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Ground and Pavement Effects using FHWA's Traffic Noise Model® 2.5

U.S. Department of Transportation

Research and Innovative Technology Administration

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13. ABSTRACT (Maximum 200 words)

The Volpe Center Acoustics Facility, in support of the Federal Highway Administration (FHWA) has been conducting a study to investigate the effects of using different ground types based on an improved understanding of the characteristics of the ground types defined in FHWA's Traffic Noise Model (TNM) version 2.5. This study also investigates the effects of using specific pavement types, as opposed to Average pavement, when the pavement type is known. The results of this study indicate that improvements in the correlation between predicted and measured results can be achieved by selecting the best ground type and pavement type for the model.

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1 square yard (sq yd, yd^2)	= 0.8 square meter (m^2)	1 square kilometer (km^2)	= 0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	= 2.6 square kilometers (km^2)	10,000 square meters (m^2)	= 1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	= 4,000 square meters (m^2)		
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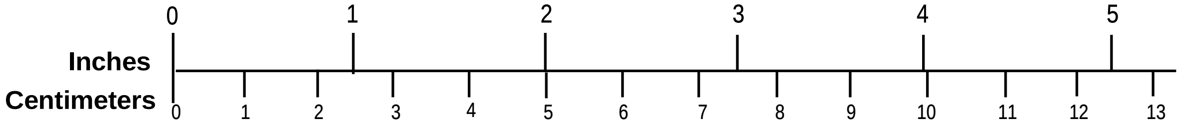

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1. Introduction

This update to the validation of the Federal Highway Administration's Traffic Noise Model (TNM) provides an evaluation of the performance of TNM Version 2.5 (TNM v2.5) for previously evaluated sites [Rochat 2002] [Rochat 2004] using specific pavement types and updated ground types in the TNM site models. This section reviews the objectives of the TNM Validation Study and reviews some of the findings which motivate the current report. Section 2 discusses the parameters controlled for this study. Section 3 presents results for site models using specific pavements. Section 4 presents results for site models using specific pavements and updated ground types. Section 5 includes a detailed analysis and discussion of the results.

The Volpe Center Acoustics Facility (VCAF), in support of the Federal Highway Administration (FHWA), has been conducting a study to quantify and assess the accuracy of FHWA's Traffic Noise Model® (TNM) and make recommendations on its use. The TNM Validation Study involves highway noise data collection and TNM modeling for the purpose of data comparison. In previous validation work, sites were chosen in order to quantify the performance of TNM under various real world conditions. Sites included open or shielded areas next to highways with acoustically soft or acoustically hard ground. Over 100 hours of measured data were compared with TNM predicted results using Average pavement for roadways [Rochat 2002].

Although the results of the 2004 addendum showed that TNM v2.5 was performing well, it was concluded that site biases could still be a factor in the outcome of predictions. It was further suggested that pavement type could affect the sound levels [Rochat 2004]. The results from the 2004 addendum also showed that over long distances ground effects were more extreme than expected, namely that acoustically soft ground types were providing too much absorption and acoustically hard ground types were providing too much reflection. Understanding of the best effective flow resistivity (EFR) for various ground types has been refined over the past decade. Based on this new understanding, ground types other than those used in the original modeling may be more appropriate.

This report evaluates the performance of TNM v2.5 when using specific pavements in order to understand how the use of specific pavements affects TNM's performance. This report also evaluates the performance of TNM v2.5 when using updated ground types for several sites to represent the actual ground types better.

2. TNM Version 2.5 Investigations on the Effect of Specific Pavement and Ground Types on Modeled Results

In order to be comparable to previous validation reports [Rochat 2002] [Rochat 2004], this study used the same sites, measurements, models (with updates to pavements and ground types as needed), and analysis procedures. A brief review of the measured data parameters, TNM modeling parameters, and data processing procedures are given in this section. More detailed descriptions can be found in Rochat [2002] and Rochat [2004].

2.1 Measured Data Parameters

Measurement sites were chosen to provide a range of commonly encountered characteristics, which are modeled by TNM users. All sites were adjacent to highways and were generally flat. Sites varied by: geographical location, number of lanes, pavement type, ground type, traffic characteristics, and by the presence / absence of barriers. Measurements were made at multiple locations for each site. Table 1 summarizes the measurement site parameters.

Table 1: Summary of Measurement Site Parameters

Site Type		Number of Sites	Ranges of Microphone Distances d=dist from roadway bb=dist behind barrier
open area	acoustically soft ground	4	d = 50 to 800 ft
	acoustically hard ground	4	d = 50 to 1273 ft
noise barrier		8	bb = 50 to 300 ft

2.2 TNM Modeling Parameters

Originally, 17 sites were measured for inclusion in the phase 1 validation studies, however, Site 07CA was excluded due to insufficient site survey data and Site 04CT was excluded due to high winds. Site 10 was composed of two-subsites, so data will be presented for 16 sites in total. The TNM models used in the 2004 addendum were used for this report, except the pavement types for all sites and the ground types for some sites were modified. Details are given in Section 2.2.1 and 2.2.2.

2.2.1 Pavement Types

TNM v2.5 contains an emissions database for several pavement types, including Portland cement concrete (PCC), dense-graded asphaltic concrete (DGAC), and open-graded asphaltic concrete (OGAC), and Average. The emission levels for each pavement type used in TNM were based on data representative of PCC, DGAC, and OGAC at the time of the REMEL analysis[1] [Menge 1998]. Eight PCC sites were used in the development of TNM's PCC pavement; twenty-nine DGAC sites were used in the development of TNM's DGAC pavement; and three OGAC sites were used in the development of TNM's OGAC pavement. Average pavement was developed by averaging the data from both PCC and DGAC sites [Fleming 1995].

In previous validation studies, Average pavement was used because FHWA requires the use of Average pavement for federal-aid projects; using Average pavement allowed the assessment of TNM's accuracy as modeled by those working on federal-aid projects, which represents a majority of TNM users. In the current study, the roadways for each site model were updated to use the emissions associated with each site's documented pavement type for two reasons. The previous studies had already assessed modeling following current user requirements, that is, using Average pavement and using site-specific pavement types allows for the assessment of model accuracy in the case that the use of site-specific pavements becomes allowed for federal-aid projects. The pavement types used for each site model are shown in Table 2.

[1] It is known that there are now some asphaltic concrete pavements in service that would be louder than average and some PCC pavements in service that would be quieter than average. The FHWA TNM Pavement Effects Implementation Study is being conducted to investigate the implementation of a broad range of AC and PCC pavements in to TNM predictions.

Table 2: Pavement Type by Site

Site	Pavement		Site	Pavement
01MA	DGAC		10CA-open	PCC
02MA	DGAC		11CA	DGAC
03MA	DGAC		12CA	PCC
05CA	PCC		13CA	OGAC
06CA	DGAC		14CA	DGAC
08CA	PCC w/ DGAC HOV		15CA	DGAC
09CA	PCC		16MA	DGAC
10CA-berm	PCC		17CT	DGAC

In general, the use of DGAC or OGAC pavement in the model will lower the total sound pressure level relative to Average pavement, so for a DGAC or an OGAC site, the use of the specific pavement will help to reduce over-predicted sound levels obtained by using Average pavement. Similarly, the use of PCC pavement in the model will increase the total sound pressure level relative to Average pavement, so for a PCC site, the use of the specific pavement will help to increase under-predicted sound levels obtained by using Average pavement. The results of including the specific pavement types are shown in Section 3.

2.2.2 Ground Types

TNM modeling results are sensitive to the effective flow resistivity (EFR) of the ground, which is a single parameter that is used to model sound absorption by ground [Embleton 1983] [Menge 1998]. Sound waves propagating over acoustically soft ground experience increased sound absorption and destructive interference, while sound waves propagating over acoustically hard ground experience increased sound reflection and decreased destructive interference. The 2004 addendum [Rochat 2004] suggested that there may be better estimates for the ground types of some ground zones in the validation models.

Table 3 provides a description of the pre-defined ground types used in TNM v2.5. Previous validation modeling used best available classification of site ground types, however, over the years, the understanding of how ground should be classified in order to obtain correct EFR values has improved. Additional analysis of the literature [Crocker 1998] [Anderson 1999]

[Anderson 2006] [Attenborough 2007] and conversations with area experts [Menge 2004] have increased the understanding of how ground types should be used in TNM. A more detailed listing of ground type classification is given in Table 4.

Table 3: Ground type categories in TNM

TNM v2.5 Ground Type Classification [Anderson 1998]	EFR (cgs Rayls)
Powder snow	10
Granular snow	40
Field grass	150
Lawn	300
Gravel, loose soil	500
Hard Soil	5000
Asphalt, concrete, water	20000

Table 4: Detailed Ground Type Descriptions [Embleton 1983] [Crocker 1998] [Menge 2004] [Anderson 2006][Attenborough 2007]

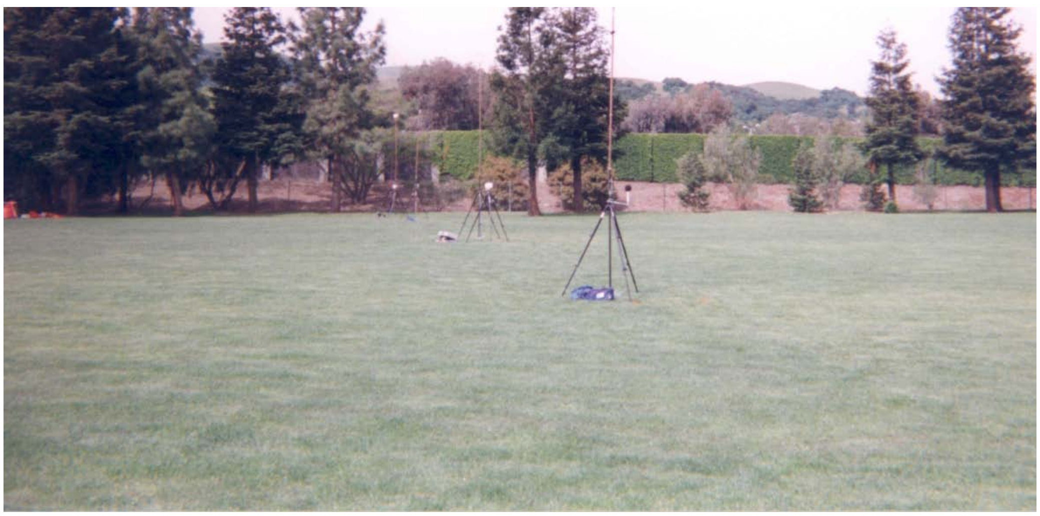
Ground Type Description	Additional Detail	EFR (cgs Rayls)			Avg EFR
Dry snow	0.1 m of newly fallen over 0.4 m older snow	10	to	30	20
Sugar snow		25	to	50	37.5
Forest floor	pine or hemlock	20	to	80	50
Grass	11.9% to 16.5% moisture content	41	to	75	58
Grass root layer in loamy sand	Porosity (volume %) 43.5 to 59.8%	62	to	314	188
Grass	rough pasture, around public buildings	125	to	300	212.5
Grass	various ratios of dirt & vegetation	150	to	600	375
Soil	various types	106	to	450	278
Sand	various types	40	to	906	473
Roadside dirt	ill-defined small rocks up to 0.1 m mesh	300	to	800	550
Dirt	roadside with rocks smaller than 4" diameter	300	to	800	550
Sandy silt	hard packed by vehicles	800	to	2500	1650
Limestone chips	1/2 to 1" mesh	1500	to	4000	2750
Old dirt road	filled mesh	2000	to	4000	3000
Exposed dirt	rain-packed	4000	to	8000	6000
Asphalt	new, various particle size	5000	to	15000	10000
Quarry dust	hard packed	5000	to	20000	12500
Asphalt	old, sealed with dust	25000	to	30000	27500
Concrete	depends on finish	30000	to	100000	65000
Concrete	Painted	200000			200000
Upper limit	set by thermal-conduction and viscous boundary layer	200000	to	1000000	600000

The descriptions given in Table 4 indicate some of the finer nuances involved with ground type classifications. For example, there is a wide range of classifications that grass can fall into and these classifications are dependent on moisture content, porosity, amount of exposed dirt, and other parameters. Conversations with Embleton [Menge 2004] indicated that for a grass to be considered a “field grass” with an EFR value of about 150 cgs Rayls (see Table 3), a strong root structure was required to break up the soil. Because many un-groomed fields have large patches of exposed dirt, only sparse grass, and little root structure, they would be better classified with a higher EFR value like 500 or 600 cgs Rayls. Upon reevaluation of the ground characteristics at validation sites, it has been determined that there are many areas adjacent to roads which were originally modeled as field grass, but may have been more appropriately modeled as lawn or loose soil in TNM.

It can also be seen by comparing Table 3 and Table 4 that the default EFR value of 20,000 cgs Rayls for asphalt, concrete, and pavement does not reflect the true range of EFR values for acoustically hard surfaces. Consider that in Table 4, asphalt can range from 5000 to 30,000 cgs Rayls. It was asserted in a report to Caltrans that the hard site EFR values are often over-estimated when using TNM’s pavement ground type since few sites are truly “hard” [Anderson 1999]. Previous TNM validation models have applied an EFR value of 20,000 cgs Rayls to all pavement ground zones, however, results for many of these sites had over-predictions which may indicate that many of these ground zones may have been more appropriately modeled with a lower EFR value, such as 10,000 cgs Rayls. Although water is not listed in Table 4, it is generally presumed that it is an acoustically hard surface, as indicated in Table 3. However, most areas modeled using water ground zones can have some scattering due to the roughness of the water surface. It was conjectured that a lower EFR value such as 10,000 cgs Rayls could improve predicted results for sites containing water ground zones.

Site 11CA – Originally modeled as Field Grass, no change

Site 12CA – Originally modeled as Lawn, no change



Site 01MA – Originally modeled as Field Grass, now modeled as Loose Soil

Site 05CA – Originally modeled as Field Grass, now modeled as Lawn

Site 13CA – Originally modeled as Water (20,000 cgs Rayls), now modeled as Custom (10,000 cgs Rayls)

Figure 1: Ground Type Examples

In order to model validation sites' ground types more appropriately and to understand the sensitivity of TNM's acoustic algorithms, ground types were modified for a subset of the validation sites. Not all sites were remodeled since several sites were already considered to have the most appropriate ground types for their site. For example, sites 11CA and 12CA provide good representations of field grass and lawn ground types respectively. See Figure 1. Some sites were remodeled because improved understanding of ground type classification indicated that a change should be made. This was the case for many sites with field grass and also for sites with asphaltic pavement which were originally modeled as having an EFR value of 20,000 cgs Rayls. Site 01MA was remodeled using loose soil instead of field grass because the vegetation was much sparser than, say for example, site 11CA. Site 05CA was remodeled using lawn instead of field grass, because, although unkempt, the vegetation is relatively short and of the same general type as site 12CA for example. Site 02MA was remodeled because, even though the ground was grass covered, it was very wet and partially frozen. For this site, several EFR values were evaluated and the best results (from using 1500 cgs Rayls) are included in this report. In addition, the EFR value for water ground zones was also reduced in order to see if the model was sensitive to this change. This is particularly of interest since water can have different surface characteristics if the surface is smooth or rough, see site 13CA in Figure 1 for an example of a water surface that is somewhat rough. The modifications to the sites are listed in Table 5.

Table 5: Ground zone updates to validation sites

Validation Site	Original Ground Type	Modified Ground Type
01MA	Field Grass (150 cgs Rayls)	Loose Soil (500 cgs Rayls)
02MA	Field Grass (150 cgs Rayls)	Custom (1500 cgs Rayls)
05CA	Field Grass (150 cgs Rayls)	Lawn (300 cgs Rayls)
09CA	Field Grass (150 cgs Rayls)	Lawn (300 cgs Rayls)
13CA	Water (20000 cgs Rayls)	Custom (10,000 cgs Rayls)
15CA	Pavement (20000 cgs Rayls)	Custom (10,000 cgs Rayls)
16MA	Field Grass (150 cgs Rayls)	Loose Soil (500 cgs Rayls)
	Pavement (20000 cgs Rayls)	Custom (10,000 cgs Rayls)
17CT	Water (20000 cgs Rayls)	Custom (10,000 cgs Rayls)

2.3 Data Calibration

In accordance with previous studies, high wind data (wind speeds > 11 mph) were excluded and the remaining data were examined with and without calibration. Calibration was performed by using the reference microphone for each site (to minimize possible site-specific biases – described further in Section 3.3.1). For sites without a barrier, the reference microphone was located approximately 50 ft from the center line of the near travel lane and 5 ft above the roadway elevation. For sites with barriers, the reference microphone was approximately 5 ft above the top of the barrier or to the side of the barrier at 5 ft above the roadway elevation. For each site, the measured sound level at the reference microphone was subtracted from the predicted sound level for the same position for each 15 minute data block, $L_{Aeq15min,predicted}$ –

$L_{Aeq15min,measured}$. This calibration value was then subtracted from the predicted sound levels for all other microphone locations at the study site.

3. TNM Version 2.5 Specific Pavement and Ground Type Results and Analysis

In this first set of modeling, specific pavement types were used but ground types not updated. The uncalibrated and calibrated results for this modeling are presented in Section 3.1. In the second set of modeling, the specific pavement types were used and the ground types were also updated for Sites 01MA, 02MA, 05CA, 09CA, 13CA, 15CA, 16MA, and 17 CT. The uncalibrated and calibrated results for this modeling are presented in Section 3.2. Analysis and discussion of the results are given in Section 3.3.

3.1 Specific Pavement Type

The uncalibrated results for the specific pavement modeling are shown in Figure 2. In this figure, the abscissa indicates the level of the measured 15-minute L_{Aeq} while the ordinate indicates the level of the predicted 15-minute L_{Aeq}. Each 15-minute datum is indicated by an orange x. A dashed blue line indicates the linear fit and solid green lines show the 95% confidence band for the linear fit. The solid black diagonal line indicates perfect (1 to 1) agreement between TNM predicted levels and measured data. Data above the black line indicate over-predictions while data below the black line indicate under-predictions.

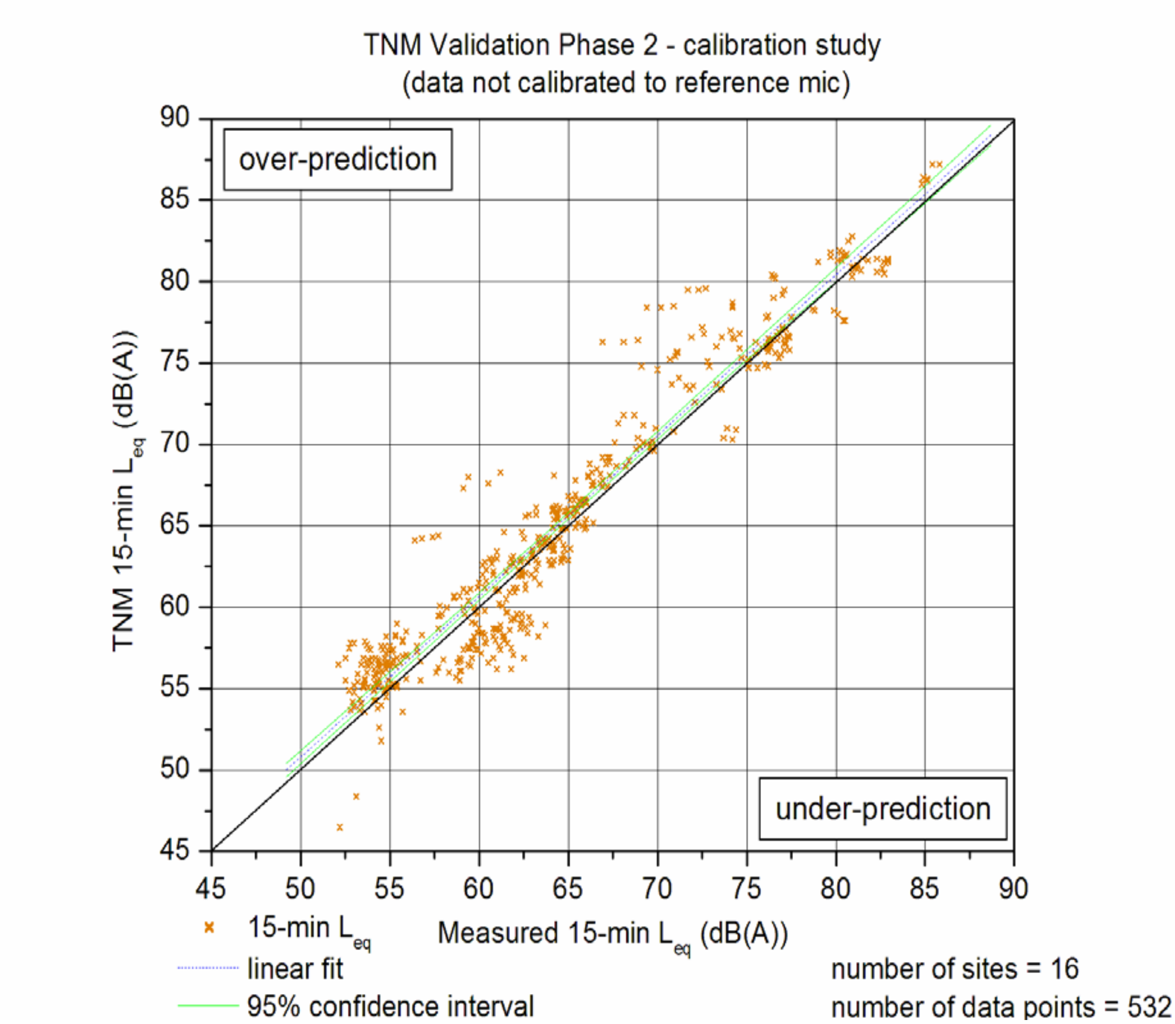


Figure 2: Specific Pavement Study – Uncalibrated Results

The specific pavement modeling data were calibrated by using reference microphones as described in Section 2.3. The range of calibration values for each 15-minute datum and the average calibration value are given for each site in Table 6. A positive calibration value indicates an over-prediction and a negative calibration value indicates an under-prediction.

Table 6: Data Calibration Values by Site (with Specific Pavement Type Updates)

	Specific Pavement	
Site ID	average calibration (dB)	calibration range (dB)
01MA (DGAC)	2.3	1.3 to 2.9
02MA (DGAC)	2.8	2.5 to 3.1
03MA (DGAC)	0	-0.2 to 0.4
05CA (PCC)	1.7	1.6 to 1.9
06CA (DGAC)	-1.2	-1.6 to -0.8
08CA PCC (HOV DGAC)	0.8	-1.0 to 1.2
09CA (PCC)	-0.3	-0.7 to -0.1
10CA-berm (PCC)	7.4	7.0 to 7.8
10CA-open (PCC)	7.3	7.0 to 7.8
11CA (DGAC)	-2.4	-2.9 to -1.7
12CA (PCC)	1.3	1.0 to 1.8
13CA (OGAC)	-3.1	-3.3 to -2.9
14CA (DGAC)	-1.7	-2.2 to -1.5
15CA (DGAC)	2	1.8 to 2.1
16MA (DGAC)	1.7	1.6 to 1.7
17CT (DGAC)	-0.2	-0.7 to 0.2
Average	1.15	

The calibrated results for the specific pavement modeling are shown in Figure 3. In this figure, the abscissa indicates the level of the measured 15-minute L_{Aeq} while the ordinate indicates the level of the predicted 15-minute L_{Aeq} adjusted by the calibration level. For further details about the graph parameter see description for uncalibrated results. Analysis and discussion of these results will be presented in Section 3.3, where results from modeling both specific pavements and updated ground types will also be discussed.

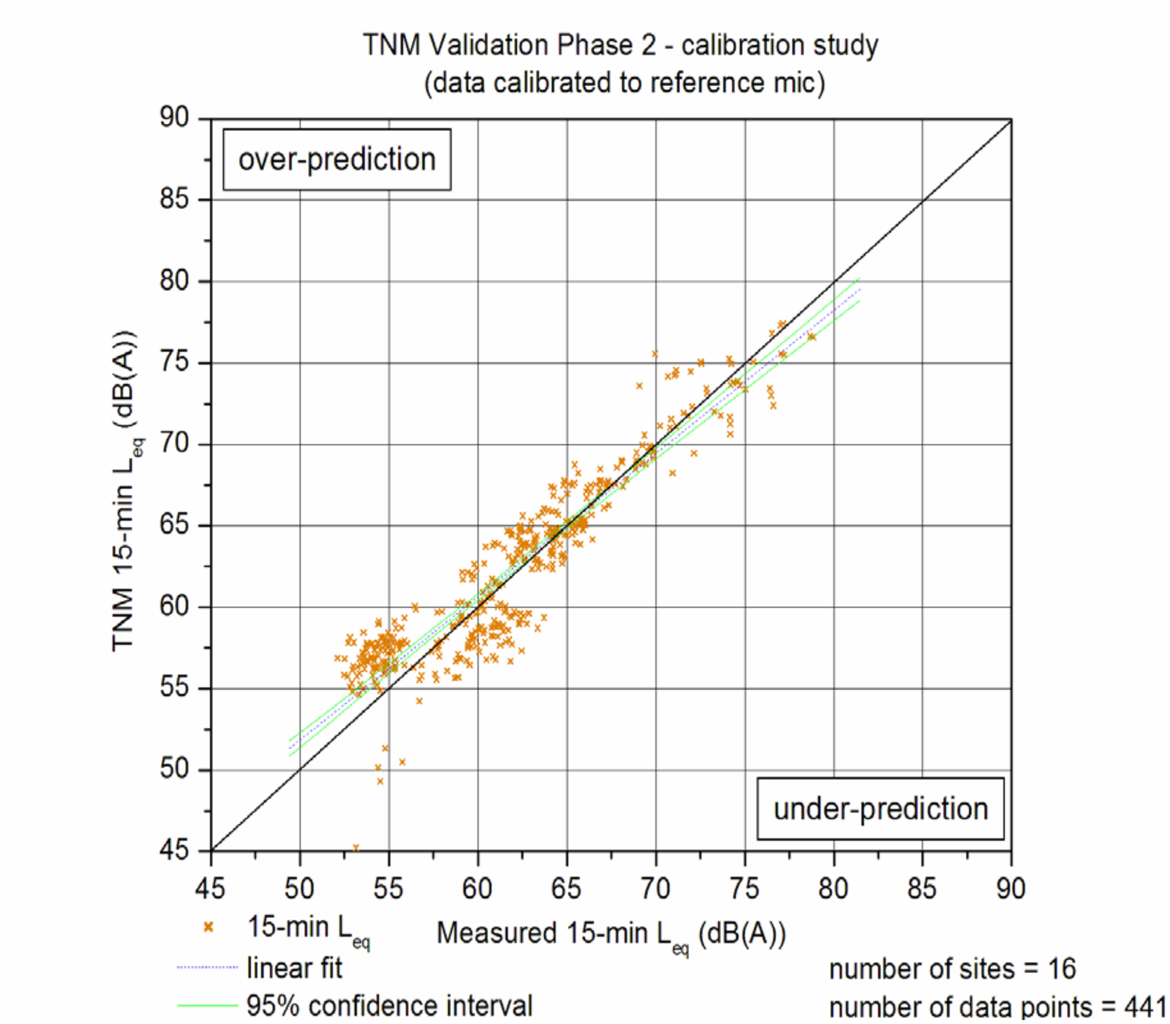


Figure 3: Specific Pavement Study – Calibrated Results

3.2 Combined Specific Pavement and Ground Type

In the second set of modeling, in addition to using specific pavement types for the models, select models had ground types updated as well. These are indicated in Table 5. The uncalibrated results for the specific pavement modeling are shown in Figure 4. The specific pavement and ground type modeling data were calibrated by using reference microphones as described in Section 2.3. The range of calibration values for each 15-minute datum and the average calibration value are given for each site in Table 7. The calibrated results for the specific pavement and ground type modeling are shown in Figure 5. For further details about the graph parameters see Section 3.1. Analysis and discussion of these results will be presented in Section

3.3, where results from modeling specific pavements (without updated ground types) will also be discussed.

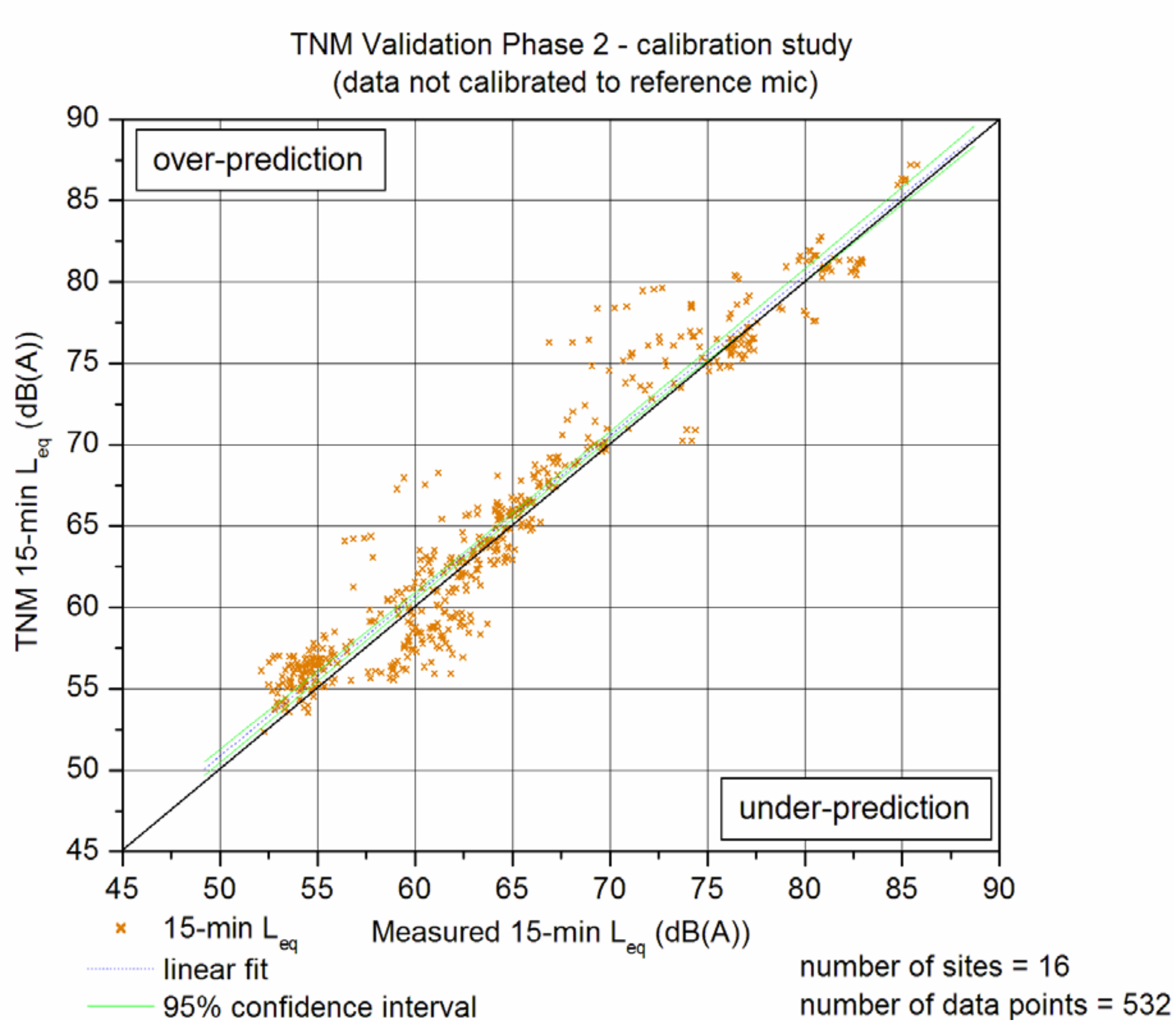


Figure 4: Specific Pavement and Ground Type Study – Uncalibrated Results

Table 7: Calibration Values by Site (with Specific Pavements and Ground Type Updates)

Site ID	Specific Pavement and Updated Ground Type average calibration (dB)	Specific Pavement and Updated Ground Type calibration range (dB)
01MA (DGAC)	2.4	1.4 to 3.0
02MA (DGAC)	3.4	3.0 to 3.7
03MA (DGAC)	0.0	-0.2 to 0.4
05CA (PCC)	1.8	1.6 to 1.9
06CA (DGAC)	-1.2	-1.6 to -0.8
08CA PCC (HOV DGAC)	0.8	-1.0 to 1.2
09CA (PCC)	-0.3	-0.7 to 0.0
10CA-berm (PCC)	7.4	7.0 to 7.8
10CA-open (PCC)	7.3	7.0 to 7.8
11CA (DGAC)	-2.4	-2.9 to -1.7
12CA (PCC)	1.3	1.0 to 1.8
13CA (OGAC)	-3.2	-3.5 to -3.0
14CA (DGAC)	-1.7	-2.2 to -1.5
15CA (DGAC)	1.8	1.6 to 1.9
16MA (DGAC)	1.8	1.6 to 1.9
17CT (DGAC)	-0.4	-0.8 to 0.0
average	1.17	

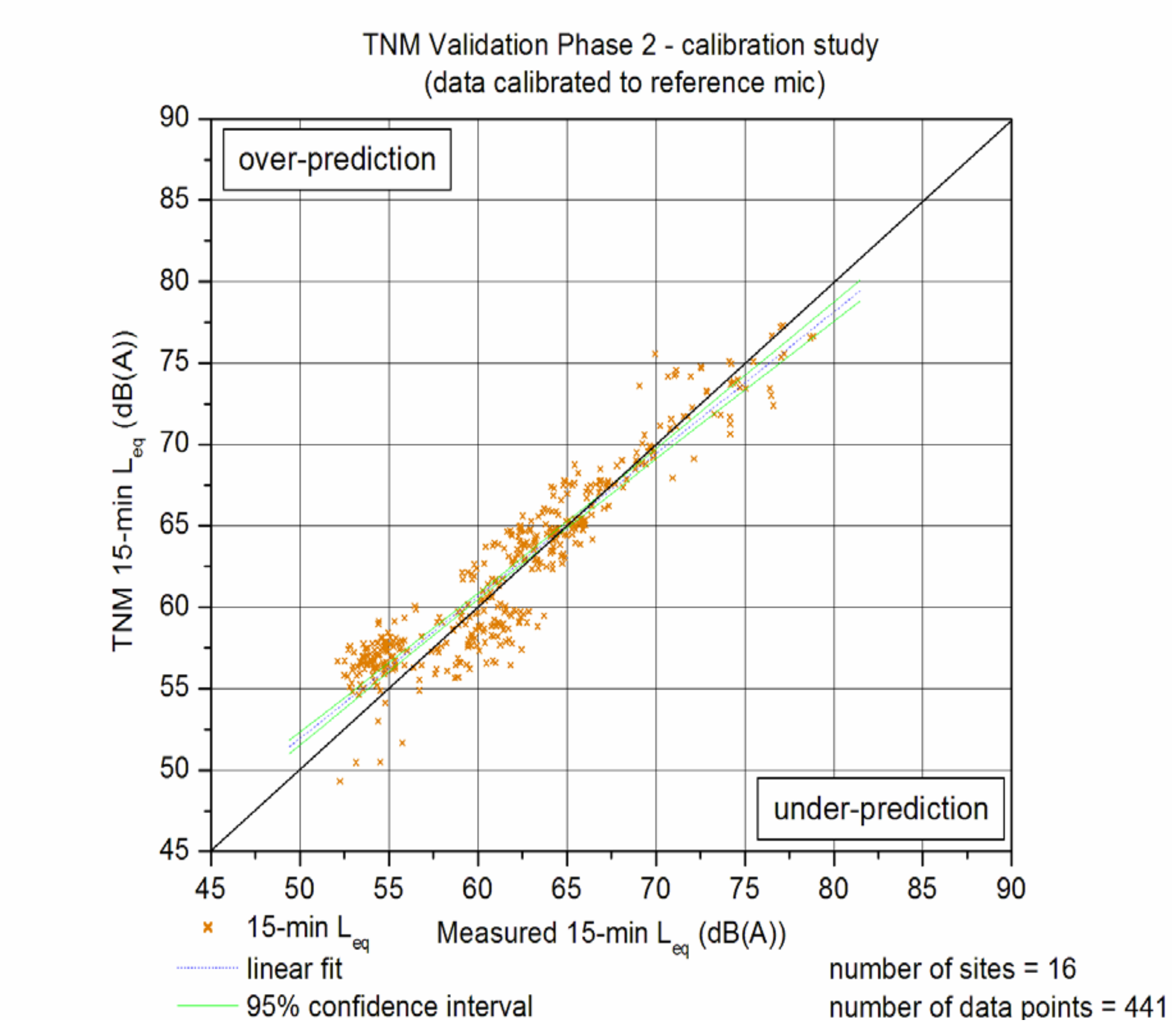


Figure 5: Specific Pavement and Ground Type Study – Calibrated Results

3.3 Analysis and Discussion

Sections 3.1 and 3.2 presented the uncalibrated and calibrated results for two sets of modeling in TNM v2.5, 1) models with specific pavements and 2) models with specific pavements and updated ground types. This section compares the performance of these two sets of modeling with the 2004 addendum, which used Average pavement and had the original ground types.

3.3.1 Comparison of Calibration Factors

Emission levels for TNM were developed by averaging measurements for each of five vehicle types from several sites for each pavement type. The averaging process minimized the effects of site specific biases, such as site-to-site variation in vehicles, pavement, and meteorological effects (e.g. temperature inversions, wind, etc.). The use of these standardized emission levels, therefore represent an average level, but each modeled site may have site specific biases which cause the measured levels to deviate from the average, thus calibration can be useful for improving performance.

Table 8 shows the average calibration and calibration range for each site for three modeling sets with 1) Average pavement, 2) specific pavement, and 3) specific pavement with updated ground types. In general, calibration levels are about the same for each modeling set. For Sites 01MA, 02MA, 03MA, 08CA, 09CA, 15CA, 16MA, and 17CT, the use of specific pavements reduces the magnitude of the calibration. In such cases the use of specific pavements could be useful. For Sites 05CA, 06CA, 10CA (berm and open), 11CA, 12CA, 13CA, and 14CA, the use of specific pavements increased the magnitude of the calibration. Both results are reasonable, since the change due to the use of the specific pavements is on the order of 1 to 2 dB, while the bias due to pavements within the same class can be about 10 dB (see Appendix E of [Fleming 1995]). For example, if a PCC site is already over-predicting with Average pavement due to the site either being a "quiet" PCC, temperature inversions, quiet vehicles, etc, then modeling with PCC pavement will increase the calibration level. For the ground type updates implemented, no calibration improvements were observed from site to site as is expected since the reference microphones are close to the road and see little effect from a change in the ground type.

Table 8: Comparison of Calibration Levels

Site ID	Average Pavement		Specific Pavement		Specific Pavement and Updated Ground Type	
	average calibration (dB)	calibration range (dB)	average calibration (dB)	calibration range (dB)	average calibration (dB)	calibration range (dB)
01MA (DGAC)	3.2	2.3 to 4.1	2.3	1.3 to 2.9	2.4	1.4 to 3.0
02MA (DGAC)	3.8	3.4 to 4.1	2.8	2.5 to 3.1	3.4	3.0 to 3.7
03MA (DGAC)	0.9	0.7 to 1.3	0	-0.2 to 0.4	0.0	-0.2 to 0.4
05CA (PCC)	0.1	0.0 to 0.1	1.7	1.6 to 1.9	1.8	1.6 to 1.9
06CA (DGAC)	0	-0.4 to 0.3	-1.2	-1.6 to -0.8	-1.2	-1.6 to -0.8
08CA PCC (HOV DGAC)	-1.1	-2.7 to -0.5	0.8	-1.0 to 1.2	0.8	-1.0 to 1.2
09CA (PCC)	-1.8	-2.4 to -1.5	-0.3	-0.7 to -0.1	-0.3	-0.7 to 0.0
10CA-berm (PCC)	5.6	5.2 to 6.0	7.4	7.0 to 7.8	7.4	7.0 to 7.8
10CA-open (PCC)	5.6	5.2 to 6.0	7.3	7.0 to 7.8	7.3	7.0 to 7.8
11CA (DGAC)	-1.3	-1.8 to -0.6	-2.4	-2.9 to -1.7	-2.4	-2.9 to -1.7
12CA (PCC)	-0.6	-0.8 to -0.1	1.3	1.0 to 1.8	1.3	1.0 to 1.8
13CA (OGAC)	-1.8	-2.0 to -1.5	-3.1	-3.3 to -2.9	-3.2	-3.5 to -3.0
14CA (DGAC)	-0.7	-1.3 to -0.4	-1.7	-2.2 to -1.5	-1.7	-2.2 to -1.5
15CA (DGAC)	2.8	2.6 to 3.0	2	1.8 to 2.1	1.8	1.6 to 1.9
16MA (DGAC)	2.8	2.7 to 2.8	1.7	1.6 to 1.7	1.8	1.6 to 1.9
17CT (DGAC)	0.6	0.2 to 1.0	-0.2	-0.7 to 0.2	-0.4	-0.8 to 0.0
Average	1.13		1.15		1.17	

The calibration values are also categorized by site type in Table 9 for Average pavement, specific pavement, and specific pavement with updated ground types. In general, calibrations are about the same for each set of models. These results indicate that, even with the use of specific pavements and the best available ground type classifications, it is still advisable to calibrate data by using a reference microphone.

Table 9: Calibration Values by Site Type

Site Type	Avg Pavement average calibration (dB)	Specific Pavement average calibration (dB)	Spec Pave & Ground Type average calibration (dB)
all	1.1	1.2	1.2
open area, soft ground	3.4	3.1	3.3
open area, hard ground	1.1	0.1	0.0
barrier, soft ground	0.0	0.7	0.7
ref mic in open	2.6	2.2	2.3
ref mic above barrier	-0.8	-0.3	-0.2

3.3.2 Linear Fit for Calibrated Data

The purpose of calibration is to account for specific characteristics of a modeled site which do not conform to standard values in TNM, for example calibration can be used to account for traffic which has higher or lower sound levels than typical traffic. Both the linearity of the fit between the measured and predicted data and the distribution of the differences between the measured and predicted data are useful characteristics to quantify how close the model is to measured data.

The relation of the linear fit to the line of perfect agreement is examined in Table 10 along with the width of the 95 percent confidence band in Table 11 for three model sets, 1) Average pavement, 2) specific pavement, and 3) specific pavement with updated ground types. (Graphs of these fits are given in Appendix A for the specific pavement models and in Appendix B for the specific pavement with updated ground types models.) Both the average difference and the average of the absolute value of differences are given in Table 10. The average difference represents the difference between the linear fit line and the perfect agreement line. The absolute value of differences indicates how well TNM is performing as a function of the amplitude of the over- and under-predictions. In general, TNM v2.5 performs well for all three modeling sets. The use of specific pavements improves the performance for open areas with soft ground, and the updated ground types further improve the results for both open areas with soft and hard ground types.

Table 10: Comparison of Differences from Linear Fit

Sites	Differences of Linear Fit from Perfect Agreement (dB) – TNM v2.5					
	average difference			average of absolute value of differences		
	Avg. Pave.	Spec. Pave.	Spec. Pave. & Updated Ground	Avg. Pave.	Spec. Pave.	Spec. Pave. & Updated Ground
all	0.2	0.0	0.0	0.8	1.0	1.0
open area, soft ground	-1.5	-1.3	-0.9	1.6	1.5	0.9
near distances	-0.9	-0.7	-0.4	0.9	0.7	0.6
far distances	-4.3	-4.0	-2.5	4.3	4.0	2.5
open area, hard ground	1.1	1.3	1.1	1.6	1.7	1.5
near distances	-0.4	-0.3	-0.4	0.9	0.9	0.9
far distances	2.2	2.5	2.1	2.2	2.5	2.1
barrier, soft ground	0.6	0.4	0.4	0.6	0.8	0.8

The average, maximum, and minimum values of the 95% confidence band, respectively are shown in Table 11. If all three values are small, and the maximum and minimum values are similar, this indicates that the data shows little variation in amplitude over a broad range of sound levels; as such, a similar data set (sound levels measured and predicted under the same conditions) would provide similar results. The difference between predicted and measured results can change over distance when inappropriate ground types are assigned. When the appropriate ground type is used, differences remain more consistent and thus it can be expected that the confidence band will be smaller than if inappropriate ground types are used. It can be seen in Table 11 that the updated ground types decrease the size of the confidence band, indicating less variation in the difference between the predicted and measured results.

Table 11: Comparison of Linear Fit 95% Confidence Bands

Sites	95% Confidence Band Width around Linear Fit (dB)								
	Average			maximum			minimum		
	Avg. Pave.	Spec. Pave.	Spec. Pave. & Updated Ground	Avg. Pave.	Spec. Pave.	Spec. Pave. & Updated Ground	Avg. Pave.	Spec. Pave.	Spec. Pave. & Updated Ground
all	0.7	0.7	0.7	1.3	1.4	1.3	0.4	0.4	0.4
open area, soft ground	1.4	1.3	1.1	2.3	2.2	1.9	0.8	0.8	0.7
near distances	1.4	1.3	1.2	2.4	2.3	2.1	0.8	0.7	0.7
far distances	1.9	2.0	1.5	3.3	3.3	2.5	1.3	1.3	1.0
open area, hard ground	0.8	0.8	0.7	1.3	1.2	1.2	0.6	0.6	0.5
near distances	1.6	1.6	1.5	2.6	2.6	2.5	1.1	1.1	1.0
far distances	0.9	0.9	0.7	1.6	1.6	1.2	0.5	0.5	0.4
barrier, soft ground	0.7	0.8	0.8	1.1	1.3	1.3	0.4	0.5	0.5

3.3.3 Level Differences between Measurements and Model for Calibrated Data

In addition to the linearity of the fit between the predicted and measured data, the difference between the measured and predicted data is also useful in understanding TNM's performance. Table 12 presents the average differences between measured data and calibrated TNM v2.5-predicted data modeled with Average pavement. The results are given as a function of microphone height, distance, ground type, and shielding (with or without a barrier). Table 13 presents the same information, except that specific pavements were used in the models. Table 14 presents the same information as well, except that specific pavements and updated ground types were used in the models.

Table 12: Average Difference between Measurement and Predicted Values (TNM v2.5 - Measured) for Average Pavement

Site Type	Mic Height (ft)	Average Differences in Sound Levels for Ranges of Distance from the Roadway						
		1-100 ft	101-200 ft	201-300 ft	301-500 ft	501-1000 ft	> 1000 ft	all distances
open area, soft ground	5	0.8	0.1	no data	-2.7	-5.7	no data	-1.5
	15	-1.1	-1.5	no data	-1.7	-3.4	no data	-1.7
open area, hard ground	5	0.6	1	no data	no data	0.7	3.9	1.3
	15	-1.5	-1.4	no data	no data	1.3	2.4	-0.5
barrier, soft ground	5	0.8	0	2	no data	no data	no data	0.7
	15	1.4	0.7	2.8	no data	no data	no data	1.2

It can be seen that each modeling set performed better at some locations / conditions than the other two. This indicates that specific pavements and updated ground types alone are not sufficient to quantify all of the variation that was observed in the 2004 validation addendum, however, it can be seen that for certain locations / conditions these updates did provide improvement. Specifically, specific pavements did offer improvements over Average pavement for open areas with acoustically soft ground at far distances, some improvement for open areas with acoustically hard ground at far distances, and some improvement for sites with barriers at near distances. Similarly, also updating ground types to use a more appropriate EFR value improved results for most open area sites (both acoustically hard and soft ground as well as near and far distances). By the appropriate use of calibration, specific pavements, and the correct selection of ground types it is possible to achieve small average differences between predicted and measured sound pressure levels.

Table 13: Average Difference between Measurement and Predicted Values (TNM v2.5 - Measured) for Specific Pavement

Site Type	Mic Height (ft)	Average Differences in Sound Levels for Ranges of Distance from the Roadway						
		1-100 ft	101-200 ft	201-300 ft	301-500 ft	501-1000 ft	> 1000 ft	all distances
open area, soft ground	5	0.9	0.2	no data	-1.7	-3.8	no data	-1.0
	15	-1.6	-0.8	no data	-1.2	-2.3	no data	-1.4
open area, hard ground	5	0.6	1.2	no data	no data	1.3	3.8	2.6
	15	-1.4	-1.5	no data	no data	1.9	2.5	1.1
barrier, soft ground	5	0.5	-0.4	0.7	no data	no data	no data	0.2
	15	1.1	0.3	3.5	no data	no data	no data	0.9

Table 14: Average Difference between Measurement and Predicted Values (TNM v2.5 - Measured) for Specific Pavement and Modified Ground Types

Site Type	Mic Height (ft)	Average Differences in Sound Levels for Ranges of Distance from the Roadway						
		1-100 ft	101-200 ft	201-300 ft	301-500 ft	501-1000 ft	> 1000 ft	all distances
open area, soft ground	5	0.9	0.6	no data	-1.0	-2.5	no data	-0.4
	15	-1.6	-0.8	no data	-1.0	-2.0	no data	-1.3
open area, hard ground	5	0.5	1.1	no data	no data	0.7	3.4	2.2
	15	-1.4	-1.5	no data	no data	1.3	2.3	0.9
barrier, soft ground	5	0.5	-0.4	0.7	no data	no data	no data	0.2
	15	1.1	0.3	3.5	no data	no data	no data	0.9

4. Next Steps

Although the selection of the most appropriate ground type will decrease the differences between measured and predicted results, over long distances, ground effects appear to be overestimated in TNM 2.5. That is, for distances greater than about 500 feet, results are being under-predicted for soft ground and over-predicted for hard ground. One possibility for these differences may be that the direct and reflected sound waves become less coherent over distance due to air turbulence and ground (or water) roughness [Chessell 1977] [Plovsing 2001]. Implementing a distance-dependent coherence function for the interacting sound waves is being investigated for possible inclusion in a future version of TNM.

5. Summary

Highway sites originally modeled as part of the validation of TNM v2.5 have been re-modeled by using the specific pavement categories (DGAC, OGAC, or PCC) available in TNM v2.5 in order to evaluate the performance of TNM v2.5 when using specific pavements rather than Average pavement. Results from these models were generally comparable to the previous results which used Average pavement. The magnitude of the calibration values decreased for some sites but increased for others. These results were expected. The use of specific pavements can only improve the predicted results when Average-pavement-predicted sound levels are low for PCC sites and are high for DGAC and OGAC sites. (Site-to-site bias can produce results for Average pavement that are the opposite of this relationship, that is, high predicted sound levels for PCC and low for DGAC and OGAC.) Like many modeling decisions, it is important to use experience and measurements to guide the decision to use specific pavements. Note: At the time of this publication, federal policy requires the use of TNM Average pavement for predicting future noise impacts for federal-aid highway projects; use of pavement types other than Average in TNM should only apply to validation studies or to special programs contracted with FHWA.

Ground types were also updated for many sites based on an improved understanding of ground type classifications. These updates resulted in decreases in the difference between measured and predicted results for most open area sites (both acoustically hard and soft ground as well as near and far distances). The choice of the appropriate ground types for a site can be complex for some general ground types such as grass (refer to Section 2.2.2 for guidance). When insufficient information is available to make the most informed decision, at a future site for example, a conservative choice of ground type should be made.

Although results improved with a better representation of ground effects, for distances greater than about 500 feet, there is still some under-prediction for soft ground and over-prediction for hard ground. As a next step, predicted results from a modified version of TNM 2.5 will be evaluated to determine if further reductions in the difference between predicted and measured results at far distances can be achieved. The modified version of TNM 2.5 will incorporate a distance-dependent coherence summation between direct and reflected sound waves. Results of this investigation may result in modifications for future versions of TNM. Further research is needed in this area and will take place in the near future, contingent on available funding.

6. References

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Appendix A: Additional Plots for Specific Pavements

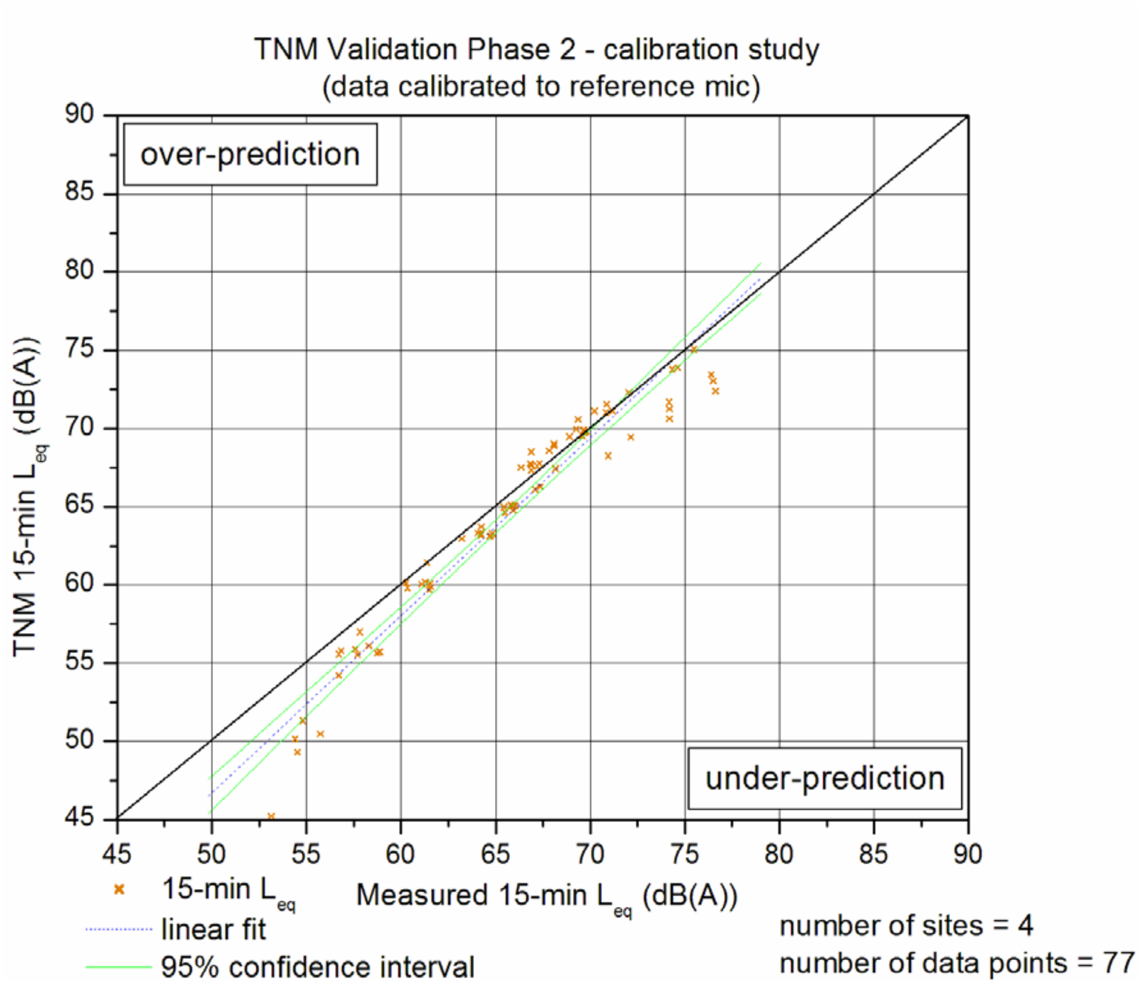
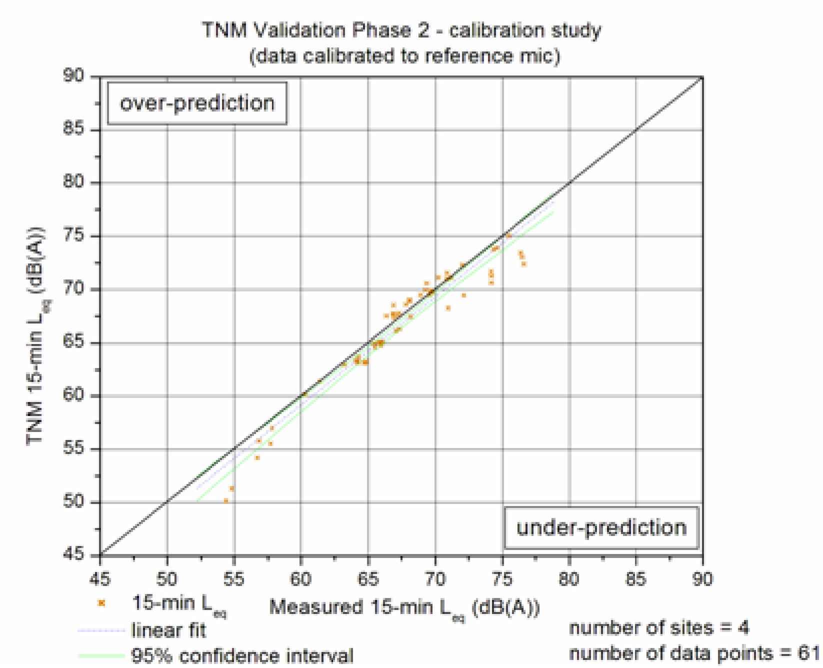


Figure 6: Specific Pavement – Open – Soft

Near



Far

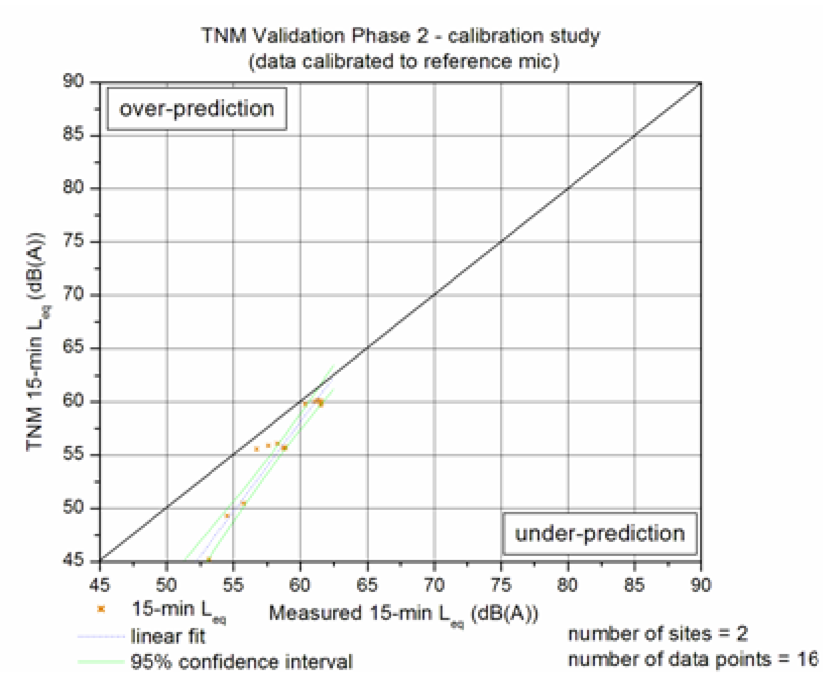


Figure 7: Specific Pavement – Open – Soft, Near and Far

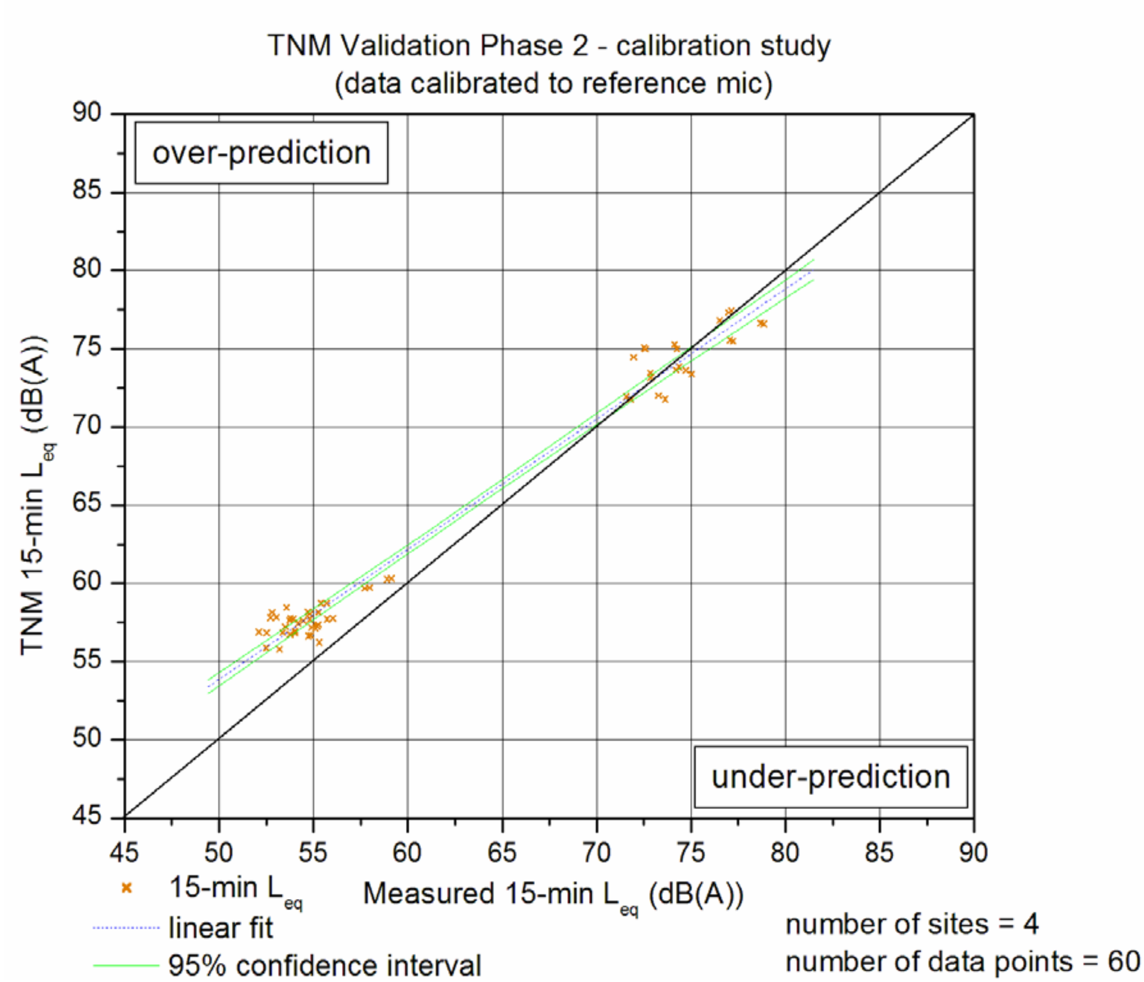
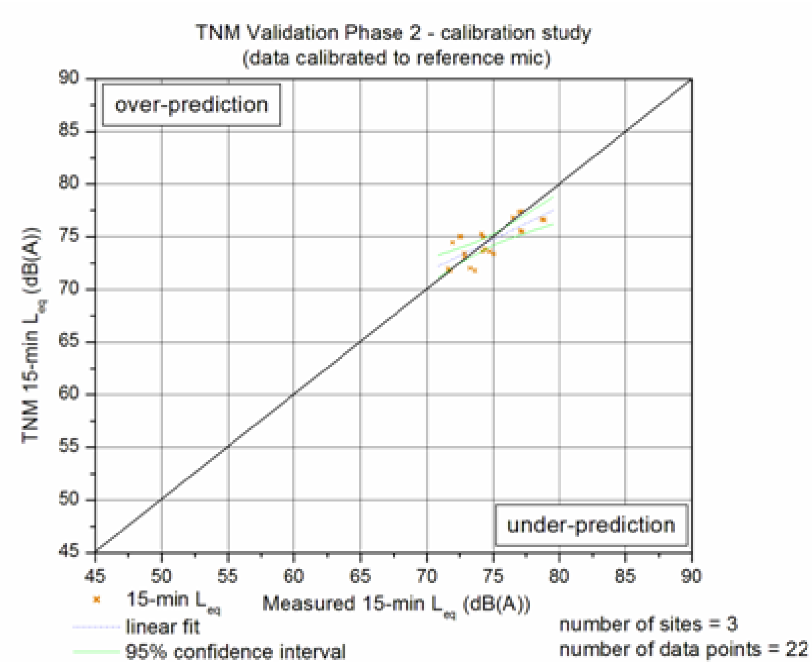


Figure 8: Specific Pavement – Open – Hard

Near



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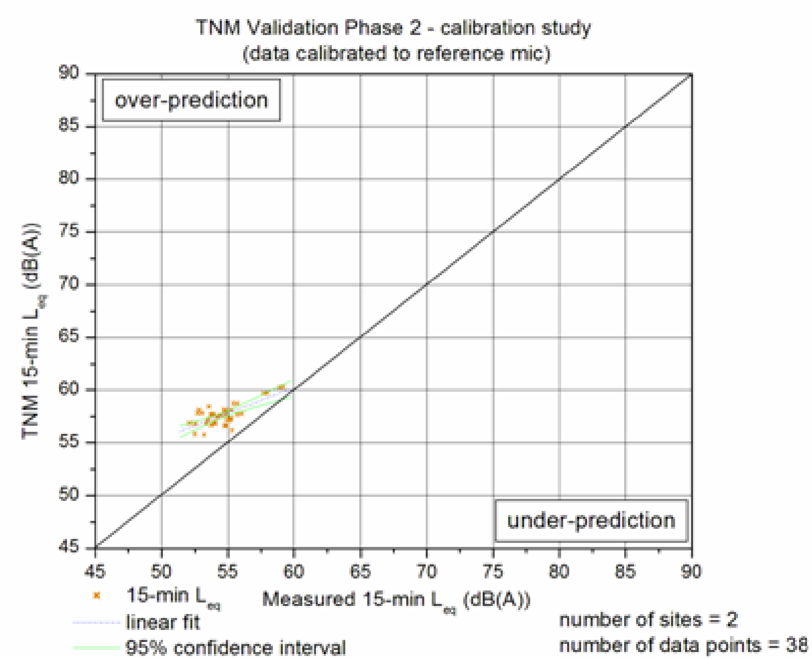


Figure 9: Specific Pavement – Open – Hard, Near and Far

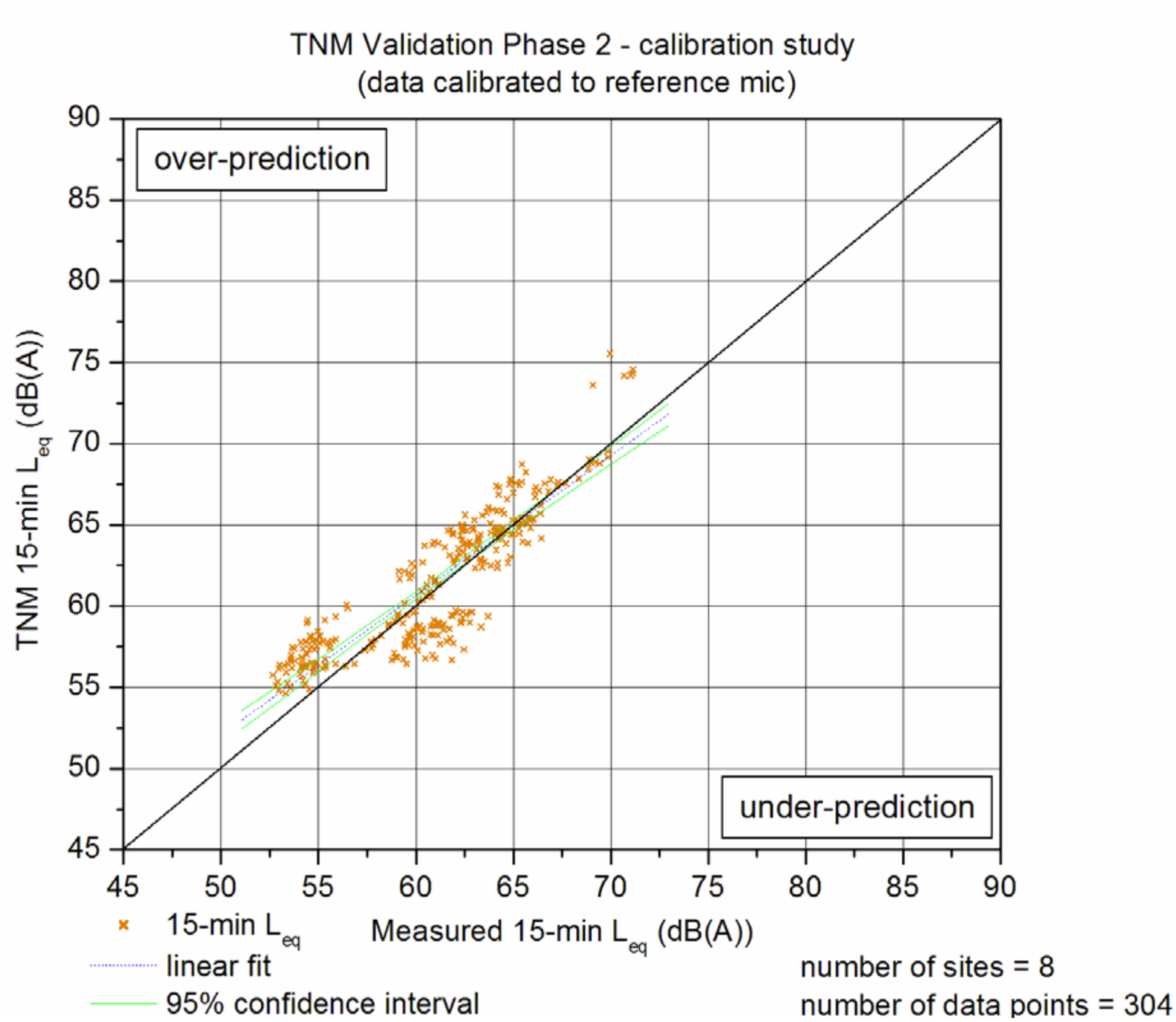


Figure 10: Specific Pavement – Barrier

Appendix B: Additional Plots for Specific Pavements with Updated Ground Types

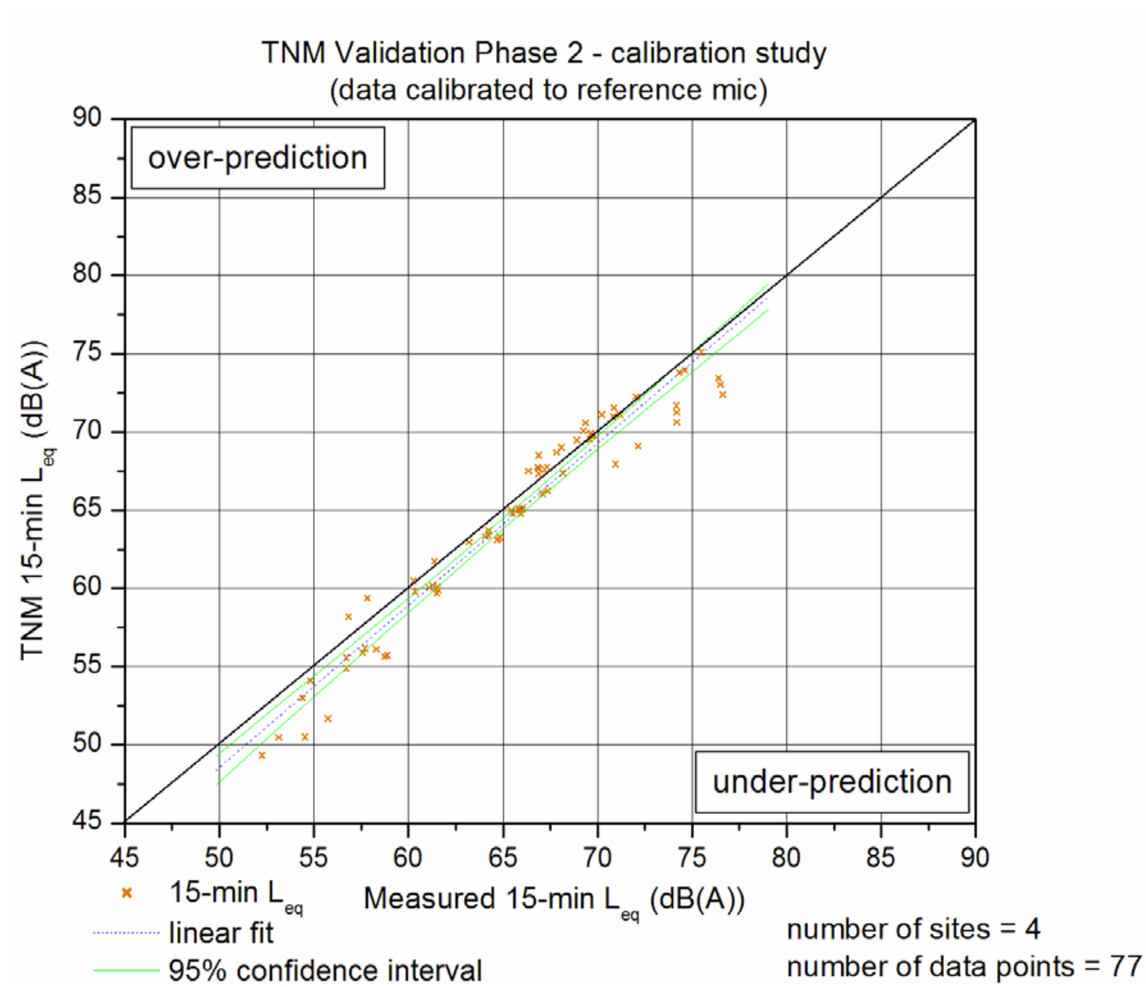
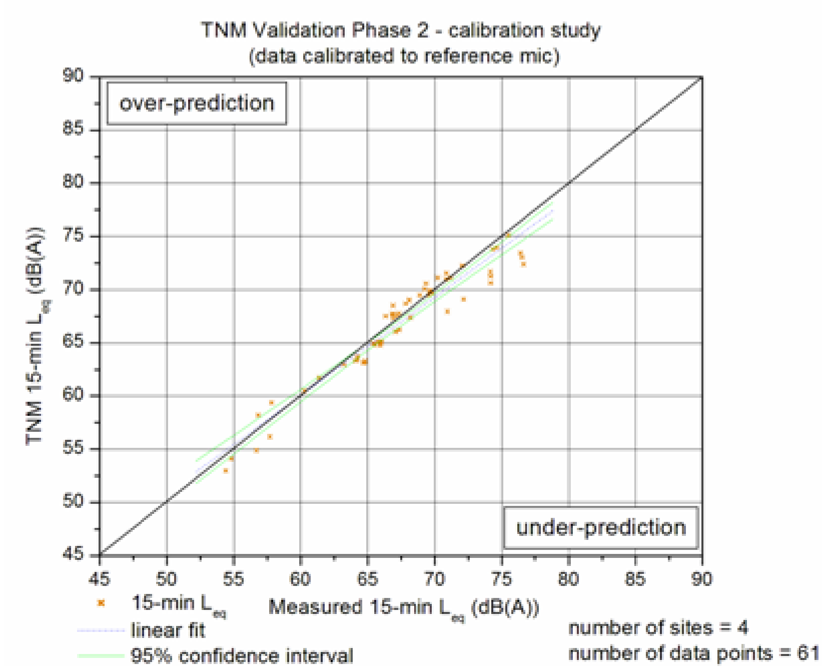


Figure 11: Specific Pavement and Updated Ground Types – Open – Soft

Near



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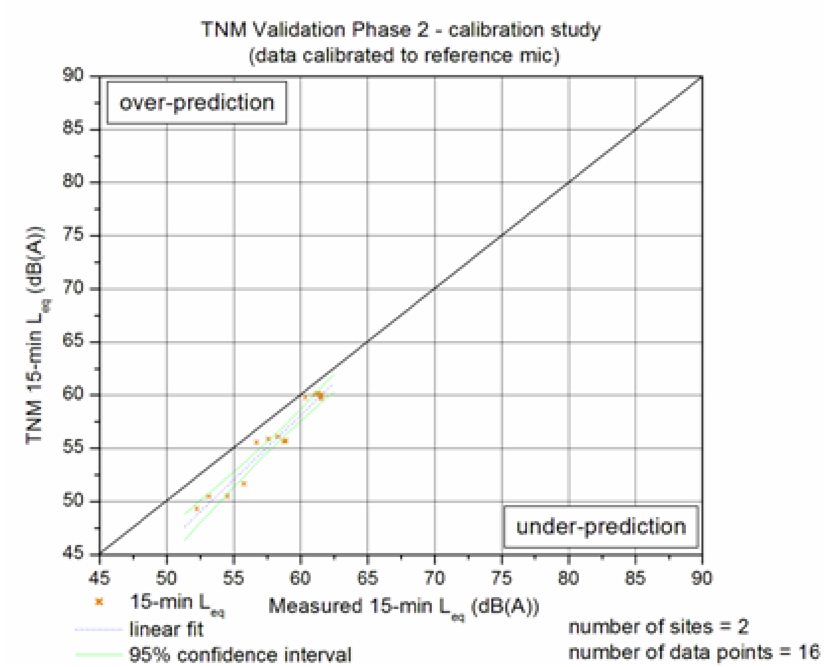


Figure 12: Specific Pavement and Updated Ground Types – Open – Soft, near and far

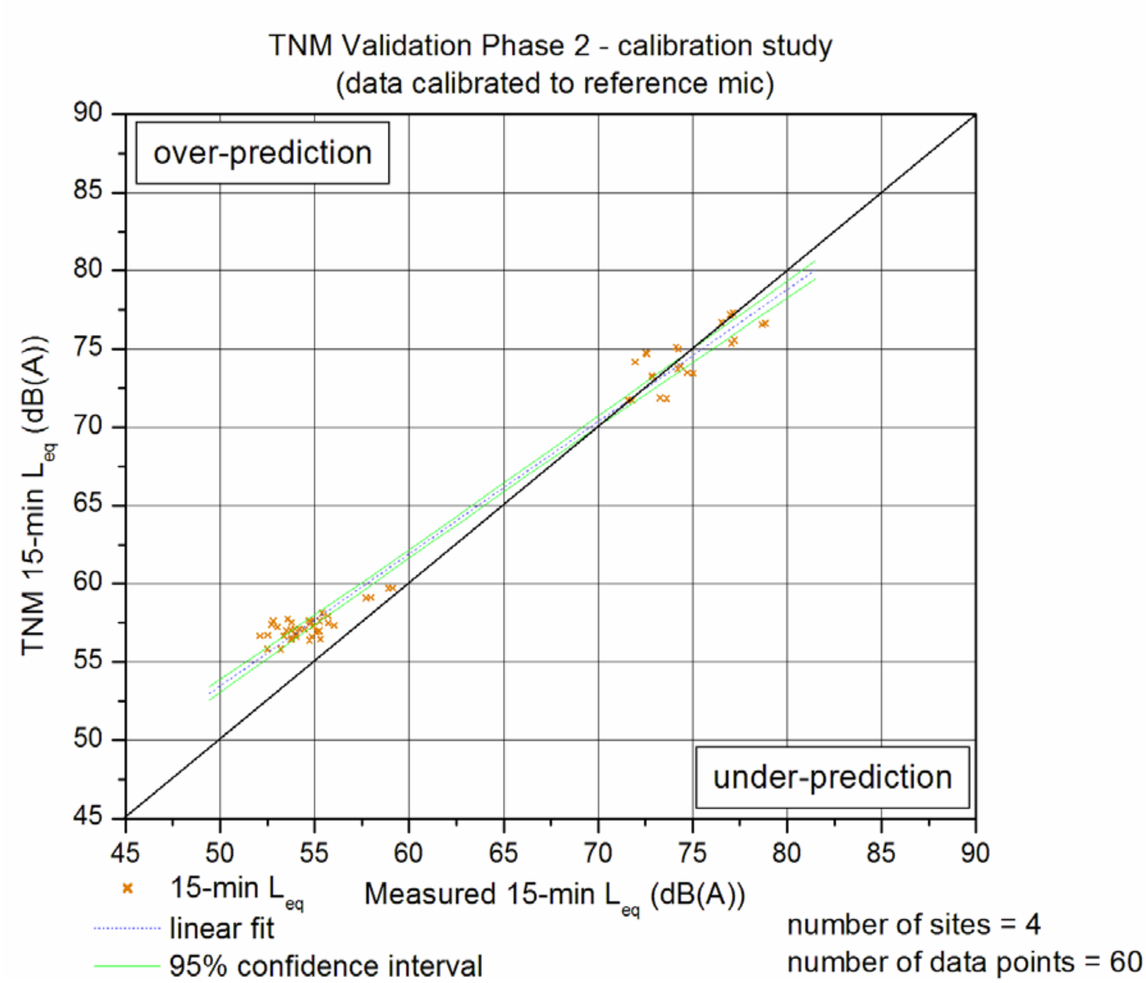
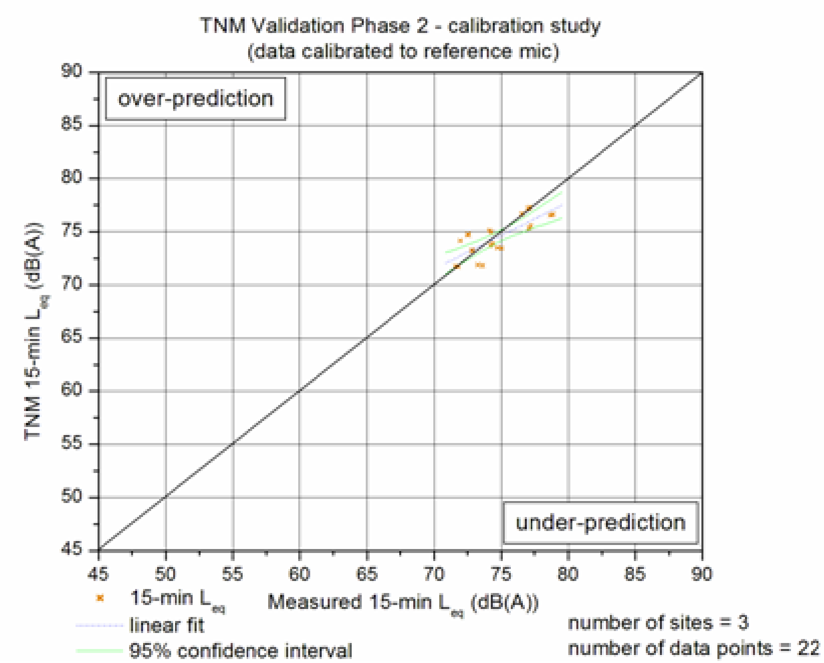


Figure 13: Specific Pavement and Updated Ground Types – Open – Hard

Near



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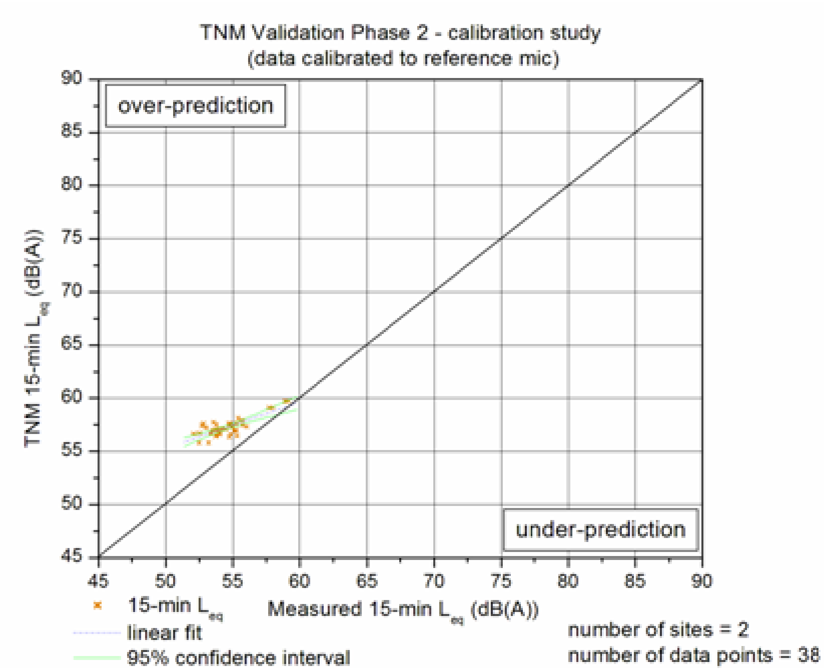

Figure 14: Specific Pavement and Updated Ground Types – Open – Hard, near and far

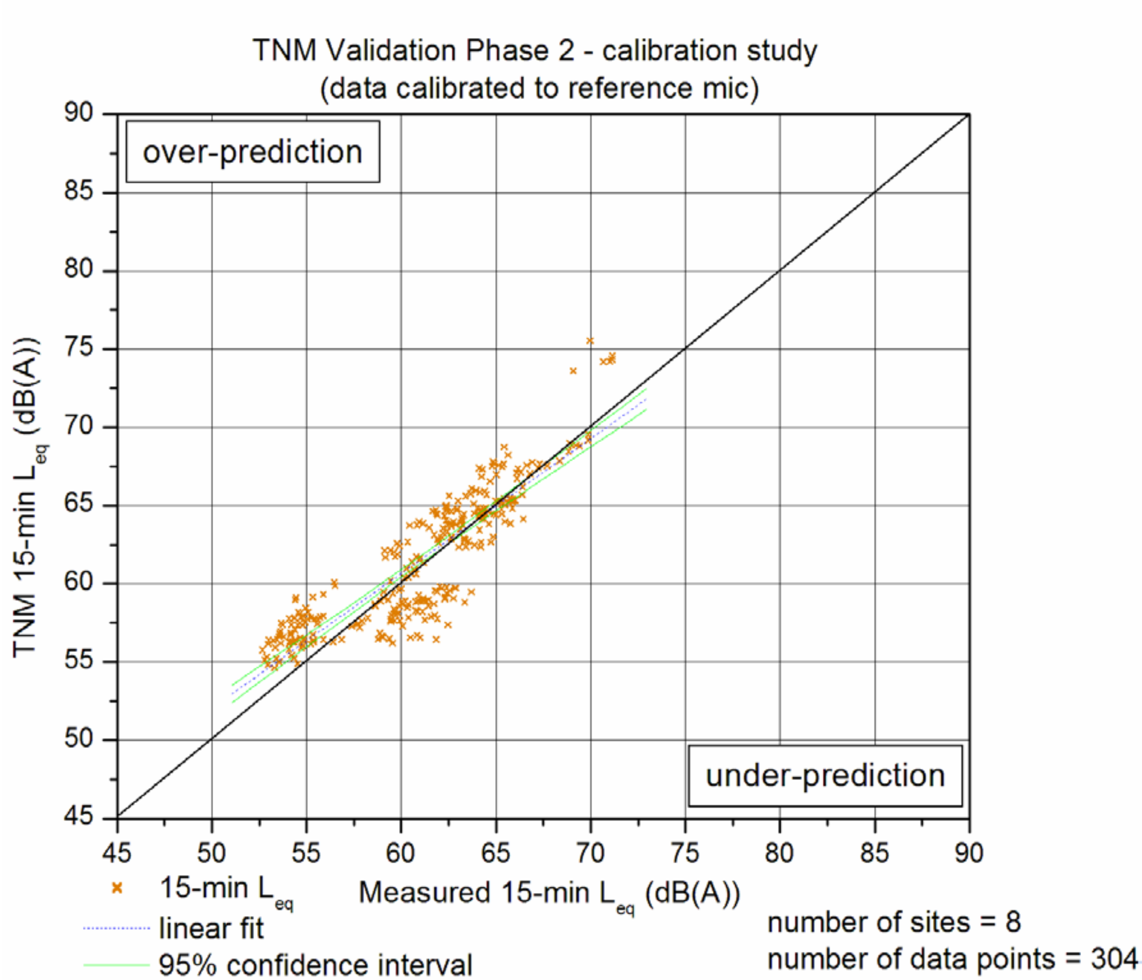

Figure 15: Specific Pavement and Updated Ground Types – Barrier