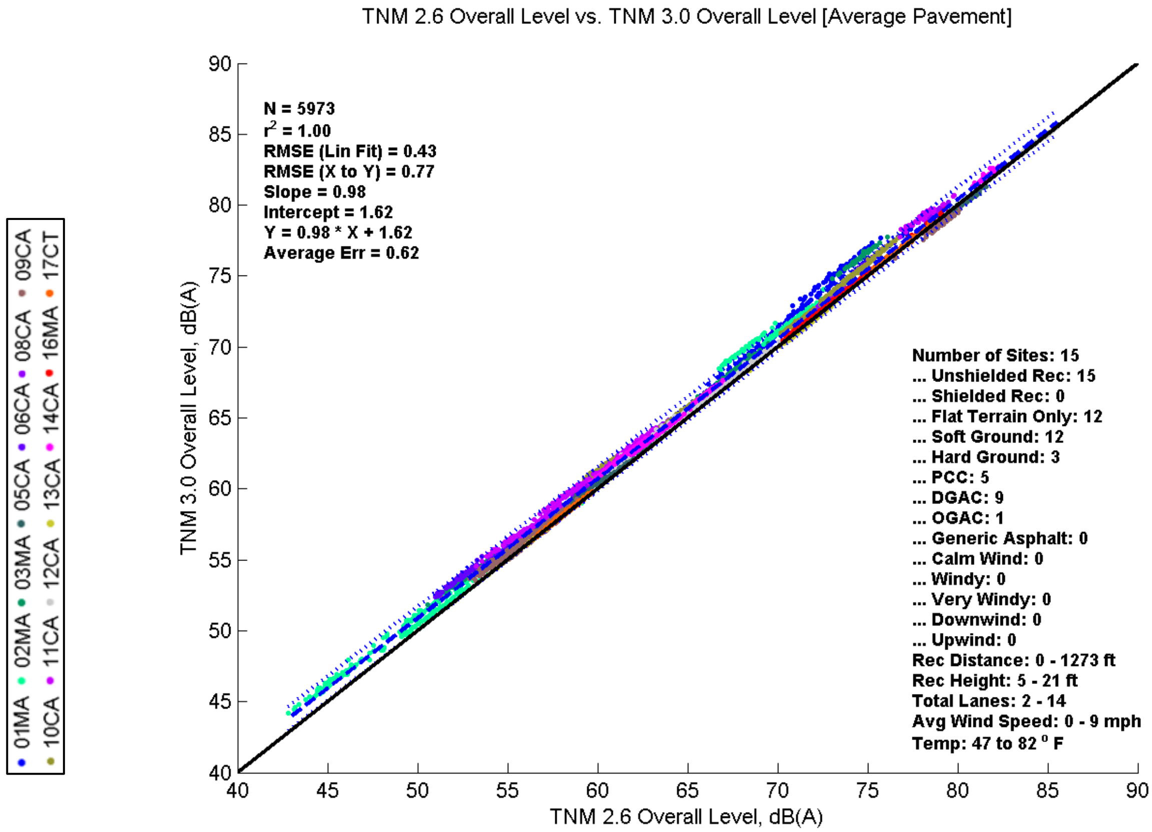


Figure 9: Comparison of Predicted Levels between TNM Version 2.6 and Version 3.0 (Measurement Data)

6.2 Predictions for Consistency Test Suite Sites

In addition to reanalyzing the historical measurement sites, sites that are included in the Consistency Test Suite were also analyzed. Although these models do not include measurement data, they do provide a greater diversity of acoustically significant structures and traffic flow as well as a greater number of receiver locations.

Figure 10 follows the same format as Figure 3 except that, due to the number and complexity of the sites, sites are not color coded in this figure. Similar to Figure 3, it can be seen in Figure 10 that there is a high degree of correlation between the two models, $r^2 = 0.96$ and that both models are equally sensitive to changes in the input parameters, slope = 1.01, but that TNM 3.0 predicts values about 2 dB lower than TNM 2.5. Although the statistical parameters indicate good average agreement, individual predictions are somewhat varied between models since 95-percent of the variation falls within +/- 5.33 dB[9] range. Note that the range of sample variation is greater than for the measurement sites. This is not

[9] *PI = 2.72 * 1.96 dB*

surprising since the CTS sites incorporate a greater number TNM features, and thus, there are a greater number of potential changes between TNM 2.5 and TNM 3.0 that could affect the results.

Since it has already been established that the change in the ellipse computation has a significant effect on the results, the rest of this analyses utilizes TNM 2.6 in order to identify other root causes. Figure 11 shows the correlation between TNM 2.6 and TNM 3.0 for the CTS sites. The average error between TNM 2.6 and 3.0 is smaller at 0.7 dB compared to 2 dB for TNM 2.5 and 3.0, so a significant portion of the variation is still explained by the differences in the computation of the Fresnel ellipse for ground impedance averaging.

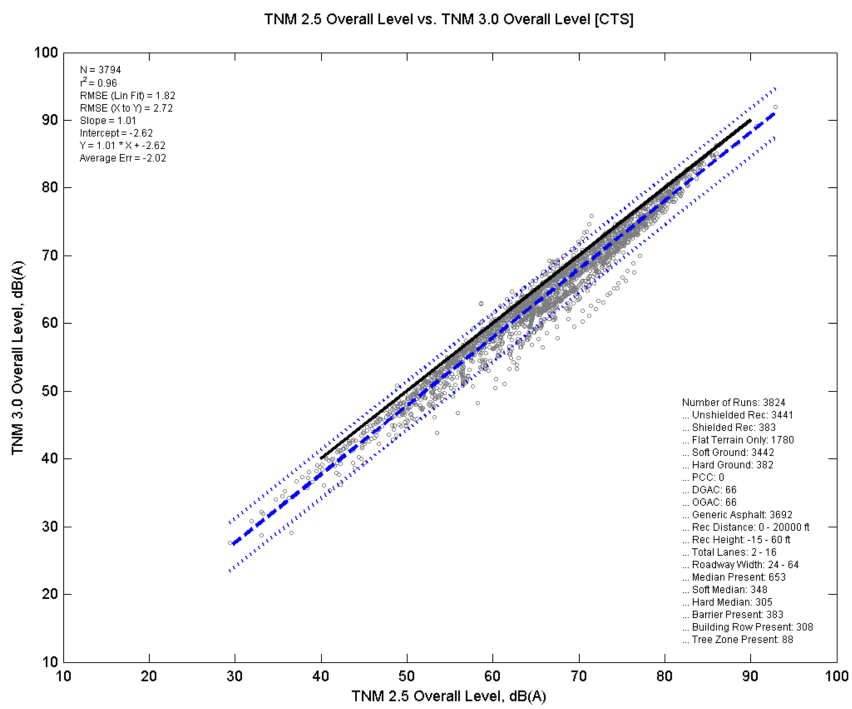


Figure 10: Comparison of Predicted Levels between TNM Version 2.5 and Version 3.0 (CTS Data)

One interesting divergence from the trend line is not readily observed when comparing all results together, but can be seen when Site 3.5.3 is highlighted, as in Figure 12. This site consists of a roadway with a set of receivers positioned near the end of the roadway oriented in a line perpendicular to the roadway. In this case, how the different versions of TNM determine the attenuation could be affected by the change in the manner in which elemental triangles are determined.

This is because, unlike most situations, the triangle geometries are exaggerated by the relative position of the receiver to the roadway. In such cases, angles become very close to zero at different rates and elemental triangle legs approach the same length at different rates. The number of triangles is not likely to affect the summation; however, the values derived from these triangles that are used in other computations, such as for the road length correction, could be affected by these differences.

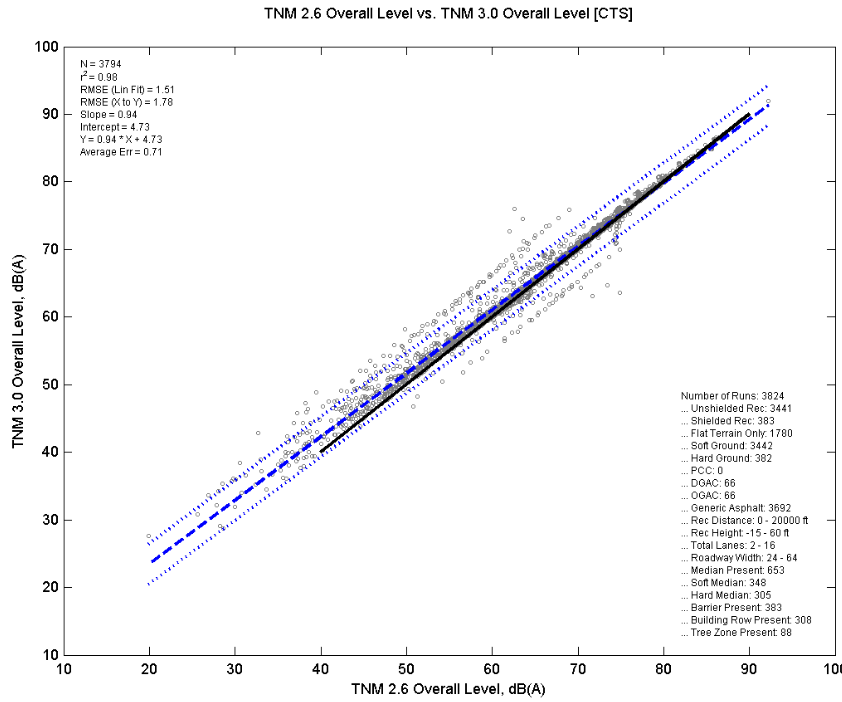


Figure 11: Comparison of Predicted Levels between TNM Version 2.6 and Version 3.0 (CTS Data)

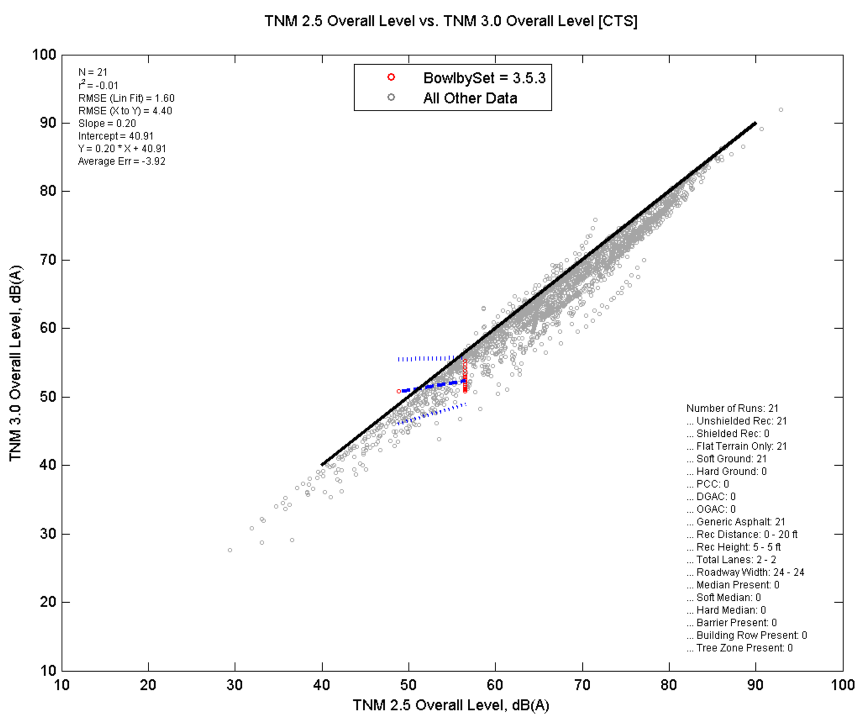


Figure 12: Comparison of Predicted Levels between TNM Version 2.6 and Version 3.0 for 3.5.3 (CTS Data)

SECTION 7 DIFFERENCES BETWEEN TNM 3.0 PREDICTIONS AND MEASUREMENTS

The differences shown in the previous sections do not indicate which version is performing better with respect to measured data. In order to determine how well a given version performs, comparisons of measured and modeled data are required. Because measured data were not available for the CTS sites, only the sites described in Section 2 are included in these comparisons.

In the following sections, four sets of comparisons to measured data are performed using modeled results from: 1) TNM 2.5 with Average pavement, 2) TNM 3.0 with Average pavement, 3) TNM 2.5 with specific pavements, and 4) TNM 3.0 with specific pavements[10]. (Note that since the goal of this section is to evaluate performance and not to identify root causes, TNM 2.6 analyses is omitted.) Although other factors are confounded with pavement type, comparing predicted and measured data modeled with specific pavement type can provide additional insight by accounting for one known deviation between sites as modeled and actual measurements. Assuming that study sites are well represented by the REMELs database, one would expect sites that had PCC roadways to be under-predicted (at least near the source) and sites that had DGAC or OGAC to be over-predicted when Average pavement is used.

Section 7.1 compares the performance of TNM 2.5 and TNM 3.0 relative to measured data for all data analyzed. However, in order to determine if TNM 3.0 is performing better or worse for a specific type of site, a more detailed analysis is required. To this end, the performances of TNM 2.5 and TNM 3.0 relative to measured data were also compared, for sites with acoustically hard or soft ground, for sites with or without a barrier, and receivers at near, medium and far distances, and on a site-by-site basis. The results of these comparisons are summarized in Sections 7.2 through 7.5.

7.1 COMPARISONS FOR ALL DATA

Figure 13 depicts the performance of TNM 2.5 and TNM 3.0 relative to measured data for all data analyzed. The formatting is similar to Figure 3, but the levels on the x-axis correspond to measured data instead of a second set of modeled data. The top left pane of Figure 13 shows TNM 2.5 with Average pavement compared to measured data, while the bottom left pane shows TNM 3.0 modeled with Average pavement compared to measured data. The right panes show TNM 2.5 and TNM 3.0 comparisons modeled with specific pavements.

As in Figure 3, the colored data points (each site is presented in a different color) represent individual 5-minute model computations; the dashed line shows the first-order linear regression between the two datasets; the dotted lines indicate the 95-percent prediction interval for any new samples; and the solid black line indicates where all results would fall if the model predicted the measured results with perfect agreement. Note that in the upper left hand corner of graph several statistical parameters are presented: the number of samples, the coefficient of determination (r^2), the root mean squared error

[10] Here specific pavement refers to the pavement identified during the site scoping and is either DGAC, OGAC, or PCC.

(RMSE), the regression slope and intercept, the regression equation, and the average error. In the lower right-hand corner, a metadata summary is provided covering the number of sites, the presence of a barrier, receiver distances and heights, number of roadway lanes, pavement type, and temperature and wind conditions included in the analysis.

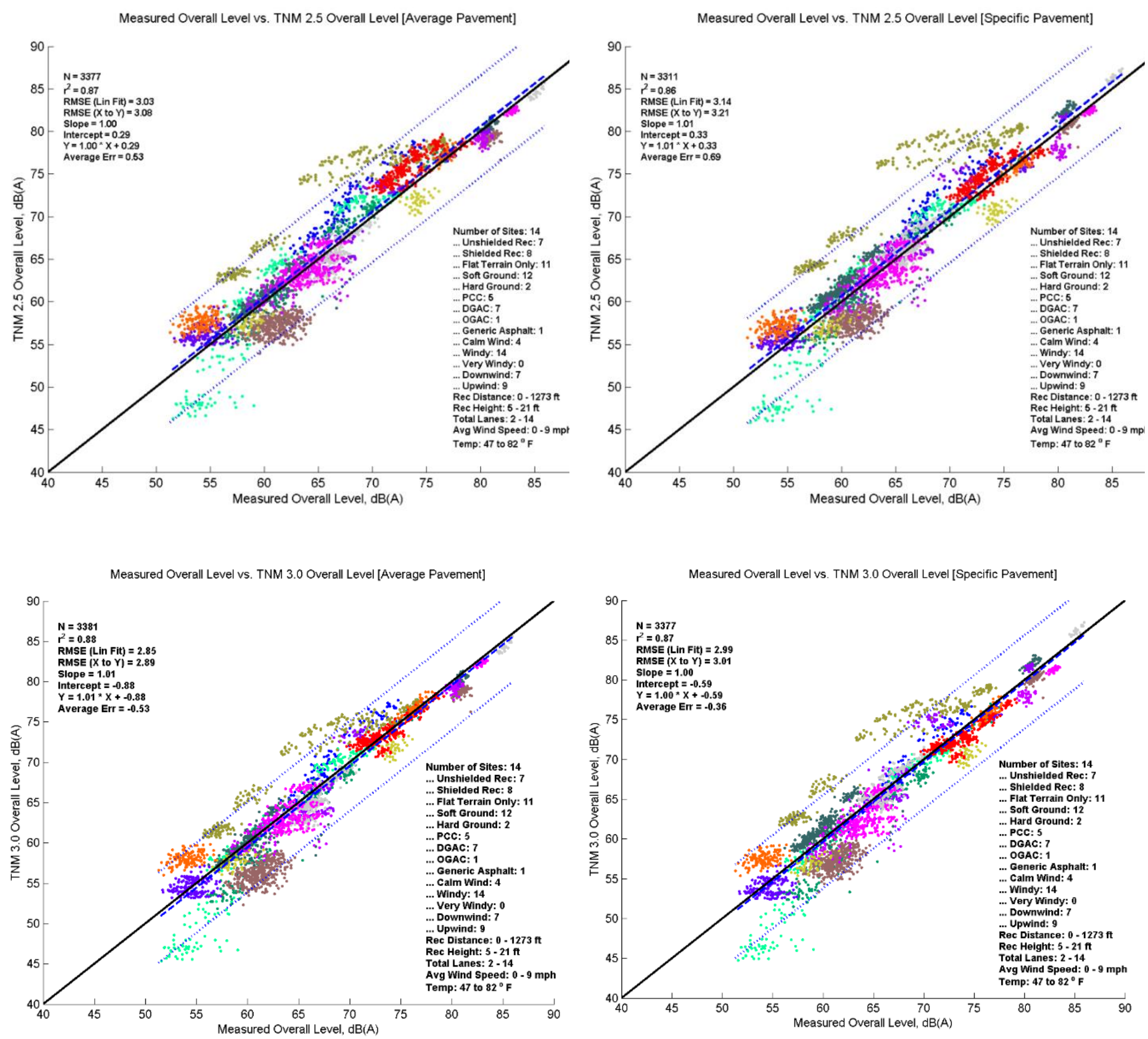


Figure 13: TNM 2.5 and 3.0 Predictions and Measured Results using Average and Specific Pavements for All Data Analyzed

Figure 13, shows that TNM 2.5 (top two graphics) on average over predicts the measured data while TNM 3.0 (bottom two graphics) under predicts the measured data. This trend is consistent over the range of measured sound levels; the offset between the solid black line and dashed regression line is nearly constant. Modeling with specific pavement types does not change the overall picture greatly; the same general trends are visible in both sets of results. These results are very consistent with the comparisons in Section 5, with the main difference being increased variation due the measured data.

In order to better compare and quantitatively describe model performance, the statistical parameters presented in the upper left-hand corner of the graphics are replicated in Table 6 below. When comparing measured to modeled data, the average error statistic provides an indication of the overall average difference between measured and modeled results. Modeled with average pavement, TNM 2.5, on average over predicts these data by 0.53 dB, while TNM 3.0 under predicts these data by 0.53 dB. Modeled with specific pavements, the average error is shifted upward to 0.69 for TNM 2.5 and -0.36 for TNM 3.0; a result of modeling 5 of the 14 sites with PCC pavement. Because PCC typically has much higher sound pressure levels than Average pavement, while DGAC has only slightly lower sound pressure levels than Average pavement for the same traffic, one would expect an upward shift in these results modeled with specific pavements.

The slope for these regressions can indicate if the error changes with a change in the x-axis values (sound level). In all four cases, the slope coefficient is equal to or nearly equal to 1.0, indicating no change in model performance over the range of sound levels.

TNM 3.0 achieves a slightly better r^2 values than TNM 2.5; however, the difference is quite small (r^2 of 0.88 compared to 0.87 for Average pavement). TNM 3.0 has an RMSE of 2.85 while TNM 2.5 has an RMSE of 3.03. This indicates that the difference between TNM 3.0 predictions and measured data are slightly less random than the difference between TNM 2.5 predictions and measured data.

TABLE 6: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – ALL DATA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	3377	3311	3381	3377
r^2	0.87	0.86	0.88	0.87
RMSE (Lin Fit)	3.03	3.14	2.85	2.99
RMSE (X to Y)	3.08	3.21	2.89	3.01
Slope	1.00	1.01	1.01	1
Intercept	0.29	0.33	-0.88	-0.59
Average Err	0.53	0.69	-0.53	-0.36
Slope 95% CI	0.99, 1.02	0.99, 1.02	0.99, 1.02	0.99, 1.02
Intercept 95% CI	-0.58, 1.17	-0.58, 1.24	-1.70, -0.06	-1.45, 0.27
Avg Err 95% CI	0.43, 0.64	0.58, 0.80	-0.63, -0.43	-0.46, -0.26

To further visualize these summary statistics, graphics in Figure 14 depict the 95% confidence intervals (CI) for the estimated slope and average error parameters. These graphics can show if differences between these values are statistically significant. Overlapping lines would indicate that the values are statistically similar, while non-overlapping lines would indicate that these values are not statistically similar. In Figure 15, the slopes of all four regression lines are statistically similar, while the average errors between 2.5 and 3.0 are not.

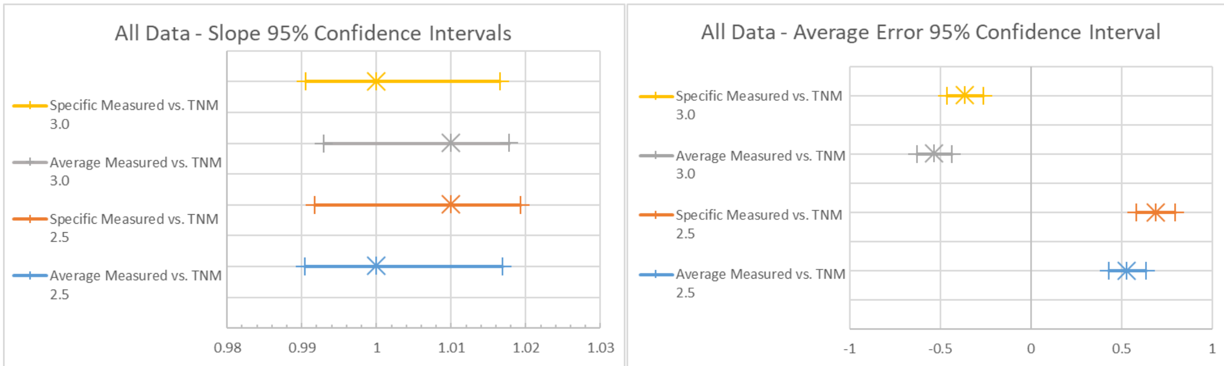


Figure 14. Confidence Intervals for Slope and Average Error Statistics - All Data Analyzed

To determine if TNM 3.0 is performing better or worse for a specific type of site, a more detailed analysis may be required. To this end, the performances of TNM 2.5 and TNM 3.0 relative to measured data were compared for sub-sets of the data including:

- Sites with acoustically hard or soft ground (Section7.2)
- Sites with or without a barrier (Section 7.3)
- Measurements at near, medium and far distances (Section 7.4).

7.2 Comparisons for Sites with Similar Ground Type

Figure 15, Table 7 and Figure 16 show the agreement between predicted and measured results for all cases where acoustically soft ground was the primary ground type between source and receiver. The soft ground data are represented by the black data points; all other data (shown in the graph but not included in the regression) are represented in the background by colored data points. When modeled with Average pavement, TNM 2.5 has good prediction results for all statistics computed and the trend line almost directly coincides with the line representing a one-to-one relationship. The average difference is just 0.23 dB. Results show slightly less agreement when modeled with specific pavements; TNM 2.5 over predicts by 0.56 dB (average error) and the slope of the trend line is now greater than one, influenced by the upward shift in predicted levels for sites modeled with PCC pavement.

TNM 3.0 on average under predicts soft ground by 0.81 dB with Average pavement and by 0.47 dB with specific pavement. Again, the slope of the trend line for specific pavements is influenced by the upward shift in predictions due to sites modeled with PCC pavement.

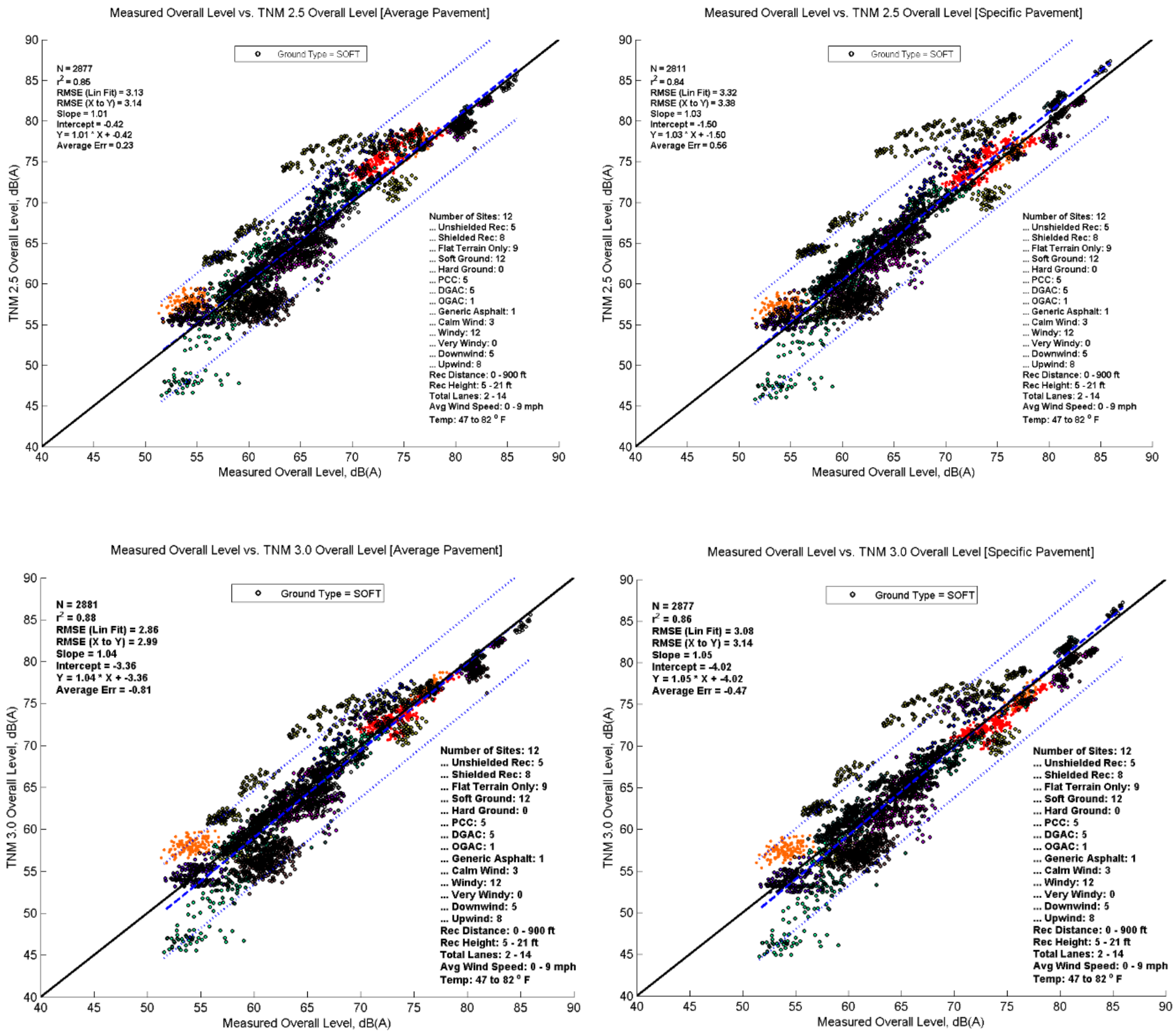
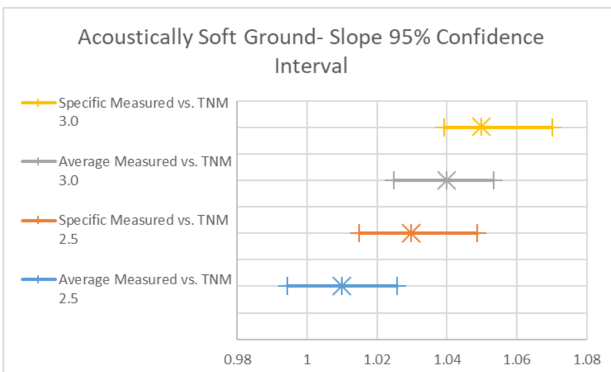


Figure 15: Comparison of TNM 2.5 and TNM 3.0 Predictions and Measured Results for Sites with Acoustically Soft Ground

TABLE 7: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – ACOUSTICALLY SOFT GROUND

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	2877	2811	2881	2877
r^2	0.85	0.84	0.88	0.86
RMSE (Lin Fit)	3.13	3.32	2.86	3.08
RMSE (X to Y)	3.14	3.38	2.99	3.14
Slope	1.01	1.03	1.04	1.05
Intercept	-0.42	-1.5	-3.36	-4.02
Average Err	0.23	0.56	-0.81	-0.47
Slope 95% CI	0.99, 1.03	1.01, 1.05	1.02, 1.05	1.04, 1.07
Intercept 95% CI	-1.45, 0.60	-2.60, -0.40	-4.30, -2.43	-5.03, -3.01
Avg Err 95% CI	0.11, 0.34	0.44, 0.67	-0.92, -0.71	-0.58, -0.35



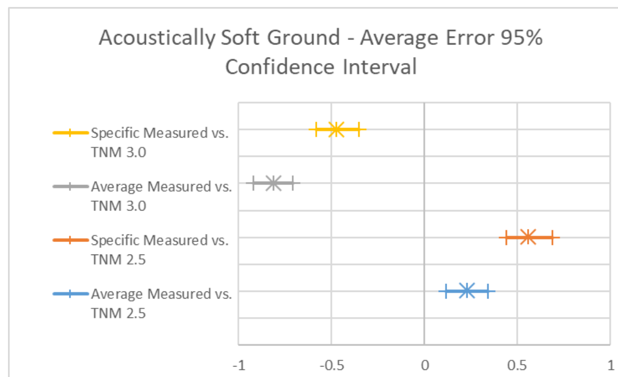


Figure 16. Confidence Intervals on Slope and Average Error Statistics - Acoustically Soft Ground

Figure 17, Table 8, and Figure 18 show the agreement between predicted and measured results for TNM 2.5 and 3.0 for all cases where hard ground was the primary ground type between source and receiver. As these trend lines are based on only two sites, conclusions drawn from these regressions could be amended in the presence of more data.

TNM 3.0 performs better for these hard ground cases, having smaller average errors and RMSE. On average both versions over predict noise levels, with over-predictions greater at farther distances[11]. As expected, the over-prediction is slightly less when modeled with specific pavement, which is DGAC for both sites. However, while TNM 2.5 also over-predicts noise levels at near distances, TNM 3.0 has smaller average errors and RMSE at near distances and actually slightly under predicts when modeled with specific pavement. When modeled with specific pavement, the average error for TNM 3.0 is lowest, as the over-prediction at far distances and under-prediction at near distances result in an average of nearly zero. (This does not inherently represent better performance, merely a preferable alignment of errors.)

[11] Although other factors play a role, in general lower sound pressure levels indicate data collected far from the roadway and higher sound pressure levels indicate data collected nearer to the roadway. This interpretation is used whenever distance is not explicitly given.

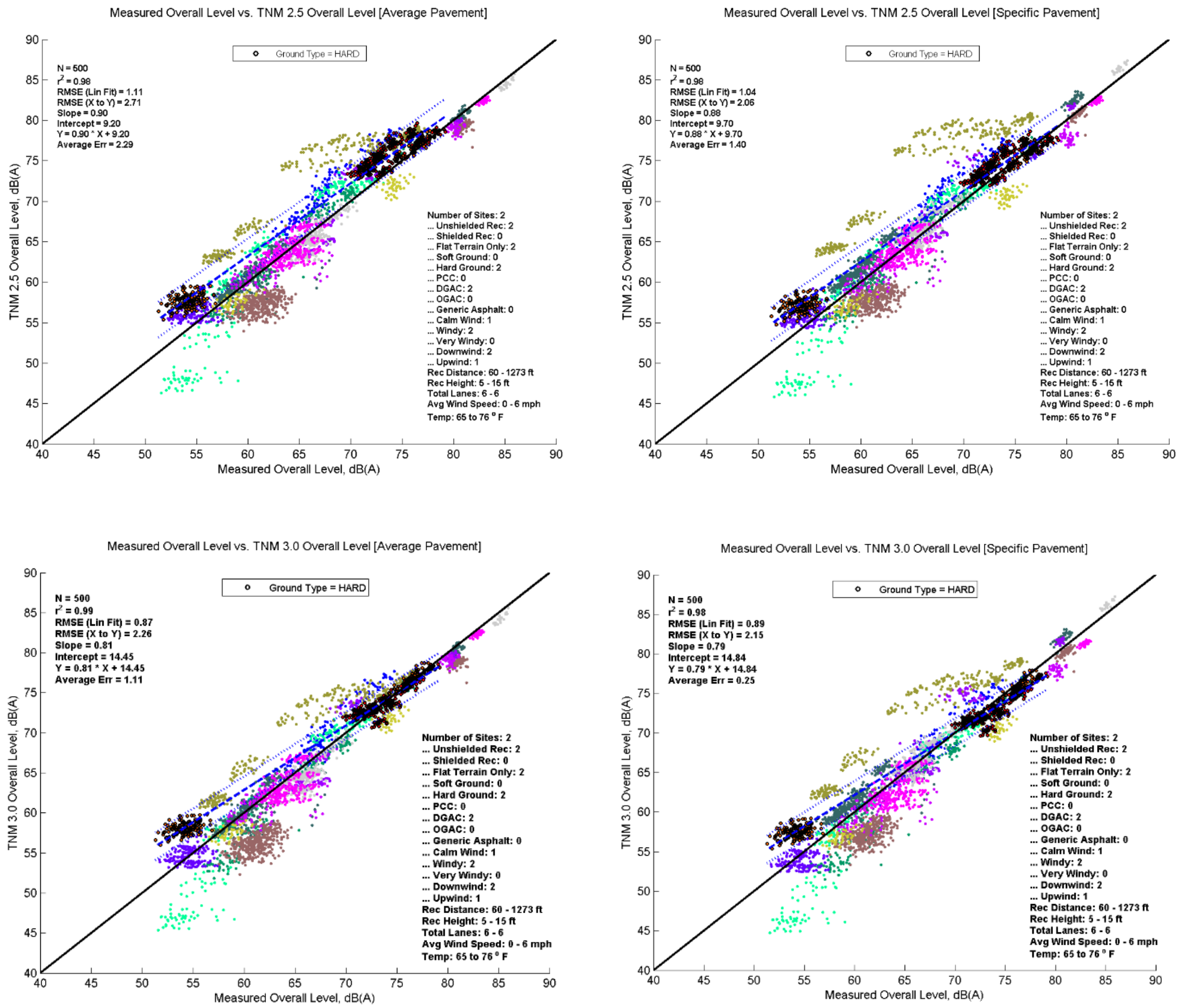


Figure 17: Comparison of TNM 2.5 and TNM 3.0 Predictions and Measured Results for Sites with Acoustically Hard Ground

Table 8: Summary Statistics for TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Acoustically Hard Ground

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	500	500	500	500
r^2	0.98	0.98	0.99	0.98
RMSE (Lin Fit)	1.11	1.04	0.87	0.89
RMSE (X to Y)	2.71	2.06	2.26	2.15
Slope	0.9	0.88	0.81	0.79
Intercept	9.2	9.7	14.45	14.84
Average Err	2.29	1.4	1.11	0.25
Slope 95% CI	0.89, 0.91	0.87, 0.89	0.80, 0.81	0.78, 0.80
Intercept 95% CI	8.46, 9.94	9.01, 10.40	13.87, 15.03	14.24, 15.43
Avg Err 95% CI	2.17, 2.42	1.26 , 1.53	0.93, 1.28	0.06, 0.44

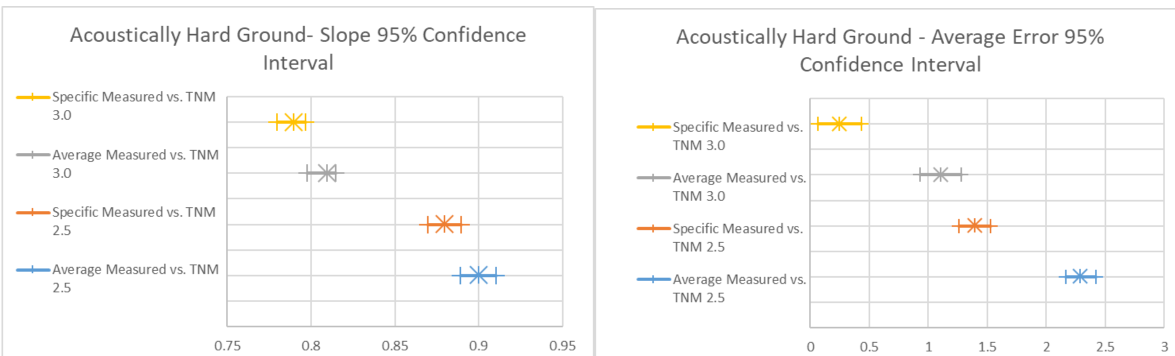


Figure 18. Confidence Intervals on Slope and Average Error Statistics - Acoustically Hard Ground

7.3 Comparisons for Barrier/Open Sites

Figure 19, Table 9, and Figure 20 show the agreement between predicted and measured results for TNM 2.5 and 3.0 for all open sites where no barrier is between source and receiver. On average, TNM 3.0 has nearly perfect agreement when modeled with Average pavement, while there is a slight under-prediction when modeled with specific pavements (most of the sites have DGAC as the specific pavement).

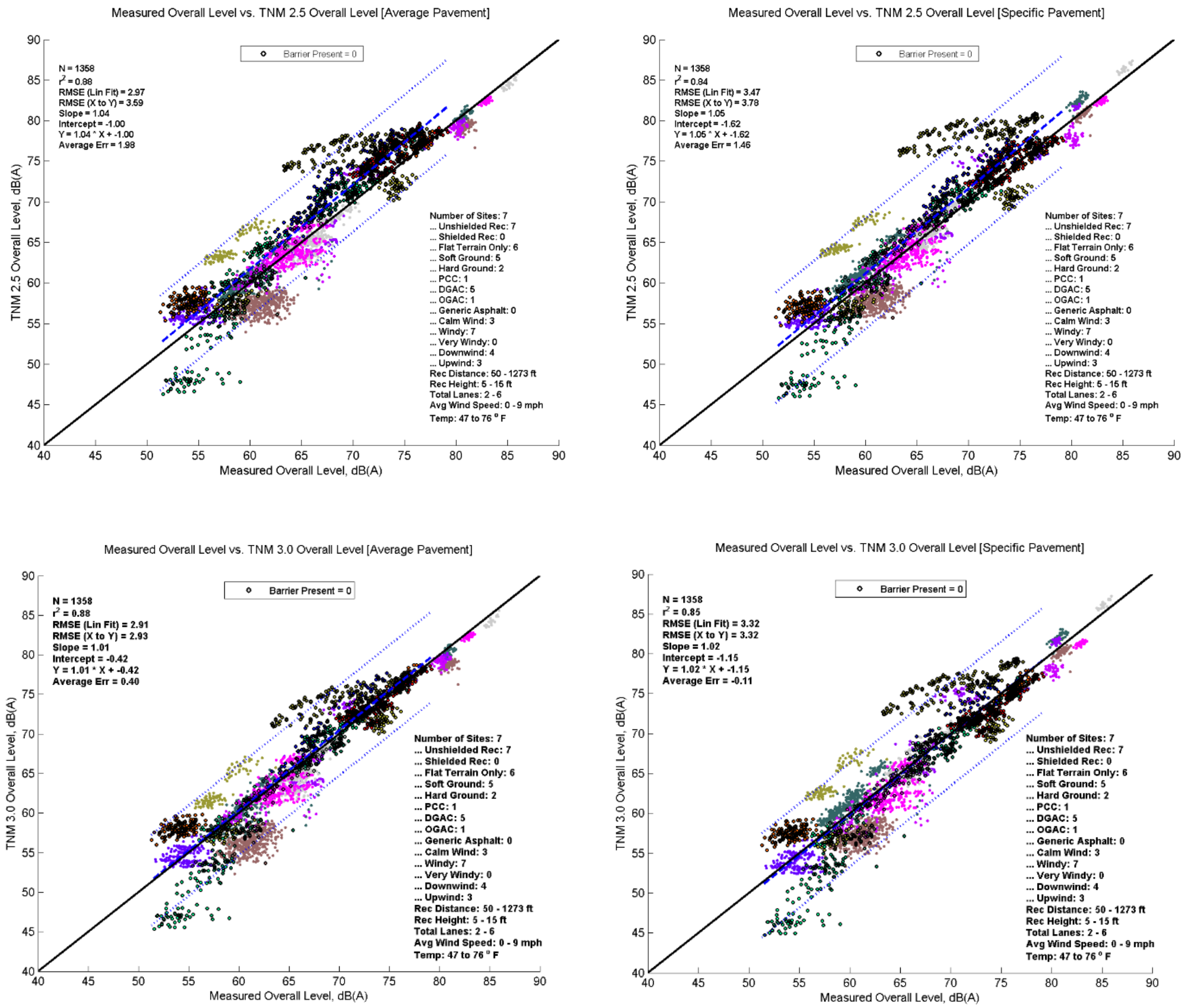
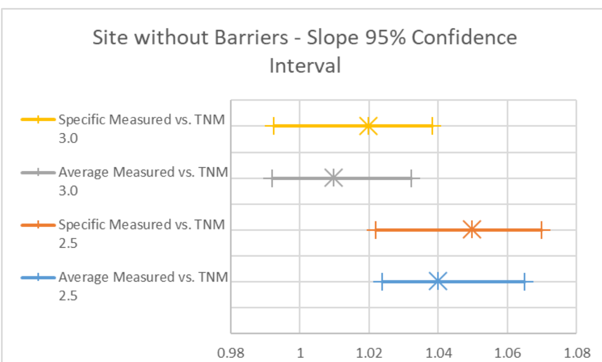


Figure 19: Comparison of TNM 2.5 and TNM 3.0 Predictions and Measured Results Sites without Barriers

TABLE 9: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – SITES WITHOUT BARRIERS

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	1358	1358	1358	1358
r^2	0.88	0.84	0.88	0.85
RMSE (Lin Fit)	2.97	3.47	2.91	3.32
RMSE (X to Y)	3.59	3.78	2.93	3.32
Slope	1.04	1.05	1.01	1.02
Intercept	-1	-1.62	-0.42	-1.15
Average Err	1.98	1.46	0.4	-0.11
Slope 95% CI	1.024, 1.07	1.02, 1.07	0.99, 1.03	0.99, 1.04
Intercept 95% CI	-2.39, 0.38	-3.25, 0.00	-1.78, 0.94	-2.70, 0.41
Avg Err 95% CI	1.83, 2.14	1.28, 1.65	0.24, 0.55	-0.29, 0.06



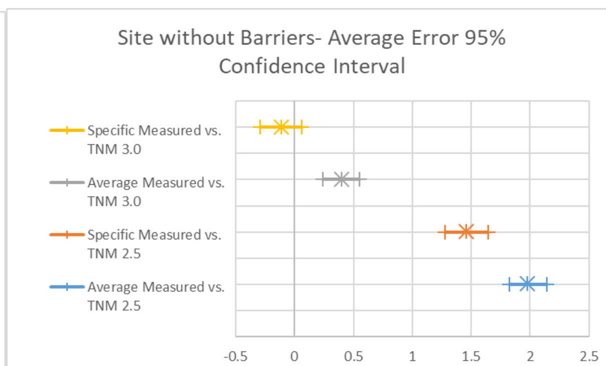


Figure 20. Confidence Intervals on Slope and Average Error Statistics - Sites without Barriers

Figure 21, Table 10 and Figure 22 show the agreement between predicted and measured results for TNM 2.5 and 3.0 for all cases where there is a barrier between source and receiver. Both versions of TNM under predict the “with Barrier” cases on average. TNM 2.5 under predicts less than TNM 3.0 (average error -0.44 vs. -1.15). The under-prediction decreases with specific pavement, as most sites in this group had PCC pavements.

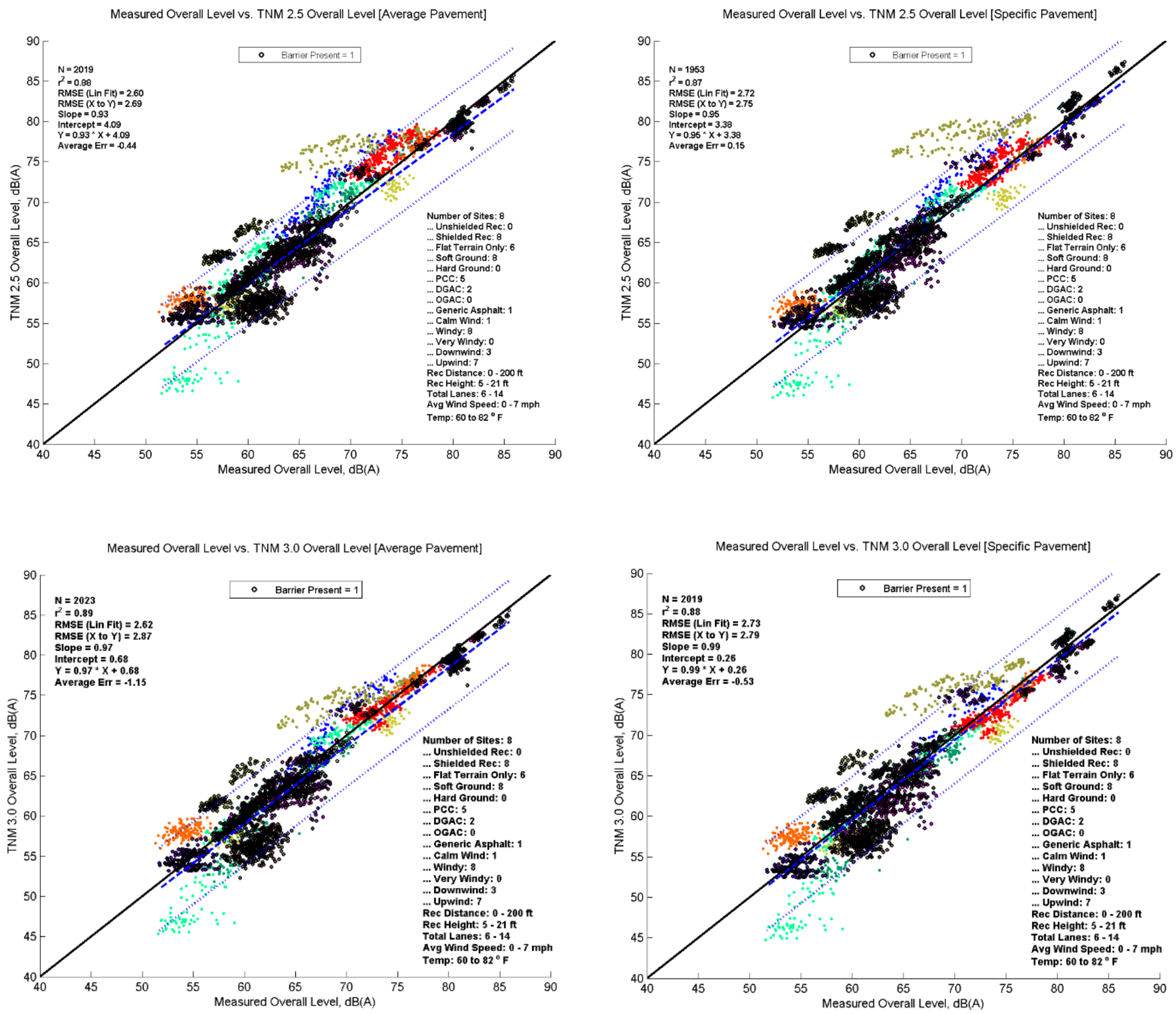


Figure 21: Comparison of TNM 2.5 and TNM 3.0 Predictions and Measured Results for Sites with Barriers

TABLE 10: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – SITES WITH BARRIERS

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	2019	1953	2023	2019
r^2	0.88	0.87	0.89	0.88
RMSE (Lin Fit)	2.6	2.72	2.62	2.73
RMSE (X to Y)	2.69	2.75	2.87	2.79
Slope	0.93	0.95	0.97	0.99
Intercept	4.09	3.38	0.68	0.26
Average Err	-0.44	0.15	-1.15	-0.53
Slope 95% CI	0.91, 0.94	0.93, 0.97	0.96, 0.99	0.97, 1.00
Intercept 95% CI	3.12, 5.06	2.34, 4.42	-0.30, 1.66	-0.76, 1.29
Avg Err 95% CI	-0.56, -0.33	0.03, 0.27	-1.27, -1.04	-0.65, -0.41

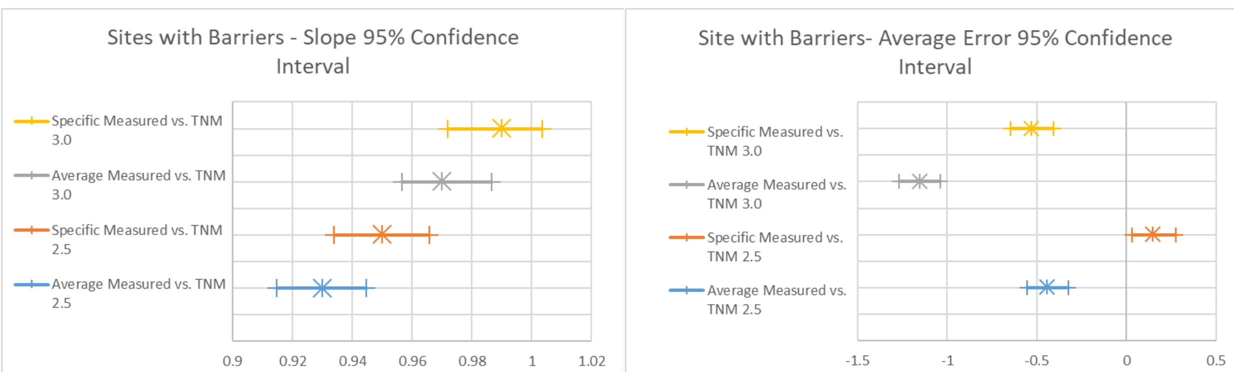


Figure 22. Confidence Intervals on Slope and Average Error Statistics - Sites with Barriers

7.4 COMPARISONS FOR MEASUREMENTS AT SIMILAR DISTANCES

Distance effects are especially difficult to analyze in the aggregate because all possible confounding factors, including hard and soft ground types and barrier presence, tend to show up in each distance category. Therefore, interactions between distance and ground type, barrier presence, and pavement type may be present at all distances. Even so, it is still useful to consider how each model is performing at various distances.

Figure 23, Table 11, and Figure 24 show the agreement between predicted and measured results for TNM 2.5 and 3.0 for distances less than 125 feet between source and receiver. Here TNM 2.5 tends to slightly over predict levels (average error = 0.78 dB) while TNM 3.0 tends to slightly under predict levels (average error = -0.17 dB). TNM 3.0's RMSE is also about 0.5 dB smaller than TNM 2.5. Otherwise, most descriptors are very similar between the two versions for this distance.

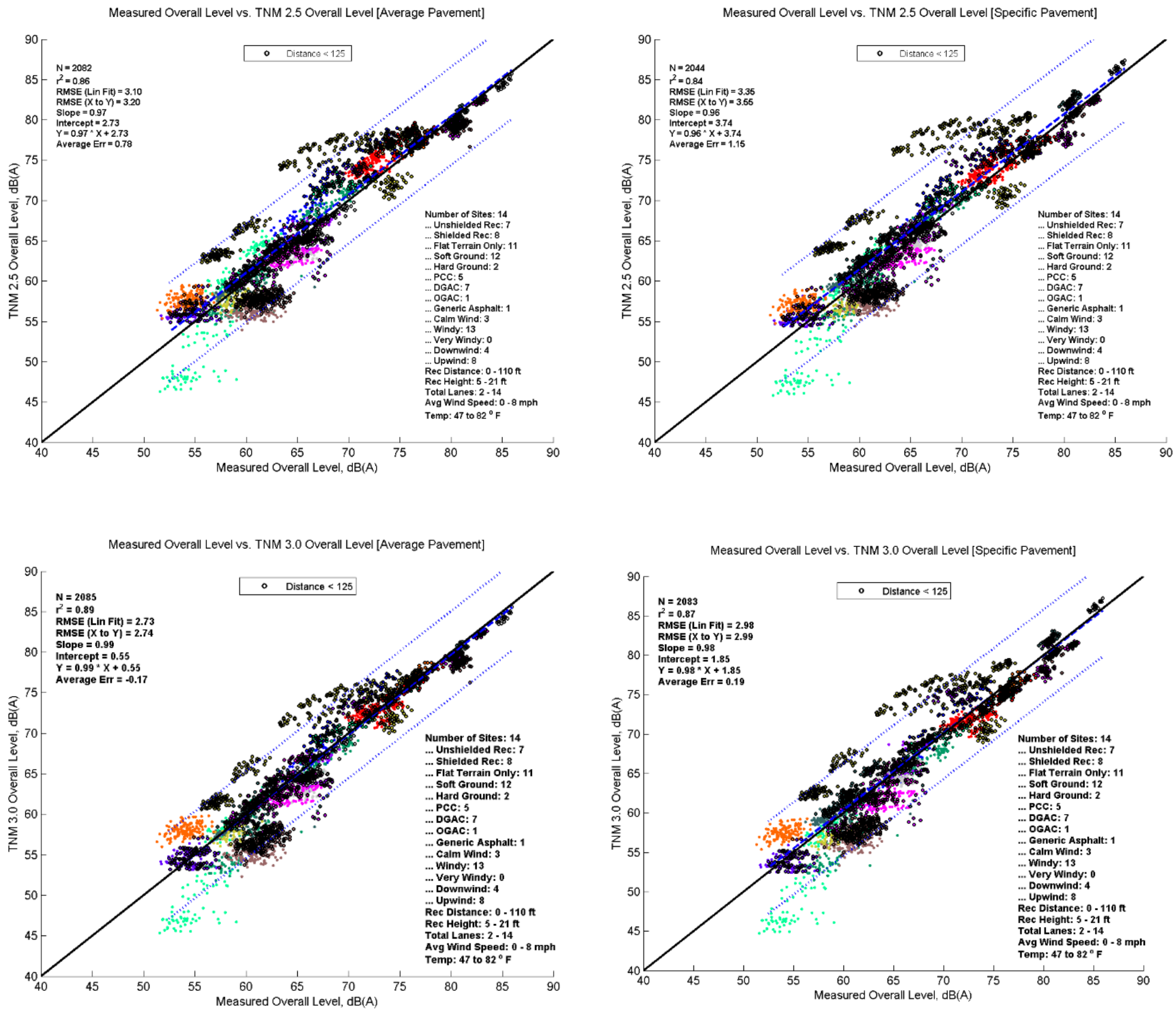


Figure 23: Comparison of TNM 2.5 and TNM 3.0 Predictions and Measured Results for Measurement Locations within 125 Feet of the Center of the Nearest Lane

TABLE 11: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS FOR MEASUREMENT LOCATIONS WITHIN 125 FEET OF THE CENTER OF THE NEAREST LANE

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	2082	2044	2085	2083
r^2	0.86	0.84	0.89	0.87
RMSE (Lin Fit)	3.1	3.35	2.73	2.98
RMSE (X to Y)	3.2	3.55	2.74	2.99
Slope	0.97	0.96	0.99	0.98
Intercept	2.73	3.74	0.55	1.85
Average Err	0.78	1.15	-0.17	0.19
Slope 95% CI	0.95, 0.99	0.94, 0.98	0.97, 1.00	0.96, 0.99
Intercept 95% CI	1.58, 3.87	2.49, 4.99	-0.46, 1.56	0.75, 2.95
Avg Err 95% CI	0.64, 0.91	1.01, 1.30	-0.29, -0.06	0.06, 0.31

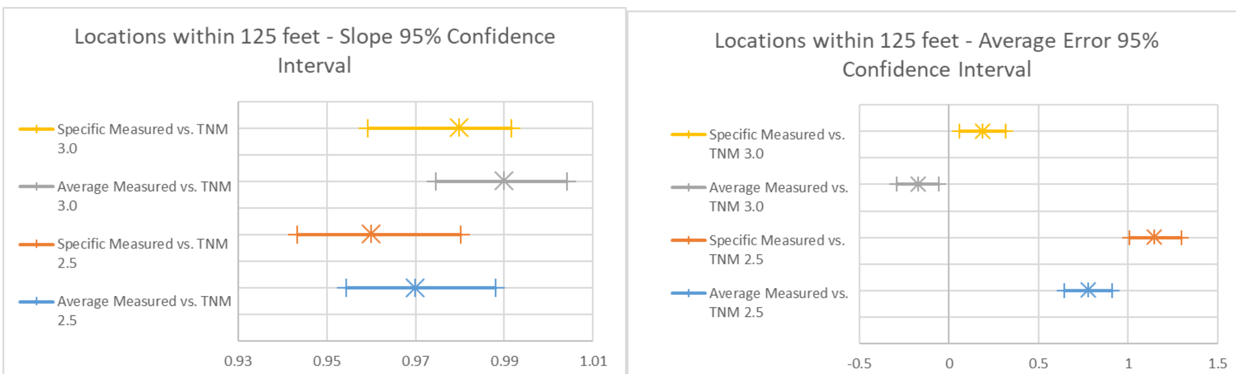


Figure 24. Confidence Intervals on Slope and Average Error Statistics - Locations within 125 Feet of the Center of the Nearest Lane

Figure 25, Table 12 and Figure 26 show the agreement between predicted and measured results for TNM 2.5 and 3.0 from 125 to 500 feet between source and receiver. TNM 2.5 on average over predicts slightly (0.18 dB) while TNM 3.0 under predicts by about 1.21 dB.

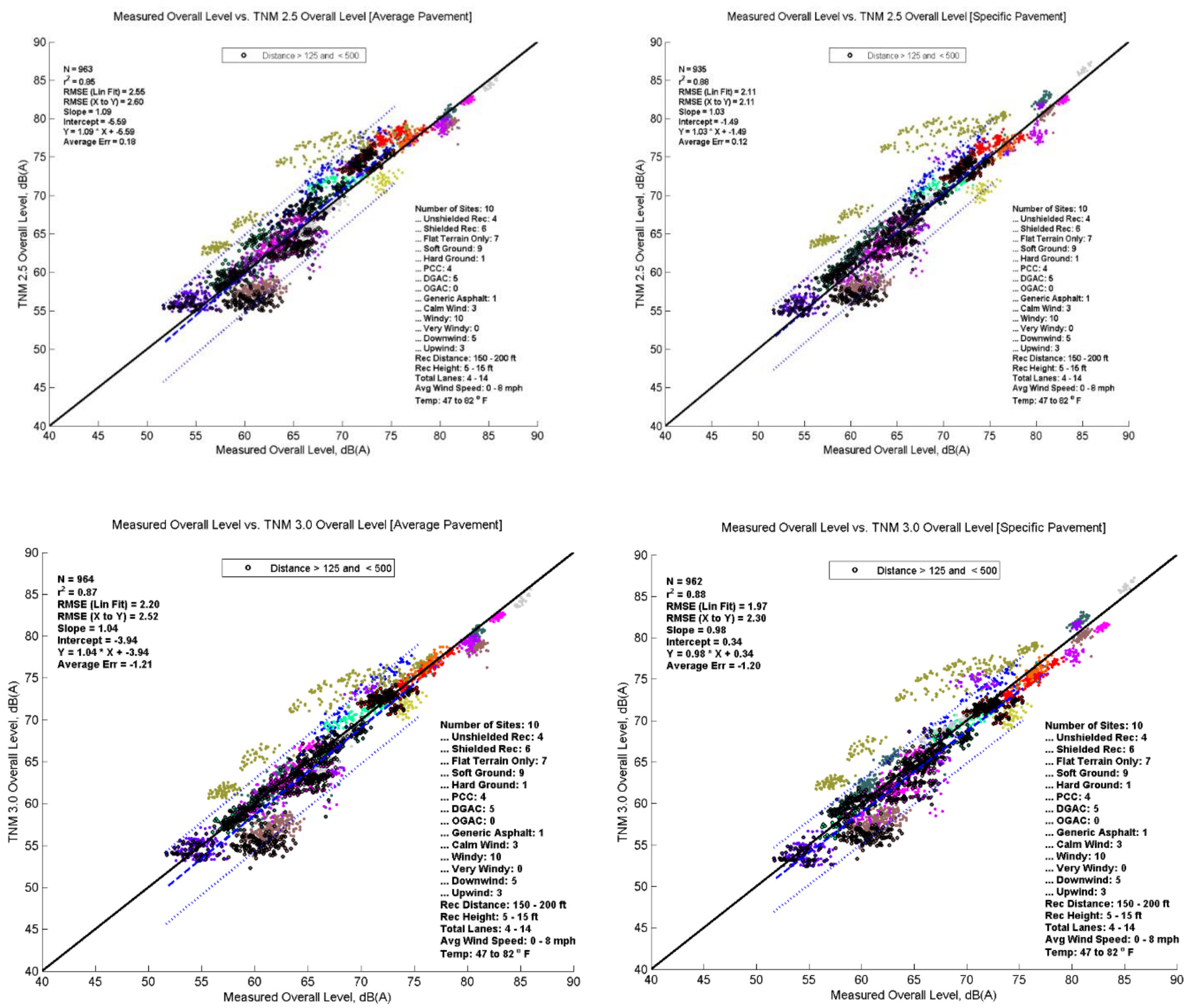


Figure 25: Comparison of TNM 2.5 and TNM 3.0 Predictions and Measured Results for Measurement Locations between 125 and 500 Feet of the Center of the Nearest Lane

Table 12: Summary Statistics for TNM 2.5 and 3.0 Predictions vs. Measured Results for Measurement Locations between 125 and 500 Feet of the Center of the Nearest Lane

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	963	935	964	962
r^2	0.85	0.88	0.87	0.88
RMSE (Lin Fit)	2.55	2.11	2.2	1.97
RMSE (X to Y)	2.6	2.11	2.52	2.3
Slope	1.09	1.03	1.04	0.98
Intercept	-5.59	-1.49	-3.94	0.34
Average Err	0.18	0.12	-1.21	-1.2
Slope 95% CI	1.06, 1.12	1.00, 1.05	1.02, 1.07	0.95, 1.00
Intercept 95% CI	-7.49, -3.70	-3.07, 0.08	-5.57, -2.30	-1.12, 1.80
Avg Err 95% CI	0.02, 0.34	-0.02, 0.25	-1.35, -1.07	-1.32, -1.07

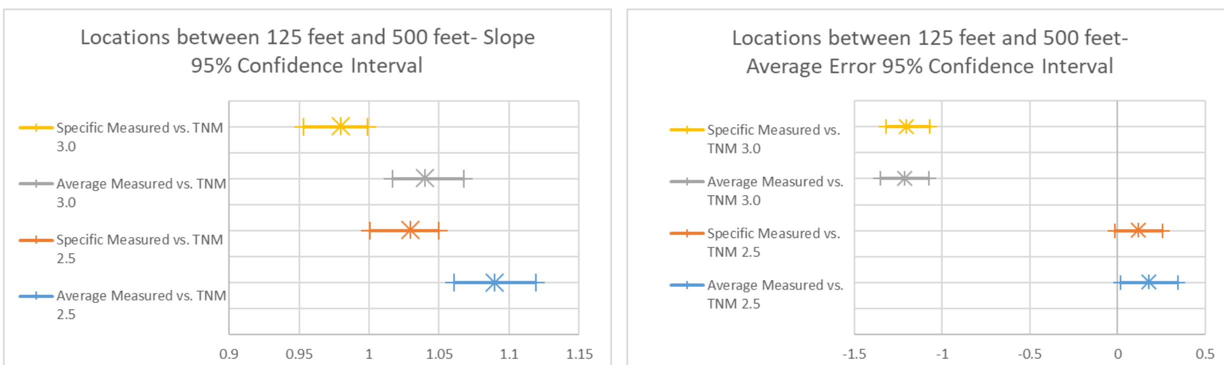


Figure 26. Confidence Intervals on Slope and Average Error Statistics - Locations between 125 and 500 Feet of the Center of the Nearest Lane

Figure 27, Table 13, and Figure 28 show the agreement between predicted and measured results for TNM 2.5 and 3.0 for distances greater than 500 feet between source and receiver. TNM 2.5 on average with measured results (average error = 0.03) while TNM 3.0 (Average pavement) under predicts by about 0.78 dB. It should be noted that, because the spread of measured data for this last distance range is short, many of the regression statistics (r^2, slope, intercept) may be exaggerated.

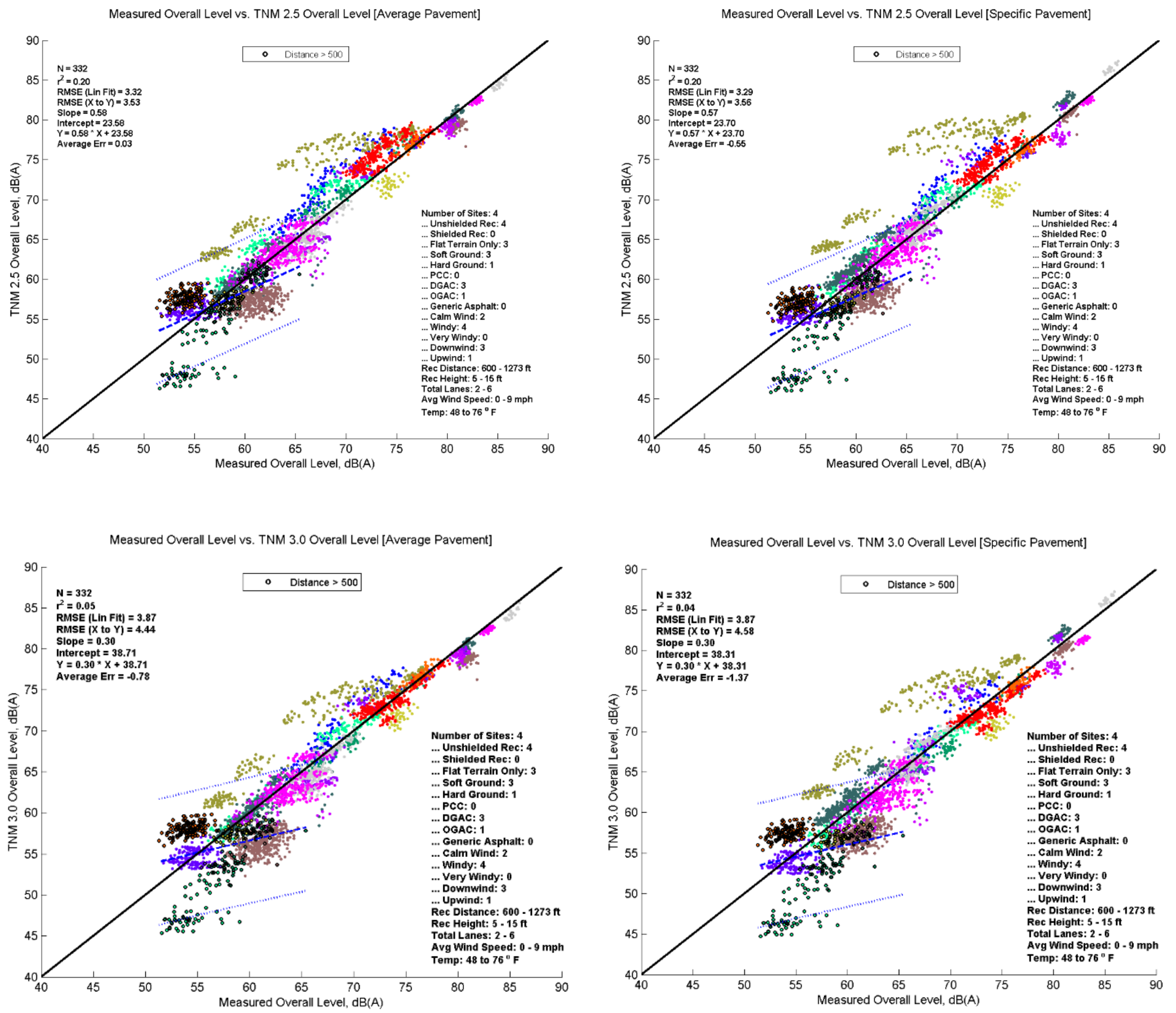


Figure 27: Comparison of TNM 2.5 and 3.0 Predictions and Measured Results for Measurement Locations Greater than 500 Feet from the Center of the Nearest Lane

TABLE 13: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS FOR MEASUREMENT LOCATIONS GREATER THAN 500 FEET OF THE CENTER OF THE NEAREST LANE

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	332	332	332	332
r^2	0.2	0.2	0.05	0.04
RMSE (Lin Fit)	3.32	3.29	3.87	3.87
RMSE (X to Y)	3.53	3.56	4.44	4.58
Slope	0.58	0.57	0.3	0.3
Intercept	23.58	23.7	38.71	38.31
Average Err	0.03	-0.55	-0.78	-1.37
Slope 95% CI	0.46, 0.70	0.45, 0.69	0.16, 0.44	0.15, 0.44
Intercept 95% CI	16.66, 30.50	16.84, 30.57	30.63, 46.79	30.24, 46.38
Avg Err 95% CI	-0.35, 0.41	-0.93, -0.18	-1.25, -0.31	-1.84, -0.90

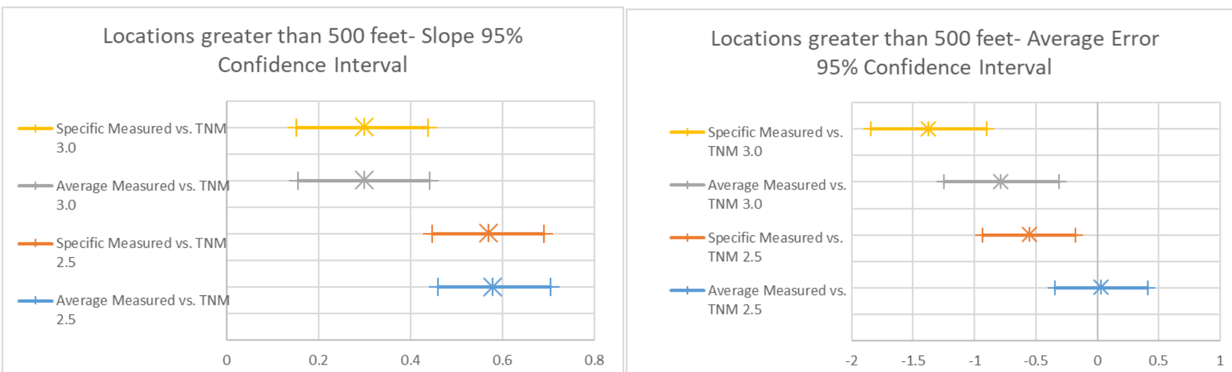


Figure 28. Confidence Intervals on Slope and Average Error Statistics - Locations greater than 500 Feet of the Center of the Nearest Lane

7.5 VARIATION BY SITE

Examining each site on its own is useful to see how well the predictions match for a specific set of conditions (compared to the aggregate groups discussed up to this point). Table 14 presents a summary of the average error statistics and site characteristics for TNM model runs for each site. In general, the trends for these individual sites will mirror trends for the groupings noted in the previous sections. For example, TNM 2.5 tends to over predict measured data while TNM 3.0 tends to under predict measured data; modeling with specific pavements increases overall levels when sites include PCC pavements; Graphics and model summary tables similar to those presented in previous sections are presented in Appendix H: Comparison of Modeled and Measured Results (Not Adjusted for Reference Microphone).

TABLE 14: META DATA AND SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS

Site ID	Site Type								Pavement	Average Error Statistic			
	Open area	Noise barrier	Soft ground	Hard ground	Mixed ground	Flat	With drop-off	Undulating		Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
01MA	X		X			X			DGAC	3.55	2.51	1.49	0.5
02MA	X		X					X	DGAC	0.34	-0.44	-1.35	-2.12
03MA	X		X			X			DGAC	0.27	-0.42	-1.97	-2.6
05CA		X	X			X			PCC	0.37	1.58	-0.12	1.26
06CA		X	X			X	X		DGAC	1.54	1.00	0.02	-0.72
08CA		X	X			X			PCC	0.01	1.25	-0.47	1.08
09CA		X	X			X	X		PCC	-3.62	-2.87	-4.55	-3.55
10CA	X	X	X			X			PCC	6.00	7.47	4.07	5.46
11CA		X			X	X			DGAC	-0.65	-1.44	-0.92	-1.84
12CA		X	X			X			PCC	-0.76	0.48	-1.21	0.22
13CA	X			X		X			OGAC	-1.76	-2.73	-1.82	-2.79
14CA		X	X			X			DGAC	-0.22	-0.22	-0.7	-1.51
16MA	X			X		X			DGAC	2.08	1.02	0	-0.99
17CT	X			X		X			DGAC	2.64	2.00	2.91	2.27

Section 8 Summary and Next Steps

The primary objective of this validation study was to quantify and assess the differences between predictions from FHWA's TNM 3.0 and acoustic data measured at practical highway sites. In order to frame these differences within the historical context of TNM development, differences in predictions between TNM 2.5 and TNM 3.0 were also examined. These comparisons were used to highlight how specific changes in the acoustics affect computed results. Differences between the predicted results were primarily found to be driven by a correction to the computation of Fresnel ellipses used to average ground impedances. This affected sites with acoustically soft ground, but did not significantly affect acoustically hard ground sites. Additionally, it was observed that acoustically soft ground sites with high receiver locations near roadways and receiver locations behind barriers had the effect of this change reduced.

Additional changes produced differences between the models for more limited conditions. Specifically, the removal of interpolation/extrapolation at the lowest and the highest one-third octave bands results in differences between the models at far distances where low frequency bands tend to dominate the overall level and the replacement of horizontal divergence with combined horizontal and vertical divergence affects receivers that have significantly different vertical heights compared to roadways. It also appears that a change in the manner in which elemental triangles may be causing differences in the computation of receivers nearly inline and near the end of a roadway.

When predictions were compared to measured data, both TNM 2.5 and TNM 3.0 performed similarly, but not identically. In general, the correlation and variance were not significantly different; however, biases as measured by average errors showed that TNM 2.5 tends to over predict measured data by about 0.5 dB while TNM 3.0 tends to under predict measured data by about 0.5 dB. The range of these differences is largely driven by the change in ellipse computations.

When TNM was developed, sub-source corrections were determined in order to project REMELs data at 50 ft on to the sources themselves so that the sound could then be propagated to an arbitrary receiver location. TNM's acoustics were used to compute these corrections. Since the version of TNM that was used to compute these corrections included the ellipse bug, it is possible that these sub-source corrections are not appropriate for the updated ellipse computations. This could explain why TNM 3.0 is predicting about 1 dB lower than TNM 2.5. Further, re-computing these corrections could reduce the observed average errors. It is recommended that the sub-source corrections be recomputed using TNM 3.0 and the datasets in this report be compared again to document any improvements obtained.

Another change to the acoustics involved in computing the highest path points for cases where more than two barriers intervened between source and receivers was not found to produce systematic differences; however, because the effect of this change is confounded with user modeling practices, it may be more significant for some users than others. Although not within the scope of this validation study[12], it should be noted that when modeling sites using TNM 3.0's projection enabled model, the

[12] *All models included in this study used orthogonal projections consistent with TNM 2.5.*

choice of projection can affect the computed results, since site geometries imported using different projections will result in slightly different locations in an orthonormal mapping, which the acoustics assumes. The degree of these differences and best practices for addressing this issue have not been determined. Given these two issues, which may be user dependent, it is recommended that a user methodology study be developed to determine modeling sensitivity to these and other issues and document best practices for issues that do not yet have documented best practices.

Finally, when comparing sites with specific pavements modeled, there was not a systematic improvement in performance. That is, in some cases using the specific pavement reduced the magnitude of average errors, while in other cases the magnitude of the average errors increased. Given the known variation in sound levels of a specific type of pavement, e.g. PCC or DGAC, it is unlikely that a single DGAC or PCC REMELs set will be sufficient to predictably improve predictions. It is recommended that further tools be developed to measure and classify pavements so that more specific pavement classes can be developed. These tools could include: software to compute REMELs and evaluate when sufficient data have been collected for a particular class of pavement; methods to convert from OBSI to REMELs; and methods to identify which pavements should be included in the same class, for example.

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APPENDIX A: MEASUREMENT SITE DESCRIPTIONS

All TNM Validation Phase 1 measurement sites are described here in detail, including site location, microphone positions, and meteorological system positions. This information has been reproduced from Rochat (2002). 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:

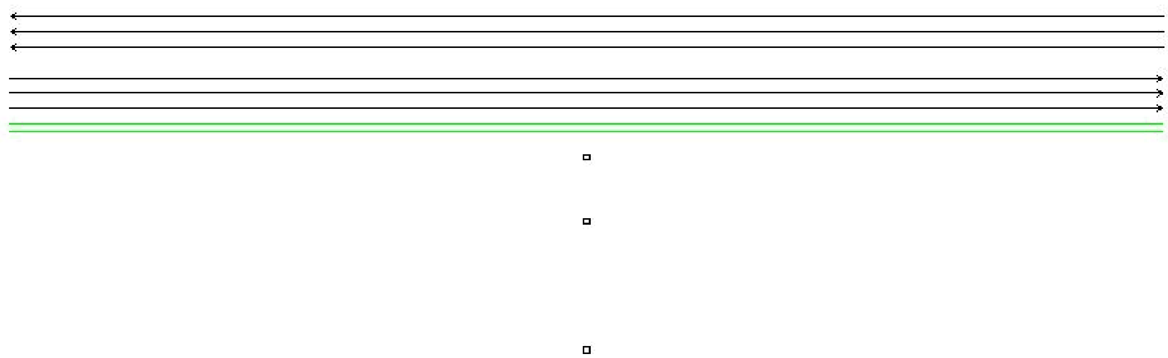
DGAC	Dense-graded asphalt concrete
OGAC	Open-graded asphalt concrete
PCC	Portland cement concrete
d	Distance from roadway
bb	Distance behind barrier

Site ID	**01MA**	
Location	Taunton, MA; Route 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 A.1 - A: Site 01MA Description and Photograph, Source: U.S. DOT, Volpe

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

plan view



skew view

Figure A.1 - B: Site 01MA TNM Model Description, TNM Plan and Skew Views

Site ID	**02MA**	
Location	Acton, MA; Route 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

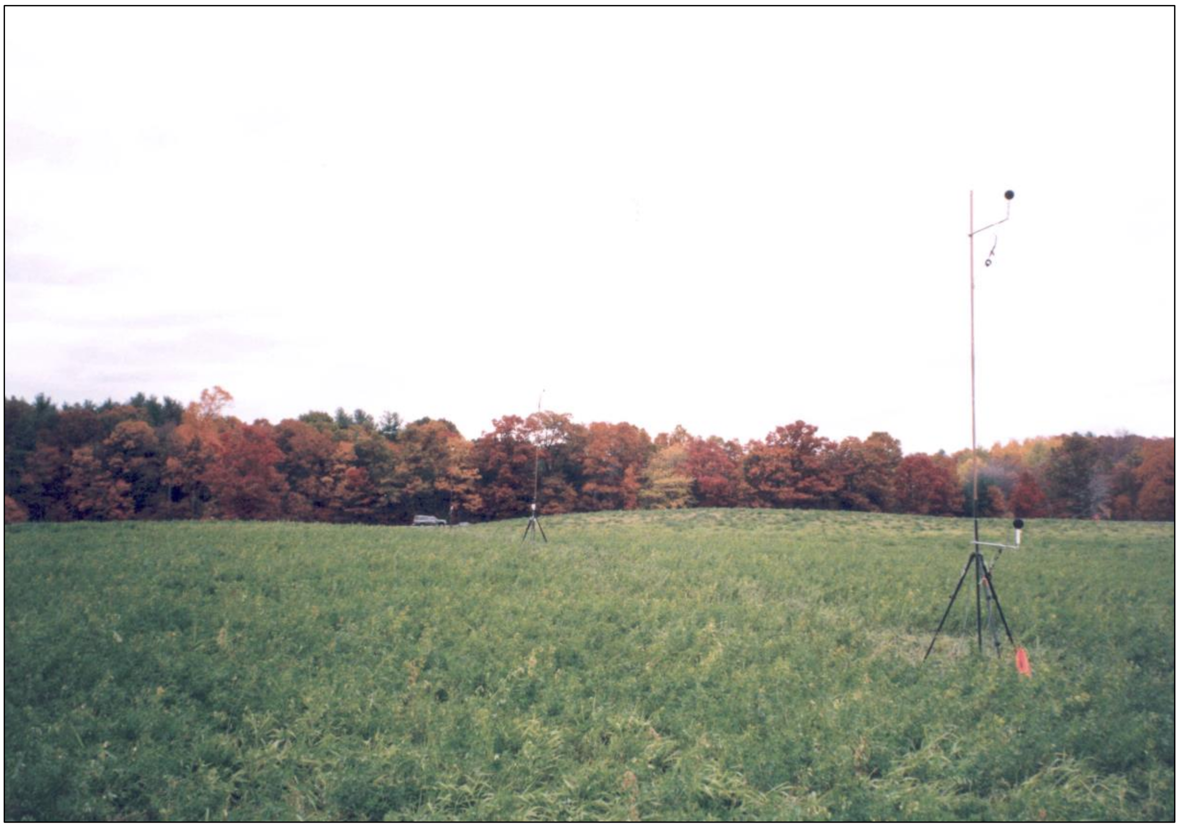
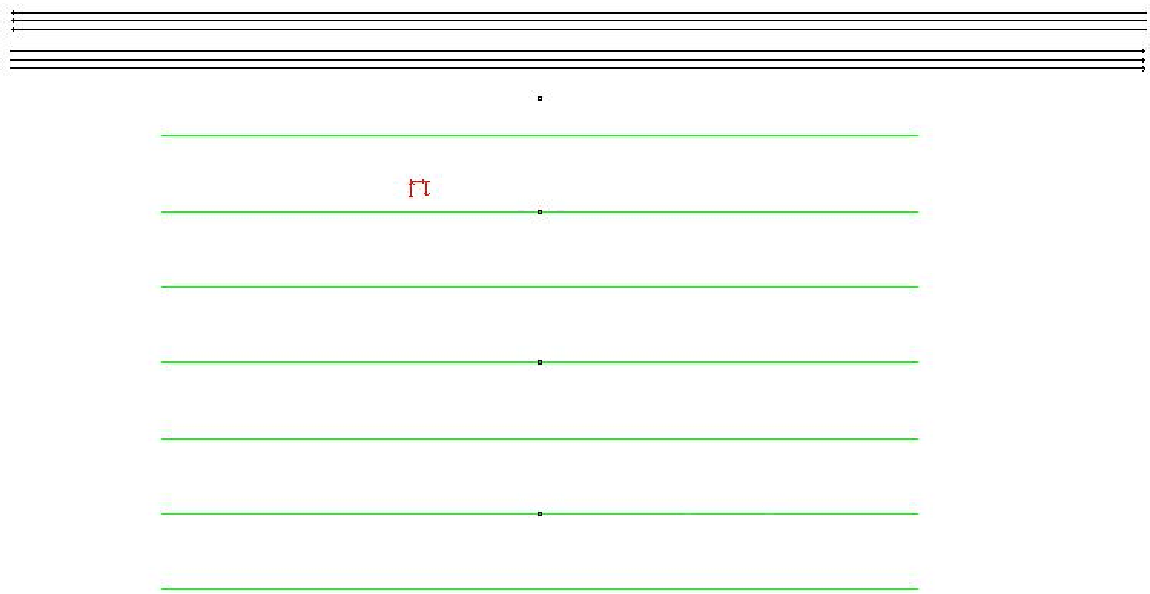


Figure A.2 - A: Site 02MA Description and Photograph, Source: U.S. DOT, Volpe

Site ID	02MA - TNM model
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

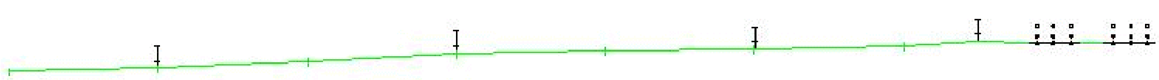


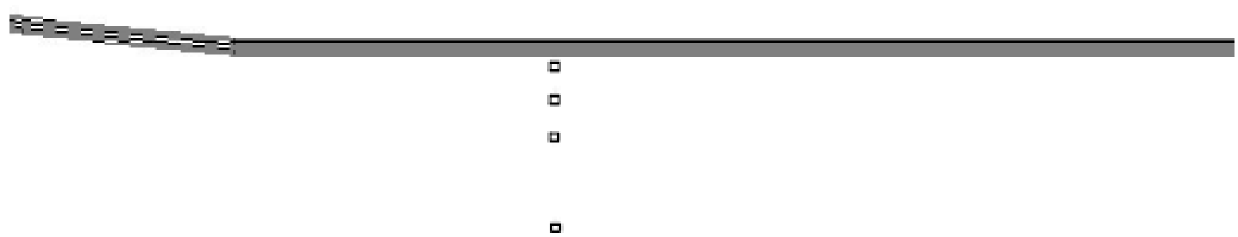
Figure A.2 - B: Site 02MA TNM Model Description, TNM Plan and Skew Views

<table>
<tr><th>Site ID</th><th colspan="2">03MA</th></tr>
<tr><td>Location</td><td colspan="2">Springfield, MA; Route 291; Northbound side; South of Exit 5; Smith & Wesson soccer fields</td></tr>
<tr><td>Site Type</td><td colspan="2">open area, flat</td></tr>
<tr><td>Ground Type</td><td colspan="2">lawn, acoustically soft</td></tr>
<tr><td>Roadway</td><td colspan="2">4 lanes, DGAC, shoulders, hard soil median</td></tr>
<tr><td>Instrumentation Positions</td><td>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</td><td>Meteorological Systems
d = 150 ft, height = 5 and 15 ft
d = 600 ft, height = 5 and 15 ft</td></tr>
</table>

Figure A.3 - A: Site 03MA Description and Photograph, Source: U.S. DOT, Volpe

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

plan view



skew view

Figure A.3 - B: Site 03MA TNM Model Description, TNM Plan and Skew Views

Site ID	**05CA**	
Location	Chino Hills, CA; Route 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 A.5 - A: Site 05CA Description and Photograph, Source: U.S. DOT, Volpe

Site ID	05CA - TNM model
Default Ground Type	field grass
Pavement Type	average
TNM objects	barrier, roadways, receivers

plan view

skew view

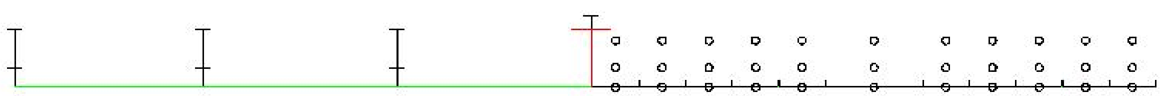


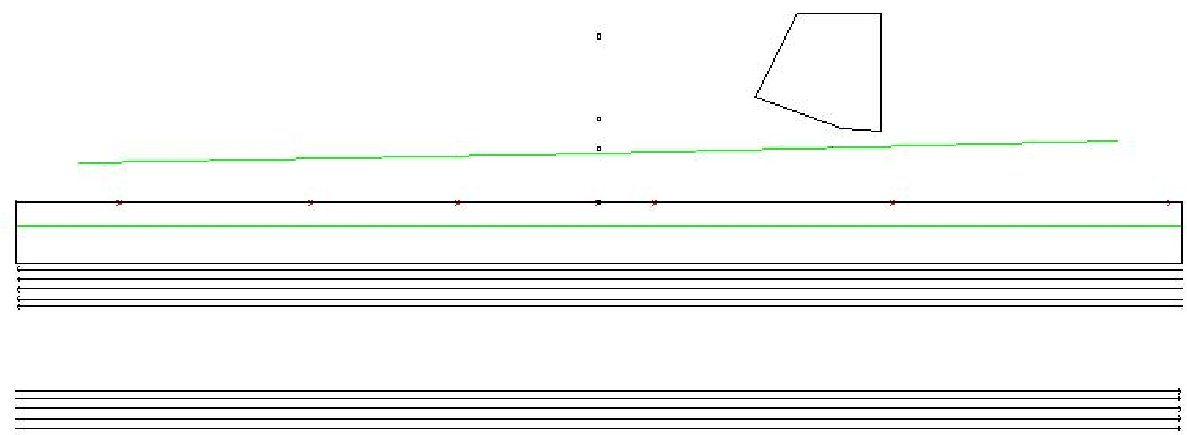
Figure A.5 - B: Site 05CA TNM Model Description, TNM Plan and Skew Views

Site ID	**06CA**	
Location	Wildomar, CA; Route 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 A.6 - A: Site 06CA Description and Photograph, Source: U.S. DOT, Volpe

Site ID	**06CA - TNM model**
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 A.6 - B: Site 06CA TNM Model Description, TNM Plan and Skew Views

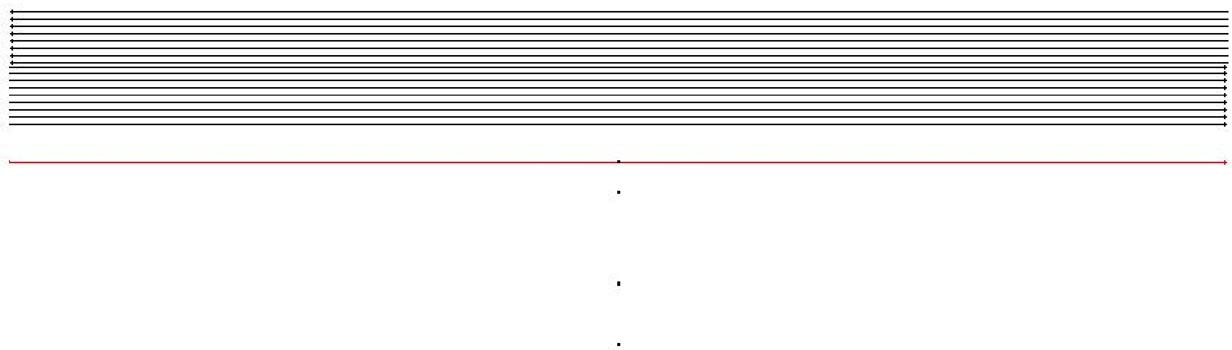
Site ID	**08CA** Measured two microphone lines: one with a single barrier (as shown and described here) and one with parallel barriers (will be analyzed in a later phase of the study)	
Location	Anaheim, CA; Route 91; Eastbound side; East of Lakeview Exit; playing fields of Peralta Canyon Park	
Site Type	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 A.8 - A: Site 08CA Description and Photograph, Source: U.S. DOT, Volpe

Site ID	08CA - TNM model
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

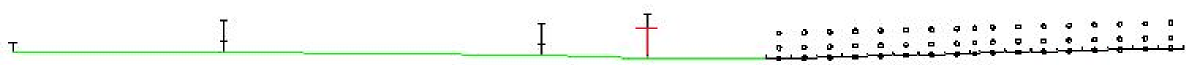


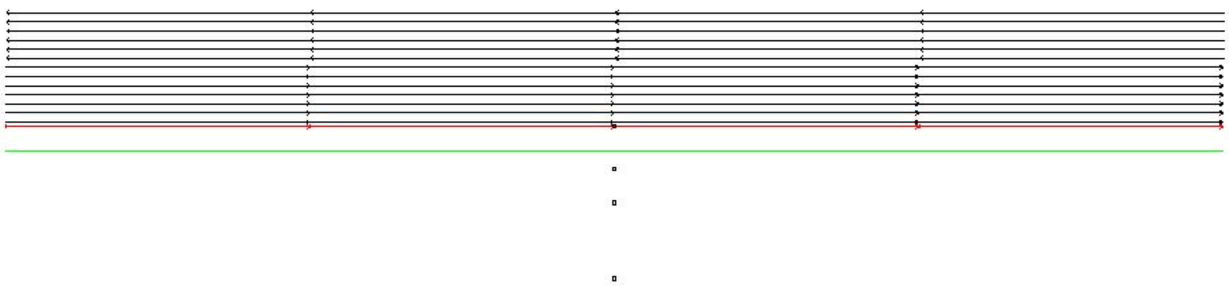
Figure A.8 - B: Site 08CA TNM Model Description, TNM Plan and Skew Views

Site ID	09CA	
Location	Chino, CA; Route 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 A.9 - A: Site 09CA Description and Photograph, Source: U.S. DOT, Volpe

Site ID	09CA - TNM model
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

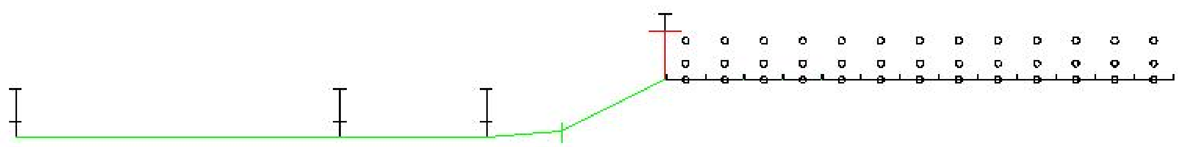


Figure A.9 - B: Site 09CA TNM Model Description, TNM Plan and Skew Views

<table>
<tr><td>Site ID</td><td colspan="2">10CA – berm
Measured two microphone lines: one with a berm (as shown and described here) and one with an open area (shown next).</td></tr>
<tr><td>Location</td><td colspan="2">Mira Loma, CA; Route 15; Southbound side; North of Limonite Ave Exit; field just North of Swan Lake Community</td></tr>
<tr><td>Site Type</td><td colspan="2">barrier (16 ft grass-covered earth berm), flat</td></tr>
<tr><td>Ground Type</td><td colspan="2">plowed dirt, acoustically soft</td></tr>
<tr><td>Roadway</td><td colspan="2">6 lanes, PCC, shoulders, hard soil median</td></tr>
<tr><td>Instrumentation Positions</td><td>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</td><td>Meteorological Systems
bb = 90 ft, height = 5 and 15 ft</td></tr>
</table>

Figure A.10 - A: Site 10CA-berm Description and Photograph, Source: U.S. DOT, Volpe

Site ID	10CA - berm - TNM model
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 A.10 - 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; Route 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 A.10 - C: Site 10CA-open Description and Photograph, Source: U.S. DOT, Volpe

Site ID	**10CA- open - TNM model**
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 A.10 - D: Site 10CA-open TNM Model Description, TNM Plan and Skew Views

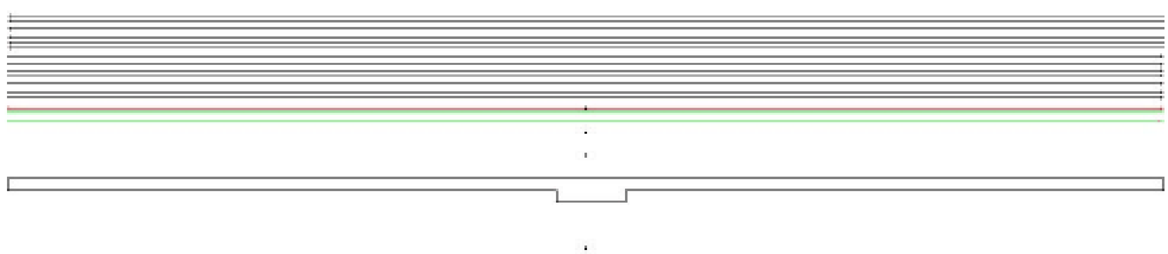
Site ID	**11CA**	
Location	Sunnyvale, CA; Route 237; Westbound side; just East of E. Caribbean Drive Exit; Eastern end of Sunnyvale Baylands County Park	
Site Type	barrier (16 ft wood), relatively flat	
Ground Type	field grass and some pavement, mixed acoustically soft and hard	
Roadway	3 lanes + 2 auxiliary 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 A.11 - A: Site 11CA Description and Photograph, Source: U.S. DOT, Volpe

Site ID	**11CA - TNM model**
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

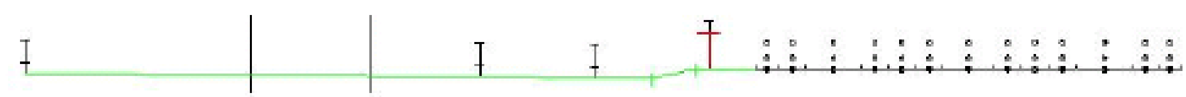


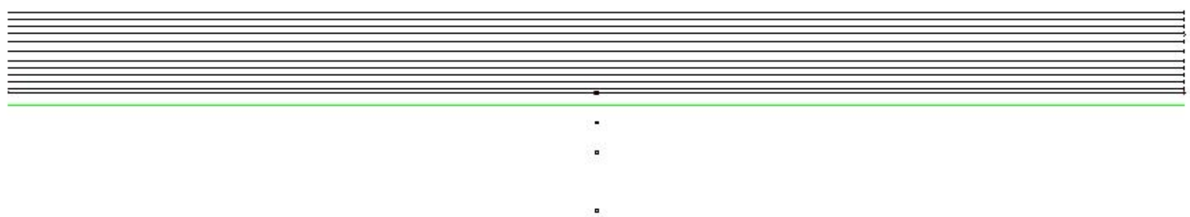
Figure A.11 - B: Site 11CA TNM Model Description, TNM Plan and Skew Views

Site ID	**12CA**	
Location	San Ramon, CA; Route 680; Northbound side; South of Bollinger Canyon Exit; Athan Downs Sports Fields (Northern most field)	
Site Type	barrier (12 ft concrete block), flat, with 6 ft drop-off from barrier	
Ground Type	lawn, acoustically soft	
Roadway	8 lanes, PCC, shoulders, pavement median	
Instrumentation Positions	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	Meteorological Systems bb = 75 ft, height = 5 and 15 ft bb = 150 ft, height = 5 and 15 ft

Figure A.12 - C: Site 12CA Description and Photograph, Source: U.S. DOT, Volpe

Site ID	12CA - TNM model
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

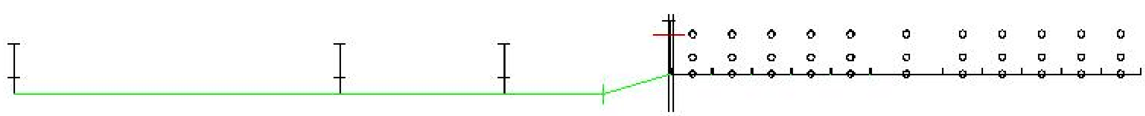


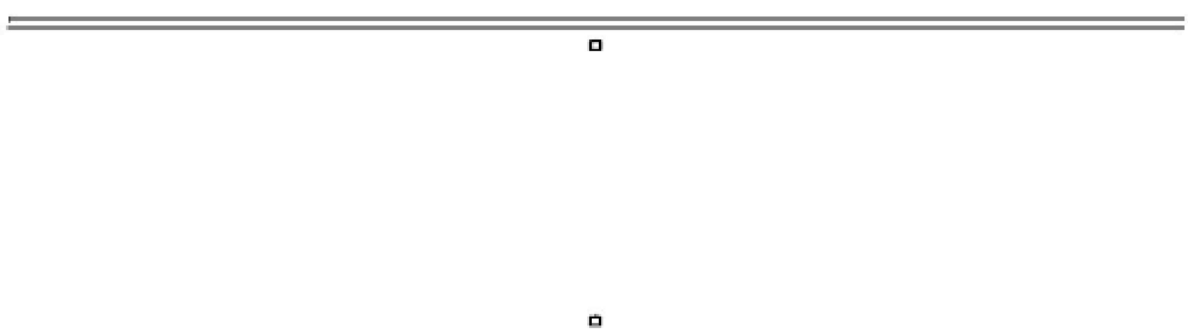
Figure A.12 - A: Site 12CA TNM Model Description, TNM Plan and Skew Views

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

Figure A.13 - A: Site 13CA Description and Photograph, Source: U.S. DOT, Volpe

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

plan view



skew view

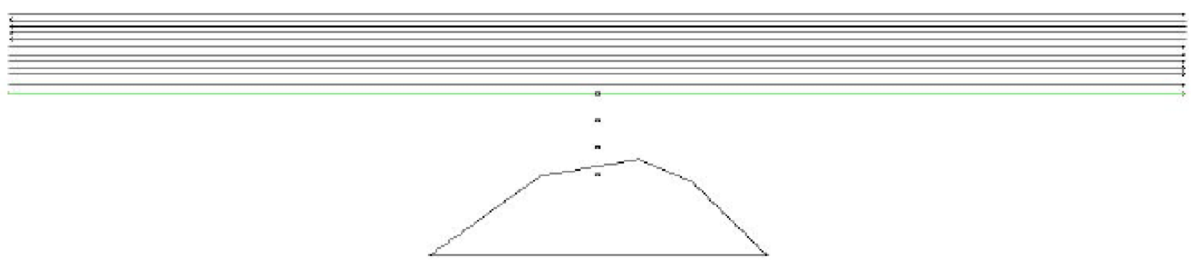
Figure A.13 - B: Site 13CA TNM Model Description, TNM Plan and Skew Views

Site ID	**14CA**	
Location	Fremont, CA; Route 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 A.14 - A: Site 14CA Description and Photograph Source: U.S. DOT, Volpe

Site ID	14CA - TNM model
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

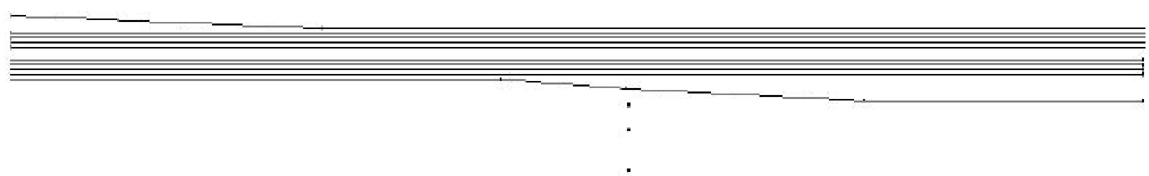
Figure A.14 - B: Site 14CA TNM Model Description, TNM Plan and Skew Views

Site ID	**15CA**	
Location	Oakland, CA; Route 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 A.15 - A: Site 15CA Description and Photograph, Source: U.S. DOT, Volpe

Site ID	15CA - TNM model
Default Ground Type	pavement
Pavement Type	average
TNM objects	roadways, receivers

plan view



skew view

Figure A.15 - B: Site 15CA TNM Model Description, TNM Plan and Skew Views

Site ID	16MA	
Location	Wayland, MA; Route 90; Eastbound side; East of Natick Exit (13); Cochituate State Park, farthest parking lot East of boat launch (adjacent to Route 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

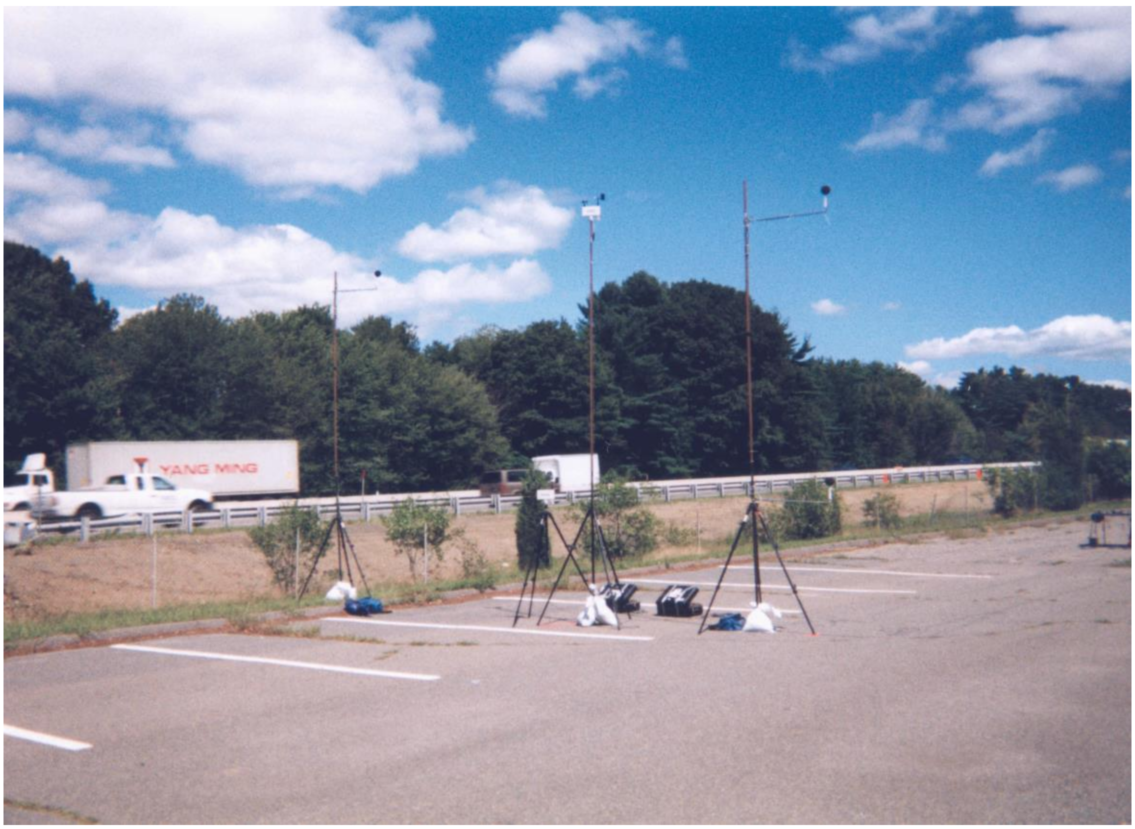
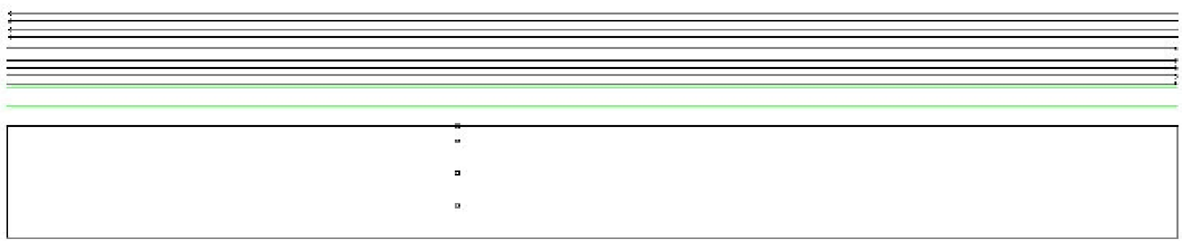


Figure A.16 - A: Site 16MA Description and Photograph, Source: U.S. DOT, Volpe

Site ID	**16MA - TNM model**
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

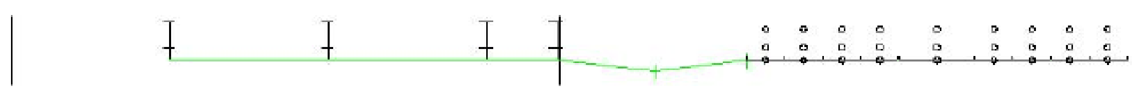


Figure A.16 - B: Site 16MA TNM Model Description, TNM Plan and Skew Views

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

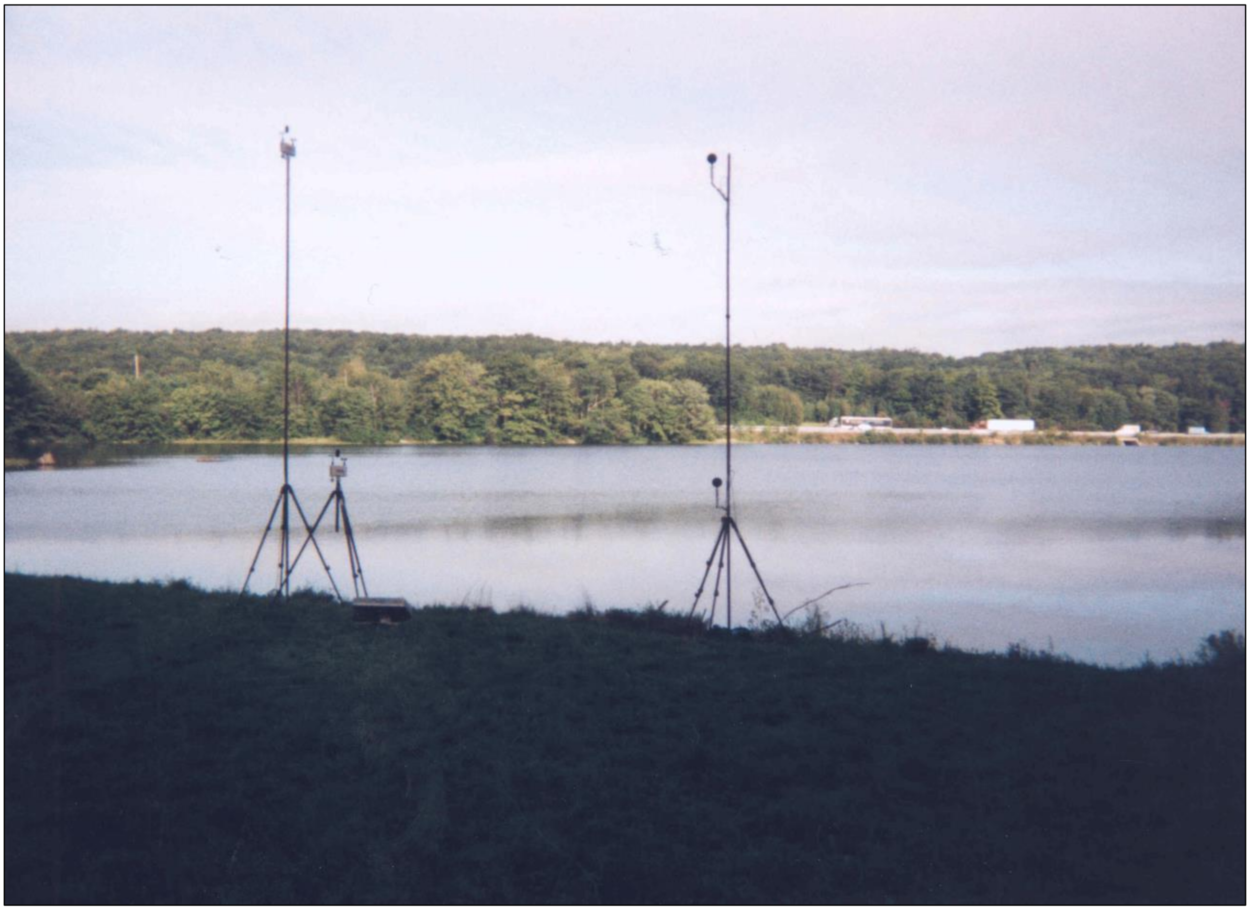


Figure A.17 - A: Site 17CT Description and Photograph, Source: U.S. DOT, Volpe

Site ID	**17CT - TNM model**
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 A.17 - B: Site 17CT TNM Model Description, TNM Plan and Skew Views

Appendix B: Measurement Instrumentation

This section discusses the instrumentation used for acoustics, meteorology, traffic analysis, and site surveys, as well as auxiliary instrumentation used in the study. For more detailed technical information, please refer to Rochat 2002[13].

B.1 Microphone System

The microphone system, shown in Figure B - 1, consists of four main components: the microphone, preamplifier, power supply and windscreen. For these measurements, ½-inch diameter pressure-response electret condenser microphones were used (Brüel and Kjær (B&K) Models 4155 and 4189). Pre-polarized, these microphones are closed off to humidity, effectively eliminating the potential for condensation. The preamplifier and power supply models were B&K Model 2671 and Model WB 1372, respectively. A B&K Model 237 foam windscreen, 3.5 inch in diameter placed on top of each microphone, served to reduce wind-effects at the microphone diaphragm and improve the signal-to-noise ratio of sound measurements.

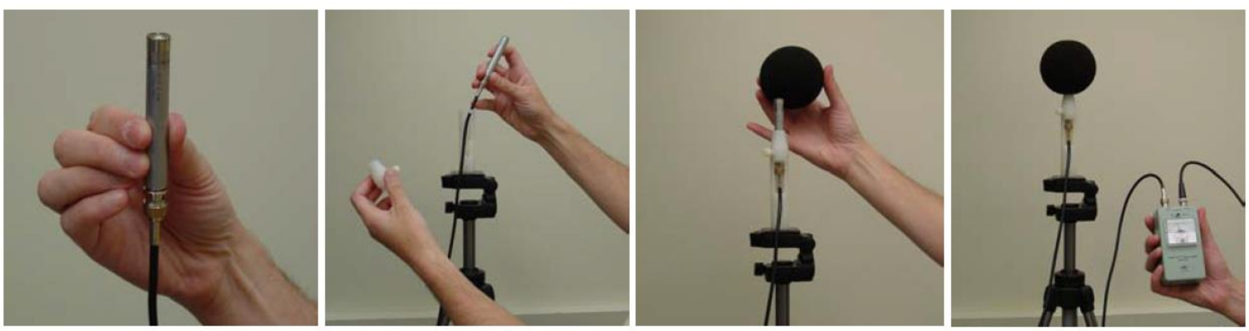


Figure B - 1: Microphone System, Source: U.S. DOT, Volpe

B.2 Spectrum Analyzer

Using four, two-channel, one-third octave-band Larson Davis Laboratories (LDL) Model 2900 spectrum analyzers can accommodate eight microphone systems set up at the acoustic observer's station. Each channel was configured to continuously measure the A-weighted equivalent sound level and its associated one-third octave-band spectrum, averaged over 5-second intervals. Multiple 5-second averaging periods were combined later in post-processing to obtain noise levels over longer time periods. The LDL 2900 is capable of storing up to 36 hours of data in this configuration. Data was periodically transferred to disk for post-processing and data analysis.

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[13] At the time of the measurements, these instruments were state of the art. We continue to use this historical dataset because it provides a method to compare performance consistent with the original validation effort. Current and future measurements involve new instrumentation that allows more efficient collection of data.

Sound Level Meter and Digital Auto Tape (DAT) Recorder

As an auxiliary system to the microphone and spectrum analyzer system, an LDL sound level meter, Model 820 in conjunction with a Sony Model TCD-D100 digital audio tape (DAT) recorder could be set up at a measurement site to obtain supplementary noise information. Like the spectrum analyzer, the sound level meter continuously measured the overall A-weighted equivalent sound levels that were averaged over 5-seconds. After measurements were completed, data were transferred to a laptop computer. The DAT recorder could continuously record up to 4 hours of data in "LP" (half-speed) mode. Each measurement day, then, required multiple tapes that would be post-processed with the spectrum analyzer to obtain one-third octave-band data.

B.3 Incident Noise Log

Throughout any measurement day, it was possible to have incident non-traffic noise sources that contaminated the data (e.g. airplanes flying overhead, lawn mowers, sirens). In order to remove the contaminated data and ensure acoustically clean data, an incident noise log was utilized. The noise log consisted of a macro-enabled spreadsheet on a palmtop computer, which allowed for a user to log a start and stop time as well as the description of any incident noise sources that could intrude on the highway traffic noise measurements. This log would be used later in analysis to remove affected data, discussed in more detail in Section 5.

B.4 Meteorological Instrumentation

Collecting meteorological measurements provides a full accounting of the conditions for the acoustic measurements and was taken with the intent of incorporating meteorological effects into future versions of TNM. When possible, four Qualimetrics Transportable Automated Meteorological Stations (TAMS) were set up at each measurement site to measure temperature, relative humidity, wind speed and direction, and ambient atmospheric pressure with a sampling period of 1-second. These data were captured on a palmtop computer and files were saved every two hours. At the end of each measurement day, the meteorological data were transferred to a laptop computer.

B.5 Traffic Analysis Instrumentation

As it was necessary to analyze traffic for determination of noise levels emitted by different vehicles, video cameras were employed to record traffic information. When available, the video camera systems were stationed on an overpass, positioned such that each camera captured traffic for up to three single-direction lanes. For highways without an overpass, cameras were positioned as high as possible along the side. The video tapes provide up to two hours of recording time on standard play, requiring the use of multiple tapes in a measurement day.

To extract the traffic data, either a manual analysis method or an automated analysis method was applied. The manual analysis involved using fixed reference points of known spacing to determine speeds of vehicles captured by video. This was the only method available for highways that had to rely on video cameras positioned along the side of the road, rather than above on an overpass. The automated analysis consisted of utilizing an Autoscope Model 2004 automated traffic detection system, which detects vehicle speeds when a user inputs fixed reference points of known spacing and the height of the cameras above the roadway.

B.6 Site Survey Instrumentation

Coordinates of all important site features – microphone positions, roadways, zones of different ground types, and significant ground undulations – were measured through the use of a differential global positioning system (dGPS). The dGPS system provides a relative, three-dimensional position accuracy of 8 in (20 cm) using a base station and a roving unit.

B.7 Other Instrumentation

The acoustical instrumentation was calibrated in the field by a calibration instrumentation system composed of a B&K Model 4231 sound calibrator for absolute level calibration, an Ivie IE-20 B pink noise generator for relative frequency response calibration, and a ½-inch microphone simulator to evaluate the instrumentation noise floor and for onsite troubleshooting of electromagnetic interference or other instrumentation problems.

For technical and safety purposes throughout the measurement process, personnel communicated through the use of hand-held transceivers.

A single digital watch served as the master clock for time synchronization of all instrumentation.

Appendix C: Measurement Field Procedures

Although placement of the acoustical and meteorological instrumentation was site-dependent due to varying terrain features and accessibility, the measurement procedure remained the same among all the sites, as outlined below. All data were collected and analyzed in general conformance with ANSI standards [ANSI 1995 and 1998] and FHWA's procedures [Lee 1996].

C.1 Surveying Measurement Sites

Each measurement site was surveyed in order to provide detailed three-dimensional position information for all relevant site features. Differential GPS measurements were taken prior to acoustical measurements and, in many cases, aided in the proper location and placement of the microphone and meteorological systems. 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, measure lines along any noise barriers and measure lines along any significant ground undulations. On average, it took 4 hours to complete a survey at a measurement site.

C.2 Measurement System Setup

Measurement teams usually consisted of three or four personnel who operated the acoustical and meteorological instrumentation and one or two individuals who operated the highway traffic analysis instrumentation.

For the acoustic measurements, microphones were placed in a line perpendicular to the roadway at various distances, measured from the center of the near travel lane for open areas and from the center of the noise barrier for barrier sites. Where possible, microphones were placed at 50 ft (15 m), 200 ft (60 m) and at the farthest distance possible. On occasion, microphones were also placed in between these locations. Meteorological systems were stationed along this microphone line between the two closest microphones and between the two farthest microphone stations. Figure C - 1 shows an example of the acoustical and meteorological instrumentations arrangements for an open area site plan view while Figure C - 2 and Figure C - 3 show the profiles for an open area site and a barrier site, respectively.

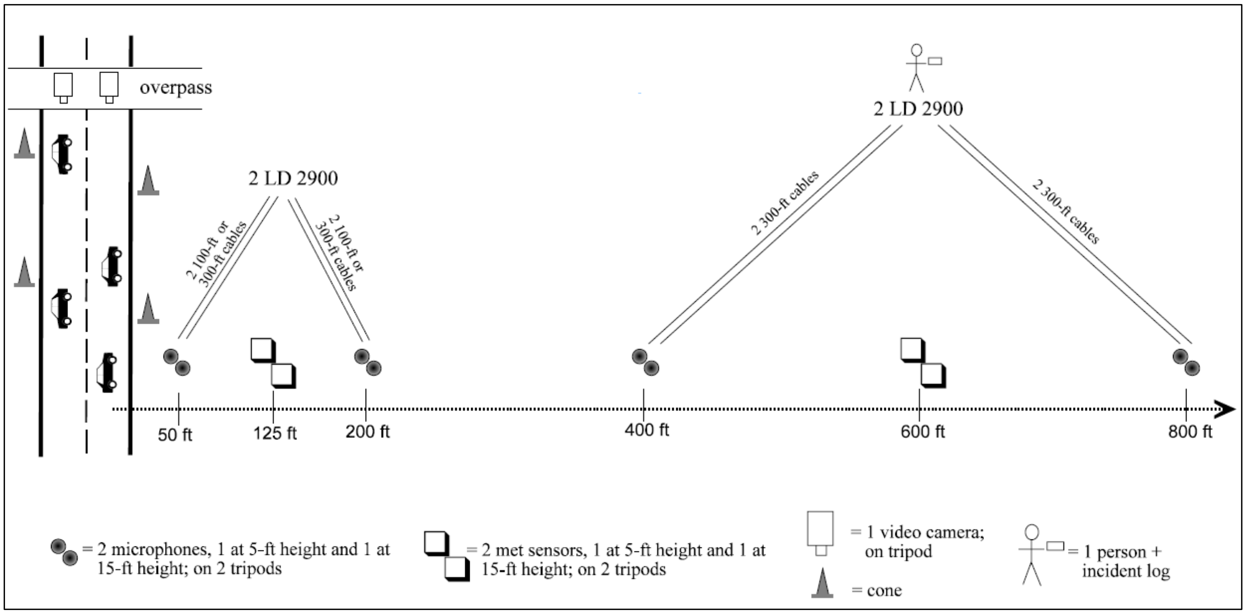

Figure C - 1: Example Instrumentation Setup for Open Area Site; Plan View

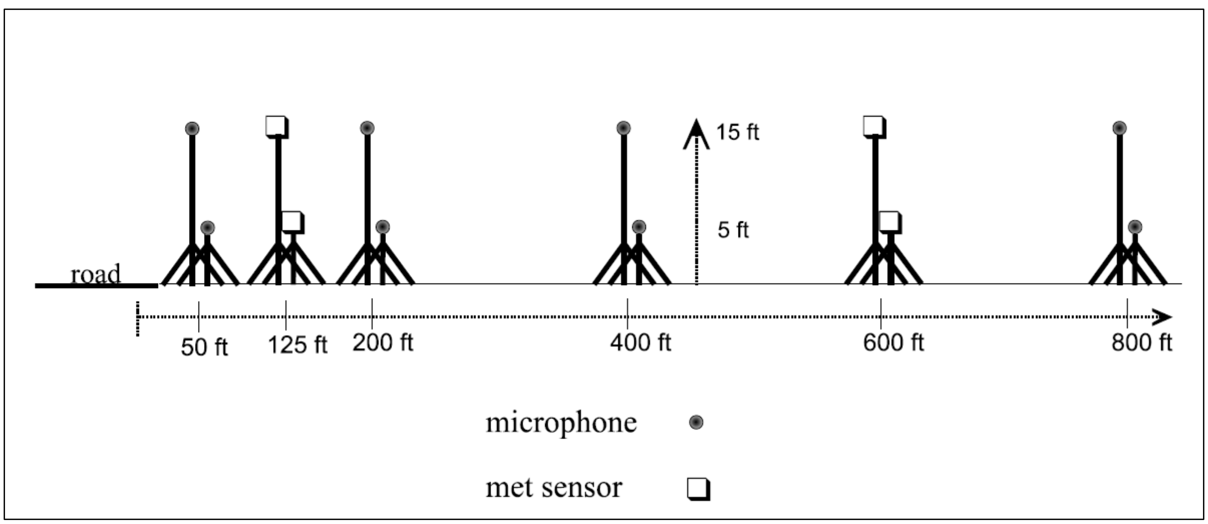

Figure C - 2: Example Instrumentation Setup for Open Area Site; Profile

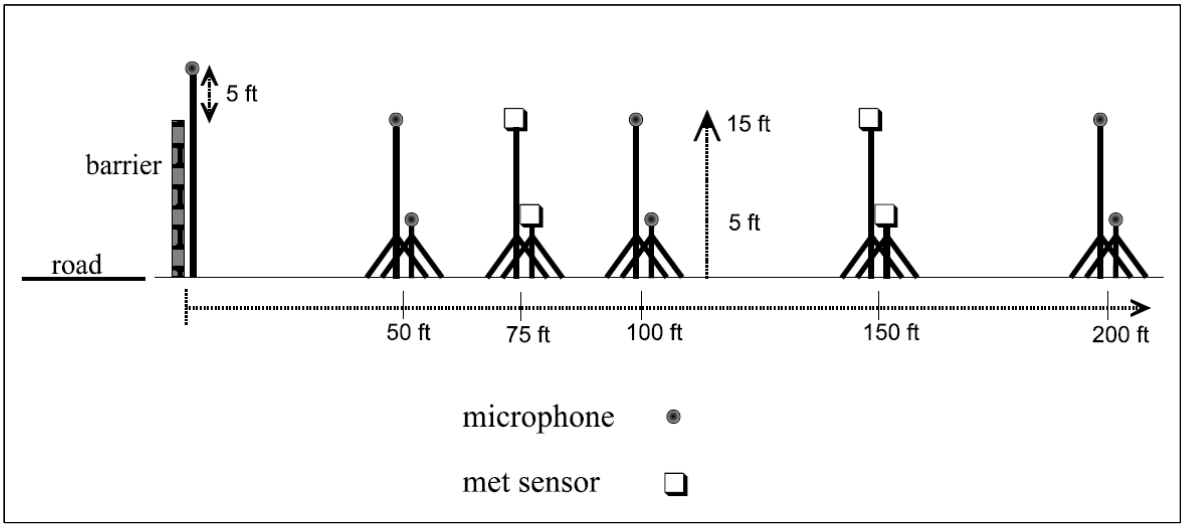

Figure C - 3: Example Instrumentation Setup for Barrier Site; Profile

The procedure for the setup of the measurement systems is as follows:

1. Microphone positions were planned and laid out according to the site terrain and accessibility limitations. If possible, rebar was driven into the ground at each location to aid in securing tripods and masts.
2. The microphone systems were assembled and attached to a tripod or a tripod and mast system at each specified location. Mast arms were adjusted appropriately to give desired height above the local ground surface. Microphones were oriented for grazing incidence along the expected line-of-sight to the highway traffic. Typically, two microphones were stationed at each distance, at heights of 5 and 15 ft (1.5 and 4.5 m) above the ground. However, if site logistics prevented situating two microphones, only one microphone was placed at the 5-ft height. For the open area sites, the microphone placed at the 50-ft (50 m) distance, or as near to that distance as possible, was designated the reference microphone. For barrier sites, a microphone located 5 ft (1.5 m) above the top of the barrier served as the reference microphone. At 10CA-berm with an open area beyond the end of the barrier subject to identical traffic conditions as the barrier, the reference microphone was placed near the end of the barrier at a height of 5 ft.
3. The spectrum analyzers and, where applicable, the sound level meters and DATs, as well as acoustic observers were positioned in full view of all of the microphones but at a distance of 100 ft (300 m) or more in order to eliminate the potential for data contamination due to observer activity.
4. Meteorological instrumentation was placed at locations between the microphone locations, at a sufficient distance from the microphone to provide representative meteorological conditions at the nearby microphone but far enough away from the microphones so that personnel could make periodic checks on the meteorological instrumentation functions and power without affecting acoustical measurements. For each meteorological station, meteorological sensors were placed at heights of 5 and 15 ft (1.5 and 4.5 m) above the local ground surface.
5. Cables were run between the instrumentation at the microphones and the spectrum analyzer at the observer location and all instrumentation was powered up.

6. The clocks of all instrumentation were synchronized.
7. A preliminary sound level calibration was performed to ensure that all equipment was working properly.
8. Thirty seconds of pink noise from a generator inserted at the preamplifier input were measured and stored to determine the frequency response characteristics of the acoustical measurement system.
9. The electronic noise floor of the entire system sans microphone was established using a non-transducive capacitive load, or a microphone simulator in place of the microphone.
10. The microphone was re-installed and a pre-measurement sound level calibration was performed.
11. The windscreen was attached to the microphone system and the preamplifier cable was secured to the mast and a leg of the tripod to prevent vibrations and audible interference. The measurement masts were positioned and the tripods and masts were secured to the rebar anchors, when available. In places were rebar was not practical, sand bags were attached to ensure stability of the mast and tripod. Figure C - 4 shows the microphone and meteorological system line at one of the measurement sites.
12. Video cameras were situated either on overpasses, on highway pedestrian bridges or along the side of the highway at the highest point possible. These cameras were adjusted so that the video could capture a clear image of the desired traffic lanes. Fixed reference points with known spacing were identified in the camera's viewing window. In the absence of fixed reference points, orange traffic cones were place in the shoulders of the roadway in the camera's field of view to serve as reference points.
13. Meteorological data collection was initiated.
14. The acoustical measurements instrumentation, including any supplementary sound level meters and DAT recorders were initiated.
15. Continuous video recordings were initiated.

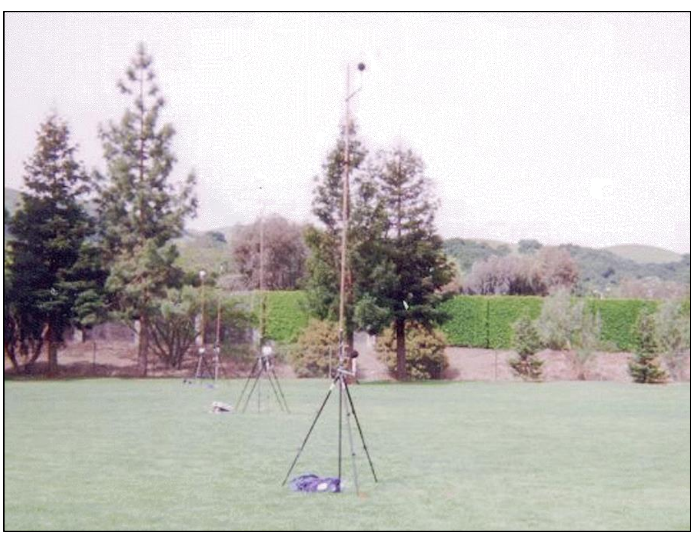

Figure C - 4: Line of Microphones and Meteorological Systems at Site 12CA, Source: U.S. DOT, Volpe

C.3 Measurements

All instrumentation operated continuously in two-hour time intervals; for most sites, six hours of data were taken. Throughout the data acquisition process, the main duties of field personnel included documenting any extraordinary acoustical occurrences near the measurement microphones or the roadway that could contaminate the noise measurements. The incident noise log previously described was used to document these interruptions. Additionally, acoustical system logs and general site logs were taken, outlining the locations of all instrumentation and instrumentation settings for calibration and data collection.

Throughout the measurement process, periodic checks were performed to monitor battery power on all devices, internal memory remaining on the spectrum analyzer, and time available on the DAT recorders and video cameras. Batteries on all devices (except for the DAT recorder) provided at least 12 hours of operation time. Although the spectrum analyzer can store up to 36 hours of averaged 5-second samples, a new file was initiated every two hours to facilitate transfer and data storage. DATs, capable of holding up to 4 hours of data, were replaced once during every six hours of measurement. For data integrity and organization, video and new files for the meteorological systems were initiated every two hours.

C.4 Measurement System Dismantling

After data acquisition, the following steps were taken:

1. A post-measurement sound level calibration was performed of the entire acoustical system and any drift from the previous calibration was documented.
2. All instrumentation was powered down and the entire system was disconnected and stored.

For data reduction and analysis, the stored sound level data from the spectrum analyzers and sound level meters were transferred to a laptop computer and the LDL binary files were converted to comma-delimited ASCII text files. The meteorological data were also saved in a comma-delimited ASCII text file. Backup of all data was completed daily.

APPENDIX D: MEASUREMENT DATA POST-PROCESSING

This information has been reproduced from Rochat (2002). The acoustical data, meteorological data, and incident log data were merged into a spreadsheet file using an in-house program called tnmval.exe. In addition to the three data files, an input file with meta data is also required to run tnmval.exe. A 5-minute averaging period was used for the data output. In addition to sound pressure level, average wind speed and direction, and average temperature, 4 different qualifiers were attached to each data block in the output:

1. An indication of the quality of the data according to incident noise
    a. GOOD – for no incident noise during the 5-minute block
    b. INCIDENT NOISE – for a block that experienced incident noise, but the noise was found to be nonintrusive
    c. 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
    a. CALM – for speeds never exceeding ~2 mph (1 m/s)
    b. 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)
    c. VERY WINDY – for winds exceeding ~11 mph (5 m/s) any time during the block
4. An indication of the wind direction along the axis perpendicular to the highway
    a. CALM – if the perpendicular wind component never exceeded ~2 mph (1 m/s)
    b. 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
    c. 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 blocks provided a short enough time interval to expose contamination and to adequately represent the wind conditions. All data blocks that had any contamination due to BAD incident noise, were overloaded, or had VERY WINDY conditions were discarded.

The site survey data were processed in order to obtain a three-dimensional map of a measurement site. Key features in the dGPS files were identified and extracted. Video traffic data were analyzed in 5-minute blocks that coincided with the 5-minute acoustic data blocks. Traffic counts, vehicle categories, volumes and speeds were determined for each lane. These data were then used to build the site models that would correspond to each 5-minute block of measured acoustic data.

Appendix E: Instrumentation System Reference

E.1 Instrumentation List

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

Spectrum Analyzer (LDL 2900):

- LDL Model 2900 Spectrum Analyzer

Sound Level Meter (LDL 820):

- LDL Model 820 Sound Level Meter

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

E.2 Configuration

LDL Model 2900 Spectrum Analyzer:

- 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.
- 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}.

LDL Model 820 Sound Level Meter:

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

SONY Model TCD-D100 DAT Recorder:

- 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.
- 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.

E.3 Operation

Set-up:

- 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.
- Interconnect equipment per Figures C.1, C.2, and C.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.
- Check instrument settings.

Calibration:

- Remove foam windscreen from microphone.
- Carefully apply calibrator to microphone.
- Carefully apply power to calibrator (114 dB setting).
- Wait ten seconds for system to stabilize.
- Perform calibration of LDL Model 2900.
- 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.
- After recording the calibration signal, turn off the calibrator and remove it from the microphone.
- Remove the microphone from the B&K Model 2671 Deltatron preamplifier.
- Attach the Ivie IE-20B Pink Noise Generator to the B&K Model 2671.
- Capture and record 30 seconds of the pink noise.
- Remove the Ivie IE-20B Pink Noise Generator from the B&K Model 2671.
- Attach the ½-in microphone simulator to the B&K Model 2671.
- Capture and record 30 seconds of microphone simulator floor.
- Remove the microphone simulator, and re-install the microphone.

- Attach the calibrator to the microphone.
- Apply power to calibrator (114 dB setting).
- Wait ten seconds for calibrator signal to stabilize.
- Check calibration level of the LDL Model 2900.
- Check calibration level of the LDL 820 SLM and record the calibration signal on the DAT recorder for a minimum of 30 seconds.
- After recording the calibration signal, turn off the calibrator and remove it from the microphone. Attach the foam windscreen.
- The acoustical system is ready for initiation of measurements.

E.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

E.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

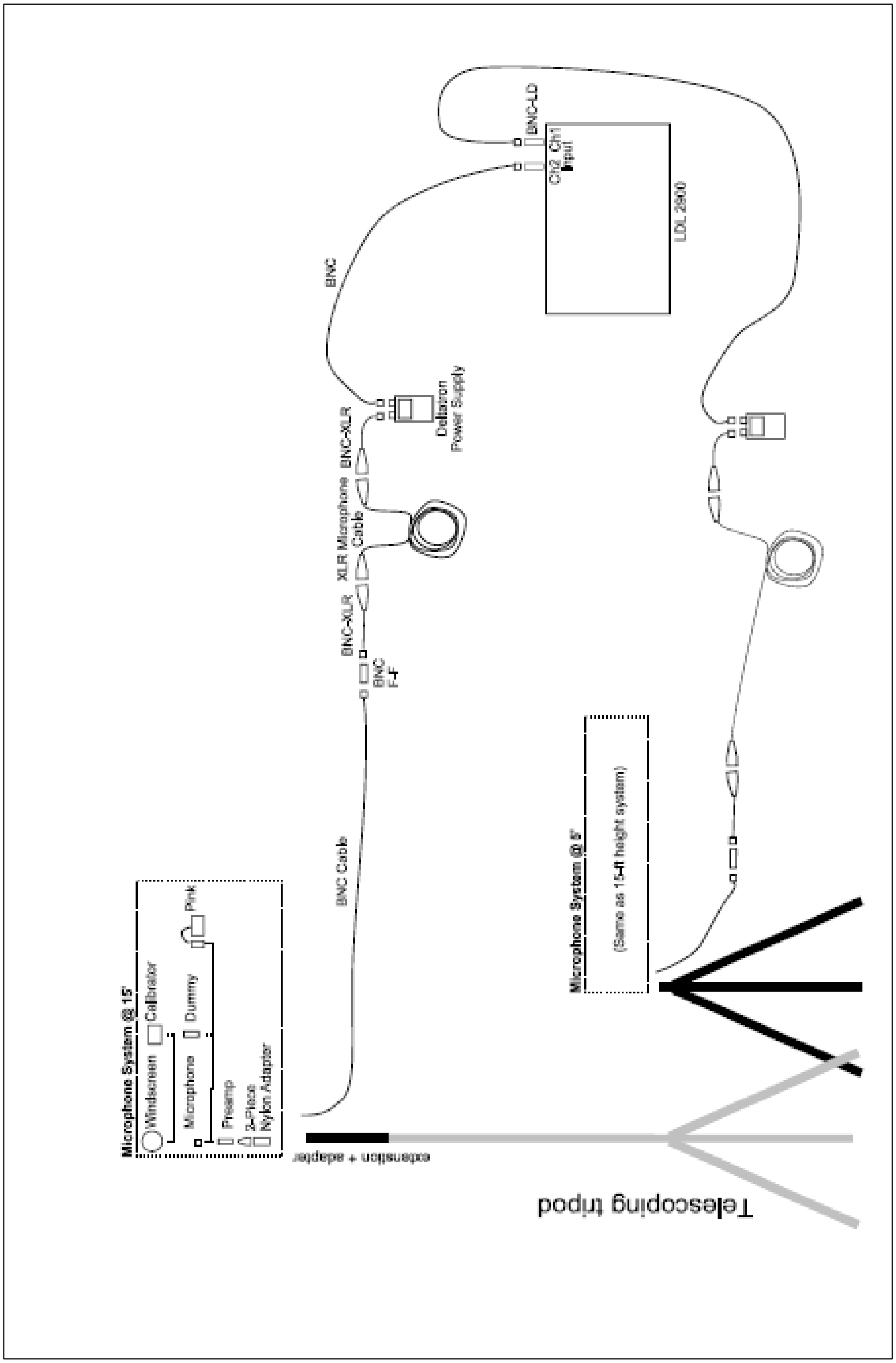

Figure E - 1: Instrumentation Diagram for LDL2900 System

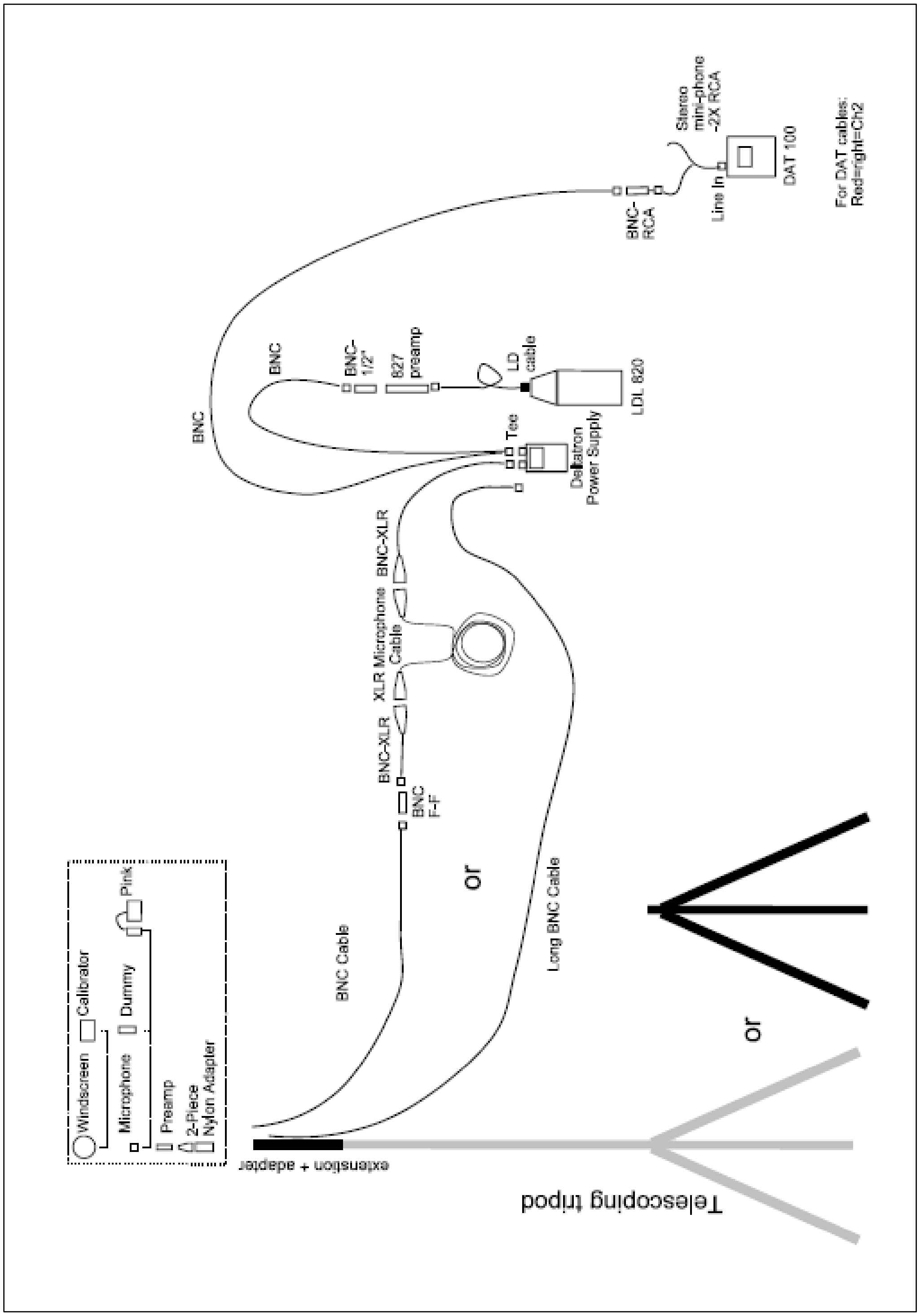

Figure E - 2: Instrumentation Diagram for LDL 820 and Sony TCD-D100 System

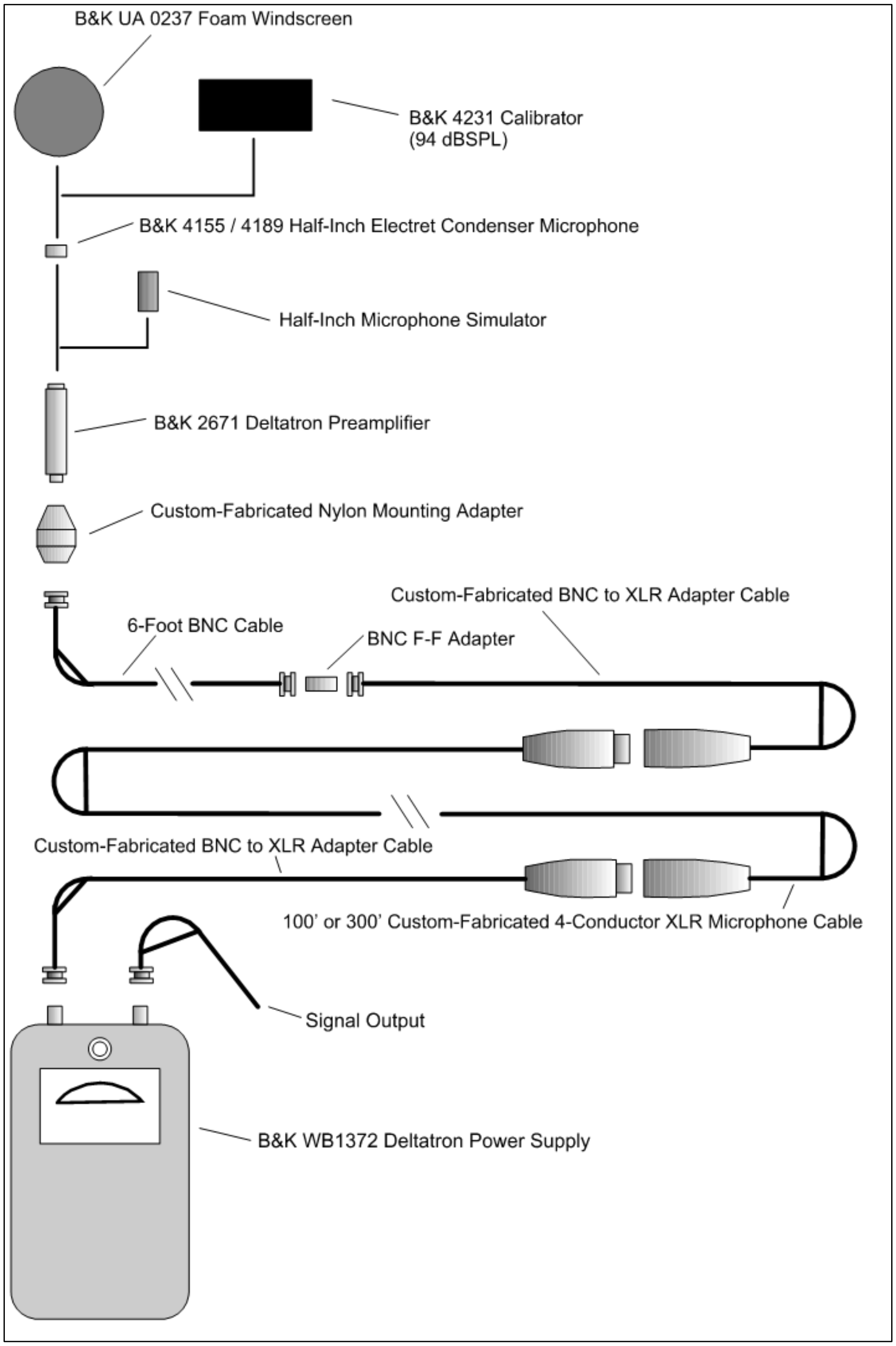

Figure E - 3: B&K Deltatron Microphone System

APPENDIX F: 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?)				

<table>
<tr><th colspan="9">Other Considerations</th></tr>
<tr><td rowspan="2">Max Receiver Distance from Centerline of Near Lane (ft)</td><td rowspan="2">Overpass for Video Camera</td><td colspan="3">Ground Undulations (ft)</td><td colspan="2">Nearby Vegetation or Other Ground Zones</td><td colspan="2">Nearby Structures</td></tr>
<tr><td>Min</td><td>Max</td><td>Avg</td><td>Description</td><td>Distance (ft)</td><td>Description</td><td>Distance (ft)</td></tr>
<tr><td></td><td rowspan="2">Yes / No</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>measured (preferred) or estimated</td></tr>
</table>

<table>
<tr><th colspan="4">Site Ownership/Approval</th></tr>
<tr><td colspan="2">State/Public Property</td><td colspan="2">Private Property</td></tr>
<tr><td>Approval</td><td>Contact Information</td><td>Approval</td><td>Contact Information</td></tr>
<tr><td>Yes / No</td><td></td><td>Yes / No</td><td></td></tr>
</table>

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

Other Comments/Observations:

Figure F - 1: Blank Site Checklist

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 F - 2: LDL 2900 Spectrum Analyzer System Log

Traffic Noise Model Validation Study

Alternate 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):

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

Figure F - 3: LDL 820 Sound Level Meter and Sony TCD-D100 DAT Recorder System Log

Traffic Noise Model Validation Study - GENERAL SITE LOG

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

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

Figure F - 4: General Site Log

APPENDIX G: COMPARISON OF MODELED RESULTS FOR TNM 2.5, 2.6, AND 3.0

G.1 TNM 2.5 AND TNM 3.0

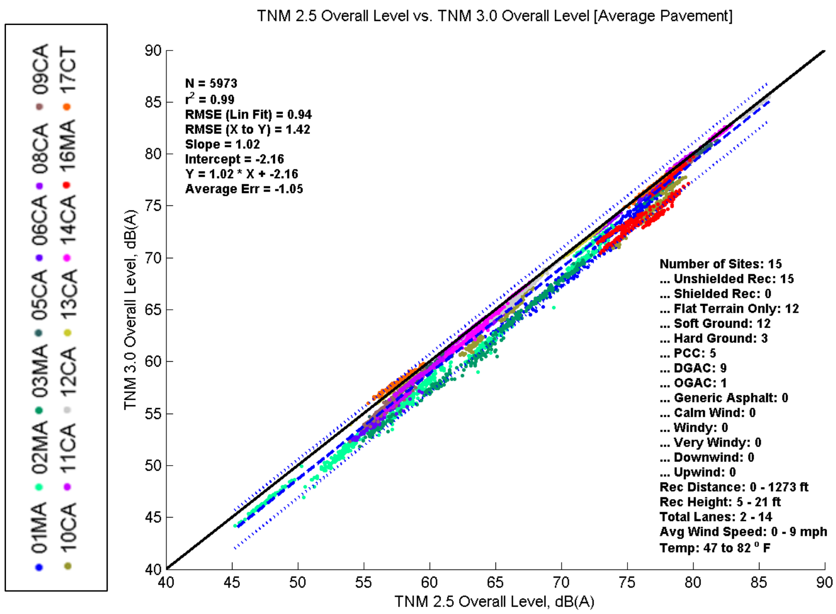

Figure G - 1: TNM 2.5 Predictions vs. TNM 3.0 Predictions using Average Pavement – All Data

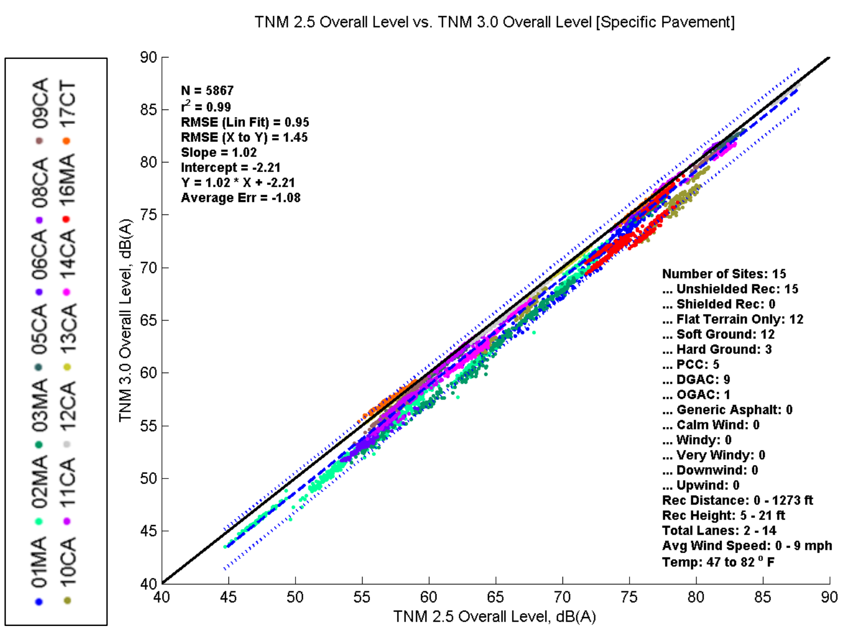

Figure G - 2: TNM 2.5 Predictions vs. TNM 3.0 Predictions using Specific Pavement – All Data

G.2 TNM 2.6 AND 3.0

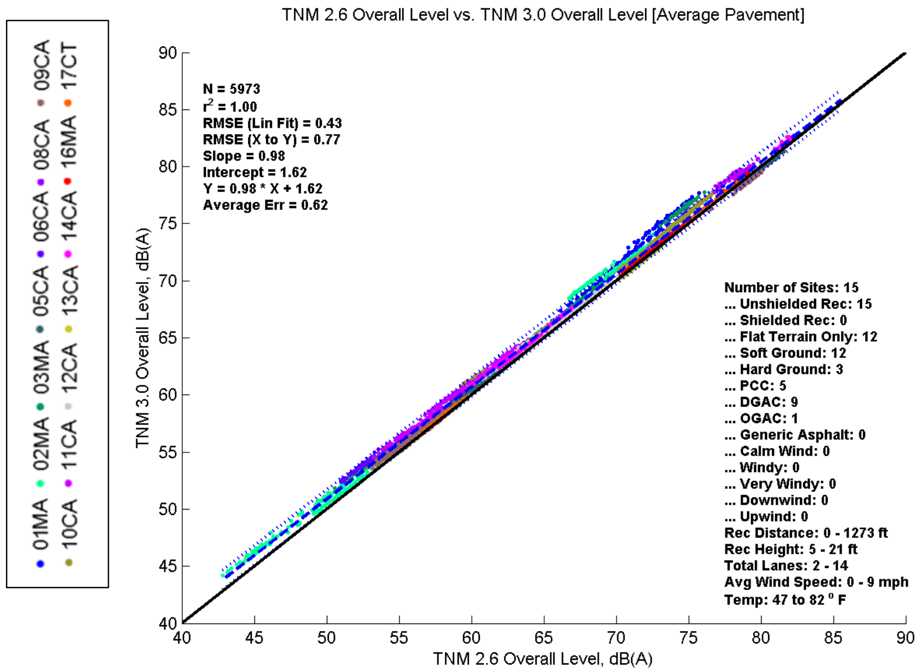

Figure G - 3: TNM 2.6 Predictions vs. TNM 3.0 Predictions using Average Pavement – All Data

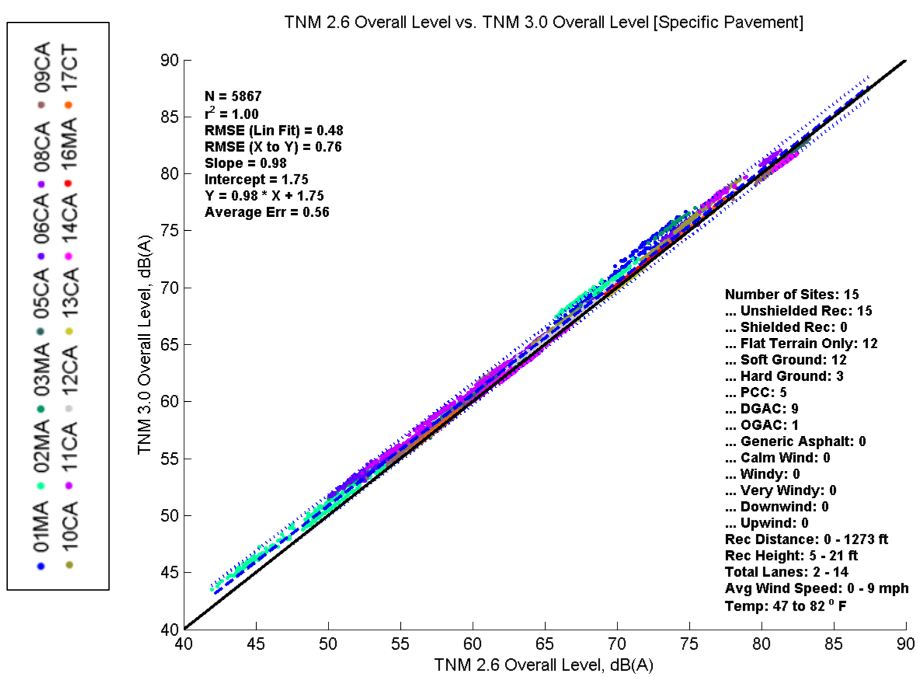

Figure G - 4: TNM 2.6 Predictions vs. TNM 3.0 Predictions using Specific Pavement – All Data

Appendix H: Comparison of Modeled and Measured Results (Not Adjusted for Reference Microphone)

In these figures, the colored circles represent individual 5-minute model computations (color coding is given in the legend); the blue dashed line shows the first-order linear regression between the two datasets; the blue dotted lines indicate the 95-percent prediction interval for any new computations; and the solid black line indicates where all results would fall if both models gave the same predictions for all analyses. Note that in the upper left-hand corner of the graph several statistical parameters are presented: the number of samples, the coefficient of determination (r^2), the root mean squared error (RMSE), the regression slope and intercept, the regression equation, and the average difference. These statistics are also repeated in the tables that follow. In the lower right-hand corner, a metadata summary is provided covering the number of sites, the presence of a barrier, receiver distances and heights, number of roadway lanes, pavement type, and temperature and wind conditions included in the analysis. Each site is presented in a different color to help highlight any potential grouping of the data.

In general, the larger the sample size, the higher the confidence for the computation of all parameters. In this report, the maximum number of modeled samples is 5987. When sub-sets are examined, the number of samples will be smaller. The r^2 provides a measure of correlation. The RMSE provides a measure of absolute variation between the two predictions and represents the sample standard deviation. A slope (m) of one indicates that for every 1-dB change in one model's prediction there will be an identical 1-dB change in the other model's prediction. If the slope is less than one, then the model on the y-axis tends to change predictions slower than the model on the x-axis and *vice versa*. If the intercept (b) is zero and the slope is one, then there is perfect agreement between the two datasets. If the intercept is negative, then the model on the y-axis predicts lower levels than the model on the x-axis for low levels and *vice versa*; however, the average difference provides a measure of the *overall bias* between the two datasets.

H.1 TNM Predictions vs. Measured Results - All Data Analyzed

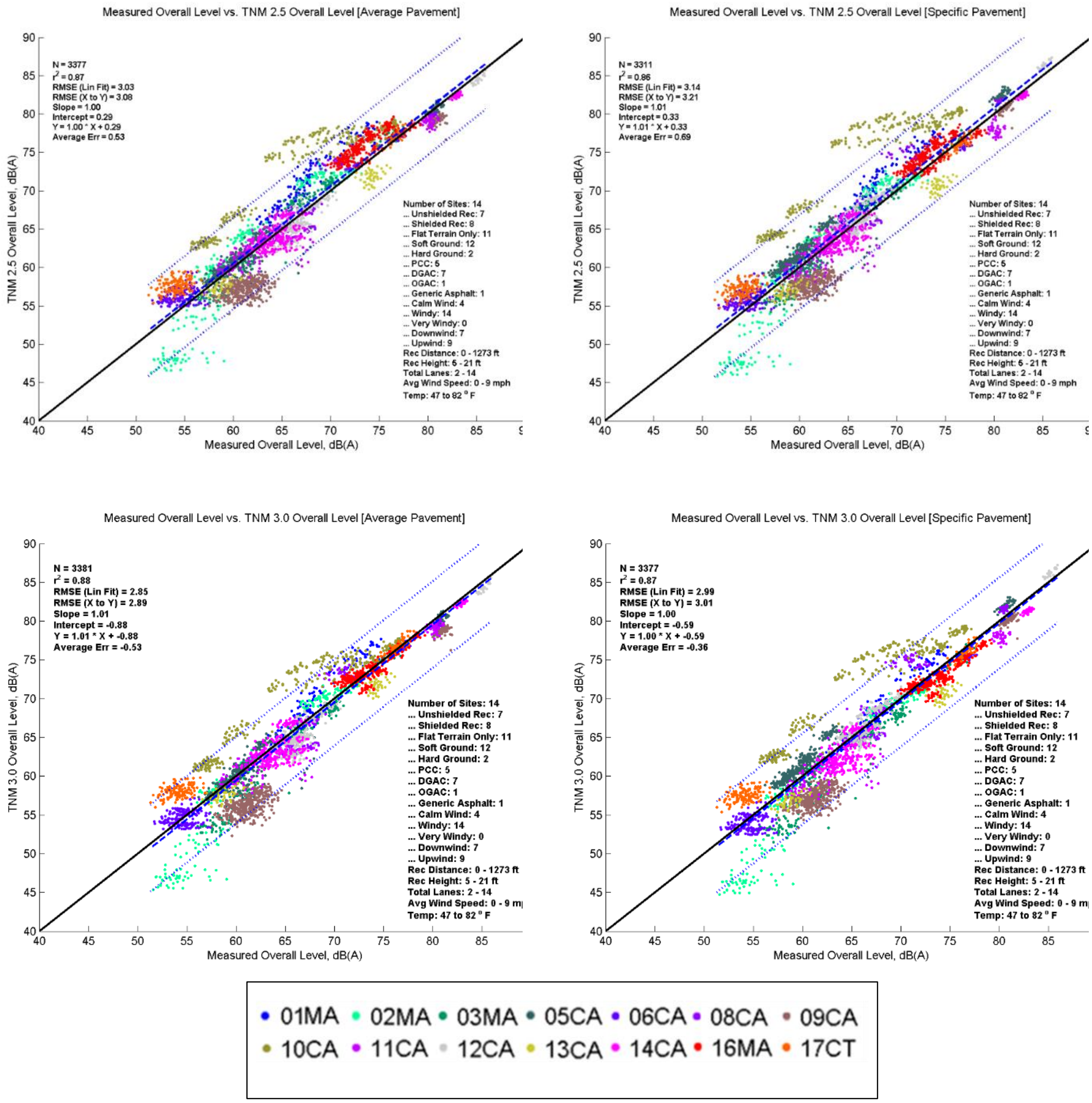

Figure H - 1: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – All Data

TABLE H - 1: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – ALL DATA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	3377	3311	3381	3377
r^2	0.87	0.86	0.88	0.87
RMSE (Lin Fit)	3.03	3.14	2.85	2.99
RMSE (X to Y)	3.08	3.21	2.89	3.01
Slope	1	1.01	1.01	1
Intercept	0.29	0.33	-0.88	-0.59
Y	1.00 * X + 0.29	1.01 * X + 0.33	1.01 * X + -0.88	1 * X + -0.59
Average Error	0.53	0.69	-0.53	-0.36
Slope 95% CI	0.9904, 1.0169	0.9917, 1.0193	0.9929, 1.0178	0.9905, 1.0166
Intercept 95% CI	-0.5799, 1.1691	-0.5835, 1.2424	-1.6994, -0.0606	-1.4548, 0.2686
Avg Err 95% CI	0.4320, 0.6367	0.5822, 0.7961	-0.6258, -0.4339	-0.4613, -0.2595

H.2 TNM Predictions vs. Measured Results - Ground Type

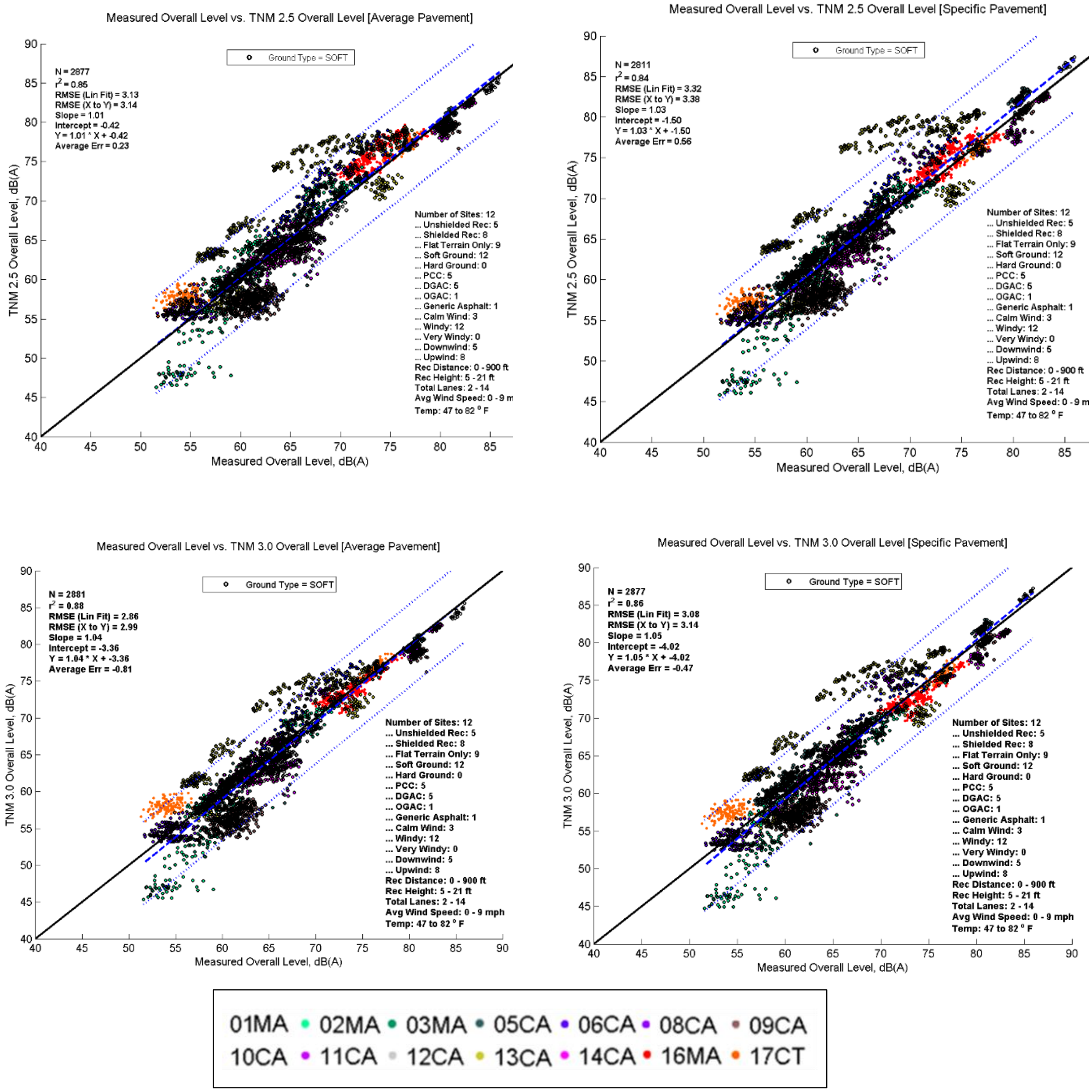

Figure H - 2: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Acoustically Soft Ground

TABLE H - 2: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – ACOUSTICALLY SOFT GROUND

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	2877	2811	2881	2877
r^2	0.85	0.84	0.88	0.86
RMSE (Lin Fit)	3.13	3.32	2.86	3.08
RMSE (X to Y)	3.14	3.38	2.99	3.14
Slope	1.01	1.03	1.04	1.05
Intercept	-0.42	-1.5	-3.36	-4.02
Y	1.01 * X + -0.42	1.03 * X + -1.50	1.04 * X + -3.36	1.05 * X + -4.02
Average Error	0.23	0.56	-0.81	-0.47
Slope 95% CI	0.9943, 1.0257	1.0149, 1.0487	1.0249, 1.0535	1.0393, 1.0701
Intercept 95% CI	-1.4472, 0.6036	-2.6034, -0.3998	-4.2985, -2.4254	-5.0286, -3.0142
Avg Err 95% CI	0.1140, 0.3430	0.4404, 0.6866	-0.9187, -0.7085	-0.5800, -0.3530

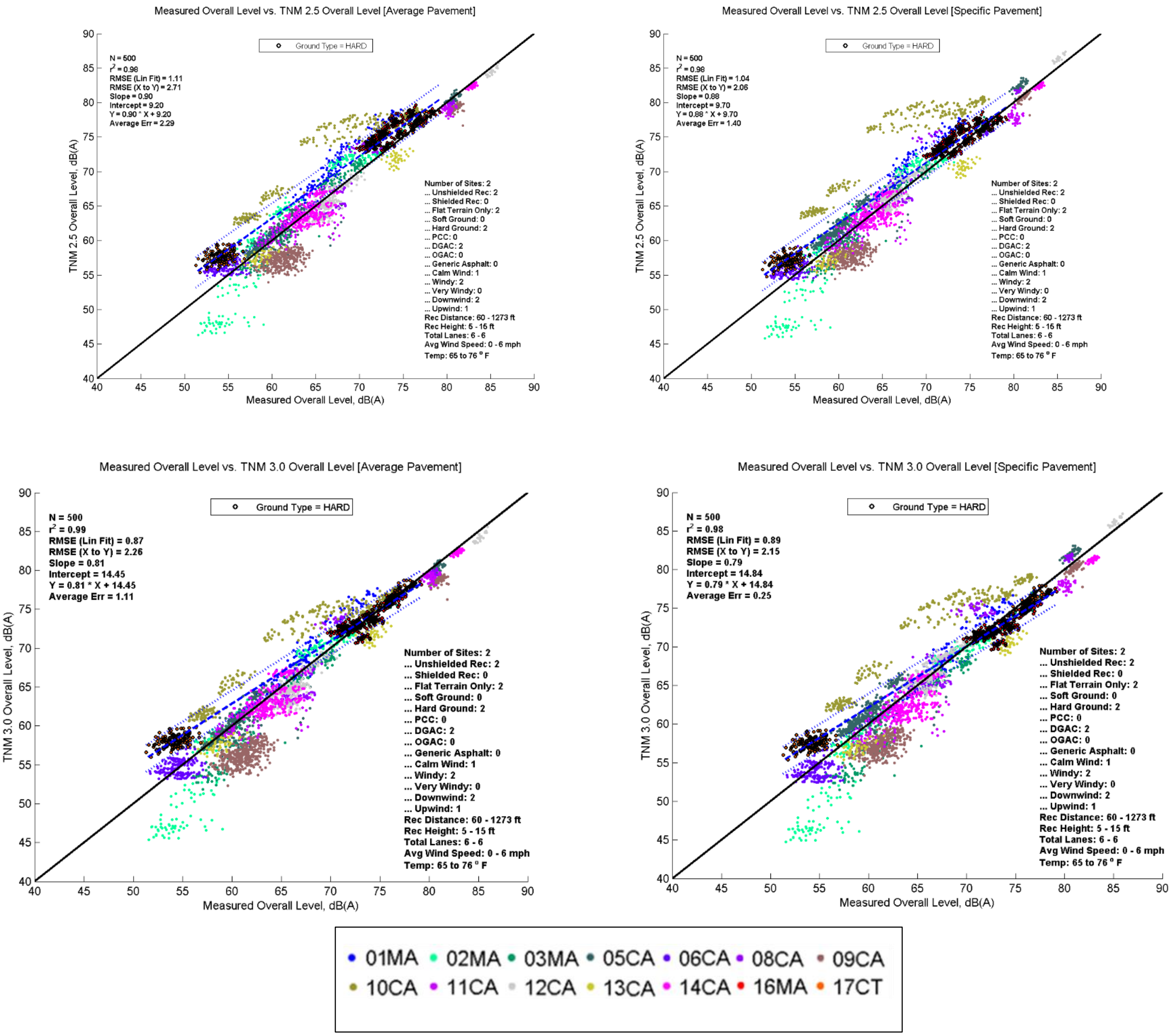

Figure H - 3: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Acoustically Hard Ground

TABLE H - 3: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – ACOUSTICALLY HARD GROUND

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	500	500	500	500
r^2	0.98	0.98	0.99	0.98
RMSE (Lin Fit)	1.11	1.04	0.87	0.89
RMSE (X to Y)	2.71	2.06	2.26	2.15
Slope	0.9	0.88	0.81	0.79
Intercept	9.2	9.7	14.45	14.84
Y	0.90 * X + 9.20	0.88 * X + 9.70	0.81 * X + 14.45	0.79 * X + 14.84
Average Error	2.29	1.4	1.11	0.25
Slope 95% CI	0.8890, 0.9103	0.8694, 0.8894	0.7979, 0.8146	0.7796, 0.7967
Intercept 95% CI	8.4623, 9.9421	9.0074, 10.3975	13.8671, 15.0255	14.2416, 15.4297
Avg Err 95% CI	2.1679, 2.4207	1.2621, 1.5286	0.9319, 1.2784	0.0628, 0.4372

H.3 TNM Predictions vs. Measured Results - Barriers

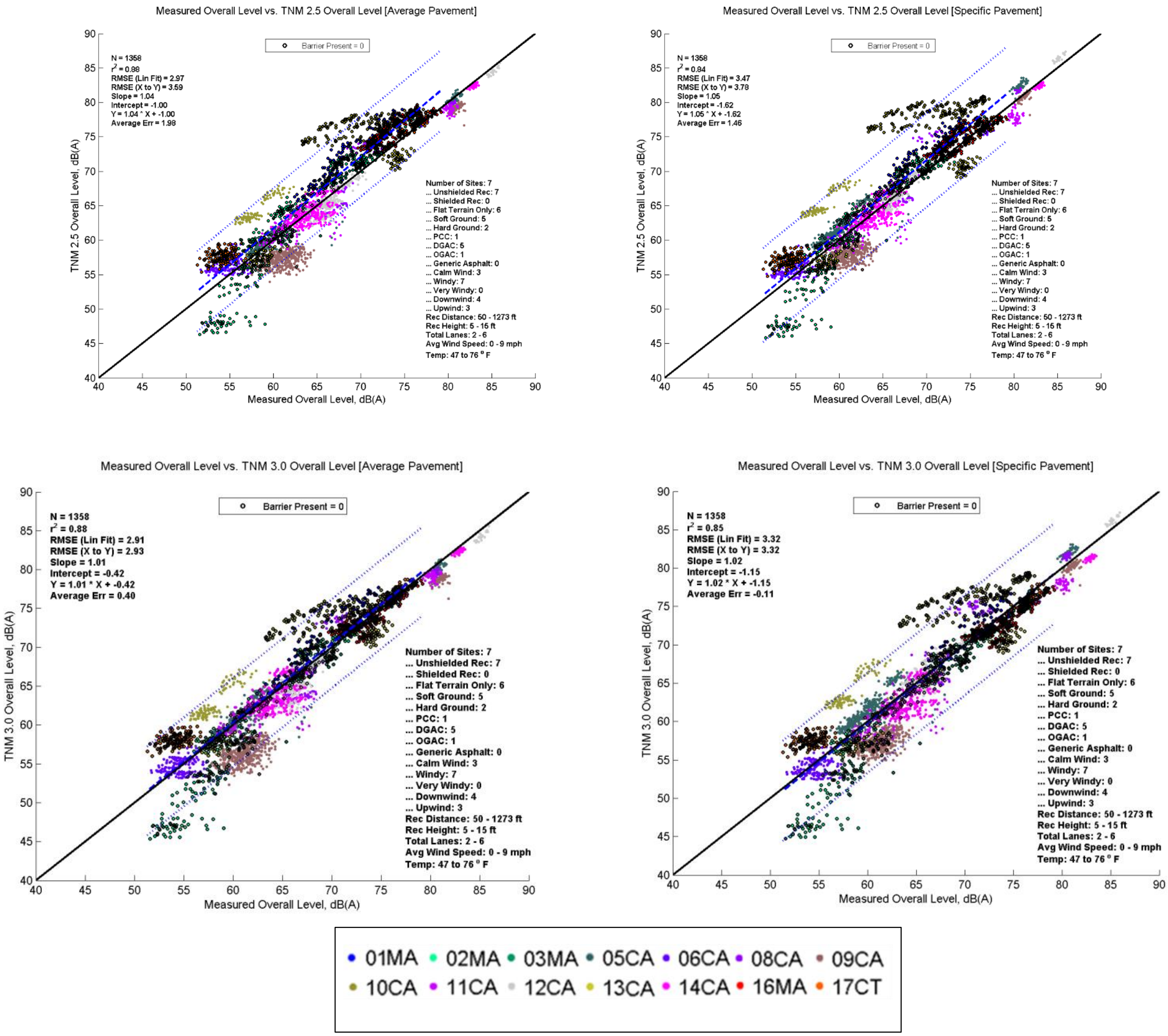

Figure H - 4: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Sites without Barriers

TABLE H - 4: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – SITES WITHOUT BARRIERS

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	1358	1358	1358	1358
r^2	0.88	0.84	0.88	0.85
RMSE (Lin Fit)	2.97	3.47	2.91	3.32
RMSE (X to Y)	3.59	3.78	2.93	3.32
Slope	1.04	1.05	1.01	1.02
Intercept	-1	-1.62	-0.42	-1.15
Y	1.04 * X + -1.00	1.05 * X + -1.62	1.01 * X + -0.42	1.02 * X + -1.15
Average Error	1.98	1.46	0.4	-0.11
Slope 95% CI	1.0239, 1.0650	1.0219, 1.0700	0.9921, 1.0323	0.9924, 1.0384
Intercept 95% CI	-2.3920, 0.3847	-3.2487, 0.0004	-1.7805, 0.9394	-2.7003, 0.4078
Avg Err 95% CI	1.8252, 2.1430	1.2760, 1.6473	0.2439, 0.5533	-0.2905, 0.0631

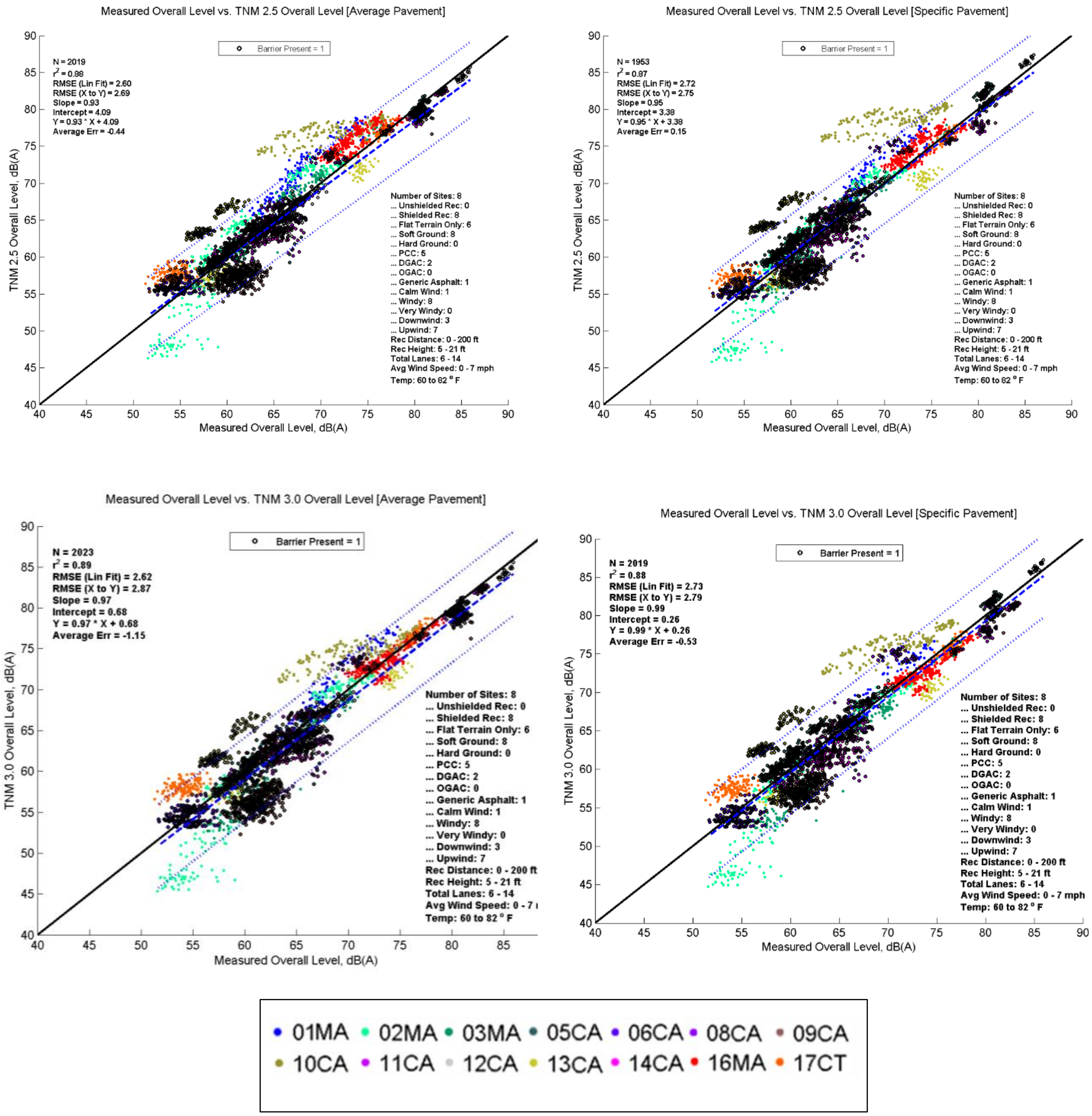

Figure H - 5: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Sites with Barriers

TABLE H - 5: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – SITES WITH BARRIERS

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	2019	1953	2023	2019
r^2	0.88	0.87	0.89	0.88
RMSE (Lin Fit)	2.6	2.72	2.62	2.73
RMSE (X to Y)	2.69	2.75	2.87	2.79
Slope	0.93	0.95	0.97	0.99
Intercept	4.09	3.38	0.68	0.26
Y	0.93 * X + 4.09	0.95 * X + 3.38	0.97 * X + 0.68	0.99 * X + 0.26
Average Error	-0.44	0.15	-1.15	-0.53
Slope 95% CI	0.9148, 0.9447	0.9339, 0.9659	0.9565, 0.9867	0.9720, 1.0035
Intercept 95% CI	3.1158, 5.0622	2.3422, 4.4155	-0.3013, 1.6561	-0.7590, 1.2864
Avg Err 95% CI	-0.5564, -0.3251	0.0303, 0.2737	-1.2675, -1.0387	-0.6457, -0.4070

H.4 TNM Predictions vs. Measured Results – Distance

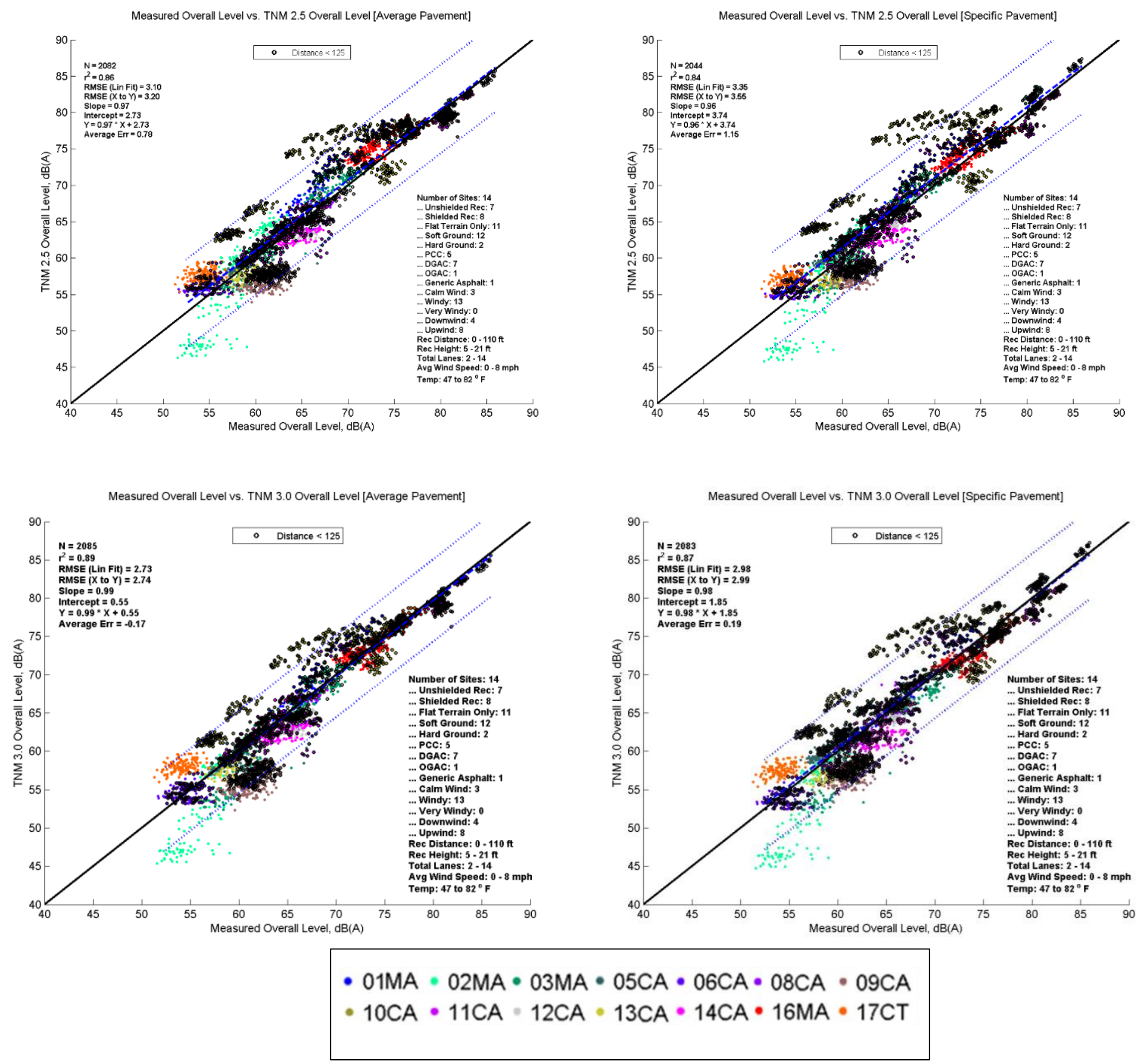

Figure H - 6: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Measurement Locations within 125 Feet of the Center of the Nearest Lane

TABLE H - 6: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – MEASUREMENT LOCATIONS WITHIN 125 FEET OF THE CENTER OF THE NEAREST LANE

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	2082	2044	2085	2083
r^2	0.86	0.84	0.89	0.87
RMSE (Lin Fit)	3.1	3.35	2.73	2.98
RMSE (X to Y)	3.2	3.55	2.74	2.99
Slope	0.97	0.96	0.99	0.98
Intercept	2.73	3.74	0.55	1.85
Y	0.97 * X + 2.73	0.96 * X + 3.74	0.99 * X + 0.55	0.98 * X + 1.85
Average Error	0.78	1.15	-0.17	0.19
Slope 95% CI	0.9544, 0.9881	0.9433, 0.9801	0.9745, 1.0042	0.9593, 0.9916
Intercept 95% CI	1.5789, 3.8733	2.4910, 4.9919	-0.4618, 1.5582	0.7491, 2.9487
Avg Err 95% CI	0.6445, 0.9117	1.0058, 1.2974	-0.2915, -0.0567	0.0586, 0.3149

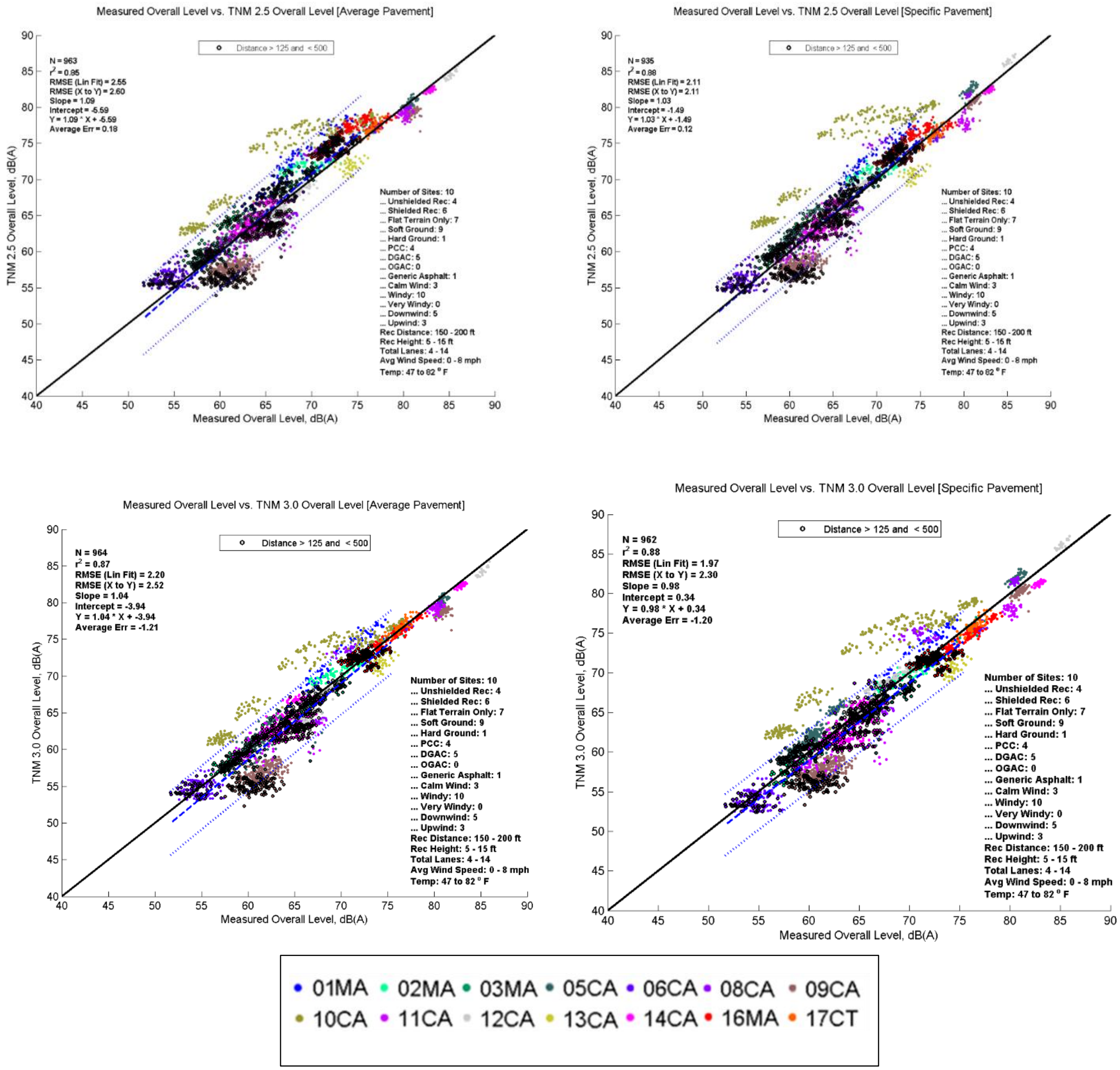

Figure H - 7: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Measurement Locations between 125 and 500 Feet of the Center of the Nearest Lane

TABLE H - 7: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – MEASUREMENT LOCATIONS BETWEEN 125 AND 500 FEET OF THE CENTER OF THE NEAREST LANE

	Average Measured vs. TNM 2.5	**Specific Measured vs. TNM 2.5**	**Average Measured vs. TNM 3.0**	**Specific Measured vs. TNM 3.0**
N	963	935	964	962
r^2	0.85	0.88	0.87	0.88
RMSE (Lin Fit)	2.55	2.11	2.2	1.97
RMSE (X to Y)	2.6	2.11	2.52	2.3
Slope	1.09	1.03	1.04	0.98
Intercept	-5.59	-1.49	-3.94	0.34
Y	1.09 * X + -5.59	1.03 * X + -1.49	1.04 * X + -3.94	0.98 * X + 0.34
Average Error	0.18	0.12	-1.21	-1.2
Slope 95% CI	1.0605, 1.1193	1.0006, 1.0497	1.0170, 1.0677	0.9534, 0.9987
Intercept 95% CI	-7.4903, -3.6969	-3.0741, 0.0846	-5.5688, -2.3021	-1.1159, 1.8032
Avg Err 95% CI	0.0159, 0.3441	-0.0156, 0.2548	-1.3529, -1.0737	-1.3199, -1.0710

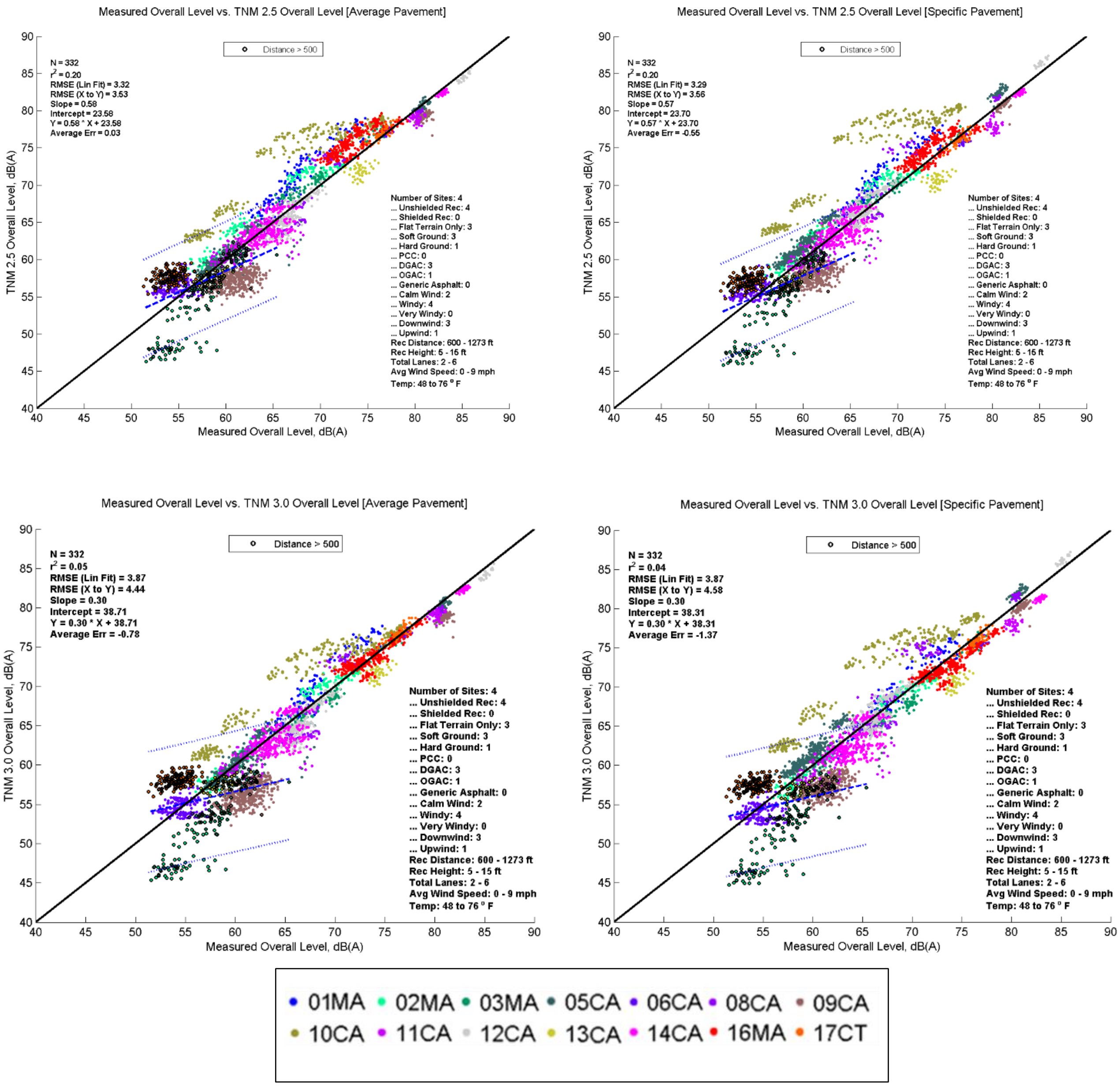

Figure H - 8: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Measurement Locations Greater than 500 Feet of the Center of the Nearest Lane

TABLE H - 8: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – MEASUREMENT LOCATIONS GREATER THAN 500 FEET OF THE CENTER OF THE NEAREST LANE

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	332	332	332	332
r^2	0.2	0.2	0.05	0.04
RMSE (Lin Fit)	3.32	3.29	3.87	3.87
RMSE (X to Y)	3.53	3.56	4.44	4.58
Slope	0.58	0.57	0.3	0.3
Intercept	23.58	23.7	38.71	38.31
Y	0.58 * X + 23.58	0.57 * X + 23.70	0.30 * X + 38.71	0.30 * X + 38.31
Average Error	0.03	-0.55	-0.78	-1.37
Slope 95% CI	0.4589, 0.7044	0.4473, 0.6909	0.1551, 0.4418	0.1519, 0.4381
Intercept 95% CI	16.6637, 30.5018	16.8356, 30.5669	30.6346, 46.7915	30.2448, 46.3812
Avg Err 95% CI	-0.3461, 0.4134	-0.9325, -0.1754	-1.2501, -0.3089	-1.8442, -0.9029

H.5 Variation by Site

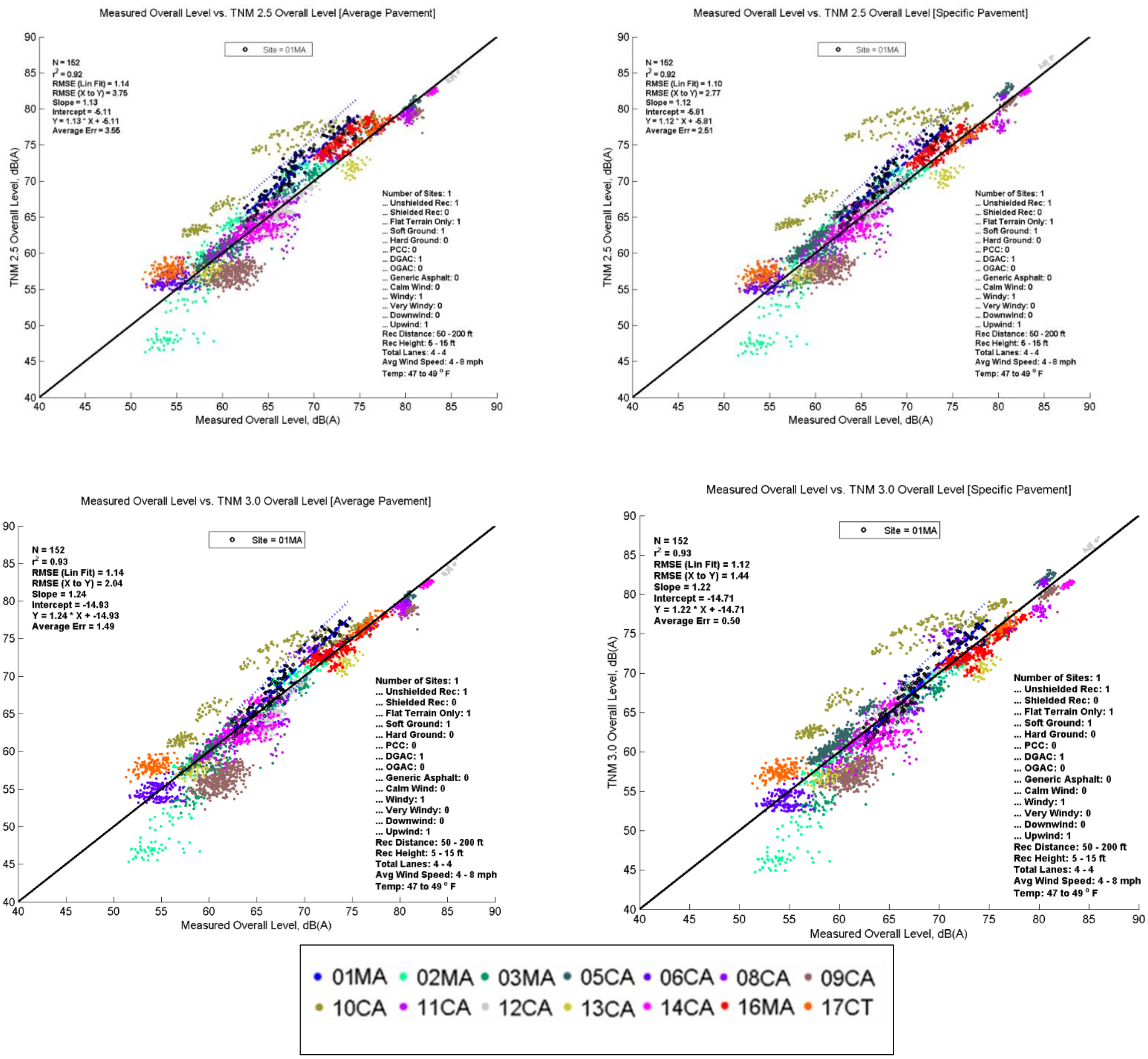

Figure H - 9: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 01MA

TABLE H - 9: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 01MA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	152	152	152	152
r^2	0.92	0.92	0.93	0.93
RMSE (Lin Fit)	1.14	1.1	1.14	1.12
RMSE (X to Y)	3.75	2.77	2.04	1.44
Slope	1.13	1.12	1.24	1.22
Intercept	-5.11	-5.81	-14.93	-14.71
Y	1.13 * X + -5.11	1.12 * X + -5.81	1.24 * X + -14.93	1.22 * X + -14.71
Average Error	3.55	2.51	1.49	0.5
Slope 95% CI	1.0746, 1.1804	1.0715, 1.1737	1.1888, 1.2946	1.1718, 1.2762
Intercept 95% CI	-8.7031, -1.5151	-9.2851, -2.3377	-18.5219, -11.3310	-18.2559, -11.1592
Avg Err 95% CI	3.3557, 3.7418	2.3274, 2.7002	1.2626, 1.7090	0.2883, 0.7197

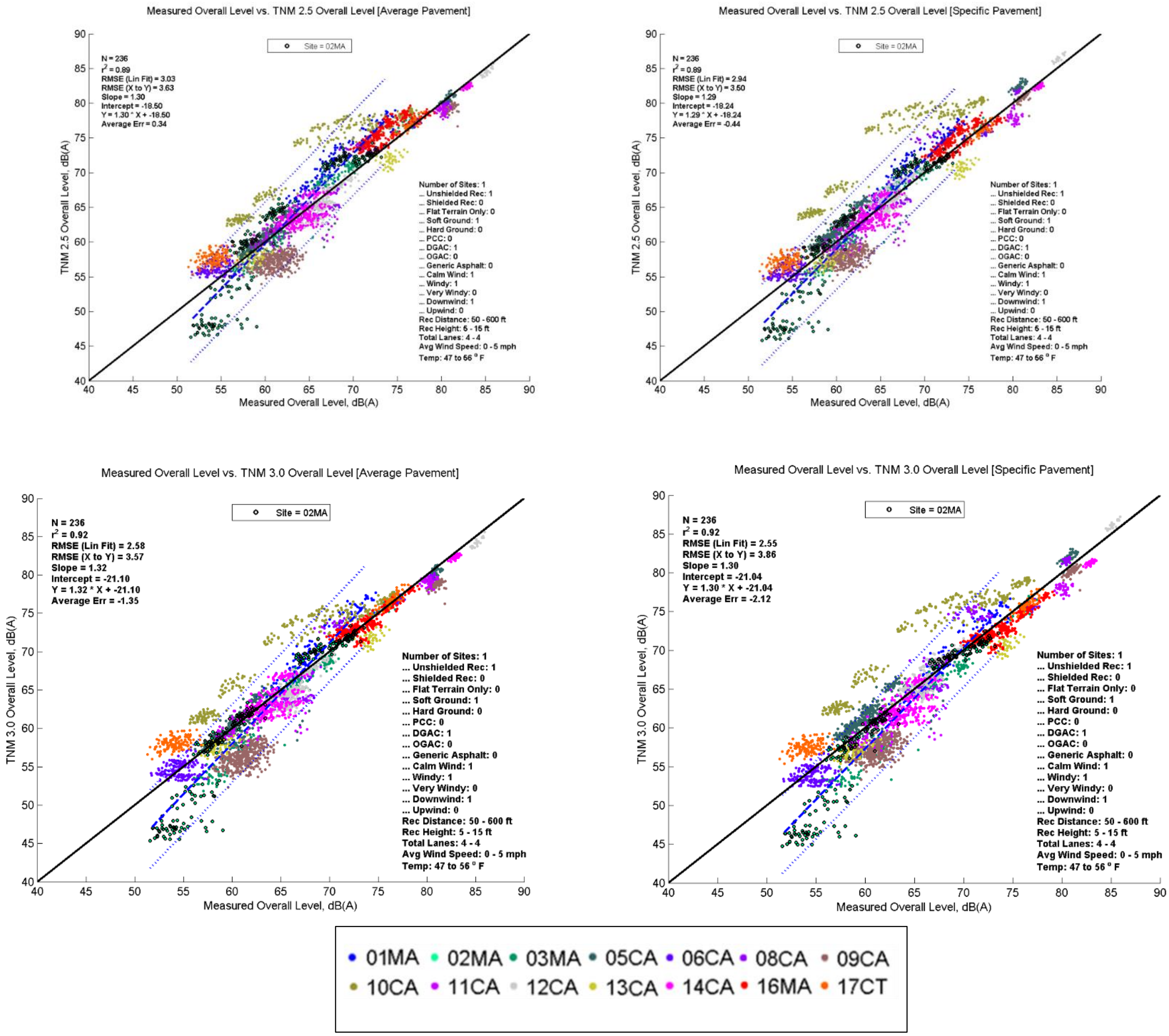

Figure H - 10: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 02MA

TABLE H - 10: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 02MA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	236	236	236	236
r^2	0.89	0.89	0.92	0.92
RMSE (Lin Fit)	3.03	2.94	2.58	2.55
RMSE (X to Y)	3.63	3.5	3.57	3.86
Slope	1.3	1.29	1.32	1.3
Intercept	-18.5	-18.24	-21.1	-21.04
Y	1.30 * X + -18.50	1.29 * X + -18.24	1.32 * X + -21.10	1.30 * X + -21.04
Average Error	0.34	-0.44	-1.35	-2.12
Slope 95% CI	1.2447, 1.3628	1.2297, 1.3439	1.2682, 1.3686	1.2553, 1.3544
Intercept 95% CI	-22.1854, -14.8208	-21.8021, -14.6719	-24.2340, -17.9695	-24.1305, -17.9444
Avg Err 95% CI	-0.1174, 0.8073	-0.8849, 0.0037	-1.7690, -0.9229	-2.5334, -1.7079

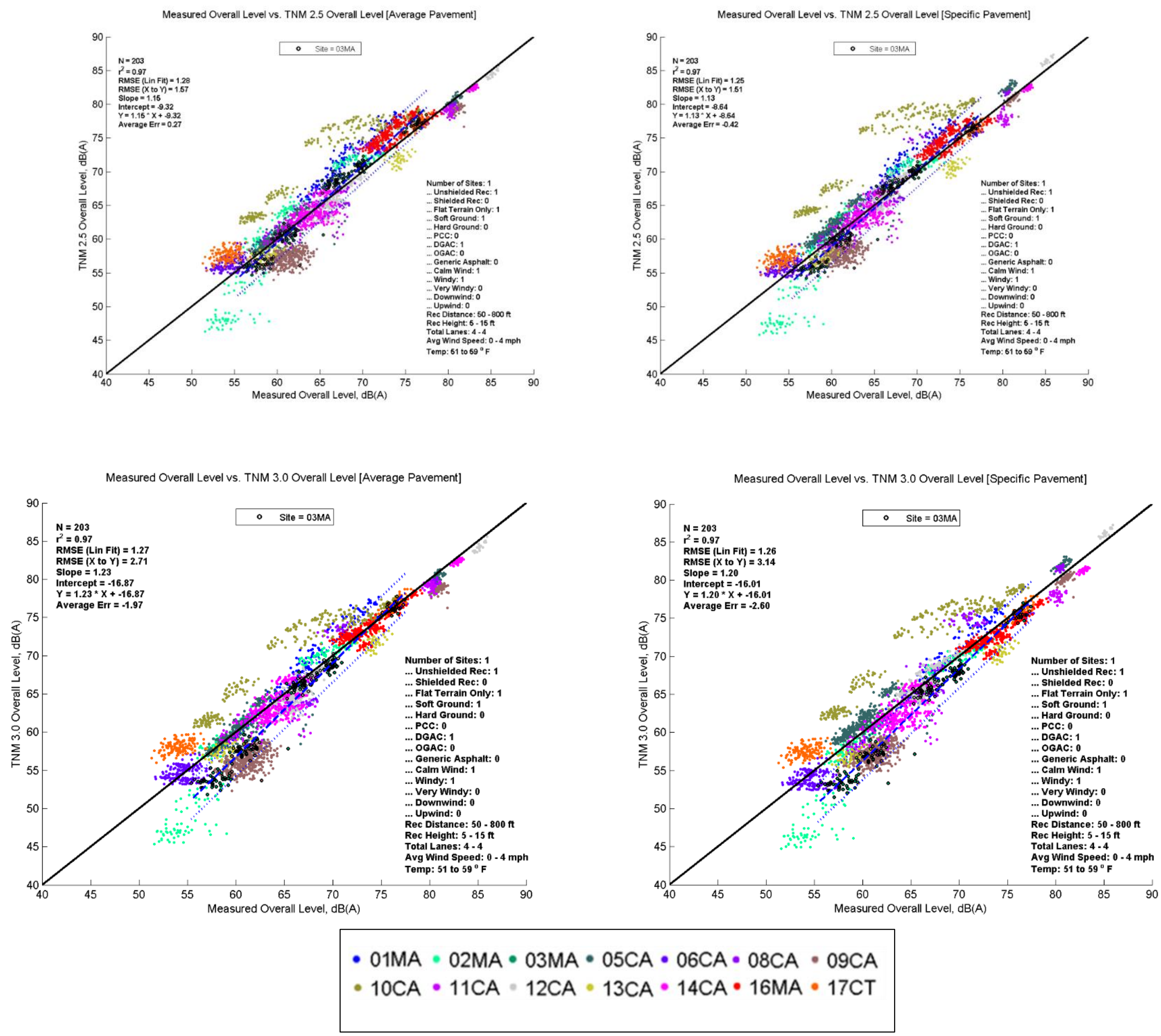

Figure H - 11: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 03MA

TABLE H - 11: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 03MA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	203	203	203	203
r^2	0.97	0.97	0.97	0.97
RMSE (Lin Fit)	1.28	1.25	1.27	1.26
RMSE (X to Y)	1.57	1.51	2.71	3.14
Slope	1.15	1.13	1.23	1.2
Intercept	-9.32	-8.64	-16.87	-16.01
Y	1.15 * X + -9.32	1.13 * X + -8.64	1.23 * X + -16.87	1.20 * X + -16.01
Average Error	0.27	-0.42	-1.97	-2.6
Slope 95% CI	1.1174, 1.1753	1.0972, 1.1538	1.1987, 1.2561	1.1761, 1.2331
Intercept 95% CI	-11.2213, -7.4106	-10.4994, -6.7808	-18.7554, -14.9785	-17.8828, -14.1300
Avg Err 95% CI	0.0590, 0.4866	-0.6203, -0.2190	-2.2260, -1.7108	-2.8463, -2.3601

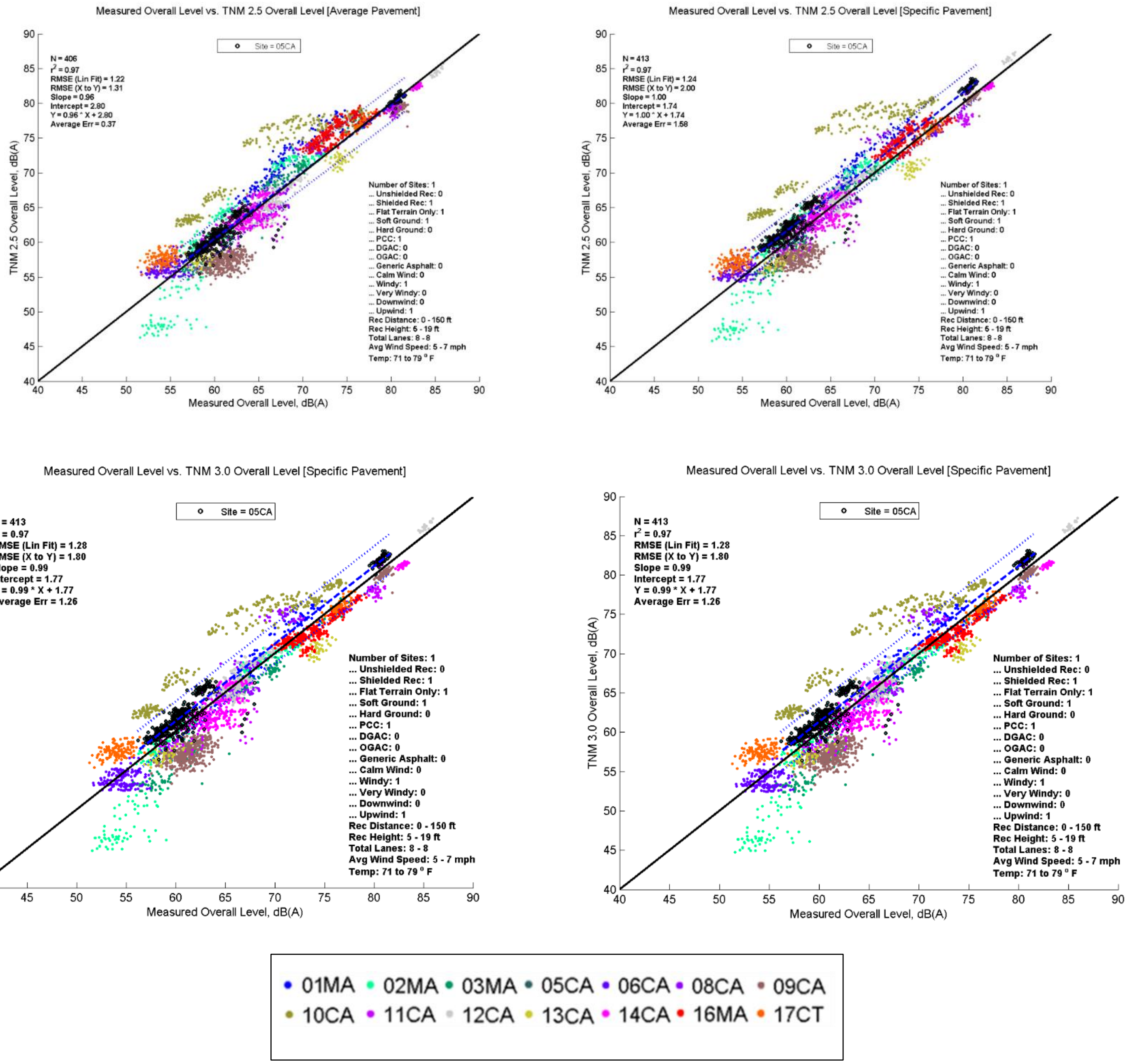

Figure H - 12: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 05CA

TABLE H - 12: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 05CA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	406	413	413	413
r^2	0.97	0.97	0.97	0.97
RMSE (Lin Fit)	1.22	1.24	1.31	1.28
RMSE (X to Y)	1.31	2	1.33	1.8
Slope	0.96	1	0.97	0.99
Intercept	2.8	1.74	1.83	1.77
Y	0.96 * X + 2.80	1.00 * X + 1.74	0.97 * X + 1.83	0.99 * X + 1.77
Average Error	0.37	1.58	-0.12	1.26
Slope 95% CI	0.9453, 0.9777	0.9811, 1.0136	0.9520, 0.9864	0.9751, 1.0088
Intercept 95% CI	1.7666, 3.8303	0.7092, 2.7798	0.7314, 2.9189	0.7016, 2.8452
Avg Err 95% CI	0.2435, 0.4877	1.4567, 1.6953	-0.2494, 0.0064	1.1387, 1.3859

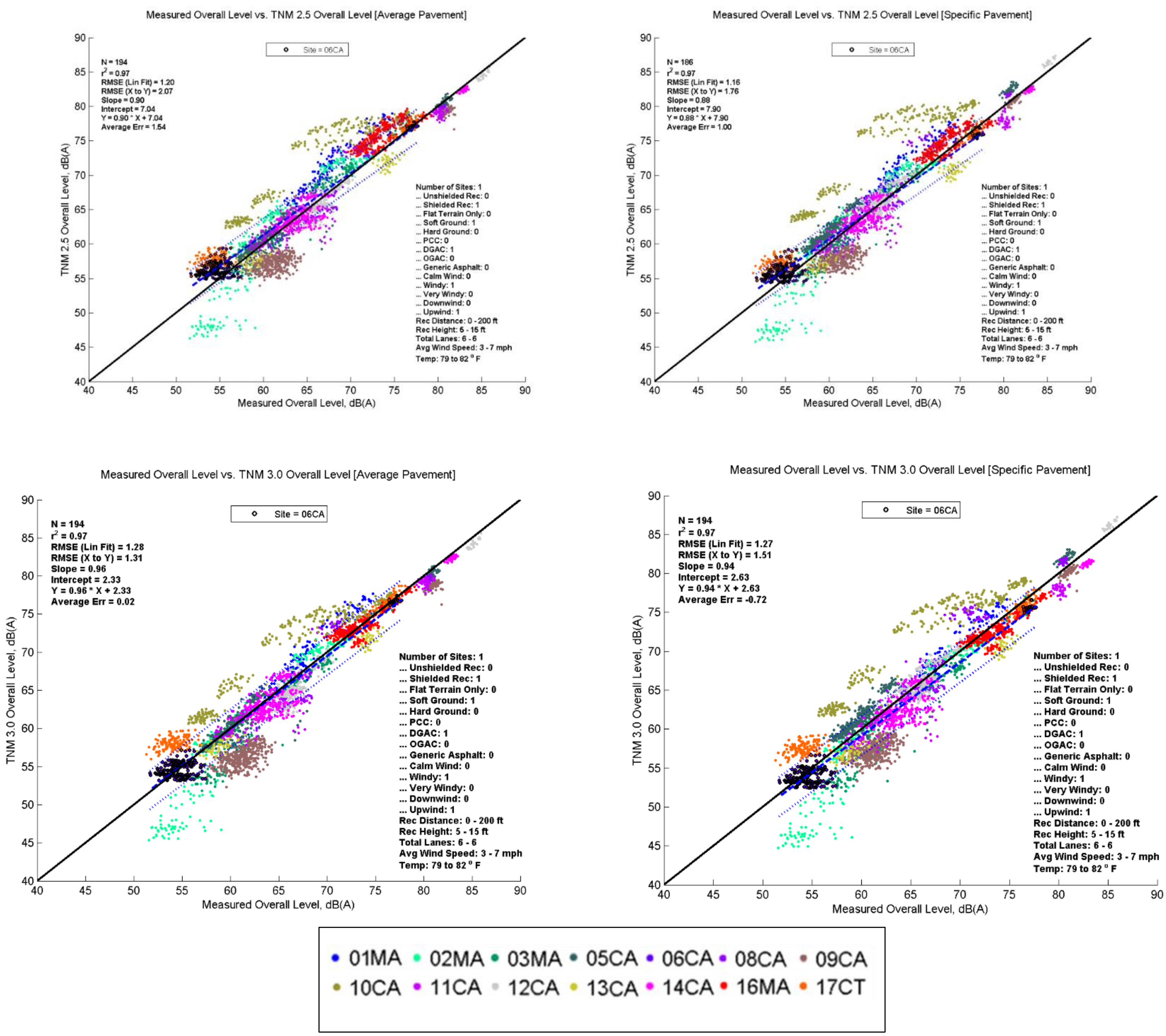

Figure H - 13: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 06CA

TABLE H - 13: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 06CA

	Average Measured vs. TNM 2.5	**Specific Measured vs. TNM 2.5**	**Average Measured vs. TNM 3.0**	**Specific Measured vs. TNM 3.0**
N	194	186	194	194
r^2	0.97	0.97	0.97	0.97
RMSE (Lin Fit)	1.2	1.16	1.28	1.27
RMSE (X to Y)	2.07	1.76	1.31	1.51
Slope	0.9	0.88	0.96	0.94
Intercept	7.04	7.9	2.33	2.63
Y	0.90 * X + 7.04	0.88 * X + 7.90	0.96 * X + 2.33	0.94 * X + 2.63
Average Error	1.54	1	0.02	-0.72
Slope 95% CI	0.8803, 0.9272	0.8566, 0.9020	0.9347, 0.9847	0.9165, 0.9662
Intercept 95% CI	5.6897, 8.3907	6.5922, 9.2092	0.8867, 3.7635	1.2042, 4.0619
Avg Err 95% CI	1.3494, 1.7393	0.7868, 1.2046	-0.1610, 0.2075	-0.9033, -0.5270

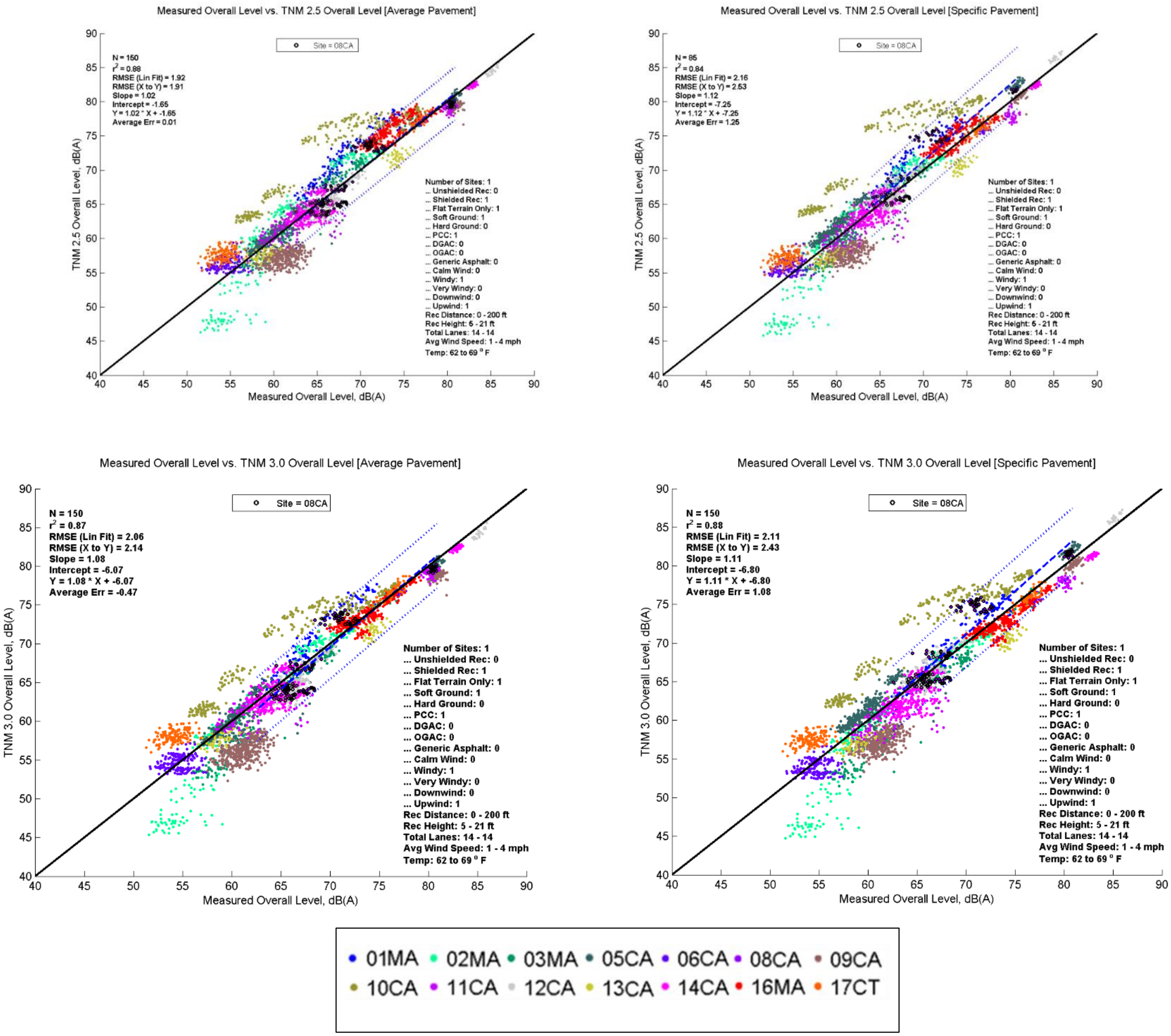

Figure H - 14: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 08CA

TABLE H - 14: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 08CA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	150	85	150	150
r^2	0.88	0.84	0.87	0.88
RMSE (Lin Fit)	1.92	2.16	2.06	2.11
RMSE (X to Y)	1.91	2.53	2.14	2.43
Slope	1.02	1.12	1.08	1.11
Intercept	-1.65	-7.25	-6.07	-6.8
Y	1.02 * X + -1.65	1.12 * X + -7.25	1.08 * X + -6.07	1.11 * X + -6.80
Average Error	0.01	1.25	-0.47	1.08
Slope 95% CI	0.9629, 1.0846	1.0188, 1.2252	1.0148, 1.1459	1.0459, 1.1802
Intercept 95% CI	-5.9033, 2.6095	-14.4485, -0.0502	-10.6519, -1.4851	-11.4949, -2.1102
Avg Err 95% CI	-0.2972, 0.3156	0.7742, 1.7183	-0.8026, -0.1314	0.7316, 1.4301

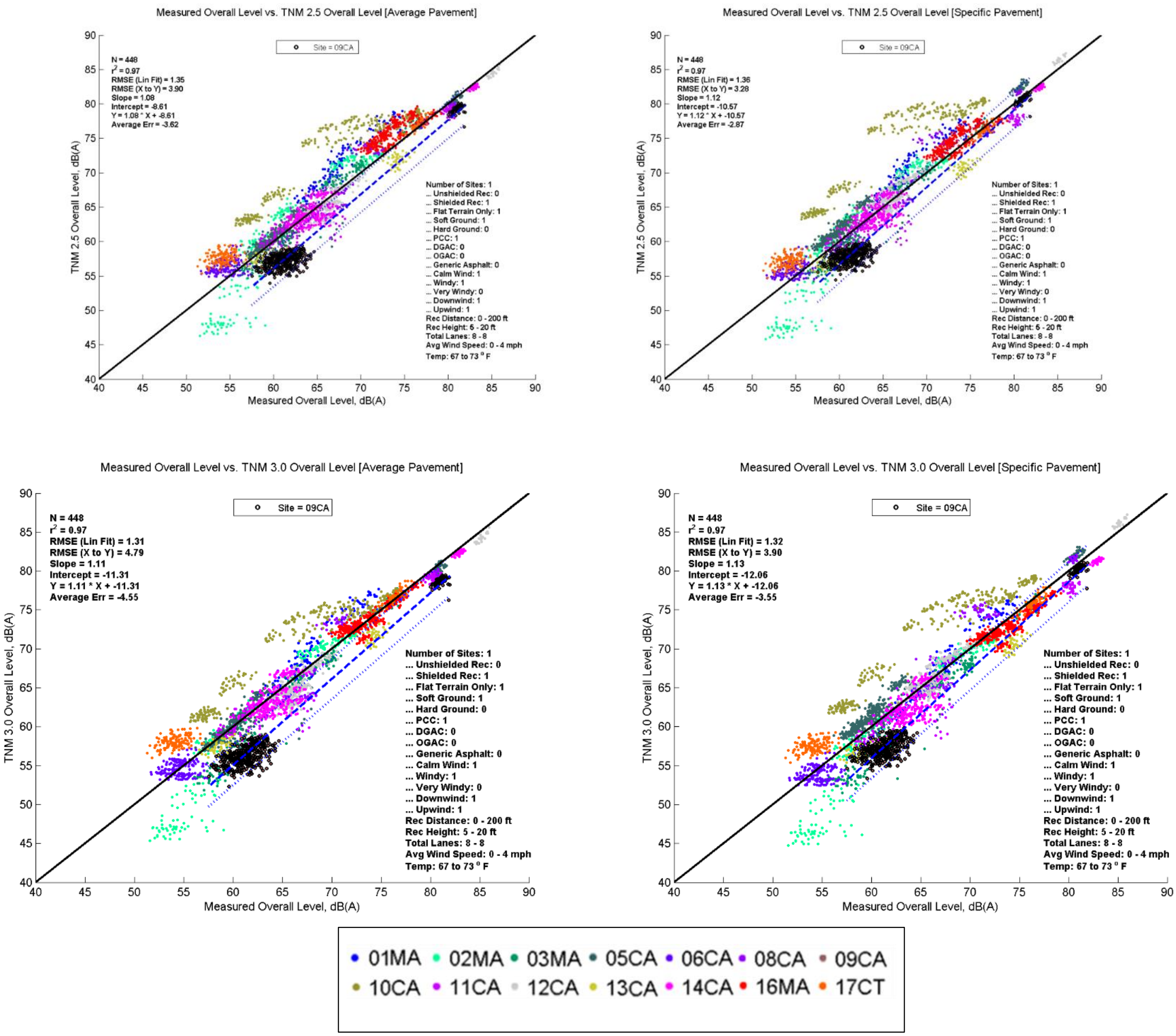

Figure H - 15: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 09CA

TABLE H - 15: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 09CA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	448	448	448	448
r^2	0.97	0.97	0.97	0.97
RMSE (Lin Fit)	1.35	1.36	1.31	1.32
RMSE (X to Y)	3.9	3.28	4.79	3.9
Slope	1.08	1.12	1.11	1.13
Intercept	-8.61	-10.57	-11.31	-12.06
Y	1.08 * X + -8.61	1.12 * X + -10.57	1.11 * X + -11.31	1.13 * X + -12.06
Average Error	-3.62	-2.87	-4.55	-3.55
Slope 95% CI	1.0603, 1.0956	1.1025, 1.1381	1.0885, 1.1228	1.1157, 1.1502
Intercept 95% CI	-9.7478, -7.4730	-11.7135, -9.4224	-12.4111, -10.2023	-13.1732, -10.9484
Avg Err 95% CI	-3.7560, -3.4865	-3.0160, -2.7195	-4.6875, -4.4086	-3.7021, -3.4025

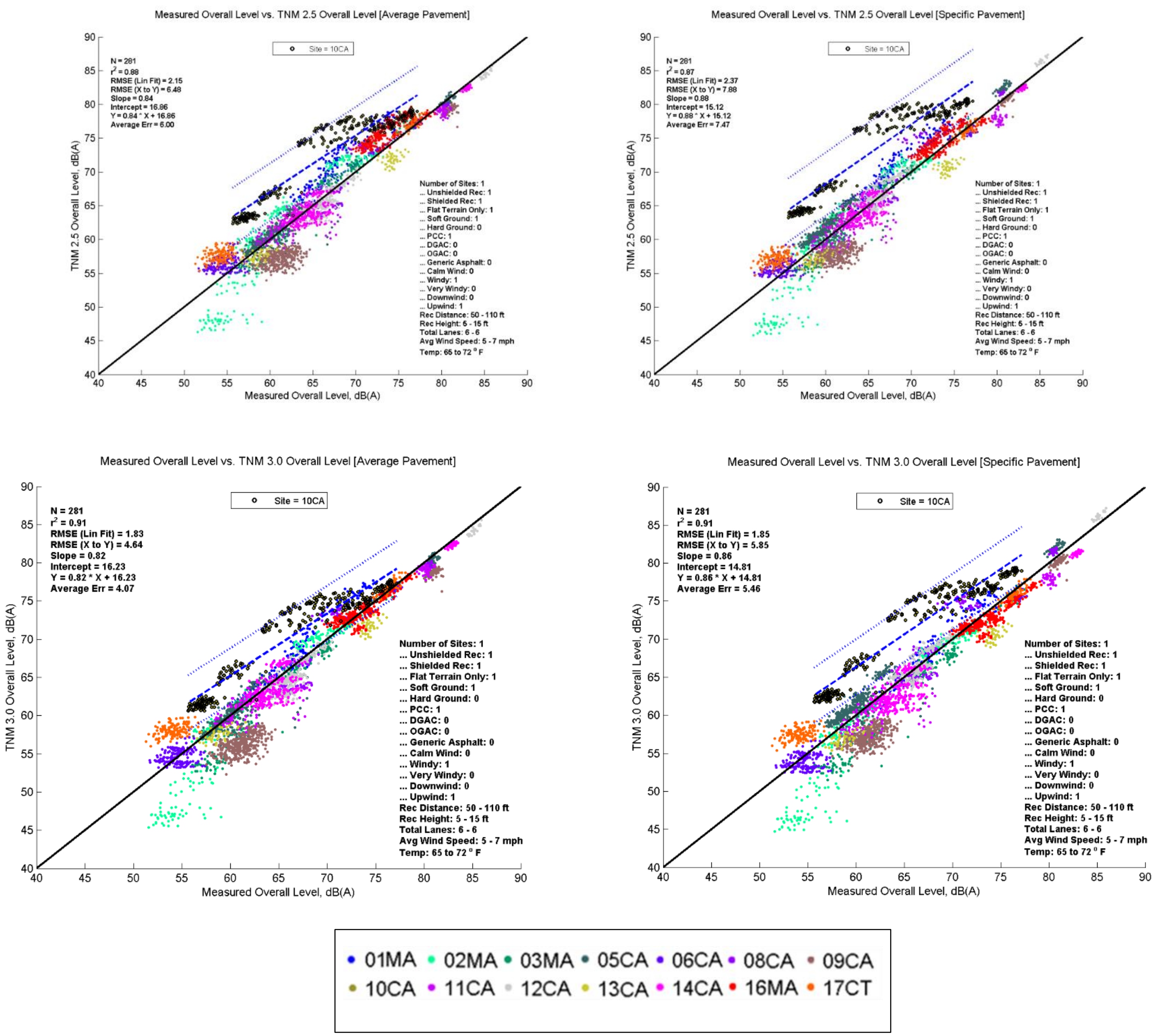

Figure H - 16: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 10CA

TABLE H - 16: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 10CA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	281	281	281	281
r^2	0.88	0.87	0.91	0.91
RMSE (Lin Fit)	2.15	2.37	1.83	1.85
RMSE (X to Y)	6.48	7.88	4.64	5.85
Slope	0.84	0.88	0.82	0.86
Intercept	16.86	15.12	16.23	14.81
Y	0.84 * X + 16.86	0.88 * X + 15.12	0.82 * X + 16.23	0.86 * X + 14.81
Average Error	6	7.47	4.07	5.46
Slope 95% CI	0.7996, 0.8722	0.8444, 0.9244	0.7853, 0.8469	0.8275, 0.8898
Intercept 95% CI	14.4432, 19.2698	12.4567, 17.7775	14.1810, 18.2777	12.7435, 16.8817
Avg Err 95% CI	5.7187, 6.2880	7.1772, 7.7626	3.8091, 4.3302	5.2206, 5.7091

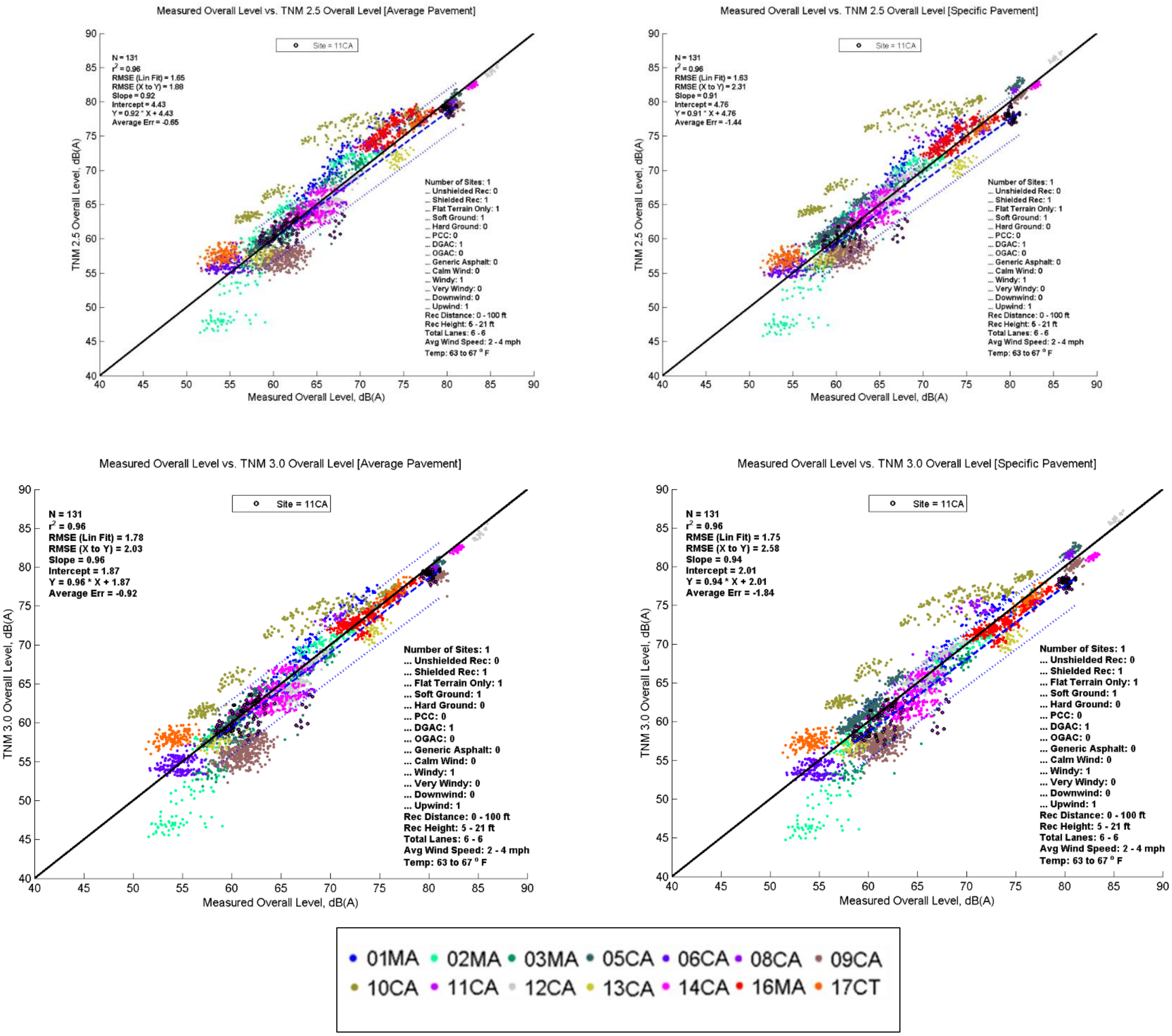

Figure H - 17: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 11CA

TABLE H - 17: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 11CA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	131	131	131	131
r^2	0.96	0.96	0.96	0.96
RMSE (Lin Fit)	1.65	1.63	1.78	1.75
RMSE (X to Y)	1.88	2.31	2.03	2.58
Slope	0.92	0.91	0.96	0.94
Intercept	4.43	4.76	1.87	2.01
Y	0.92 * X + 4.43	0.91 * X + 4.76	0.96 * X + 1.87	0.94 * X + 2.01
Average Error	-0.65	-1.44	-0.92	-1.84
Slope 95% CI	0.8932, 0.9565	0.8771, 0.9396	0.9245, 0.9929	0.9095, 0.9768
Intercept 95% CI	2.2733, 6.5939	2.6322, 6.8975	-0.4646, 4.2085	-0.2887, 4.3027
Avg Err 95% CI	-0.9560, -0.3490	-1.7507, -1.1292	-1.2346, -0.6141	-2.1533, -1.5316

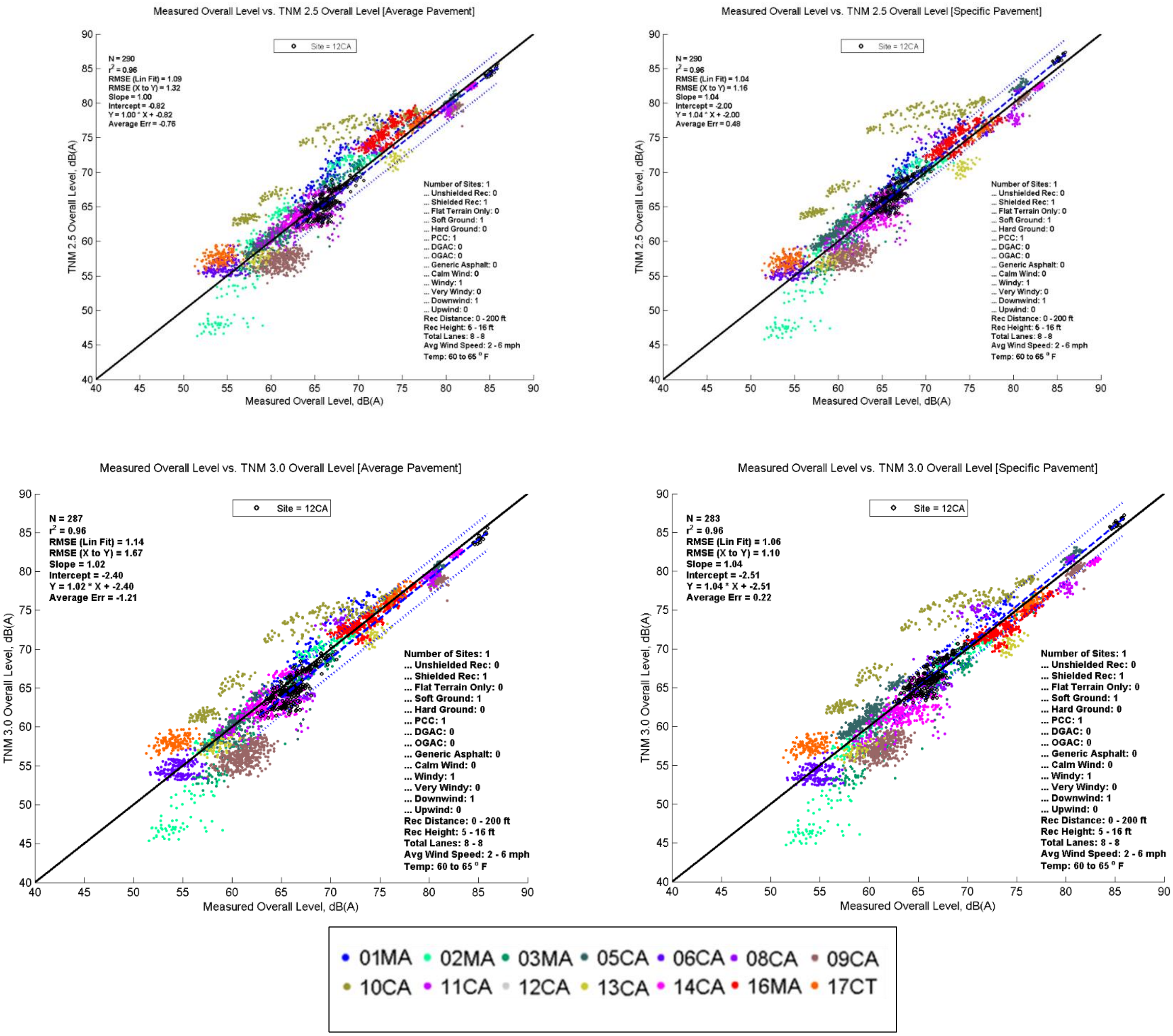

Figure H - 18: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 12CA

TABLE H - 18: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 12CA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	290	290	287	283
r^2	0.96	0.96	0.96	0.96
RMSE (Lin Fit)	1.09	1.04	1.14	1.06
RMSE (X to Y)	1.32	1.16	1.67	1.1
Slope	1	1.04	1.02	1.04
Intercept	-0.82	-2	-2.4	-2.51
Y	1.00 * X + -0.82	1.04 * X + -2.00	1.02 * X + -2.40	1.04 * X + -2.51
Average Error	-0.76	0.48	-1.21	0.22
Slope 95% CI	0.9769, 1.0249	1.0139, 1.0596	0.9925, 1.0427	1.0170, 1.0638
Intercept 95% CI	-2.4425, 0.8057	-3.5519, -0.4536	-4.1047, -0.7004	-4.0973, -0.9223
Avg Err 95% CI	-0.8825, -0.6319	0.3615, 0.6046	-1.3468, -1.0821	0.0939, 0.3464

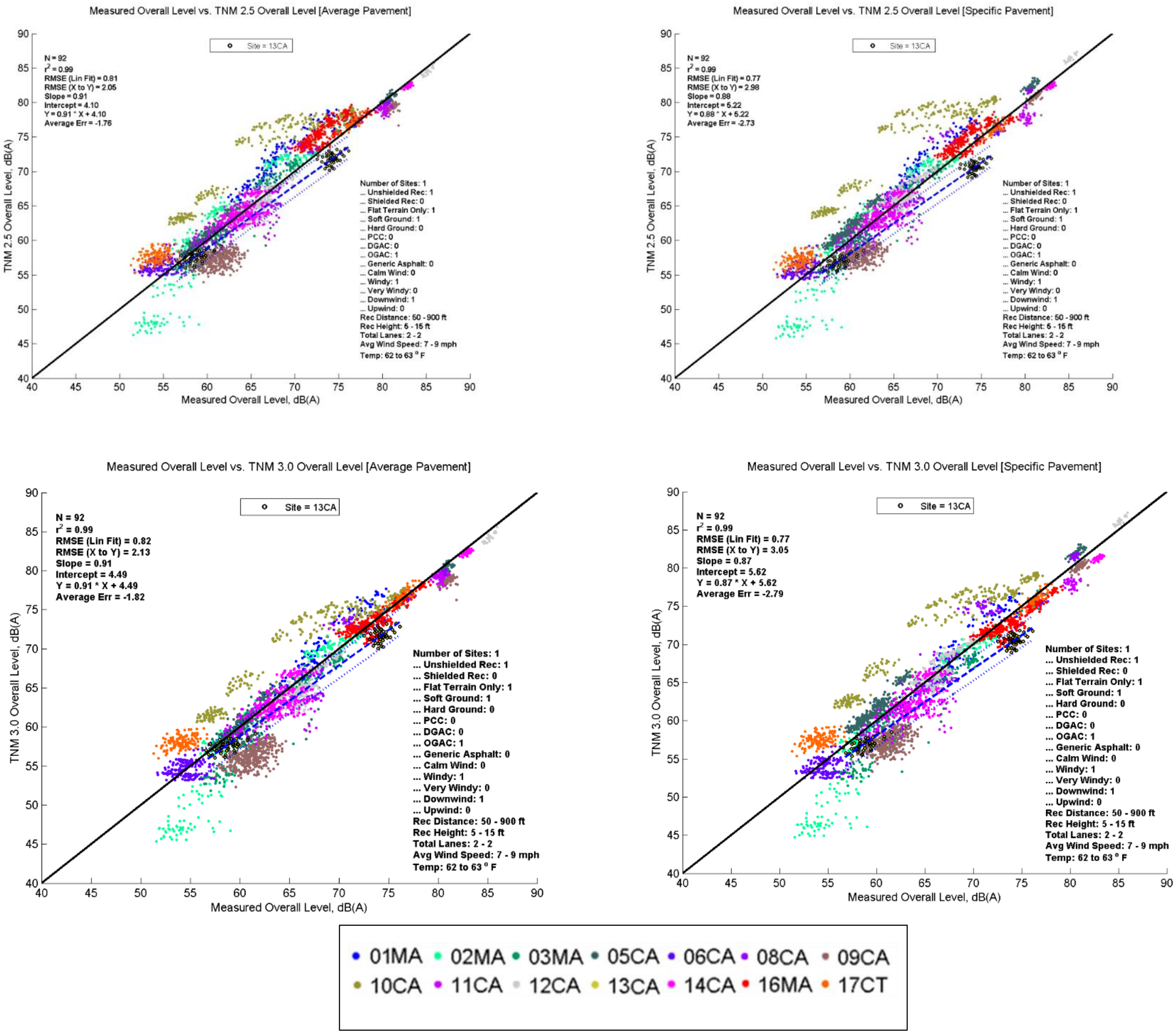

Figure H - 19: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 13CA

TABLE H - 19: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 13CA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	92	92	92	92
r^2	0.99	0.99	0.99	0.99
RMSE (Lin Fit)	0.81	0.77	0.82	0.77
RMSE (X to Y)	2.05	2.98	2.13	3.05
Slope	0.91	0.88	0.91	0.87
Intercept	4.1	5.22	4.49	5.62
Y	0.91 * X + 4.10	0.88 * X + 5.22	0.91 * X + 4.49	0.87 * X + 5.62
Average Error	-1.76	-2.73	-1.82	-2.79
Slope 95% CI	0.8906, 0.9331	0.8603, 0.9005	0.8836, 0.9265	0.8533, 0.8937
Intercept 95% CI	2.6778, 5.5230	3.8797, 6.5646	3.0542, 5.9245	4.2707, 6.9753
Avg Err 95% CI	-1.9779, -1.5425	-2.9732, -2.4783	-2.0452, -1.5932	-3.0429, -2.5291

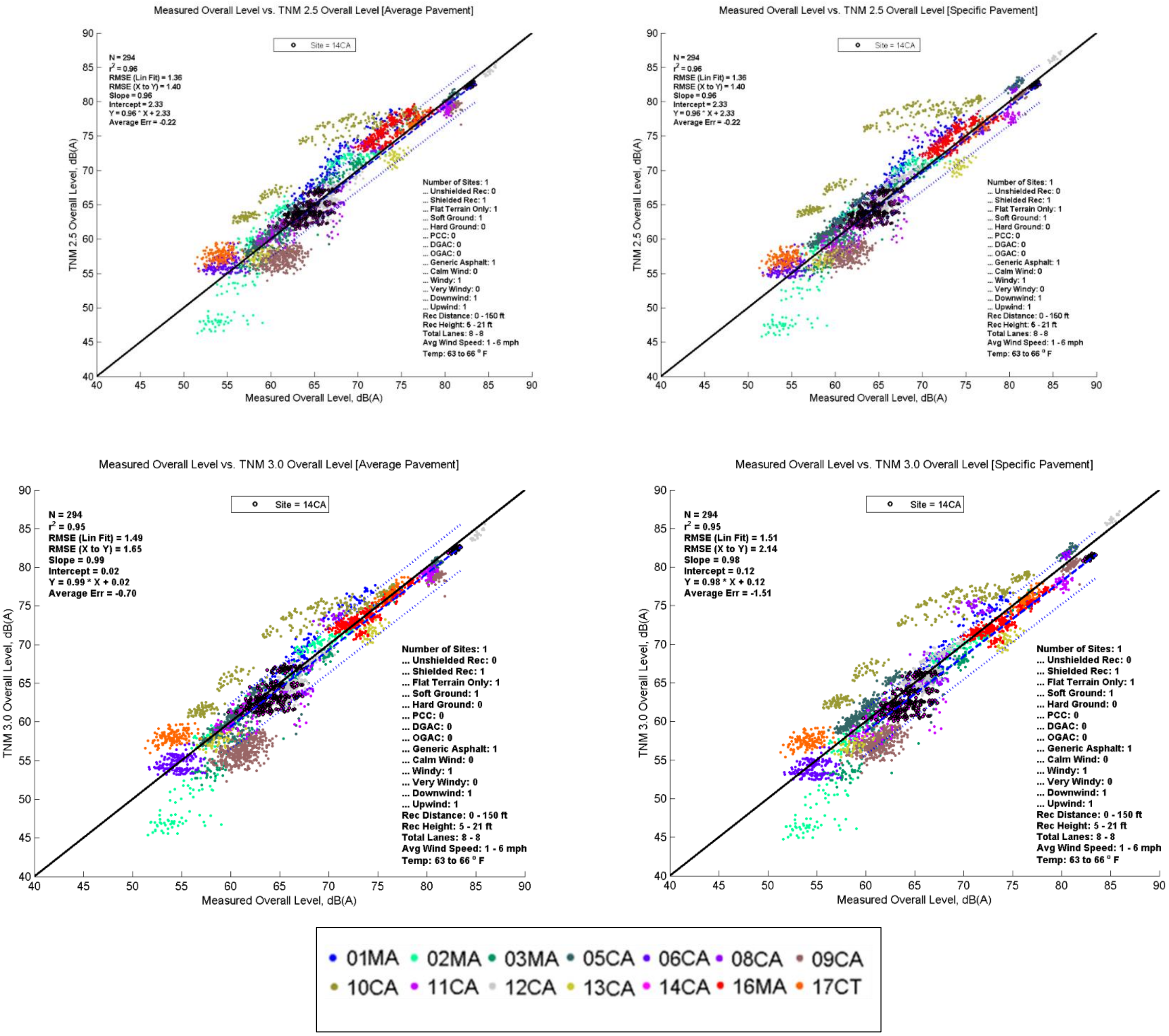

Figure H - 20: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 14CA

TABLE H - 20: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 14CA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	294	294	294	294
r^2	0.96	0.96	0.95	0.95
RMSE (Lin Fit)	1.36	1.36	1.49	1.51
RMSE (X to Y)	1.4	1.4	1.65	2.14
Slope	0.96	0.96	0.99	0.98
Intercept	2.33	2.33	0.02	0.12
Y	0.96 * X + 2.33	0.96 * X + 2.33	0.99 * X + 0.02	0.98 * X + 0.12
Average Error	-0.22	-0.22	-0.7	-1.51
Slope 95% CI	0.9385, 0.9851	0.9385, 0.9851	0.9636, 1.0148	0.9498, 1.0016
Intercept 95% CI	0.7673, 3.9014	0.7673, 3.9014	-1.7019, 1.7432	-1.6238, 1.8622
Avg Err 95% CI	-0.3818, -0.0660	-0.3818, -0.0660	-0.8711, -0.5296	-1.6815, -1.3343

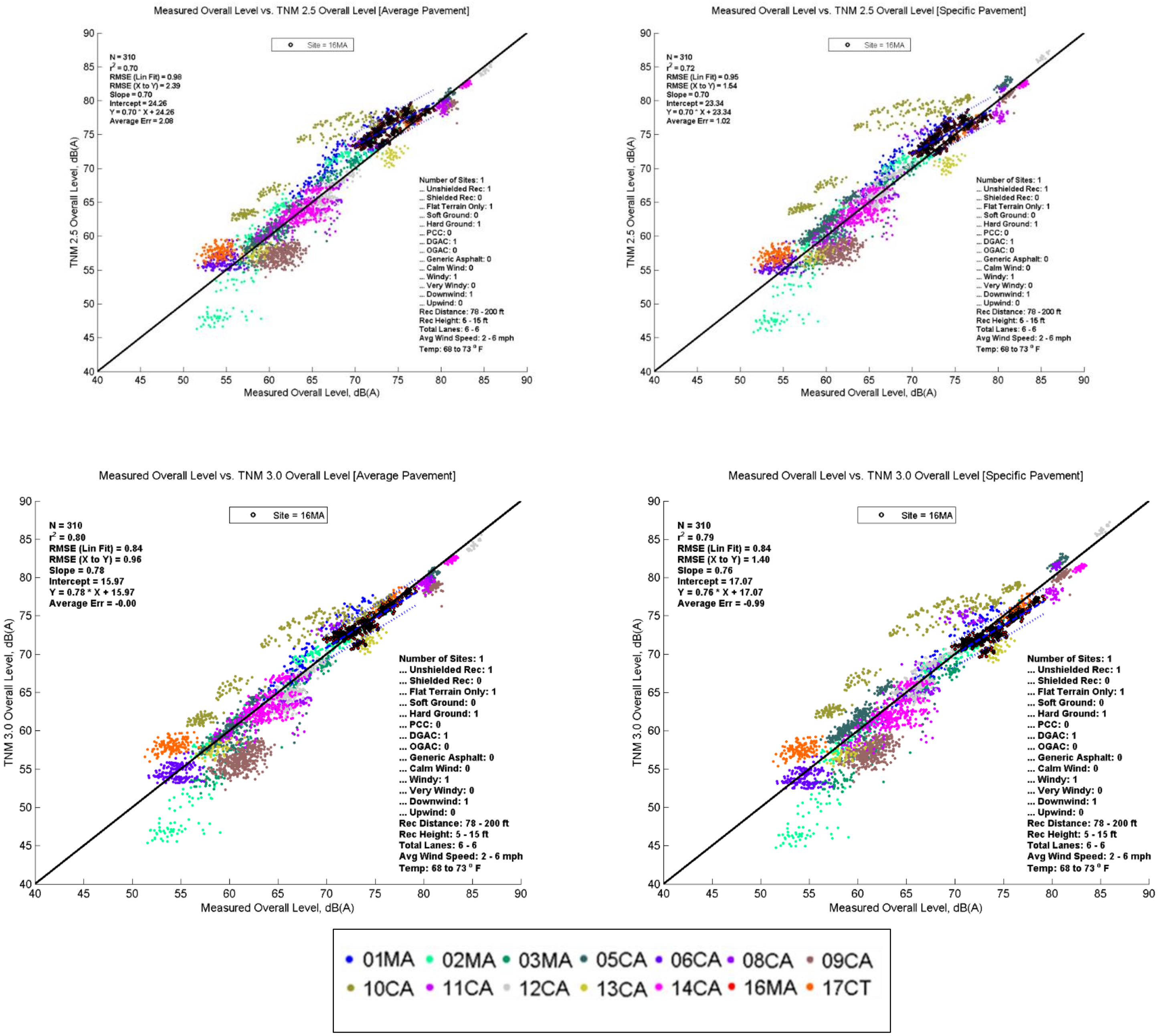

Figure H - 21: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 16MA

TABLE H - 21: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 16MA

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	310	310	310	310
r^2	0.7	0.72	0.8	0.79
RMSE (Lin Fit)	0.98	0.95	0.84	0.84
RMSE (X to Y)	2.39	1.54	0.96	1.4
Slope	0.7	0.7	0.78	0.76
Intercept	24.26	23.34	15.97	17.07
Y	0.70 * X + 24.26	0.70 * X + 23.34	0.78 * X + 15.97	0.76 * X + 17.07
Average Error	2.08	1.02	0	-0.99
Slope 95% CI	0.6493, 0.7503	0.6489, 0.7470	0.7403, 0.8273	0.7122, 0.7989
Intercept 95% CI	20.5246, 27.9884	19.7132, 26.9605	12.7571, 19.1842	13.8680, 20.2778
Avg Err 95% CI	1.9505, 2.2119	0.8944, 1.1510	-0.1106, 0.1040	-1.0956, -0.8746

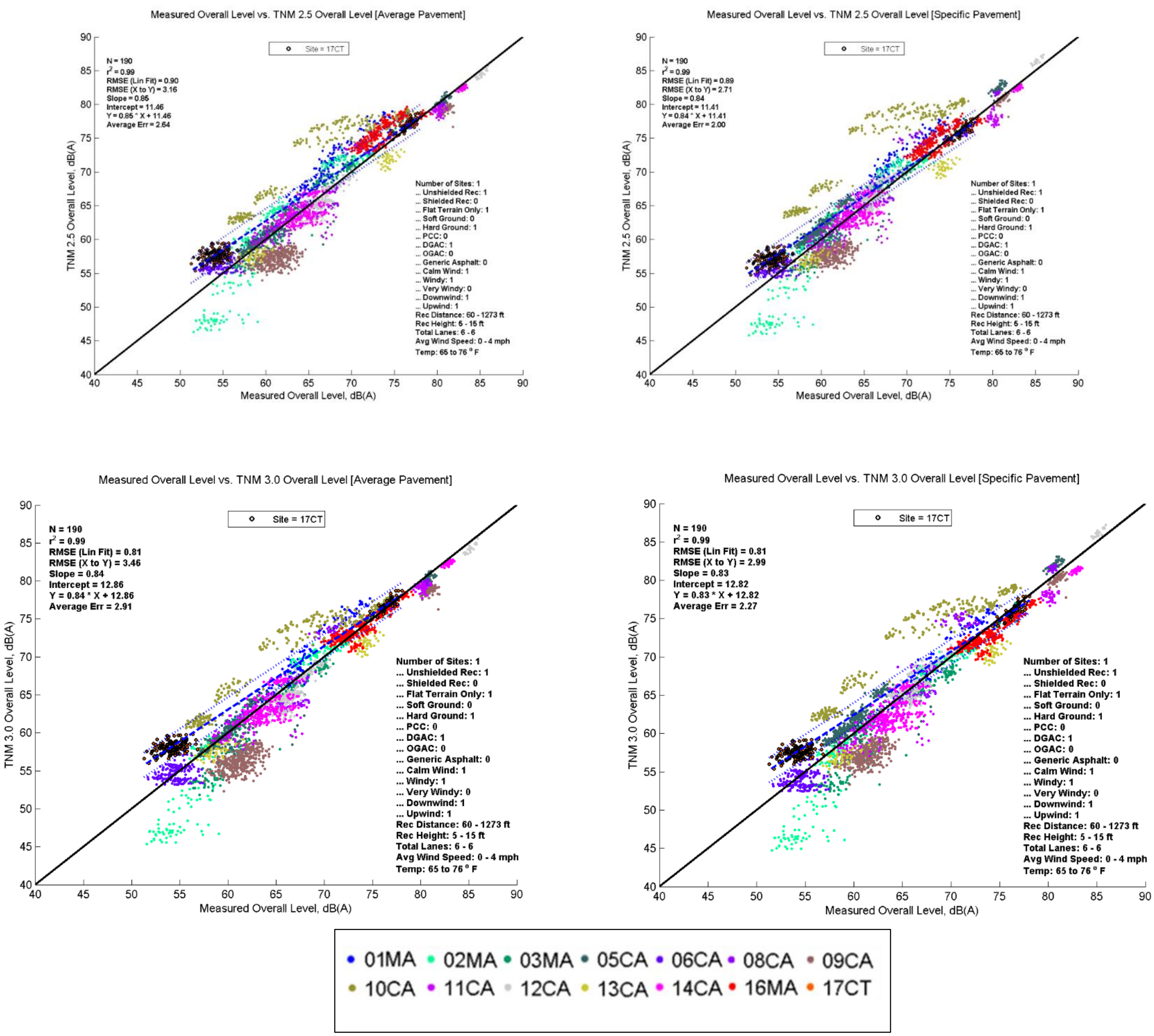

Figure H - 22: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 17CT

TABLE H - 22: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 17CT

	Average Measured vs. TNM 2.5	**Specific Measured vs. TNM 2.5**	**Average Measured vs. TNM 3.0**	**Specific Measured vs. TNM 3.0**
N	190	190	190	190
r^2	0.99	0.99	0.99	0.99
RMSE (Lin Fit)	0.9	0.89	0.81	0.81
RMSE (X to Y)	3.16	2.71	3.46	2.99
Slope	0.85	0.84	0.84	0.83
Intercept	11.46	11.41	12.86	12.82
Y	0.85 * X + 11.46	0.84 * X + 11.41	0.84 * X + 12.86	0.83 * X + 12.82
Average Error	2.64	2	2.91	2.27
Slope 95% CI	0.8422, 0.8673	0.8325, 0.8573	0.8248, 0.8473	0.8148, 0.8374
Intercept 95% CI	10.6843, 12.2291	10.6517, 12.1759	12.1678, 13.5578	12.1237, 13.5133
Avg Err 95% CI	2.3941, 2.8899	1.7440, 2.2628	2.6479, 3.1795	1.9861, 2.5440

APPENDIX I: COMPARISON OF MODELED AND MEASURED RESULTS (ADJUSTED FOR REFERENCE MICROPHONE)

In these figures, the colored circles represent individual 5-minute model computations (color coding is given in the legend); the blue dashed line shows the first-order linear regression between the two datasets; the blue dotted lines indicate the 95-percent prediction interval for any new computations; and the solid black line indicates where all results would fall if both models gave the same predictions for all analyses. Note that in the upper left-hand corner of the graph several statistical parameters are presented: the number of samples, the coefficient of determination (r^2), the root mean squared error (RMSE), the regression slope and intercept, the regression equation, and the average difference. These statistics are also repeated in the tables that follow. In the lower right-hand corner, a metadata summary is provided covering the number of sites, the presence of a barrier, receiver distances and heights, number of roadway lanes, pavement type, and temperature and wind conditions included in the analysis. Each site is presented in a different color in order to help highlight any potential grouping of the data.

In general, the larger the sample size, the higher the confidence for the computation of all parameters. In this report, the maximum number of modeled samples is 5987. When sub-sets are examined, the number of samples will be smaller. The r^2 provides a measure of correlation. The RMSE provides a measure of absolute variation between the two predictions and represents the sample standard deviation. A slope (m) of one indicates that for every 1-dB change in one model's prediction there will be an identical 1-dB change in the other model's prediction. If the slope is less than one, then the model on the y-axis tends to change predictions slower than the model on the x-axis and *vice versa*. If the intercept (b) is zero and the slope is one, then there is perfect agreement between the two datasets. If the intercept is negative, then the model on the y-axis predicts lower levels than the model on the x-axis for low levels and *vice versa*; however, the average difference provides a measure of the *overall bias* between the two datasets.

I.1 TNM Predictions vs. Measured Results - All Data Analyzed

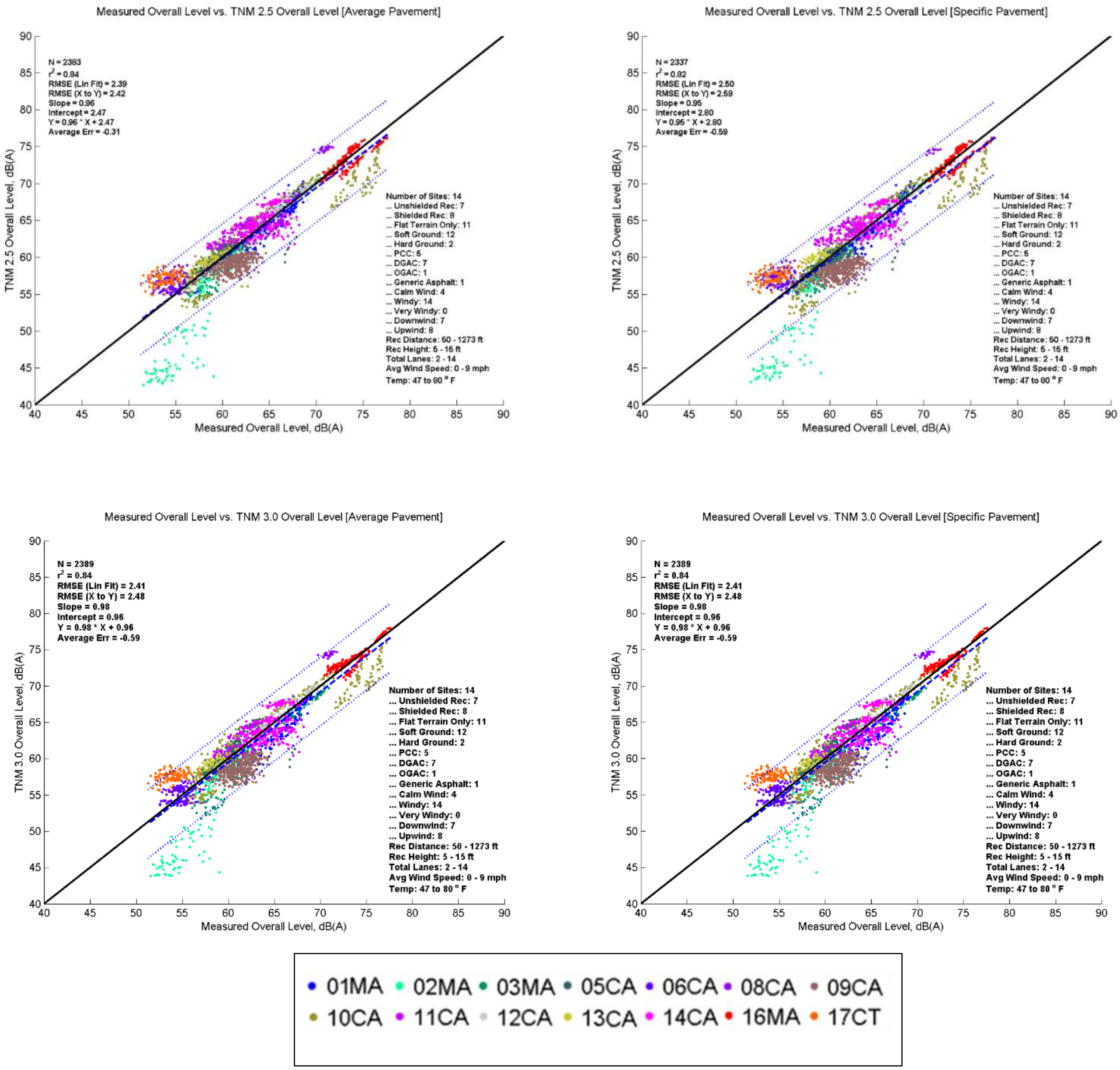

Figure I - 1: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – All Data, adj.

TABLE I - 1: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – ALL DATA, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	2383	2337	2389	2389
r^2	0.84	0.82	0.84	0.84
RMSE (Lin Fit)	2.39	2.5	2.41	2.41
RMSE (X to Y)	2.42	2.59	2.48	2.48
Slope	0.96	0.95	0.98	0.98
Intercept	2.47	2.8	0.96	0.96
Y	0.96 * X + 2.47	0.95 * X + 2.80	0.98 * X + 0.96	0.98 * X + 0.96
Average Error	-0.31	-0.59	-0.59	-0.59
Slope 95% CI	0.9387, 0.9728	0.9280, 0.9640	0.9581, 0.9924	0.9581, 0.9924
Intercept 95% CI	1.3935, 3.5421	1.6632, 3.9287	-0.1181, 2.0423	-0.1181, 2.0423
Avg Err 95% CI	-0.4064, -0.2133	-0.6877, -0.4831	-0.6886, -0.4954	-0.6886, -0.4954

I.2 TNM Predictions vs. Measured Results - Ground Type

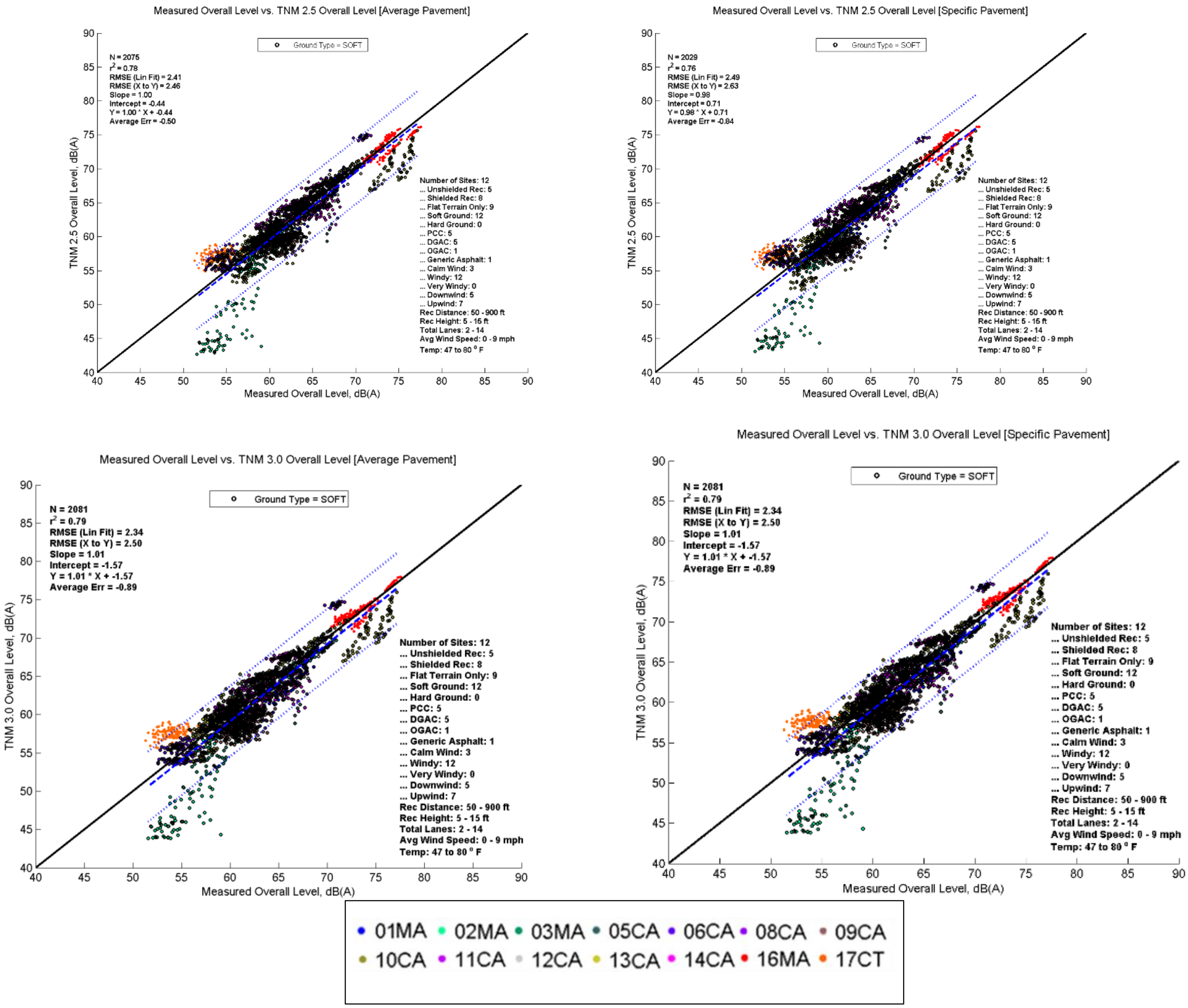

Figure I - 2: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Acoustically Soft Ground, adj.

TABLE I - 2: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – ACOUSTICALLY SOFT GROUND, ADJ.

	Average Measured vs. TNM 2.5	**Specific Measured vs. TNM 2.5**	**Average Measured vs. TNM 3.0**	**Specific Measured vs. TNM 3.0**
N	2075	2029	2081	2081
r^2	0.78	0.76	0.79	0.79
RMSE (Lin Fit)	2.41	2.49	2.34	2.34
RMSE (X to Y)	2.46	2.63	2.5	2.5
Slope	1	0.98	1.01	1.01
Intercept	-0.44	0.71	-1.57	-1.57
Y	1.00 * X + -0.44	0.98 * X + 0.71	1.01 * X + -1.57	1.01 * X + -1.57
Average Error	-0.5	-0.84	-0.89	-0.89
Slope 95% CI	0.9764, 1.0218	0.9511, 0.9990	0.9889, 1.0330	0.9889, 1.0330
Intercept 95% CI	-1.8616, 0.9733	-0.7824, 2.2025	-2.9430, -0.1909	-2.9430, -0.1909
Avg Err 95% CI	-0.6031, -0.3958	-0.9464, -0.7291	-0.9856, -0.7845	-0.9856, -0.7845

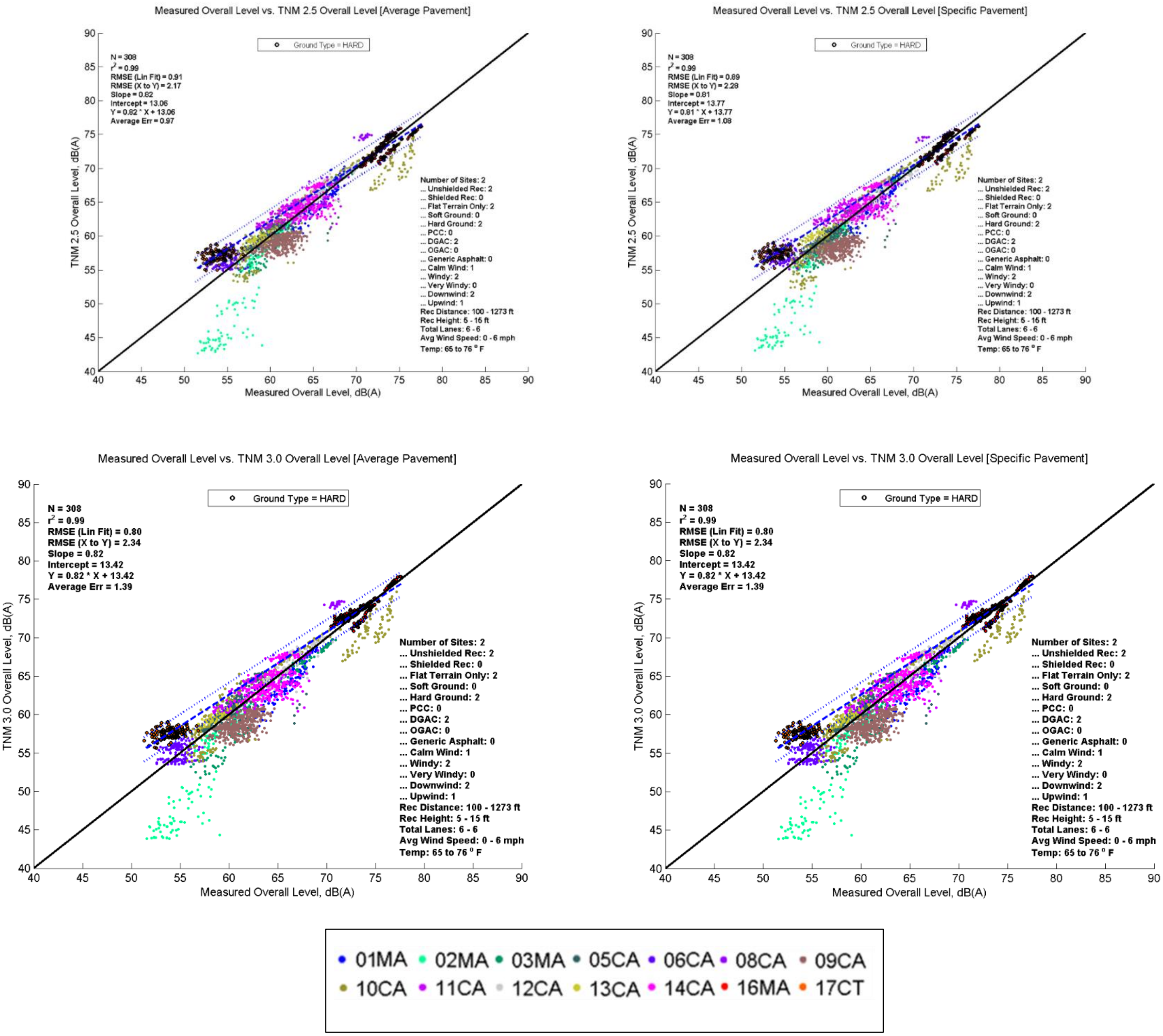

Figure I - 3: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Acoustically Hard Ground, adj.

TABLE I - 3: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – ACOUSTICALLY HARD GROUND, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	308	308	308	308
r^2	0.99	0.99	0.99	0.99
RMSE (Lin Fit)	0.91	0.89	0.8	0.8
RMSE (X to Y)	2.17	2.28	2.34	2.34
Slope	0.82	0.81	0.82	0.82
Intercept	13.06	13.77	13.42	13.42
Y	0.82 * X + 13.06	0.81 * X + 13.77	0.82 * X + 13.42	0.82 * X + 13.42
Average Error	0.97	1.08	1.39	1.39
Slope 95% CI	0.8073, 0.8289	0.7987, 0.8197	0.8097, 0.8285	0.8097, 0.8285
Intercept 95% CI	12.3408, 13.7888	13.0599, 14.4724	12.7874, 14.0514	12.7874, 14.0514
Avg Err 95% CI	0.7500, 1.1849	0.8525, 1.3019	1.1770, 1.5986	1.1770, 1.5986

I.3 TNM PREDICTIONS VS. MEASURED RESULTS - BARRIERS

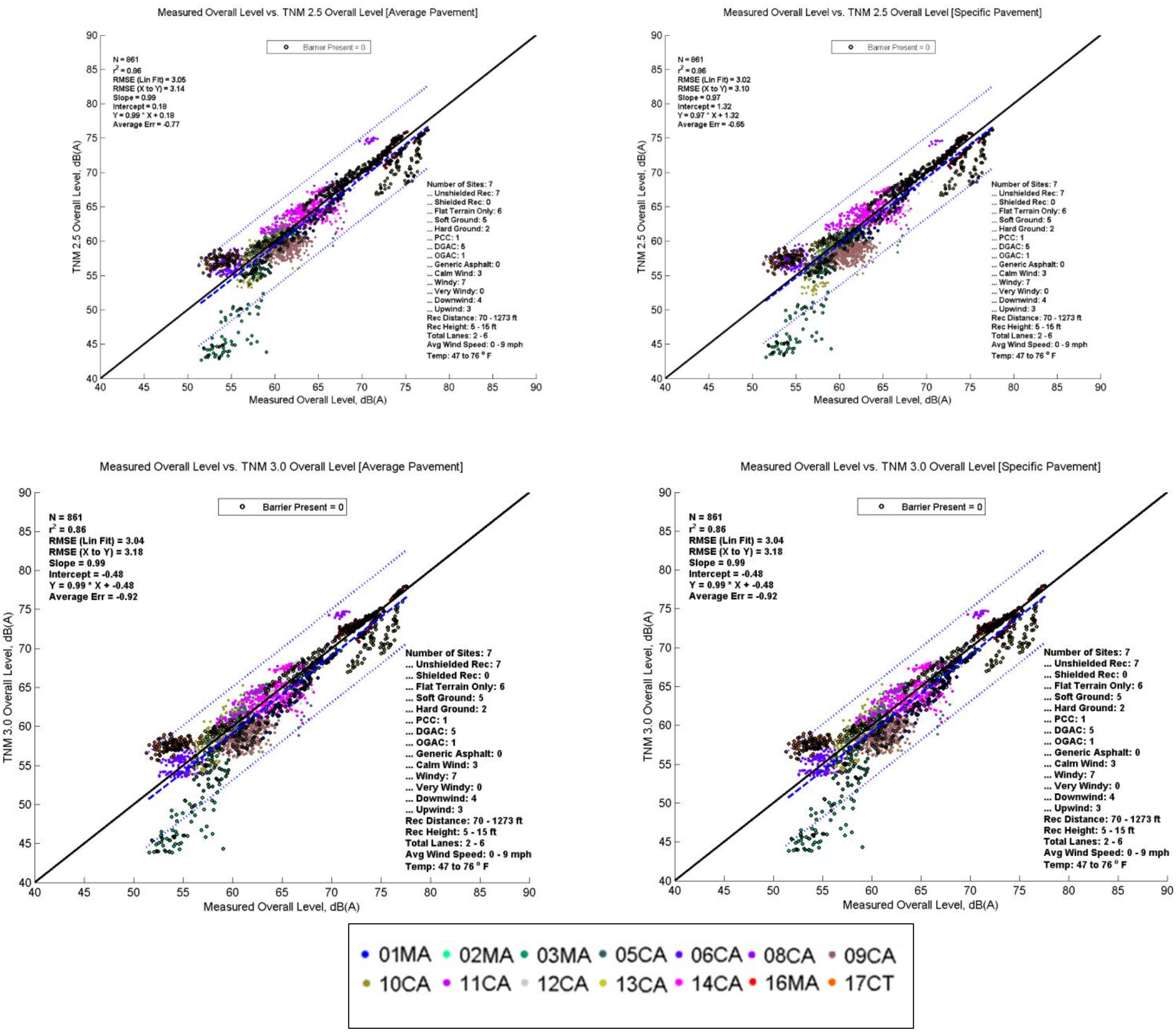

Figure I - 4: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Site without Barriers, adj.

TABLE I - 4: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – SITE WITHOUT BARRIERS, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	861	861	861	861
r^2	0.86	0.86	0.86	0.86
RMSE (Lin Fit)	3.05	3.02	3.04	3.04
RMSE (X to Y)	3.14	3.1	3.18	3.18
Slope	0.99	0.97	0.99	0.99
Intercept	0.18	1.32	-0.48	-0.48
Y	0.99 * X + 0.18	0.97 * X + 1.32	0.99 * X + -0.48	0.99 * X + -0.48
Average Error	-0.77	-0.65	-0.92	-0.92
Slope 95% CI	0.9587, 1.0120	0.9433, 0.9961	0.9666, 1.0198	0.9666, 1.0198
Intercept 95% CI	-1.5630, 1.9152	-0.4088, 3.0449	-2.2182, 1.2574	-2.2182, 1.2574
Avg Err 95% CI	-0.9758, -0.5689	-0.8497, -0.4447	-1.1269, -0.7205	-1.1269, -0.7205

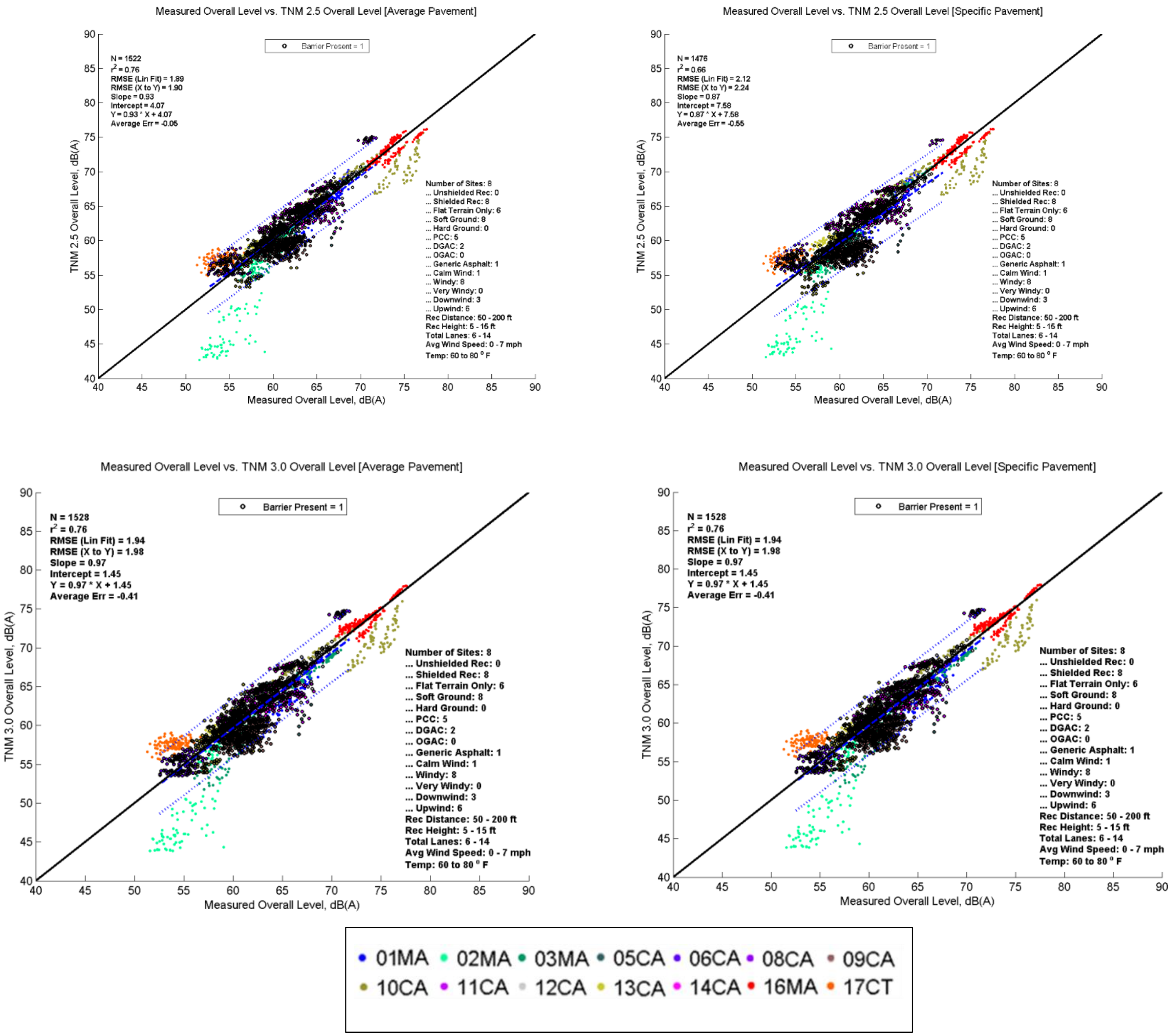

Figure I - 5: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Site with Barriers, adj.

TABLE I - 5: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – SITE WITH BARRIERS, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	1522	1476	1528	1528
r^2	0.76	0.66	0.76	0.76
RMSE (Lin Fit)	1.89	2.12	1.94	1.94
RMSE (X to Y)	1.9	2.24	1.98	1.98
Slope	0.93	0.87	0.97	0.97
Intercept	4.07	7.58	1.45	1.45
Y	0.93 * X + 4.07	0.87 * X + 7.58	0.97 * X + 1.45	0.97 * X + 1.45
Average Error	-0.05	-0.55	-0.41	-0.41
Slope 95% CI	0.9064, 0.9596	0.8359, 0.8991	0.9425, 0.9971	0.9425, 0.9971
Intercept 95% CI	2.4334, 5.7147	5.6405, 9.5239	-0.2301, 3.1391	-0.2301, 3.1391
Avg Err 95% CI	-0.1438, 0.0473	-0.6601, -0.4385	-0.5025, -0.3077	-0.5025, -0.3077

I.4 TNM Predictions vs. Measured Results - Distance

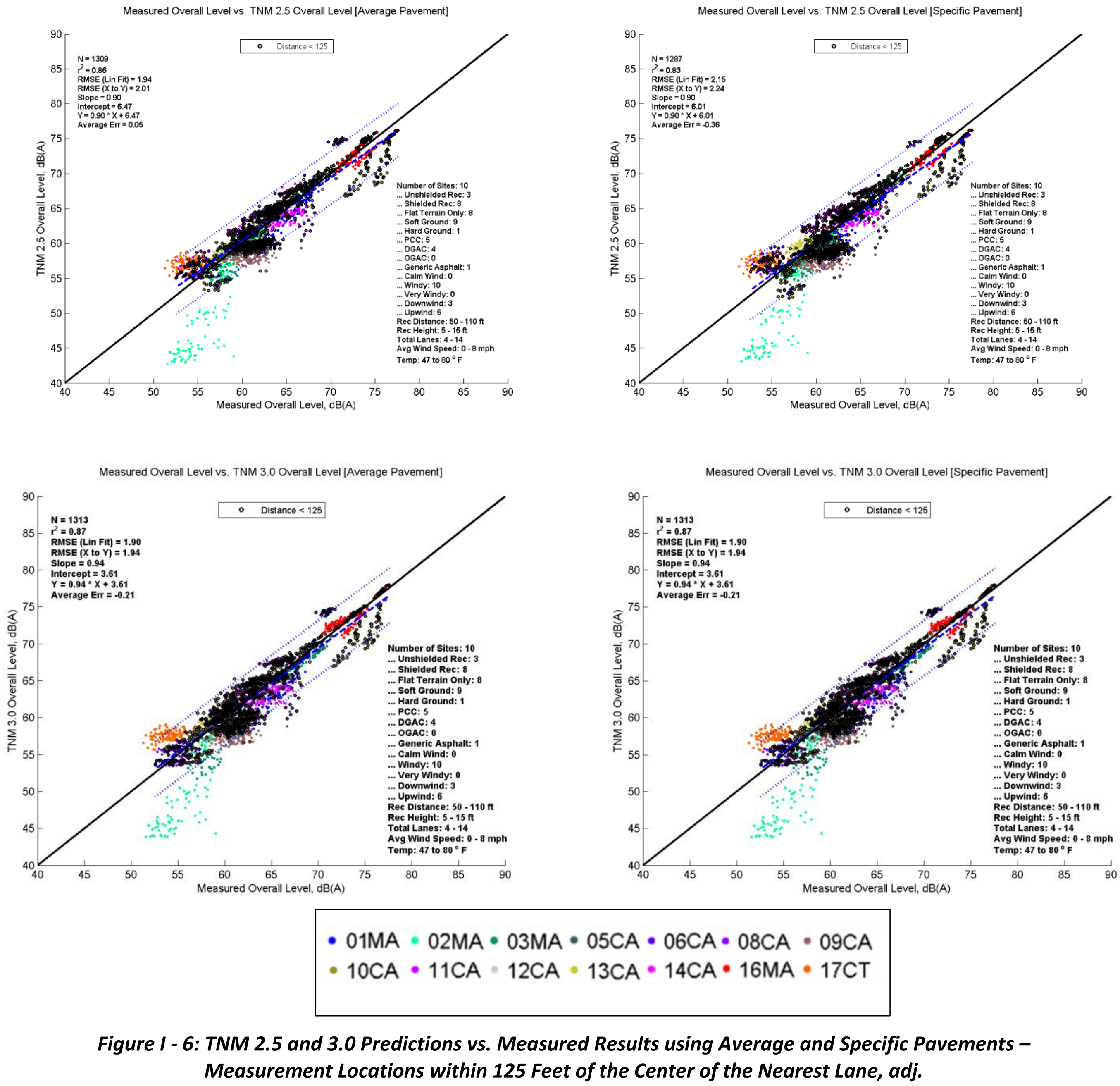

Figure I - 6: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Measurement Locations within 125 Feet of the Center of the Nearest Lane, adj.

TABLE I - 6: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – MEASUREMENT LOCATIONS WITHIN 125 FEET OF THE CENTER OF THE NEAREST LANE, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	1309	1287	1313	1313
r^2	0.86	0.83	0.87	0.87
RMSE (Lin Fit)	1.94	2.15	1.9	1.9
RMSE (X to Y)	2.01	2.24	1.94	1.94
Slope	0.9	0.9	0.94	0.94
Intercept	6.47	6.01	3.61	3.61
Y	0.90 * X + 6.47	0.90 * X + 6.01	0.94 * X + 3.61	0.94 * X + 3.61
Average Error	0.05	-0.36	-0.21	-0.21
Slope 95% CI	0.8790, 0.9186	0.8774, 0.9217	0.9131, 0.9525	0.9219, 0.9636
Intercept 95% CI	5.2134, 7.7358	4.6016, 7.4228	2.9103, 5.4192	1.9731, 4.6198
Avg Err 95% CI	-0.0624, 0.1553	-0.4776, -0.2358	-0.2065, -0.0055	-0.4385, -0.2184

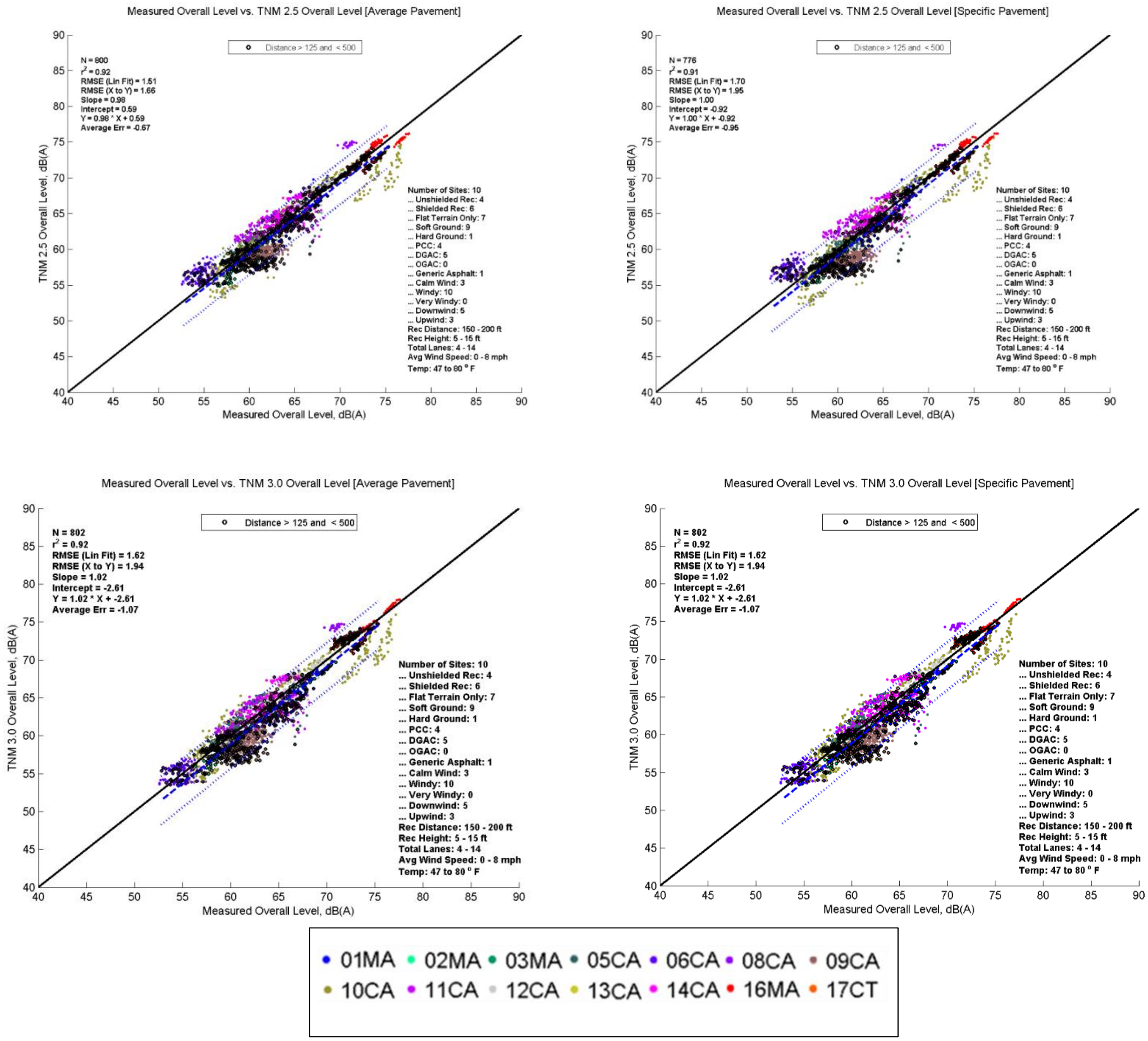

Figure I - 7: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Measurement Locations between 125 and 500 Feet of the Center of the Nearest Lane, adj.

TABLE I - 7: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – MEASUREMENT LOCATIONS BETWEEN 125 AND 500 FEET OF THE CENTER OF THE NEAREST LANE, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	800	776	802	802
r^2	0.92	0.91	0.92	0.92
RMSE (Lin Fit)	1.51	1.7	1.62	1.62
RMSE (X to Y)	1.66	1.95	1.94	1.94
Slope	0.98	1	1.02	1.02
Intercept	0.59	-0.92	-2.61	-2.61
Y	0.98 * X + 0.59	1.00 * X + -0.92	1.02 * X + -2.61	1.02 * X + -2.61
Average Error	-0.67	-0.95	-1.07	-1.07
Slope 95% CI	0.9605, 0.9999	0.9773, 1.0218	1.0030, 1.0451	1.0030, 1.0451
Intercept 95% CI	-0.6701, 1.8518	-2.3477, 0.5020	-3.9520, -1.2594	-3.9520, -1.2594
Avg Err 95% CI	-0.7778, -0.5679	-1.0701, -0.8304	-1.1844, -0.9602	-1.1844, -0.9602

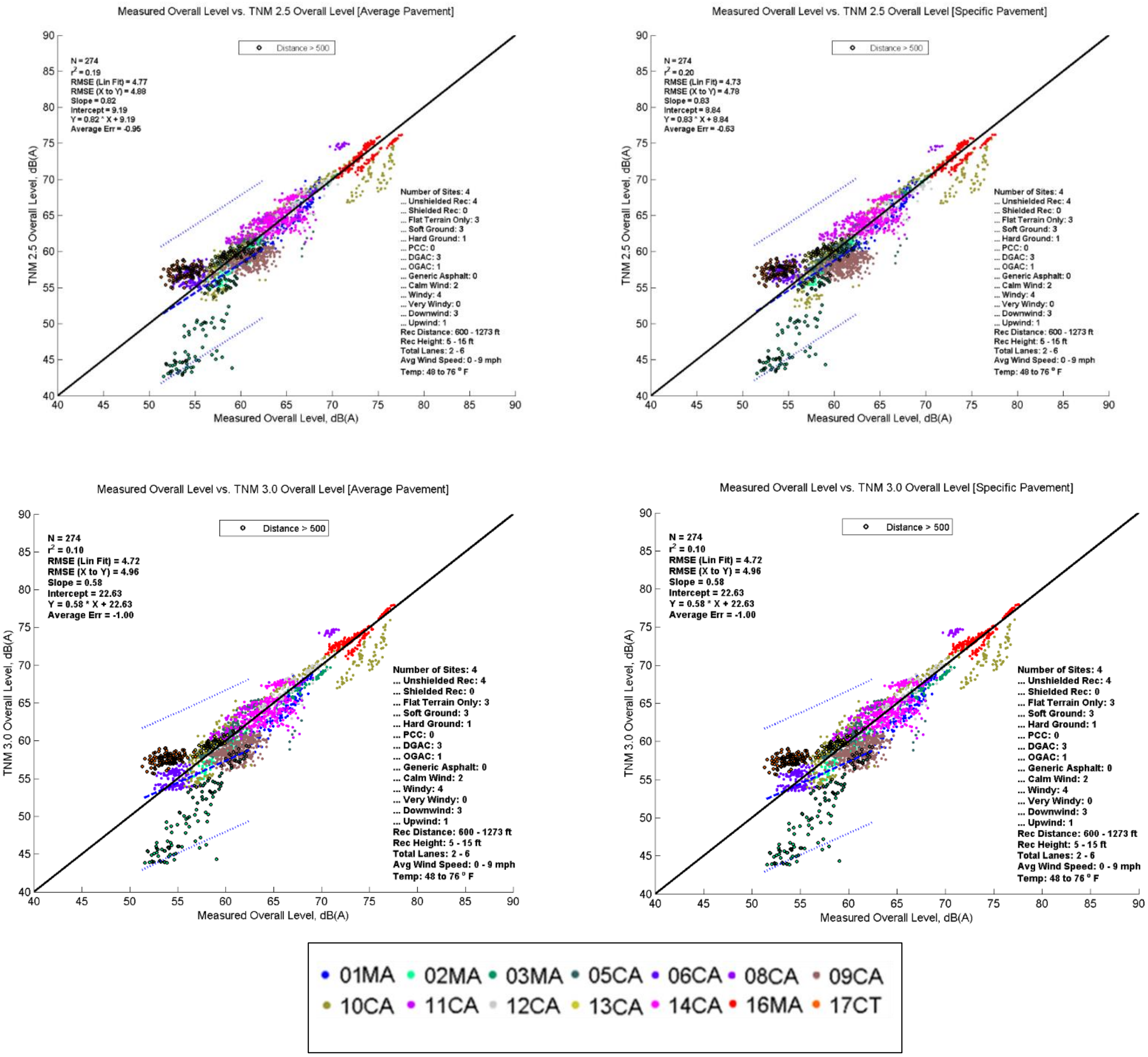

Figure I - 8: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – Measurement Locations Greater than 500 Feet of the Center of the Nearest Lane, adj.

TABLE I - 8: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – MEASUREMENT LOCATIONS GREATER THAN 500 FEET OF THE CENTER OF THE NEAREST LANE, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	274	274	274	274
r^2	0.19	0.2	0.1	0.1
RMSE (Lin Fit)	4.77	4.73	4.72	4.72
RMSE (X to Y)	4.88	4.78	4.96	4.96
Slope	0.82	0.83	0.58	0.58
Intercept	9.19	8.84	22.63	22.63
Y	0.82 * X + 9.19	0.83 * X + 8.84	0.58 * X + 22.63	0.58 * X + 22.63
Average Error	-0.95	-0.63	-1	-1
Slope 95% CI	0.6189, 1.0193	0.6328, 1.0295	0.3804, 0.7764	0.3804, 0.7764
Intercept 95% CI	-2.0500, 20.4202	-2.2958, 19.9686	11.5171, 33.7373	11.5171, 33.7373
Avg Err 95% CI	-1.5199, -0.3847	-1.1881, -0.0641	-1.5790, -0.4277	-1.5790, -0.4277

I.5 Variation by Site

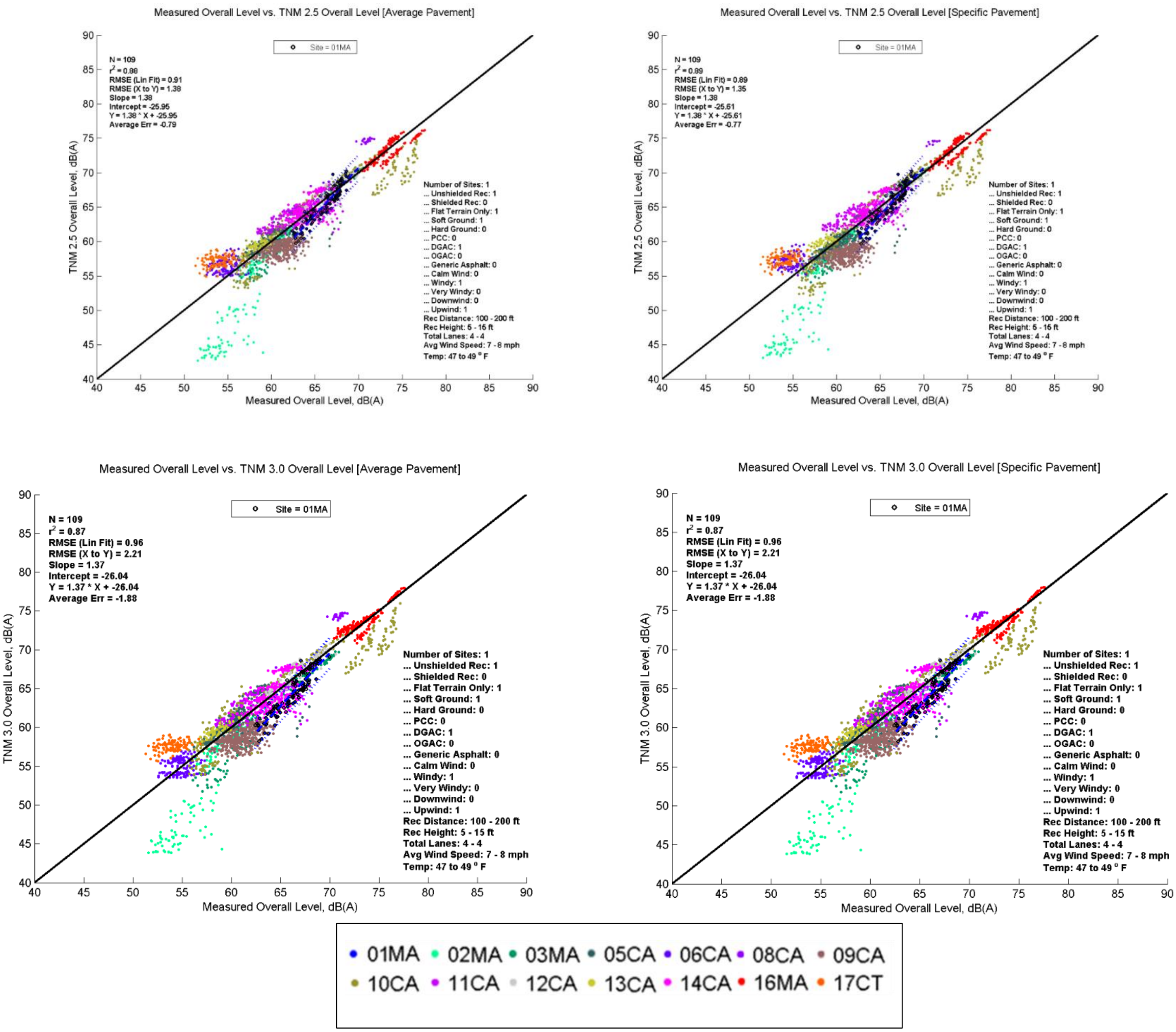

Figure I - 9: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 01MA, adj.

TABLE I - 9: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 01MA, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	109	109	109	109
r^2	0.88	0.89	0.87	0.87
RMSE (Lin Fit)	0.91	0.89	0.96	0.96
RMSE (X to Y)	1.38	1.35	2.21	2.21
Slope	1.38	1.38	1.37	1.37
Intercept	-25.95	-25.61	-26.04	-26.04
Y	1.38 * X + -25.95	1.38 * X + -25.61	1.37 * X + -26.04	1.37 * X + -26.04
Average Error	-0.79	-0.77	-1.88	-1.88
Slope 95% CI	1.2866, 1.4752	1.2833, 1.4691	1.2657, 1.4662	1.2657, 1.4662
Intercept 95% CI	-32.1752, -19.7174	-31.7489, -19.4805	-32.6667, -19.4190	-32.6667, -19.4190
Avg Err 95% CI	-1.0033, -0.5773	-0.9805, -0.5604	-2.0950, -1.6576	-2.0950, -1.6576

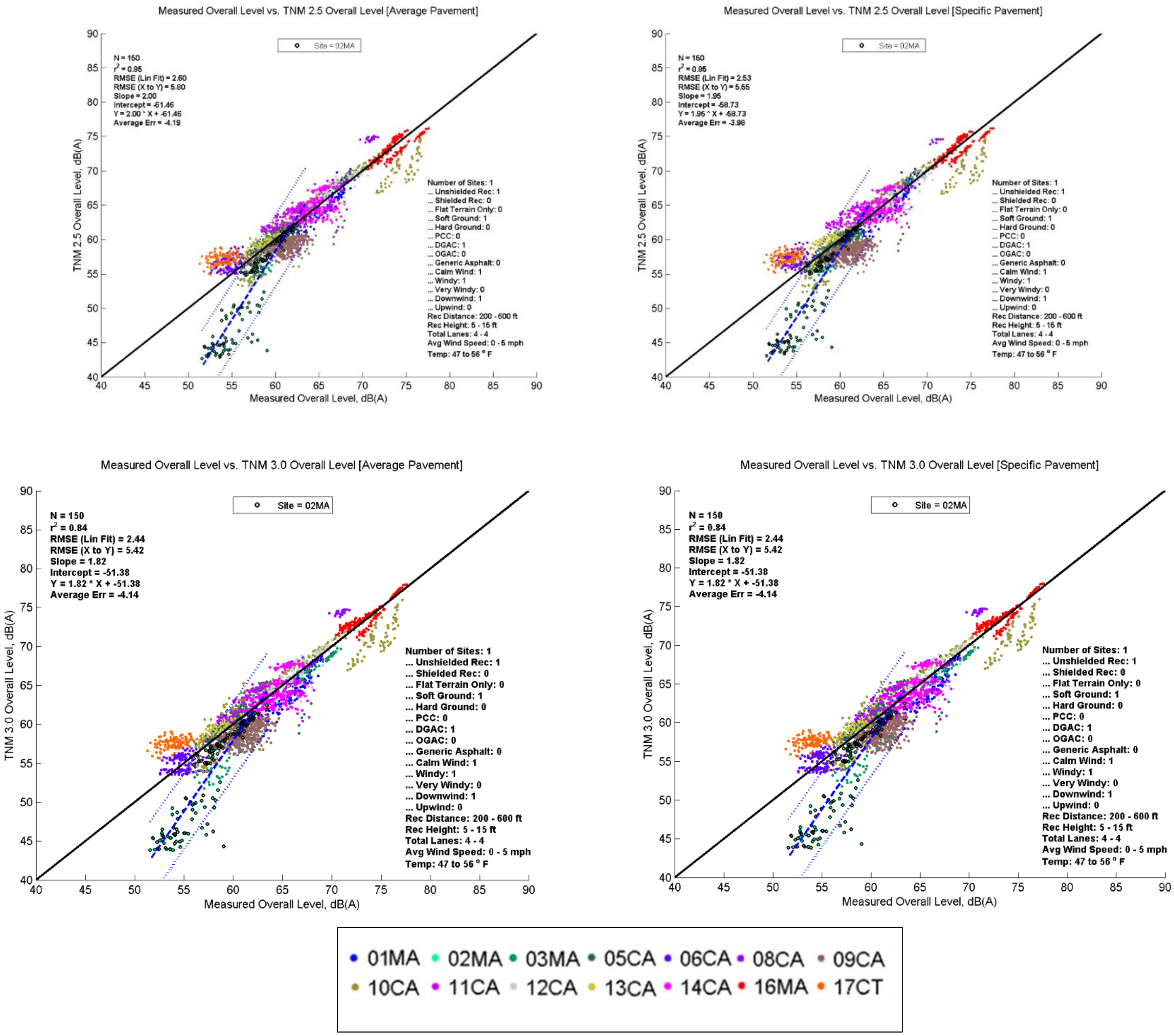

Figure I - 10: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 02MA, adj.

TABLE I - 10: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 02MA, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	150	150	150	150
r^2	0.85	0.85	0.84	0.84
RMSE (Lin Fit)	2.6	2.53	2.44	2.44
RMSE (X to Y)	5.8	5.55	5.42	5.42
Slope	2	1.95	1.82	1.82
Intercept	-61.46	-58.73	-51.38	-51.38
Y	2.00 * X + -61.46	1.95 * X + -58.73	1.82 * X + -51.38	1.82 * X + -51.38
Average Error	-4.19	-3.98	-4.14	-4.14
Slope 95% CI	1.8600, 2.1308	1.8198, 2.0834	1.6941, 1.9479	1.6941, 1.9479
Intercept 95% CI	-69.2631, -53.6605	-66.3219, -51.1342	-58.6876, -44.0661	-58.6876, -44.0661
Avg Err 95% CI	-4.8363, -3.5487	-4.6010, -3.3607	-4.7049, -3.5805	-4.7049, -3.5805

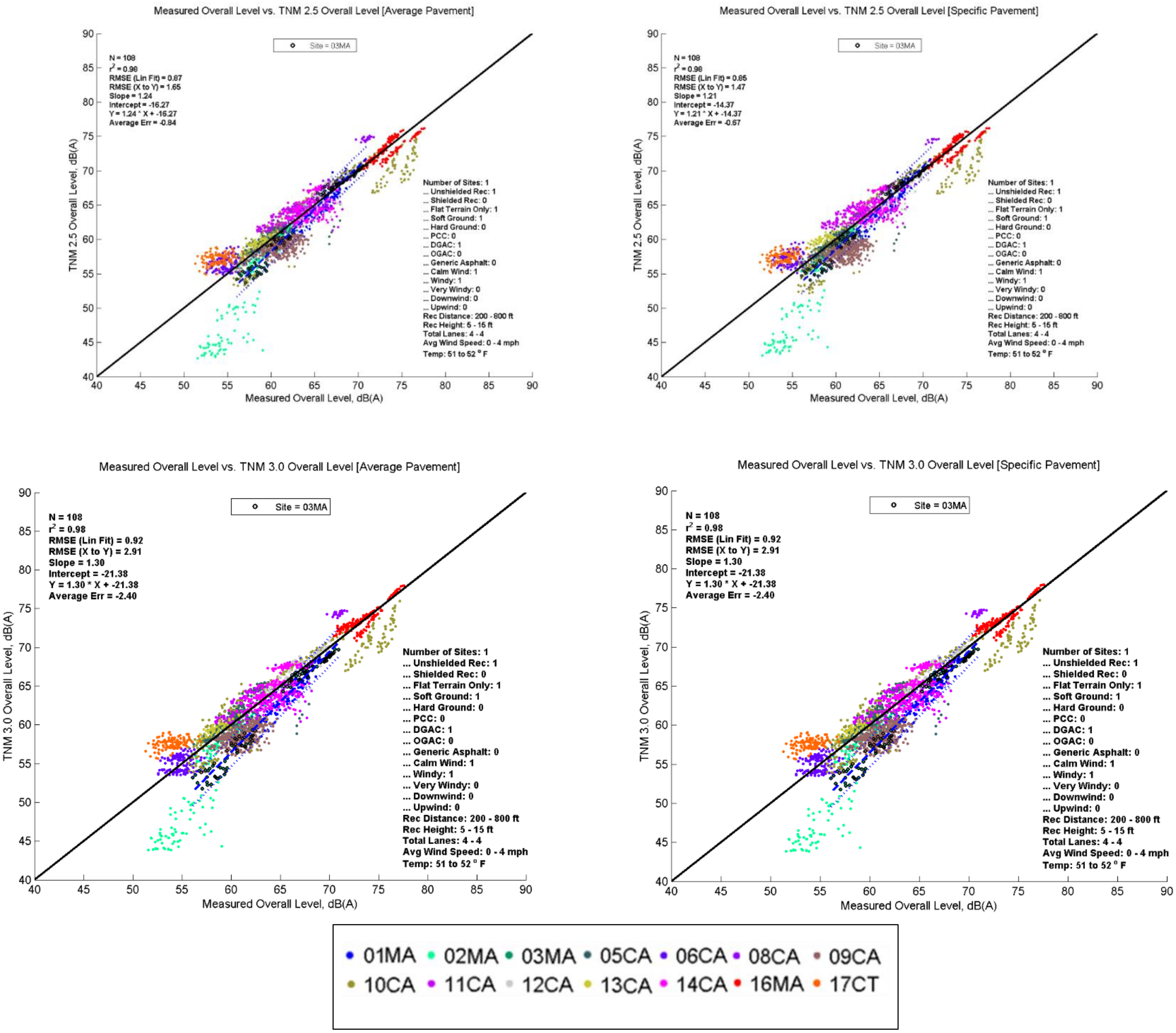

Figure I - 11: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 03MA, adj.

TABLE I - 11: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 03MA, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	108	108	108	108
r^2	0.98	0.98	0.98	0.98
RMSE (Lin Fit)	0.87	0.85	0.92	0.92
RMSE (X to Y)	1.65	1.47	2.91	2.91
Slope	1.24	1.21	1.3	1.3
Intercept	-16.27	-14.37	-21.38	-21.38
Y	1.24 * X + -16.27	1.21 * X + -14.37	1.30 * X + -21.38	1.30 * X + -21.38
Average Error	-0.84	-0.67	-2.4	-2.4
Slope 95% CI	1.2061, 1.2766	1.1800, 1.2484	1.2595, 1.3342	1.2595, 1.3342
Intercept 95% CI	-18.5294, -14.0066	-16.5612, -12.1734	-23.7696, -18.9826	-23.7696, -18.9826
Avg Err 95% CI	-1.1080, -0.5710	-0.9202, -0.4267	-2.7109, -2.0829	-2.7109, -2.0829

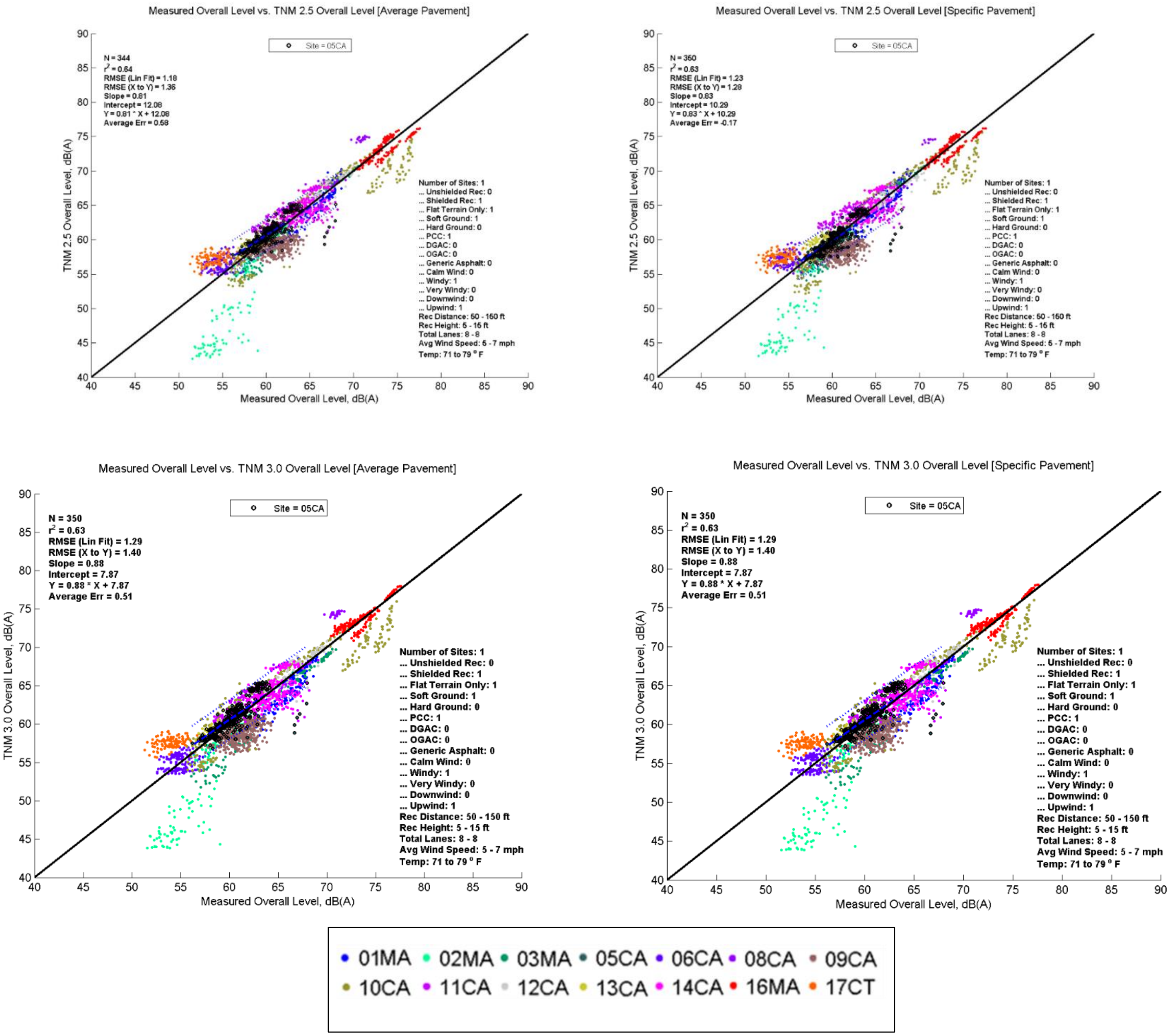

Figure I - 12: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 05CA, adj.

TABLE I - 12: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 05CA, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	344	350	350	350
r^2	0.64	0.63	0.63	0.63
RMSE (Lin Fit)	1.18	1.23	1.29	1.29
RMSE (X to Y)	1.36	1.28	1.4	1.4
Slope	0.81	0.83	0.88	0.88
Intercept	12.08	10.29	7.87	7.87
Y	0.81 * X + 12.08	0.83 * X + 10.29	0.88 * X + 7.87	0.88 * X + 7.87
Average Error	0.58	-0.17	0.51	0.51
Slope 95% CI	0.7447, 0.8741	0.7598, 0.8934	0.8076, 0.9484	0.8076, 0.9484
Intercept 95% CI	8.1756, 15.9827	6.2606, 14.3278	3.6183, 12.1175	3.6183, 12.1175
Avg Err 95% CI	0.4467, 0.7079	-0.3048, -0.0387	0.3687, 0.6436	0.3687, 0.6436

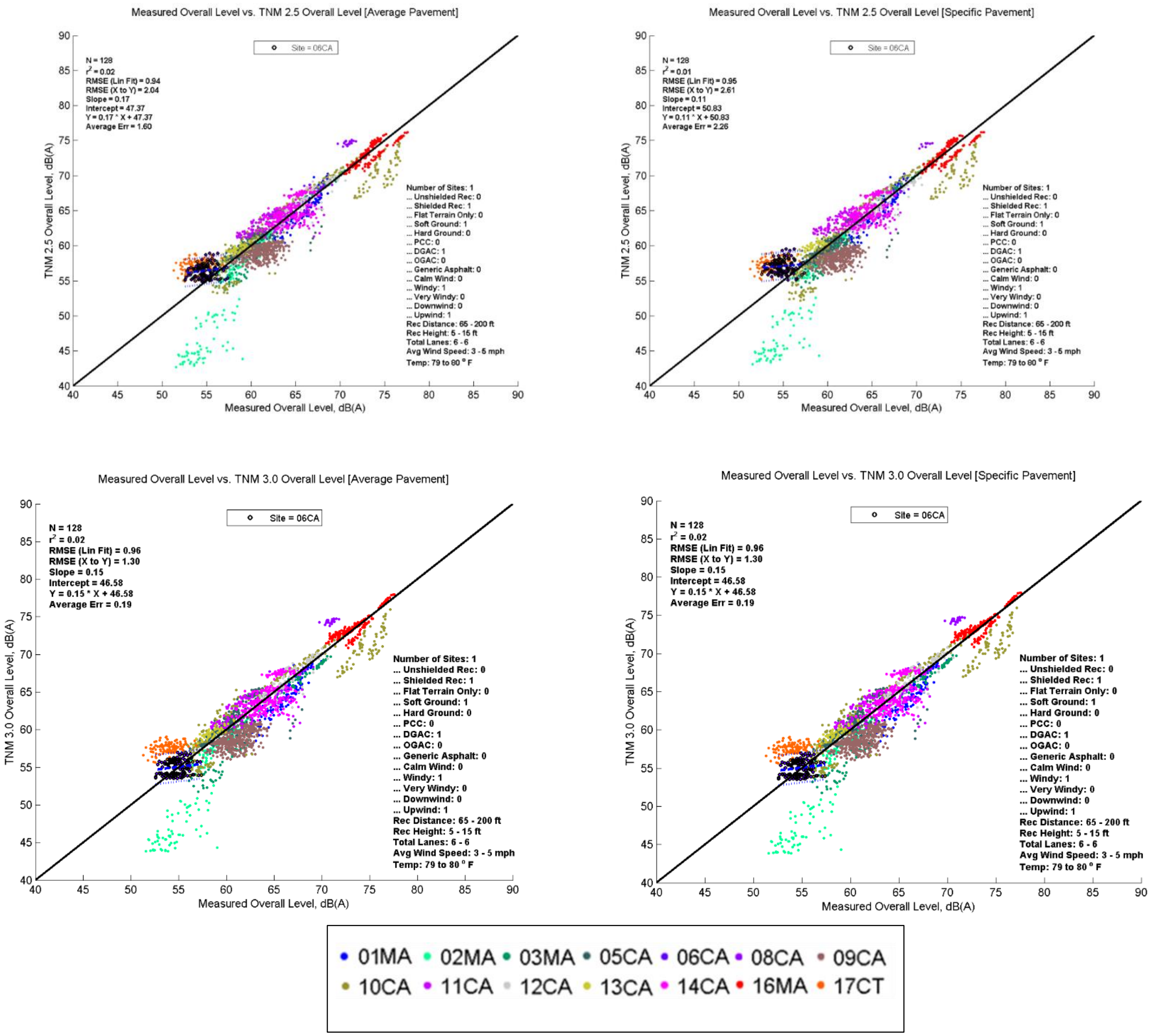

Figure I - 13: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 06CA, adj.

TABLE I - 13: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 06CA, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	128	128	128	128
r^2	0.02	0.01	0.02	0.02
RMSE (Lin Fit)	0.94	0.95	0.96	0.96
RMSE (X to Y)	2.04	2.61	1.3	1.3
Slope	0.17	0.11	0.15	0.15
Intercept	47.37	50.83	46.58	46.58
Y	0.17 * X + 47.37	0.11 * X + 50.83	0.15 * X + 46.58	0.15 * X + 46.58
Average Error	1.6	2.26	0.19	0.19
Slope 95% CI	0.0066, 0.3245	-0.0453, 0.2741	-0.0076, 0.3158	-0.0076, 0.3158
Intercept 95% CI	38.6483, 56.0869	42.0699, 59.5889	37.7130, 55.4565	37.7130, 55.4565
Avg Err 95% CI	1.3784, 1.8197	2.0301, 2.4851	-0.0336, 0.4147	-0.0336, 0.4147

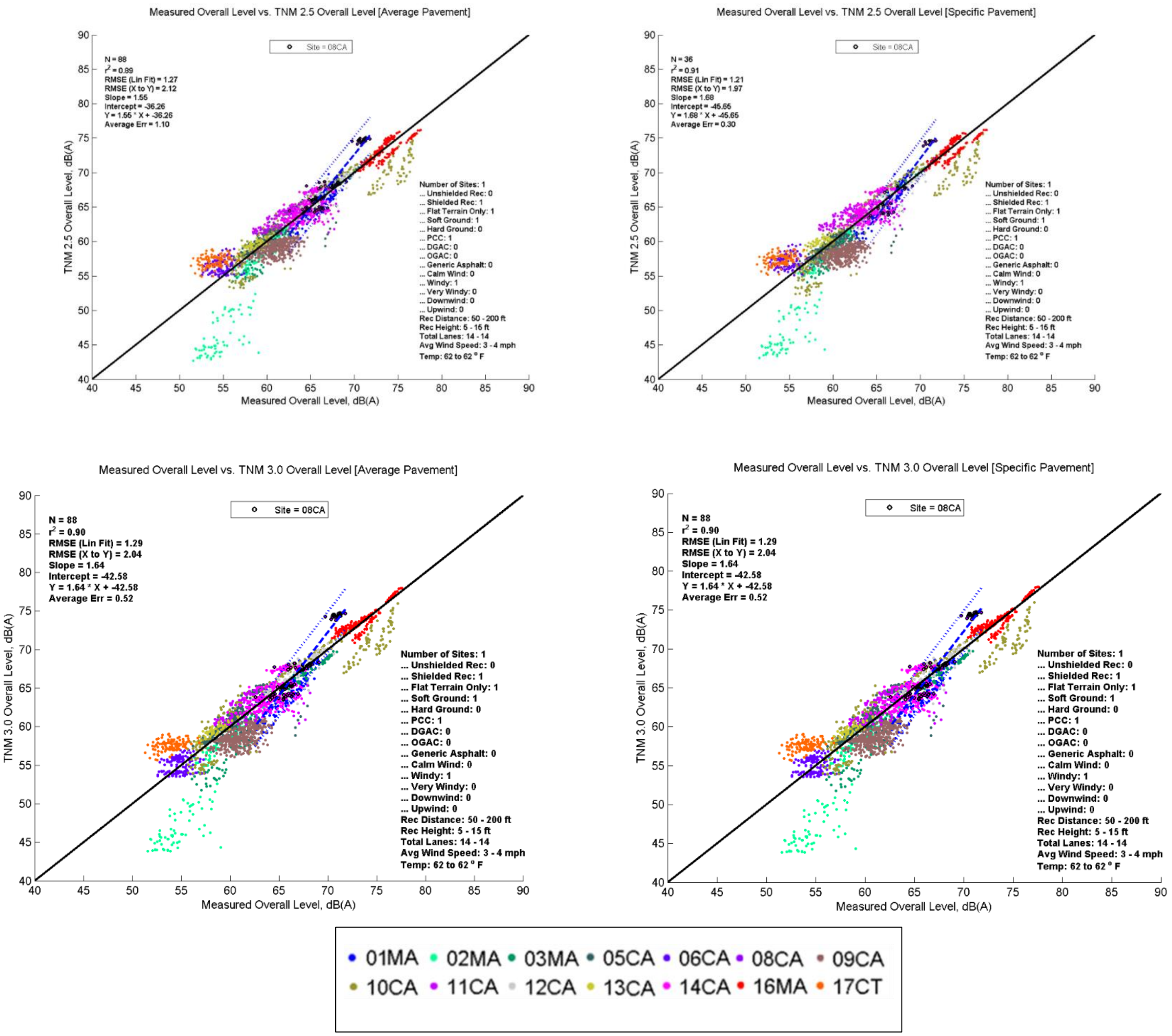

Figure I - 14: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 08CA, adj.

TABLE I - 14: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 08CA, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	88	36	88	88
r^2	0.89	0.91	0.9	0.9
RMSE (Lin Fit)	1.27	1.21	1.29	1.29
RMSE (X to Y)	2.12	1.97	2.04	2.04
Slope	1.55	1.68	1.64	1.64
Intercept	-36.26	-45.65	-42.58	-42.58
Y	1.55 * X + -36.26	1.68 * X + -45.65	1.64 * X + -42.58	1.64 * X + -42.58
Average Error	1.1	0.3	0.52	0.52
Slope 95% CI	1.4413, 1.6686	1.5076, 1.8532	1.5244, 1.7560	1.5244, 1.7560
Intercept 95% CI	-43.9161, -28.6042	-57.3278, -33.9750	-50.3840, -34.7823	-50.3840, -34.7823
Avg Err 95% CI	0.7251, 1.4839	-0.3458, 0.9443	0.1089, 0.9364	0.1089, 0.9364

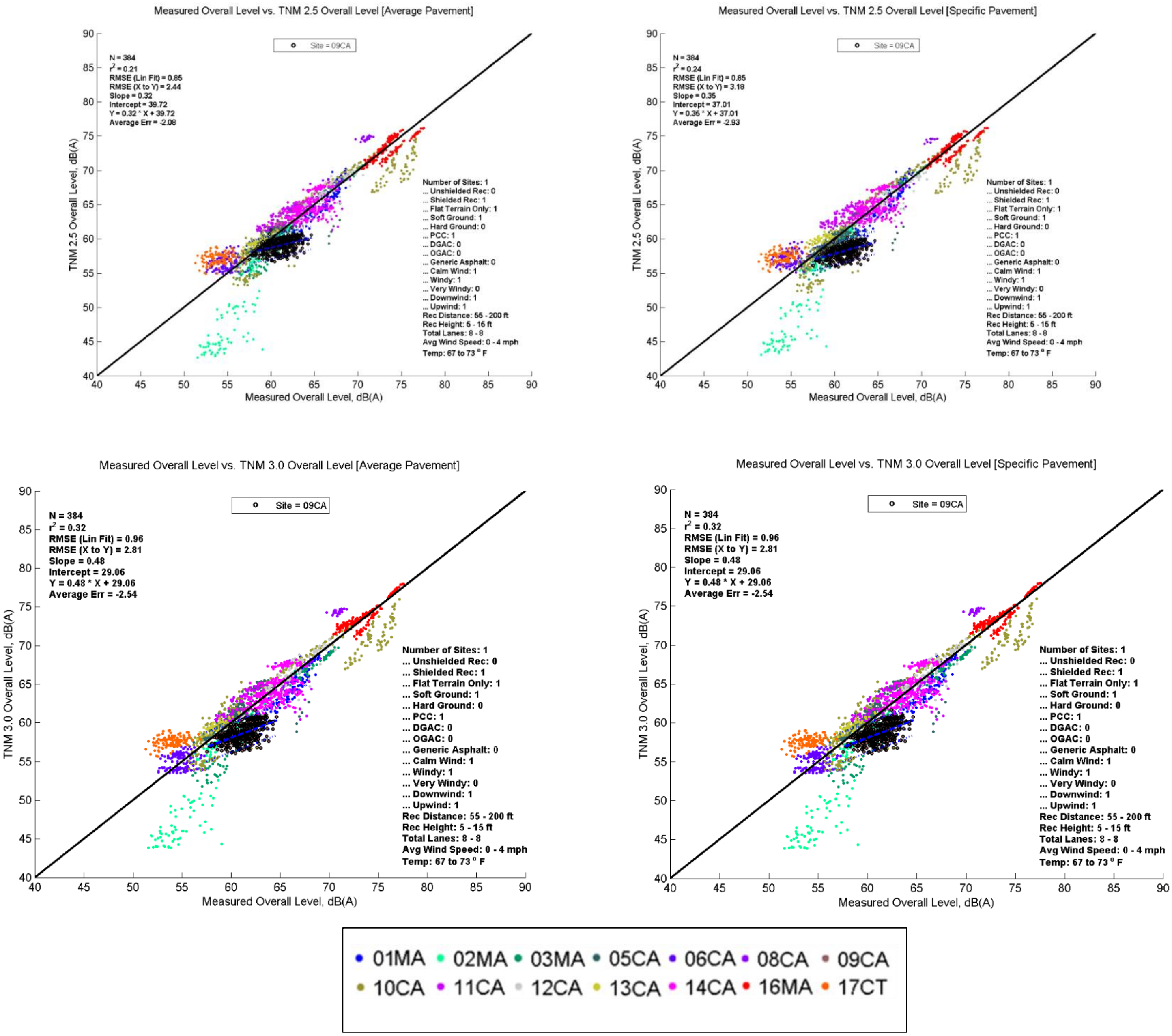

Figure I - 15: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 09CA, adj.

TABLE I - 15: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 09CA, ADJ.

	Average Measured vs. TNM 2.5	**Specific Measured vs. TNM 2.5**	**Average Measured vs. TNM 3.0**	**Specific Measured vs. TNM 3.0**
N	384	384	384	384
r^2	0.21	0.24	0.32	0.32
RMSE (Lin Fit)	0.85	0.85	0.96	0.96
RMSE (X to Y)	2.44	3.18	2.81	2.81
Slope	0.32	0.35	0.48	0.48
Intercept	39.72	37.01	29.06	29.06
Y	0.32 * X + 39.72	0.35 * X + 37.01	0.48 * X + 29.06	0.48 * X + 29.06
Average Error	-2.08	-2.93	-2.54	-2.54
Slope 95% CI	0.2546, 0.3784	0.2855, 0.4083	0.4134, 0.5531	0.4134, 0.5531
Intercept 95% CI	35.9341, 43.5074	33.2512, 40.7640	24.7921, 33.3337	24.7921, 33.3337
Avg Err 95% CI	-2.2093, -1.9552	-3.0558, -2.8088	-2.6603, -2.4211	-2.6603, -2.4211

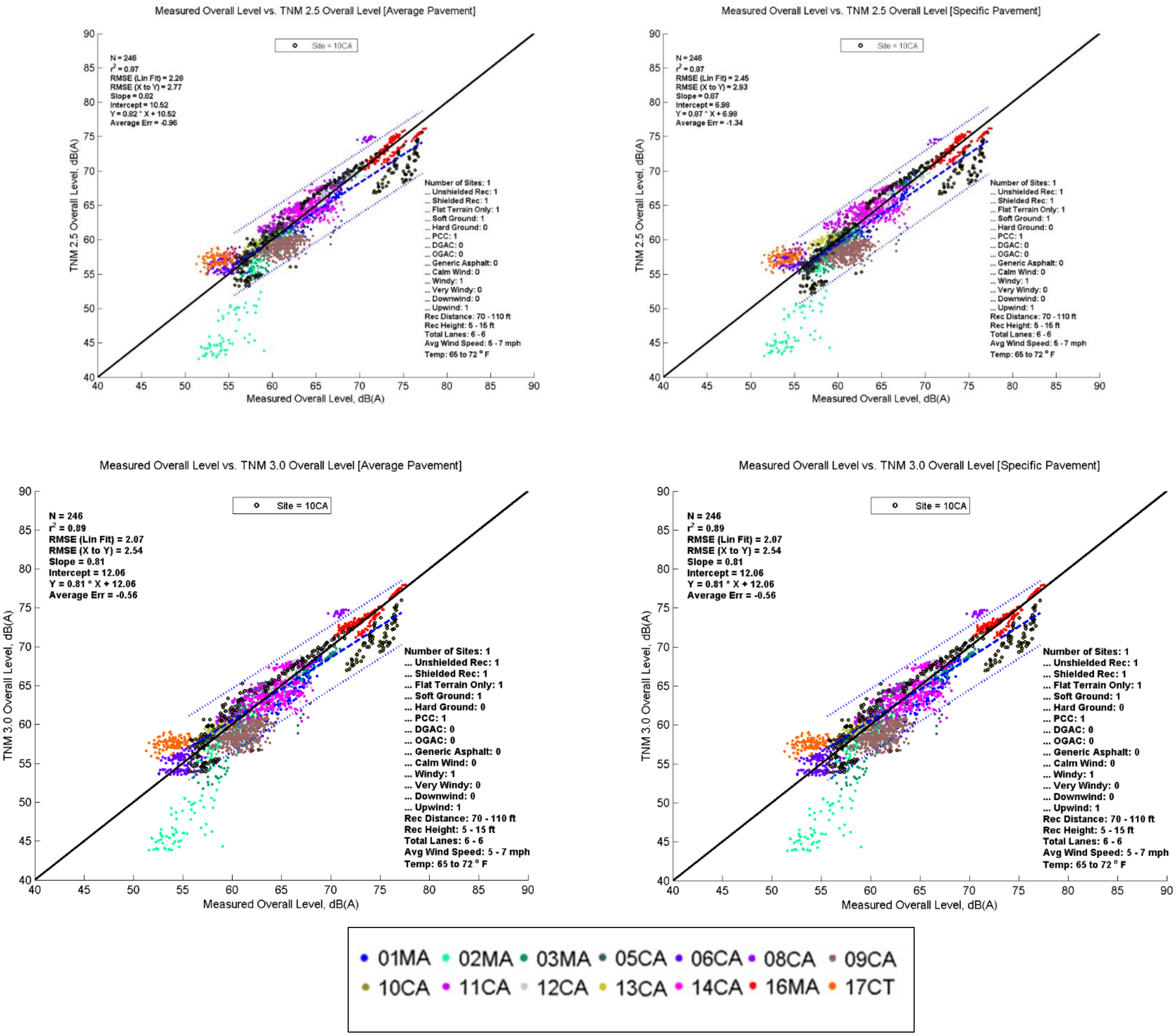

Figure I - 16: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 10CA, adj.

TABLE I - 16: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 10CA, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	246	246	246	246
r^2	0.87	0.87	0.89	0.89
RMSE (Lin Fit)	2.28	2.45	2.07	2.07
RMSE (X to Y)	2.77	2.93	2.54	2.54
Slope	0.82	0.87	0.81	0.81
Intercept	10.52	6.98	12.06	12.06
Y	0.82 * X + 10.52	0.87 * X + 6.98	0.81 * X + 12.06	0.81 * X + 12.06
Average Error	-0.96	-1.34	-0.56	-0.56
Slope 95% CI	0.7848, 0.8647	0.8301, 0.9158	0.7711, 0.8435	0.7711, 0.8435
Intercept 95% CI	7.8876, 13.1481	4.1595, 9.7997	9.6722, 14.4413	9.6722, 14.4413
Avg Err 95% CI	-1.2823, -0.6317	-1.6660, -1.0139	-0.8745, -0.2532	-0.8745, -0.2532

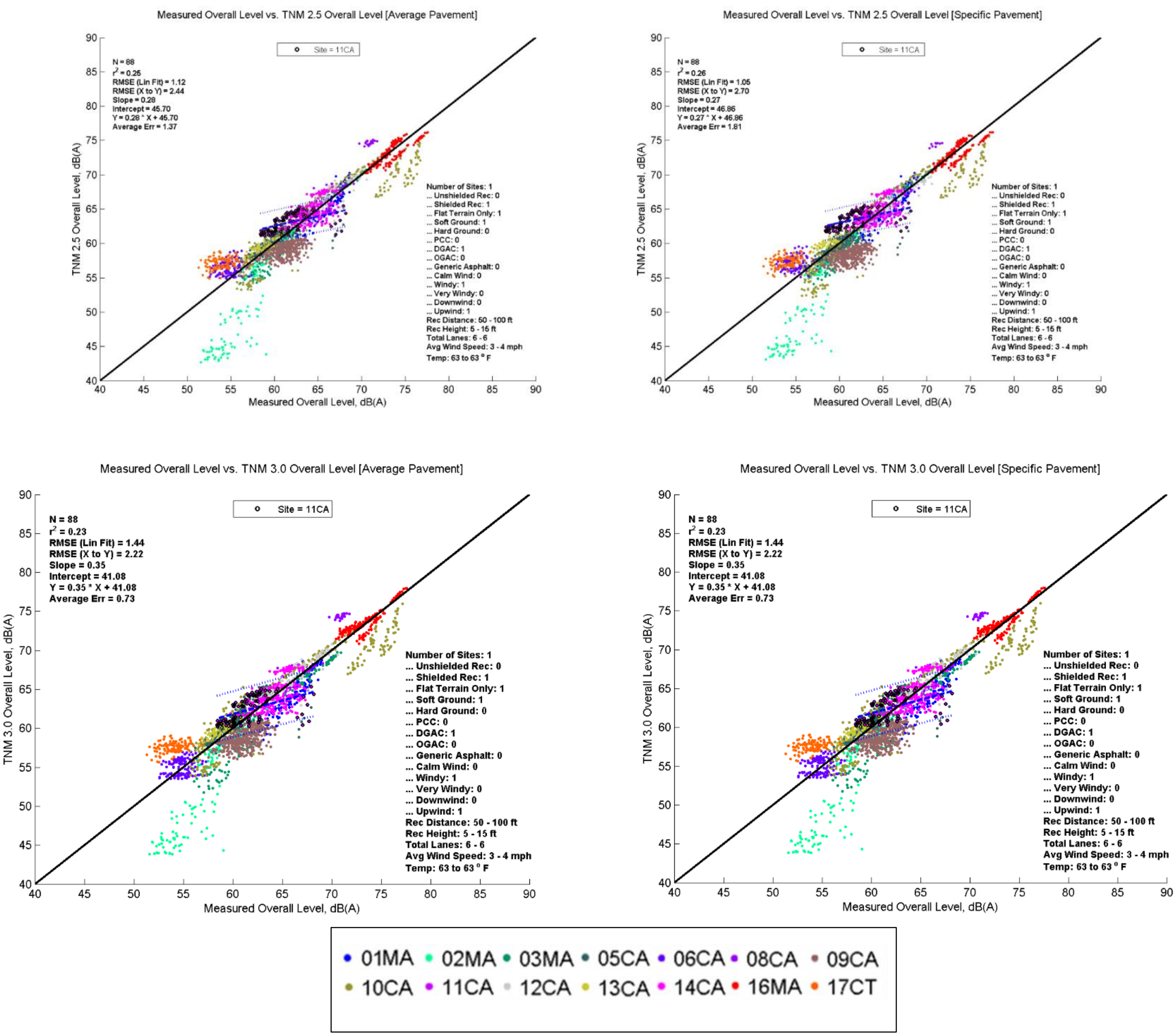

Figure I - 17: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 11CA, adj.

TABLE I - 17: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 11CA, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	88	88	88	88
r^2	0.25	0.26	0.23	0.23
RMSE (Lin Fit)	1.12	1.05	1.44	1.44
RMSE (X to Y)	2.44	2.7	2.22	2.22
Slope	0.28	0.27	0.35	0.35
Intercept	45.7	46.86	41.08	41.08
Y	0.28 * X + 45.70	0.27 * X + 46.86	0.35 * X + 41.08	0.35 * X + 41.08
Average Error	1.37	1.81	0.73	0.73
Slope 95% CI	0.1800, 0.3814	0.1748, 0.3631	0.2160, 0.4746	0.2160, 0.4746
Intercept 95% CI	39.4909, 51.9091	41.0555, 52.6657	33.1062, 49.0573	33.1062, 49.0573
Avg Err 95% CI	0.9467, 1.7929	1.3894, 2.2289	0.2942, 1.1730	0.2942, 1.1730

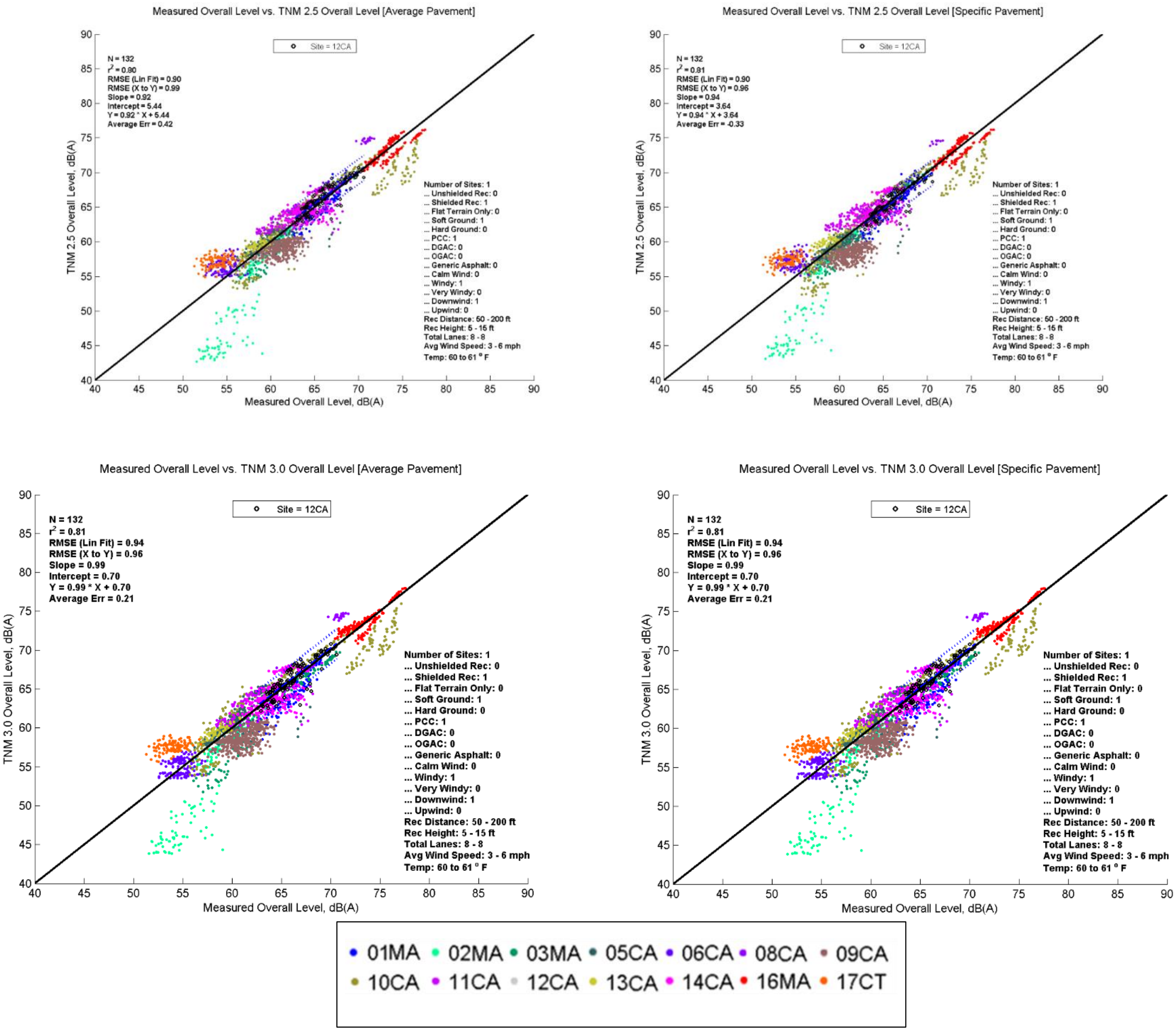

Figure I - 18: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 12CA, adj.

TABLE I - 18: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 12CA, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	132	132	132	132
r^2	0.8	0.81	0.81	0.81
RMSE (Lin Fit)	0.9	0.9	0.94	0.94
RMSE (X to Y)	0.99	0.96	0.96	0.96
Slope	0.92	0.94	0.99	0.99
Intercept	5.44	3.64	0.7	0.7
Y	0.92 * X + 5.44	0.94 * X + 3.64	0.99 * X + 0.70	0.99 * X + 0.70
Average Error	0.42	-0.33	0.21	0.21
Slope 95% CI	0.8455, 1.0022	0.8607, 1.0188	0.9099, 1.0752	0.9099, 1.0752
Intercept 95% CI	0.2770, 10.6097	-1.5717, 8.8556	-4.7459, 6.1558	-4.7459, 6.1558
Avg Err 95% CI	0.2670, 0.5754	-0.4841, -0.1745	0.0531, 0.3741	0.0531, 0.3741

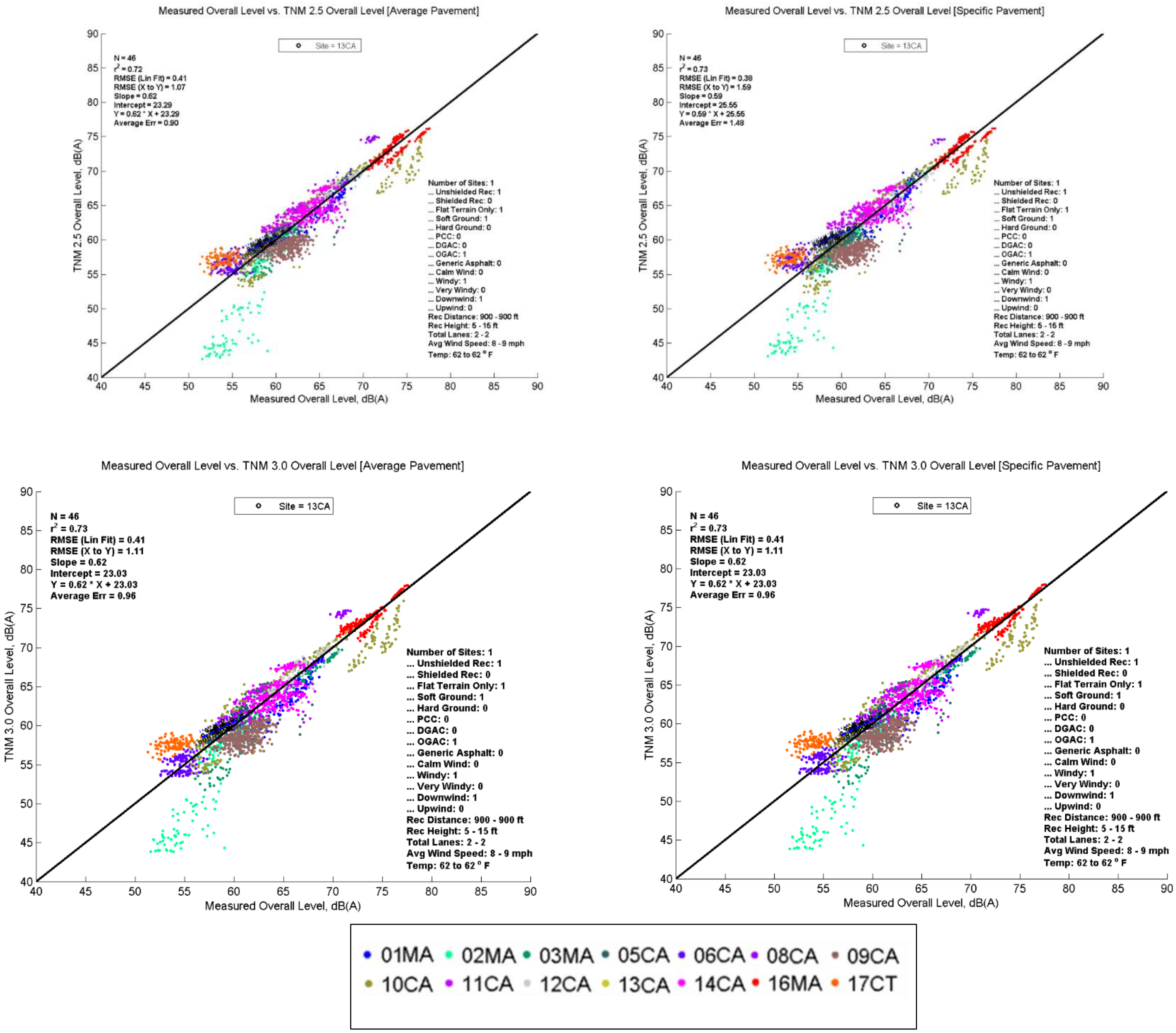

Figure I - 19: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 13CA, adj.

TABLE I - 19: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 13CA, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	46	46	46	46
r^2	0.72	0.73	0.73	0.73
RMSE (Lin Fit)	0.41	0.38	0.41	0.41
RMSE (X to Y)	1.07	1.59	1.11	1.11
Slope	0.62	0.59	0.62	0.62
Intercept	23.29	25.55	23.03	23.03
Y	0.62 * X + 23.29	0.59 * X + 25.55	0.62 * X + 23.03	0.62 * X + 23.03
Average Error	0.9	1.48	0.96	0.96
Slope 95% CI	0.5066, 0.7304	0.4860, 0.6938	0.5123, 0.7358	0.5123, 0.7358
Intercept 95% CI	16.7242, 29.8594	19.4532, 31.6525	16.4678, 29.5853	16.4678, 29.5853
Avg Err 95% CI	0.7355, 1.0684	1.3132, 1.6478	0.7947, 1.1250	0.7947, 1.1250

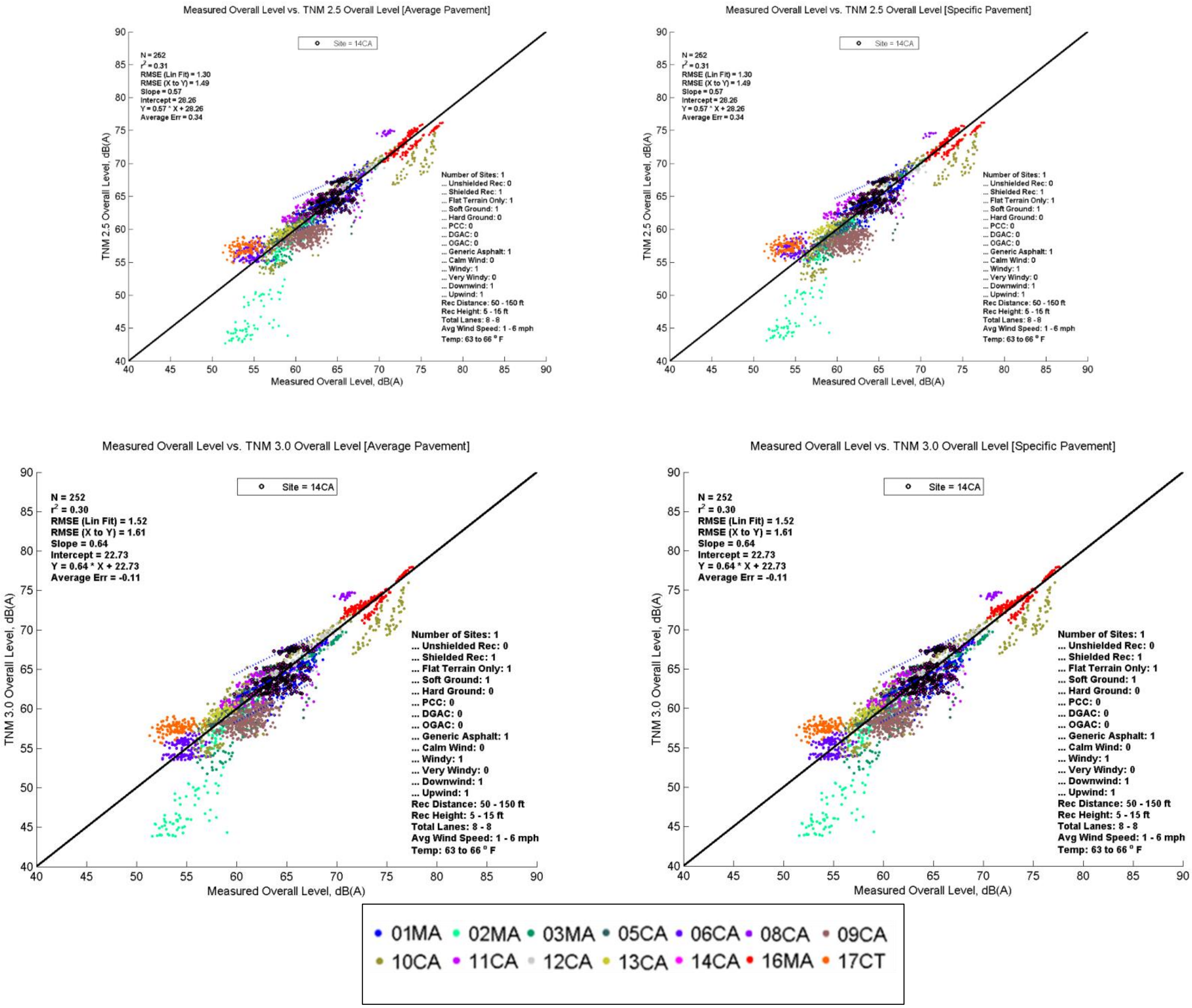

Figure I - 20: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 14CA, adj.

TABLE I - 20: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 14CA, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	252	252	252	252
r^2	0.31	0.31	0.3	0.3
RMSE (Lin Fit)	1.3	1.3	1.52	1.52
RMSE (X to Y)	1.49	1.49	1.61	1.61
Slope	0.57	0.57	0.64	0.64
Intercept	28.26	28.26	22.73	22.73
Y	0.57 * X + 28.26	0.57 * X + 28.26	0.64 * X + 22.73	0.64 * X + 22.73
Average Error	0.34	0.34	-0.11	-0.11
Slope 95% CI	0.4611, 0.6702	0.4611, 0.6702	0.5224, 0.7669	0.5224, 0.7669
Intercept 95% CI	21.5409, 34.9840	21.5409, 34.9840	14.8716, 30.5956	14.8716, 30.5956
Avg Err 95% CI	0.1624, 0.5217	0.1624, 0.5217	-0.3062, 0.0910	-0.3062, 0.0910

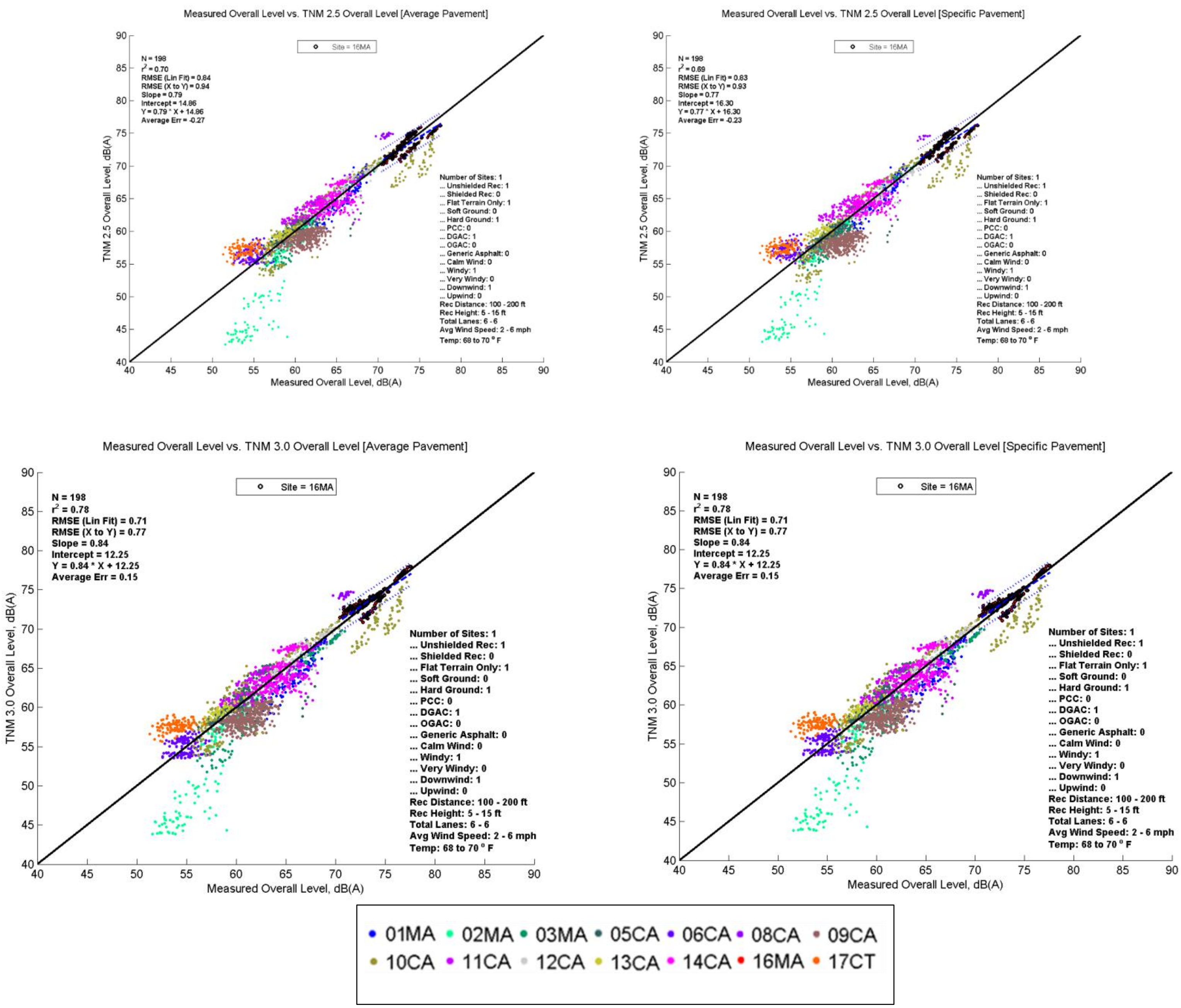

Figure I - 21: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 16MA, adj.

TABLE I - 21: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 16MA, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	198	198	198	198
r^2	0.7	0.69	0.78	0.78
RMSE (Lin Fit)	0.84	0.83	0.71	0.71
RMSE (X to Y)	0.94	0.93	0.77	0.77
Slope	0.79	0.77	0.84	0.84
Intercept	14.86	16.3	12.25	12.25
Y	0.79 * X + 14.86	0.77 * X + 16.30	0.84 * X + 12.25	0.84 * X + 12.25
Average Error	-0.27	-0.23	0.15	0.15
Slope 95% CI	0.7208, 0.8671	0.7026, 0.8473	0.7733, 0.8972	0.7733, 0.8972
Intercept 95% CI	9.4858, 20.2364	10.9867, 21.6167	7.6947, 16.8043	7.6947, 16.8043
Avg Err 95% CI	-0.3997, -0.1486	-0.3522, -0.1002	0.0422, 0.2535	0.0422, 0.2535

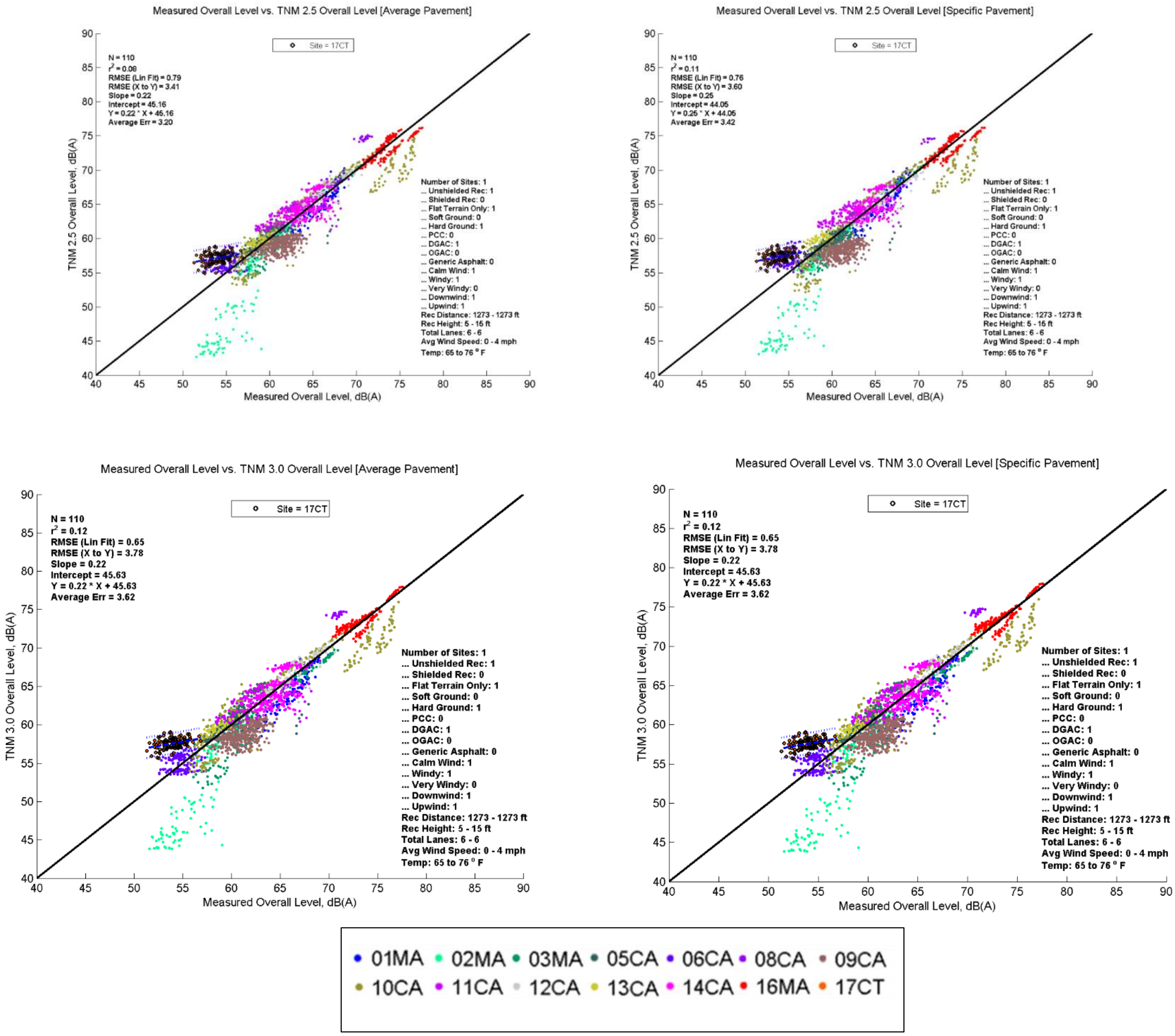

Figure I - 22: TNM 2.5 and 3.0 Predictions vs. Measured Results using Average and Specific Pavements – 17CT, adj.

TABLE I - 22: SUMMARY STATISTICS FOR TNM 2.5 AND 3.0 PREDICTIONS VS. MEASURED RESULTS USING AVERAGE AND SPECIFIC PAVEMENTS – 17CT, ADJ.

	Average Measured vs. TNM 2.5	Specific Measured vs. TNM 2.5	Average Measured vs. TNM 3.0	Specific Measured vs. TNM 3.0
N	110	110	110	110
r^2	0.08	0.11	0.12	0.12
RMSE (Lin Fit)	0.79	0.76	0.65	0.65
RMSE (X to Y)	3.41	3.6	3.78	3.78
Slope	0.22	0.25	0.22	0.22
Intercept	45.16	44.05	45.63	45.63
Y	0.22 * X + 45.16	0.25 * X + 44.05	0.22 * X + 45.63	0.22 * X + 45.63
Average Error	3.2	3.42	3.62	3.62
Slope 95% CI	0.0907, 0.3546	0.1196, 0.3750	0.1130, 0.3303	0.1130, 0.3303
Intercept 95% CI	38.0356, 52.2799	37.1535, 50.9394	39.7638, 51.4915	39.7638, 51.4915
Avg Err 95% CI	2.9836, 3.4211	3.2115, 3.6350	3.4172, 3.8223	3.4172, 3.8223