FHWA-HEP-11-005
DOT-VNTSC-FHWA-11-01

November 2010
Final Report

Investigation of Temperature Correction for Tire/Pavement Noise Measurements

Prepared for:
United States Department of Transportation
Federal Highway Administration
Office of Natural Environment
Washington, DC 20590

Prepared by:
United States Department of Transportation
Research and Innovative Technology Administration
Volpe National Transportation Systems Center
Environmental Measurement and Modeling Division
Cambridge, MA 02142

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE November 2010	3. REPORT TYPE AND DATES COVERED Final Report

4. TITLE AND SUBTITLE
Investigation of Temperature Correction for Tire/Pavement Noise Measurements

5. FUNDING NUMBERS
HW66 / HVZ90

6. AUTHOR(S)
Judith L. Rochat

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Research and Innovative Technology Administration
John A. Volpe National Transportation Systems Center
Environmental Measurement and Modeling Division, RVT-41
Acoustics Facility
Cambridge, MA 02142

8. PERFORMING ORGANIZATION REPORT NUMBER
DOT-VNTSC-11-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Highway Administration (FHWA)
Office of Natural Environment
Washington, DC 20590

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
FHWA-HEP-11-005

11. SUPPLEMENTARY NOTES
FHWA program managers: Mark Ferroni, Adam Alexander

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
The Volpe Center Acoustics Facility, in support of the Federal Highway Administration, investigated the influence of temperature on tire/pavement noise in order to provide guidance on correcting for temperature variations in measured sound levels. Several traffic noise and vehicle pass-by data sets with broad variation in both pavement and air temperatures were examined to help determine trends relating to the effects of temperature. The parameters investigated include: air vs. pavement temperature, single vehicle types vs. mixed traffic, and pavement type. Since the effects of temperature appeared to be fairly small over temperature ranges available for the data sets examined, care was taken to apply the proper statistics to determine if the slope of the regression line for sound level as a function of temperature was, in fact, not zero. Results show that there is usually a trend of slightly decreasing sound levels with increasing temperatures, although the strength of the effect varies by temperature measurement medium (air vs. pavement), vehicle type, and pavement type, and there are exceptions. The application of various temperature correction schemes to wayside measured data shows that it is possible to reduce error related to temperature variations, but one should do so cautiously, with the understanding that application of generic or semi-generic corrections may lead to an unnecessary or unfavorable outcome in some cases.

14. SUBJECT TERMS
Highway traffic noise, temperature effects, tire/pavement interaction noise, asphalt pavements, concrete pavements

15. NUMBER OF PAGES
70

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

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

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

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

AREA (APPROXIMATE)

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

MASS - WEIGHT (APPROXIMATE)

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

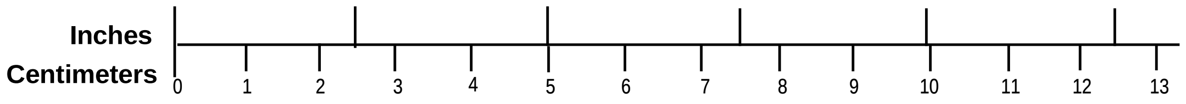
VOLUME (APPROXIMATE)

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

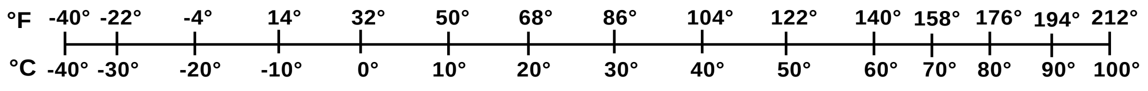
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



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

Updated 6/17/98

ACKNOWLEDGEMENTS

The author wishes to thank the Federal Highway Administration (FHWA) for support of this study through the Surface Transportation Environment and Planning Cooperative Research Program (STEP). The author also wishes to thank the FHWA, the Arizona Department of Transportation (ADOT), and the California Department of Transportation (Caltrans) for allowing the use of data from various studies in which the U.S. Department of Transportation / Research and Innovative Technology Administration / Volpe National Transportation Systems Center (Volpe Center) has participated.

TABLE OF CONTENTS

Section **Page**

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Background

Understanding how various pavements affect highway traffic noise that reaches nearby communities is an important aspect of highway noise prediction and noise mitigation. Related research includes measuring traffic or vehicle pass-by noise on the side of the road (wayside) and comparing results for different pavements [Sandberg 2002][ISO 11819-1][Rochat 2009-2]. In order to make such comparisons, it is important to minimize sound level differences due to influences by parameters other than pavement. Examples of such parameters are: site geometry, site ground type next to the roadway, and meteorological conditions. While ideally these parameters would be the same at each measurement site, that is not realistically the case. Although steps can be taken to minimize these influences, one parameter, temperature, can vary not only from site to site, but also over time during measurements at a single site. In order to address the influence on sound level due to temperature variation, three questions need to be answered:

1. How much does temperature affect measured sound levels?
2. Should corrections be applied to the measured sound levels to remove the temperature effect?
3. How should temperature corrections be applied?

1.2 Study Overview and Report Organization

In order to answer these questions, the first step was to review literature on the topic of temperature effects; a review of the literature can be found in Section 2. Next, available measured data sets with broad temperature ranges were identified; a description of the data sets can be found in Section 3. The data were then analyzed in terms of determining temperature coefficients, identifying trends, and applying temperature corrections; a description of each data analysis process can be found in Section 4. Results of the data analysis and a discussion of the findings are given in Section 5. Conclusions follow in Section 6.

2. LITERATURE REVIEW

The following reference material was reviewed, each with information regarding temperature effects on data from tire/pavement noise measurements: Sandberg 2002, Sandberg 2004, Anfosso 2006, Jabben 2006, and Bendtsen 2009. Below, some general trends are identified as well as some suggestions for semi-generic temperature corrections to apply to other studies.

2.1 General Trends of Temperature Effects

It was found that several researchers have identified a general trend of slightly decreasing vehicle pass-by noise levels with increasing temperature, where the effect can be dependent on pavement type, pavement surface texture, and vehicle type (tire type), although there are exceptions. Tire hardness (colder is harder) and pavement properties (that are affected by heat) can both contribute to the temperature effect on noise levels. For cars, the influence of temperature on sound level data is greater for dense-graded asphalt pavements than for porous or open-graded pavements and is greater for porous or open-graded asphalt pavements than for cement concrete pavements. For trucks, it is difficult to see any consistent temperature influence, though some studies show that the effect is less for trucks than for cars. Also, rough-textured pavement surfaces show a large effect from temperature, and smooth-textured surfaces show less effect.

The measured temperature effect typically ranges from -0.028 to -0.056 dB per 1 °F increase (-0.05 to -0.10 dB per 1 °C increase), although there were extremes out to -0.11 dB per 1 °F (-0.20 dB per 1 °C). Two studies showed temperature effects are greatest in the mid to high frequency range (630 to 1000 Hz and up), although another study showed that the frequencies most affected by temperature are both low frequencies (< 500 Hz) and high frequencies (1.5 – 5 kHz).

Regarding temperature measurements, it has been discussed in the literature that there is a good relationship between ambient air and road surface temperature, and a fairly good relationship between tire tread surface and road surface temperature. The noise-temperature relationship is better between air temperature and noise than between tire temperature and noise. This information helps to guide which temperature measurements to use for studying the noise-temperature relationship.

2.2 Consideration of Semi-Generic Temperature Corrections

Some semi-generic temperature correction coefficients have been recommended, which differentiate among major groups of vehicles (tires) and major groups of road surfaces [Sandberg 2004][Bendtsen 2009]; please refer to Table 1 and Table 2. As can be seen, the recommendations are somewhat different. For an 18 °F (10 °C) air temperature increase for cars driving on DGAC (dense-graded asphalt), the Sandberg 2004 correction scheme would require an adjustment of 18°F*(-0.050) = -0.9 dB [10°C*(-0.09) = -0.9 dB], and the Bendtsen 2009 correction scheme would require an adjustment of 18°F *(-0.034) = -0.6 dB [10°C*(-0.06) = -0.6 dB]. An International Organization for Standardization working group is discussing the topic of semi-generic correction schemes further.

Table 1. Possible semi-generic corrections based on each major group of vehicles (tires) and each major group of road surfaces [Sandberg 2004].

Temperature correction coefficient (dB/°F, dB/°C)		Tire/vehicle and road surface
-0.050	-0.09	Car + ISO, SMA, DGAC (dense-graded asphalt)
-0.033	-0.06	Car + porous asphalt
-0.028	-0.05	Car + diamond ground cement concrete
-0.017	-0.03	Truck + any surface

Table 2. Possible semi-generic corrections based on one group of vehicles and each major group of road surfaces [Bendtsen 2009].

Temperature coefficient (dB/°F, dB/°C)		Tire/vehicle and road surface
-0.034	-0.06	Car + DGAC (dense-graded asphalt)
-0.029	-0.05	Car + OGAC (open-graded asphalt)
-0.029	-0.05	Car + all asphalt types
-0.024	-0.04	Car + cement concrete
-0.017	-0.03	Truck + any surface

3. DATA SETS INVESTIGATED

Before recommendations can be made on whether or not temperature corrections should be applied, and if so, what the corrections should be, more data sets need to be investigated to determine the relationship between sound level and temperature for various parameters. As such, data sets from three studies were examined: 1) the Arizona Department of Transportation (ADOT) Quiet Pavement Pilot Program (AZ QPPP) [ADOT 2006]; 2) the California Department of Transportation (Caltrans) Thin Lift Study [Rochat 2009-1]; and 3) the Federal Highway Administration (FHWA) Traffic Noise Model Pavement Effects Implementation Study (TNM PEI) [Volpe 2008]. All data were collected by the Volpe Center.

Note: All data examined were measured on the side of the road (wayside). Since wayside measurement methodologies inherently incorporate sound propagation effects, it is also good to examine close-proximity tire/pavement noise data. Other investigators are currently in the process of analyzing close-proximity tire/pavement noise data they have collected for their research. (Aside: Determining the relationship using wayside noise measurement data may more accurately capture the temperature effect as experienced by people living near a highway.)

3.1 AZ QPPP Data

Data from the ADOT Quiet Pavement Pilot Program (AZ QPPP) [ADOT 2006] was used to help study the effects of temperature. This study applies a time-averaged methodology, Continuous-Flow Traffic Time-Integrated Method (CTIM) [Rochat 2009], which results in 5-minute A-weighted equivalent sound levels ($L_{Aeq5min}$) for mixed traffic. Data were collected at a distance of 50 ft (15 m) from the center of the near travel lane. Data were collected for two different pavement types: uniform transversely tined Portland cement concrete (PCC) and asphalt rubber friction course (ARFC, open-graded asphalt with crumb rubber in binder) new and aged 1 year. The average range of temperature variation for this study was 11 °F (6 °C) for air and 27 °F (15 °C) for pavement. Note: the percentage of heavy trucks for each set of data is less than 10% by traffic volume.

3.2 Caltrans Thin Lift Study Data

Data from the Caltrans Thin Lift Study [Rochat 2009-1] was used to help study the effects of temperature. This study applies a modified version of the Statistical Pass-By methodology (SPB) [ISO 11819-1], influenced by another pass-by methodology, one based on the TNM database (REMEL) collection procedure [Lee 1996], which results in vehicle pass-by A-weighted fast-response maximum sound levels (L_{AFmx}) for automobiles and heavy trucks. Data were collected at a distance of 50 ft (15 m) from the center of the near travel lane. Data were collected for five different pavement types/configurations, two of which were analyzed in this study: dense-graded asphalt (DGAC) and open-graded asphalt (OGAC) 75 mm thickness. The average range of temperature variation for this study was 26 °F (14 °C) for air and 62 °F (34 °C) for pavement.

3.3 FHWA TNM PEI Study Data

Data from the Federal Highway Administration (FHWA) Traffic Noise Model [Volpe 2008] Pavement Effects Implementation Study (TNM PEI Study) were used to help study the effects of temperature. This study applies the REMEL data collection procedure [Lee 1996], which results in vehicle pass-by A-weighted fast-response maximum sound levels (L_{AFmx}) for automobiles and heavy trucks. Data were collected at a distance of 50 ft (15 m) from the center of the near travel lane. Data were collected for several pavement types, three of which were analyzed in this study: DGAC, longitudinally tined PCC, and longitudinally ground PCC. The average range of temperature variation for this study was 19 °F (10 °C) for air and 30 °F (17 °C) for pavement.

4. DATA ANALYSIS

4.1 Temperature Coefficient

For each data set, sound level is plotted as function of either air or pavement temperature. Sound level is represented by L_{AFmx} values for single pass-by events or by $L_{Aeq5min}$ values for the time-averaged data. Next, a linear regression analysis is conducted for each set of data, resulting in the corresponding regression line equation:

L = a + bT,
where:
L is the sound level (dB),
T is the temperature (degree F or C),
a, b are the constants (a is the offset, b is the slope). (1)

The slope b is called the *temperature coefficient*. The temperature coefficient equates to the decibel amount the sound changes per degree F or C; a negative sign means decreasing noise with increasing temperature. Temperature coefficients can be converted from degrees F to degrees C using the following equation: (b for °F)*(9/5) = (b for °C); they can be converted from degrees C to degrees F using the following equation: (b for °C)*(5/9) = (b for °F).

Please refer to Sections 5.1 and 5.2 and Appendices A and B for results.

4.2 Temperature Coefficient Veracity

As can be found in literature and in this study, linear regression line slopes for sound level as a function of temperature are very small (magnitude usually less than 0.1). It was determined that statistics need to be applied to quantify the slope's uncertainty.

Investigations determined that the appropriate statistical parameter to apply is the P-value [Anderson 2008]. The P-value is a quantitative parameter to determine if the zero-slope line lies within a specified confidence region of the regression line through the measured data; it is used to determine the percent chance that the true slope does not equal zero: 100*(1 minus P-value), which quantifies the slope's uncertainty. If the percent chance that the slope is truly not zero (also referred to as "percent certain") is above some threshold, this indicates that there is an effect of temperature on highway noise. (Aside: Although R-squared is often used to determine the validity of a relationship between two parameters, it is an inappropriate statistical parameter to apply to slope uncertainty. The R-squared values are calculated and shown in Appendix B, Table 7, along with percent certain, just so it can be seen that the R-squared values clearly do not evaluate the slope uncertainty.)

For each data set examined in this study, the P-value was used to determine the percent certain (percent chance that the slope was truly not zero or that the zero slope line did not lie with the 95% confidence region of the regression line). For this study, the percent-certain threshold was set at 70%, as can be seen in some of the results and discussions in Section 5.2 and Appendix B. Setting the percent certain threshold at 70% means that there is a 70-100% chance that the acceptable temperature coefficients are valid or that a genuine relationship exists between sound level and temperature for each data set.

4.3 Determining Trends in Temperature Coefficient Data

In order to identify trends, air temperature coefficients were examined as a function of the following parameters:

- General pavement type [dense-graded asphalt (DGAC), open-graded asphalt (OGAC, RAC), and Portland cement concrete (PCC)]; and
- Vehicle type (autos and heavy trucks).

Temperature coefficients were plotted on a bar chart and then categorized in terms of general pavement type and vehicle type. Please refer to Section 5.3 and Appendix B for results.

In addition to the bar chart of air temperature coefficients, the data were also examined in terms of histograms. Histograms were generated for three scenarios: all data, by categories as seen in Table 3 (Section 5), and by categories as seen in Table 4 (Section 5). The range of bins was from -0.2 to 0.2 in increments of 0.025 dB per degrees F. Please refer to Section 5.3 and Appendix B for results.

4.4 Applying Temperature Corrections

In order to determine the effect of applying temperature corrections to measured sound levels, two analyses were performed: 1) examination of temperature coefficients for a set shift in temperature with various correction schemes applied, and 2) examination of sample wayside sound level data sets with various correction schemes applied. Please refer to Section 5.4 and Appendix C for results.

<u>Examination of potential dB-error for a set shift in temperature with various correction schemes applied</u>

For this analysis, the air temperature coefficients for all data sets were multiplied by 18 °F (10 °C) to demonstrate the expected errors associated with a change in temperature of 18 °F (10 °C), without making any corrections. Then various temperature correction schemes were applied to see if they would decrease the error associated with temperature effects. This is a procedure similar to that found in Sandberg 2004.

The various correction schemes that are applied are listed in Table 5 in Section 5. For no corrections and for each scheme, the average expected error over an 18 °F (10 °C) change is calculated by taking the average of all values. The standard deviation, standard error of the average, and confidence range of the average are also calculated, and an F-test is performed to determine whether or not there is evidence that the variability of the data decreases upon applying various temperature correction schemes.

<u>Examination of sample wayside sound level data sets with various correction schemes applied</u>

For this analysis, sound levels are plotted as a function of time of day for specific sample data sets. For each data set, semi-generic temperature correction schemes (Tables 1-4) and a data-set-specific temperature correction scheme are applied (all corrections were made to 68 °F (20 °C)), and a linear regression analysis is performed for each to determine the slope; no analysis is performed to determine the percent certainty of the slope. Slopes for the corrected data are compared to the uncorrected data to see if the sound levels “flatten out” over time. For example, if a slope showed that the sound levels were decreasing over time, where the temperatures were increasing over time, applying corrections should ideally show that the sound levels are fairly consistent over time and that the slope is nearly horizontal.

4.5 Comparison of Air and Pavement Temperatures

Air and pavement temperatures were compared to determine whether either of them is preferable for analysis in studying temperature coefficients. For each data set, air temperature is plotted as a function of pavement temperature, a linear regression analysis is performed, and the R-squared value is determined, which provides an assessment of the relationship between air and pavement temperatures. Please refer to Section 5.5 and Appendix D for results.

5. RESULTS AND DISCUSSION

5.1 Linear Regression of Data

As described in the previous section, sound level data points are plotted as a function of temperature in order to determine the equation for the linear fit, and thus the temperature coefficient. Figure 1 shows an example of this process in degrees Fahrenheit using the AZ QPPP data; this example shows both the air and pavement temperature regression lines for three data sets. Regression lines for all data sets can be found in Appendix A.

As can be seen, in each case in the example, the slope or temperature coefficient for the air temperature linear fit is larger than that for the pavement temperature, since the pavement temperature covers a much broader range for the same measured sound pressure levels. This is being noted to highlight the fact that it is possible to make sound level adjustments using either an air or pavement temperature coefficient, but that air temperature coefficients should be used only with sound level/air temperature data pairs and pavement temperature coefficients should be used only with sound level/pavement temperature data pairs.

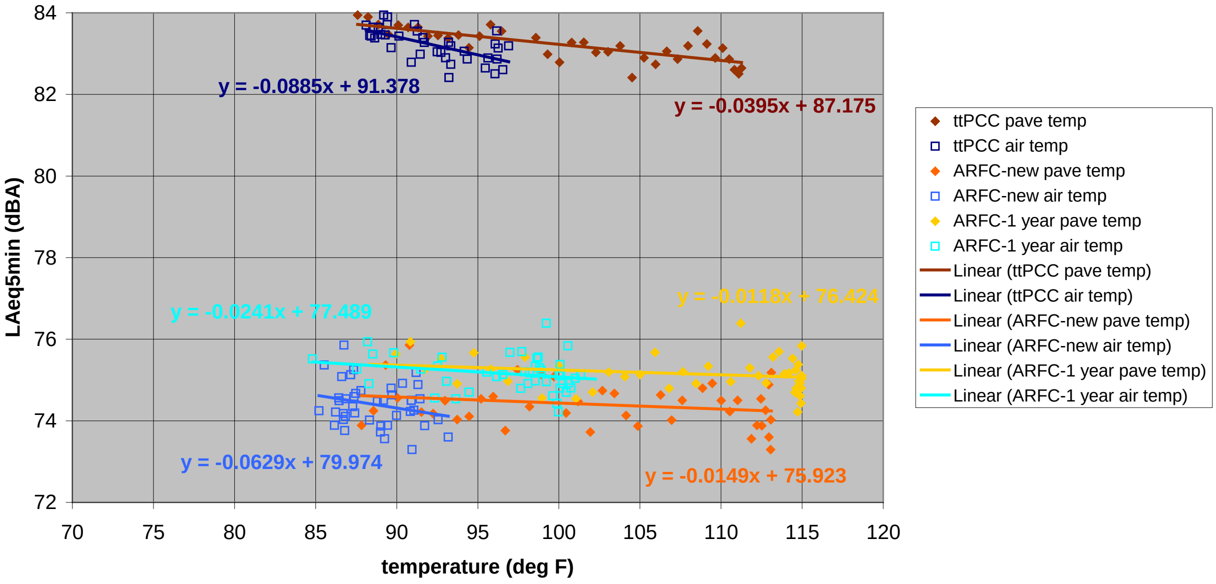


Figure 1. AZ QPPP Site 3C sound levels as a function of temperature, with regression line coefficients.

5.2 Temperature Coefficients

Figure 2 shows the air temperature coefficients for all the data sets in degrees Fahrenheit (a table of all temperature coefficients can be found in Appendix A). The pattern of the bars indicates the vehicle type, the color of the bars indicates the general pavement type, and the data point font color indicates the data certainty, as indicated in the figure key. Listed are key observations of the results shown in Figure 2:

- A majority of the coefficients are indicating that the sound levels slightly decrease as the temperatures increase (negative temperature coefficients), although there are several data sets indicating that the sound levels are slightly increasing as the temperatures increase. The coefficients with 70% or greater certainty range from +0.055 to -0.147 dB/°F (+0.10 to -0.26 dB/°C), with an average of -0.047 dB/°F (-0.08 dB/°C).
- There are both positive and negative temperature coefficients for autos and heavy trucks, although most of the auto coefficients are negative. The data sets involving mixed traffic are showing only negative temperature coefficients, all having 70% or greater certainty.
- The temperature coefficients for DGAC are scattered across the plot, ranging from +0.043 to -0.108 dB/°F (+0.08 to -0.19 dB/°C) with 70% certainty or greater.
- The temperature coefficients for OGAC and ARFC are also scattered across the plot, ranging from +0.055 to -0.063 dB/°F (+0.10 to -0.11 dB/°C) with 70% certainty or greater.
- The temperature coefficients for longitudinally tined and ground and transversely tined PCC are on the right hand side of the plot (one positive coefficient, but the certainty is < 70%), ranging from -0.035 to -0.147 dB/°F (-0.06 to -0.26 dB/°C) with 70% certainty or greater.

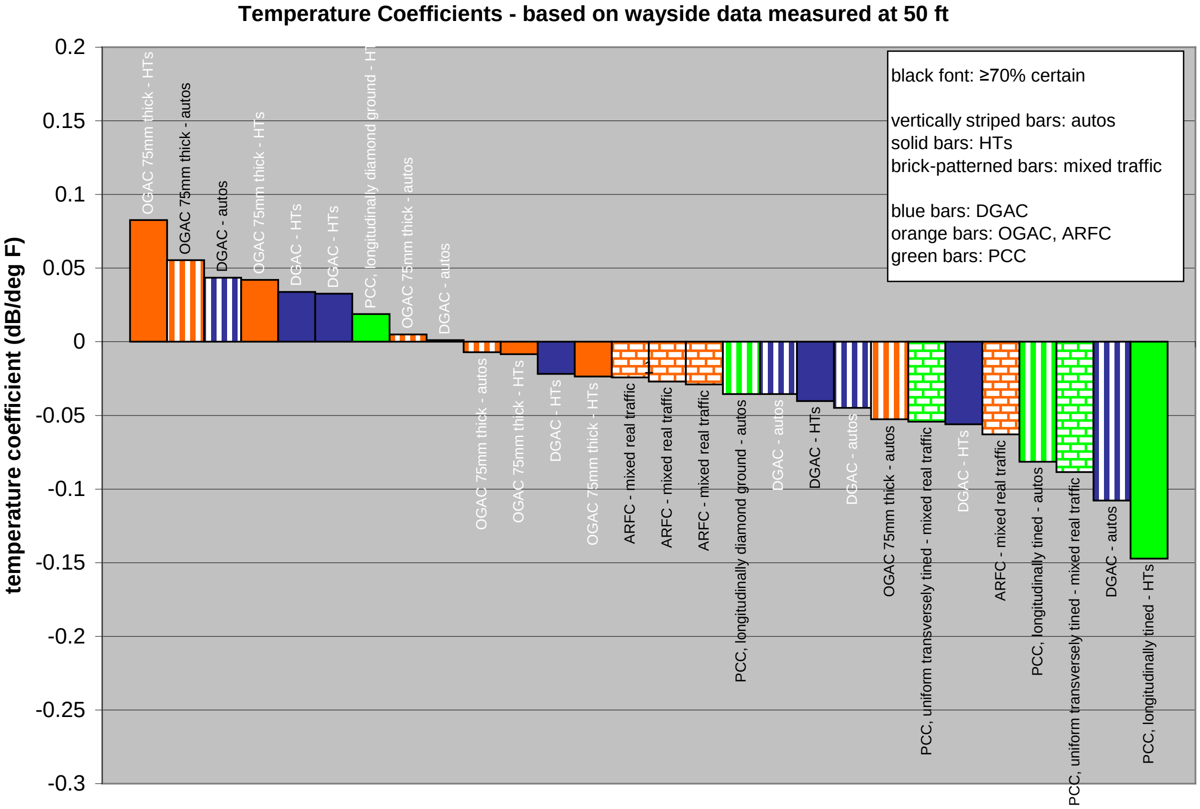


Figure 2. Air temperature coefficients for all data sets examined. The text for each data set is a description of each pavement type and vehicle type, also indicated more generally as described in the key. The color of the text indicates the certainty of the temperature coefficient – there is a 70% or more chance that the black-font data point values are truly not zero.

For the purposes of comparing to literature and for analysis relating to the application of temperature corrections, temperature coefficient data were then categorized according to the two following semi-generic temperature correction schemes:

1. autos by each pavement type, heavy trucks for any pavement type, mixed traffic by each pavement type
2. autos and mixed traffic together by each pavement type, heavy trucks by each pavement type

Scheme #1 is similar to that shown for Sandberg 2004 and Bendtsen 2009 (see Table 1 and Table 2), with the addition of mixed traffic for a vehicle type. Scheme #2 is based on a combination of literature-based categories and examination of histograms of various categories for the data examined in this study (more information regarding the histograms is available in Section 5.3); the difference from literature schemes is that the heavy truck category is divided by pavement (surface) type.

Averages of air temperature coefficients for the two categorization schemes are shown in Table 3 and Table 4. All of the tables show averages for all temperature coefficients, not just 70% or greater certainty data.

Table 3. Categorized average air temperature coefficients, Scheme #1.

Temperature coefficient (dB/°F, dB/°C)		Tire/vehicle and road surface
-0.029	-0.05	Autos + DGAC (dense-graded asphalt)
-0.006	-0.01	Autos + OGAC (open-graded asphalt)
-0.058	-0.11	Autos + PCC (longitudinally tined and ground, transversely tined)
-0.008	-0.01	Heavy Trucks + any surface
-0.036	-0.06	Mixed Traffic + ARFC (open-graded)
-0.071	-0.13	Mixed Traffic + PCC (transversely tined)

Table 4. Categorized average air temperature coefficients, Scheme #2.

Temperature coefficient (dB/°F, dB/°C)		Tire/vehicle and road surface
-0.029	-0.05	Autos, mixed traffic + DGAC (dense-graded asphalt)
-0.018	-0.03	Autos, mixed traffic + OGAC (open-graded asphalt), ARFC (open-graded)
-0.065	-0.12	Autos, mixed traffic + PCC (longitudinally tined and ground, transversely tined)
-0.010	-0.02	Heavy Trucks + DGAC (dense-graded asphalt)
0.023	0.04	Heavy Trucks + OGAC (open-graded asphalt)
-0.064	-0.12	Heavy Trucks + PCC (longitudinally tined and ground, transversely tined)

Table 3, Scheme #1, shows that the *mixed traffic + PCC* category has the most effect due to temperature; for air temperature, the temperature coefficient is -0.071 dB/°F or -0.71 dB per 10 degree F increase (-0.13 dB/°C or -1.3 dB per 10 degree C increase). The *autos + open-graded asphalt* category has the least effect from temperature; for air temperature, the temperature coefficient is -0.006 dB/°F or -0.06 dB per 10 degree F increase (-0.01 dB/°C or -0.1 dB per 10 degree C increase).

Table 4, Scheme #2, shows that the autos, *mixed traffic + PCC* category has the most effect due to temperature; for air temperature, the temperature coefficient is -0.065 dB/°F or -0.65 dB per 10 degree F increase (-0.12 dB/°C or -1.2 dB per 10 degree C increase). (Note: *heavy trucks + PCC* is a close second.) The *heavy trucks + dense-graded asphalt* category has the least effect from temperature; for air temperature, the temperature coefficient is -0.010 dB/°F or -0.10 dB per 10 degree F increase (-0.02 dB/°C or -0.2 dB per 10 degree C increase).

Comparing either scheme (Table 3 and Table 4) with the semi-generic corrections found in literature (Table 1 and Table 2), it can be seen that there are some similarities and some dissimilarities. In terms of pavement type, the semi-generic schemes in this report generally show that there is a decrease in sound level with increase in temperature, and that the most effect due to temperature is for PCC, then DGAC, then OGAC (and ARFC); an exception is that the *heavy trucks + OGAC* category is actually showing an increase in sound level with increase in temperature. For the semi-generic schemes from literature (Table 1 and Table 2), there is a decrease in sound level with increase in temperature, and the most effect due to temperature is for the DGAC category, then OGAC or porous, then PCC; note: although not apparent from Table 1 and Table 2, literature has also shown that, for some data sets, there is an increase in sound level with increase in temperature. In Scheme #2 (Table 4), it is clear that the temperature coefficient varies widely by pavement type for heavy trucks, whereas literature schemes use a single category: *heavy trucks + any surface*, with heavy trucks being the lowest-amplitude coefficient value of any of their categories.

It was stated in the literature that rough-textured pavement surfaces show a large effect from temperature, and smooth-textured surfaces show less effect. Since the PCC surfaces in this study were textured with longitudinally tined and diamond ground PCC and transversely tined PCC, it is possible that the higher temperature effects seen with PCC in this study (as compared to the literature) can be attributed to some of the rougher textures on these pavements. If a large enough data set were available with varying PCC surface textures, analysis may show that, due to the variation in temperature effect, a semi-generic temperature correction scheme should sub-categorize PCC by different surface textures.

5.3 Trends in Temperature Coefficient Data

There are no apparent trends when examining the bar chart in Figure 2 (this figure can also be seen in Appendix B in slightly larger format). There is perhaps a hint of the trend of PCC appearing more in the right hand side of the bar chart, but the categories by pavement type and vehicle type are mostly scattered about the chart.

This is investigated further in the histogram charts seen in Appendix B, Section B.2. Looking at a histogram of all air temperature coefficients, it first appears that the coefficients are randomly distributed, however, division according to semi-generic Scheme #1 (Table 3) shows that some groupings consistently result in similar coefficients while other groups do indeed appear to have randomly distributed coefficients. Similarly, division according to semi-generic Scheme #2 (Table 4), like Scheme #1, shows that some groupings consistently result in similar coefficients while other groups do indeed appear to have randomly distributed coefficients; in particular, it is clear that categories for heavy trucks in Scheme #2 help reduce the scatter seen in Scheme #1 for heavy trucks. Both schemes indicate that some categorization is better than no categorization, implying that if a correction scheme were to be applied to account for temperature variation, a semi-generic scheme would be better than a generic scheme (single correction value for all vehicle and pavement categories).

5.4 Applying Temperature Corrections

As discussed in Section 4.4, in order to determine the effect of applying temperature corrections to measured sound levels, two analyses were performed: 1) examination of potential dB-errors for a set shift in temperature with various correction schemes applied, and 2) examination of sample wayside sound level data sets with various correction schemes applied.

For the first analysis, examining the dB-error for a set shift in temperature with various correction schemes applied, the results are shown in Table 5 (please also refer to Figure 16 in Appendix C). The temperature shift is 18 °F (10 °C). As can be seen, the average potential error due to temperature variation without any corrections is -0.41 dB; this is improved upon with each successive application of correction schemes (going from left to right), where the average is then

0.0 dB for the error associated with data-set-specific temperature corrections, as is expected. For the data examined in this report, the semi-generic schemes with the smallest average errors are Schemes #1 and #2 (Table 3 and Table 4): 0.02 and 0.0 dB. There is 95% certainty that the true average is within the confidence ranges listed; for no corrections, this range is ±0.3574 dB, and the range decreases only slightly with the generic and each semi-generic scheme. Although the average errors improve when applying corrections, there is no statistical evidence that the variation in data has decreased, other than for the data-set-specific corrections. Further, notice that the average of magnitude of errors decreases only slightly with the generic and semi-generic correction schemes applied. (Note: for Sandberg 2004 and Bendtsen 2009 correction schemes, the vehicle designation “car” was used in cases that included mixed traffic; the mixed traffic had less than 10% heavy trucks.)

Table 5. Potential dB error for a change in temperature of 18 °F (10 °C) based on various temperature correction schemes – applying schemes to data sets in this study.

	Temperature Correction Schemes						
			Semi-generic				
Statistics	None	Generic (-0.033 °F, -0.06 °C)	Sandberg 2004	Bendtsen 2009	This report Scheme #1	This report Scheme #2	This report data-set-specific
Average of magnitudes	0.81	0.72	0.71	0.69	0.62	0.64	0.00
Average	-0.41	0.19	0.12	0.03	0.02	0.00	0.00
Standard deviation	0.9286	0.9286	0.9251	0.9200	0.8441	0.7882	0.0000
Standard error of average	0.1787	0.1787	0.1780	0.1771	0.1624	0.1517	0.0000
Confidence range(±) of average*	0.3574	0.3574	0.3561	0.3541	0.3249	0.3034	0.0000
Evidence of decreased variability?**		no	no	no	no	no	yes

* 95% confidence interval for the true average

** Evidence based on an F-test that variability of the no-correction case is larger than the with-correction case

So what does this all mean? It is possible to reduce the sound level error associated with temperature variations by correcting all measured data to a reference temperature, typically 68 °F (20 °C), thus allowing potentially improved comparisons among data sets. However, caution should be exercised when doing so; unless it is possible to determine data-set-specific temperature corrections with certainty, application of a generic or semi-generic temperature correction scheme may result in unnecessary or unfavorable sound level adjustments, making comparisons worse than if no corrections were applied.

Table 6. Regression line slopes for sample data sets (sound level as a function of time of day), with and without temperature corrections applied.

	Temperature Correction Schemes					
Data set description (HT = heavy truck)	None	Semi-generic				This report data-set-specific
		Sandberg 2004	Bendtsen 2009	This report Scheme #1	This report Scheme #2	
Autos + DGAC, pass-by measurements	3.539	6.880	5.811	5.487	5.487	0.666
Autos + DGAC, pass-by measurements	0.469	4.158	2.997	2.609	2.609	0.395
Autos + OGAC, pass-by measurements	-6.495	-3.531	-3.890	-5.956	-4.878	-1.734
Autos + PCC (diamond ground), pass-by measurements	-7.545	-2.046	-2.831	3.847	5.222	-0.671
HTs + OGAC, pass-by measurements	4.346	5.638	6.626	4.954	2.598	1.153
HTs + PCC (longitudinally tined), pass-by measurements	-11.627	-10.544	-9.715	-11.118	-7.548	-2.257
Mixed traffic + ARFC (open-graded), time-averaged measurements	-2.980	-0.229	-0.562	0.022	-1.479	-0.979
Mixed traffic + PCC (transversely tined), time-averaged measurements	-7.638	-5.740	-6.011	-2.827	-3.233	-1.675

In examining sample wayside sound level data sets with various correction schemes applied, it is possible to see cases where applying corrections improved the data and where it made the data worse (explained more below). For this examination, eight data sets were analyzed, chosen from the data sets analyzed in this report. Table 6 shows the slopes for each data set with no corrections, each of the four semi-generic corrections, and data-set-specific corrections. Each data set description includes the vehicle type(s), pavement type, and the type of wayside noise measurements taken. The closer a slope is to zero, the less the sound level is influenced by temperature over the time period of the measurements (there may be other influences on the sound levels which are also affecting the slope, but generally, the slope can be attributed to temperature change for these data sets); when the sound levels are influenced less by temperature, the data are described as “improved,” and when the sound levels are influenced more by temperature over time, the data are described as “worse.” Green-highlighted cells indicate that the temperature correction scheme provided notable improvement, yellow-highlighted cells indicated that the correction scheme provided some improvement, and pink highlighted cells indicate that the results are worse than before applying the temperature corrections. None of the corrections schemes stands out as being particularly good for all data sets; the only temperature corrections that consistently provide notable improvement are data-set-specific temperature corrections. Example graphical representations of the slopes can be found in Appendix C.

5.5 Comparison of Air and Pavement Temperatures

All plots comparing air and pavement temperatures can be seen in Appendix D. Very good correlation between air and pavement temperature would result in an R-squared value near 1.0. The average R-squared value is 0.832, with a standard deviation of 0.133. So although there are some cases with less than good correlation, overall, the correlation is good between air and pavement temperature.

Since it is usually easier and much safer to measure air temperature than pavement temperature and since the correlation is good between air and pavement temperature, it is possible to measure only air temperature to determine relationships between sound levels and temperature.

As a reminder, the value for air and pavement temperature coefficients will be different and should be applied only to the corresponding sound level / temperature data pairs. In literature, it is standard to see semi-generic temperature correction schemes showing only *air* temperature correction coefficients, which should be applied only to sound level / *air* temperature data pairs.

6. CONCLUSIONS

Results of this study have shown that sound levels usually decrease slightly with increasing temperatures, although there are exceptions where sound levels actually increase slightly with increasing temperatures or where a relationship between sound level and temperature is not certain. In many cases, without applying temperature corrections, there may be error due to temperature variations. This error can affect comparisons among data sets, whether the comparison is among different sites/pavements or whether it is the same site/pavement over time. There are a couple of ways to reduce this error:

1. Take the precaution of measuring sound level data under similar meteorological conditions, so that temperature variations are minimized.
2. Correct for temperature variations using temperature correction coefficients.

If one were to correct for temperature variations using a temperature coefficient (correcting to a reference temperature, typically 68 °F or 20 °C), the best results come from applying a temperature coefficient directly calculated from each set of measured data (data-set-specific correction). (Sections 4.1 and 4.2 describe how to determine the temperature coefficient for a data set and how to determine the certainty of the relationship between sound level and temperature.) Analysis has shown that application of data-set-specific corrections is the only method that reduces error associated with temperature variations while avoiding unnecessary or unfavorable adjustments.

But what if a relationship between sound level and temperature cannot be determined for a specific data set? Such may be the case when temperature does not change much over the measurement period. It is possible to reduce the sound level error associated with temperature variations by applying a generic (single correction value) or semi-generic (correction values grouped by vehicle and pavement types) temperature correction scheme. However, caution should be taken when doing so. In some cases, application of a generic or semi-generic temperature correction scheme may result in unnecessary or unfavorable sound level adjustments, making comparisons among data sets worse than if no corrections were applied.

Semi-generic corrections appear to provide better results than a generic correction, but it is unknown as to which semi-generic correction scheme is most applicable to a particular data set. Literature and this report have shown varying semi-generic temperature correction schemes and values, which indicates that determination of semi-generic schemes is very much a function of the data sets being examined and the categories chosen. Only an extremely large database of temperature coefficients and their associated vehicle and pavement types would allow for a nationally or internationally representative semi-generic temperature correction scheme. As mentioned in the literature review section, an International Organization for Standardization working group is in the process of determining the best possible semi-generic correction scheme [Sandberg 2004], based on a large temperature coefficient database. It will need to be determined if the resulting semi-generic correction scheme is applicable to data sets such as the ones used for analysis in this report; at this point, one of the unknowns is what might be recommended for cement concrete surfaces since the correction schemes published thus far did not include a variety of surface textures to determine cement concrete temperature correction coefficients.

As can be seen throughout literature and this report, the effect air temperature has on wayside-measured sound levels can range from about +0.055 to -0.147 per 1 °F (+0.10 to -0.26 per 1 °C) increase. That means that for every 10 degrees F increase, there is the potential for a +0.55 to -1.47 dB error due to temperature variation. When trying to assess the effects of various pavement types or ages on wayside noise levels, such errors, especially when multiplied due to larger temperature variations, can affect comparisons and interpretation of results.

So what is a practitioner to do when measuring wayside sound levels for vehicles or traffic and wishing to compare data?

I. When possible, measure data under similar meteorological conditions.
II. Determine if it is necessary to make temperature corrections.
    a. Example where temperature corrections are recommended:
        i. Measurements for data sets being compared were made under dissimilar meteorological conditions (difference in average air temperatures greater than, say, 7 °F – see II.b.i below).
    b. Example where temperature corrections are not recommended:

        i. Measurements for data sets being compared were made under similar meteorological conditions (difference in average air temperatures within, say, 7 °F, which could result it an extreme error of 0.147*7 = ~1 dB but would likely be less). With these small temperature changes, the risk of potentially applying an unnecessary or unfavorable correction is likely not worthwhile considering the associated small magnitude of error.

III. When possible, determine the relationship and its certainty between sound level and temperature for each data set, resulting in a data-set-specific temperature correction coefficient. When certain of the sound level/temperature relationship, apply the data-set-specific temperature correction to each of the data points. For now, it is recommended to present data with and without temperature corrections.

IV. When it is not possible to determine a relationship between sound level and temperature, consider the application of a semi-generic temperature correction scheme. Considerations are listed below. If proceeding with a semi-generic temperature correction scheme, it is recommended to report which correction scheme is being used as well as the corresponding temperature correction coefficients, and to apply corrections based on these coefficients to each of the data points. For now, it is recommended to present data with and without temperature corrections. Considerations:

    a. Applying a semi-generic scheme will likely improve comparability of data sets, but there is a risk of impairing comparability.
    b. Look to the International Organization for Standardization (ISO) for current recommendations on semi-generic temperature correction schemes, assessing the applicability to your study before proceeding. Such assessment may include identifying whether a particular pavement type is properly represented in the scheme; for example, for cement concrete pavements, there should probably be some differentiation among surface treatments. The temperature coefficients for the ISO will likely be listed in degrees C, so if temperatures were measured in degrees F, convert the coefficients to degrees F (see Section 4.1 for conversions) or convert measured temperatures to degrees C, in order to apply the proper temperature correction coefficients.

V. Consider what reference temperature to correct to. Typically all data sets are corrected to 68 °F (20 °C). However, within a single study, the average temperatures of the data sets may be far from the typical reference temperature. If there is no interest in making comparisons to outside studies, using a reference temperature that is closer to the data set averages in the study is desirable. This would minimize potential unnecessary or unfavorable sound level adjustments that would be compounded when making adjustments for large temperature differences, particularly when applying a semi-generic temperature correction scheme.

It is possible that future road vehicle and traffic noise measurement standards or guidance materials will require the application of sound level adjustments based on temperature, but in the interim, it is best to proceed cautiously. Following the guidance provided in this report should help to improve comparability among data sets by reducing variations in sound levels due to temperature differences, while preserving the original data.

Please note that, at this time, the Federal Highway Administration (FHWA) does not plan to account for temperature effects, as described in this report, in the FHWA Traffic Noise Model® (TNM®).

REFERENCES

ADOT 2006 — *Progress Report No. 2, Quiet Pavement Pilot Program*, Arizona Department of Transportation, Phoenix, Arizona, USA (2006).

Anderson 2008 — Anderson, Grant, “Slope uncertainty in linear regression,” document provided to the Volpe Center for the purposes on the FHWA Highway Traffic Noise Temperature Effects Study (2008).

Anfosso 2006 — Anfosso-Lédée, Fabienne and Yves Pichaud, “Temperature effect on tyre-road noise,” Applied Acoustics (2006).

Bendtsen 2009 — (refers to a combination of Bendtsen 2009-1 and Bendtsen 2009-2)

Bendtsen 2009-2 — Bendtsen, Hans, et al., “Temperature influence on OBSI noise measurements,” presentation at Transportation Research Board Committee on Transportation-Related Noise and Vibration summer meeting (2009).

Bendtsen 2009-1 — Bendtsen, Hans, et al., *Temperature influence on road traffic noise – Californian OBSI measurement study*, Report 169, Road Directorate, Danish Road Institute, Copenhagen, Denmark (2009).

CTIM 2009 — *Determining the Influence of Road Surfaces on Traffic Noise Using a Continuous-Flow Traffic Time-Integrated Method (CTIM)* (draft guidance), Federal Highway Administration-sponsored tire/pavement noise expert task group (2009).

ISO 11819-1 — *Acoustics - Method for Measuring the Influence of Road Surfaces on Traffic Noise – Part 1: “The Statistical Pass-By Method,”* International Standard ISO 11819-1, International Organization for Standardization, Geneva, Switzerland (1997).

Jabben 2006 — Jabben, J. and C.J.M Potma, “The influence of temperature, rainfall and traffic speeds on noise emissions of motorways,” Proceedings of Inter-Noise 2006, Honolulu, Hawaii, U.S. (2006).

Kujpers 2006 — Kujpers, Ard, “Tyre stiffness and temperature,” M+P Raadgevende ingenieurs bv memo to ISO Working Group 27 (2006).

Lee 1996 — Lee, Cynthia S.Y. and Gregg G. Fleming, *Measurement of Highway Related Noise*, Report No. FHWA-PD-96-046, U.S. Department of Transportation, Volpe National Transportation Systems Center, Acoustics Facility, Cambridge, MA, USA, (1996).

Rochat 2009-2 — Rochat, Judith L. , “Developing U.S. wayside methods for measuring the influence of road surfaces on traffic noise,” Proceedings of Inter-Noise 2009, Ottawa, Canada (2009).

Rochat 2009-1 — Rochat, Judith L. and David R. Read, “Noise benefits of asphalt pavements – trends at ages up to 52 months,” Noise Control Engineering Journal, Volume 57 (2) (2009).

Sandberg 2004 — Sandberg, Ulf, “Semi-generic temperature corrections for tyre/road noise,” Proceedings of Inter-Noise 2004, Prague, Czech Republic (2004).

Sandberg 2002 — Sandberg, Ulf and Jerzy Ejsmont, *Tyre/Road Noise Reference Book*, INFORMEX Ejsmont & Sandberg Handelsbolag, Kisa, Sweden (2002).

Volpe 2008 — U.S. DOT / RITA Volpe Center is conducting research for the FHWA TNM Pavement Effect Implementation Study, a small set of REMEL data was collected in 2007 and analyzed in 2008.

APPENDIX A. TEMPERATURE COEFFICIENTS

This appendix shows all data points (temperature, sound level), the linear regression, and the corresponding temperature coefficient for each data set. Keep in mind, the slope of each line equation is the temperature coefficient. The first subsection shows each of the plots, and the second subsection shows the temperature coefficients in tabular form, along with their corresponding percent certain values and other data set information.

A.1 Plots of All Data Points and Linear Regression for Each Data Set

Below are 9 plots: 2 plots showing the AZ QPPP data (one for each site, representing 3 data sets each for a total of 6 data sets), 4 plots showing the Caltrans Thin Lift Study data (one for each site or pavement type at various ages and one for each pavement-temperature medium – air or pavement, representing a total of 16 data sets), and 3 plots showing the FHWA TNM PEI Study data (one for each site, representing a total of 6 data sets).

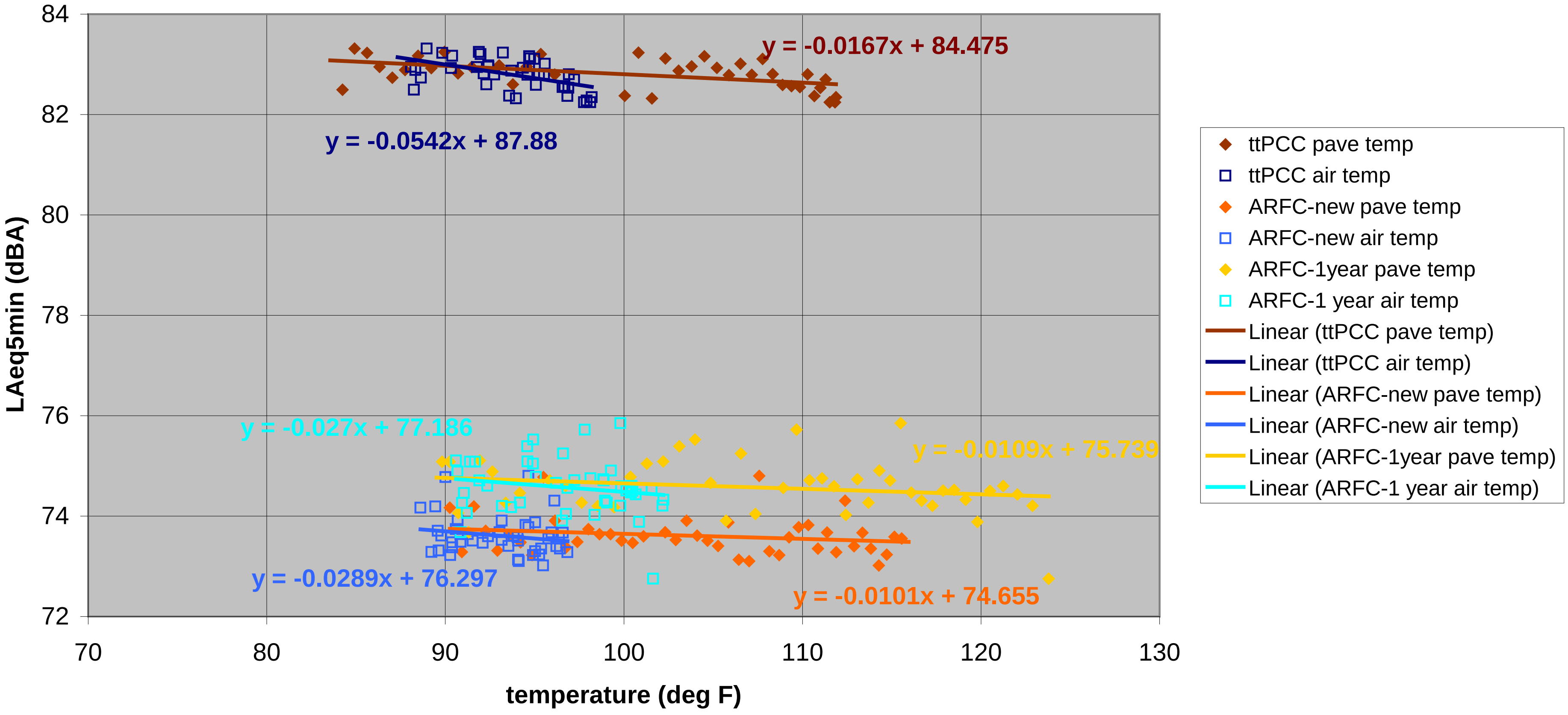


Figure 3. AZ QPPP data for Site 3B (mixed traffic) – sound levels plotted as a function of air and pavement temperature for three data sets. In the legend, ttPCC = transversely tined PCC, ARFC-new is asphalt rubber friction course shortly after construction, and ARFC-1 year is asphalt rubber friction course approximately 1 year after construction.

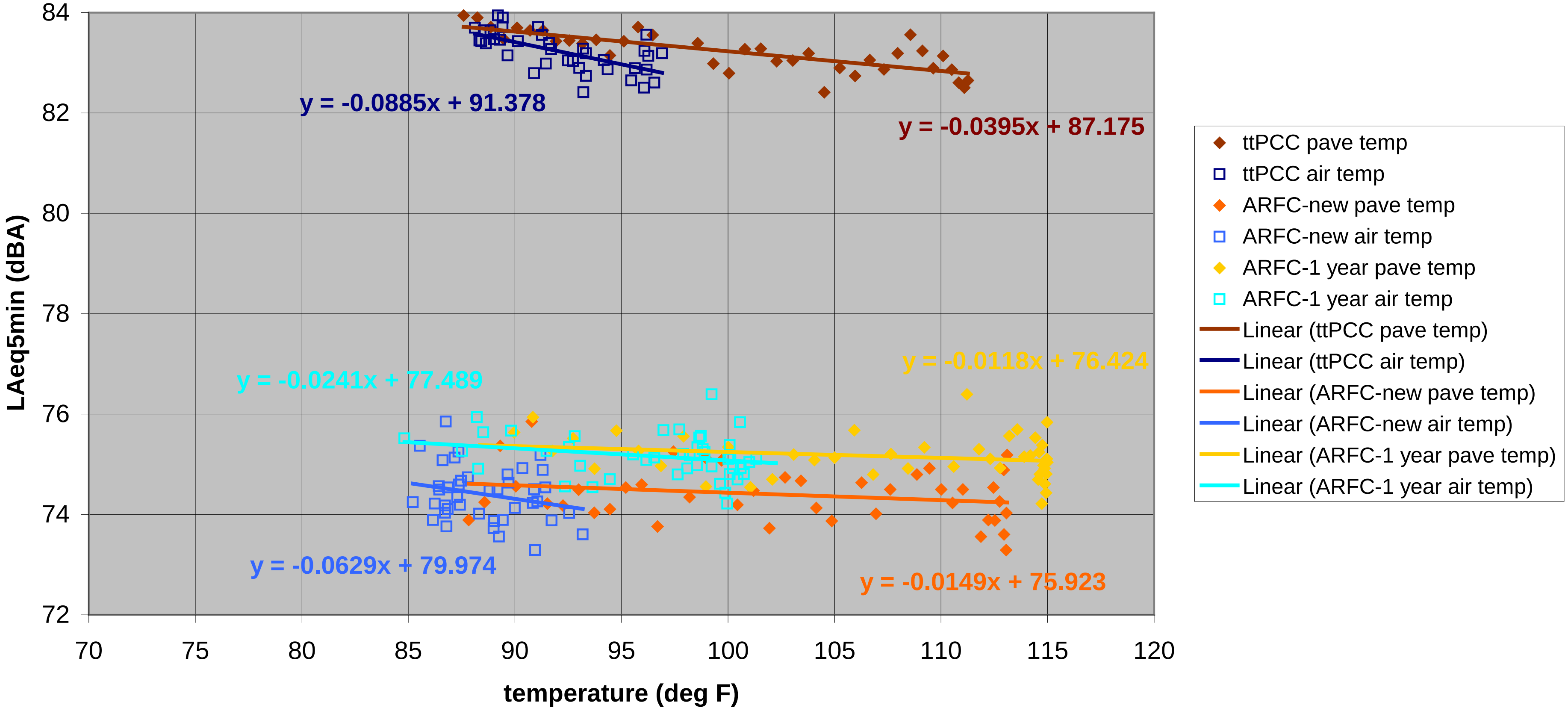


Figure 4. AZ QPPP data for Site 3C (mixed traffic) – sound levels plotted as a function of air and pavement temperature for three data sets. In the legend, ttPCC = transversely tined PCC, ARFC-new is asphalt rubber friction course shortly after construction, and ARFC-1 year is asphalt rubber friction course approximately 1 year after construction.

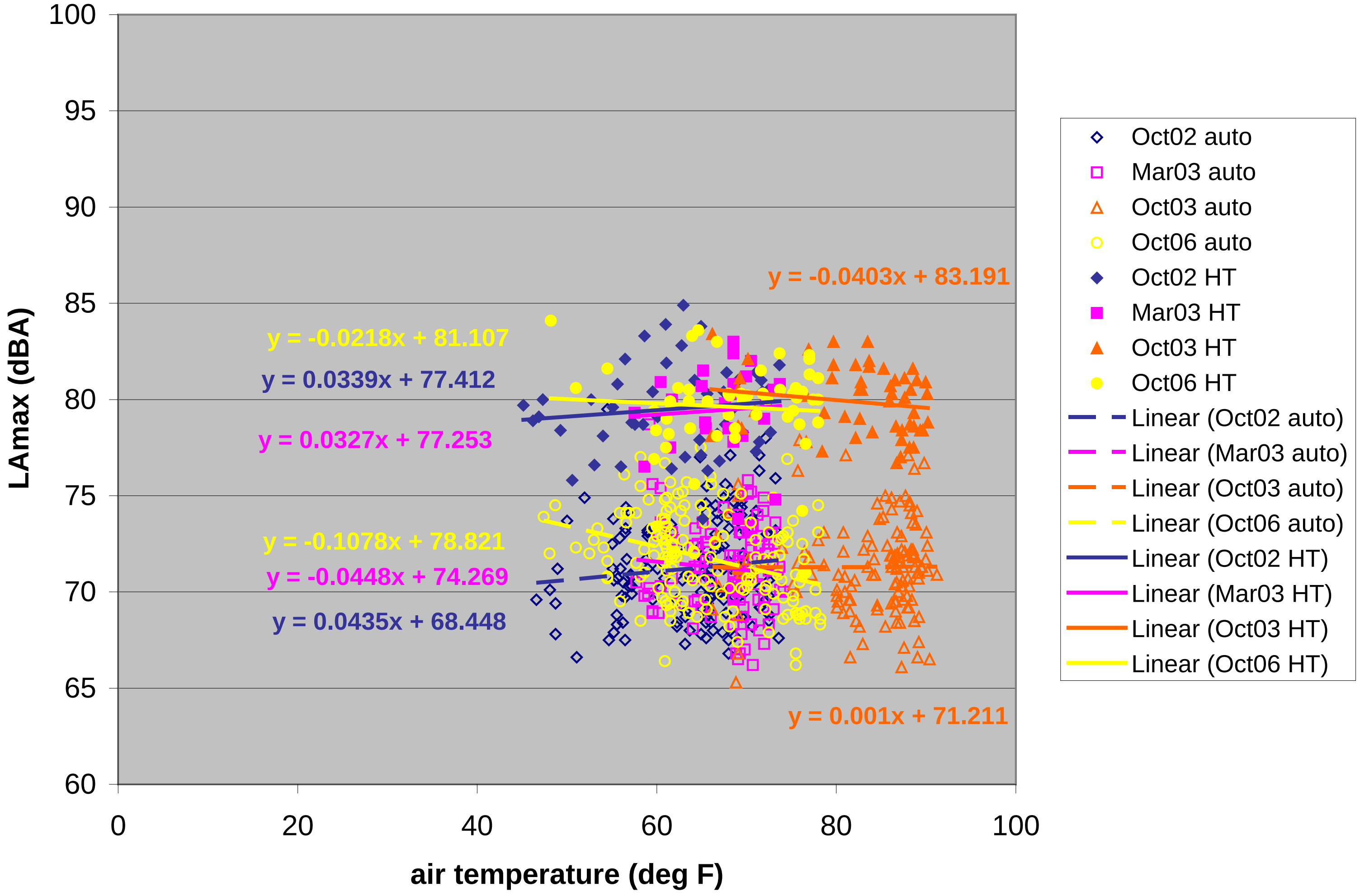


Figure 5. Caltrans Thin Lift Study data for DGAC site – sound levels plotted as a function of air temperature for two data sets: autos and heavy trucks. In the legend, Oct02, Mar03, Oct03, and Oct06 represent pavement aged 4, 10, 16, and 52 months, respectively.

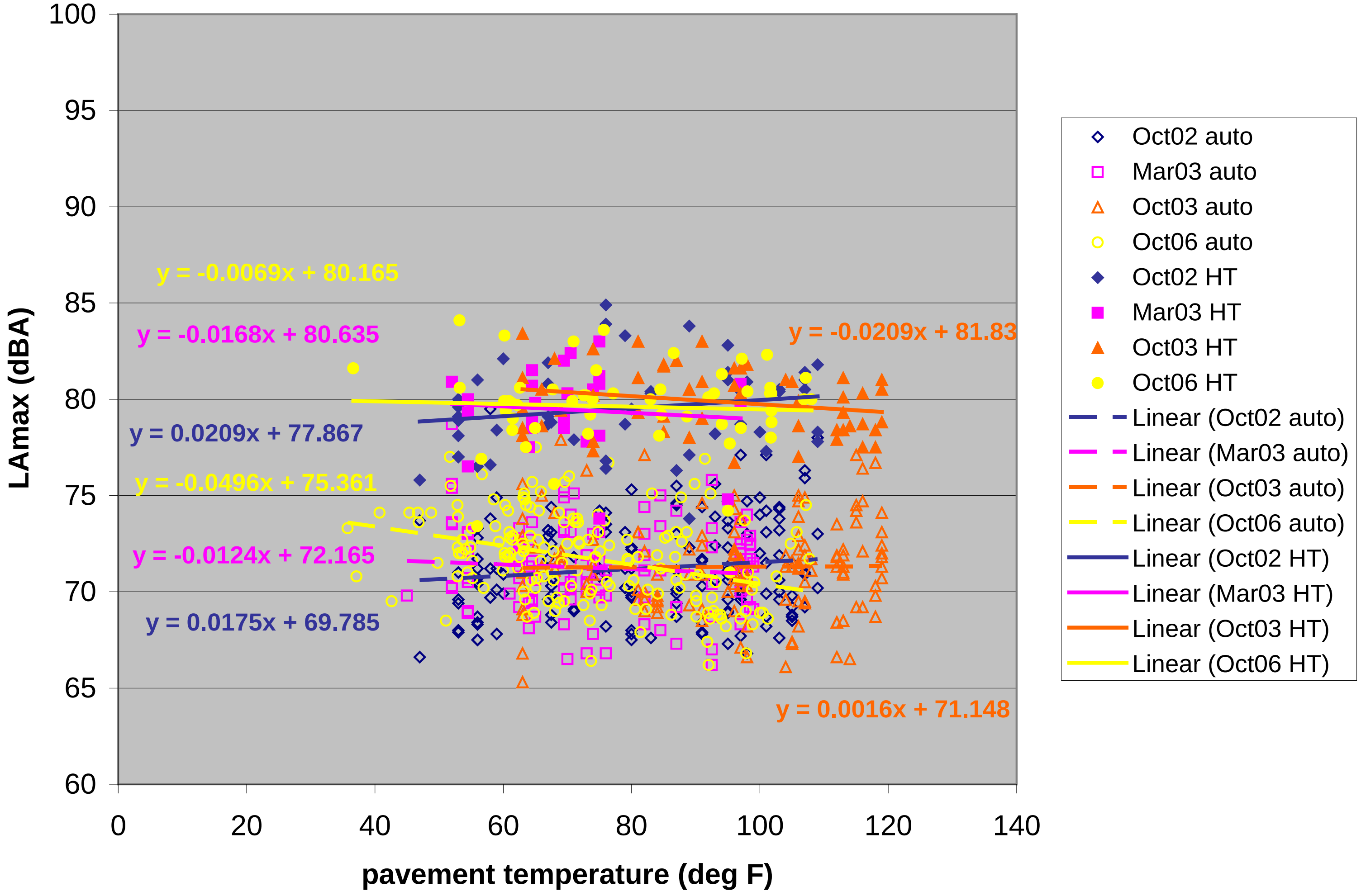


Figure 6. Caltrans Thin Lift Study data for DGAC site – sound levels plotted as a function of pavement temperature for two data sets: autos and heavy trucks. In the legend, Oct02, Mar03, Oct03, and Oct06 represent pavement aged 4, 10, 16, and 52 months, respectively.

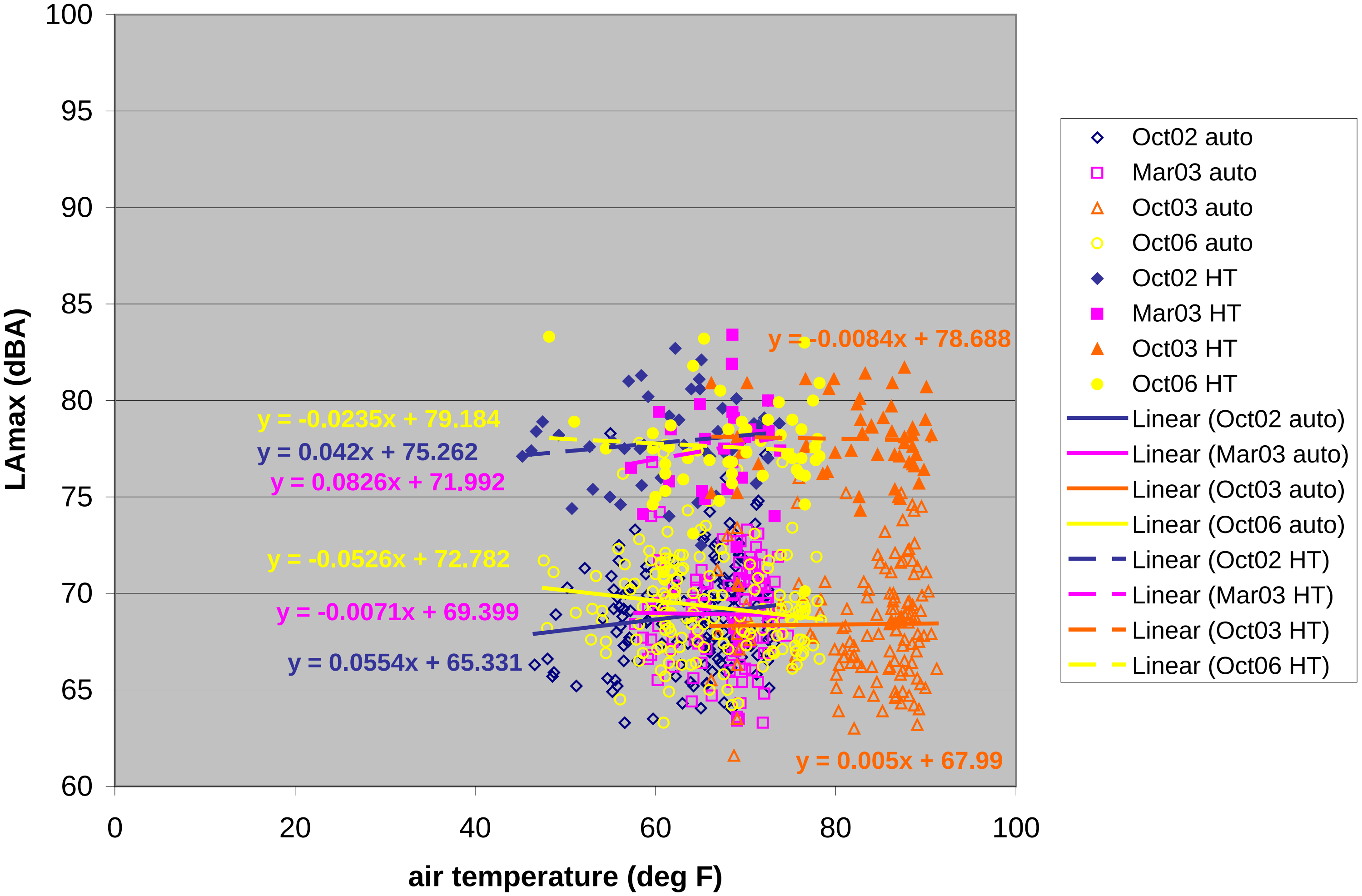


Figure 7. Caltrans Thin Lift Study data for OGAC site – sound levels plotted as a function of air temperature for two data sets: autos and heavy trucks. In the legend, Oct02, Mar03, Oct03, and Oct06 represent pavement aged 4, 10, 16, and 52 months, respectively.

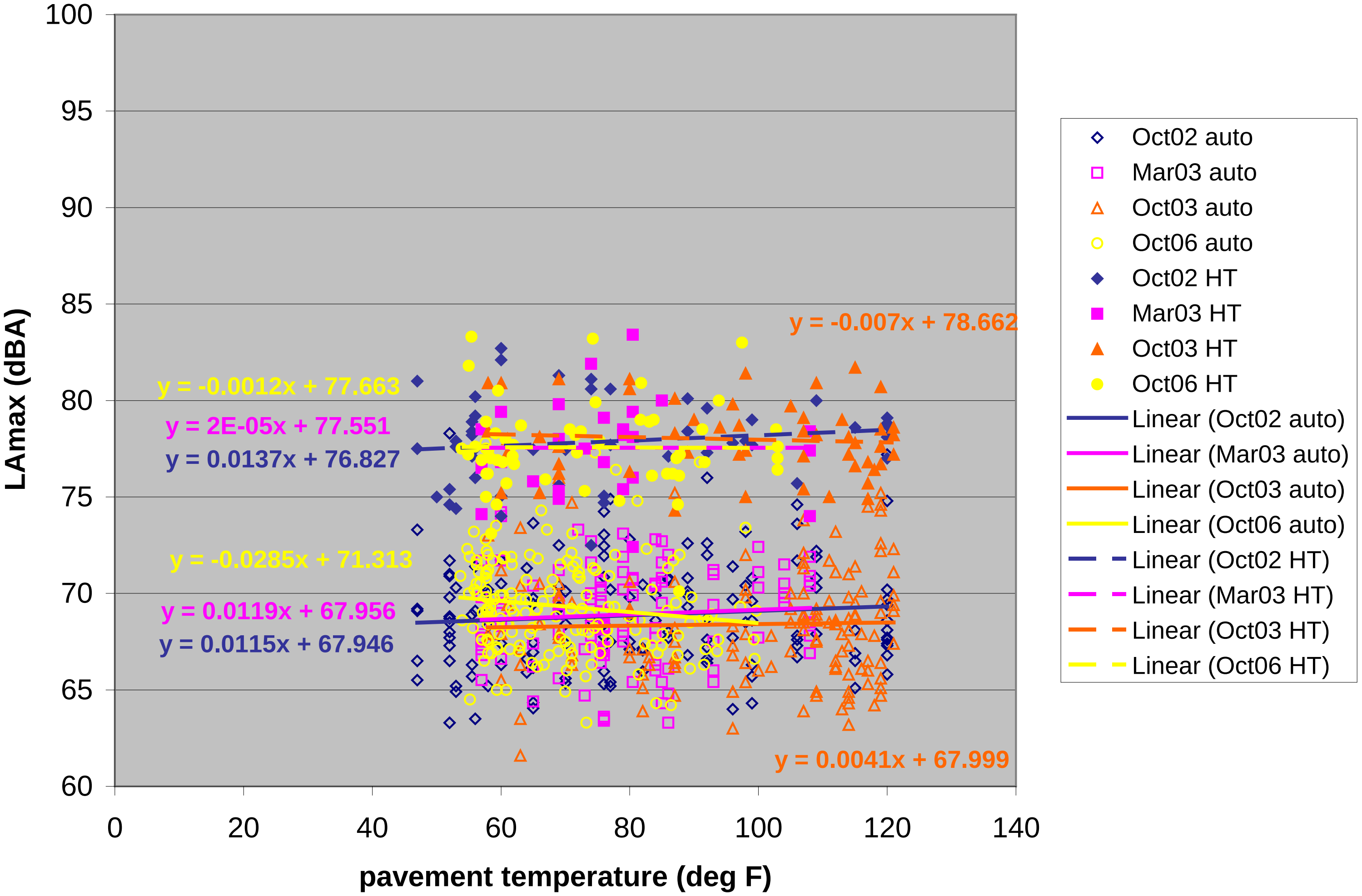


Figure 8. Caltrans Thin Lift Study data for OGAC site – sound levels plotted as a function of pavement temperature for two data sets: autos and heavy trucks. In the legend, Oct02, Mar03, Oct03, and Oct06 represent pavement aged 4, 10, 16, and 52 months, respectively.

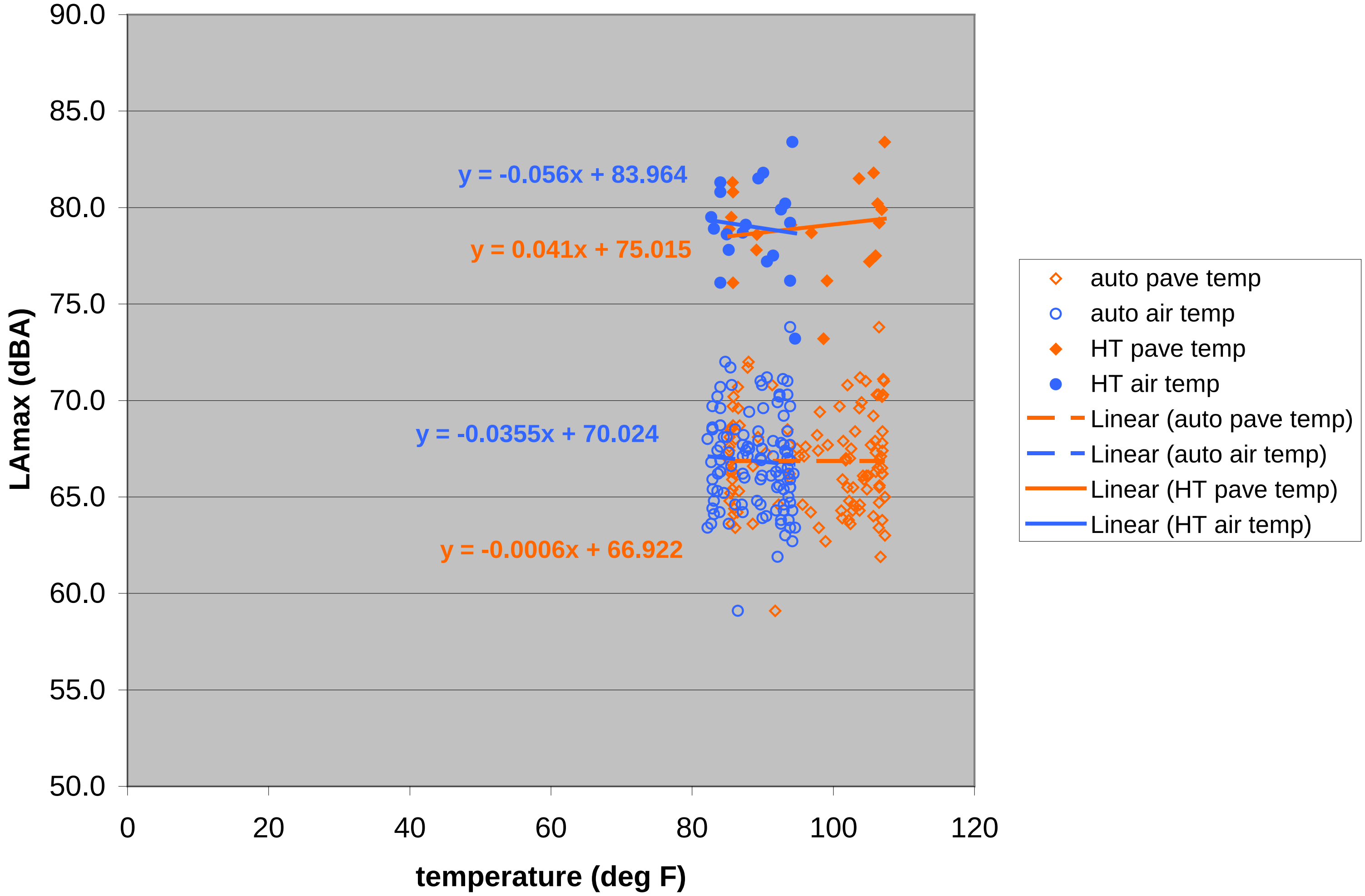


Figure 9. FHWA TNM PEI Study data for Site RL01MA (DGAC) – sound levels plotted as a function of air and pavement temperature for two data sets: autos and heavy trucks.

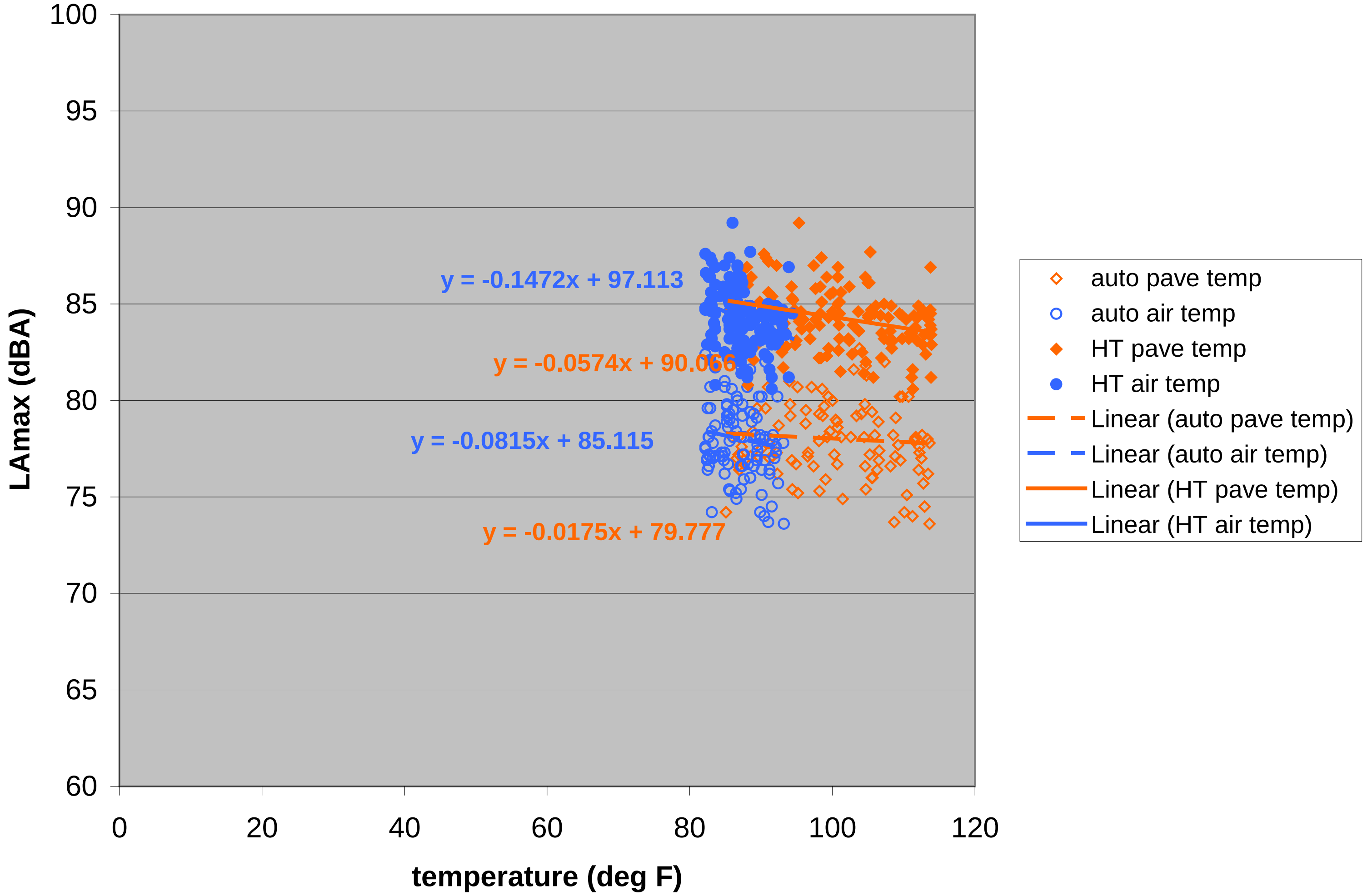


Figure 10. FHWA TNM PEI Study data for Site RL03CA (PCC, longitudinally tined) – sound levels plotted as a function of air and pavement temperature for two data sets: autos and heavy trucks.

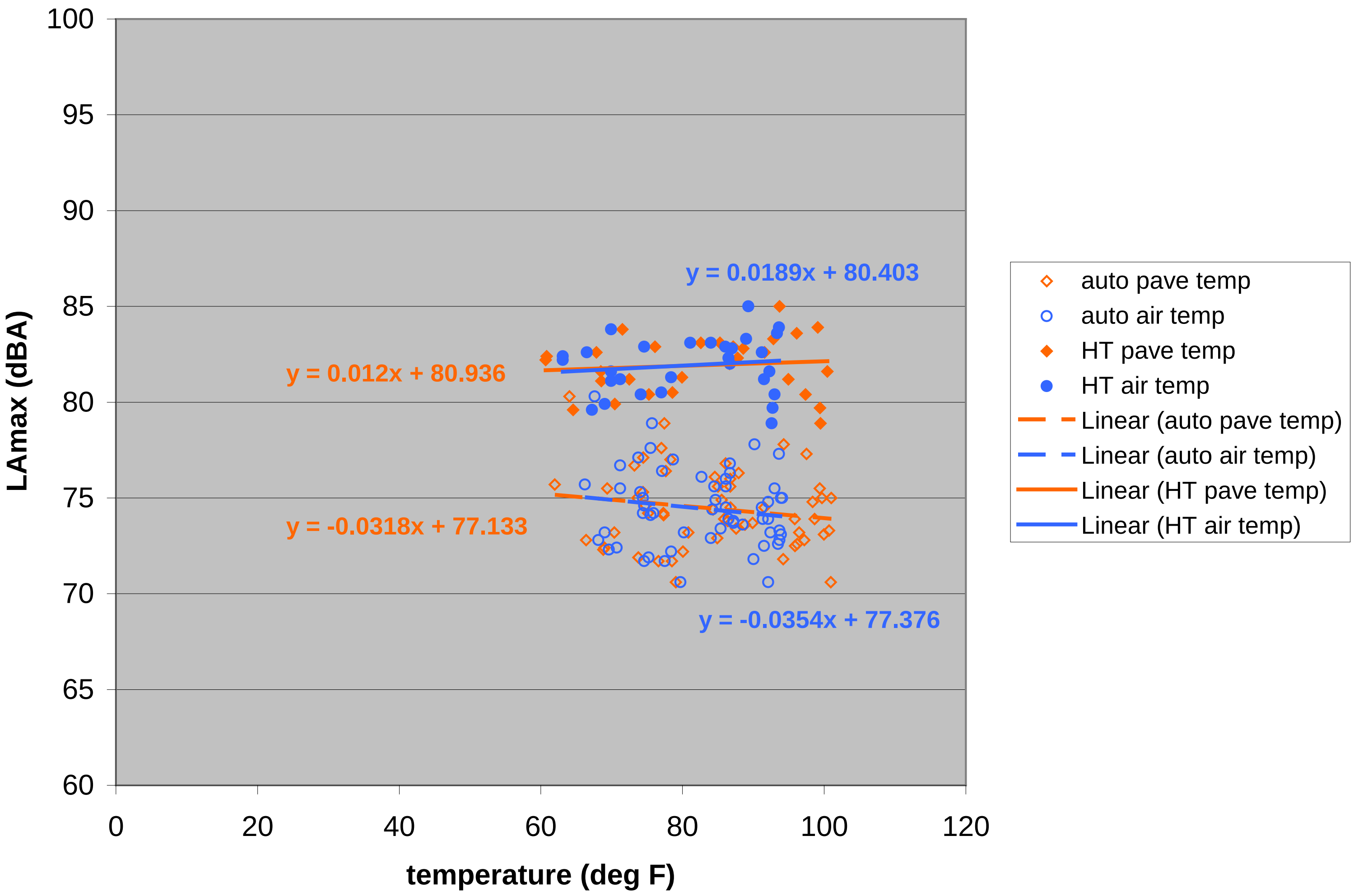


Figure 11. FHWA TNM PEI Study data for Site RL04CA (PCC, longitudinally diamond ground) – sound levels plotted as a function of air and pavement temperature for two data sets: autos and heavy trucks.

A.2 Temperature Coefficients and Percent Certain for Each Data Set

The table in this section provides information about each data set, including the calculated temperature coefficient and percent certain.

Table 7. Information for all data sets, including temperature coefficient, percent certain, pavement type, vehicle type(s), and temperature range.

Study and site	Measurement methodology	Pavement type	Pavement age (months)	Vehicle(s)	Number of data points	Temperature coefficient (dB/°F increase)		Temperature coefficient (dB/°C increase)		100*(1-Pvalue) percent certain		R-squared	Air temperature (°F)			Pavement temperature (°F)		
				autos = automobiles HTs = heavy trucks		air	pavement	air	pavement	air	pavement		min	max	change over measurements	min	max	change over measurements
AZ QPPP Site 3B	time-averaged	ARFC	12	mixed traffic	44	-0.027	-0.011	-0.05	-0.02	76.3	82.1	0.032	91	102	12	90	124	34
AZ QPPP Site 3B	time-averaged	PCC, uniform transversely tined	?	mixed traffic	40	-0.054	-0.017	-0.10	-0.03	99.9	99.9	0.272	87	98	11	84	112	28
AZ QPPP Site 3B	time-averaged	ARFC	new	mixed traffic	40	-0.029	-0.010	-0.05	-0.02	77.6	81.4	0.035	89	97	8	90	116	26
AZ QPPP Site 3C	time-averaged	ARFC	12	mixed traffic	42	-0.024	-0.012	-0.04	-0.02	88.9	86.1	0.060	85	102	17	88	115	27
AZ QPPP Site 3C	time-averaged	PCC, uniform transversely tined	?	mixed traffic	37	-0.088	-0.039	-0.16	-0.07	100.0	100.0	0.423	88	97	9	88	111	24
AZ QPPP Site 3C	time-averaged	ARFC	new	mixed traffic	37	-0.063	-0.015	-0.11	-0.03	88.5	86.6	0.061	85	93	8	88	113	25
Caltrans LA138 Site 1	pass-by	DGAC	4	autos	150	0.043	0.018	0.08	0.03	81.5	86.5	0.012	45	74	29	47	109	62

Caltrans LA138 Site 1	pass-by	DGAC	4	HTs	50	0.034	0.021	0.06	0.04	58.1	78.7	0.014	45	74	29	47	109	62
Caltrans LA138 Site 1	pass-by	DGAC	10	autos	113	-0.045	-0.012	-0.08	-0.02	63.0	62.2	0.007	58	74	17	45	99	54
Caltrans LA138 Site 1	pass-by	DGAC	10	HTs	25	0.033	-0.017	0.06	-0.03	24.8	33.4	0.004	58	74	17	45	99	54
Caltrans LA138 Site 1	pass-by	DGAC	16	autos	136	0.001	0.002	0.00	0.00	2.7	10.7	0.000	66	91	25	63	119	56
Caltrans LA138 Site 1	pass-by	DGAC	16	HTs	53	-0.040	-0.021	-0.07	-0.04	77.7	90.1	0.029	66	91	25	63	119	56
Caltrans LA138 Site 1	pass-by	DGAC	52	autos	166	-0.108	-0.050	-0.19	-0.09	100.0	100.0	0.116	47	78	31	36	108	72
Caltrans LA138 Site 1	pass-by	DGAC	52	HTs	54	-0.022	-0.007	-0.04	-0.01	37.8	29.4	0.005	47	78	31	36	108	72
Caltrans LA138 Site 2	pass-by	OGAC 75mm thick	4	autos	150	0.055	0.012	0.10	0.02	87.8	73.8	0.016	45	74	29	47	120	73
Caltrans LA138 Site 2	pass-by	OGAC 75mm thick	4	HTs	50	0.042	0.014	0.08	0.03	69.6	69.6	0.022	45	74	29	47	120	73
Caltrans LA138 Site 2	pass-by	OGAC 75mm thick	10	autos	113	-0.007	0.012	-0.01	0.02	9.9	54.6	0.000	57	75	17	57	108	51
Caltrans LA138 Site 2	pass-by	OGAC 75mm thick	10	HTs	25	0.083	0.000	0.15	0.00	52.0	0.0	0.022	57	75	17	57	108	51
Caltrans LA138 Site 2	pass-by	OGAC 75mm thick	16	autos	136	0.005	0.004	0.01	0.01	10.4	26.0	0.000	66	91	25	58	121	63
Caltrans LA138	pass-by	OGAC 75mm thick	16	HTs	53	-0.008	-0.007	-0.01	-0.01	17.8	42.0	0.001	66	91	25	58	121	63

Site 2																		
Caltrans LA138 Site 2	pass-by	OGAC 75mm thick	52	autos	166	-0.053	-0.029	-0.10	-0.05	94.4	91.7	0.022	48	78	31	54	103	49
Caltrans LA138 Site 2	pass-by	OGAC 75mm thick	52	HTs	54	-0.024	-0.001	-0.04	0.00	40.8	4.7	0.006	48	78	31	54	103	49
TNM PEI REMEL RL01MA	pass-by	DGAC	old	autos	112	-0.035	-0.001	-0.06	0.00	45.8	1.6	0.003	82	95	12	85	107	22
TNM PEI REMEL RL01MA	pass-by	DGAC	old	HTs	19	-0.056	0.041	-0.10	0.07	32.0	47.1	0.010	83	95	12	85	107	22
TNM PEI REMEL RL03CA	pass-by	PCC, longitudinally tined	?	autos	105	-0.082	-0.017	-0.15	-0.03	77.3	52.0	0.014	82	93	11	85	114	29
TNM PEI REMEL RL03CA	pass-by	PCC, longitudinally tined	?	HTs	135	-0.147	-0.057	-0.26	-0.10	99.9	99.9	0.086	82	94	12	86	114	28
TNM PEI REMEL RL04CA	pass-by	PCC, longitudinally diamond ground	?	autos	57	-0.035	-0.032	-0.06	-0.06	73.6	79.3	0.023	66	94	28	62	101	39
TNM PEI REMEL RL04CA	pass-by	PCC, longitudinally diamond ground	?	HTs	29	0.019	0.012	0.03	0.02	51.3	40.6	0.018	63	94	31	61	100	40

APPENDIX B. CATEGORIZED AIR TEMPERATURE COEFFICIENTS

This appendix shows air temperature coefficients from all the data sets categorized by vehicle type and pavement type. Section B.1 shows a bar chart of temperature coefficients for all data sets and Section B.2 shows histograms of the categorized temperature coefficients.

B.1 Bar Chart of Temperature Correction Coefficients

The bar chart on the following page shows the temperature correction coefficients in degrees Fahrenheit (F) for each data set categorized by vehicle type and pavement type. In addition, black font indicates temperature coefficients that were determined to be ≥ 70% certain (there is a 70% or greater chance that the slope of the regression line is truly not zero, i.e., that there is actually a relationship between temperature and sound level), and white font indicates temperature coefficients that were determined to be < 70% certain.

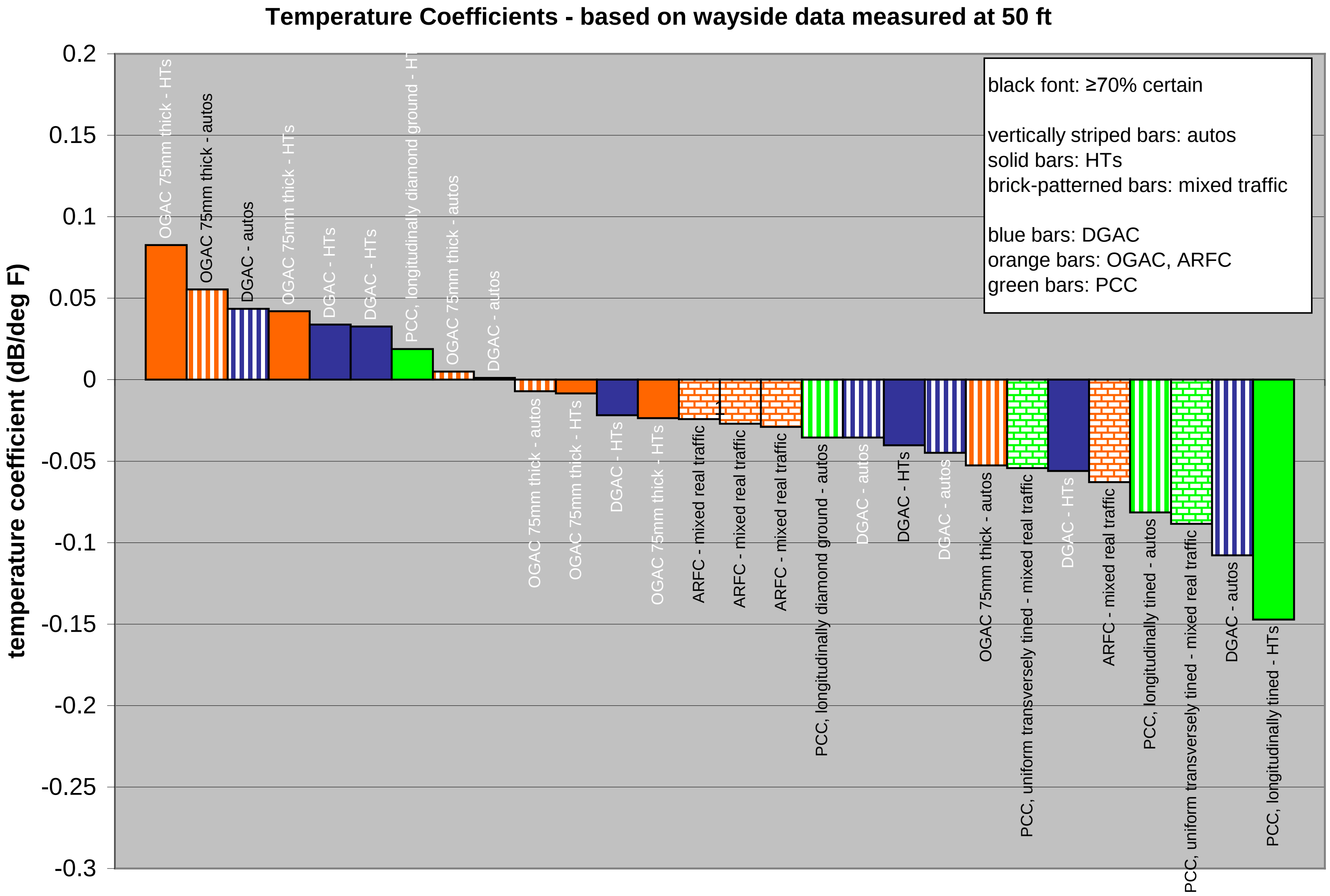


Figure 12. Bar chart of air temperature coefficients in degrees F categorized by vehicle type and pavement type.

B.2 Histograms of Temperature Correction Coefficients

The following three figures show histograms of the air temperature correction coefficients in degrees Fahrenheit (F).

Figure 13 shows a histogram for all temperature coefficients.

Figure 14 shows histograms for the following vehicle and pavement categories (semi-generic Scheme #1):

1. autos + DGAC
2. autos + OGAC
3. autos + PCC (longitudinally tined and ground)
4. heavy trucks + any surface
5. mixed traffic + ARFC (open-graded)
6. mixed traffic + PCC (transversely tined)

Figure 15 shows histograms for the following vehicle and pavement categories (semi-generic Scheme #2):

1. autos, mixed traffic + DGAC
2. autos, mixed traffic + OGAC, ARFC
3. autos, mixed traffic + PCC (longitudinally tined and ground, transversely tined)
4. heavy trucks + DGAC
5. heavy trucks + OGAC
6. heavy trucks + PCC (longitudinally tined and ground)

Keep in mind that the percentage of heavy trucks is less than 10% for the mixed traffic in the data used to determine the temperature coefficients.

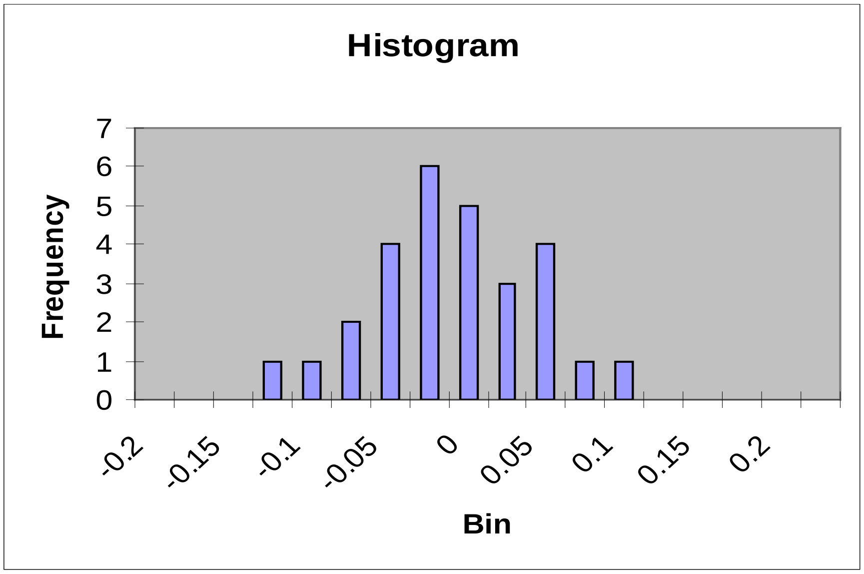
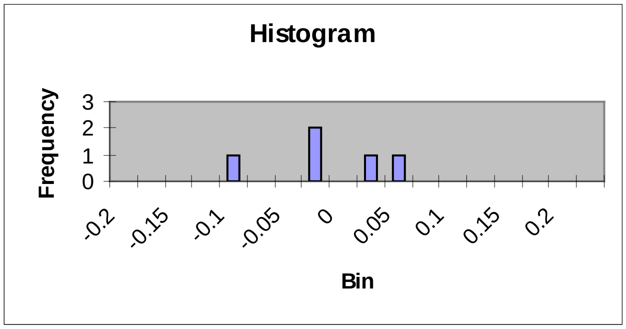
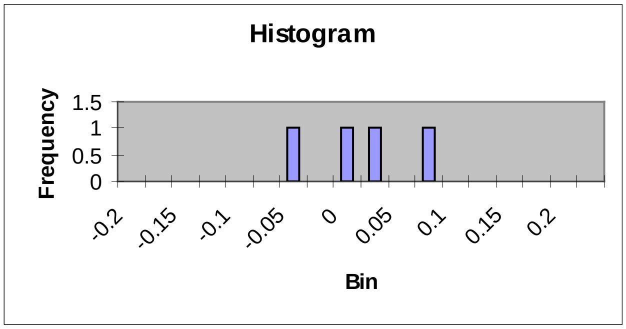


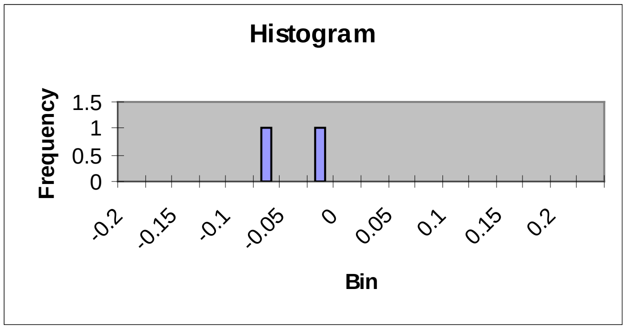
Figure 13. Histogram: Frequency of air temperature coefficient in bins ranging from -0.2 to 0.2 in steps of 0.025 in degrees F. All data, uncategorized.



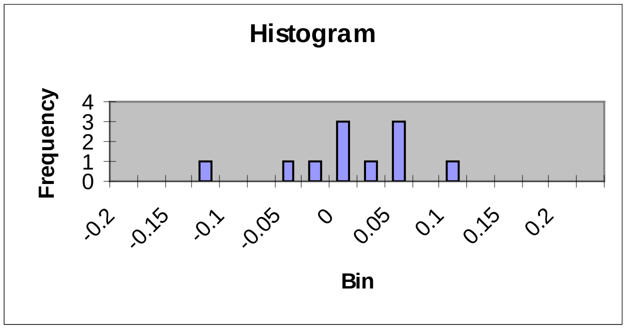
(1) autos + DGAC



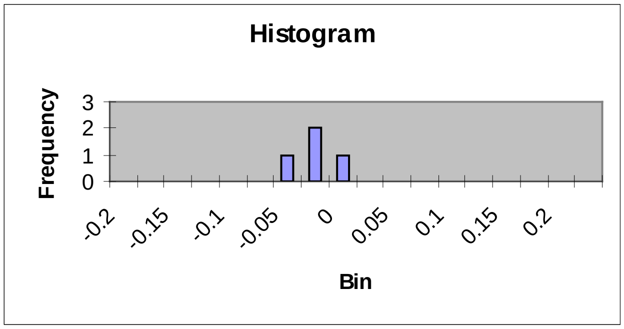
(2) autos + OGAC



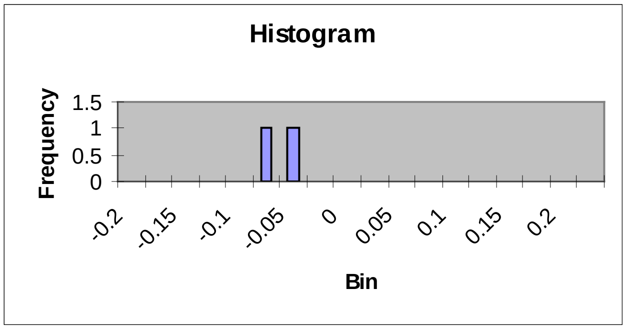
(3) autos + PCC (long. tined and ground)



(4) heavy trucks + any surface

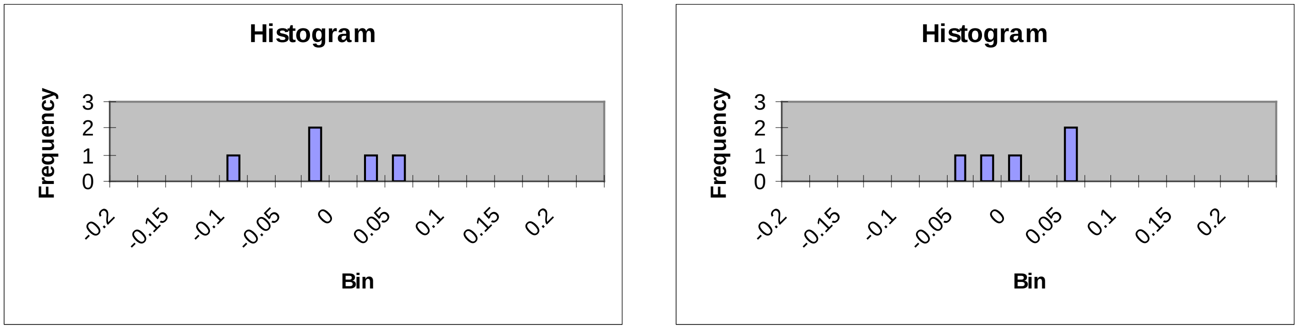


(5) mixed traffic + ARFC

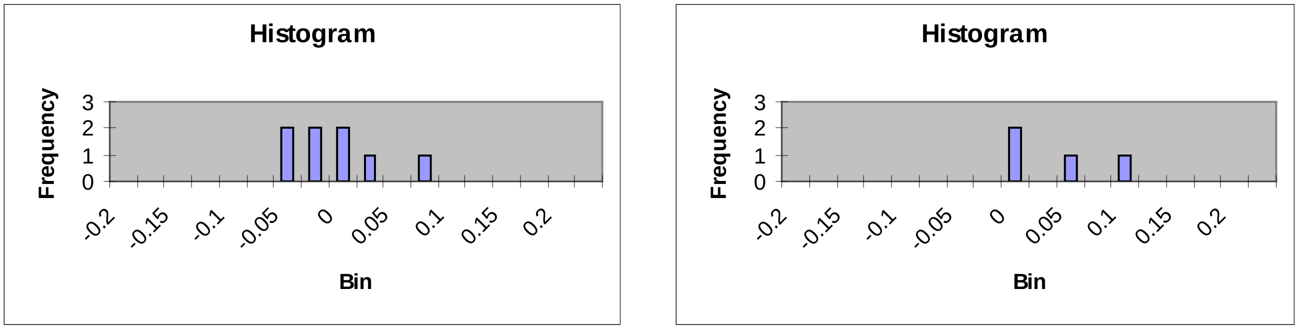


(6) mixed traffic + PCC (transversely tined)

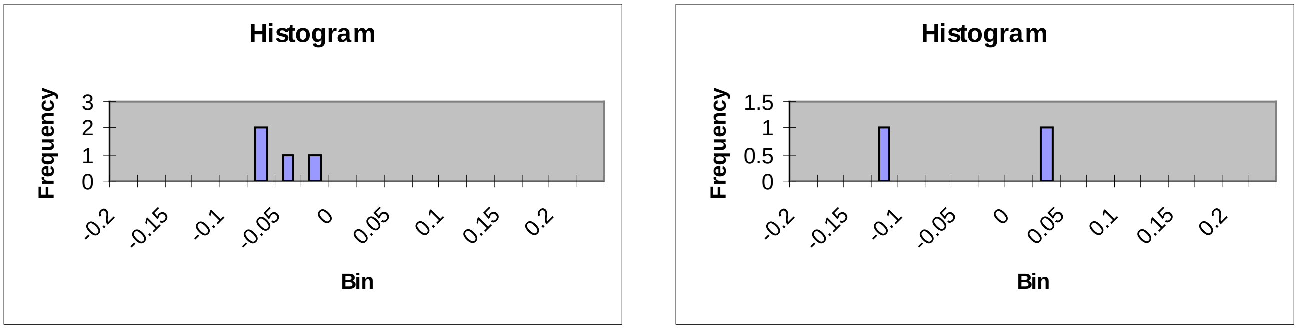
Figure 14. Histograms: Frequency of air temperature coefficient in bins ranging from -0.2 to 0.2 in steps of 0.025 in degrees F. The six categories listed above are for semi-generic Scheme #1 and include autos for each pavement type, heavy trucks for any pavement type, and mixed traffic for each pavement type.



(1) autos, mixed traffic + DGAC **(4) heavy trucks + DGAC**



(2) autos, mixed traffic + OGAC, ARFC **(5) heavy trucks + OGAC**



(3) autos, mixed traffic + PCC (long. tined and ground, trans. tined) **(6) heavy trucks + PCC (long. tined and ground)**

Figure 15. Histograms: Frequency of air temperature coefficient in bins ranging from -0.2 to 0.2 in steps of 0.025 in degrees F. The six categories listed above are for semi-generic Scheme #2 and include autos and mixed traffic together for each pavement type, and heavy trucks for each pavement type.

APPENDIX C. APPLYING TEMPERATURE CORRECTIONS

This appendix shows results of two examinations where temperature corrections are applied: Section C.1 shows an examination of potential dB-error for a set shift in temperature with various correction schemes applied, and Section C.2 shows an examination of sample wayside sound level data sets with various correction schemes applied.

C.1 Potential dB-Error for a Set Shift in Temperature

Figure 16 below shows the data and regression lines for the potential dB-error for all data sets with the following applications: no temperature corrections, generic temperature corrections, four semi-generic temperature corrections, and data-set-specific temperature corrections. The errors assume an 18 °F (10 °C) change in temperature. Please refer to Table 5 in Section 5.4 for the related statistics.

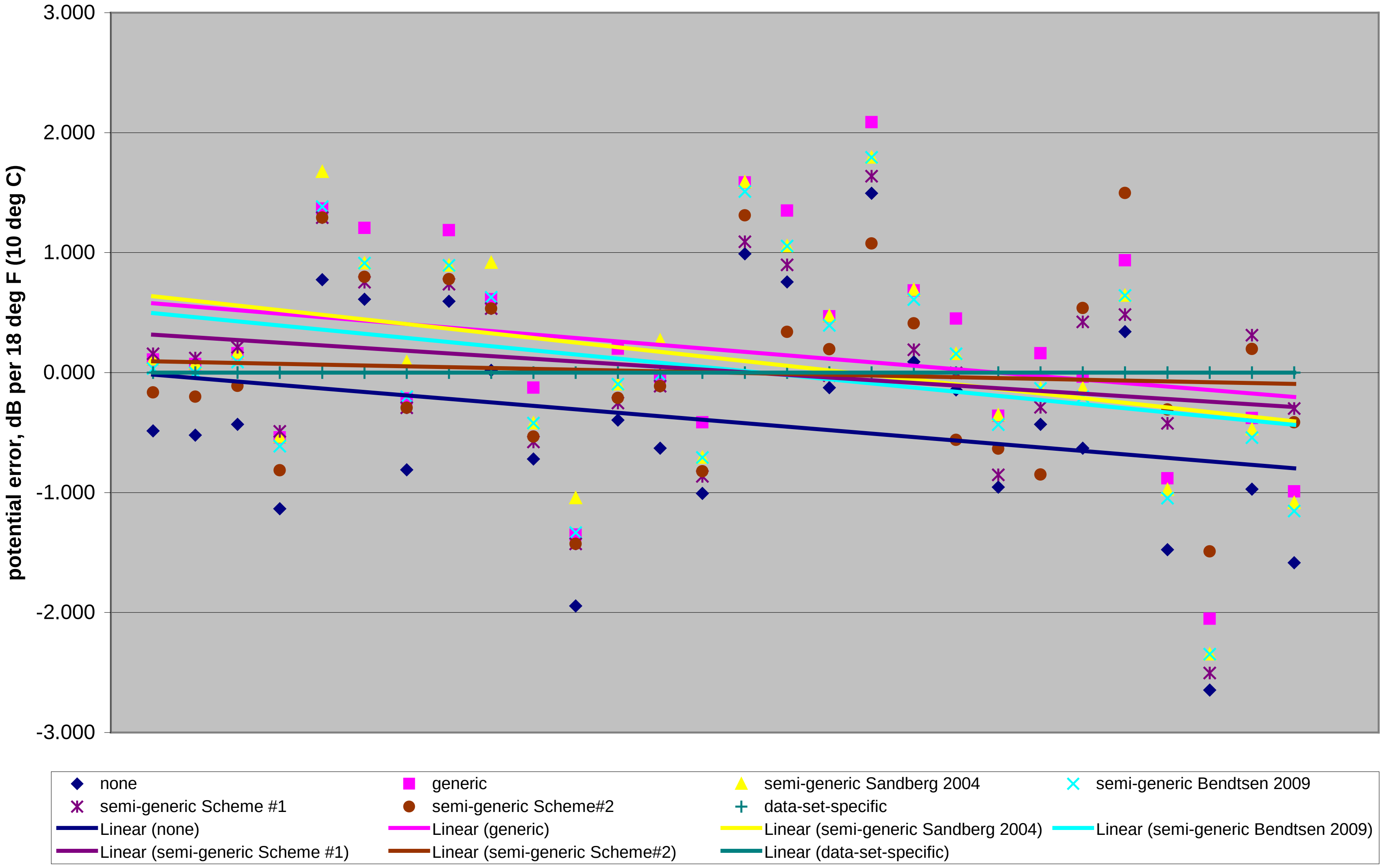
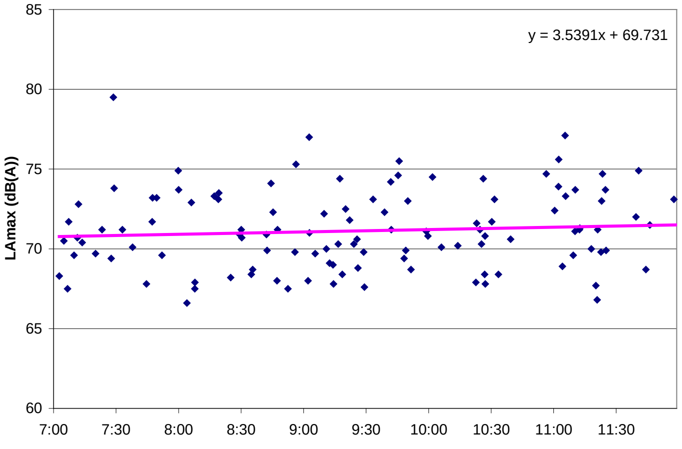


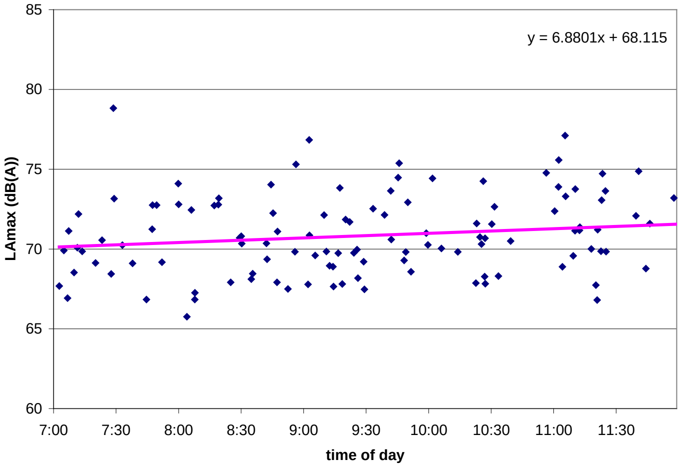
Figure 16. Air temperature coefficients with various correction schemes applied (potential error) per 18 °F (10 °C).

C.2 Sample Data Sets with Correction Schemes Applied

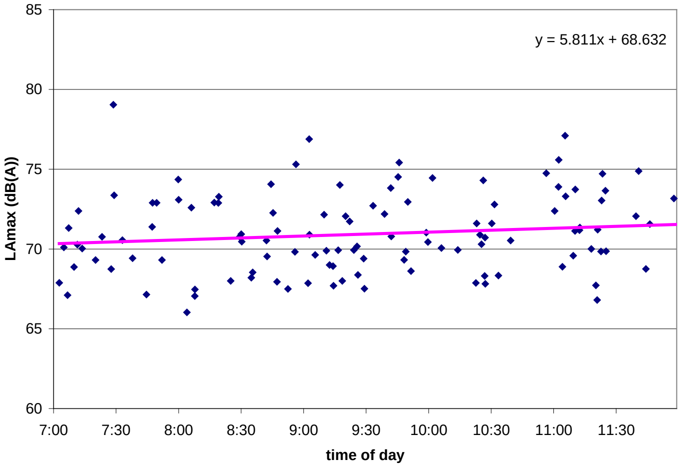
Of the eight data sets analyzed as described in Sections 4.4 and 5.4, two of the data sets are shown in the below figures, each with the following temperature correction applications: no corrections, each of the four semi-generic corrections, and data-set-specific corrections. All corrections were made to 68 °F (20 °C). Since the slopes are so small, it is difficult to see changes, however, looking for the number of steps in the regression line is an indication for how horizontal the line is (notice that with the data-set-specific corrections applied in Figure 17, there is only one step in the line, which indicates that the line is almost perfectly horizontal or that the slope is almost zero).



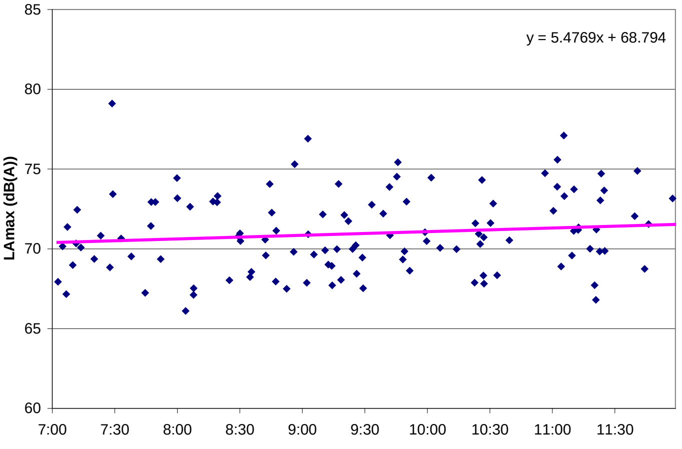
(1) no corrections



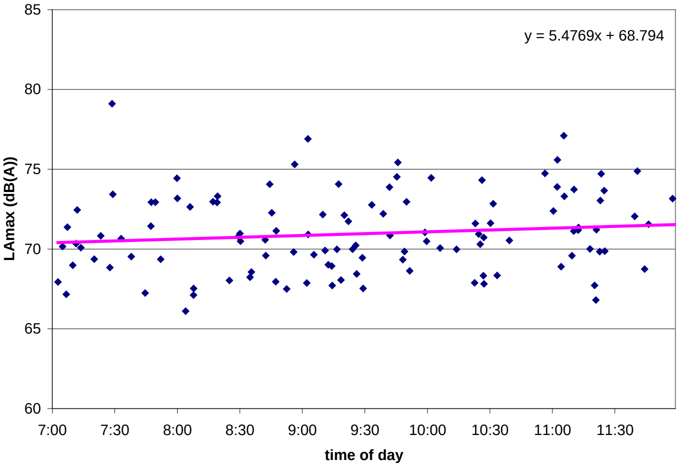
(2) semi-generic corrections, Sandberg 2004



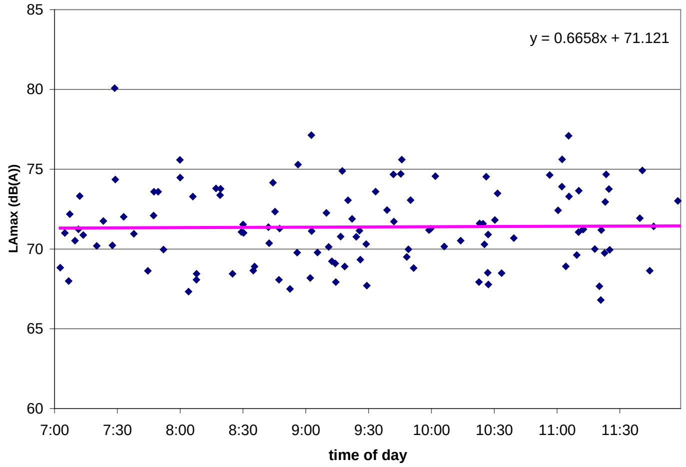
(3) semi-generic corrections, Bendtsen 2009



(4) semi-generic corrections, Scheme #1

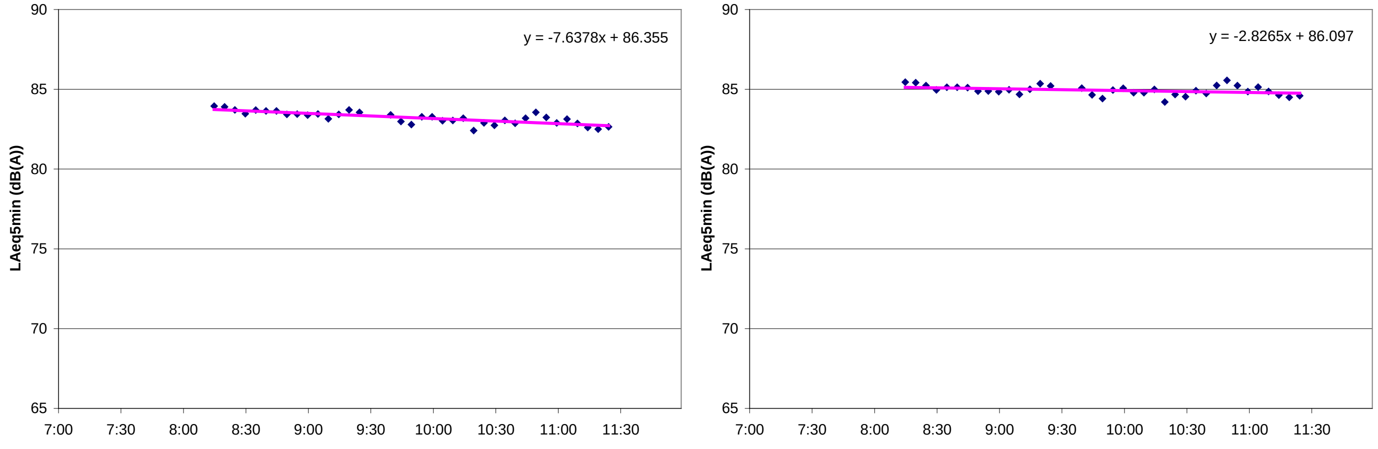


(5) semi-generic corrections, Scheme #2



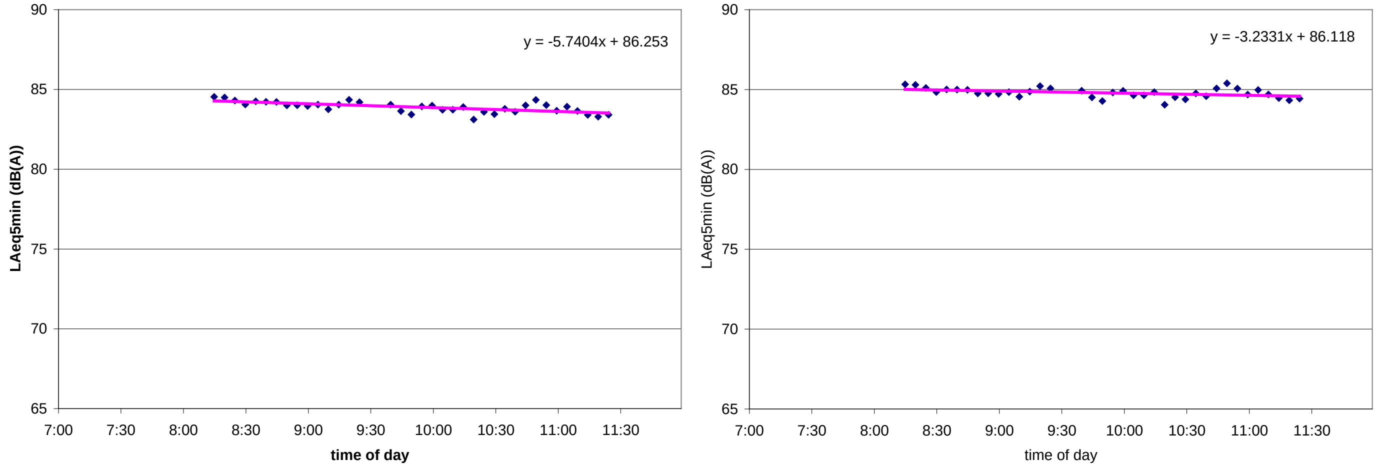
(6) data-set-specific corrections

Figure 17. Autos + DGAC, pass-by measurements. Sound levels as a function of time with linear regression with various temperature correction schemes applied, correcting to 68 °F (20 °C).



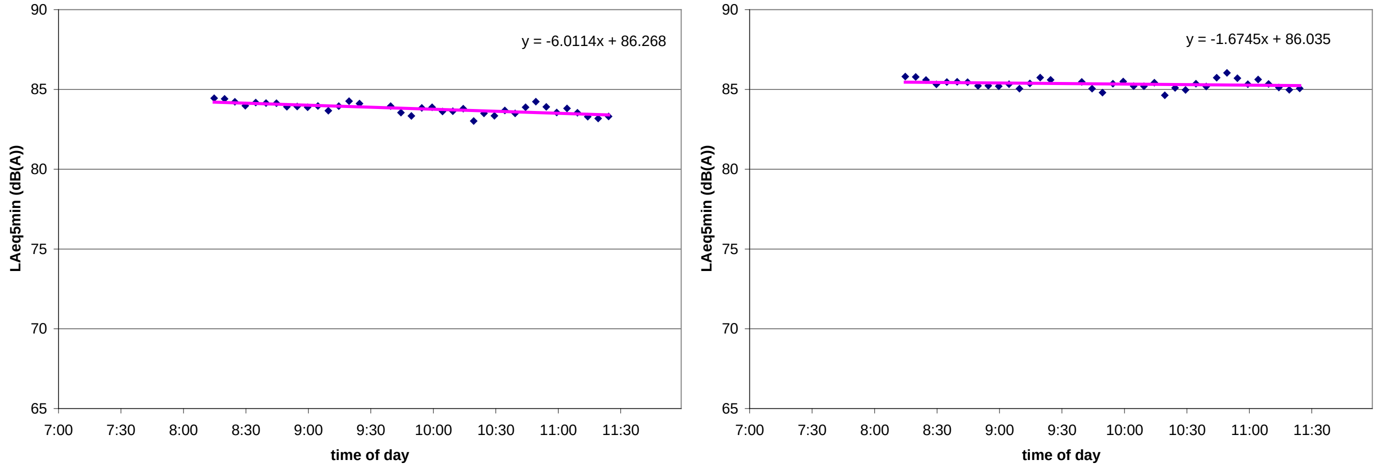
(1) no corrections

(4) semi-generic corrections, Scheme #1



(2) semi-generic corrections, Sandberg 2004

(5) semi-generic corrections, Scheme #2



(3) semi-generic corrections, Bendtsen 2009

(6) data-set-specific corrections

Figure 18. Autos + PCC, time-averaged measurements. Sound levels as a function of time with linear regression with various temperature correction schemes applied, correcting to 68 °F (20 °C).

APPENDIX D. COMPARING AIR AND PAVEMENT TEMPERATURES

Temperature data for each study is seen in the below four figures. The AZ QPPP data are shown with all 6 data sets on the same plot. The Caltrans Thin Lift Study data are divided into two plots, one for DGAC and one for OGAC, with each plot showing the pavement at four different ages. The FHWA TNM PEI Study data are shown with all 3 data sets on the same plot.

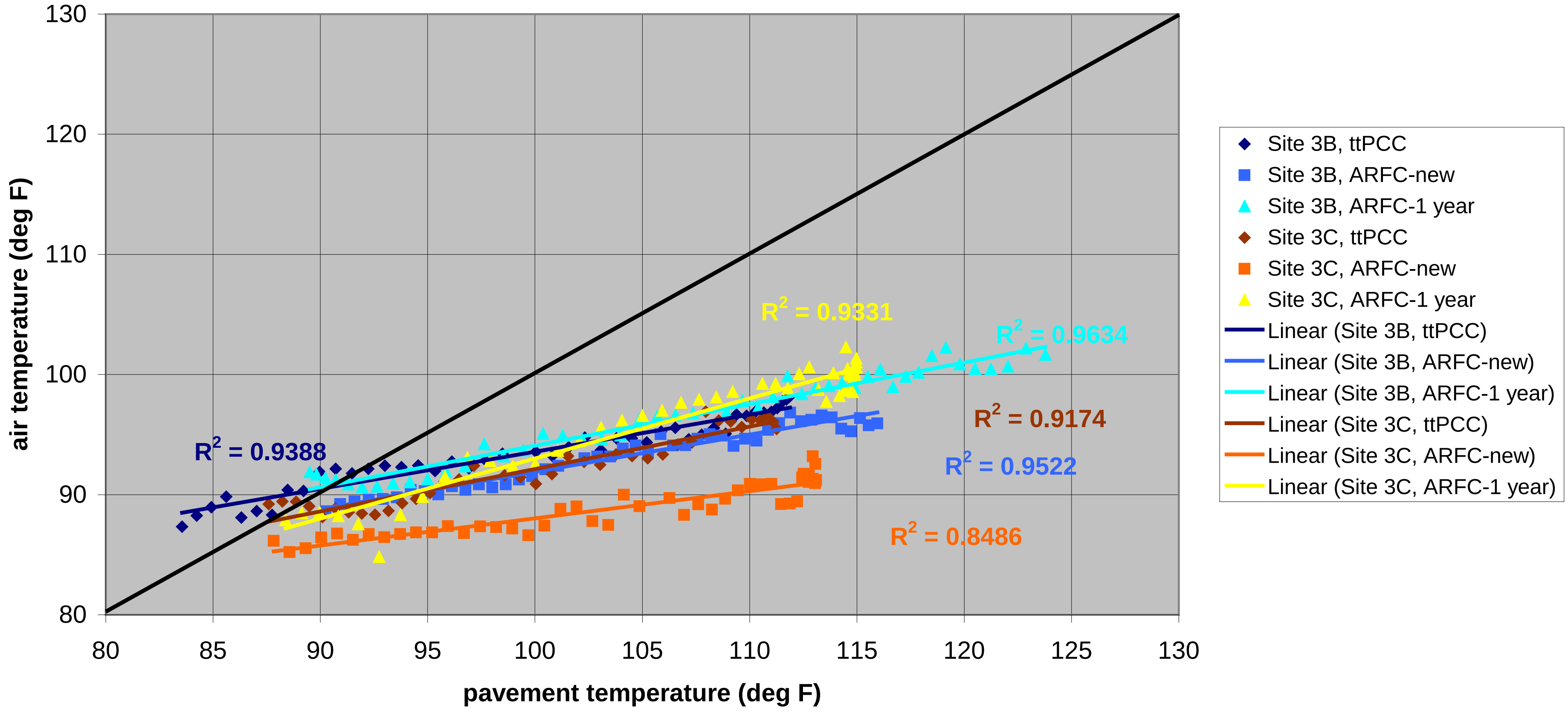


Figure 19. Comparison of air and pavement temperatures for AZ QPPP data. In the legend, ttPCC = transversely tined PCC, ARFC-new is asphalt rubber friction course shortly after construction, and ARFC-1 year is asphalt rubber friction course approximately 1 year after construction.

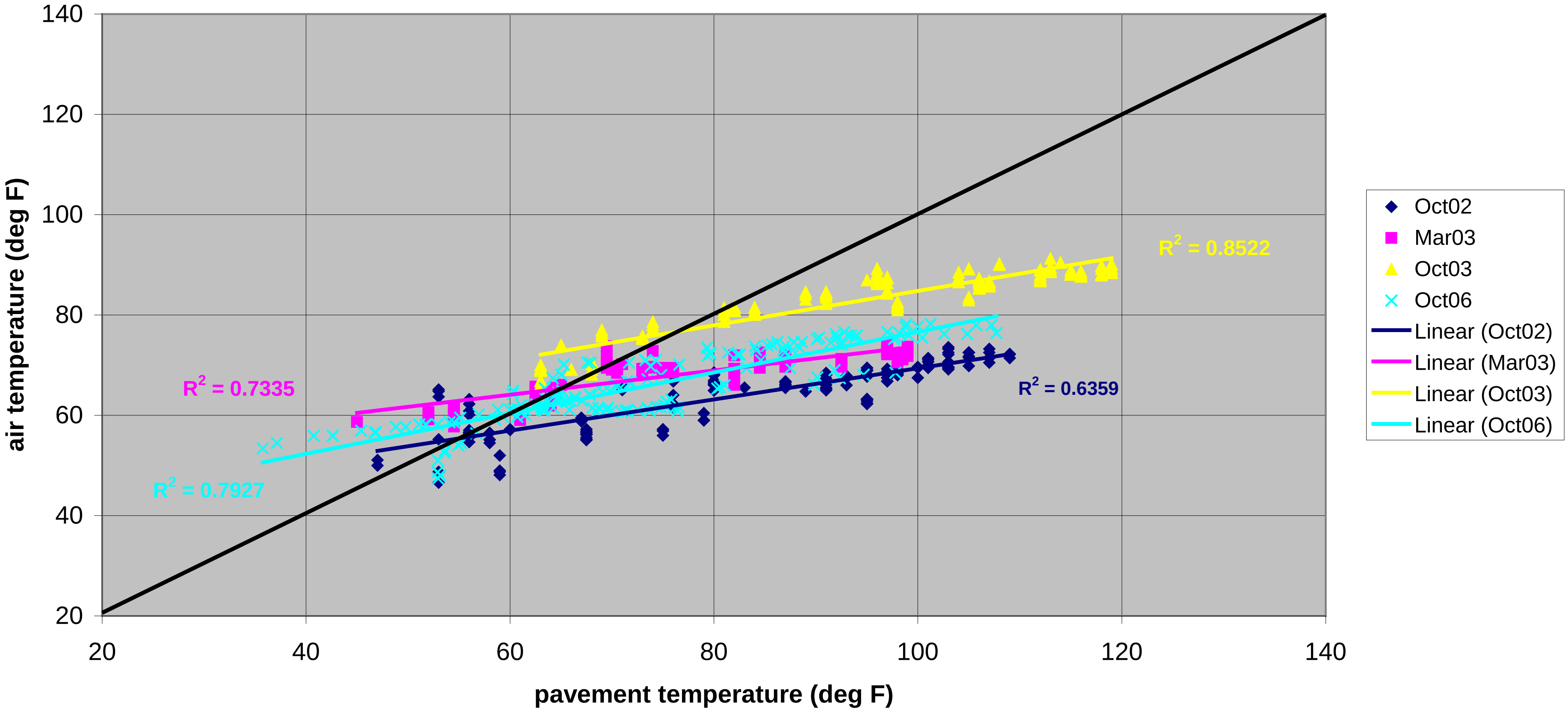


Figure 20. Comparison of air and pavement temperatures for Caltrans Thin Lift Study data for DGAC. In the legend, Oct02, Mar03, Oct03, and Oct06 represent pavement aged 4, 10, 16, and 52 months, respectively.

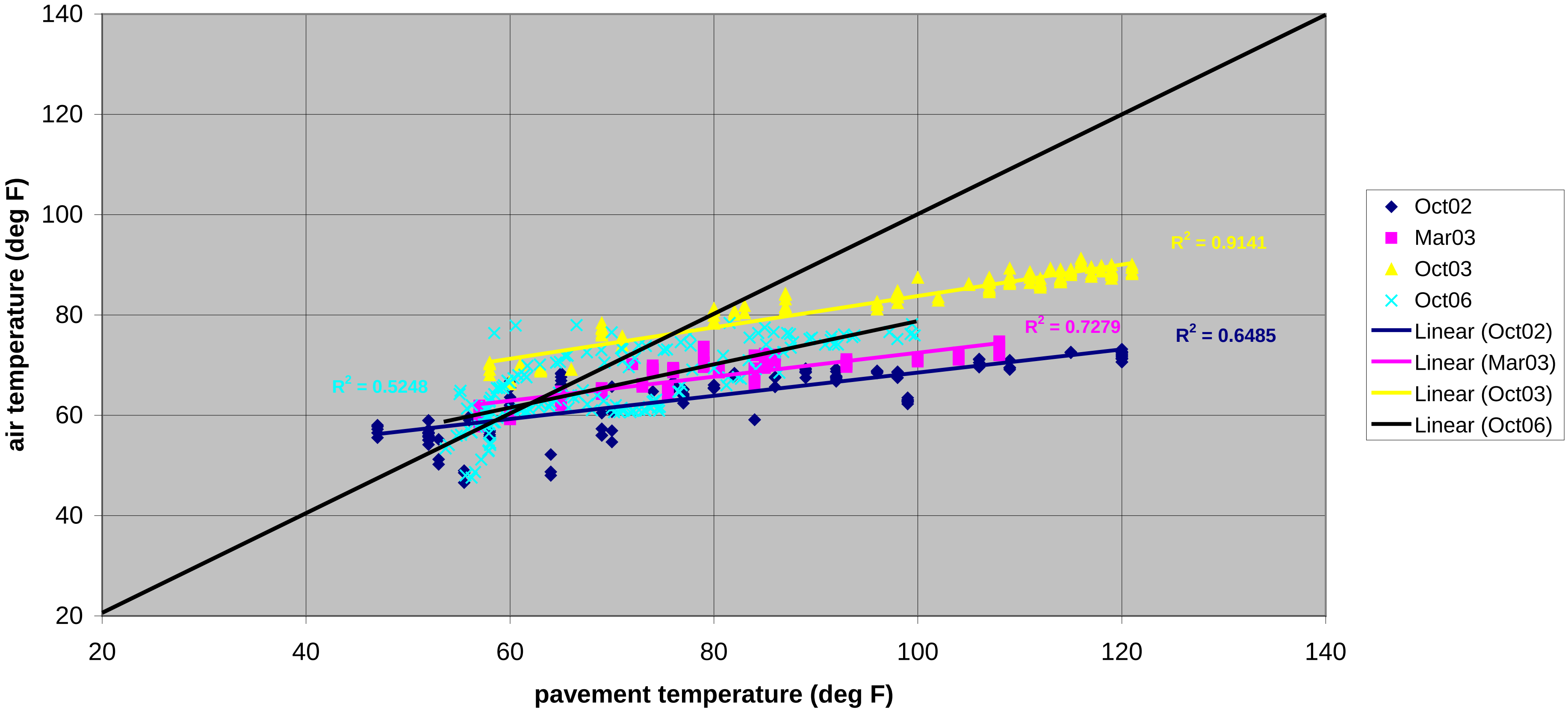


Figure 21. Comparison of air and pavement temperatures for Caltrans Thin Lift Study data for OGAC. In the legend, Oct02, Mar03, Oct03, and Oct06 represent pavement aged 4, 10, 16, and 52 months, respectively.

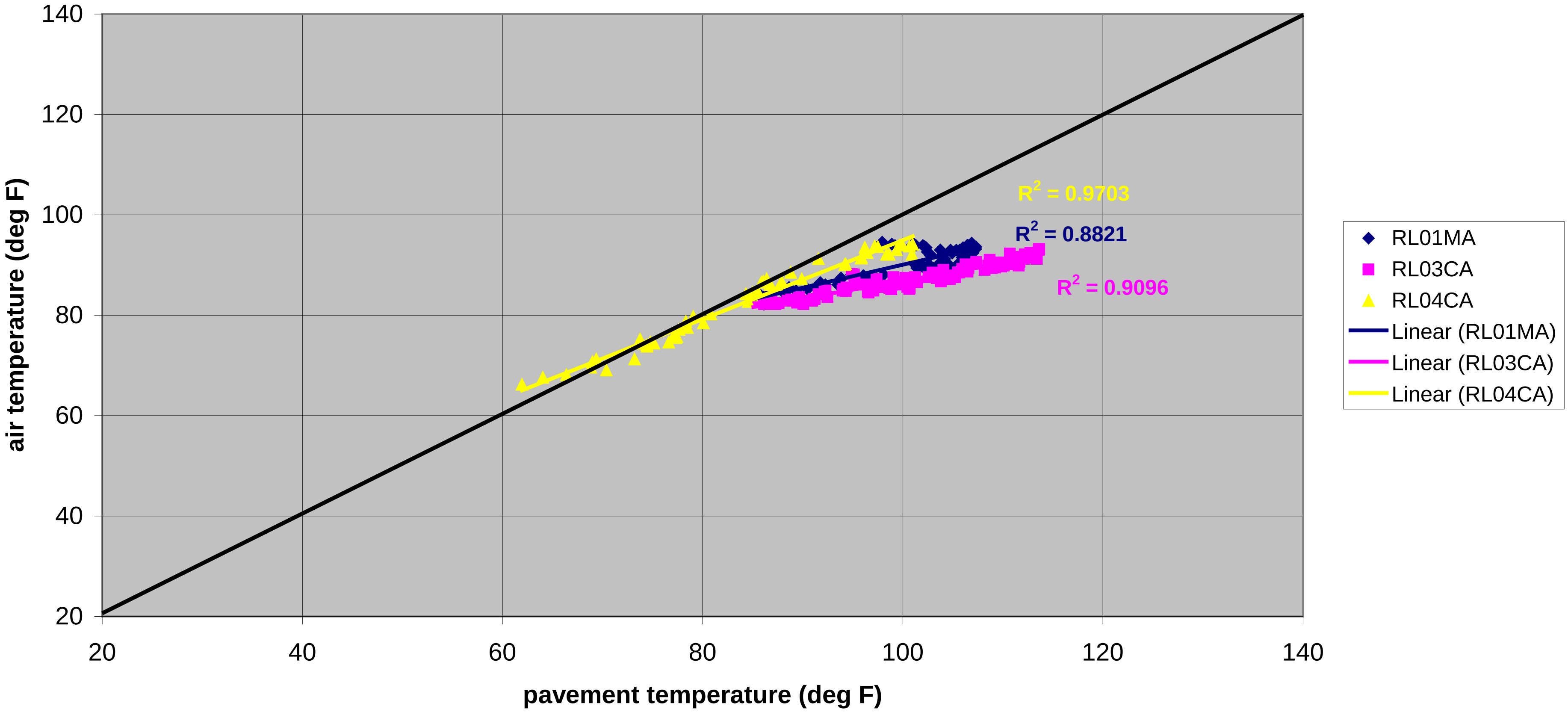


Figure 22. Comparison of air and pavement temperatures for FHWA TNM PEI Study data. In the legend, RL01MA = DGAC, RL03CA = longitudinally tined PCC, and RL04CA = longitudinally diamond ground PCC.