# Effectiveness of RWIS Bridge Temperature Simulators

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**16. Abstract**

Bridge deck simulators (BDSs), 6 in (15 cm) concrete cubes with an embedded temperature probe, are intended as a cost-effective substitute for RWIS pavement sensors to represent conditions likely on bridge decks in an area near an RWIS station. In this study, the effectiveness of the BDSs to predict the temperature on nearby bridge decks was evaluated. Nine sites were selected by ODOT across the state of Ohio (six in northeastern region and three in southwestern region) which were instrumented with BDSs and Nu Metrics pavement sensors on the bridge deck and (with one exception) on the road surface off the bridge. The use of BDSs appears to be unique to Ohio. A survey in the state of Ohio indicated little use was being made of BDS information.

RWIS temperature data collected at five minute intervals during winter season 2004-2005 were analyzed and the unusable data were weeded out by removing redundant entries, blank or incomplete entries, extreme temperature readings, and entries where sensor data were not updated. Correlation analysis was performed on the "cleaned" data from the nine sites for the air and BDS temperatures versus bridge deck and road temperatures, and also for air versus BDS temperatures. Separate correlations were made with all-day data and with nighttime data free of solar radiation effects. For both all-day and nighttime data, the BDS was found to better correlate with bridge deck and road temperatures than was the air temperature.

The nighttime data were then further analyzed to determine 90%, 95%, 99% prediction limits for the prediction of bridge deck and road temperatures based on the BDS and air temperature values. Again, the prediction limits for bridge and road temperatures using the BDS were generally tighter than when using air temperature.

Finite element analyses (FEA) were performed for the nine sites using ALGOR V18 software to investigate the temperature behavior of the bridge deck and the BDS for the air temperature profiles reflecting extreme positive and negative temperature gradients recorded at each site. The FEA modeling provided information about how the BDS and the bridge deck temperature change as a function of the air temperature and time.

Larger concrete cube sizes, up to 24 in (61 cm) on a side, were investigated with FEA in an exploratory manner. The 24 in (61 cm) cube almost exactly matched the simulated bridge deck temperature profiles under a variety of air temperature loads. The FEA temperature profiles showed that the existing BDS does not always closely represent the true temperature behavior of the bridge deck, but that a concrete cube 4 times larger on a side would compare much better.

Yearly training of maintenance personnel in the use of the BDS and RWIS is recommended.


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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

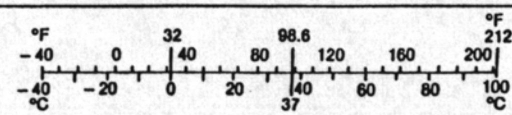
| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimetres | mm |
| ft | feet | 0.305 | metres | m |
| yd | yards | 0.914 | metres | m |
| mi | miles | 1.61 | kilometres | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | millimetres squared | $mm^2$ |
| $ft^2$ | square feet | 0.093 | metres squared | $m^2$ |
| $yd^2$ | square yards | 0.836 | metres squared | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | kilometres squared | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | millilitres | mL |
| gal | gallons | 3.785 | litres | L |
| $ft^3$ | cubic feet | 0.028 | metres cubed | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | metres cubed | $m^3$ |

NOTE: Volumes greater than 1000 L shall be shown in $m^3$.

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams | Mg |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5(F-32)/9 | Celcius temperature | °C |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimetres | 0.039 | inches | in |
| m | metres | 3.28 | feet | ft |
| m | metres | 1.09 | yards | yd |
| km | kilometres | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | millimetres squared | 0.0016 | square inches | $in^2$ |
| $m^2$ | metres squared | 10.764 | square feet | $ft^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | kilometres squared | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | millilitres | 0.034 | fluid ounces | fl oz |
| L | litres | 0.264 | gallons | gal |
| $m^3$ | metres cubed | 35.315 | cubic feet | $ft^3$ |
| $m^3$ | metres cubed | 1.308 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.205 | pounds | lb |
| Mg | megagrams | 1.102 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact)** | | |
| °C | Celcius temperature | 1.8C + 32 | Fahrenheit temperature | °F |




* SI is the symbol for the International System of Measurement

(Revised April 1989)

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These appendices may be downloaded from http://www.dot.state.oh.us/research/Maintenance.htm.

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# 1 Statement of the Problem

Increased public safety and savings in the cost of anti-icing and de-icing operations can be expected through the use of more accurate predictions of bridge deck condition. Public safety is enhanced when decisions to deploy forces are made that would not be made in the absence of reliable information. On the other hand, operational savings accrue from decisions not to deploy forces when deployment would be unnecessary or ineffective. Properly calibrated bridge deck simulators should improve confidence in both kinds of decisions while avoiding the significant installation and maintenance expense of in-road pavement sensors.

As of the beginning of this study in December 2004, ODOT had installed 41 bridge deck simulators as part of its expanded RWIS deployment. Most of these simulators were located at county garages in the central and southern parts of the state. The initial SSI RWIS installations located in Districts 2, 6, and 12 did not include bridge deck simulators. The bridge deck simulator consists of a temperature probe embedded in a 6”x6”x6.5” (15.2 cm x 15.2 cm x 16.5 cm) block of concrete and mounted to the same pole as the air weather sensors in the RWIS installation. Bridge deck simulators are generally used as surrogates for pavement sensors installed in roads and bridges. They are cheaper to install than pavement sensors and do not require the maintenance that pavement sensors require, such as replacement after repaving operations, or battery replacement for the Nu Metrics sensors used in most parts of the state. Besides the pavement temperature, ODOT’s pavement sensors also record pavement status (wet or dry), the amount of salt present (for SSI sensors), and traffic average speed and count (for Nu Metrics sensors). In addition to the pavement sensor and/or bridge deck simulator data, ODOT’s RWIS stations also measure such air weather parameters as air temperature, wind speed and direction, relative humidity, precipitation, and visibility distance.

The bridge deck simulators are intended as a cost-effective solution to represent conditions likely on bridge decks in the area. These prototype sensors need to be validated and correlated to actual bridge conditions to determine how to best interpret their data for use in winter maintenance.

Some of ODOT’s RWIS pavement sensors are installed on bridge decks, though generally not near bridge deck simulators. The two exceptions to this rule before the beginning of this study were Site 7 in Crawford County and Site 9 in Stark County, where the bridge deck simulator and nearby instrumented bridge deck were part of the same installation. It was natural to build a program of correlating bridge deck simulator temperatures to actual bridge and pavement temperatures around these two sites, but additional sites were necessary to represent various additional situations, including bridges over water versus bridges over dry land, different pavement or bridge surfaces, various parts of the state, and geometrical configurations. As a result, ODOT selected seven additional existing RWIS sites for this study at which bridge deck simulators were installed.

In addition, it is desired to be able to model the reaction of bridges under various temperature gradient conditions as a tool for assisting in predicting weather behavior, thus a bridge temperature modeling task was added to this project.

# 2 Objectives of the Study

The objectives of this project are as follows:

- Perform literature search and review and summarize applicable materials.
- Survey ODOT Districts and/or Counties and other state DOT's relative to their utilization of bridge deck simulators.
- For use in operational decisions, design the best possible process for reducing data from all the simulators and providing indications of the true condition of nearby bridge decks.
- In all phases of the study, exploit opportunities to redesign and interpret the output from the bridge deck simulators to improve their value.
- Investigate available heat exchange models applicable for bridges under varying climatic conditions
- Utilize available heat exchange models for bridges, refine available models or develop a new model within the scope of the project that can be used for weather related bridge operational activities.
- Establish confidence levels for readings

The specific method for the project is to select RWIS sites with both bridge deck simulators and pavement sensors in bridges and usually also in the road. Then the temperature data for an extended period of time during a winter season for each site was analyzed and the various temperatures compared to see how the bridge and road temperatures are related to the bridge deck simulator and air temperatures. The RWIS temperature data were supplied in files by ODOT and are described in more detail later. In addition, finite element techniques are used to simulate the temperature behavior of bridges under temperature gradients.

# 3 Background and Significance of Work

## 3.1 Previous Research on the ODOT RWIS Network

The Ohio Research Institute for Transportation and the Environment (ORITE) has completed five phases of Road Weather Information Systems (RWIS) and winter maintenance related research under the title *Evaluation of ODOT Roadway/Weather Sensor Systems for Snow and Ice Removal Operations*. The first phase consisted of an extensive analysis of how ODOT should expand its RWIS network from the initial three Districts, 2, 6, and 12, into a statewide network [1]. The study included an extensive literature search, in-depth surveys of winter maintenance personnel throughout the United States and beyond, field trips to inspect RWIS installations in other states, lifetime cost analyses, and a product review. Recommendations were made for creating a statewide RWIS network that was minimal yet adequate. Additional recommendations for creating a weather conscious culture in the department that would predispose county personnel to use the system were made because user buy-in is one of the biggest hurdles to realizing the full value of RWIS installations.

In investigating the available RWIS systems for Part I, it was found that very little was known about the accuracy of the pavement sensors. Thus a pavement sensor bench test was conducted as a second part of the study [2]. The study consisted of installing pavement sensors in concrete blocks cut from a bridge deck then cooling them in a climate chamber under various conditions, including different levels of temperature, different amounts of fluid, and different amounts of the two deicers most commonly used in Ohio, salt (NaCl) and calcium chloride ($CaCl_2$). The pavement sensor blocks were continuously monitored with ORITE's independent measurement instrumentation. The study results were inconclusive in that none of the sensors gave outstandingly accurate temperature readings when compared to ORITE's calibrated temperature probes.

In the fall of 2002 and winter of 2003 ORITE conducted Phase III - *Optimization of Salt Brine Pre-Treatment Application Rates and Frequencies* to determine the longevity and anti-icing effectiveness of brine application on various pavement surfaces [3]. A series of field tests on five pavement types were conducted to identify brine decay rates due to time and traffic. Phase III yielded predictive equations for decay of brine as a function of traffic and time for three of the five pavements. In-field measurements indicated extensive loss of initial brine which was attributed to pavement surface conditions, such as porosity. Field data were integrated with laboratory studies that simulated various pavement surface environmental conditions in order to provide guidance for a protocol on anti-icing prior to potential snow/ice events.

Most recently, two additional phases were conducted. Part IV, *Optimization of Pretreatment or Anti-Icing Protocol for Snow/Ice* [4], attempted to refine the results of Phase III, including extending the brine durability studies to longer times and under different brine application rates, including 20 gallons per lane mile (gplm) (47 liters per lane kilometer (lplkm)) and 80 gplm (188 lplkm) in addition to the standard 40 gplm (94 lplkm). A slower application speed with 40 gplm (94 lplkm) was also tried to approximate the effect of a zero-velocity spreader. The study also included observation of the effect of various amounts of pretreatment during actual winter events on a test section of AC pavement on US23 in Circleville, some controlled laboratory studies on the behavior of brine on AC and PCC surfaces, and surveys of brine pretreatment practices used in various states and the county garages in Ohio. Results of the comparison of different brine pretreatment levels was inconclusive because the mild winters during the study meant few data points, and ODOT's winter maintenance salt trucks generally arrived at the test area before there was any differentiation of the different test sections.

Concurrent with Part IV was Part V: *Vehicular Speed Associated with Winter Pavement Conditions* [5]. The aim of this project was to determine how to best use the speed and traffic data gathered by the Nu Metrics pavement sensors to augment standard weather measures as an indicator of road conditions, in particular, whether speed data could be used to determine the level of service. The Nu Metrics sensors record a traffic count and speed every five minutes, though if there are radio transmission problems from the sensor to the RPU, the data will be updated and stored on the sensor until the data are successfully transmitted. These traffic data were gathered during storm events and correlated to observed pavement and driving conditions at two sites in Ohio. Pavement condition was photographed and also ascertained by surveying motorists at rest areas near the two selected RWIS sites in northeastern Ohio. Some information was also gathered from speed data collected in two studies by other investigators.

## 3.2 Description of Bridge Deck Simulators

ODOT has expanded its network from 3 districts (2, 6, and 12) to a statewide network in response to the ORITE's evaluation of RWIS technologies [1]. Though the related bench test of pavement sensors was inconclusive [2], other factors were used by ODOT to select a system.  At many locations, particularly in the southern half of the state, instead of installing pavement sensors in the road, a bridge deck simulator was installed.  A bridge deck simulator is a 6”x6”x6.5” (15.2 cm x 15.2 cm x 16.5 cm) block of concrete with a temperature sensing element, similar to the temperature probes used in the pavement temperature bench test [2], embedded near the top of the block, as shown in Figure 1 and Figure 2.  It is intended to provide an indication of bridge deck temperatures, as opposed to air or road surface temperatures, without the added maintenance and reinstallation charges associated with sensors embedded in the pavement.  The bridge deck simulators are typically mounted on the same pole as the air weather sensors for a particular RWIS, as seen in Figure 3.  Often these installations are at a county garage or outpost, as one aim of the RWIS expansion was to cover every county in the state.  In the northern part of the state the RWIS installations included Nu Metrics pavement sensors, which measure traffic count and speeds in addition to pavement temperature.

**Figure 1.  Bridge Deck Simulator as mounted on RWIS air weather sensor pole at Site 31 near the Athens County Garage.**

**Figure 2. Bridge deck simulator and nearby equipment cabinets on RWIS sensor pole at Site 31, Athens County Garage. The temperature sensor wire can be observed coming out of the pole at the top center of the near side of the block.**

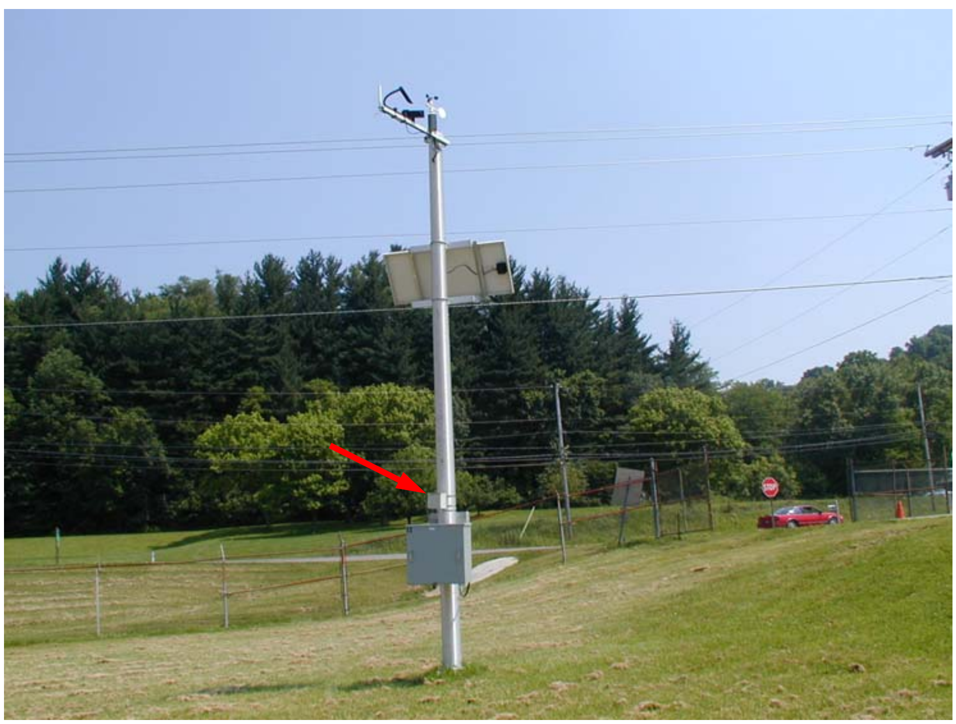


**Figure 3. ODOT RWIS weather station at Site 31 in the Athens County Garage compound. The arrow points to the bridge deck simulator attached to the pole. At the top are various air weather sensors and about a third of the way down is a solar panel.**

# 4 Literature review

## 4.1 Finite element models for thermal behavior of bridges

Finite element models for various conditions of bridge decks have been developed in the past, primarily to determine stress under loads. Given this context, it is no surprise that the majority of the finite element method (FEM) literature concerning heat flow in bridges is focused on the stresses due to thermal expansion. For example, Satpathi *et al*. (1999) utilized thermal gradient determinations from instrumentation of the bridge deck as well as a finite element model to determine if cracks in the pre-stressed concrete originated from thermal gradients or traffic [6].

Rahman and George [7] provide a description of a finite layer element program for computing stresses and displacements resulting from non-linear temperature gradients in continuous skew slab-girder bridges. Their paper provides information regarding experimental investigations and insight into problems previous modelers have encountered.

To address the use of thermosyphons (heat pipes) used to maintain ice-free bridge decks, work was conducted by Nydahl, Peel, and Lee [8] on heat transfer related to cooling of the bridge deck by the understructure and other extended structures such as guardrails and signposts.

Tong, Tham, and Francis [9] presented the results of a comprehensive investigation on the thermal behavior of steel bridges carried out in Hong Kong. A method for predicting bridge temperatures from given meteorological conditions is briefly discussed. The theoretical results were validated by temperature measurements on experimental models mounted on the roof of a building as well as on an existing steel bridge. Both the theoretical and field results confirmed the validity of the one-dimensional heat transfer model on which most design codes are based. Values of design thermal loading for a 50-year return period are determined from the statistics of extremes over 40 years of meteorological information in Hong Kong. The design temperature profiles for various types of steel bridge deck with different thickness of bituminous surfacing were developed.

Individual climatic impacts to bridge decks have also been modeled. Parametric studies of solar radiation and its effect on bridge deck temperatures via thermal loadings was modeled by Hirst [10], who determined that thermal loadings are related to all climatic factors, not just solar radiation and are extremely variable.

## 4.2 FEM on bridges for winter maintenance

FEM studies of thermal behavior for winter maintenance are few and far between. A three-dimensional heat transfer computer program was described by Nydahl and Pell [11] which is capable of modeling the thermal response of bridges, roadways and runways to their transient natural environment and internal heat sources. The methodology can be used to predict the frequency, length and severity of freeze-thaw cycles and the preferential icing that the bridge deck encounters and also the effect that changes in the heat transfer characteristics, both active and passive, will have. A detailed comparison of the response of an existing bridge to its environment, as measured with embedded thermistors, and the response predicted by the model were presented.

Greenfield et al [12] reported on a one-dimensional finite-difference algorithm (BridgeT) that they developed that simulates vertical heat transfer in a bridge based on evolving meteorological conditions as supplied by a weather forecast model. This algorithm simulates bridge deck surface temperature at 1-min intervals and calculates volume per unit area (i.e., depth) of frost deposited, melted, and sublimed. Although the model was reportedly sensitive to cloud forecasts, the model provided surface temperatures within 1°C (1.8°F) of measured values over a 40 hour forecast if supplied with accurate weather forecasts.

Takle and Greenfield [13] developed a finite-difference program that predicts bridge surface temperature by simulating vertical heat transfer in a bridge in response to evolving weather conditions. The depth of frost deposited, melted, or sublimed is estimated based on a vapor flux calculation using the bridge surface temperature and concurrent meteorological variables from a weather forecast model. The results obtained from the model were compared with measured surface temperatures from a Roadway Weather Information Systems station and the model realistically represented the early morning low temperatures and temperature trends. Improvements in forecast quality, especially humidity and radiation were suggested for improvements in bridge frost and surface temperature forecasts.

## 4.3 Predicting and modeling frost and adverse weather on bridges

The number of times bridge frost and roadway frost occurs in Iowa was determined from questionnaires completed by highway maintenance personnel and from 4000 frost observations. An expert system to provide twenty hour forecasts of roadway and bridge frost was constructed by Takle [14] from the analysis of meteorological conditions which was further evaluated by human forecasters. It was found in the study that the expert system was more accurate than the human forecast when supplied with perfect forecasts of commonly forecasted meteorological variables. From this study human forecasters were observed to provide relatively unbiased forecasts for bridge frost but were highly biased toward reducing false alarms for roadway frosts. A suggestion was made to use the expert system to separate it as a management tool for forecast accuracy and decision making criteria.

A dynamic stochastic approach for road and bridge forecasting was discussed by Mewes and Hart [15] using a pavement surface condition model. The Highway Condition Analysis and Prediction System (HiCAPS$^{TM}$) model, developed to support Meridian winter forecasting requirements, was used for the analysis. This model uses a one-dimensional unsteady heat flow equation to model heat fluxes and storage within the pavement and its substrate. The bias and error variance of the road and bridge surface temperature forecasts as a function of time of day or lead time were calculated based on the observations made from the model and the corresponding values from the road weather information system. This procedure was repeated for the dew point temperatures and, assuming a Gaussian distribution, probability density functions were constructed around the baseline road or bridge temperature and dew temperature forecasts. A method to calculate the probability of frost occurring based on a road or bridge temperature forecast and a dew point forecast was provided. The effect of the adsorption of the moisture on the roadway by anti-icing materials even while the dew point temperature is less than the pavement temperature was not considered in the model. The author states that little information was available on how to differentiate between scientific and treatable frost.

Analysis of pavement temperatures in Iowa was conducted by Knollhoff et al (1998) [16]. Differences between urban and rural patterns of temperature and temperature changes under different types of weather conditions were examined. Pavement temperature behavior from late afternoon to early morning was analyzed as the cooling part of the temperature-change cycle is most critical for maintenance decisions. January pavement temperature data from urban/rural sites for both bridges and roadways in/near Cedar Rapids and Des Moines were used to evaluate nighttime trends and differences of temperatures at different locations and under different weather conditions. Preliminary results showed that urban roadway pavement temperatures near both Des Moines and Cedar Rapids are 2 to 5F° (1.1 to 2.8 C°) higher than rural roadway pavement temperatures under clear sky conditions but only 1 to 2 or 1 to 3F° (0.6 to 1.1 or 1.7 C°) higher under cloudy conditions or when cloud cover is changing. The authors concluded that the pavement temperatures provide roadway maintenance personnel guidance for treating roadways for frost and ice conditions.

A model based on a simple concept of moisture flux to the surface was developed by Knollhoff et al (2003) [17] to calculate frost accumulation on the bridge decks in Iowa based on the data from roadway weather stations or forecasts of dew point temperatures, air temperature, surface temperature and wind speed. A logistical regression procedure was developed to determine the probability of frost formation for a given calculated frost depth as perceived by winter maintenance personnel. The study showed that the model had good accuracy in assessing frost accumulation on bridge decks and it can be used as a winter maintenance operations tool. However, the accuracy of the model can decrease based on the uncertainty in the input data supplied to the model. Threshold frost depths were established to determine the optimum combination of probability of detection and the probability of false detection of frost formation.

A computer model to predict the surface temperature and time of wetness (and time of freezing) of concrete bridge decks is developed and documented by Bentz [18]. The model was developed based on a one dimensional finite difference scheme and includes heat transfer by conduction, convection, and radiation. The effects of environmental conditions were considered using the meteorological year data files available from the National Renewable Energy Laboratory. The results indicated that the surface temperatures, time of wetting and number of freeze-thaw cycles vary based on the geographical location. The results of this model can be utilized as input to a windows-based computer program for sorptivity-based service life predictions for the cases of sulfate attack and freeze-thaw deterioration.

## 4.4 Relationship between air and surface temperature

Sherif and Hassan [19] used data collected by RWIS stations in the City of Ottawa in Ontario to devise a procedure that maximizes the utility of a batch of data containing a mixture of complete, partially complete, and unusable entries. Then they went on to study the relationship between the pavement surface temperature and weather variables. The weather variables analyzed were the air temperature, dew point, relative humidity, wind speed, wind gust, and wind direction. Statistical models were developed, and variables whose estimated coefficients are not statistically significant were eliminated using a stepwise regression technique. The remaining variables were further examined according to their contribution to the criterion of best fit and their physical relationships to each other to eliminate multicollinearities. The models were further corrected for the autocorrelation in their error structures. The final version of the developed models can be used as part of the decision-making process for winter maintenance operations depending on the predictions of pavement surface temperature.

# 5 Survey of ODOT county managers about the utilization of bridge deck simulators

A telephone survey was conducted and twenty four county managers (two counties for each of the twelve districts) were selected randomly and contacted. The questionnaire consisted of seven questions on the procedure the county managers used to predict bridge deck temperatures, the use of bridge deck simulators and the perceived usefulness of bridge deck simulators, the exact wording of the questions and the response choices are reproduced in Table 1. The county managers were also asked how they obtained advance weather forecast information. Five county managers answered the questions of the telephone survey, and fifteen responded to the subsequent email survey that was emailed to the county managers through the district offices. Of these respondents, one county answered both by telephone and email, and for tallying purposes, the email survey was regarded as superseding the earlier phone response. This left a total of 19 unique respondents. All responses are tabulated in Table 1.

Question 1 asked how the county personnel estimate the temperatures of the bridge decks or try to estimate if there is a danger of bridge decks freezing. The options provided in the questionnaire and corresponding percent choosing were: pavement sensor temperature (53%), bridge deck simulator (BDS) temperature (32%), air temperature from RWIS (68%), portable or mobile thermometer (e.g. Road Watch) (84%), and guess based on weather information (42%). Respondents could select more than one option. Thus portable thermometers are the most popular choice followed by RWIS air temperature. The lower frequency for pavement sensor and BDS temperatures may reflect the fact that these sensors are not available everywhere. For instance all three counties in District 12 responded, and none of these counties have BDS and neither do the surrounding counties, excepting a few sites equipped with BDS and pavement sensors. Some counties may look at BDS data from their own RWIS and bridge sensors in neighboring counties or vice versa, though the responses do not probe that deeply into how and from where the data are acquired and used. On the other hand, some of the answers are suspect, for instance one county said they used the pavement sensor on the bridge deck only, though it is known to the researchers that this county has a bridge deck simulator attached to the RWIS pole in the garage compound and no pavement sensors installed in bridges. Other phone respondents claimed to use all options. Another county was aware of the bridge deck simulator but did not use it much as personnel felt it was not accurate enough. Two counties responding by telephone said they used the bridge deck simulator on a daily basis for the prediction of the temperature on the bridge decks nearby in the winter season.

Question 2 asked how frequently managers checked BDS temperatures to determine bridge temperatures. The most frequent responses were “never” (37%) and “there are no BDS in our county” (21%). Most of these “never” are also from counties that actually have no BDS or BDS in addition to pavement sensors at the same site. Of the five remaining respondents (excluding the redundant telephone response), one selected three choices: “daily”, “prior to applying pretreatment” and “once in a while depending on conditions”, while the other four were evenly split between “daily” and “once in a while”. These five counties that consulted BDS answered questions 3-6, with sometimes input from another that was consistent with their not having any BDS. Subsequent percentages are of those counties that actually answered that question.

Question 3 asked if the respondent or someone else compared the readings of BDS and pavement sensors on the bridge deck. Two (40%) said yes, two (40%) said no, and one (20%) said they knew of no nearby sensors on bridge decks.

Question 4 asked if respondents thought the BDS was accurate compared to pavement sensors on bridge decks. Only one county (25%) selected “accurate”, which we defined as within 2F° (1.1C°). Another county said the BDS was not accurate enough to be useful, and two others (50%) didn’t know.

Question 5 asked if the respondents saw the BDS as a useful replacement for a pavement sensor on a bridge deck. Three counties (50%) said BDS was “somewhat useful”, one (17%) said “not useful”, and the other two (33%) said “don’t know”.

Question 6 asked how accurate BDS temperatures were in relation to bridge surface temperatures regardless of the presence of pavement sensors. One county (17%) said the BDSs were accurate (within 2F° (1.1C°)), another (17%) said the temperatures were not accurate enough to be useful, and the other four (67%) didn’t know.

All counties answered Question 7 regarding sources of weather information. In the telephone survey, all five counties used the same four sources: DTN, local TV, ODOT radio room, and web sites. In the email survey, respondents ranked the sources, and these rankings were aggregated. If not choosing an option was counted as 0 and averaged in with the others, the most highly ranked sources of weather information were SCAN*Cast, followed by web site, Weather channel, local TV, and DTN (the last two tied). However if these 0s are ignored in averaging, the favorites were SCAN*Cast and DTN. DTN ranked so much higher this way because those counties that used it preferred it to other sources. Web sources were third followed by a tie between weather channel and TV weather. More in-depth questioning and a higher response rate would be required to ascertain what weather information sources counties favor.

The limited information from the telephone survey indicates that even though the county managers were generally aware of the presence of bridge deck simulators, they did not find them accurate enough to be used as tools for bridge temperature prediction or winter maintenance decision-making. Some county personnel seemed to be uncertain about whether there were bridge deck simulators or actual pavement sensors in the local RWIS. Indeed some county garage personnel have indicated through to the researchers that they do not use the RWIS data collected at the local RWIS site and that they had no training with the system.

**Table 1. Survey questions and response from ODOT county garages**

| | Telephone N=5 | | | | | E-Mail N=15 | | | | | | | | | | | | | | | Both N=19* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Question** | **Adams (D9)** | **Ashland (D3)** | **Athens (D10)** | **Hocking (D10)** | **Jackson (D9)** | **Allen (D1)** | **Champaign (D7** | **Crawford (D3)** | **Cuyahoga (D12** | **Geauga (D12)** | **Harrison (D11)** | **Hocking (D10)** | **Huron (D3)** | **Lake (D12)** | **Logan (D3)** | **Medina (D3)** | **Portage (D4)** | **Putnam (D1)** | **Shelby (D7)** | **Van Wert (D1)** | **total** | |
| **1.** How do you estimate the temperature of bridge decks or try to estimate if there is a danger of bridge decks freezing? | | | | | | | | | | | | | | | | | | | | | | |
| o Pavement sensor on bridge deck | x | x | x | o | x | | x | x | x | x | | | | x | | | x | | | | 10 | 53% |
| o Bridge deck simulator on RWIS | x | x | | o | x | | | x | | | x | | x | | | | | | | | 6 | 32% |
| o Air temperature from RWIS | x | x | | o | x | | | x | x | x | x | x | x | x | x | x | | | x | | 13 | 68% |
| o Measure with handheld thermometer or truck mounted pavement thermometer (e.g. Road Watch) | x | x | | o | x | x | x | x | | x | x | x | | x | x | x | x | x | x | x | 16 | 84% |
| o Guess based on forecast information | x | x | | o | x | x | | | | | | | | x | | | | x | x | x | 8 | 42% |
| o We don't measure or estimate temperature on bridges | | | | | | | | | | | | | | | | | | | | | 0 | 0% |
| **2.** During the past two winter seasons how frequently did you or another person use the bridge deck simulator temperature readings to determine bridge deck temperatures in the area? | | | | | | | | | | | | | | | | | | | | | | |
| o On a daily basis | | | | o | x | | | x | | | | | x | | | | | | | | 3 | 16% |
| o Prior to applying pretreatment | | | | | | | | x | | | | | | | | | | | | | 1 | 5% |
| o Once in a while depending on conditions | | | | | | | | x | | | x | x | | | | | | | | | 3 | 16% |
| o Never | | | | | | x | | | | x | | | | x | | x | x | x | | x | 7 | 37% |
| o There are no bridge deck simulators in our county (Skip to Q7) | | | | | | | x | | x | | | | | | x | | | | x | | 4 | 21% |
| **3.** Did you or another person compare the temperature readings from the bridge deck simulator with the temperatures from the sensors on the bridge deck? | | | | | | | | | | | | | | | | | | | | | | |
| o Yes | | | | o | x | | | x | | | | | | | | | | | | | 2 | 40% |
| o No | | | | | | | | | | | x | x | | | | | | | | | 2 | 40% |
| o Not aware of sensors on bridge decks near by | | | | | | | | | | | | | | | | x | | | | | 1 | 20% |
| o Don't know | | | | | | | | | | | | | | | | | | | | | 0 | 0% |
| **4.** How accurate in your opinion were the bridge deck simulator temperature readings compared to the temperatures from the sensors on the bridge decks? | | | | | | | | | | | | | | | | | | | | | | |
| o Very accurate (within ±1ºF) | | | | | | | | | | | | | | | | | | | | | 0 | 0% |
| o Accurate (within ±2ºF) | | | | | | | | x | | | | | | | | | | | | | 1 | 25% |
| o Not accurate enough to be useful | | | | o | x | | | | | | | | | | | | | | | | 1 | 25% |
| o Don't know | | | | | | | | | | | x | x | | | | | | | | | 2 | 50% |
| **5.** In your opinion how useful or effective is the bridge deck simulator as a replacement for the sensors on the bridge deck? | | | | | | | | | | | | | | | | | | | | | | |
| o Very useful | | | | | | | | | | | | | | | | | | | | | 0 | 0% |
| o Somewhat useful | | | | | | | | x | | | | x | x | | | | | | | | 3 | 50% |
| o Not useful | | | | o | x | | | | | | | | | | | | | | | | 1 | 17% |
| o Don't know | | | | | | | | | | | x | | | | | x | | | | | 2 | 33% |
| **6.** How accurate in your opinion were the bridge deck simulator temperature readings compared to the temperatures of bridge decks in the proximity of the RWIS site? | | | | | | | | | | | | | | | | | | | | | | |
| o Very accurate (within about ±1ºF) | | | | | | | | | | | | | | | | | | | | | 0 | 0% |
| o Accurate (within about ±2ºF) | | | | | | | | x | | | | | | | | | | | | | 1 | 17% |
| o Not accurate enough to be useful | | | | o | x | | | | | | | | | | | | | | | | 1 | 17% |
| o Don't know | | | | | | | | | | | x | x | x | | | x | | | | | 4 | 67% |
| **7.** For your advance weather information what do you use? If more than one, please rank in order of importance (5=most important for e-mail survey only) | | | | | | | | | | | | | | | | | | | | | **average** | **rank of average** |
| o Data transmission network (DTN) | x | x | x | o | x | 5 | 0 | 5 | 3 | 0 | 5 | 2 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 5 | 2 | 4.5 |
| o Weather channel | | | | | | 0 | 2 | 3 | 4 | 3 | 4 | 3 | 0 | 3 | 3 | 2 | 2 | 0 | 4 | 0 | 2.2 | 3 |
| o Local TV weather | x | x | x | o | x | 0 | 3 | 2 | 1 | 4 | 0 | 4 | 0 | 2 | 4 | 4 | 1 | 0 | 5 | 0 | 2 | 4.5 |
| o SCAN*Cast | | | | | | 0 | 4 | 4 | 5 | 5 | 0 | 0 | 5 | 5 | 5 | 3 | 4 | 0 | 3 | 0 | 2.9 | 1 |
| o ODOT Radio Room | x | x | x | o | x | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| o Web site | x | x | x | o | x | 0 | 5 | 0 | 2 | 1 | 0 | 5 | 4 | 4 | 2 | 5 | 5 | 0 | 2 | 0 | 2.3 | 2 |
| o Other weather information | | | | | | 0 | 0 | 0 | 0 | 2 | 3 | 0 | 0 | 1 | 0 | 0 | 3 | 0 | 0 | 0 | 0.6 | 6 |

*Note: Hocking County responded to both telephone and email surveys. Only their email survey responses are counted in the totals

# 6 Descriptions of research sites

Nine RWIS sites across the state were eventually selected for this project. Site 7 in Crawford County and Site 9 in Stark County were found by the researchers by searching through the Buckeye Traffic website, which presents current RWIS data at http://www.buckeyetraffic.org/rwis/nosvg/ (accessed August 18, 2006). The presence of a bridge deck simulator and bridge pavement sensors at the same site suggested the method for this study. ODOT and contractor M.H. Corbin selected eight additional RWIS sites with bridges at which to install bridge deck simulators for this project. Seven of these sites were actually installed and studied in this project, while the last site, Site 96 at the intersection of SR315 and I270, was dropped from the study. In addition to Sites 7 and 9, the other sites in this study include Site 59 in Warren County, Site 68 in Summit County, Site 69 in Hamilton County, Site 70 on the Hamilton/Clermont County line, Site 86 in Lorain County, Site 88 in Ashtabula County, and Site 91 on the Portage/Mahoning County line. Figure 4 shows the locations of the RWIS sites selected for this study as blue dots with site numbers on the map of RWIS locations in Ohio taken from the old Buckeye Traffic website.

Installation and configuration of the bridge deck simulators at the added sites were completed in January 2005, and the data used in this study cover the period January 21-April 5 2005. For Sites 7 and 9, additional data beginning in November 1, 2004 and ending January 19, 2005 were also provided. No data were recorded at any site on January 20, 2005.

Figure 5 and Figure 6 are manufacturer drawings depicting the two kinds of bridge deck simulators analyzed in this study, the former with the temperature probe cable entering from the rear and the latter with the cable entering from the bottom. Both drawings depict the bridge deck simulator (BDS) upside down; in practice the block is installed so the bolt points down and is secured to a mount on the RWIS tower.

Table 2 (English units) and Table 3 (metric units), provide basic information on each site, including ODOT site number, location description, elevation, what feature the bridge was built over, information on placement of sensors, distance of sensors from the RWIS tower as measured using a handheld GPS device or estimated where that was not practical, and whether the temperature probe cable entered from the rear or the bottom of the bridge deck simulator. The rest of this chapter features pictures and additional information obtained at each site by the research team. This information includes a table of temperatures recorded on the bridge deck simulator and each pavement sensor or the surrounding pavement surface with a handheld infrared temperature gun, air temperature as recorded by the built-in thermometer in the research vehicle, and corresponding RWIS data taken from the obtained data files. As can be seen from the map in Figure 4, the sites are clustered in three groups, with Sites 59, 69, and 70 in southwest Ohio, Site 7 in north central Ohio, and the rest in northeast Ohio. Of these, only Site 88 in Ashtabula County and possibly Site 68 in Summit County or Site 86 in Lorain County are in the lake effect snow belt in the Cleveland –Ashtabula area. The sites in the southwestern cluster were visited on January 25, 2005, and the others on February 3-4, 2005.

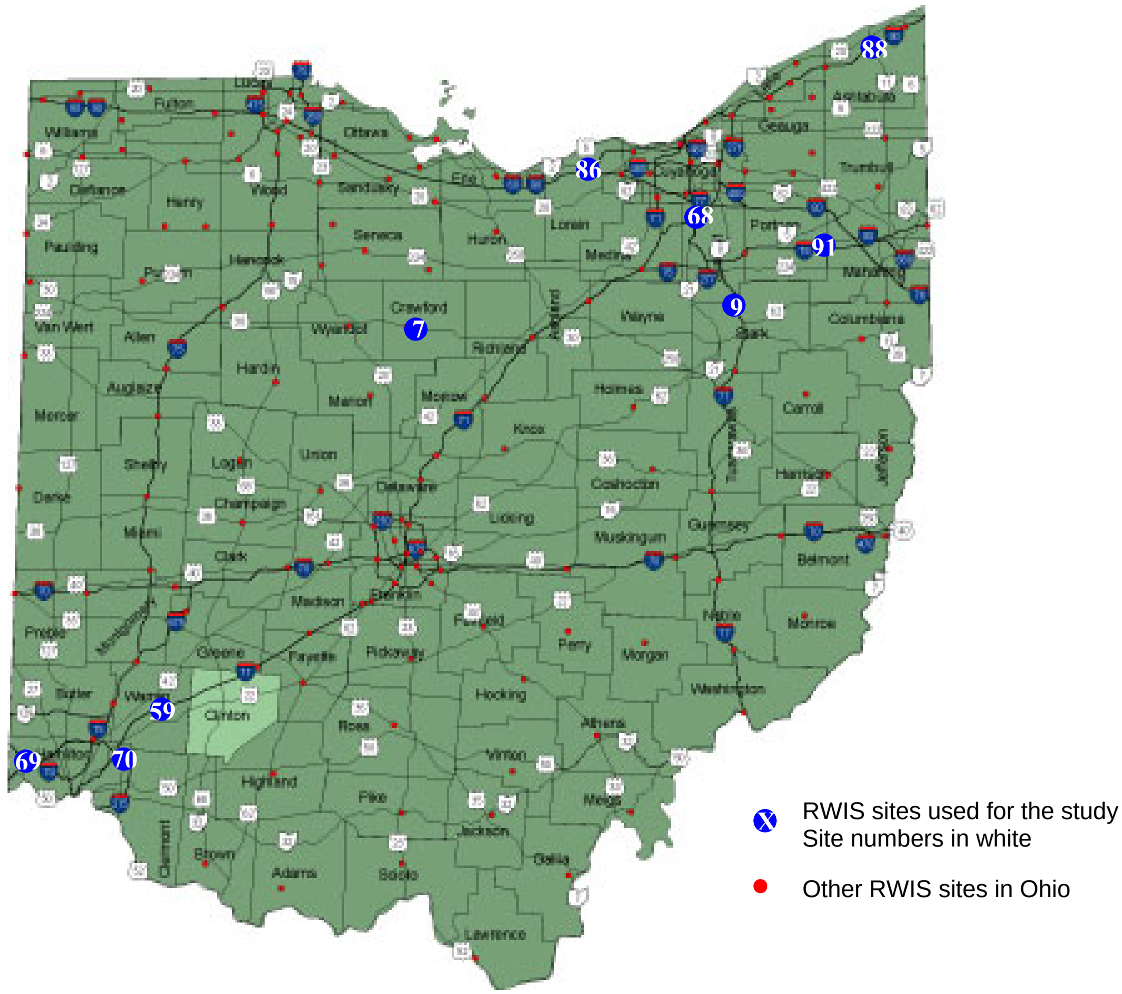



**Figure 4. Map of RWIS Locations used for the study [Map adapted from Buckeye Traffic RWIS website]**

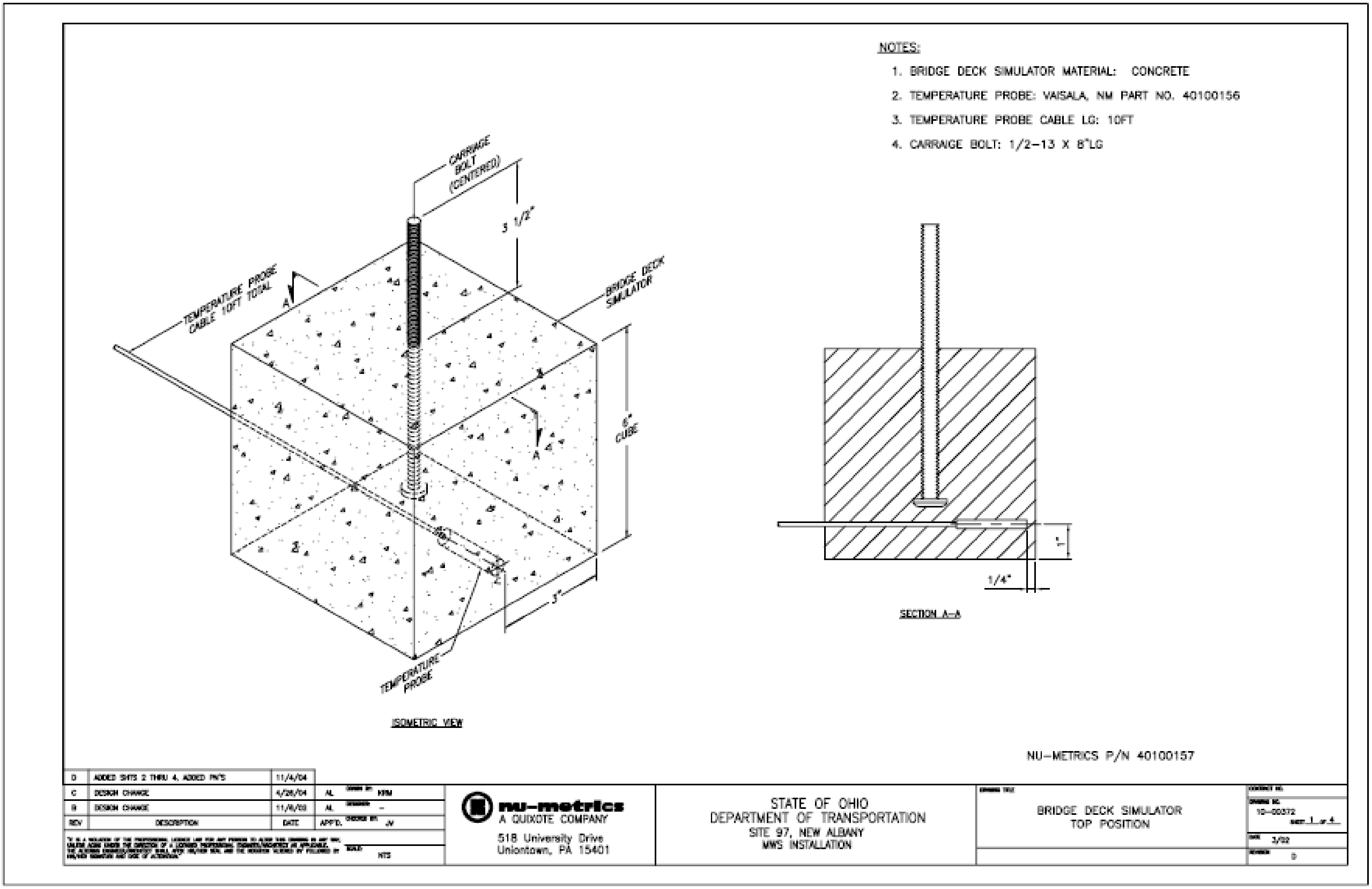



Figure 5. Bridge Deck Simulator design with probe cable entering from rear. Drawing supplied by Nu Metrics.

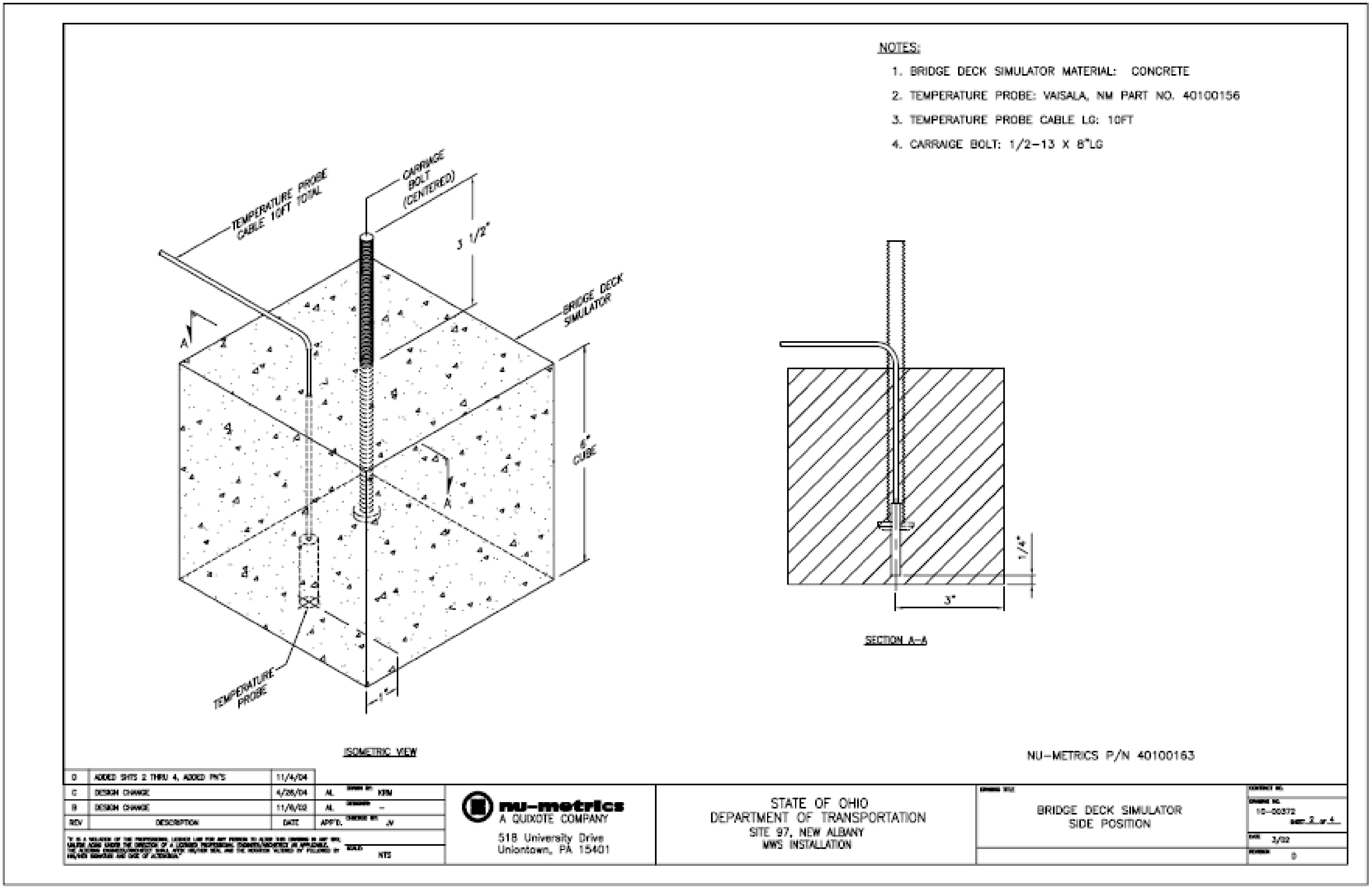



**Figure 6. Bridge Deck Simulator design with probe cable entering from bottom. Drawing supplied by Nu Metrics.**

**Table 2. Site descriptions for RWIS Bridge Temperature Simulator Project (English units).**

| | | | | | Bridge Sensors* | | Road Sensors* | | Bridge Deck Simulator (BDS) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Site No. | Location | Elevation (ft) | Bridge type | Bridge over | Sensor numbers (traffic direction) | Distance To BDS (ft) | Sensor numbers (traffic direction) | Distance To BDS (ft) | Sensor number | Probe entry |
| 7 | US30 Bucyrus, Crawford County | 1030 | Steel beam | Road | 5 (W) | 112.3 | 1, 2 (E), 3, 4 (W) | 116.5, 177.7 | 6 | Rear |
| 9 | I77 Beldon Vil. Exit, North Canton, Stark County (ramp bridge) | 1125 | Steel beam (ramp) | I77 | 1 (over I77, W) | 266.9 | None | - | 2 | Rear |
| 59 | I71 MM34 Jer. Mor. Bridge, Warren County | unknown | Steel understructure | River | 1, 2 (N) | 270 | 3, 4 (S) | 369.5 | 5 | Front (collapsed) |
| 68 | I271@I77 Summit County | 1115 | Steel beam | I77 | 1, 2 (E) | 149.6 & 184.4 | 3, 4 (W), 5, 6 (I77 N) | 407.5, ~200 | 7 | Rear |
| 69 | I275 MM21 Hamilton County | 520 | Steel beam | River | 3, 4 (W) | 226.5 | 1 (not working), 2 (E) | 103.6 | 5 | Bottom |
| 70 | I275 Hamilton-Clermont County line | 634 | Concrete | River | 1, 2, 3 (N) | 352 | 4, 5, 6 (S) | 148.7 | 7 | Rear |
| 86 | I90@Black River (near SR 57), Lorain County (road less exposed) | 649 | Steel beam | River and road | 3, 4 (W) AC* | 104.3 & 216.4 | 1, 2 (E) | 390 | 5 | Rear |
| 88 | I90@SR11 Ashtabula County | 884 | Steel beam | I90 | 5 (SR11 S) | 171.5 | 1, 2 (E), 3, 4 (W) | ~300, ~250 | 6 | Rear |
| 91 | I76 Portage-Mahoning County line | 1023 | Steel beam | Ravine and road | 3, 4 (S) | 122.6 & 151.3 | 1, 2 (N) | 269.3 & 308.7 | 5 | Bottom |

Sensor numbering convention is as follows, sensor number 1 is in the east or north bound traffic lane, and succeeding sensors are in sequence in lanes crossing the road (e.g. 2 is passing lane, 3 is passing lane in opposite direction, 4 is driving lane in opposite direction for a 4-lane road), and the next number(s) may be for a sensor on a cross road or bridge (Sites 68, 88; for Site 7 Sensor 5 is on the bridge on US30 in the westbound passing lane), and the last number is for the bridge deck simulator.

At all sites the sensors are highly exposed and away from all shading with the exception of the road sensors at Site 86, which are next to a cut bank that shades the road in the morning.

*All road surfaces are asphalt, and all bridge surfaces are Portland cement concrete, except Site 86, where the bridge has an asphalt overlay.

**Table 3. Site descriptions for RWIS Bridge Temperature Simulator Project (metric units).**

| | | | | | Bridge Sensors* | | Road Sensors* | | Bridge Deck Simulator (BDS) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Site No. | Location | Elevation (m) | Bridge type | Bridge over | Sensor numbers (traffic direction) | Distance To BDS (m) | Sensor numbers (traffic direction) | Distance To BDS (m) | Sensor number | Probe entry |
| 7 | US30 Bucyrus, Crawford County | 313.9 | Steel beam | Road | 5 (W) | 34.2 | 1,2 (E), 3, 4 (W) | 35.5, 54.2 | 6 | Rear |
| 9 | I77 Beldon Vil. Exit, North Canton, Stark County (ramp bridge) | 342.9 | Steel beam (ramp) | I77 | 1 (over I77, W) | 81.4 | None | - | 2 | Rear |
| 59 | I71 MM34 Jer. Mor. Bridge, Warren County | unknown | Steel understructure | River | 1, 2 (N) | 82.3 | 3, 4 (S) | 112.6 | 5 | Front (collapsed) |
| 68 | I271@I77 Summit County | 339.9 | Steel beam | I77 | 1, 2 (E) | 45.6 & 56.2 | 3, 4 (W), 5, 6 (I77 N) | 124.2, ~60 | 7 | Rear |
| 69 | I275 MM21 Hamilton County | 158.5 | Steel beam | River | 3, 4 (W) | 69.0 | 1 (not working), 2 (E) | 31.6 | 5 | Bottom |
| 70 | I275 Hamilton-Clermont County line | 193.2 | Concrete | River | 1, 2, 3 (N) | 107.3 | 4, 5, 6 (S) | 45.3 | 7 | Rear |
| 86 | I90@Black River (near SR 57), Lorain County (road less exposed) | 197.8 | Steel beam | River and road | 3, 4 (W) AC* | 31.8 & 66.0 | 1, 2 (E) | 118.9 | 5 | Rear |
| 88 | I90@SR11 Ashtabula County | 269.4 | Steel beam | I90 | 5 (SR11 S) | 52.3 | 1, 2 (E), 3, 4 (W) | ~90, ~75 | 6 | Rear |
| 91 | I76 Portage-Mahoning County line | 311.8 | Steel beam | Ravine and road | 3, 4 (S) | 37.4 & 46.1 | 1, 2 (N) | 82.1 & 94.1 | 5 | Bottom |

Sensor numbering convention is as follows, sensor number 1 is in the east or north bound traffic lane, and succeeding sensors are in sequence in lanes crossing the road (e.g. 2 is passing lane, 3 is passing lane in opposite direction, 4 is driving lane in opposite direction for a 4-lane road), and the next number(s) may be for a sensor on a cross road or bridge (Sites 68, 88; for Site 7 Sensor 5 is on the bridge on US30 in the westbound passing lane), and the last number is for the bridge deck simulator.
At all sites the sensors are highly exposed and away from all shading with the exception of the road sensors at Site 86, which are next to a cut bank that shades the road in the morning.
*All road surfaces are asphalt, and all bridge surfaces are Portland cement concrete, except Site 86, where the bridge has an asphalt overlay.

## 6.1 Site 7: Crawford County, US30 mile marker 7.1

The site visit occurred at 12:02 PM on February 4. The sky was clear.

The bridge is on US30 over a small road (not a ramp bridge as indicated on the Buckeye Traffic website) and has steel beam construction. The bridge is extremely exposed and the bridge surface is concrete and the road surface is asphalt.

The bridge deck simulator location is N 40°49.601′, W 82°58.947′ at an elevation 1030 ft (313.9 m) above sea level. The air temperature was around 34°F (1.1°C) and the wind was moderate, in south direction. The bridge deck simulator is on south side of the pole with the probe cable entering from rear and the temperature, as measured with the ORITE handheld infrared thermometer, was 4.8, 11.8, 7.8°C (40.6, 53.2, 46.0°F) (W, S, E sides respectively); W side was particularly shaded from the sun. Bridge deck simulator is 56.6 ft (17.3 m) from east end of the bridge.

Bridge sensors are located at N 40°49.609′, W 82°58.966′, and 112.3 ft (34.2 m) away from the simulator. Bridge sensors are on the westbound lanes, pavement sensors on the eastbound and westbound lanes with temperatures of 16.8°C (62.2°F) in the passing lane and 8.6°C (47.5°F) in the pavement adjacent to the sensor at the time of the visit.

Pavement sensors on westbound lanes are at N 40°49.602′, W 82°58.910′, 177.7 ft (54.2 m) from simulator. This site is unusual in that each lane has two pavement sensors installed, even though only one is listed on Buckeye Traffic as active. It cannot be determined which sensor is the one reporting data, so temperatures were measured on both sensors and the adjacent pavement in each lane. Sensor results are averaged for the comparison in Table 4. In the passing lane the sensors are separated by 51 in (1.30 m), in the driving lane they are separated by 92 inches (2.34 m). Temperatures of the passing lane sensors were 16.4, 17.2°C (61.5 and 63.0°F) and adjacent pavement: 8.2, 5.8°C (46.8, 42.4°F) and driving lane sensors were 14.2, 16.2°C (57.6, 61.2°C) and adjacent pavement: 5.2, 5.2 °C (41.4°F).

Pavement sensors on eastbound lanes are at N 40°49.597′, W 82°58.920′, 116.5 ft (35.5 m) from simulator (passing lane sensors).There are two sensors in each lane. In the passing lane the sensors are separated by 125 in (3.18 m), in the driving lane they are separated by 100 in (2.54 m). There is 42.2 ft (12.9 m) between the sensors in the passing lane and the sensors in the driving lane. Temperatures of the passing lane sensor were 15.0, 14.4°C (59.0, 57.9°F) adjacent pavement: 7.2, 5.2°C (45.0, 41.9°F) and the driving lane sensor temperatures were 16.8, 17.6°C (62.2, 63.0°F) and adjacent pavement: 7.2, 6.2°C (45.0, 43.2°F).

Table 4 compares the ORITE measured temperatures to those given in the RWIS data file at the time of the visit, and Figure 7 shows pictures of the bridge deck simulator, the bridge, and pavement sensors. Of particular note is the exposed temperature probe end in the bridge deck simulator visible in Figure 7c and the redundant pavement sensors in Figure 7d. It is not known which of the two sensors was being recorded, and all four lanes of US30 had similar pairs of sensors.

**Table 4. Sensor temperatures for Site 7 in Crawford County**

| Sensor | ODOT Temperature | | ORITE Temperature | | Difference (ODOT-ORITE) | |
|---|---|---|---|---|---|---|
| | (°C) | (°F) | (°C) | (°F) | (C°) | (F°) |
| Air Temperature | 2 | 35.6 | 1.1 | 33.98 | 0.9 | 1.62 |
| 1-EB Driving | 18.4 | 65.12 | 17.2 | 62.96 | 1.2 | 2.16 |
| 2-EB Passing | 18 | 64.4 | 14.7 | 58.46 | 3.3 | 5.94 |
| 3-WB Passing | 18.2 | 64.76 | 16.8 | 62.24 | 1.4 | 2.52 |
| 4-WB Driving | 18 | 64.4 | 15.2 | 59.36 | 2.8 | 5.20 |
| 5- WB Passing (B) | 17.7 | 63.86 | 16.8 | 62.24 | 0.9 | 1.62 |
| 6-Bridge Deck Simulator | 10.4 | 50.72 | 8.1 | 46.58 | 2.3 | 4.14 |

**a. Side rear view of bridge deck simulator block showing temperature probe cable entering from the rear.**

**b. Westbound bridge on US30 at Site 7. The bridge is over a two-lane road.**

**c) Extreme close-up of bridge deck simulator showing exposed tip of temperature probe**

**d) Pair of pavement sensors in passing lane of US30 westbound. The shadows of the researchers measuring temperature of a pavement sensor with the infrared thermometer can be seen**

**Figure 7. Pictures of a) bridge deck simulator, b) bridge, c) close-up of bridge deck simulator, and d) pair of redundant pavement sensors in westbound passing lane at Site 7 in Crawford County.**

## 6.2 Site 9: Northern Stark County, I77 Beldon Vil. St., Exit 109A

The time and date of visit was 11:04 AM on February 3, 2005. The sky was overcast.

The bridge is a single lane ramp bridge over I77 which has concrete surface steel beam construction. It is extremely exposed with no cover. Bridge deck simulator is located at N 40°51.304′, W 81°24.451′ with an elevation of 1125 ft (342.9 m) above sea level and had slight winds in North direction. There was no nut holding the simulator block in place; the bridge deck simulator was loose in the mount.

The bridge deck simulator is on the south side of the pole with the probe cable entering from rear, and the temperature of the bridge deck simulator was 2.6, 2.8, 2.6°C (36.7, 37.0, 36.7°F) (E, S, W sides respectively) .It was located at 120.5 ft (36.7 m) from east end of bridge. Bridge sensor is located at N 40°51.303′, W 81°25.004′, 266.9 ft (81.4 m) away from the simulator, and had a temperature of 5.4°C (41.7°F). The temperature of the bottom of the bridge was 3.4°C (38.1°F), though this was a long distance measurement and possibly inaccurate.

Table 5 compares the ORITE measured temperatures to RWIS sensor readings at the same time. Figure 8 shows photographs of the bridge sensor, the bridge deck simulator, the bridge, and the RWIS RPU. Of particular note, Figure 8b shows the loose alignment of the bridge deck simulator block, due to the lack of a nut securing the block to the mounting bracket.

**Table 5. Sensor temperatures for Site 9 in Stark County**

| Sensor | ODOT temperature | | ORITE Temperature | | Difference (ODOT-ORITE) | |
|---|---|---|---|---|---|---|
| | (°C) | (°F) | (°C) | (°F) | (C°) | (F°) |
| Air Temperature | 1.5 | 34.7 | Not measured | Not measured | - | - |
| 1-Ramp (B) | 3.4 | 38.12 | 5.4 | 41.72 | -2 | -3.6 |
| 2-Bridge Deck Simulator | 0.1 | 32.18 | 2.7 | 36.86 | -2.6 | -4.68 |

**a. Lone pavement sensor at Site 9, installed on the single lane of the ramp bridge over I77**

**b. BDS sitting on mount attached to RWIS station pole**

**c. Ramp bridge over I77.**

**d. RWIS Station with BDS**

**Figure 8. Pictures of RWIS and bridge at Site 9 on I77 near Canton.**

## 6.3 Site 59: Warren County, Jeremiah Morrow Bridge on I71

The site was visited at 11:35 AM on January 25, 2005. The bridge has a steel understructure and is situated over the Little Miami River at mile marker 34 of I71. RWIS site GPS coordinates are N39°25.253′ W 84°04.988′. The elevation above sea level was not recorded. The temperature of the bridge deck simulator block was measured at 8.8°C (47.8°F). The strap securing the bridge deck simulator block to the pole was broken, and the block and mounting bracket were resting on the RPU cabinet.

The bridge deck sensors are on northbound lanes. The bridge surface is concrete and southbound lanes have sensors in asphalt pavement away from the bridge. The location of the median edge of road by bridge deck sensors is N39°25.233′ W 84°06.026′, and the temperature of the nearest bridge deck sensor was measured at +1.0°C (33.8°F). The distance from the bridge deck simulator to the median edge of road by the bridge deck sensors is 270 ft (82.3 m). The coordinates of the inside edge of road by pavement sensors is N39°25.282′ W 84°05.924′, and the temperature of the pavement sensor was recorded as +5.2°C (41.4°F). Distance from the bridge deck simulator to the median edge of road by the pavement sensors is 369.5 ft (112.6 m).

Table 6 compares the ORITE measured temperatures to RWIS sensor readings at the same time. Figure 9 shows photographs of the RWIS weather station, the bridge, the bridge deck simulator, and the bridge sensors. Of particular note, Figure 9c shows the bridge deck simulator block and broken mounting bracket resting on the RPU cabinet.

**Table 6. Sensor temperatures for Site 59 in Warren County**

| Sensor | ODOT temperature | | ORITE Temperature | | Difference (ODOT-ORITE) | |
|---|---|---|---|---|---|---|
| | (°C) | (°F) | (°C) | (°F) | (C°) | (F°) |
| Air Temperature | 1.8 | 35.2 | Not measured | Not measured | - | - |
| 1-NB Driving (B) | 8.7 | 47.7 | - | - | - | - |
| 2-NB Passing (B) | 8.2 | 46.8 | 1 | 33.8 | 7.2 | 13.0 |
| 3-SB Passing | 3.4 | 38.1 | 5.2 | 41.4 | 1.4 | -3.24 |
| 4-SB Driving | 0.0* | 32.0 | - | - | - | - |
| 5-Bridge Deck Simulator | -4.6 | 23.7 | 8.8 | 47.8 | 0.9 | -24.1 |

*Note: The temperature of the road pavement sensor in Lane 4 was recorded at 0°C (32°F) for two hours while the temperature reported by the other road pavement sensor climbed over 5°C (9°F). The site visit occurred about 1.5 hours into this two hour period.

**a. RWIS tower and weather station**

**b. Jeremiah Morrow Bridge at Site 59, showing steel construction underneath**

**c. Close-up of bridge deck simulator and broken bracket resting on RPU cabinet**

**d. Pavement sensors on bridge. Sensor in driving lane is directly in front of Professor Zwahlen.**

**Figure 9. Pictures of a) RWIS weather instrument tower, b) bridge, c) bridge deck simulator, and d) pavement sensors on bridge at Site 59 in Warren County**

## 6.4 Site 68: Northern Summit County, I271 at I77.

The time and date of visit was 12:06 AM on February 3, 2005. The sky was overcast and clearing.

The bridge is on I271 over I77 with steel beam construction, and is extremely exposed with no cover. Bridge surface is concrete while both roads are asphalt.

The bridge deck simulator is located at N 41°13.702′, W 81°37.684′ with an elevation of 1115 ft (339.9 m) above sea level. There were moderate wind gusts in northern direction with air temperature at 45°F (7.2°C). The bridge deck simulator is on south side of pole with probe cable entering from rear. The bridge deck simulator temperature was measured at 3.4, 3.8, 3.8°C (38.1, 38.8, 38.8°F) (W, S, E sides respectively). Bridge Deck simulator is 31.1 ft (9.5 m) from the south (west) end of bridge.

The bridge pavement sensors are located at N 41°13.711′, W 81°37.657′, 149.6 and 184.4 ft (45.6 and 56.2 m) away from the simulator. Bridge sensors are on the northbound (eastbound) lanes of I271, and a temperature of 5.8°C (42.4°F) was measured in the passing lane.

The pavement sensors on the southbound (westbound) lanes of I271 are at N 41°13.678′, W 81°37.759′, 407.5 ft (124.2 m) from the simulator (plus additional 24 ft (7.3 m) to the driving lane sensor) and the passing lane sensor had a temperature of 4.6°C (40.3°F). A second set of pavement sensors on northbound lanes of I77 are at N 41°13.733′, W 81°37.630′, about 200 ft (60 m) from the simulator (plus additional 12 ft (one lane width) (3.66 m) to the driving lane sensor). This distance was estimated because it was not possible to walk the GPS to these sensors from the weather tower. The temperature was measured at 4.2°C (39.6°F) in the driving lane.

Table 7 compares the ORITE measured temperatures to RWIS sensor readings at the same time. Figure 10 shows photographs of the RWIS weather station and the bridge.

**Table 7. Sensor temperatures for Site 68 in Summit County**

| Sensor | ODOT temperature | | ORITE Temperature | | Difference (ODOT-ORITE) | |
|---|---|---|---|---|---|---|
| | (°C) | (°F) | (°C) | (°F) | (C°) | (F°) |
| Air Temperature | 1.2 | 34.2 | 7.2 | 45.0 | -6 | -10.8 |
| 1-NB Driving (B) | 4 | 39.2 | - | - | - | - |
| 2-NB Passing (B) | 3.2 | 37.8 | 5.8 | 42.4 | -2.6 | -4.7 |
| 3-SB Passing | 4.4 | 39.9 | 4.6 | 40.3 | -0.2 | -0.36 |
| 4-SB Driving | 5 | 41.0 | - | - | - | - |
| 5- I77 NB Driving | 3.4 | 38.1 | 4.2 | 39.6 | -0.8 | -1.4 |
| 6- I77 NB Passing | 4.4 | 39.9 | - | - | - | - |
| 7-BDS | -1.4 | 29.5 | 3.7 | 38.7 | -5.1 | -9.2 |

**a. RWIS and Bridge**

**b. Side view of northbound lanes of bridge on I271 from I77.**

**Figure 10. Pictures of a) RWIS weather station and b) bridge at Site 68 in Summit County**

## 6.5 Site 69: Hamilton County, I275 at White Water River

The site was visited at 10:37 AM on January 25, 2005. The sky was clear.

The bridge has a steel understructure and is situated over the White Water River at Mile Marker 21 of I275. The RWIS tower is located at N39°11.078′ W 84°47.495′ with an elevation of 520 ft (158.5 m) above sea level and the temperature of the bridge deck simulator block was 7.2, 8.2, 8.4°C (45.0, 46.8, 47.1°F).

The bridge deck sensors are on southbound lanes. Bridge surface is concrete and the northbound lanes have sensors in asphalt pavement away from bridge. The location of inside edge of the road by the bridge deck sensors is N39°11.076′ W 84°47.547′. The measured temperature of the bridge deck sensor in the passing lane was +3.2°C (37.8°F), while the distance from bridge deck simulator to inside edge of road by bridge deck sensors is 226.5 ft (69.0 m).

The location of the inside edge of the road by pavement sensors is N39°11.076′ W 84°47.477′. The measured temperature of the pavement sensor in the passing lane was 2.2°C (36.0°F), and the distance from bridge deck simulator to the median edge of road by the pavement sensors is 103.6 ft (31.6 m).

Table 8 compares the ORITE measured temperatures to RWIS sensor readings at the same time. Figure 11 shows photographs of the RWIS weather station, bridge, and bridge deck simulator. Of particular note is Figure 11c showing the unusually brownish and rough concrete on the bridge deck simulator.

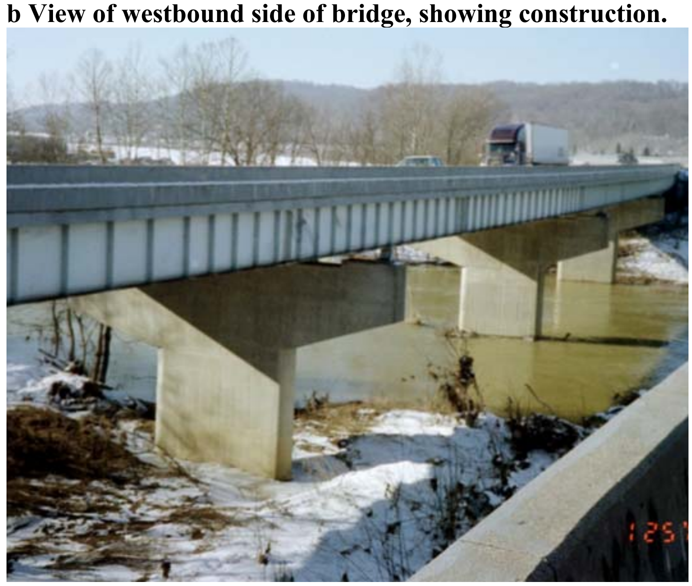
**Table 8. Sensor temperatures for Site 69 in Hamilton County**

| Sensor | ODOT temperature | | ORITE Temperature | | Difference (ODOT-ORITE) | |
|---|---|---|---|---|---|---|
| | (°C) | (°F) | (°C) | (°F) | (C°) | (F°) |
| Air Temperature | -1.5 | 29.3 | Not measured | - | - | - |
| 1-NB Driving | No data | - | - | - | - | - |
| 2-NB Passing | 1.4 | 34.5 | 3.2 | 37.8 | -1.8 | -3.2 |
| 3-SB Passing (B) | 6.2 | 43.2 | 2.2 | 36.0 | 4 | 7.2 |
| 4-SB Driving (B) | 6 | 42.8 | - | - | - | - |
| 5-Bridge Deck Simulator | -2.3 | 27.9 | 7.9 | 46.2 | -10.2 | -18.4 |

**a. RWIS station at Site 69**

**b View of westbound side of bridge, showing construction.**

**c. Close-up of bridge deck simulator, showing brownish color and rough texture of the concrete**



**d. Eastbound side of bridge, including river**

**Figure 11. Pictures of a) RWIS weather tower, b) westbound side of bridge, c) bridge deck simulator, and d) eastbound side of bridge at Site 69 in Hamilton County**

## 6.6 Site 70: Hamilton/Clermont County line on I275

The site was visited at about 10:00 AM on January 25, 2005. The sky was overcast.

The bridge is made of concrete and is situated over the Little Miami River. The RWIS tower is located at N39°14.233′ W 84°17.748′ with an elevation of 634 ft (193.2 m) above sea level. The bridge deck sensors are on the three northbound lanes. The bridge surface is concrete while the three southbound lanes have sensors in the asphalt pavement away from bridge. The location of inside edge of road by bridge deck sensors is N39°14.286′ W 84°17.791′. The temperatures of the bridge deck sensors were -13.5, -15.5, -16°C (56.3, 59.9, and 60.8°F) and the distance from the bridge deck simulator to median edge of road by the bridge deck sensors is 352 ft (107.3 m).

The GPS coordinates of the median edge of road by pavement sensors is N39°14.213′ W 84°17.737′. The temperatures of the pavement sensors were -7.5, -9, -9.5°C (45.5, 48.2, 49.1°F) while the distance from the bridge deck simulator to the median edge of road by the pavement sensors is 148.7 ft (45.3 m).

Table 9 compares the ORITE measured temperatures to RWIS sensor readings at the same time. Figure 12 shows photographs of the RWIS weather station, bridge, and bridge deck simulator. Of particular note is Figure 12c showing the brownish concrete of the bridge deck simulator.

**Table 9. Sensor temperatures for Site 70 at Hamilton/Clermont County line**

| Sensor | ODOT temperature (°C) | ODOT temperature (°F) | ORITE Temperature (°C) | ORITE Temperature (°F) | Difference (ODOT-ORITE) (C°) | Difference (ODOT-ORITE) (F°) |
|---|---|---|---|---|---|---|
| Air Temperature | -1.7 | 28.9 | Not measured | - | - | - |
| 1-NB Driving (B) | 0.6 | 33.1 | -16 | 3.2 | 16.6 | 29.9 |
| 2-NB Center (B) | 1.4 | 34.5 | -15.5 | 4.1 | 16.9 | 30.4 |
| 3-NB Passing (B) | 1.0 | 33.8 | -13.5 | 7.7 | 14.5 | 26.1 |
| 4-SB Passing | 3.5 | 38.3 | -7.5 | 18.5 | 11 | 19.8 |
| 5-SB Center | 0.6 | 33.1 | -9 | 15.8 | 9.6 | 17.3 |
| 6-SB Driving | 0.4 | 32.7 | -9.5 | 14.9 | 9.9 | 17.8 |
| 7-Bridge Deck Simulator | -3.4 | 25.9 | Not measured | - | - | - |

**a. Bridge deck simulator at Site 70 mounted on RWIS station pole.**

**b. View of bridge at Site 70. Note concrete construction**

**c) Close-up of bridge deck simulator showing quality of concrete**

**d) View of pavement sensors in all three southbound lanes of I275**

**Figure 12. Pictures of a) bridge deck simulator on pole, b) bridge, c) bridge deck simulator block, and d) pavement sensors at Site 70 at Hamilton/Clermont County line.**

## 6.7 Site 86: Lorain County, I90 at Black River

The time and date of the site visit was 9:45 AM on February 4, 2005. Sky was clear but not quite sunny. The air temperature was measured at around 37°F (2.8°C) with wind blowing slowly in the southwest direction.

The bridge is on I90 over the Black River and an unidentified two-lane unmarked road (not at SR57, as listed at Buckeye Traffic, which is a couple miles west) and has steel beam construction. The bridge is somewhat exposed; however, there is a cut slope to the west that shades the road, the weather station, and perhaps sometimes the bridge. The bridge surface has an asphalt overlay and the road surface off the bridge is also asphalt.

The bridge deck simulator GPS coordinates are N 41°24.620′, W 82°06.015′ with an elevation of 649 ft (197.8 m) above sea level. A small aggregate was used in the BDS block. The bridge deck simulator is on south side of the pole with the probe cable entering from the rear. The bridge deck simulator temperature was 3.6, +0.2, -0.6°C (38.5, 32.4, 30.9°F) (W, S, E sides respectively) W side was particularly shaded from the sun. The BDS was located at 32.4 ft (9.9 m) from the west end of bridge.

The bridge pavement sensors are located at N 41°24.632′, W 82°06.016′, 104.3 ft (31.8 m) (passing lane) and 216.4 ft (66.0 m) (driving lane) (N 41°24.646′, W 82°06.008′) away from the simulator. The bridge sensors are on the westbound lanes. Observed temperatures were -3.6°C (25.5°F) on the passing lane and -5.0°C (23.0°F) on the driving lane. The pavement sensors on eastbound lanes are at N 41°24.560′, W 82°06.044′ and are 390 ft (118.9 m) from the bridge deck simulator. The observed temperature was -5.0°C (23.0°F).

Table 10 compares the ORITE measured temperatures to RWIS sensor readings at the same time. It should be noted that the eastbound driving lane RWIS reading did not change with the other temperatures over time. Figure 13 shows photographs of the RWIS weather station, bridge deck simulator, and bridge. Of particular note is Figure 13d showing the asphalt overlay on the bridge deck. This was the only site with an asphalt overlay on the bridge. Figure 14 shows two views of the pavement sensors including the road sensors in the shade of the hillside and a closer view of a pavement sensor in the bridge.

**Table 10. Sensor temperatures for Site 86 in Lorain County**

| Sensor | ODOT temperature (°C) | ODOT temperature (°F) | ORITE Temperature (°C) | ORITE Temperature (°F) | Difference (ODOT-ORITE) (C°) | Difference (ODOT-ORITE) (F°) |
|---|---|---|---|---|---|---|
| Air Temperature | -2.1 | 28.2 | 2.8 | 37.0 | -4.9 | -8.8 |
| 1-EB Driving | -6.4* | 20.5 | - | - | - | - |
| 2-EB Passing | -2.2 | 28.0 | 5.0 | 41 | -7.2 | -13.0 |
| 3-WB Passing (B) | 0.0 | 32 | -3.6 | 25.5 | 3.6 | 6.48 |
| 4-WB Driving (B) | 2.0 | 35.6 | -5.0 | 23 | 7 | 12.6 |
| 5-Bridge Deck Simulator | -2.0 | 28.4 | 1.1 | 34.0 | -3.1 | -5.6 |

*Note: The temperature value for Sensor 1 (EB driving lane) was fixed at -6.4°C (20.5°F) from 7:41-10:41 on this date, at which point the temperature jumped 7C° (12.6F°).

**a. View of RPU unit at Site 86 on I90 in Lorain County**

**b. Side rear view of bridge deck simulator at Site 86 showing cable entry from rear.**

**c. I90 bridge over the Black River and a small road at Site 86.**

**d. View of top of bridge on I90 westbound at Site 86 showing asphalt overlay. A pavement sensor can be seen in the middle of the passing lane just ahead of the vehicle in the driving lane**

**Figure 13. Pictures of a) RWIS tower, b) BDS, c) bridge and d) bridge pavement sensor for Site 86 in Lorain County**

a. View of pavement sensor in passing lane of I90 eastbound at Site 86. Note shading from trees on slope to south of road.

b. Pavement sensor on westbound driving lane of the bridge deck at Site 86. The sensor is just left of the top corner of the patch in the asphalt overlay.

**Figure 14. Pictures of pavement sensors in the a) road and b) bridge at Site 86 in Lorain County**

## 6.8 Site 88: Ashtabula County, I90 at SR11

The time and date of visit was 3:45 PM on February 3, 2005. The sky was clear. The air temperature was measured at 39°F (3.9°C) by the truck's thermometer, and winds were blowing slightly in the northwest direction.

The bridge is on SR11 over I90 at mile marker 229 and has steel beam construction. It is extremely exposed with no cover. The bridge surface is concrete and the road surface where the sensors are on I90 is asphalt. The bridge deck simulator location is at N 41°49.728′, W 80°45.945′ with an elevation of 884 ft (269.4 m) above sea level.

The bridge deck simulator is on the south side of the pole with the probe cable entering from the rear. The temperature of the bridge deck simulator was 5.6, 5.8, 4.8°C (42.1, 42.4, 40.6°F) (W, S, E sides respectively) with the sun shining on the east side. The bridge deck simulator is located 106.6 ft (32.5 m) from the north end of bridge.

The bridge pavement sensor is located at N 41°49.702′, W 80°45.934′, 171.5 ft (52.3 m) away from the bridge deck simulator. The bridge sensor is on the southbound passing lane of SR11 overpass. The temperature was around 4.8°C (40.6°F).

There are pavement sensors in all four lanes of I90 just west of the overpass. The pavement sensors on westbound lanes of I90 are at N 41°49.687′, W 80°45.986′, which is about 250 ft (75 m) from the bridge deck simulator, a distance that was estimated because it was not possible to take the GPS unit directly from the sensor pole to the side of I90. The recorded pavement temperature was 4.4°C (39.9°F). The pavement sensors on the eastbound lanes of I90 are at N 41°49.675′, W 80°45.986′, which is about 300 ft (100 m) from simulator. The temperature of the sensor was 3.8°C (38.8°F).

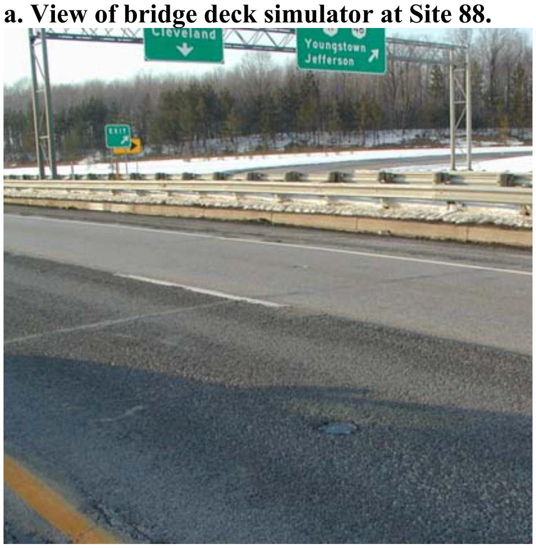
Table 11 compares the ORITE measured temperatures to RWIS sensor readings at the same time. Figure 15 shows photographs of the bridge deck simulator, the bridge, and two of the pavement sensors in I90.

**Table 11. Sensor temperatures for Site 88 in Ashtabula County**

| Sensor | ODOT temperature (°C) | ODOT temperature (°F) | ORITE Temperature (°C) | ORITE Temperature (°F) | Difference (ODOT-ORITE) (C°) | Difference (ODOT-ORITE) (F°) |
|---|---|---|---|---|---|---|
| Air Temperature | 1.3 | 34.3 | 3.9 | 39.0 | -2.6 | -4.7 |
| 1-EB Driving | No data | - | - | - | - | - |
| 2-EB Passing | 7.7 | 45.9 | 3.8 | 38.8 | 3.9 | 7.0 |
| 3-WB Passing | 8.4 | 47.1 | 4.4 | 39.9 | 4 | 7.2 |
| 4-WB Driving | 8 | 46.4 | - | - | - | - |
| 5- SR11 NB Passing (B) | 8.2 | 46.8 | 4.8 | 40.6 | 3.4 | 6.1 |
| 6-Bridge Deck Simulator | 5.8 | 42.4 | 5.7 | 42.3 | 0.1 | 0.2 |

**a. View of bridge deck simulator at Site 88.**

**b. Top view of SR11 southbound bridge over I90.**




**c. view of pavement sensors in westbound lanes of I90**

**d. view under bridge showing construction**

**Figure 15. Pictures of a) bridge deck simulator, b) bridge, c) pavement sensors in I90 westbound lanes, and d) underside of bridge at Site 88 in Ashtabula County.**

## 6.9 Site 91: Portage/Mahoning County line on I76

The time and date of visit was 2:26 PM on February 3, 2005. The sky was overcast with air temperature of 37°F (2.8°C) and winds blowing slowly in the west direction.

The bridge is on I76 over a ravine and a small road at Mile Marker 50 near the Portage/Mahoning County line. It has a steel beam construction and is highly exposed with no cover. The bridge surface is concrete while the road surface is asphalt.

The bridge deck simulator is located at N 41°06.072′, W 81°01.364′ with an elevation of 1023 ft (311.8 m) above sea level. The bridge deck simulator is on the south side of the pole with the probe cable entering from the bottom. The bridge deck simulator temperature was 5.8, 5.8, 5.8°C (42.4°F) (W, S, E sides respectively). The bridge deck simulator is 22.7 ft (6.9 m) from the west end of the bridge.

The bridge pavement sensors are located at N 41°06.067′, W 81°01.338′, at 122.6 and 151.3 ft (37.4 and 46.1 m) away from the simulator. The bridge sensors are on the westbound lanes. The temperature of the bridge sensors was measured at 6.2°C (43.2°F). The pavement sensors on eastbound lanes are at N 41°06.089′, W 81°01.426′, 269.3 and 308.7 ft (82.1 and 94.1 m) from the simulator. The temperature was 7.2°C (45.0°F) in the passing lane.

Table 12 shows the ORITE measured temperatures. No RWIS data were available for this date (February 3, 2005), so no comparison is possible. Figure 16 shows photographs of the RWIS RPU and weather instrument tower, the bridge, the bridge deck simulator, and the pavement sensors.

**Table 12. Sensor temperatures for Site 91 at Portage/Mahoning County line**

| Sensor | ODOT temperature (°C) | ORITE Temperature (°C) | (°F) |
|---|---|---|---|
| Air Temperature | No data | 2.8 | 37 |
| 1-EB Driving | No data | - | - |
| 2-EB Passing | No data | 7.2 | 45.0 |
| 3-WB Passing (B) | No data | 6.2 | 43.2 |
| 4-WB Driving (B) | No data | - | - |
| 5-Bridge Deck Simulator | No data | 5.8 | 42.4 |

**a. View of RPU at Site 91 on I76 near Portage Mahoning County line at approximately mile marker 50.**

**b. View of bridge on I76 at Site 91 showing ravine and road.**

**c. close up of bridge deck simulator**

**d. Research Engineer Sam Khoury making a GPS measurement near the pavement sensor in the passing lane. The sensor in the driving lane is visible in the center of the lane just ahead of the raised pavement marker.**

**Figure 16. Pictures of a) RWIS tower, b) bridge, c) bridge deck simulator, and d) pavement sensors at Site 91 at Portage/Mahoning County line**

# 7 Methodology for data analysis

## 7.1 Reception and preparation of data files

Once the sites were selected and the bridge deck simulators installed, the data collection and processing effort began on January 21, 2005 and lasted through April 5, after the last winter storm during the first weekend of April. Periodically, the ODOT Office of Maintenance Administration data manager would email the research team comma-separated value (csv) files that were generated by Nu Metrics-supplied software. The data files were compiled from the daily Microsoft Access database files and comprised two files for each day from each site. Filenames were coded, for instance "W05_007110104.csv" contained weather data ("W") gathered every 5 minutes ("05") from Site 7 ("007") on November 1, 2004 ("110104"=11/01/04). The weather data included the air temperature and all other weather tower measures, such as humidity, wind speed and direction, dew point, visibility, precipitation rate and type, as well as some site information and the subsurface temperature (where available). The date was given in standard American format (e.g. "11/1/2004") and time in 24 hour units (e.g. 13:47). Data were recorded every 5 minutes, beginning at 00:06 (6 minutes after midnight) and ending at 00:01 (1 minute after the next midnight, but with the previous day's date included), making a total of 288 readings per day. The data were never sorted because these final entries with the incorrect dates would appear at the beginning of each day instead of at the end where they belonged. Even though the temperature readings at 00:01 represent mostly data from the date listed, the date should be incremented to match the actual date of the data report. This would enable anyone using the data, especially multiple days combined, to sort data (e.g. by highest temperature) and then easily resort into a correct chronological order.

Data basically followed the NTSC data dictionary, except the quantitative measures were multiplied by ten. The relevance here is that the temperature data were taken from the NTSC form in the Access database where it was reported in tenths of a degree Celsius, and translated into degrees Celsius in the csv file. The second file had the same filename except it began with the letter Z. This file included the pavement sensor data, including date and time automatically filled in by algorithm, all the traffic data available from the sensor, and the temperature, also in degrees Celsius. Data from each pavement sensor was reported in succession; that is all 288 values from Sensor 1 were followed by the 288 values from Sensor 2 and so on through the last sensor, the bridge deck simulator.

One large Microsoft Excel spreadsheet was created for each site, which combined all the data from each day into one long file covering the 75 days from January 21 through April 5, 2005, a total of 21,588 data points once the spurious entries during the daylight savings change (02:06-03:01 on April 3, 2005) were removed.

For Sites 7 and 9, additional data files from November 1, 2004 through January 19, 2005 were made available; data from January 20 were not available for any site, apparently. The additional data for Sites 7 and 9 comprised another 23,040 data points, which when combined with the previous 75 days would make 44,628 data points, which far exceeded the 32,000 point maximum that Excel allows for plotting relationships. Thus data for Sites 7 and 9 were broken into two portions, one for data through January 19, and the other for the same January 21-April 5 period recorded for the other sites. When nighttime data were extracted from these data files, they were combined so that there is only one data file of nighttime data for each of Sites 7 and 9 since the number of data points was low enough for Excel to handle. Additionally, for Site 7, temperature data beginning very late on November 2 through 18:46 on November 29 were generally static, with values changing once or twice per day, if that; a typical example is shown in Figure 17. In summary, data for all sites run from January 21, 2005 – April 5, 2005, with Site 7 having additional data from 18:46 November 29, 2004 – January 19, 2005 and Site 9 having additional data from November 1, 2004 – January 19, 2005. There are a few additional instances of data files missing for specific sites, for instance February 2-3, 2005 for Site 91. In all instances, the correlation analyses use the data that were available to the researchers. Since the ultimate goal was to relate the temperature of the bridge or pavement to the temperature of the bridge deck simulator at the same time, the continuity in the missing data points is not needed for the analysis.

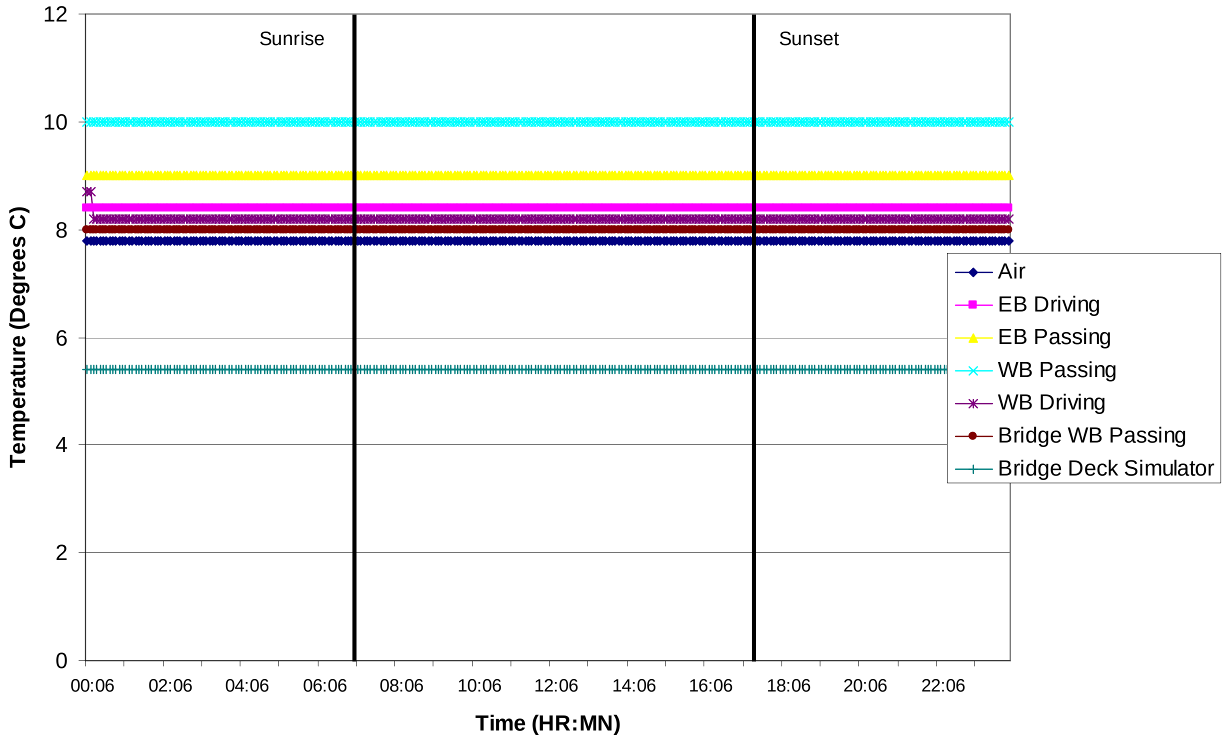



**Figure 17. Temperature data recorded at Site 7, November 3, 2004.**

The pavement sensor temperature data in the “Z” file corresponded to the data in the “W” files, so that in creating the “C” file combining the weather and pavement data in a single spreadsheet, the pavement temperature data were pasted into additional columns, one for each sensor. Additional columns were created to hold the averages of multiple pavement sensors, for instance for the two sensors in the two lanes of a bridge and another for the two sensors in the pavement. While the typical RWIS sensor installation featured a bridge on the main line with two sensors (driving and passing lanes) and two on the pavement off the bridge also in the main line, there were a number of variations from this pattern, such as Site 7 (pavement sensors in each of 4 lanes and one bridge sensor on the main line), Site 9 (one bridge sensor only), Site 68 (two additional pavement sensors on I77), Site 70 (three lanes in each direction), and Site 88 (four pavement sensors on main line, one sensor in the bridge overpass on SR11). These sensor configurations are discussed in Chapter 6.

It became quickly apparent that the behavior of temperature sensors was very different under the influence of solar radiation. Figure 18 shows typical behavior, from Site 7 on January 21. The five pavement sensors fairly closely track each other. The air temperature fluctuates much less; it rises some during the day and goes down at night, while the pavement sensors rise much higher during the day and dip below the air temperatures at night. The maximum daylight temperature difference in the graph is about 15C° (27F°). The bridge deck simulator stays between the pavement sensors and the air temperature during the day, and dips below all the temperatures at night. While some of these differences may reflect consistent (and small) differences in calibration, the main features are the large differences during daylight (the difference in Figure 18 is representative; there was even a small amount of slight snow around midday (10:00-18:00), according to the RWIS precipitation sensor) and the bridge deck simulator situated somewhere between the air temperature and the pavement sensors. Because of this large difference under sunlight, it was decided to examine nighttime data, particularly since solar radiation data were unavailable. In Chapter 10, this question is examined a bit more by looking at solar radiation gathered by RWIS sites in Kentucky and relating to data at the sites in this study nearest to Kentucky. To separate nighttime data, sunrise and astronomical twilight data were gathered from the sunlight-sunset calendar website [20], which presents a calendar for a given month at a given location with times for sunrise, sunset, civil twilight, nautical twilight, and astronomical twilight. Civil, nautical, and astronomical twilight are defined as the times when the sun is at 6, 12, and 18 degrees below the horizon, respectively. Specifically astronomical twilight defines the time at which solar radiation ceases to contribute to sky illumination. Astronomical twilight was typically about 1:35 after sunset; the actual difference would vary by up to 3 minutes from this value depending on the exact date and latitude. Given that there is some time lag for solar radiation to heat pavement and for pavement to cool off after radiation was removed, it was felt that sunrise and astronomical twilight times would best bracket the period when solar radiation had a major influence on pavement temperature, and that nighttime temperatures between astronomical twilight and sunrise would be free of solar influence. In the large data files, the sunrise and astronomical twilight times were marked by underlining those rows whose time best matched the times given by the calendar for that day.

After marking the sunrise and astronomical twilight times, the data were then analyzed by hand to remove temperature anomalies of various types. These are specified in more detail in subsequent sections, but generally included unrealistically high temperatures that appeared, usually only for one five-minute interval, blank data values, values that indicated that for whatever reason a pavement sensor did not successfully report data, and so on. Among the anomalies, it was observed that Site 69 would register an air temperature of around 100°C (212°F) at about 8:16 or 8:21 each morning, but the surrounding temperatures were in the range expected. It was also observed that one of the road pavement sensors consistently read 0 and had to be removed from the analysis. Occasionally extremely high or low (e.g. -40°C (-40°F)) temperatures would appear in data from other sites as well, though not as predictably as for Site 69. Often the last reading of the day, at 00:01 from many sites, and sometimes the last few readings, would be blank, and thus had to be excluded. Otherwise, anomalies were not so predictable, and one had to search for stretches of time where the temperature readings did not change; if this meant a pavement sensor was not reporting, the traffic counts during these periods would be 0, and when the sensor did report, a large cumulative count figure would appear, since the sensor had been programmed to save traffic count data until it could report. It is not known exactly why pavement sensors sometimes fail to report; the typical explanation is some sort of interference with the radio signal to the RPU, perhaps from passing traffic. At any rate, such data had to be excluded from the analysis since it was clear that the pavement sensor temperature was not at that time following the simulator or the air temperature, which did change. There are also times where the RPU could not report data, and in the data files these show up as a series of readings with the time value repeated, e.g. 12:16 is reported as the time every five minutes for an hour and then 13:21 appears with updated data. In these cases, all the data at 12:16 are repeated on each line, and it is clear that the data in the file are not following temperature fluctuations in actual weather. These cases may be due to some sort of interference with the cell phone signal that the RPU uses to send the data to the central server. In an upgraded RPU system, one desirable feature might be to include some internal back up so that an hour or two worth of readings could be backed up in these cases, and then all the data uploaded when the signal can get through; while in these cases up-to-date data may then not be instantly available for immediate maintenance use, the data would then be available in the archives for retrospective analysis. It is not known to the researchers how much of a programming challenge such a system would present. An even better solution to this problem would be a more reliable mode of communication, such as dedicated land phone lines, but the installation and maintenance costs may be prohibitive. A more comprehensive list of these data issues follows in Section 7.3.

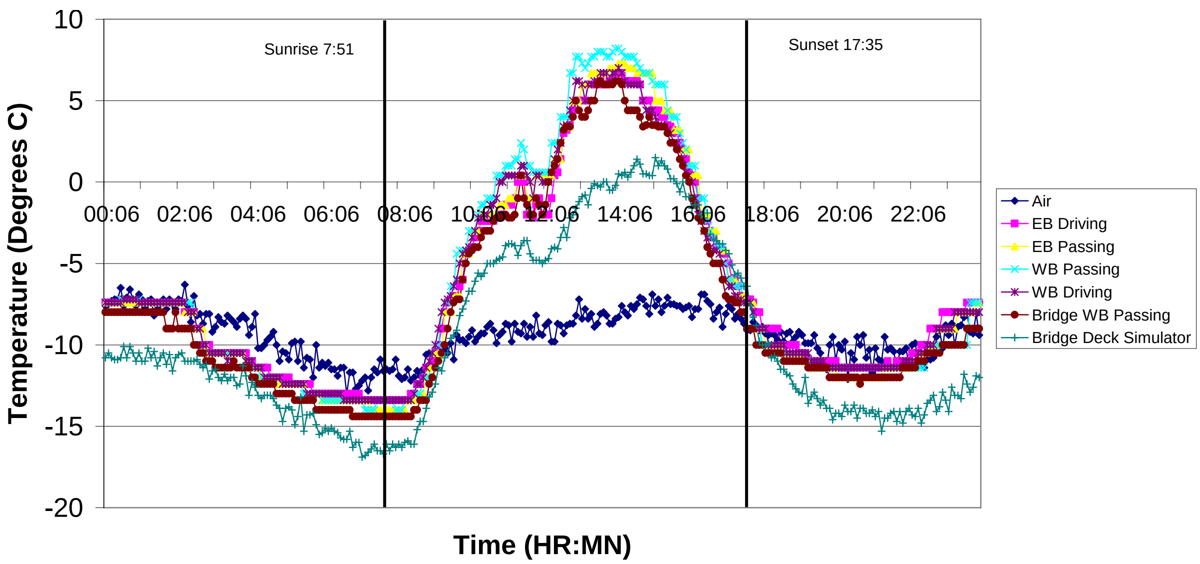



**Figure 18. Temperature data from January 21, 2005 for Site 7, Crawford County.**

## 7.2 Temperature resolution of sensors

A careful examination of the data files shows some of the limits to the temperature resolution of the sensors. It is not known the extent to which these limitations are a result of the design of the sensors and software and how much result from the manufacturing process, but the patterns repeat across different sites, indicating they are built into the equipment. In this study, three different temperature sensors are used at the RWIS sites: air temperature sensors manufactured by Vaisala, bridge deck simulators built by Nu Metrics according to the plans previously shown in Figure 5 and Figure 6 using Vaisala temperature sensors, and the pavement sensors manufactured by Nu Metrics. The following observations were made by studying the patterns in the data. For each site 21,588 at least data points were recorded, and even with the deletions described in the next section, each site had well over 10,000 data points spread unevenly over a range from about -20°C (-4°F) to +40°C (104°F) for pavement sensors and a considerably lower upper limit for air temperatures. In the heart of the temperature range, which was about -10°C (14°F) to +10°C (50°F) there were hundreds of data points in each degree bin, making it extremely unlikely that any missing temperature values noted below are due to chance. These observations are based primarily on a detailed analysis of all-day data from Sites 9 and 59, but were seen to apply to all sites.

### 7.2.1 Air and BDS temperatures

The air and bridge deck simulator (BDS) probes were both manufactured by Vaisala and behaved fairly similarly. The air temperature was reported to the nearest 0.1°C (0.18°F), and no values were seen to not occur. The bridge deck simulator temperature was also reported to the nearest 0.1°C (0.18°F), but every fifth or sixth value was skipped. A sequence of the missing values in BDS temperatures observed for Site 59 included . . . -10.7°C, -10.1°C, -9.6°C, -9.0°C, -8.5°C, -7.9°C, -7.4°C, -6.8°C, -6.2°C, -5.7°C, . . . (. . . 12.74°F, 13.82°F, 14.72°F, 15.80°F, 16.70°F, 17.78°F, 18.68°F, 19.76°F, 20.84°F, 21.74°F, . . . ). The limitation to 0.1°C (0.18°F) in these sensors is consistent with the NTCIP standard, where temperature is reported as an integer in tenths of a degree C.

### 7.2.2 Pavement temperatures

The Nu Metrics pavement sensors embedded in roads and bridges behaved somewhat differently. Again the data were reported to the central server in an NTCIP format and duly converted in values with a tenths place in degrees C (e.g. -10.7°C (12.74°F)), but when correlations of a single pavement sensor, such as the solitary bridge sensors installed at Sites 7, 9, and 88, were made with air or BDS temperatures, horizontal stripes were seen in the graphs where certain values were not observed. By sorting the temperature data, it was quickly seen where these gaps were. A careful study of values recorded on Sites 9 and 59 showed that the recorded and excluded values were the same except for outlying points outside the range of the other site. Table 13 lists all the temperature values observed by the single pavement sensor at Site 9, which was embedded in a bridge. No other values were observed, for instance there were no readings of 0.1°C, 0.2°C, or 0.3°C (32.18°F, 32.36°F, or 32.54°F) because there are no values between 0.0°C (32.0°F) and 0.4°C (32.72°F). These excluded ranges can be as large as 1.6C° (2.88F°), and several are 1.0C° (1.8F°) or more, including particularly the interval just below the freezing point, from -1.0°C (30.2°F) to 0.0°C (32.0°F). Table 14 lists the excluded ranges at least 1.0C° (1.8F°) in size seen at both Sites 9 and 59 (except that the three intervals at the lowest temperatures were not observed at Site 59 because temperatures never were observed that were that low). A quick scan of the other data files did not turn up any individual pavement sensor data points that fell in these excluded ranges, so it can be presumed that these values are somehow built into the system. The absence of these values can be seen as horizontal white streaks in the data clouds in some of the correlation graphs, such as Figure 49, Figure 50, and Figure 53 through Figure 56 for Site 9, which are presented in section 9.2.

**Table 13. Temperature values observed by pavement sensor in bridge at Site 9, Stark County. Original data were given in Celsius. No other values were observed during the entire winter.**

| (°C) | | | | | (°F) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| -22 | -3 | 9.5 | 20.7 | 32 | -7.60 | 26.60 | 49.10 | 69.26 | 89.60 |
| -21 | -2.4 | 10 | 21 | 32.3 | -5.80 | 27.68 | 50.00 | 69.80 | 90.14 |
| -20 | -2.2 | 10.3 | 21.5 | 32.7 | -4.00 | 28.04 | 50.54 | 70.70 | 90.86 |
| -18.4 | -2 | 10.7 | 22 | 33 | -1.12 | 28.40 | 51.26 | 71.60 | 91.40 |
| -18 | -1.4 | 11 | 22.4 | 33.3 | -0.40 | 29.48 | 51.80 | 72.32 | 91.94 |
| -17.4 | -1 | 11.5 | 22.7 | 33.7 | 0.68 | 30.20 | 52.70 | 72.86 | 92.66 |
| -17 | 0 | 12 | 23 | 34 | 1.40 | 32.00 | 53.60 | 73.40 | 93.20 |
| -16.4 | 0.4 | 12.3 | 23.2 | 34.3 | 2.48 | 32.72 | 54.14 | 73.76 | 93.74 |
| -16 | 0.6 | 12.7 | 23.4 | 34.7 | 3.20 | 33.08 | 54.86 | 74.12 | 94.46 |
| -14.4 | 1 | 13 | 23.7 | 35 | 6.08 | 33.80 | 55.40 | 74.66 | 95.00 |
| -14 | 1.4 | 13.3 | 24 | 36 | 6.80 | 34.52 | 55.94 | 75.20 | 96.80 |
| -13.4 | 2 | 13.7 | 24.4 | 36.3 | 7.88 | 35.60 | 56.66 | 75.92 | 97.34 |
| -13 | 2.4 | 14 | 24.7 | 36.7 | 8.60 | 36.32 | 57.20 | 76.46 | 98.06 |
| -12.4 | 3 | 14.3 | 25 | 37 | 9.68 | 37.40 | 57.74 | 77.00 | 98.60 |
| -12 | 3.2 | 14.7 | 26 | 37.5 | 10.40 | 37.76 | 58.46 | 78.80 | 99.50 |
| -11.4 | 3.4 | 15 | 26.4 | 38 | 11.48 | 38.12 | 59.00 | 79.52 | 100.40 |
| -11 | 3.5 | 15.5 | 26.7 | 38.3 | 12.20 | 38.30 | 59.90 | 80.06 | 100.94 |
| -10.5 | 4 | 16 | 27 | 38.5 | 13.10 | 39.20 | 60.80 | 80.60 | 101.30 |
| -10 | 4.4 | 16.3 | 27.4 | 38.7 | 14.00 | 39.92 | 61.34 | 81.32 | 101.66 |
| -9 | 5 | 16.7 | 27.7 | 39 | 15.80 | 41.00 | 62.06 | 81.86 | 102.20 |
| -8 | 6 | 17 | 28 | 39.5 | 17.60 | 42.80 | 62.60 | 82.40 | 103.10 |
| -7.4 | 6.2 | 17.3 | 28.2 | 40 | 18.68 | 43.16 | 63.14 | 82.76 | 104.00 |
| -7.2 | 6.7 | 17.7 | 28.5 | 40.5 | 19.04 | 44.06 | 63.86 | 83.30 | 104.90 |
| -7 | 7 | 18 | 28.7 | 41 | 19.40 | 44.60 | 64.40 | 83.66 | 105.80 |
| -6.4 | 7.3 | 18.2 | 29 | 42 | 20.48 | 45.14 | 64.76 | 84.20 | 107.60 |
| -6 | 7.7 | 18.4 | 29.3 | 42.5 | 21.20 | 45.86 | 65.12 | 84.74 | 108.50 |
| -5 | 8 | 18.7 | 29.7 | 43 | 23.00 | 46.40 | 65.66 | 85.46 | 109.40 |
| -4.4 | 8.2 | 19 | 30 | 43.3 | 24.08 | 46.76 | 66.20 | 86.00 | 109.94 |
| -4.2 | 8.4 | 19.5 | 30.5 | 43.7 | 24.44 | 47.12 | 67.10 | 86.90 | 110.66 |
| -4 | 8.7 | 20 | 31 | 44 | 24.80 | 47.66 | 68.00 | 87.80 | 111.20 |
| -3.4 | 9 | 20.3 | 31.5 | 44.3 | 25.88 | 48.20 | 68.54 | 88.70 | 111.74 |

**Table 14. Excluded ranges of temperature larger than 1.0C° (1.8F°) observed at Site 9 and at Site 59. Ranges at temperatures below -16°C (3.2°F) were seen at Site 9 only as temperatures did not go down that far at Site 59**

| lower (°C) | upper (°C) | lower (°F) | upper (°F) |
|---|---|---|---|
| -22 | -21 | -7.60 | -5.80 |
| -21 | -20 | -5.80 | -4.00 |
| -20 | -18.4 | -4.00 | -1.12 |
| -16 | -14.4 | 3.20 | 6.08 |
| -10 | -9 | 14.00 | 15.80 |
| -9 | -8 | 15.80 | 17.60 |
| -6 | -5 | 21.20 | 23.00 |
| -1 | 0 | 30.20 | 32.00 |
| 5 | 6 | 41.00 | 42.80 |
| 25 | 26 | 77.00 | 78.80 |
| 35 | 36 | 95.00 | 96.80 |
| 41 | 42 | 105.80 | 107.60 |

## 7.3 Criteria for deletion of data anomalies

As indicated above, there were some anomalies in the data that indicated that the pavement or air temperature was either not being updated in a timely manner or otherwise clearly did not reflect actual conditions. A large amount of labor was involved in eliminating these data from the analysis so that the correlation analysis would reflect legitimate relationships between air, bridge deck simulator, bridge deck, and pavement temperatures. The data handling process for the assembled "C" data files, once all the weather and pavement data from each day had been combined into one large data file for each site, went as follows in these instructions to the members of the research team actually analyzing the data.

Data anomalies were to be identified and handled in the following order:

1. Daylight Savings Time changeover: The redundant entries for 2:01 AM on Sunday, April 3, 2005, were deleted. The first one was kept as it is an actual reading.

At this point, astronomical twilight (evening) and sunrise were marked on the air temperature record by adding a border where that time occurred. Then the individual air temperature data worksheet was copied to a new worksheet marked "All" and the temperature columns for each sensor in numerical order were added. From now on, deleted lines of data were copied to a deleted data worksheet.

2. Missing temperatures for air and bridge deck simulator: The air and bridge deck simulator were generally the most reliable of the temperature sensors. If either the air temperature or the bridge deck simulator (BDS) temperature was blank, or both were blank, then the line was moved to the deleted data worksheet. Researchers were instructed to resist the temptation to sort the data so the blanks rise to the top because that would scramble the data at the 0:01 time each day (which had the previous day's date on it because of a bug in the program that was used to extract the data from ODOT's database). This kept the data points in order, but not being able to sort and resort data made data processing time consuming.

At this point one should be able to make correlation graphs such as road sensor versus air temperature or road sensor versus BDS temperature. If they looked more like sine waves than like a cloud or diagonal line of points, then it was necessary to find some more missing air and/or BDS temperatures as above.

3. Extreme temperatures for air or bridge deck simulator. If the temperature was extremely high (e.g. 100.1°C or -40°C), it was assumed to be bogus. The criterion applied was if one of these temperatures jumped up or down by more than 10°C and changes back to about the original limit after one or two readings (more if there is repeating time, discussed below), and most of the other sensors did not follow suit. The line was moved to the deleted data worksheet. These points were obvious on a time series plot – one could put the cursor over the point in question and identify temperature value in question, then search for it on the worksheet with the data, verify that it meets the criterion involved, and move the line to the deleted data worksheet.
4. Repeating time. Sometimes the weather and air temperature data would repeat from the previous line. In this case the time will be unchanged, creating duplicate readings. The first line was kept and the others moved (sometimes there was one, sometimes there were several) to the deleted data worksheet.

Now the "All" worksheet was copied to an "all night" worksheet and the daytime data deleted from the new worksheet.

Researchers then identified the road sensors and bridge sensors and copied all the "All" data into two more sheets, one for road data and one for bridge data. For each sheet, the following was conducted:

5. Check for non-functioning sensors. Typically such a sensor would either repeat data or report 0 or blanks over the entire period of observation or close to it. In this case this sensor was ignored and work continued with the data for the other sensor. The average road or average bridge temperature was adjusted to not exclude the nonreporting sensor.

The following kinds of data were moved to the deleted data page. Researchers were instructed to insert a line or row on the deleted data worksheet identifying where road deleted sensor data began and then one where deleted bridge data began. These steps were followed first for the road sensors on the road data work sheet and then for the bridge sensors on bridge data worksheet and for night and day data.

6. Blank temperatures in road or bridge sensors (whichever one was under consideration at the time). Data were moved to deleted data worksheet.
7. Extreme temperatures in road or bridge sensors. Same criteria as Step 3. Data were moved to deleted data worksheet.
8. Repeating data I. The pavement sensor temperature readings tended to fluctuate less than those for the air temperature and bridge deck simulators. However the pavement sensors often got into a mode where they repeated the same data for a long time when they should change. If one road or bridge sensor varied while the other was repeating the same value for more than 5 times, then researchers were instructed to delete all but the first reading and move the rest to the deleted data worksheet. Another clue used was if the temperature difference between the repeating data sensor and the other exceeds 4C° (7.2F°).
9. Repeating data II. Another clue was if the data repeated five or more times and the traffic count for the suspect sensor was zero (on the traffic data in the "sensor X" worksheet) while the data repeat. After all the zero traffic counts, there would be a high count, which

could be as high as over 1000 vehicles if the situation was maintained for hours. If one sensor had zero traffic while the other was reading regular traffic, then the lines were moved to the deleted data worksheet. If both sensors were reading zero traffic for an extended period, a check against the other sensors was made (road sensors if working with bridge sensor data and vice versa) to see if there was traffic. Researchers were advised to move the questionable data if there was traffic on the other sensors. Though researchers also checked the time – if it was 3 AM then it was reasonably possible that there was low traffic on the road, especially on a passing lane or a ramp, whereas if it was closer to 3PM and there were zero traffic readings then it is likely the sensor is not reporting new data and the data should be removed. Note that one cannot tell from the data file if there was a lane closure; researchers worked on the assumption that there were no closures, and if there were, they were brief enough to not materially affect the project.

Thus the final data files typically included separate worksheets for nighttime and 24-hour versions of data from each set of pavement sensors, that is a pair of worksheets for road pavement sensors and another pair for bridge pavement sensors, and even a third in the case of Site 68 for the sensors on I77. Data for all sensors were in each pair of sheets, but only the data for the indicated sensors and the air and BDS temperatures were considered in eliminating data from that sheet. This was because during a time when data were problematic for the road sensors, the data from the bridge sensors may have been fine. These various data sheets then served as the foundations for the correlation analysis.

Two sets of graphs were made for each site, time series plots and correlations. These are discussed in Chapter 8 and Chapter 9, respectively.

# 8 Time Series Graphs

The time series graph consists of temperature for the entire period of the experiment plotted as a line graph. When all the data are plotted, they show the temperature fluctuations as a function of time. Time series graphs were made for average bridge sensor temperatures with air and bridge deck simulator temperatures, and for average road sensor temperatures with air and bridge deck simulator temperatures. Since air and bridge deck simulator temperatures are present on all graphs, their presence will be assumed in the descriptions as follows. Similar graphs were made containing nighttime data only. Some of these sites, including the example site below, Site 7 road data, had individual sensor data plotted in addition to average values. In some cases, Sites 7, 9, and 88 bridge sensors and Site 69 road sensors there was only one sensor recording temperature and thus the average was that sensor value.

The time series were useful for getting an overview of the temperature fluctuations, particularly their ranges, the presence of anomalies, and sustained discrepancies between sensors. When all 75 days of data are plotted in one graph, it can be hard to pick out a single day and get a detailed view, though the daytime peaks are clearly visible when daytime data are included. Site 7 is presented as an example, and time series graphs for the other sites are included in Electronic Appendix A, presented in electronic form.

## 8.1 Example: Site 7 Crawford County

A complete set of time series is presented for Site 7 on US30 in Crawford County. As previously described in Section 6.1, there are four road sensors and one bridge sensor, all on US30.

### 8.1.1 Bridge sensor time series graphs

Figure 19 shows a plot of all the raw temperature data for the solitary bridge sensor, and Figure 20 shows the same data, but modified to exclude problem data points using the procedure outlined in Section 7.3. In Figure 19, the equal number of points per day is used to set the tick marks on the horizontal axis for the same point each day and the category labels ("18:46") placed every fifth day. The category labels and tick marks are placed at 18:46 because the data begin at 18:46 on November 29, 2004. Some problematic data points are clearly visible in Figure 19, such as those that are above or below the top or bottom of the graph. Because the data reduction procedure removes certain data points, it is no longer possible in Excel to place tick marks at the same location each day and the category labels in Figure 20 are those selected by the program. The tick marks are actually placed at each value (every five minutes) and are so dense as to make a thick horizontal axis. That said, the peaks in Figure 20 and in other full day time series graphs still indicate each day, assuming the percentage of good data points retained in the graphs is high; in the case of Site 7 bridge data shown in Figure 20 this percentage is over 97%. Similar graphs for the period January 21-April 5 are shown in Figure 21 (raw data) and Figure 22 (modified data). On the raw data graph in Figure 21, the category labels are at 00:06 because the data begin at 00:06 on January 21. Modified nighttime only data are graphed in Figure 23. The daily peaks largely disappear. Also tick marks and category labels follow the Excel defaults since the number of data points per day varies, both because the length of night time changes during the study period and because some data points have been removed. The nighttime data cover the full range from November 29, 2004 – April 5, 2005, since the number of nighttime data points was less than the maximum that Excel would plot.

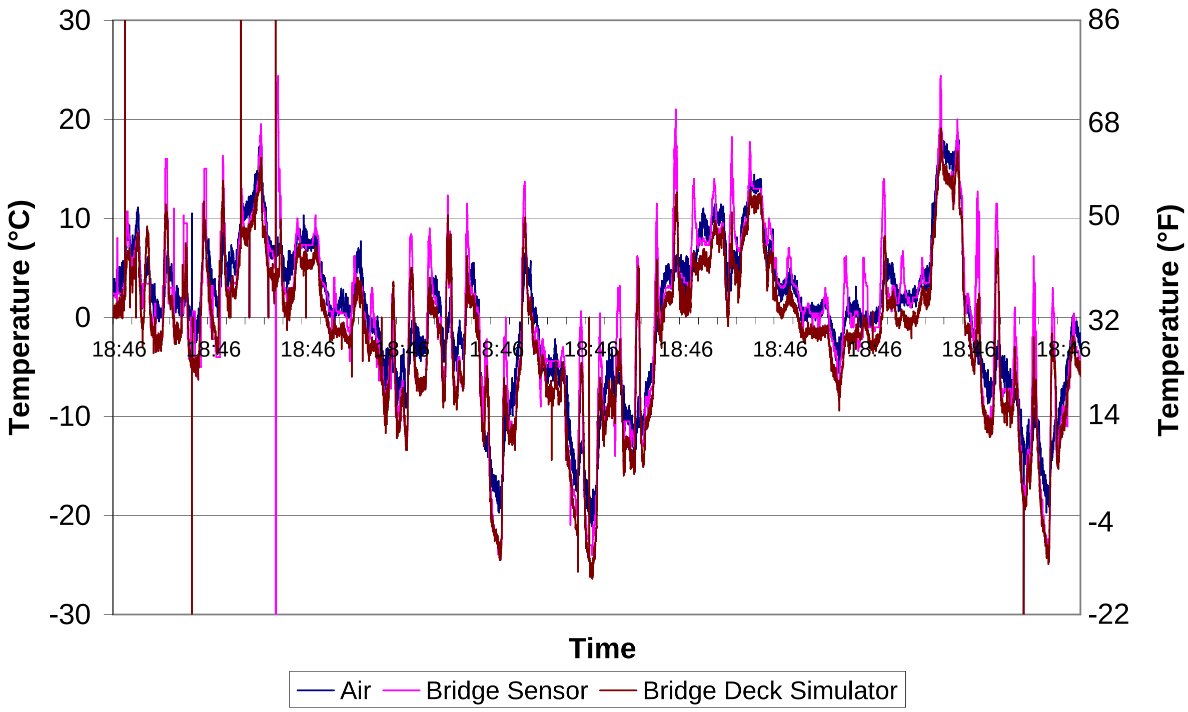



**Figure 19. Time series graph with full day raw data for Site 7 US 30 Crawford County bridge sensor November 29, 2004 - Jan19, 2005.**

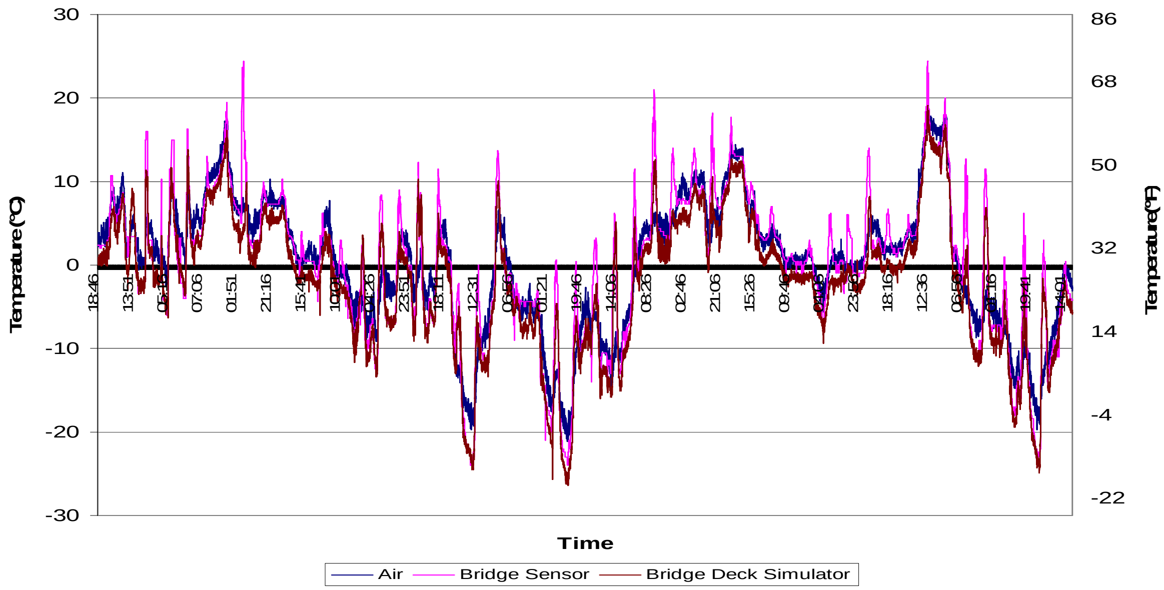



**Figure 20. Time series graph with full day modified data for Site 7 US 30 Crawford County bridge sensor November 29, 2004-January 19, 2005.**

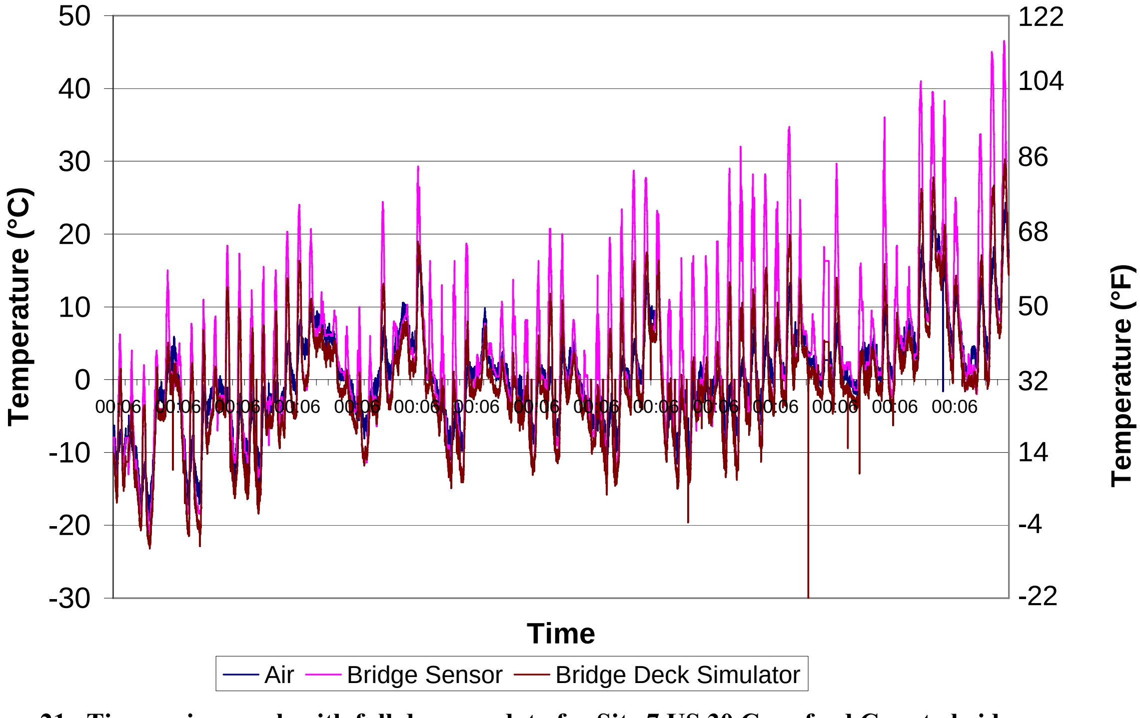



**Figure 21. Time series graph with full day raw data for Site 7 US 30 Crawford County bridge sensor January 21-April 5, 2005**

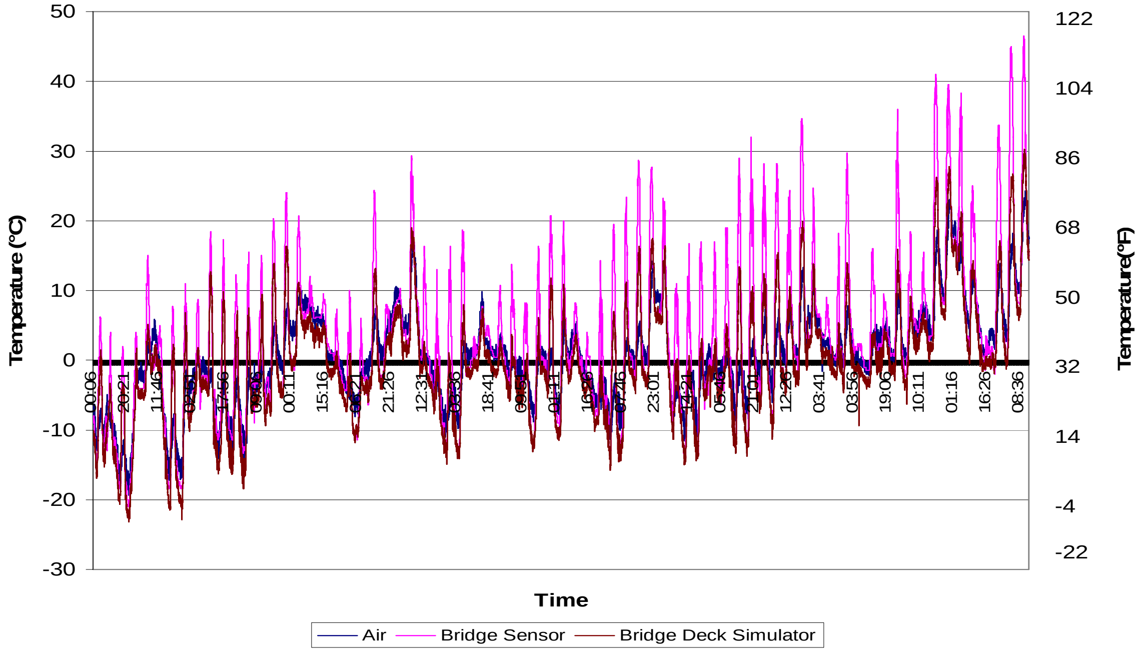



**Figure 22. Time series graph with full day modified data for Site 7 US 30 Crawford County bridge sensor January 21-April 5, 2005.**

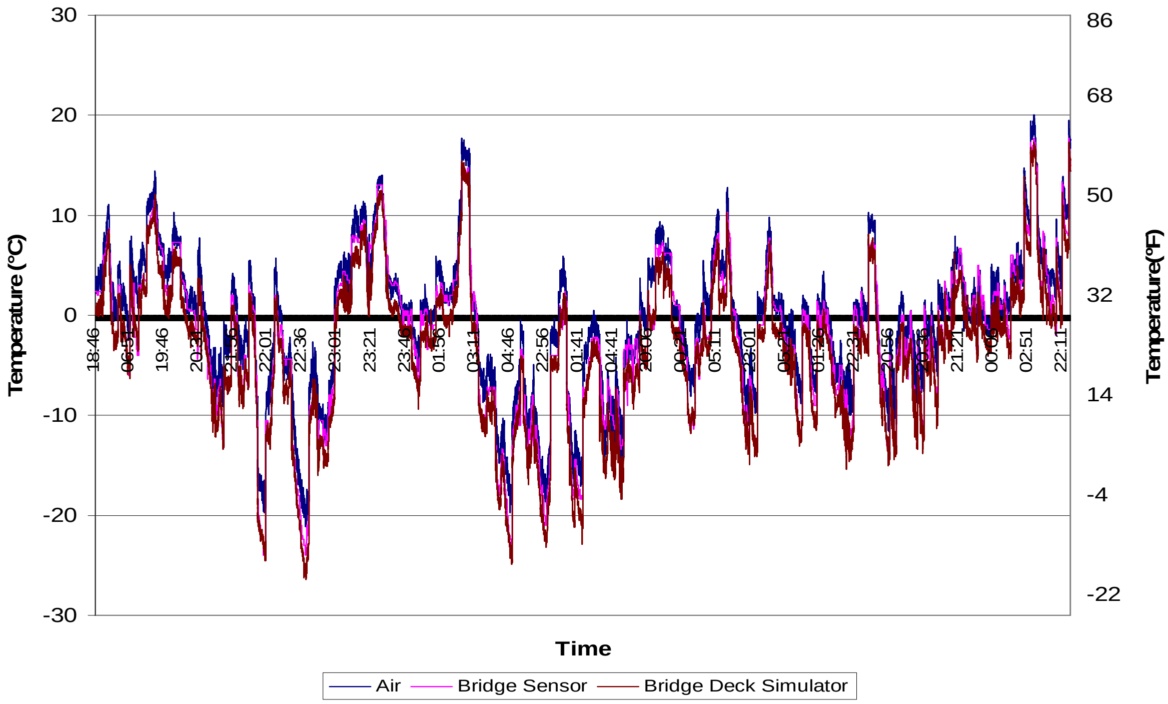



**Figure 23. Time series graph of nighttime modified data for Site 7 US 30 Crawford County bridge sensor November 29, 2004-January 19, 2005**

## 8.1.2 Road sensor time series graphs

Time series graphs for the four road sensors on US30 at Site 7 are presented here. Figure 24 shows the raw average road sensor data for November 29, 2004 through January 19, 2005, and

Figure 25 shows the modified data set from the same period of time. Figure 26 and Figure 27 show the raw and modified average road sensor data for the January 21-April 5, 2004 period. The same general comments as before apply, for instance the horizontal axes on the raw data have one tick mark per day, at 18:46 for the November 29, 2004 – January 19, 2005 period and at 00:06 for the January 21-April 5, 2005 period. Category labels in the raw data graphs appear every fifth day. Tick marks on modified data appear every 5 minutes and category labels are somewhat arbitrary there since some of the data were removed. Figure 28, Figure 29, Figure 30, and Figure 31 represent the same data as Figure 24, Figure 25 Figure 26, and Figure 27, respectively, except the data for all four road sensors are plotted instead of the average of the four values. In Figure 28, Sensor 2 can be seen to deviate noticeably from the other sensors, particularly towards the right-hand side of the graph. However these discrepancies are taken care of in the modified data in Figure 29, and they appear to be absent in the latter part of the raw data set, shown in Figure 30. Figure 32 shows the modified nighttime time series data for all the road sensors. Similar graphs for other sites are in Electronic Appendix A.

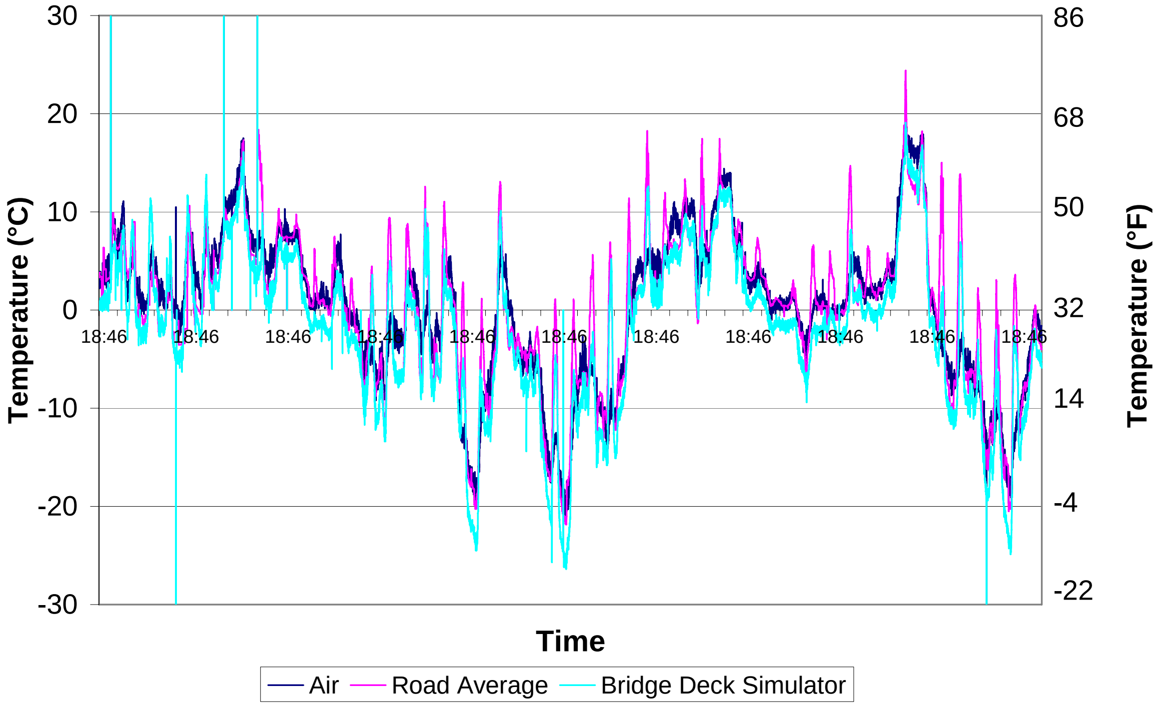



**Figure 24. Time series graph with average full day raw data for Site 7 US 30 Crawford County road sensor November 29, 2004-January 19, 2005**

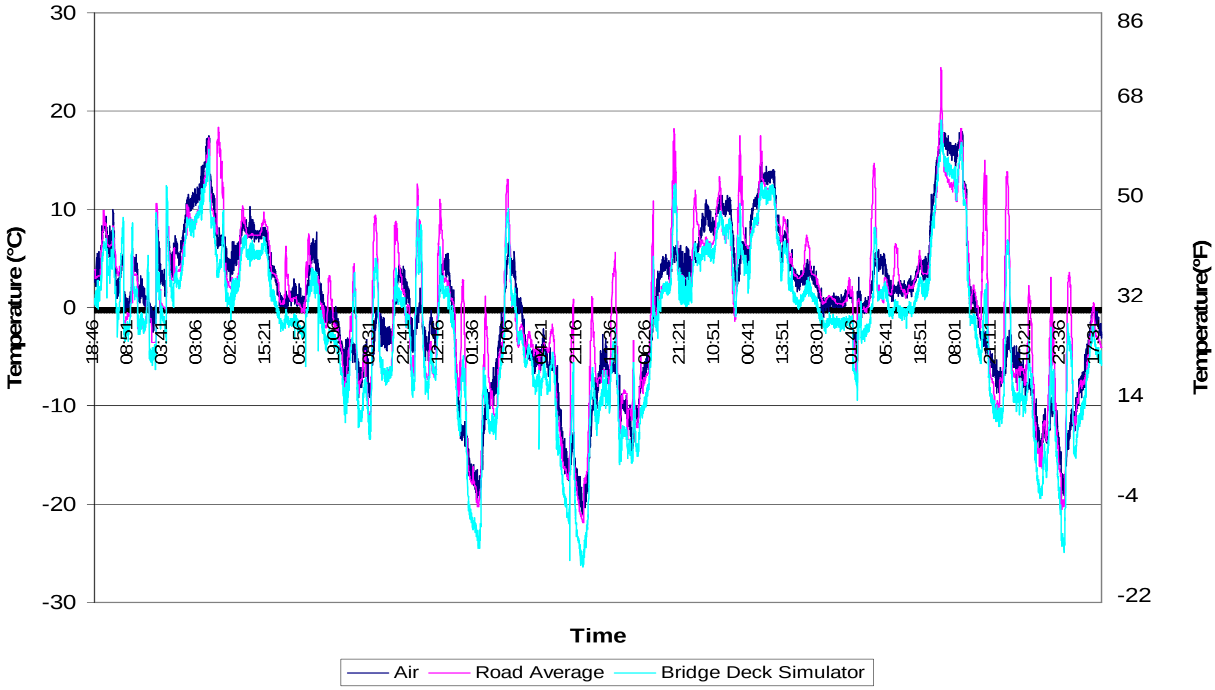



**Figure 25. Time series graph with average full day modified data for Site 7 US 30 Crawford County road sensor November 29, 2004-January 19, 2005**

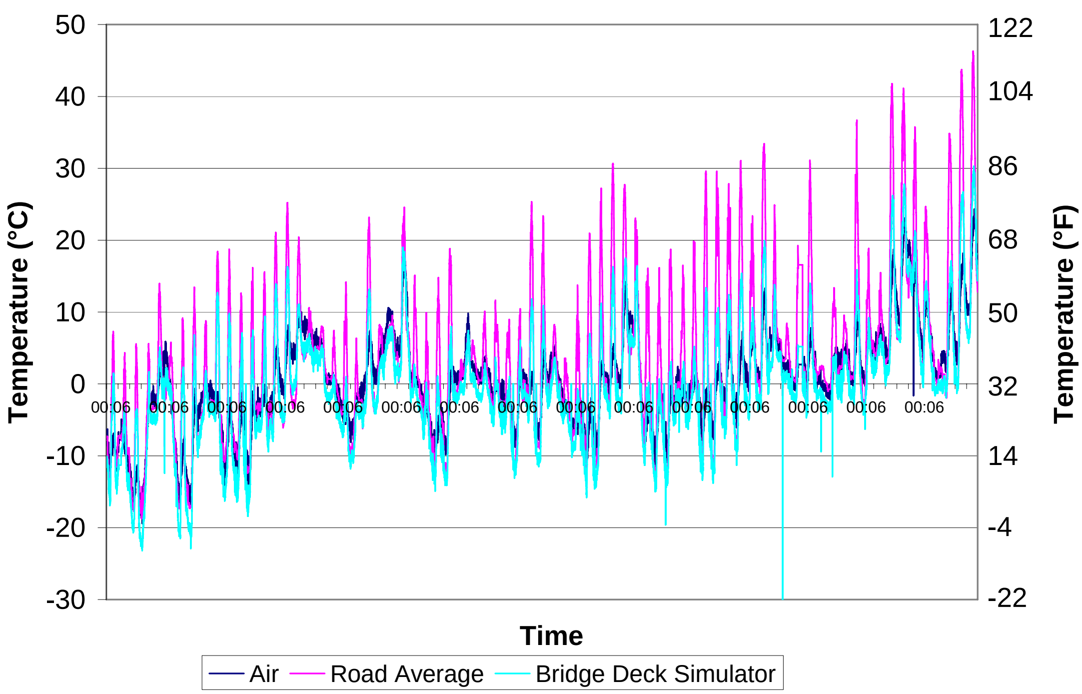



**Figure 26. Time series graph with average full day raw data for Site 7 US 30 Crawford County road sensor January 21-April 5, 2005**

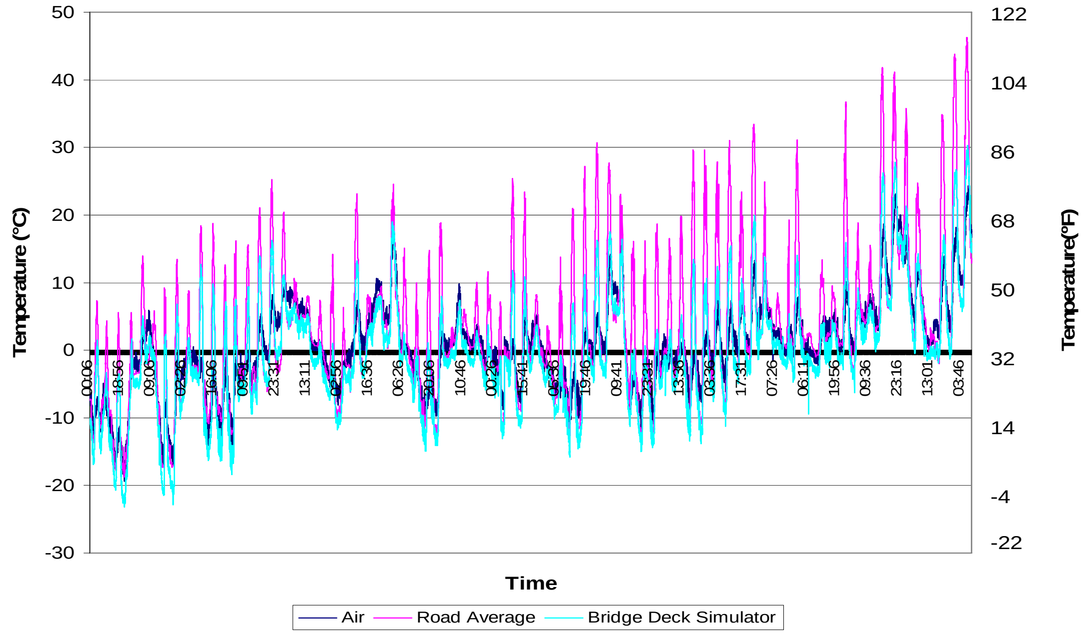



**Figure 27. Time series graph with average full day modified data for Site 7 US 30 Crawford County bridge sensor January 21-April 5, 2005**

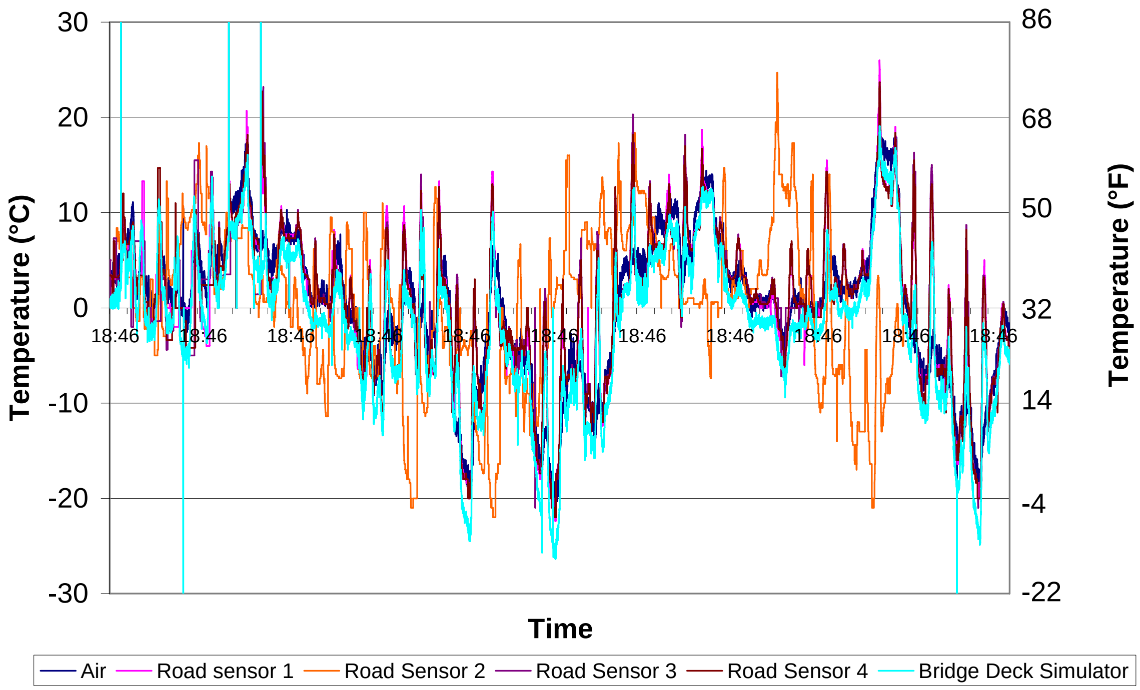



**Figure 28. Time series graph with full day raw data of all road sensors for Site 7 US 30 Crawford County November 29, 2004- January 19, 2005**

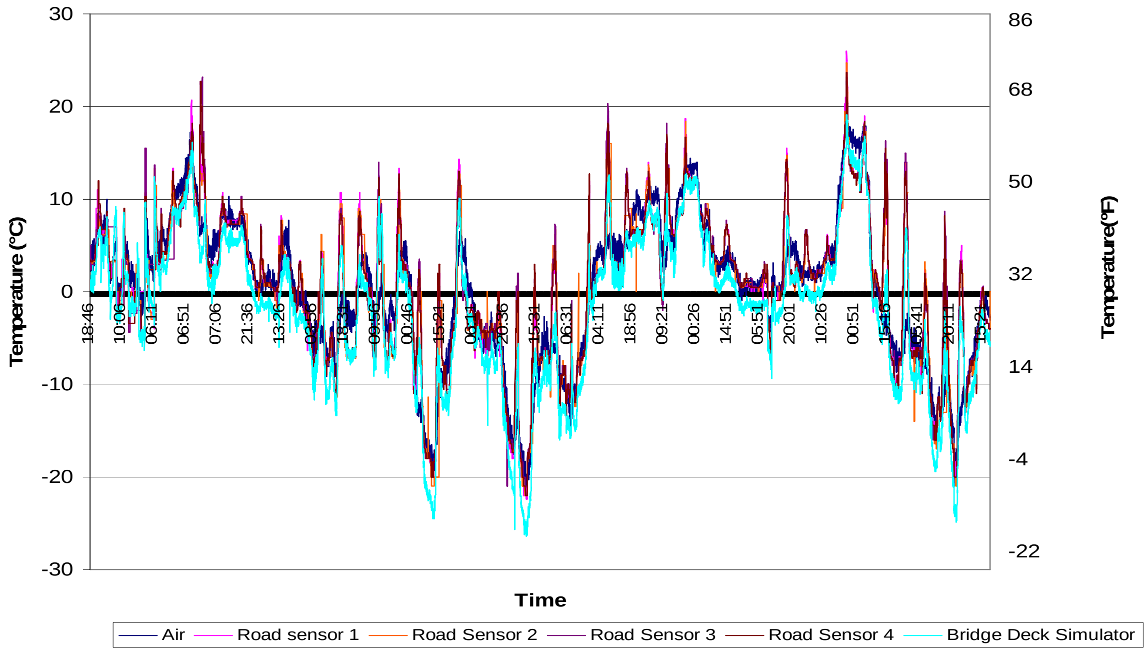



**Figure 29. Time series graph with modified full day data of all four road sensors for Site 7 US 30 Crawford County November 29, 2004- January 19, 2005**

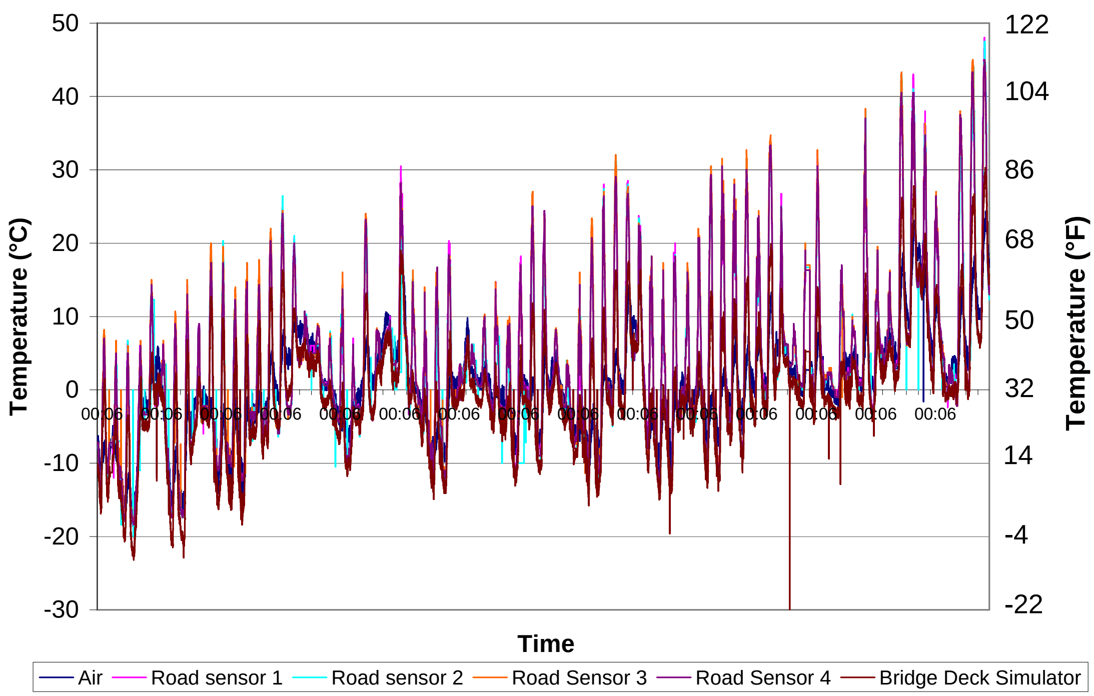



**Figure 30. Time series graph with full day raw data of all four road sensors for Site 7 US 30 Crawford County January 21-April 5, 2005**

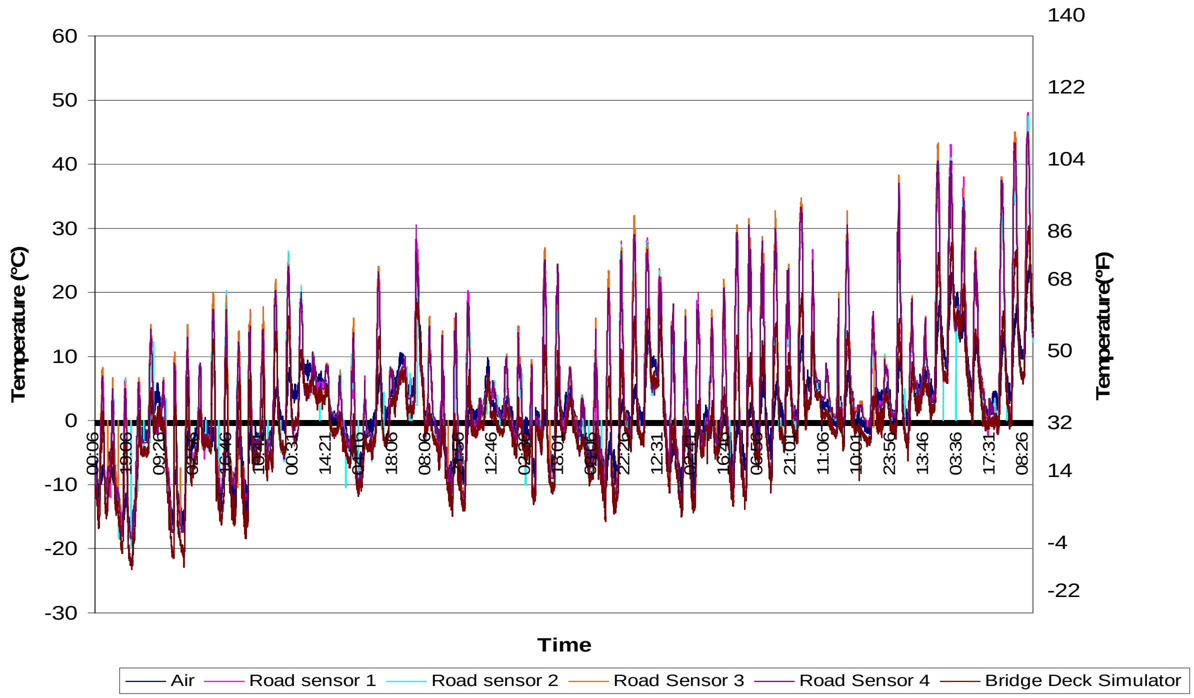



**Figure 31. Time series graph with full day modified data of all four road sensors for Site 7 US 30 Crawford County January 21-April 5, 2005**

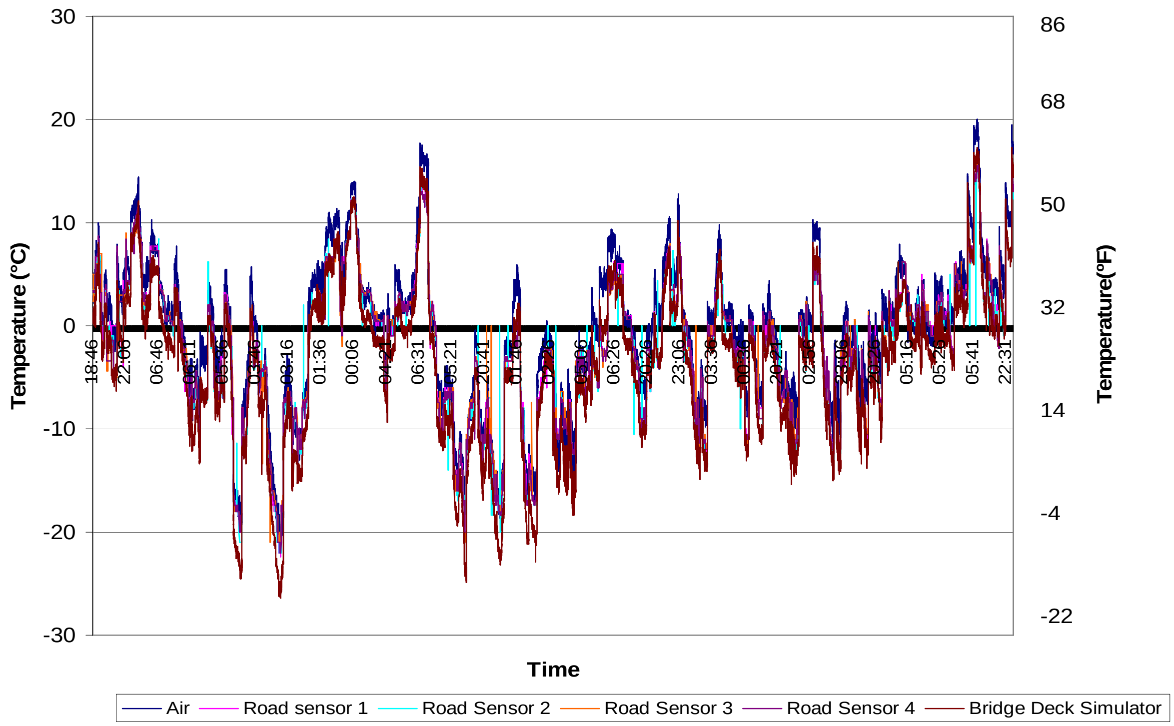



**Figure 32. Time series graph with modified nighttime data of all four road sensors for Site 7 US 30 Crawford County November 29, 2004- April 5, 2005**

# 9 Correlation results

The correlation analysis proceeded as follows. Where there was more than one regularly functioning pavement sensor in the bridge or road, the values from these sensors were averaged; else the single functioning sensor was used to represent the bridge or road temperatures. Since Site 68 had road sensors on two different roads (I271 and I77), these were averaged separately. Then the following temperatures were correlated for each site: Air and bridge deck simulator (BDS), bridge and air, bridge and BDS, road and air, road and bridge. These were performed on nighttime data sets, and then on full day data sets. For Sites 7 and 9, the full day data were broken into two pieces, the first ending on January 19, 2005, and the second containing the January 21, 2005-April 5, 2005 period used at all other sites; no data were recorded for January 20 at any of the sites. Nighttime data for Sites 7 and 9 included one graph for the full range of dates.

These correlations were performed on the reduced data sets after processing as described previously in Chapter 7. One temperature was plotted against the other, both in Celsius, and Excel's line fit option used to generate a line fit and correlation coefficient $R^2$. A standard error value in Celsius was computed using the STEYX function. In the following, the correlation graphs are presented for each site in the order described in the previous paragraph, with additional axis labels in Fahrenheit. In the graphs, the fit equations are for both temperatures in Celsius. Then after all the graphs, the line fit parameters are presented for all the sites in summary tables for nighttime and daytime data in both Celsius and Fahrenheit. Averages and standard deviations for all the fit parameters across all sites are also presented.

Each correlation graph is set up as follows. The horizontal axis indicates the "independent" variable, for instance in Figure 33 it is the air temperature. The title for this axis in metric units (Celsius, or °C) is at the bottom of the graph and the corresponding labels on the axis are underneath the axis, which is at the center of the graph. The corresponding Fahrenheit (°F) title is at the top of the graph and the Fahrenheit labels are above the horizontal axis. These are actually numerals in boxes placed at the tick marks with the conversion of the corresponding Celsius value underneath. Similarly the independent variable, bridge deck simulator temperature in Celsius (°C) in Figure 33, has a label running vertically along the left edge of the graph. The corresponding axis labels are to the right of the vertical axis at the center of the graph. The Fahrenheit (°F) title runs along the right hand edge and the axis labels are on the right side of the vertical axis at the tick marks. In general, the axis title runs parallel to the axis it goes with, and the numerical labels that go with the title are on the same side of the axis as the corresponding title.

## 9.1 Site 7 Crawford County

### 9.1.1 Night Time Correlation Graphs

Figure 33 shows the correlation between the air temperature and the bridge deck simulator (BDS) temperature for Site 7 in Crawford County. Figure 34 and Figure 35 respectively show the correlations of the air and BDS temperatures with the single bridge sensor temperature. The horizontal striping occurs because the Nu Metrics pavement sensors report only certain temperature values and exclude others. Figure 36 and Figure 37 respectively show the correlations of the air and BDS temperature with the average of temperatures of the four road sensors. The averaging smears out the striping effect noted for the bridge sensor graphs.

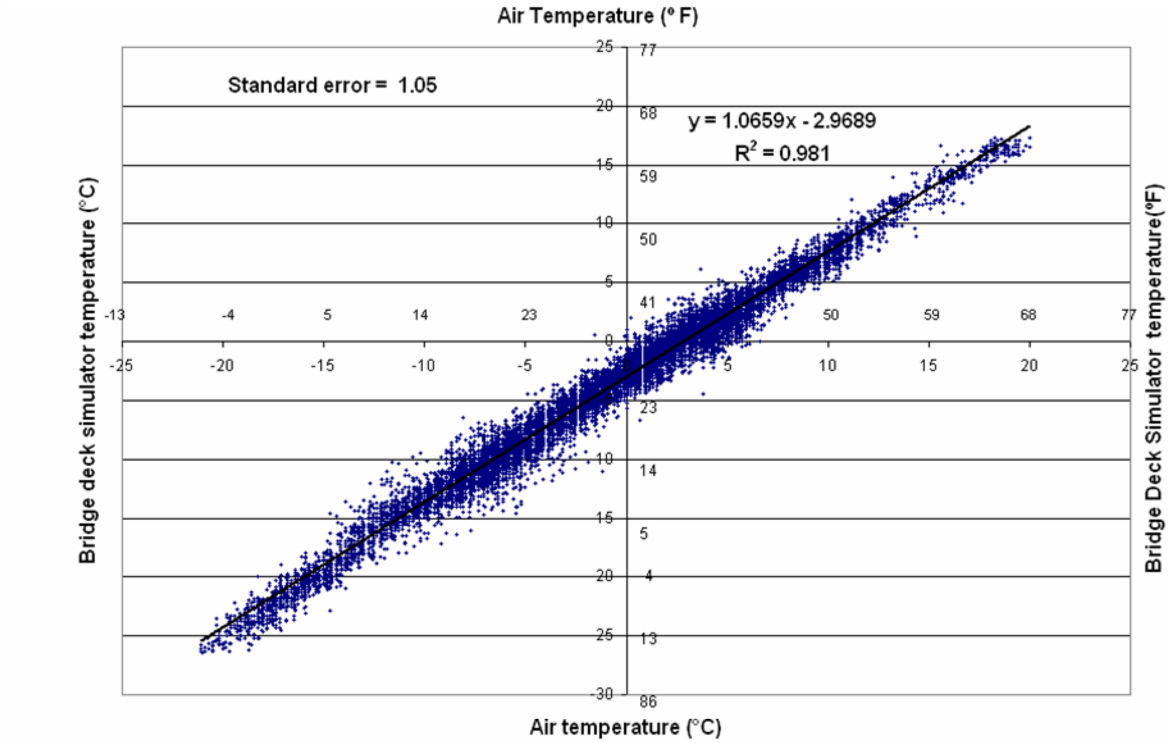



**Figure 33. Air versus BDS nighttime temperature correlation graph for Site 7 US 30 Crawford County, November 29, 2004 - April 5, 2005**

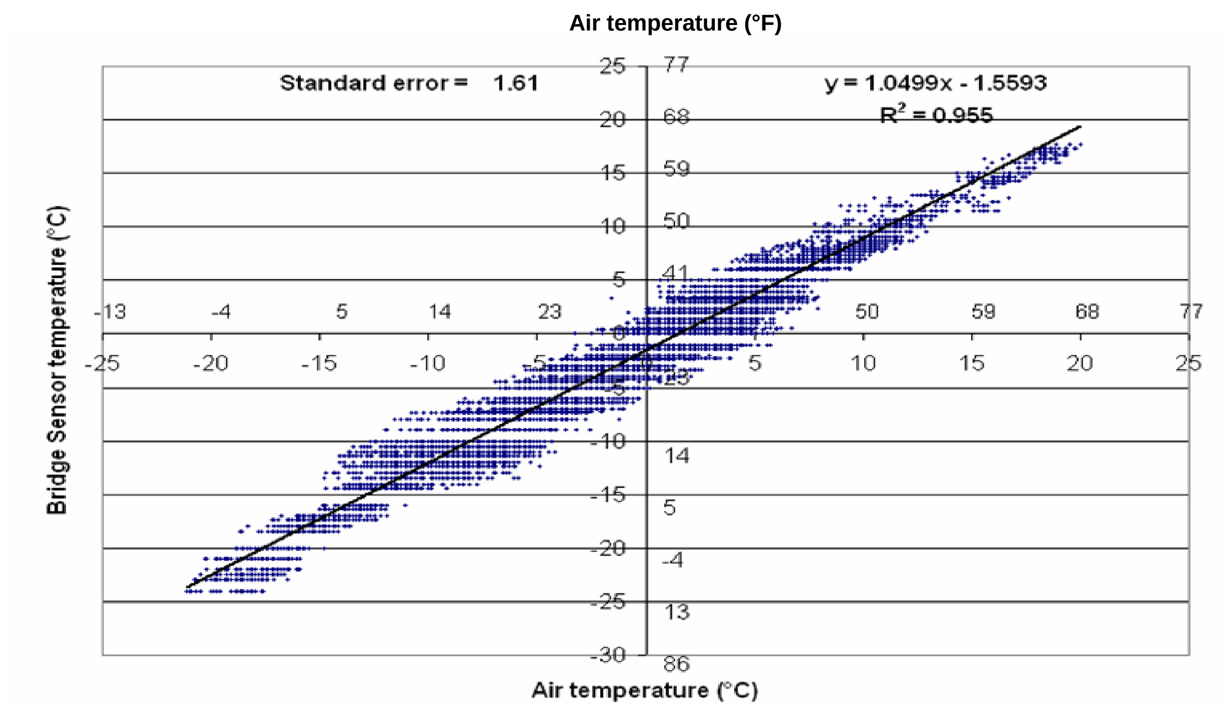



**Figure 34. Air versus bridge nighttime temperature correlation graph for Site 7 US 30 Crawford County, November 29, 2004 - April 5, 2005**

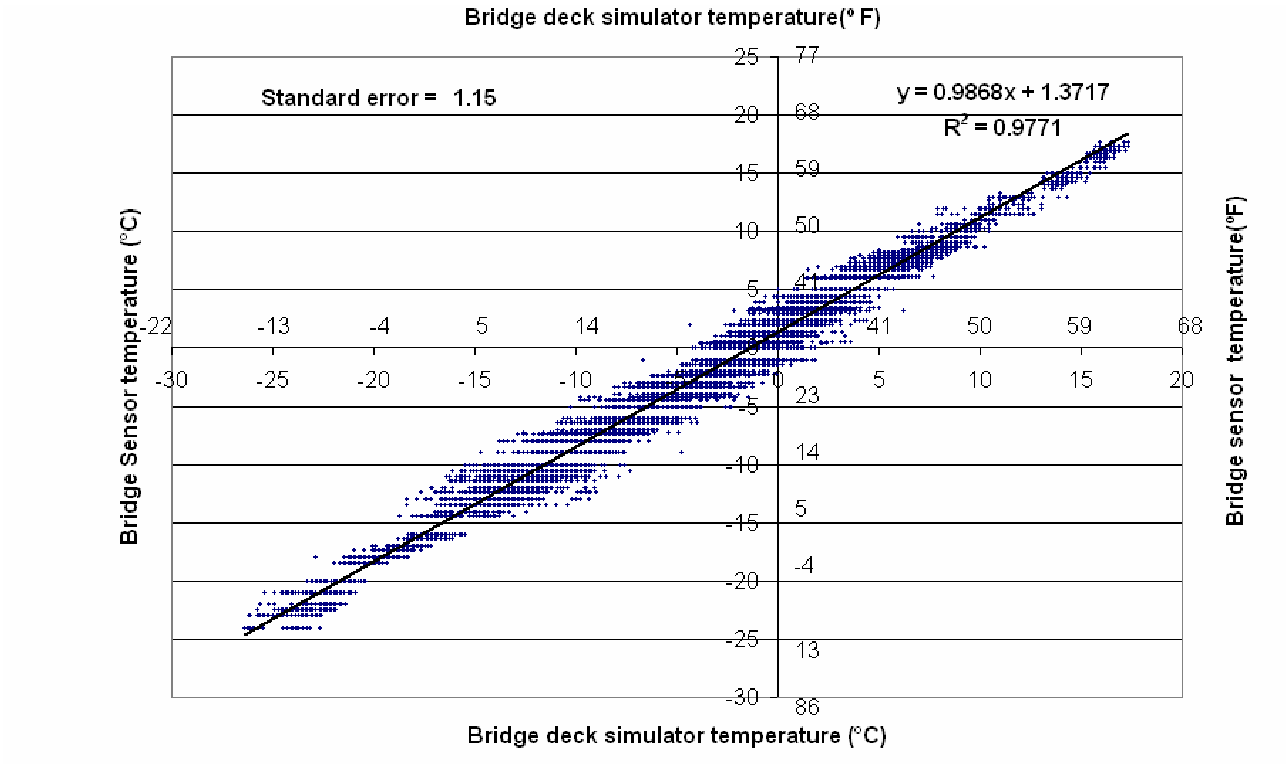



Figure 35. BDS versus bridge nighttime temperature correlation graph for Site 7 US 30 Crawford County, November 29, 2004- April 5, 2005

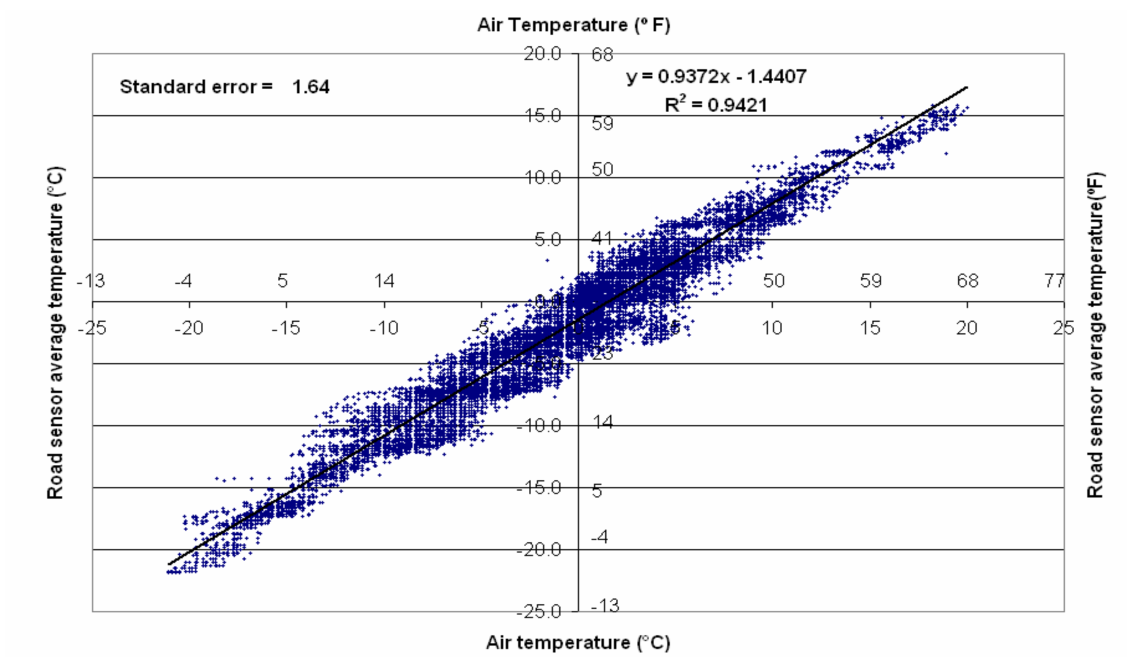



Figure 36. Air versus road nighttime temperature correlation graph for Site 7 US 30 Crawford County, November 29, 2004- April 5, 2005

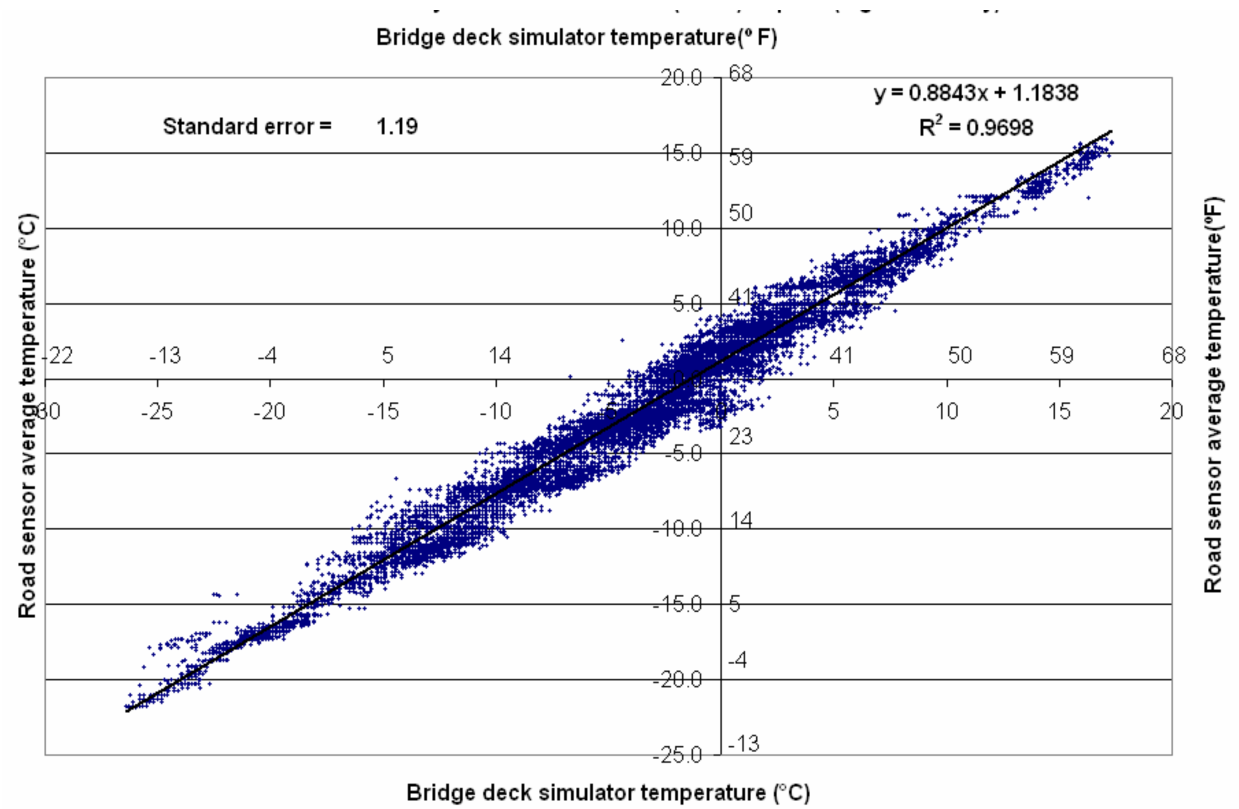



**Figure 37. BDS versus road nighttime temperature correlation graph for Site 7 US 30 Crawford County, November 29, 2004- April 5, 2005**

## 9.1.2 Daytime Correlations

Figure 38 and Figure 39 show the air versus BDS temperature correlation for all day data, separated into November 29, 2004-January 19, 2005 (Part 1) in Figure 38 and January 21, 2005-April 5, 2005 (Part 2) in Figure 39. Figure 40 and Figure 41 show the air versus bridge all-day temperature correlations for Parts 1 and 2 of the data, respectively. Figure 42 and Figure 43 show the BDS versus bridge all-day temperature correlations for Parts 1 and 2 of the data. Figure 44 and Figure 45 show the air versus average road all-day temperature correlations for Parts 1 and 2 of the data. Figure 46 and Figure 47 show the BDS versus average road all-day temperature correlations for Parts 1 and 2 of the data.

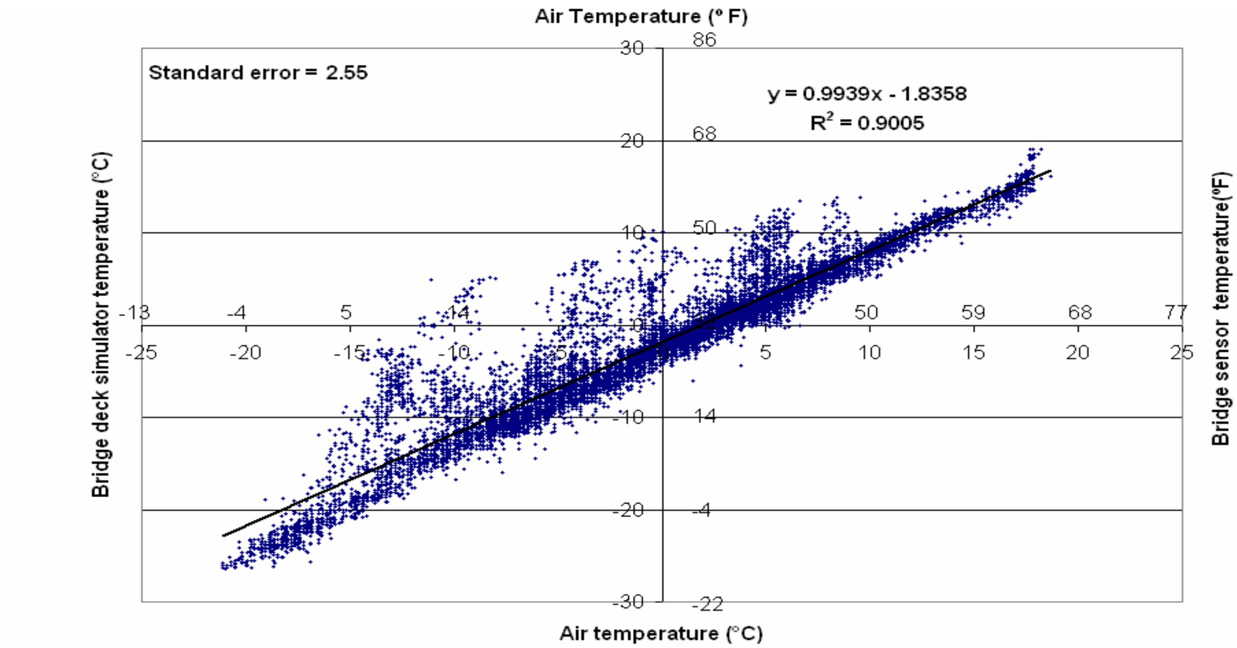



**Figure 38. Air versus BDS all day temperature correlation graph for Site 7 US 30 Crawford County, November 29, 2004- January 19, 2005**

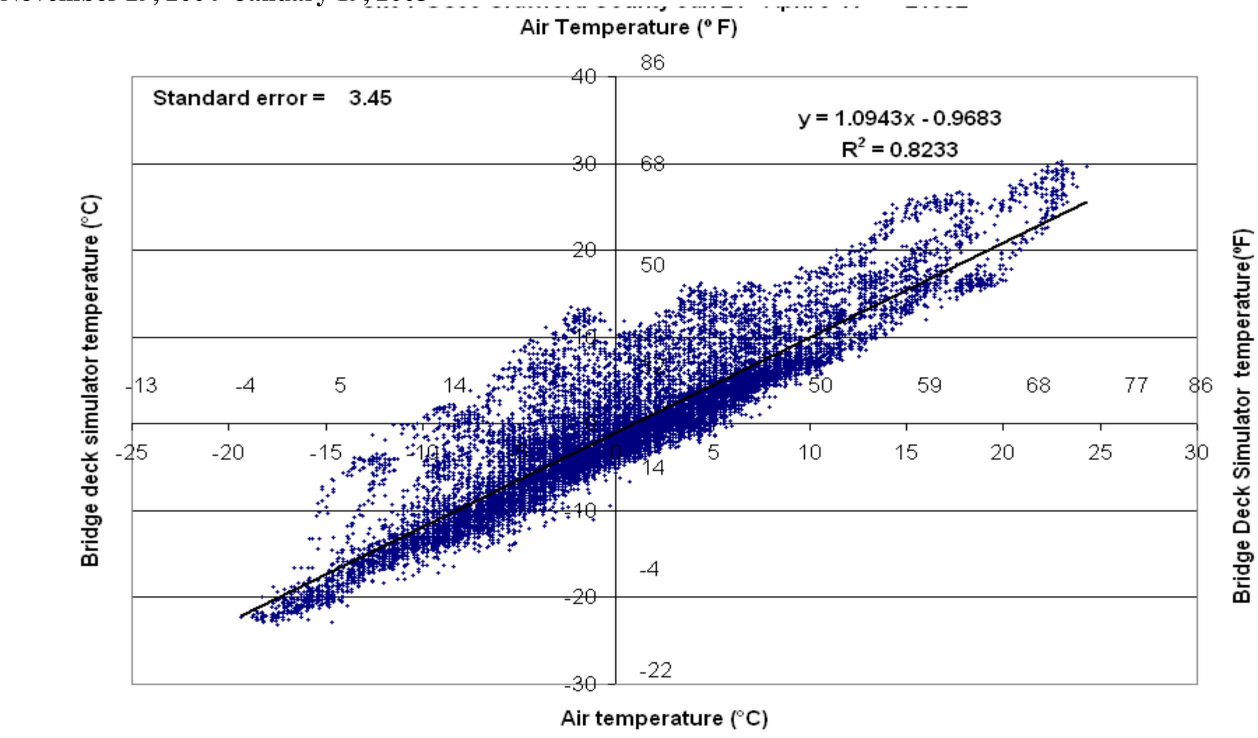



**Figure 39. Air versus BDS all day temperature correlation graph for Site 7 US 30 Crawford County, January 21 - April 5, 2005**

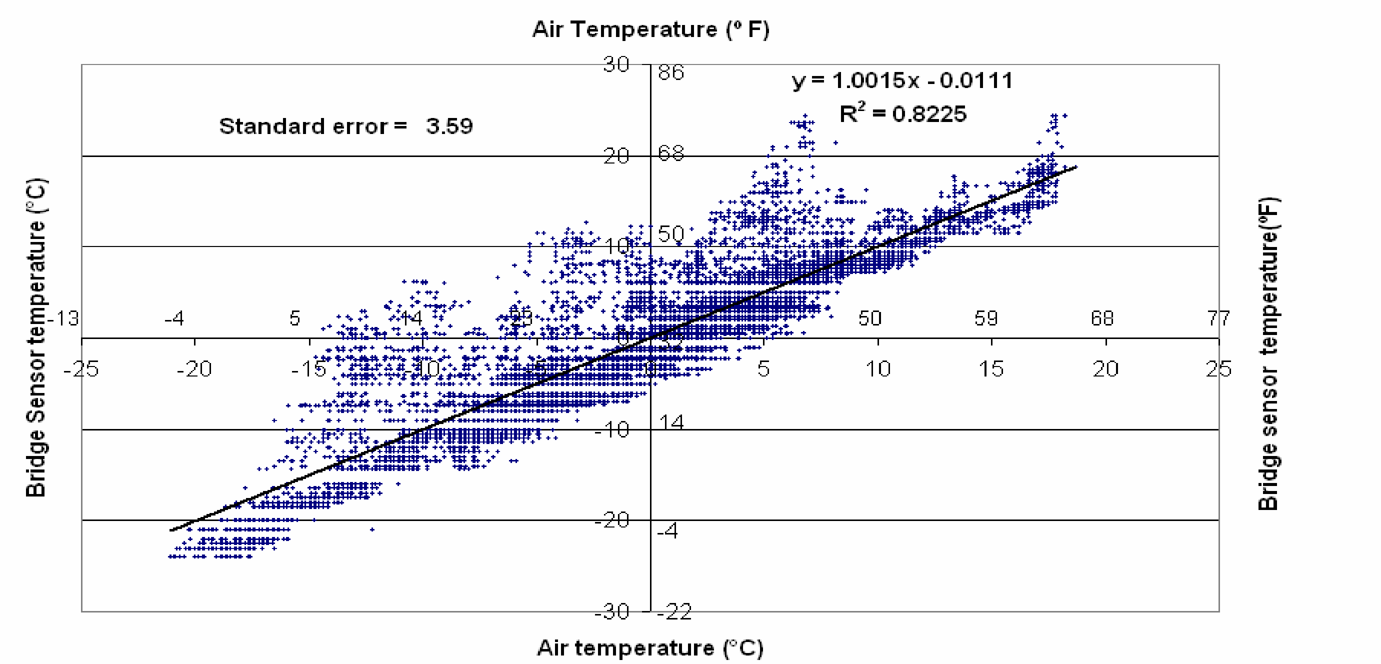



**Figure 40. Air versus bridge all-day temperature correlation graph for Site 7 US 30 Crawford County, November 29, 2004- January 19, 2005**

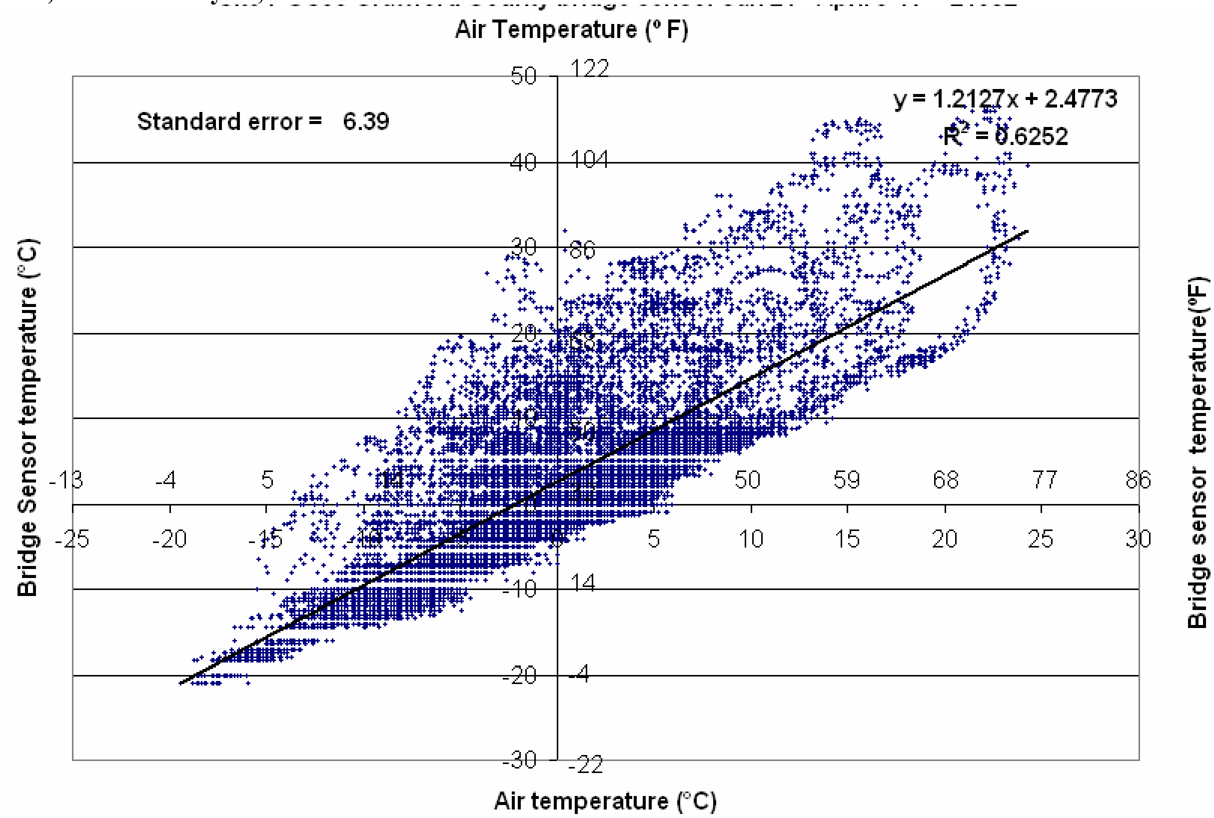



**Figure 41. Air versus bridge all-day temperature correlation graph for Site 7 US 30 Crawford County, January 21 - April 5, 2005**

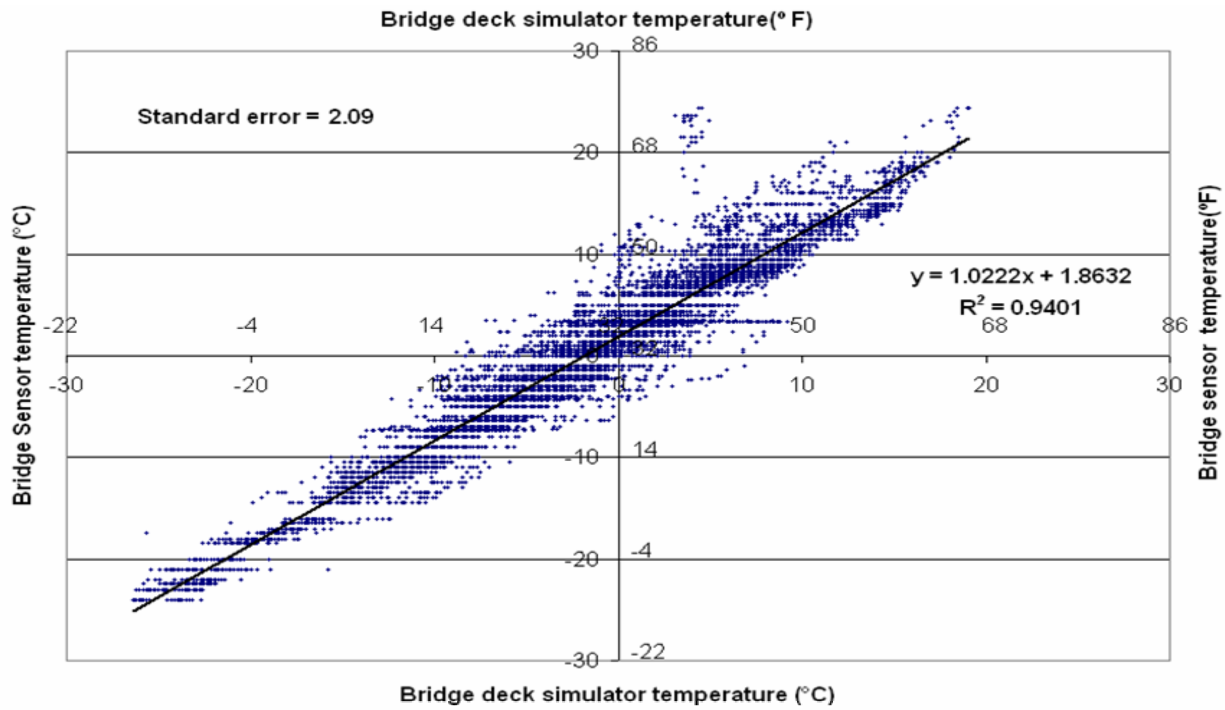



**Figure 42. BDS versus bridge all-day temperature correlation graph for Site 7 US 30 Crawford County, November 29, 2004- January 19, 2005**

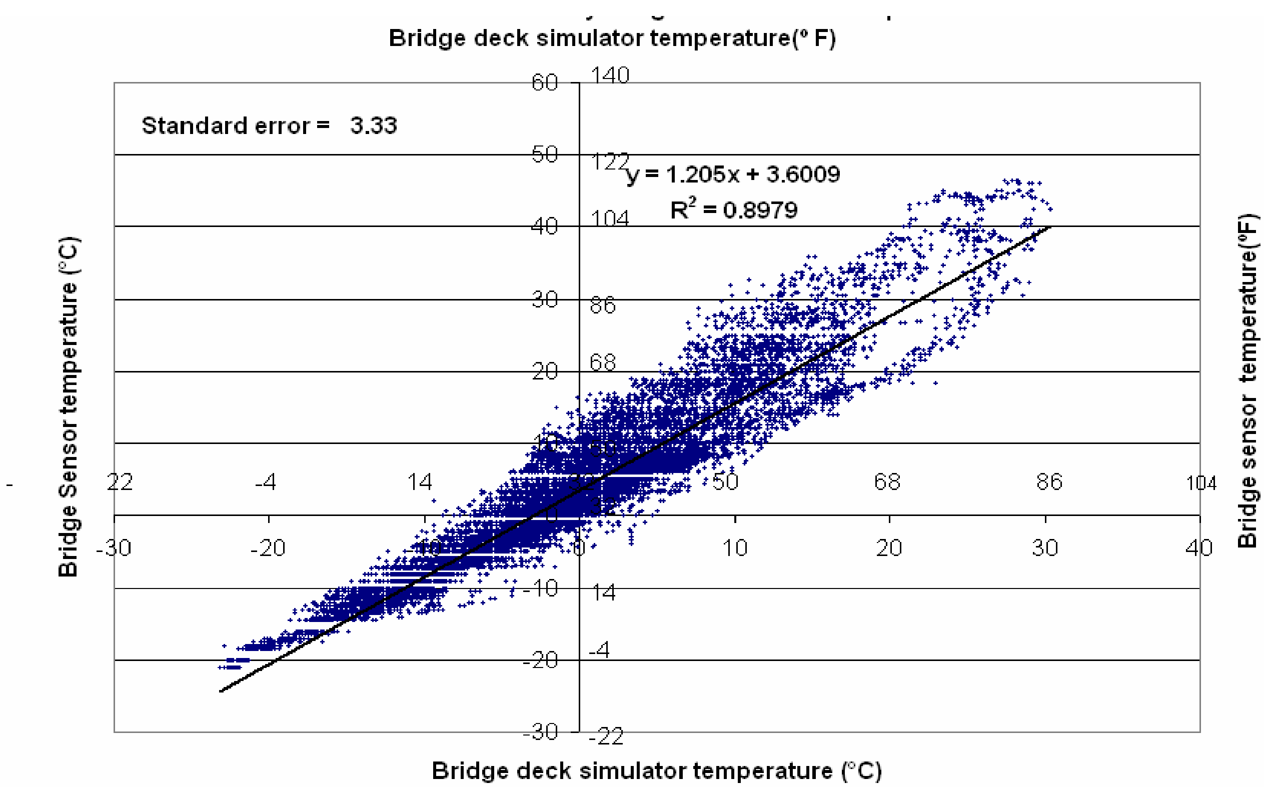



**Figure 43. BDS versus bridge all-day temperature correlation graph for Site 7 US 30 Crawford County, January 21 - April 5, 2005**

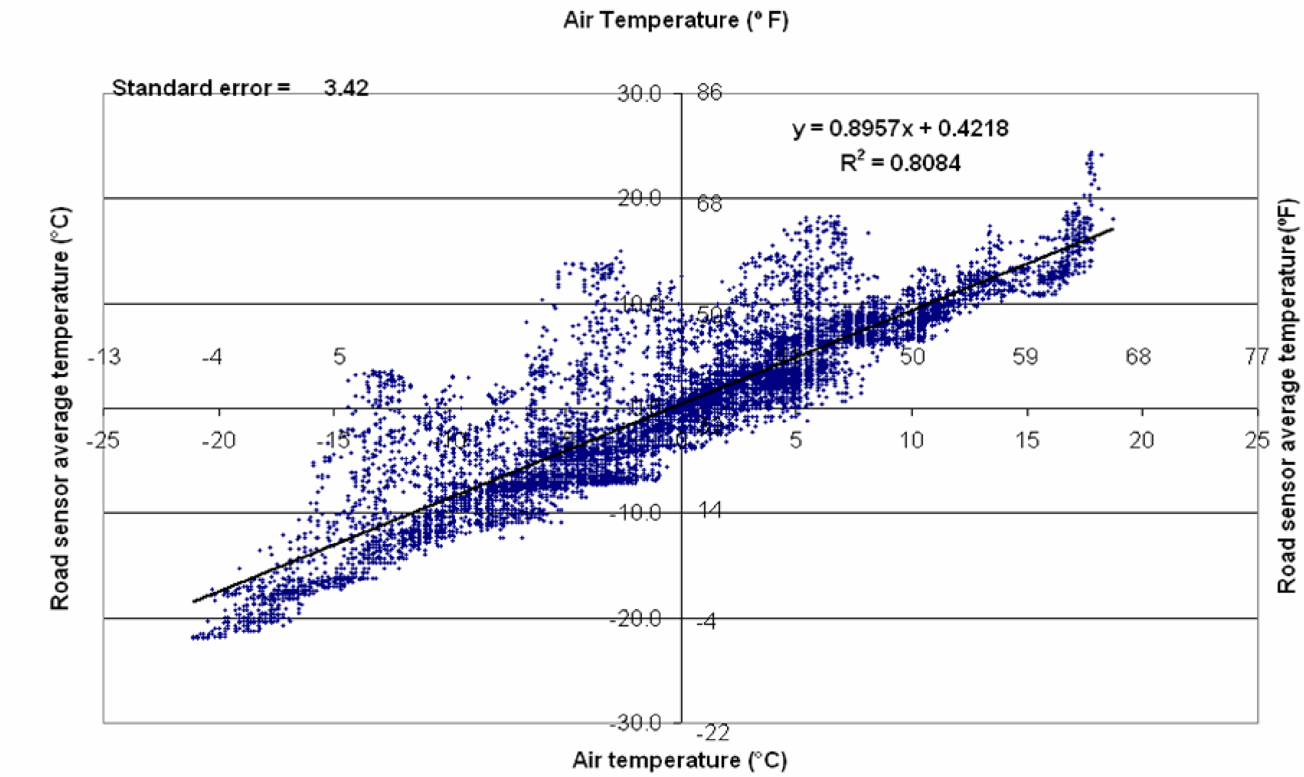



**Figure 44. Air versus road all-day temperature correlation graph for Site 7 US 30 Crawford County, November 29, 2004- January 19, 2005**

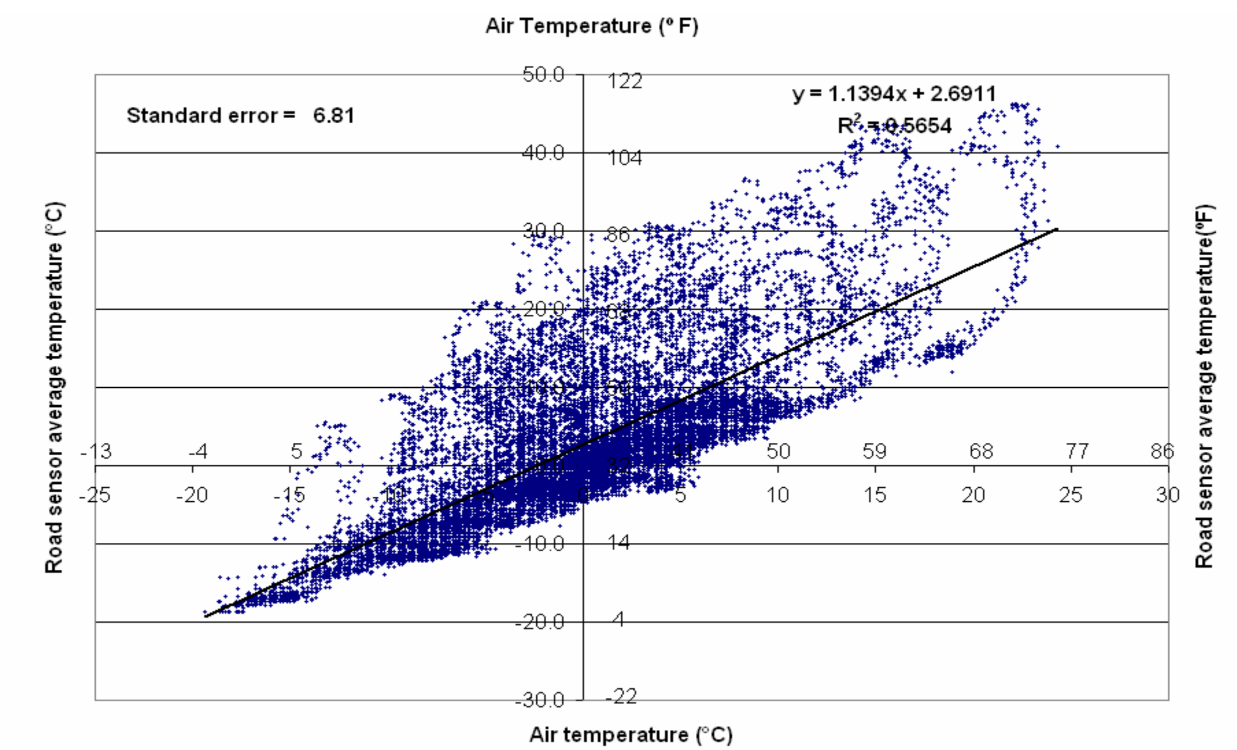



**Figure 45. Air versus road all-day temperature correlation graph for Site 7 US 30 Crawford County, January 21 – April 5, 2005**

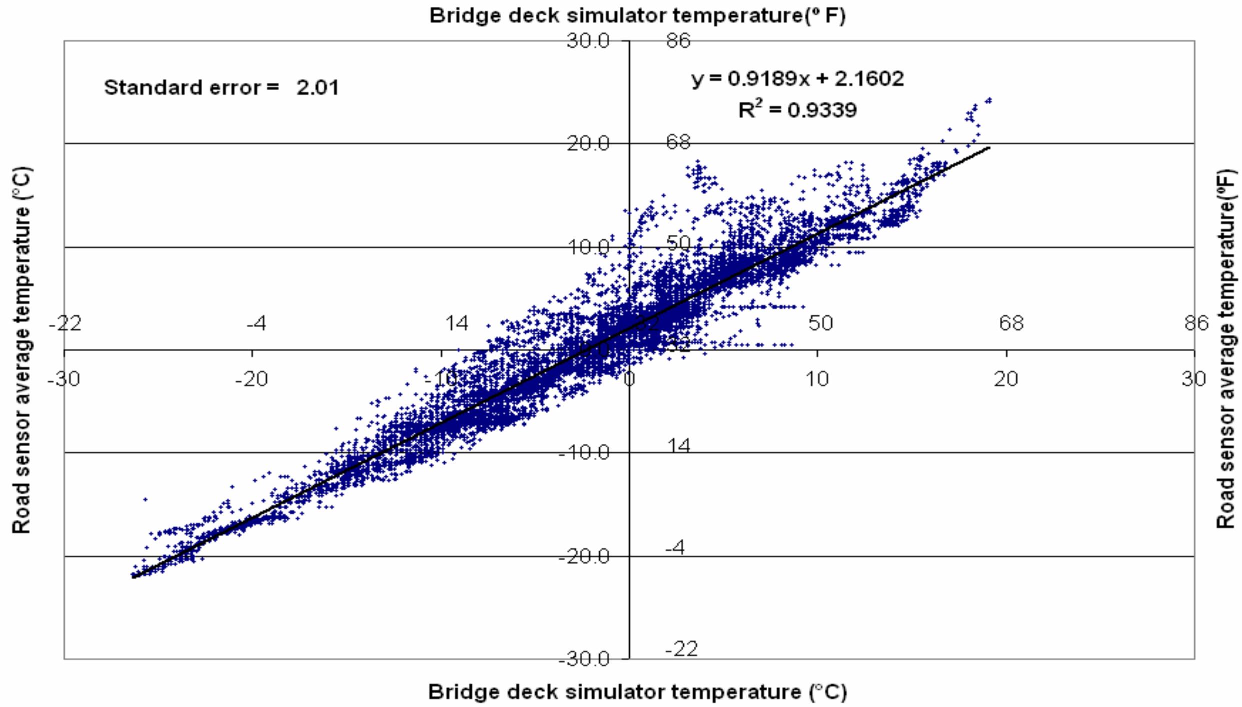



**Figure 46. BDS versus road all-day temperature correlation graph for Site 7 US 30 Crawford County, November 29, 2004- January 19, 2005**

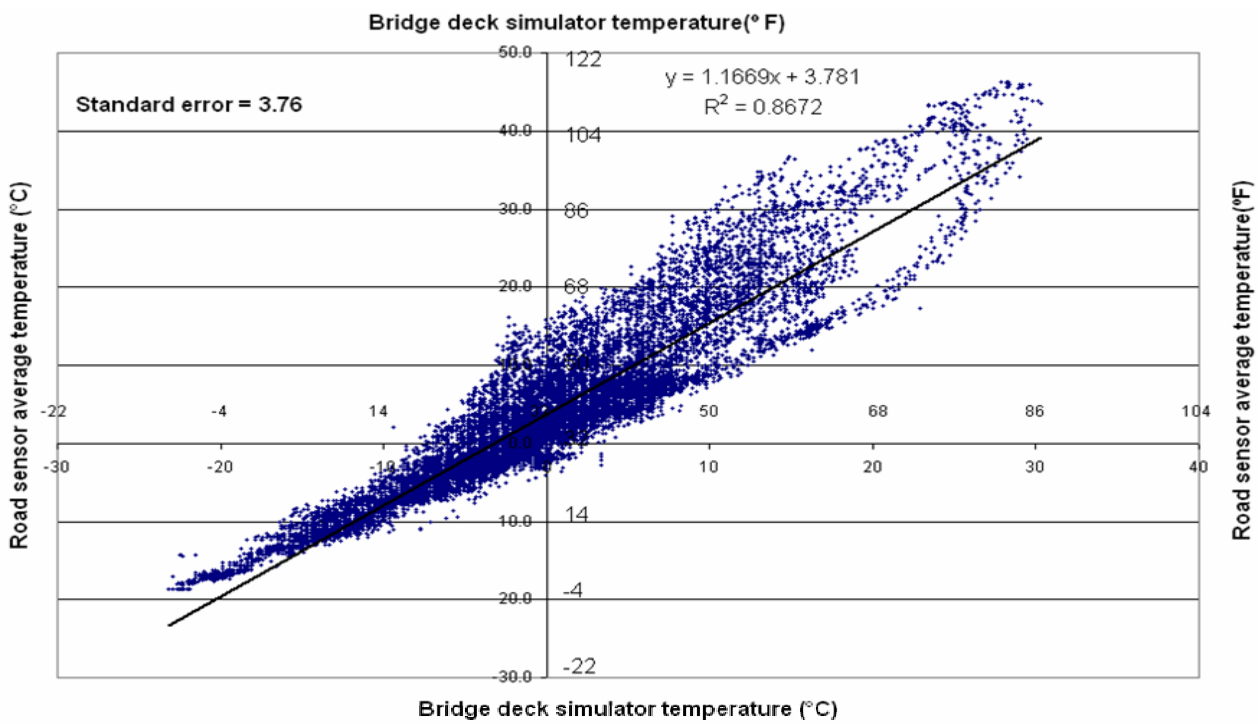



**Figure 47. BDS versus road all-day temperature correlation graph for Site 7 US 30 Crawford County, January 21, 2005 – April 5, 2005**

## 9.2 Site 9 Stark County

### 9.2.1 Night time correlations

Figure 48 shows the correlation between the air temperature and the bridge deck simulator (BDS) temperature for Site 9 in Stark County. Figure 49 and Figure 50 respectively show the correlations of the air and BDS temperatures with the single bridge sensor temperature. The same horizontal striping as observed at Site 7 occurs here, for the same reason.

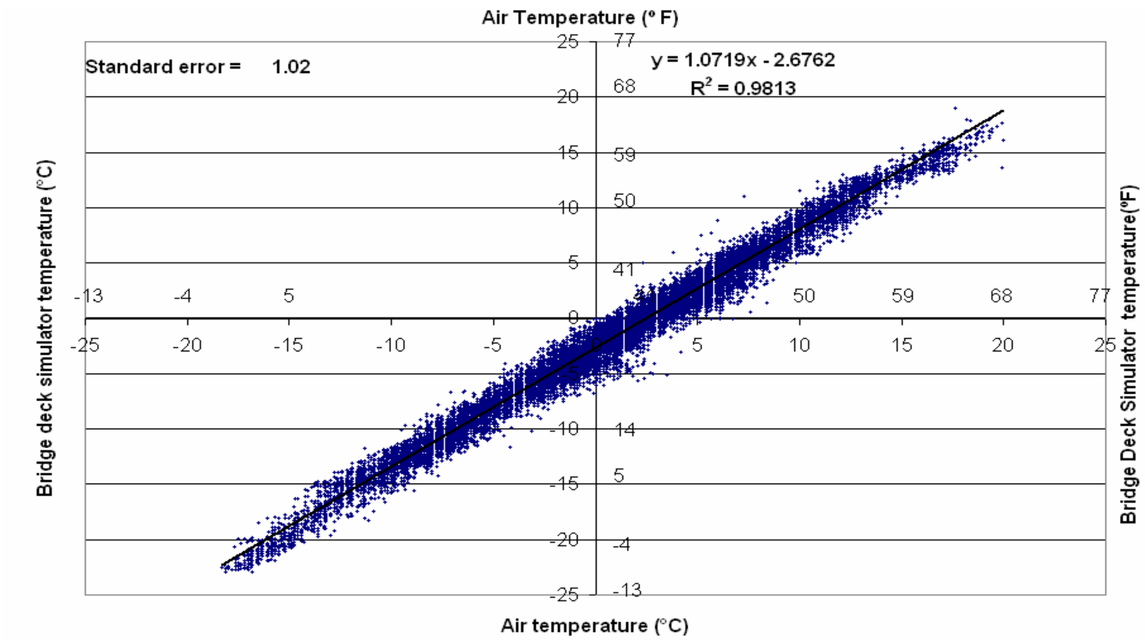



**Figure 48. Air versus BDS nighttime temperature correlation graph for Site 9 I77 Stark County, November 1, 2004- April 5, 2005**

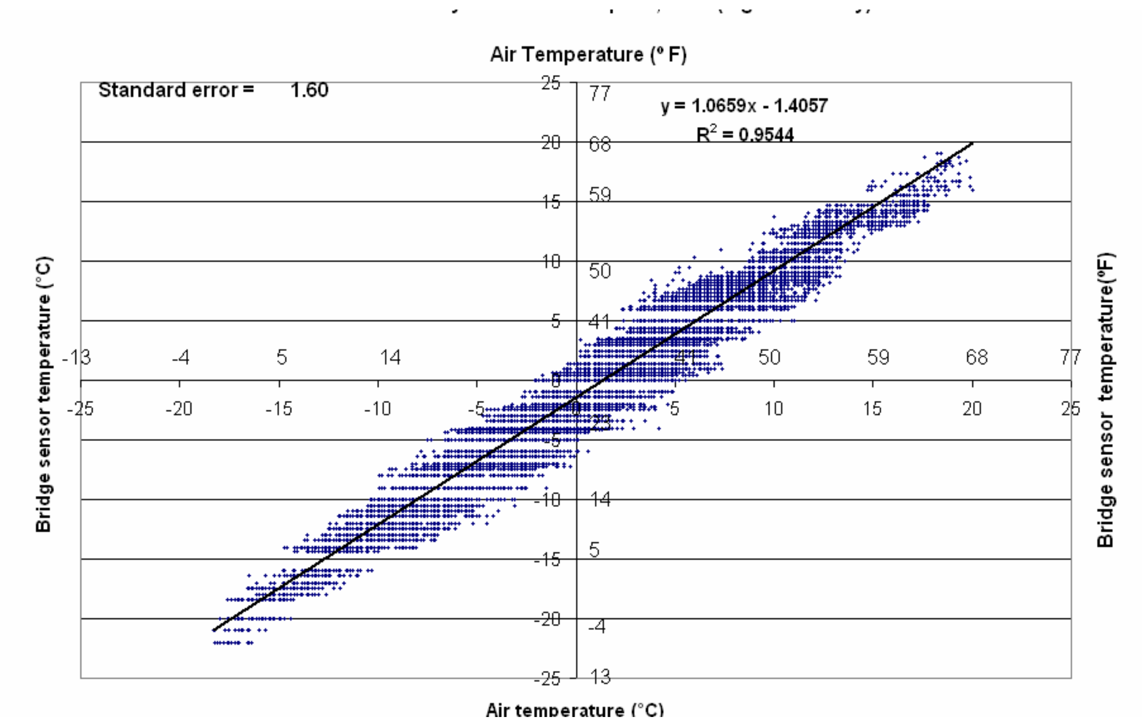



**Figure 49. Air versus bridge nighttime temperature correlation graph for Site 9 I77 Stark County, November 1, 2004- April 5, 2005**

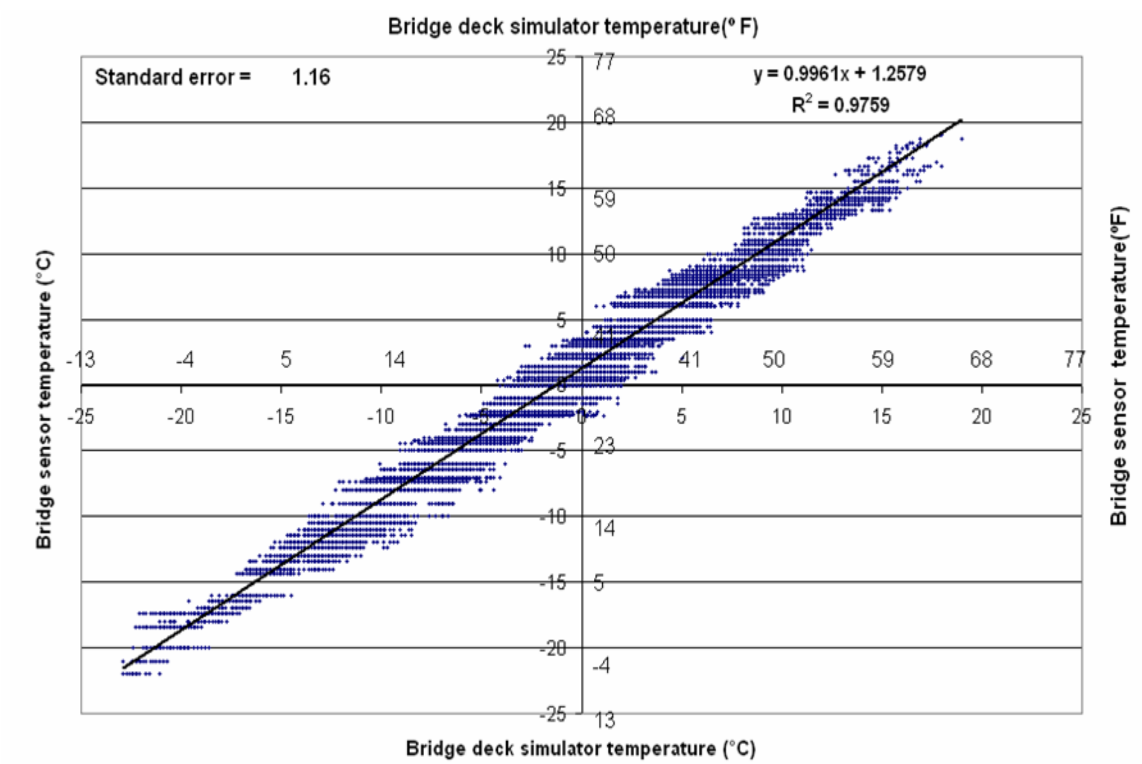



**Figure 50. BDS versus bridge nighttime temperature correlation graph for Site 9 I77 Stark County, November 1, 2004- April 5, 2005**

### 9.2.2 Day time correlations

Figure 51 and Figure 52 show the air versus BDS temperature correlation for all day data, separated into November 1, 2004 – January 19, 2005 (Part 1) and January 21, 2005-April 5, 2005 (Part 2), respectively. Figure 53 and Figure 54 show the air versus bridge all-day temperature correlations for Parts 1 and 2 of the data, respectively. Figure 55 and Figure 56 show the BDS versus bridge all-day temperature correlations for Parts 1 and 2 of the data.

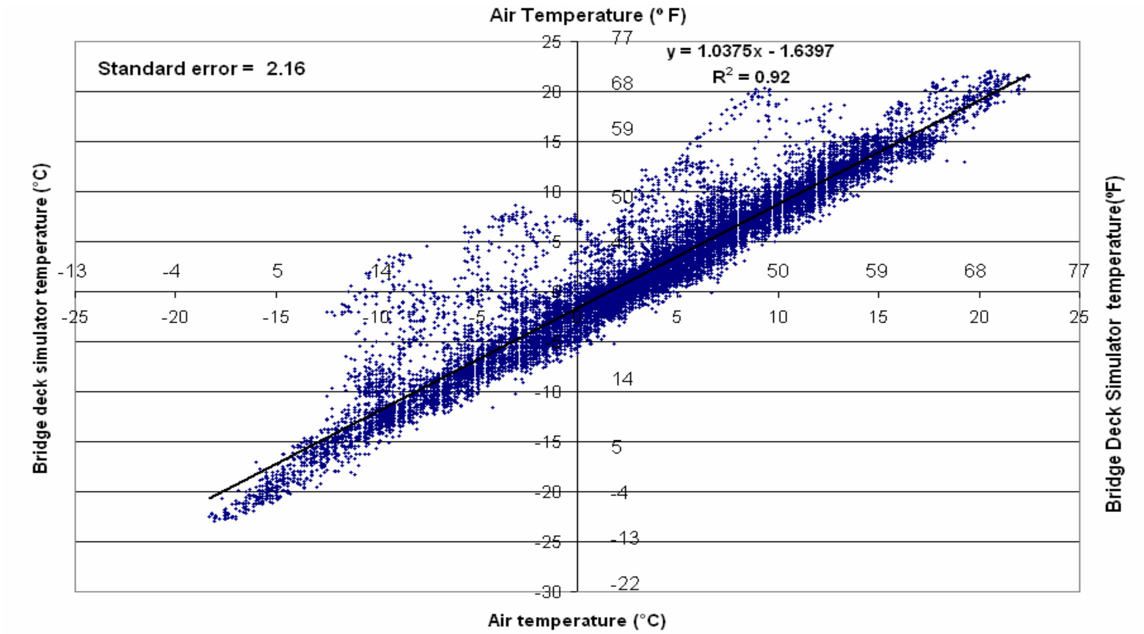



**Figure 51. Air versus BDS all-day temperature correlation graph for Site 9 I77 Stark County, November 1, 2004- January 19, 2005**

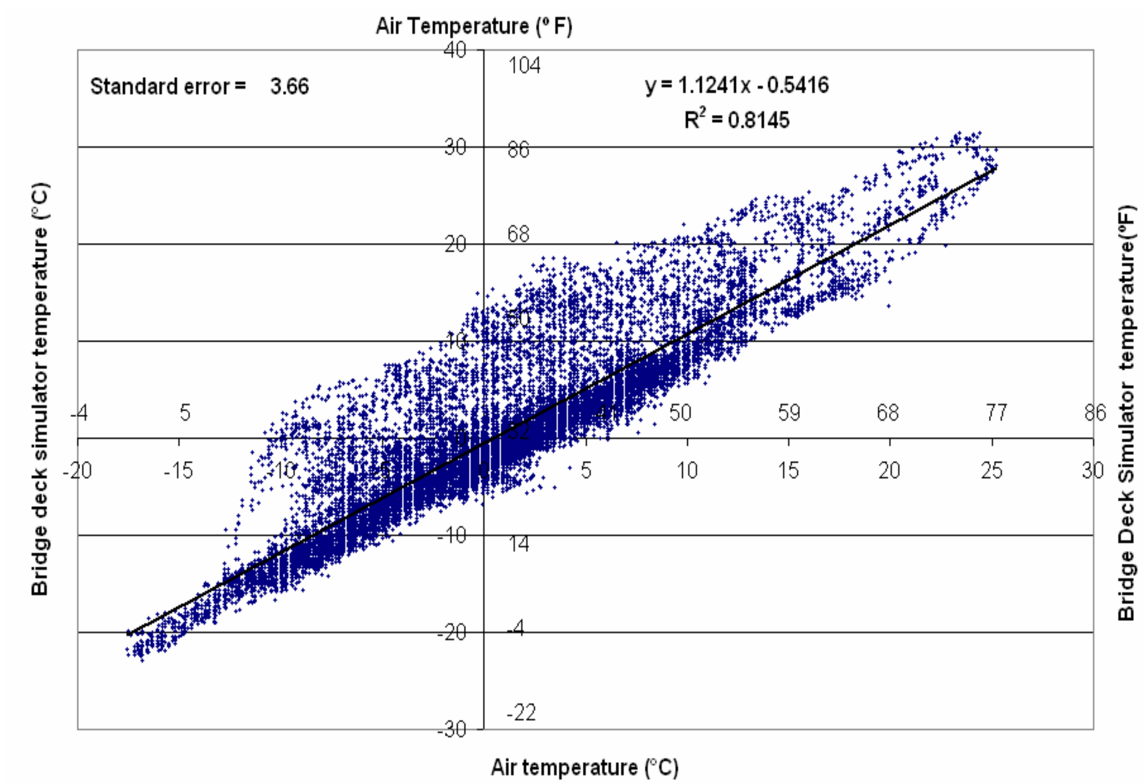



**Figure 52. Air versus BDS all-day temperature correlation graph for Site 9 I77 Stark County, January 21 - April 5, 2005**

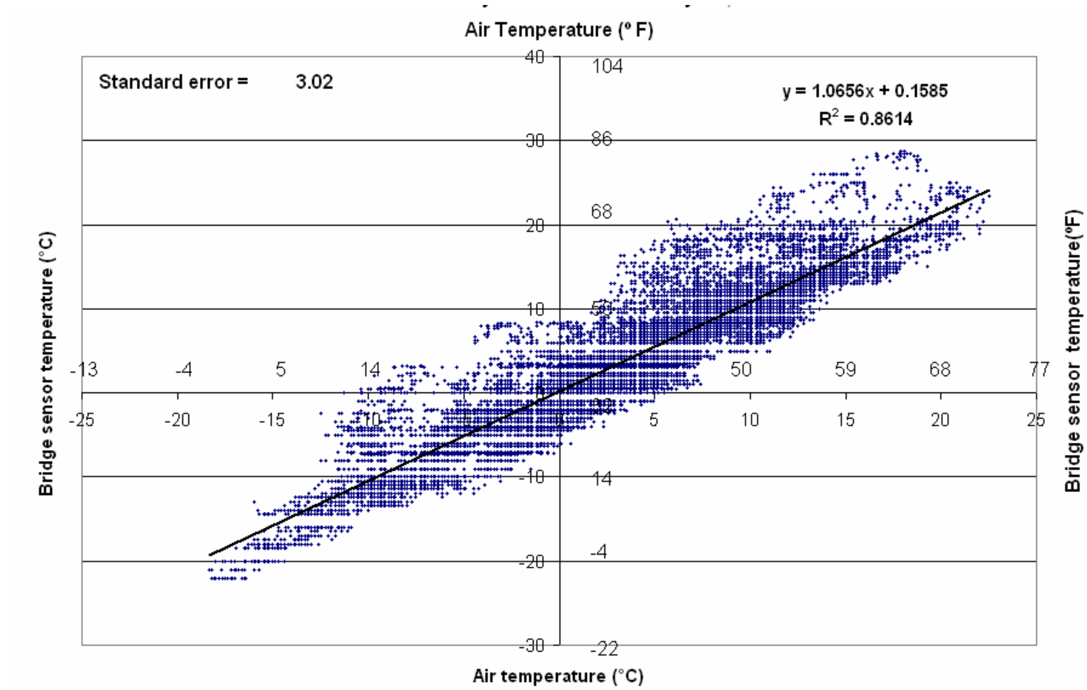



**Figure 53. Air versus bridge all-day temperature correlation graph for Site 9 I77 Stark County, November 1, 2004- April 5, 2005**

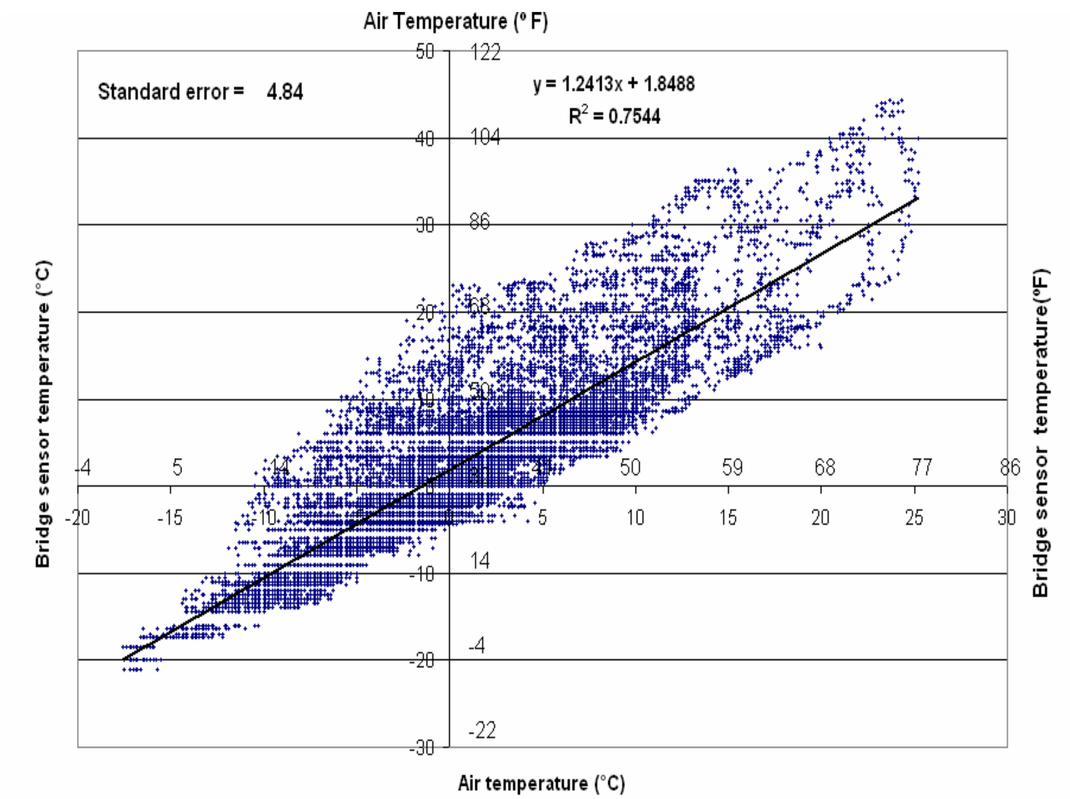



**Figure 54. Air versus bridge all-day temperature correlation graph for Site 9 I77 Stark County, January 21 - April 5, 2005**

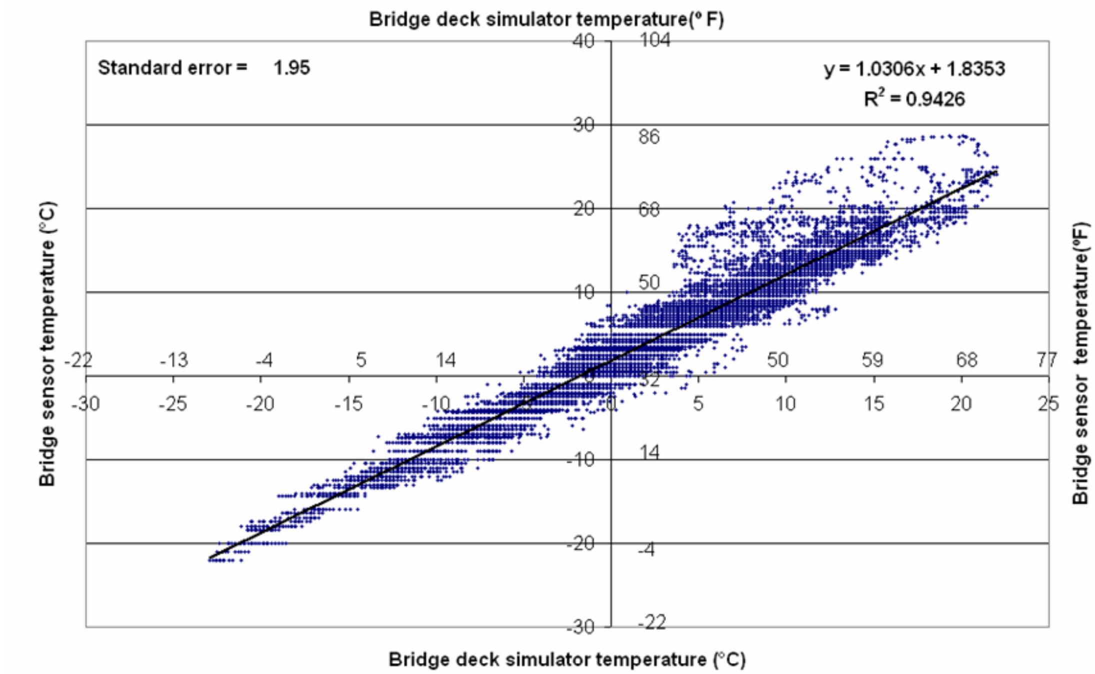



**Figure 55. BDS versus bridge all-day temperature correlation graph for Site 9 I77 Stark County, November 1, 2004- January 19, 2005**

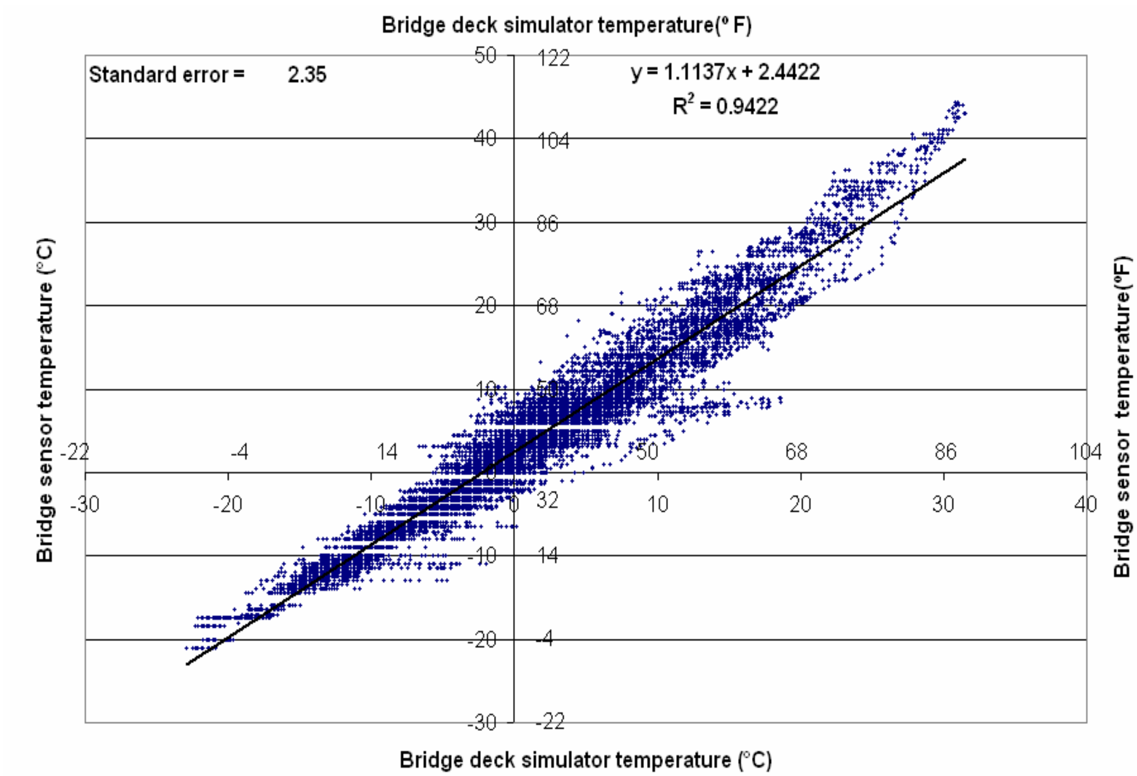



**Figure 56. BDS versus bridge all-day temperature correlation graph for Site 9 I77 Stark County, January 21 - April 5, 2005**

## 9.3 Site 59 Warren County

### 9.3.1 Night time correlations

Figure 57 shows the correlation between the air temperature and the bridge deck simulator (BDS) temperature for Site 59 in Warren County. Figure 58 and Figure 59 respectively show the correlations of the air and BDS temperatures with the average bridge sensor temperature. Figure 60 and Figure 61 respectively show the correlations of the air and BDS temperature with the average of temperatures of the road sensors.

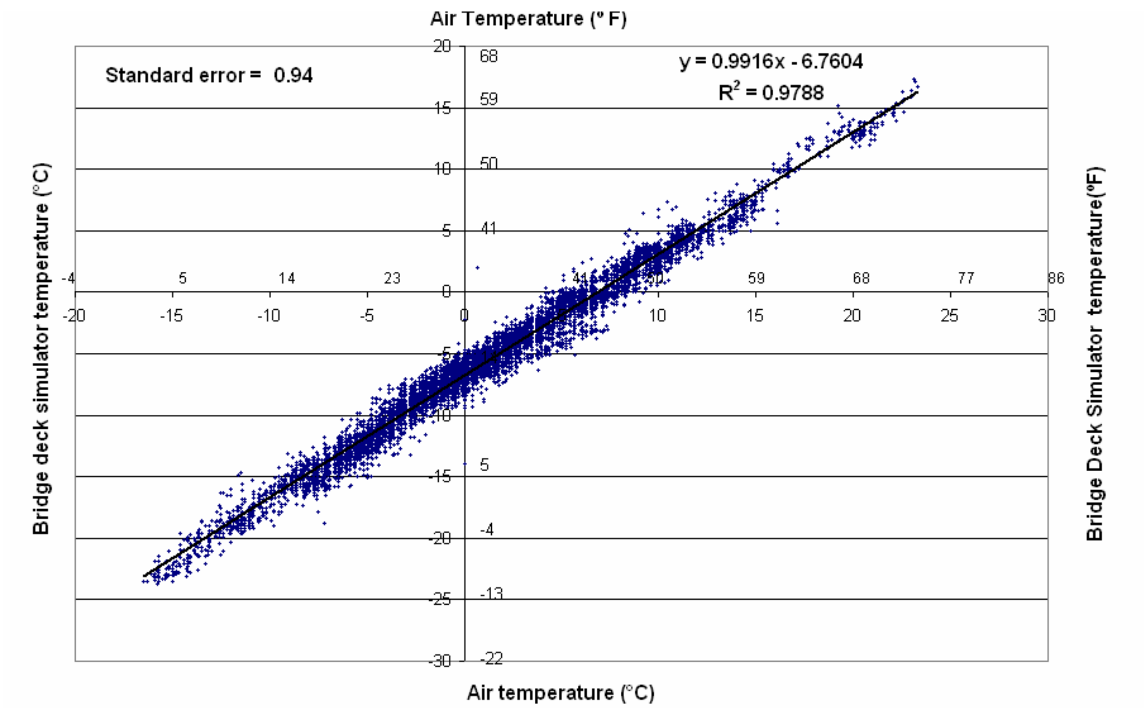



**Figure 57. Air versus BDS nighttime temperature correlation graph for Site 59 I71 Warren County, January 21 - April 5, 2005**

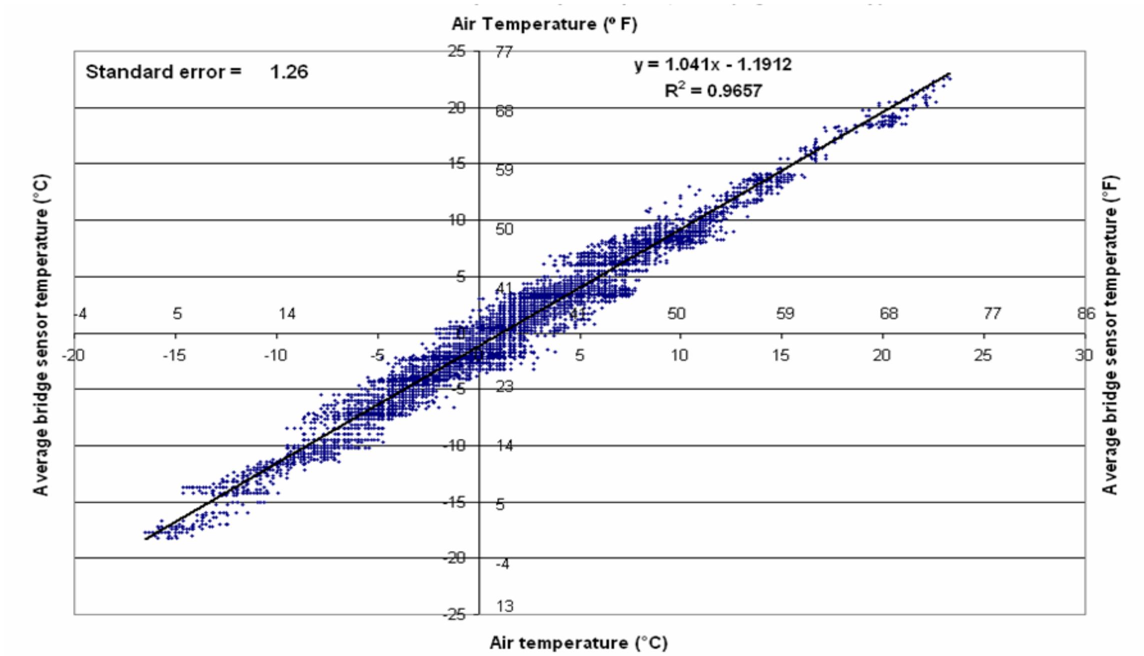



**Figure 58. Air versus bridge nighttime temperature correlation graph for Site 59 I71 Warren County, January 21 - April 5, 2005**

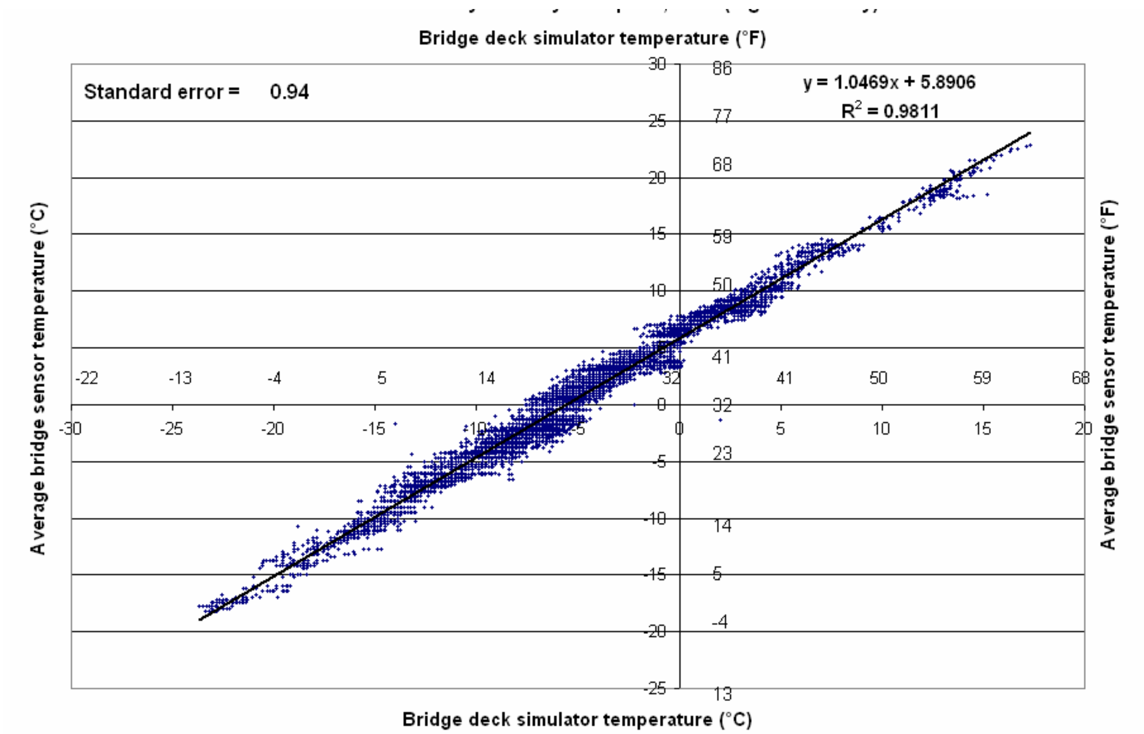



**Figure 59. BDS versus bridge nighttime temperature correlation graph for Site 59 I71 Warren County, January 21 - April 5, 2005**

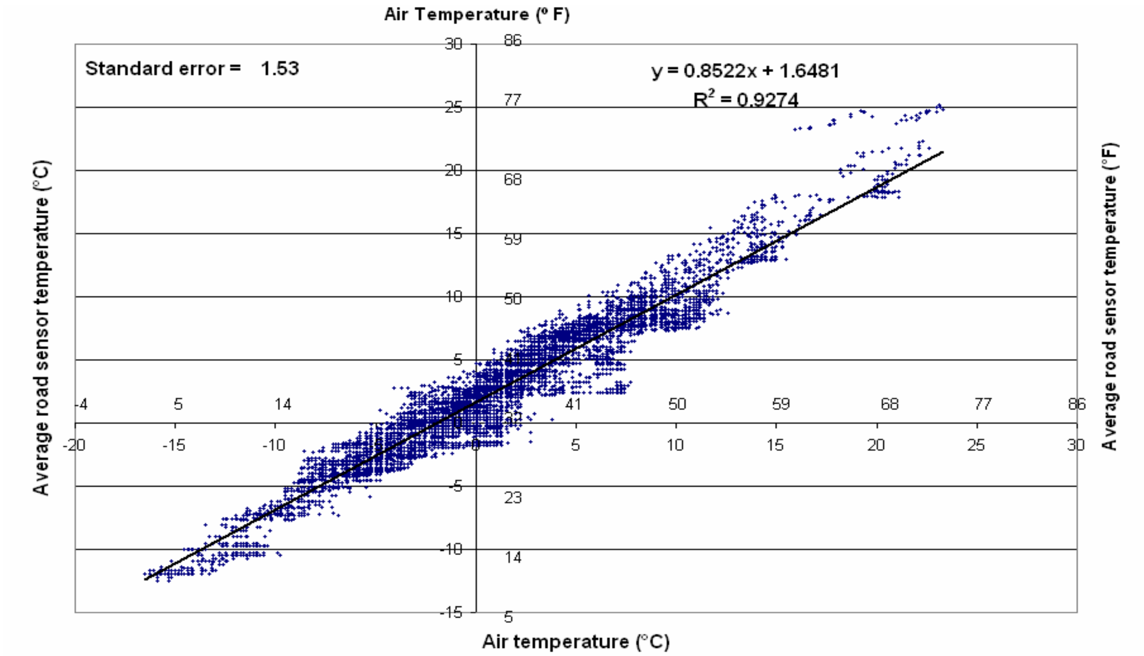



**Figure 60. Air versus road nighttime temperature correlation graph for Site 59 I71 Warren County, January 21 - April 5, 2005**

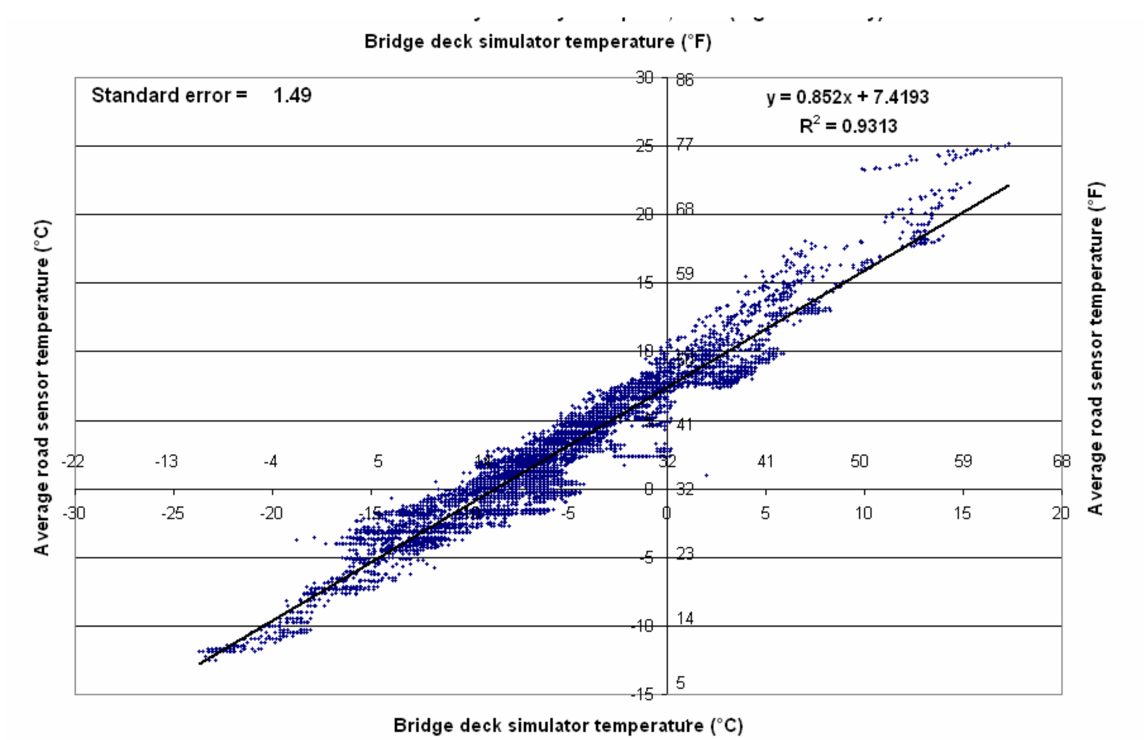



**Figure 61. BDS versus road nighttime temperature correlation graph for Site 59 I71 Warren County, January 21 - April 5, 2005**

## 9.3.2 Day time correlations

Figure 62 shows the air versus BDS temperature correlation for all day data for the entire data collection period of January 21, 2005-April 5, 2005. Figure 63 and Figure 64 show the air and BDS versus bridge all-day temperature correlations, respectively. Figure 65 and Figure 66 show the air and BDS versus average road all-day temperature correlations.

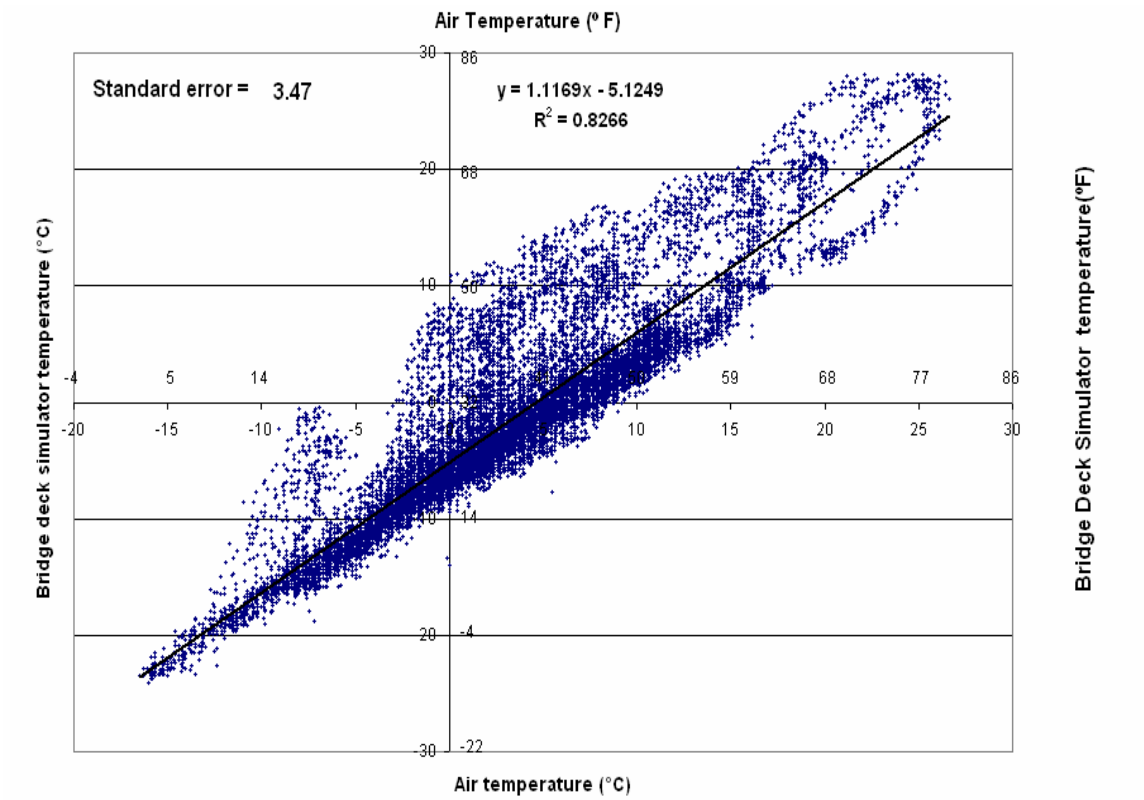



**Figure 62. Air versus BDS all-day temperature correlation graph for Site 59 I71 Warren County, January 21 - April 5, 2005**

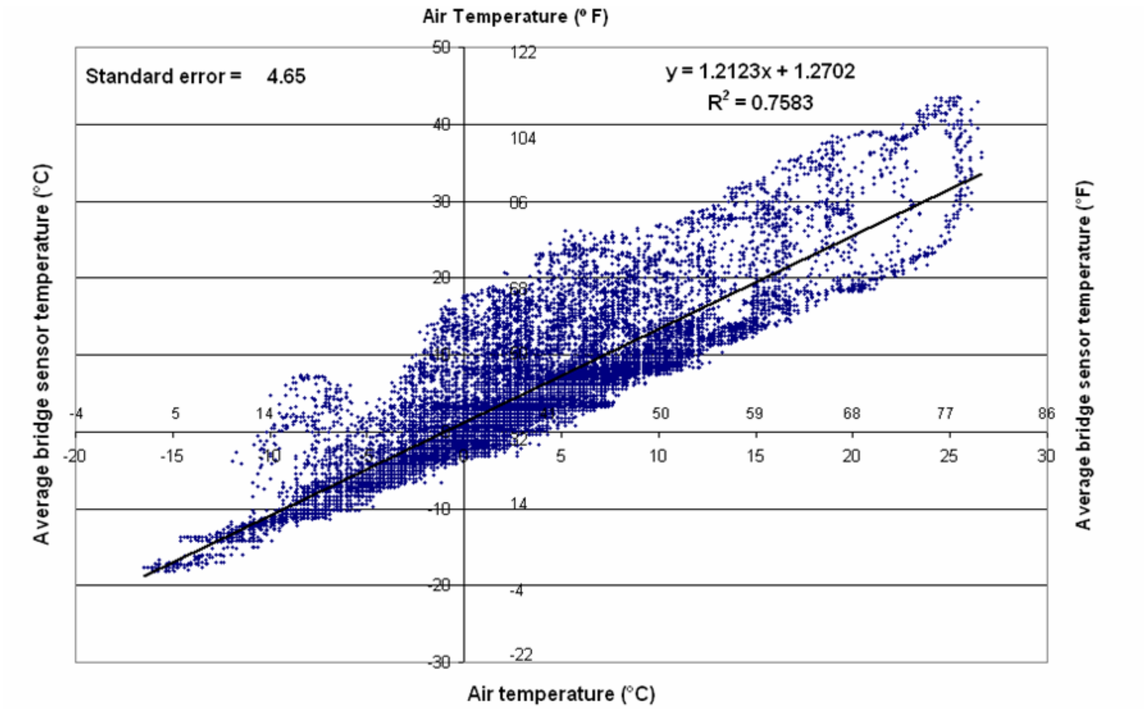



**Figure 63. Air versus bridge all-day temperature correlation graph for Site 59 I71 Warren County, January 21 - April 5, 2005**

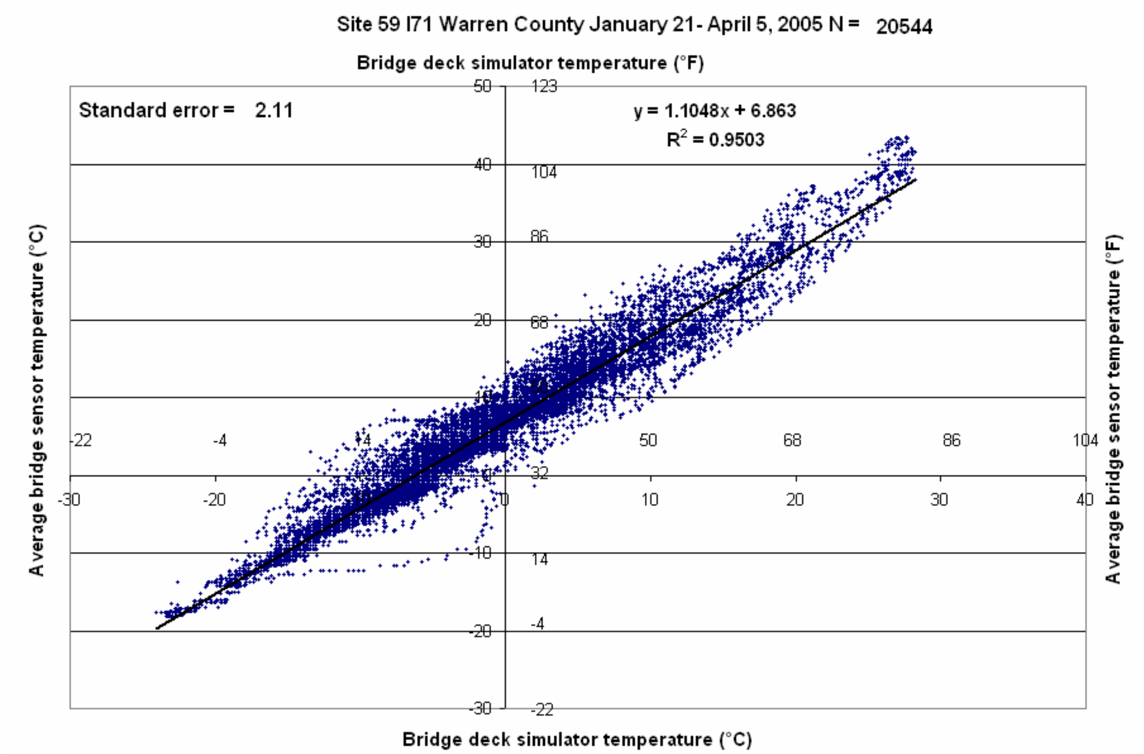



**Figure 64. BDS versus bridge all-day temperature correlation graph for Site 59 I71 Warren County, January 21 - April 5, 2005**

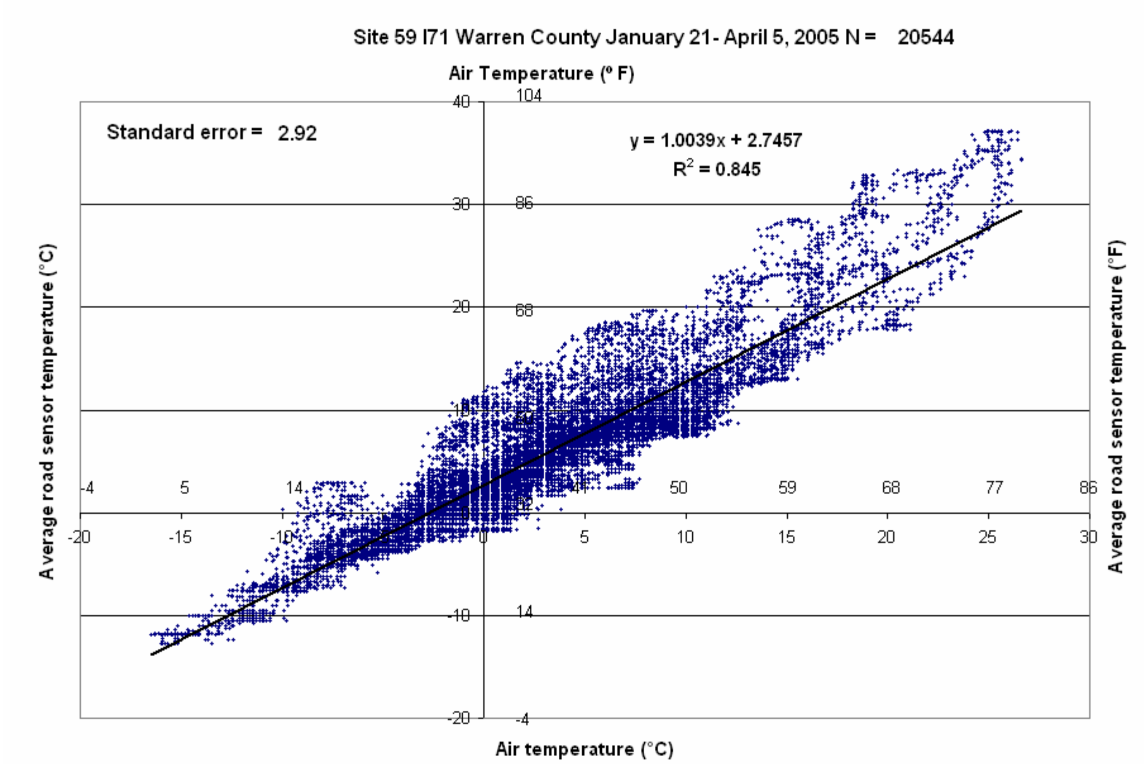



**Figure 65. Air versus road all-day temperature correlation graph for Site 59 I71 Warren County, January 21 - April 5, 2005**

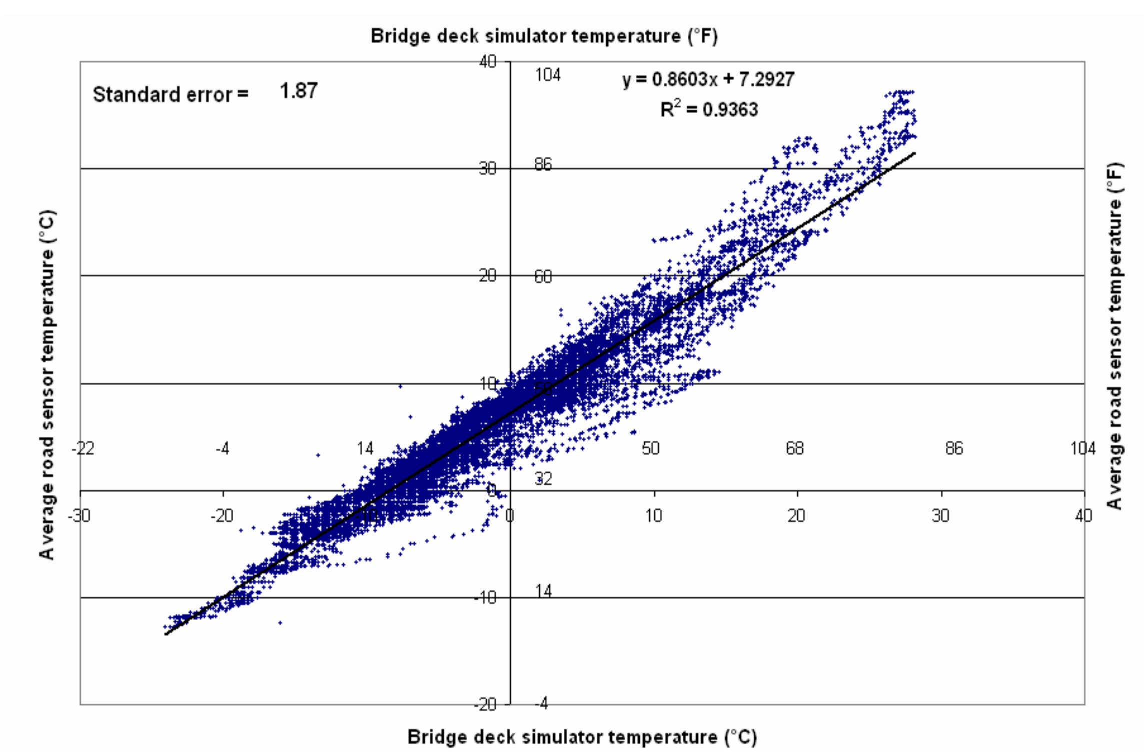



**Figure 66. BDS versus road all-day temperature correlation graph for Site 59 I71 Warren County, January 21 - April 5, 2005**

## 9.4 Site 68 Summit County

### 9.4.1 Night time correlations

Figure 67 shows the correlation between the air temperature and the bridge deck simulator (BDS) temperature for Site 68 in Summit County. Figure 68 and Figure 69 respectively show the correlations of the air and BDS temperatures with the average bridge sensor temperature. Figure 70 and Figure 71 respectively show the correlations of the air and BDS temperature with the average of temperatures of the road sensors on I271. Figure 72 and Figure 73 respectively show the correlations of the air and BDS temperature with the average of temperatures of the road sensors on I77.

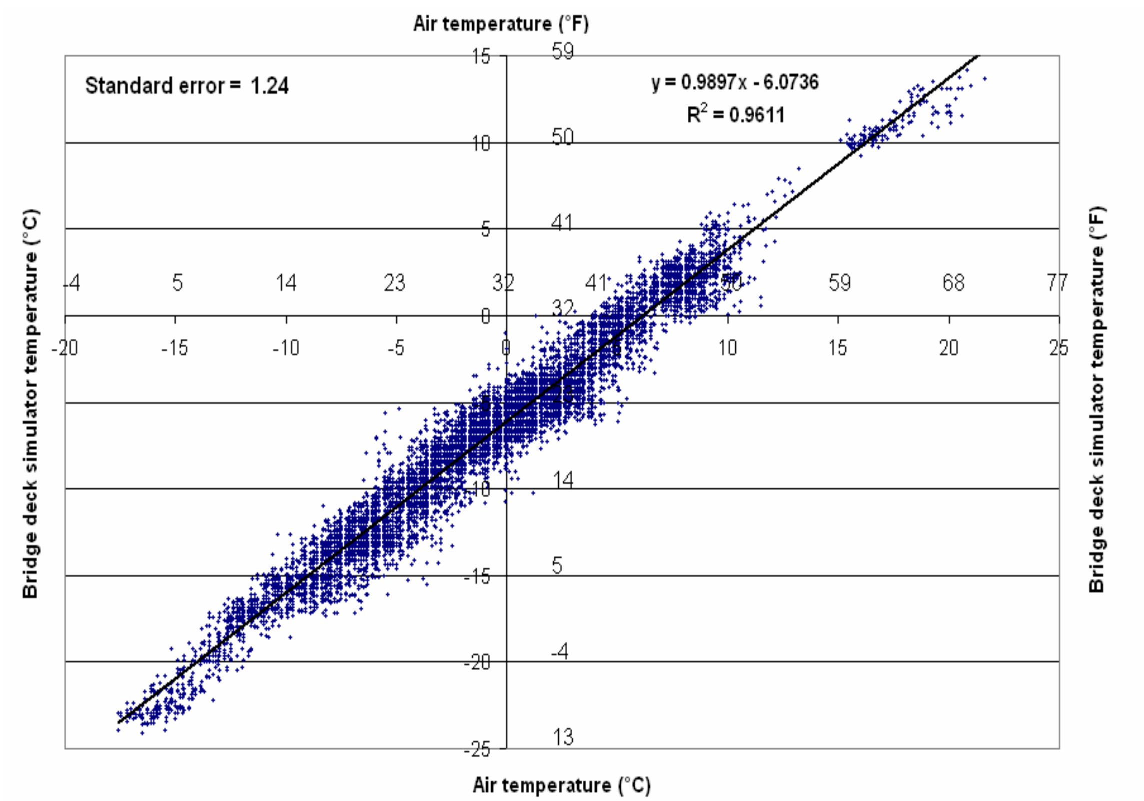



**Figure 67. Air versus BDS nighttime temperature correlation graph for Site 68 I271 and I77 Summit County, January 21 - April 5, 2005**

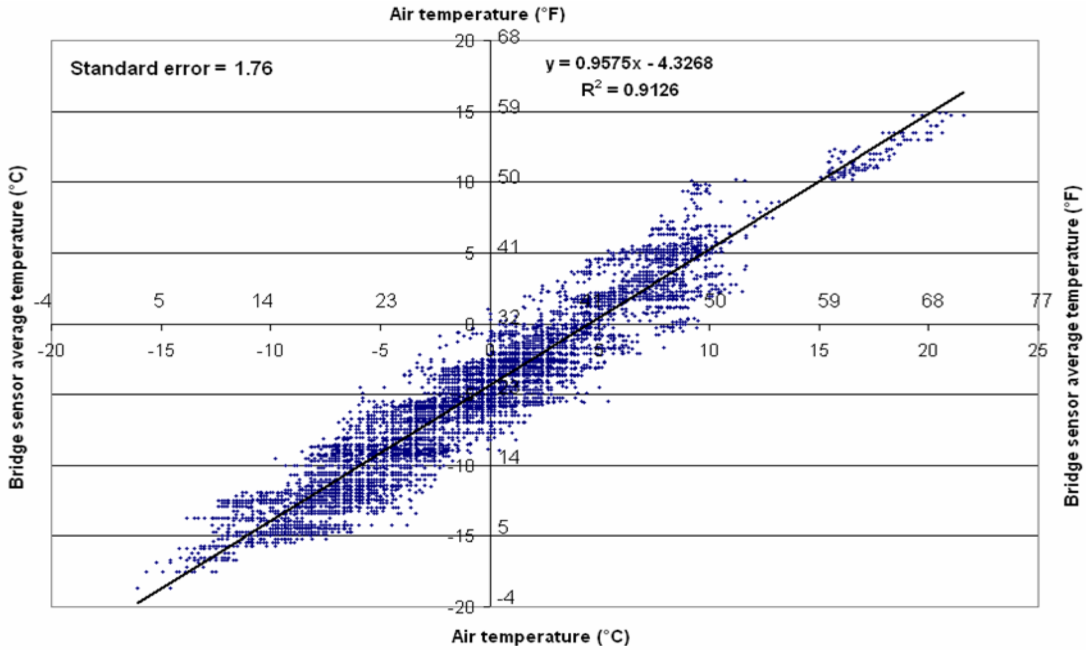



**Figure 68. Air versus bridge nighttime temperature correlation graph for Site 68 I271 Summit County January 21 – April 5, 2005**

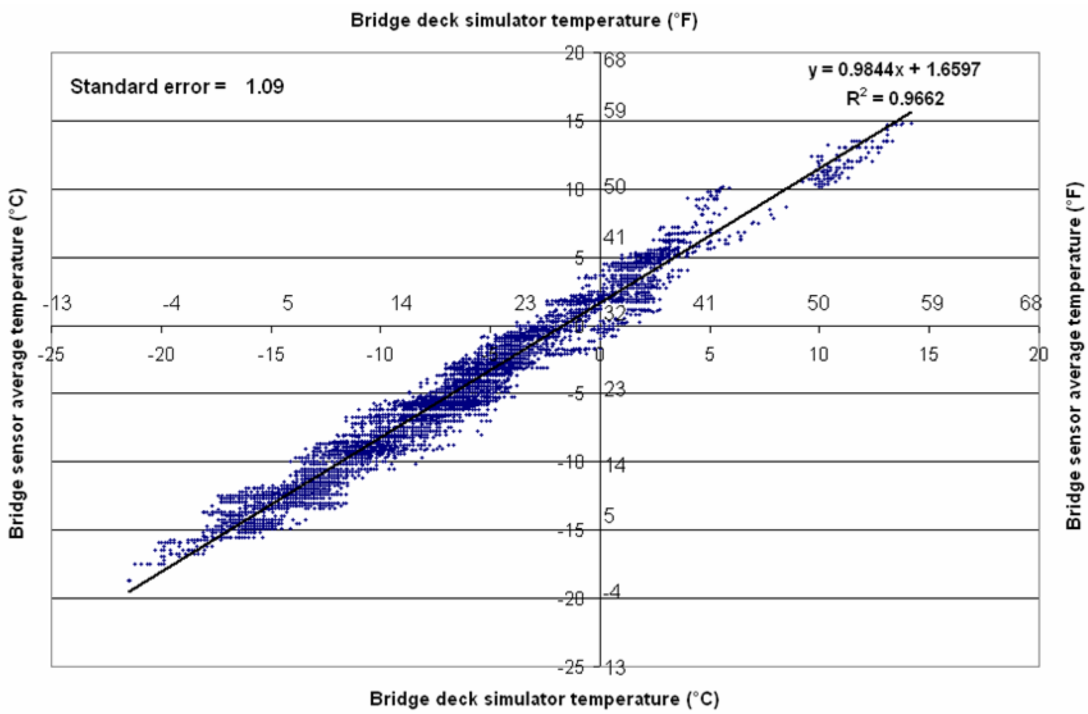



**Figure 69. BDS versus bridge nighttime temperature correlation graph for Site 68 I271 Summit County January 21 - April 5, 2005**

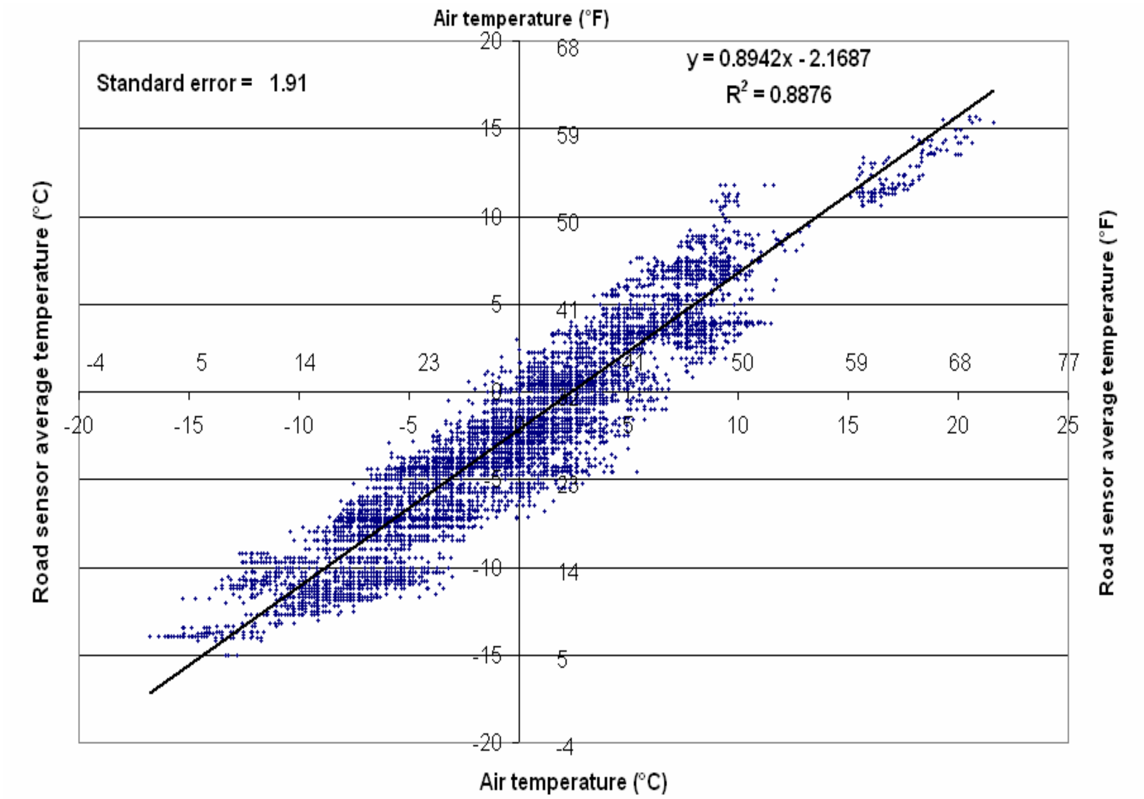



**Figure 70. Air versus road nighttime temperature correlation graph for Site 68 I271 Summit County (Sensors 3 & 4) January 21 - April 5, 2005**

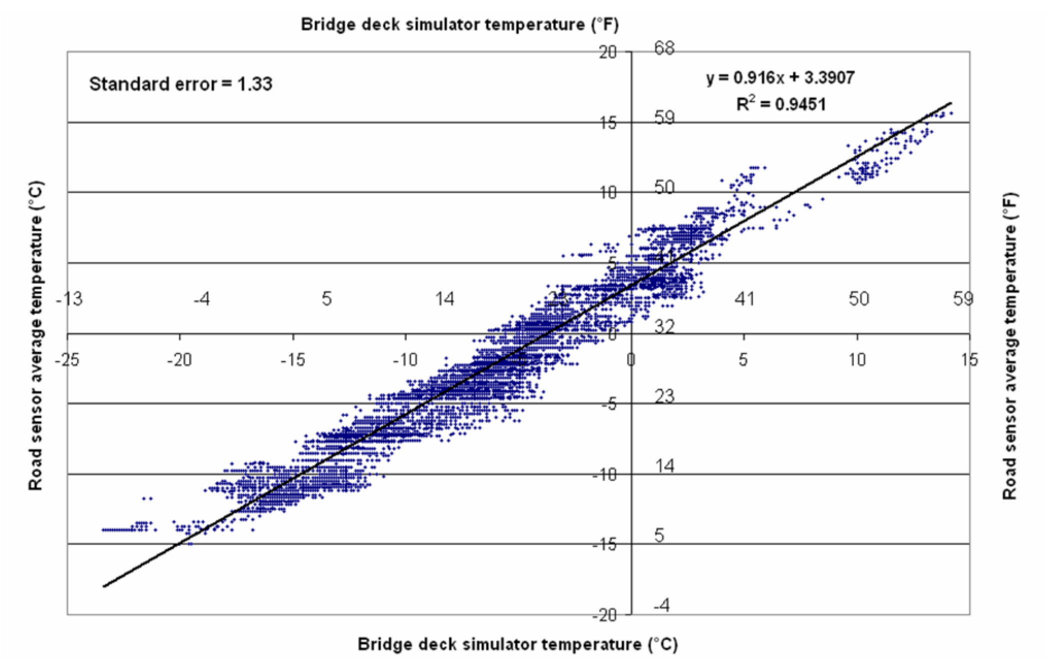



**Figure 71. BDS versus road nighttime temperature correlation graph for Site 68 I271 Summit County (Sensors 3 & 4) January 21 - April 5, 2005**

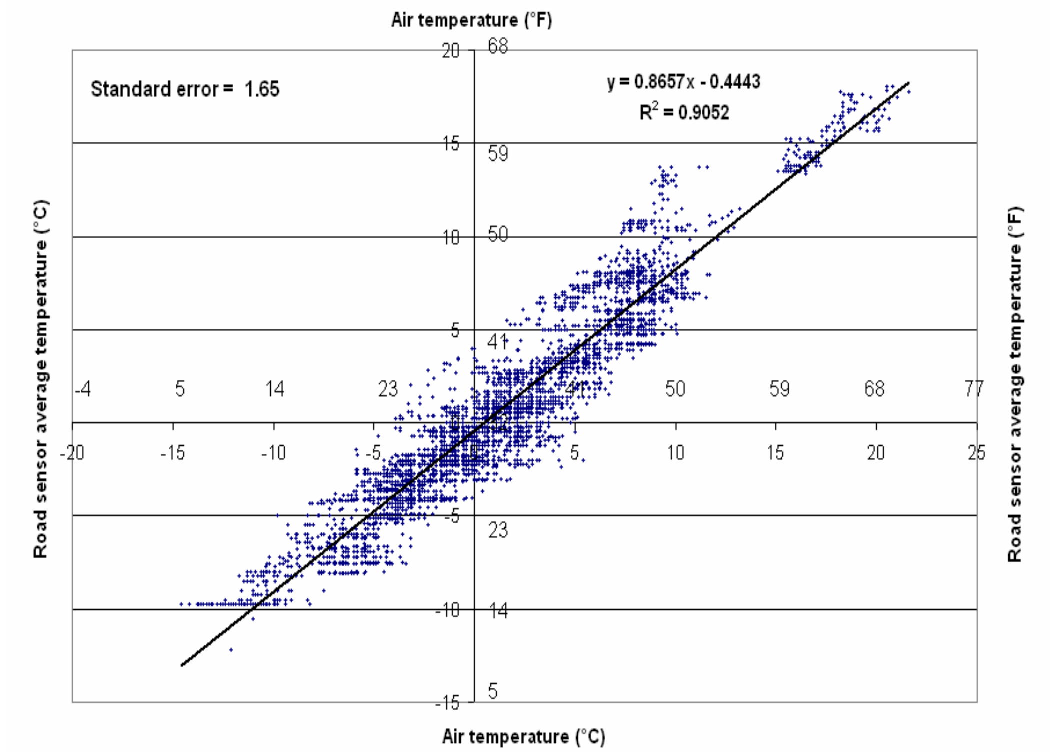



**Figure 72. Air versus road nighttime temperature correlation graph for Site 68 I77 Summit County (Sensors 5 & 6) January 21 - April 5, 2005**

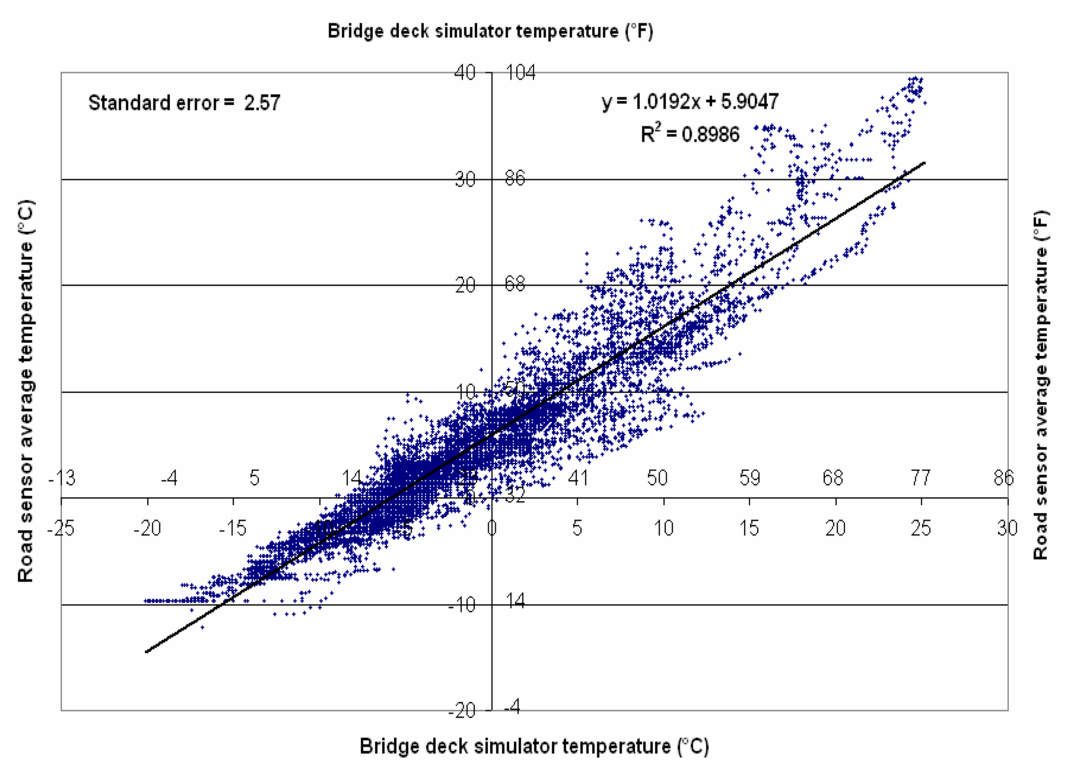



**Figure 73. BDS versus road nighttime temperature correlation graph for Site 68 I77 Summit County (Sensors 5 & 6) January 21 - April 5, 2005**

## 9.4.2 Day time Correlation

Figure 74 shows the air versus BDS temperature correlation for all day data for the entire data collection period of January 21, 2005-April 5, 2005. Figure 75 and Figure 76 show the air and BDS versus bridge all-day temperature correlations, respectively. Figure 77 and Figure 78 show the air and BDS versus average road all-day temperature correlations on I271. Figure 79 and Figure 80 show the air and BDS versus average road all-day temperature correlations on I77.

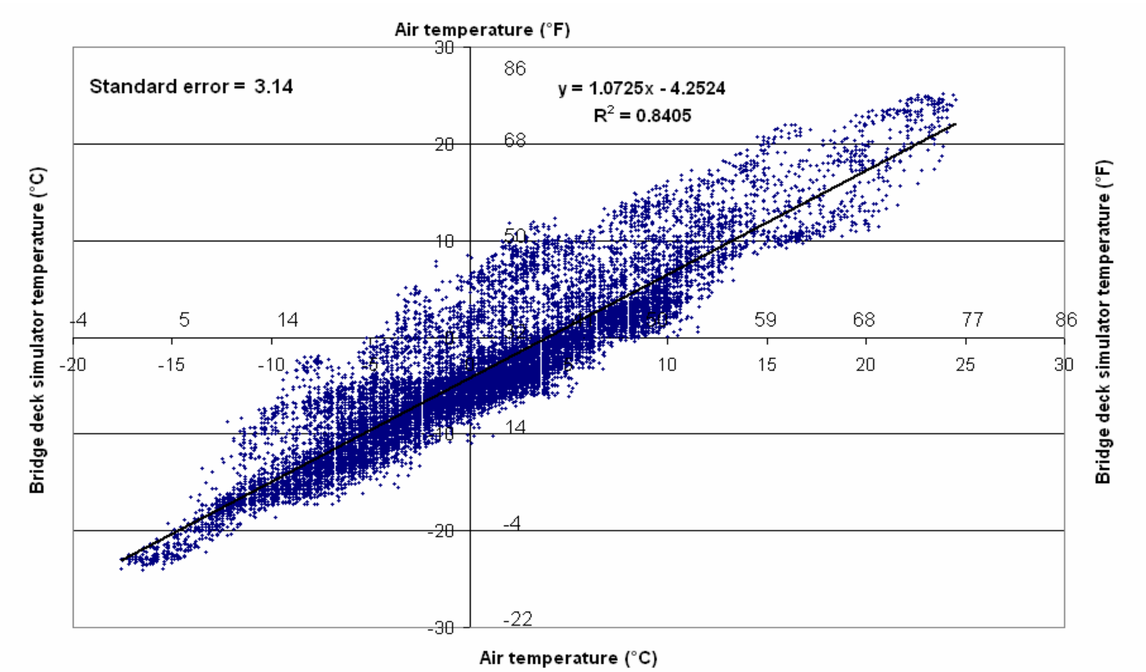



**Figure 74. Air versus BDS all-day temperature correlation graph for Site 68 I271 and I77 Summit County, January 21 - April 5, 2005**

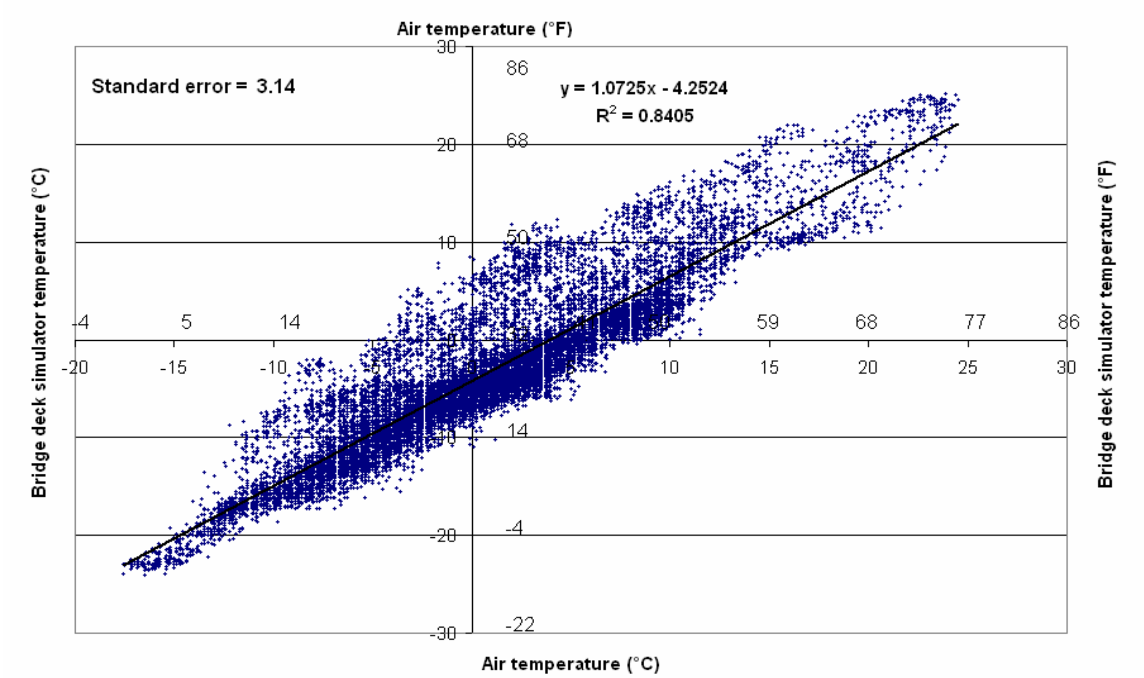



**Figure 75. Air versus bridge all-day temperature correlation graph for Site 68 I271 Summit County, January 21 - April 5, 2005**

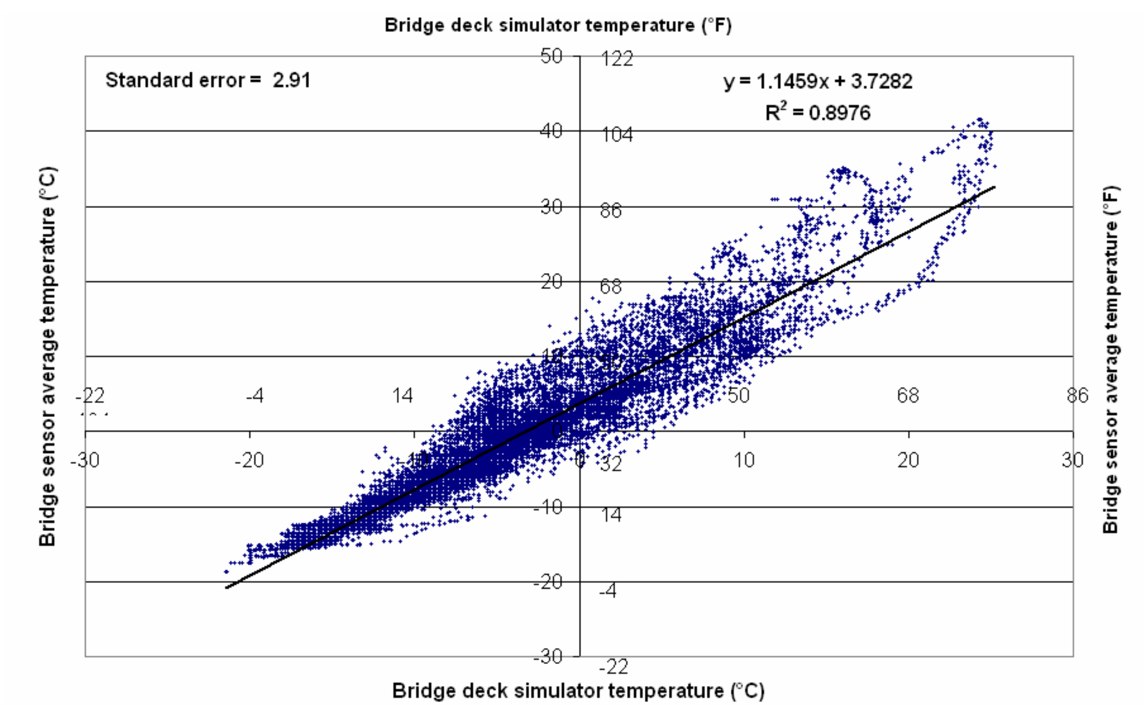



**Figure 76. BDS versus bridge all-day temperature correlation graph for Site 68 I271 Summit County, January 21 - April 5, 2005**

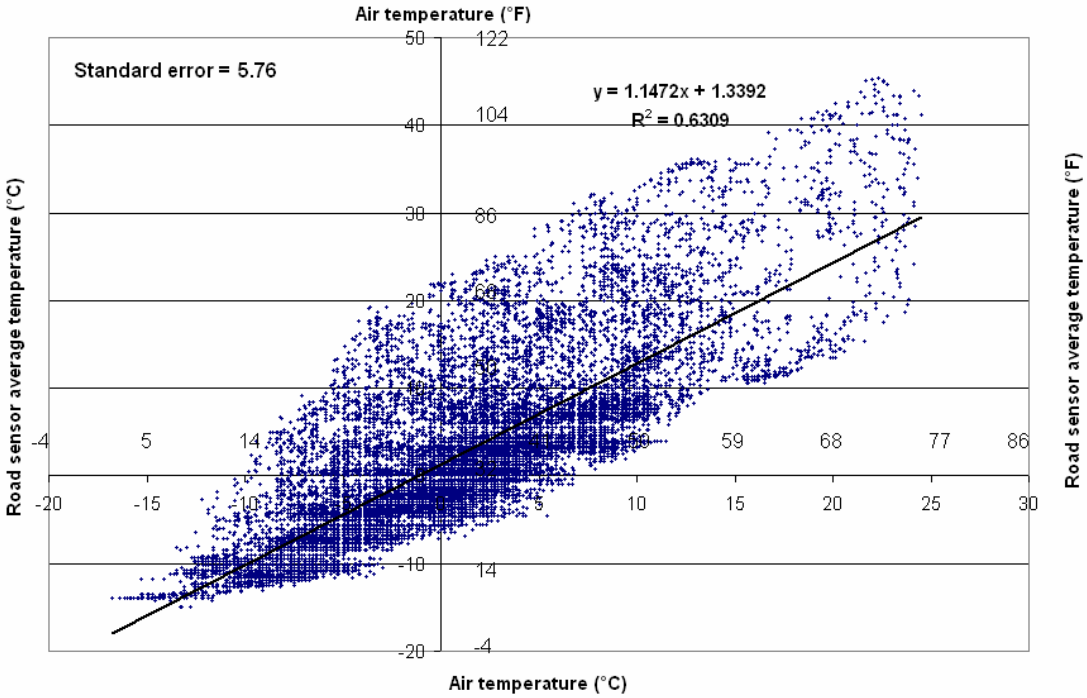



**Figure 77. Air versus road all-day temperature correlation graph for Site 68 I271 Summit County (Sensors 3 & 4) January 21 - April 5, 2005**

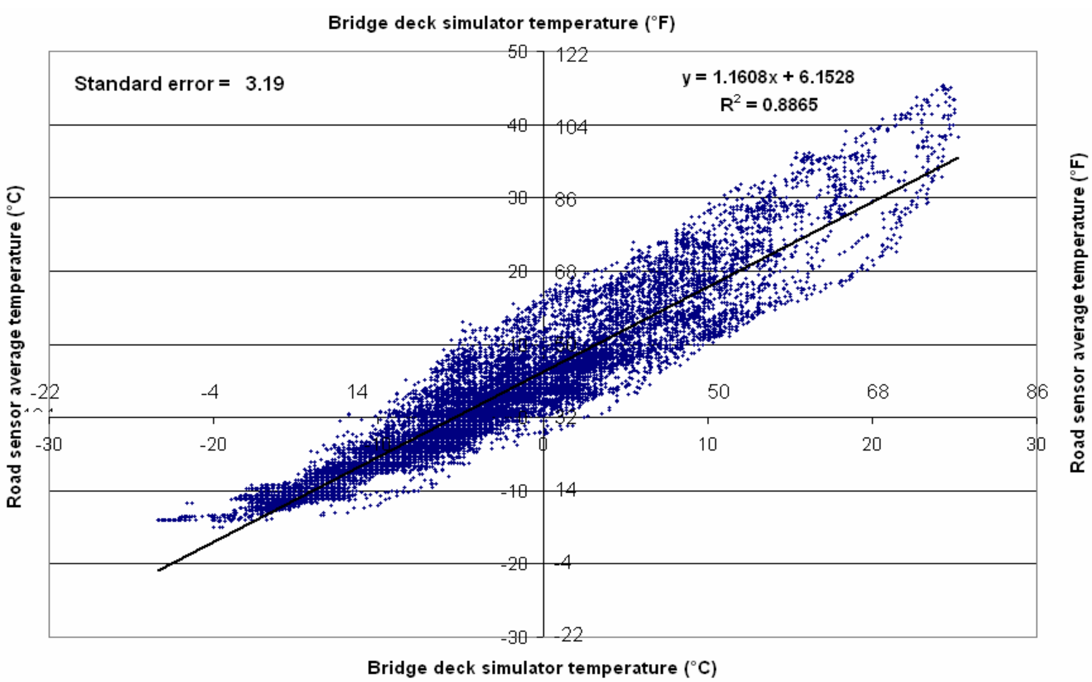



**Figure 78. BDS versus road all-day temperature correlation graph for Site 68 I271 Summit County (Sensors 3 & 4) January 21 - April 5, 2005**

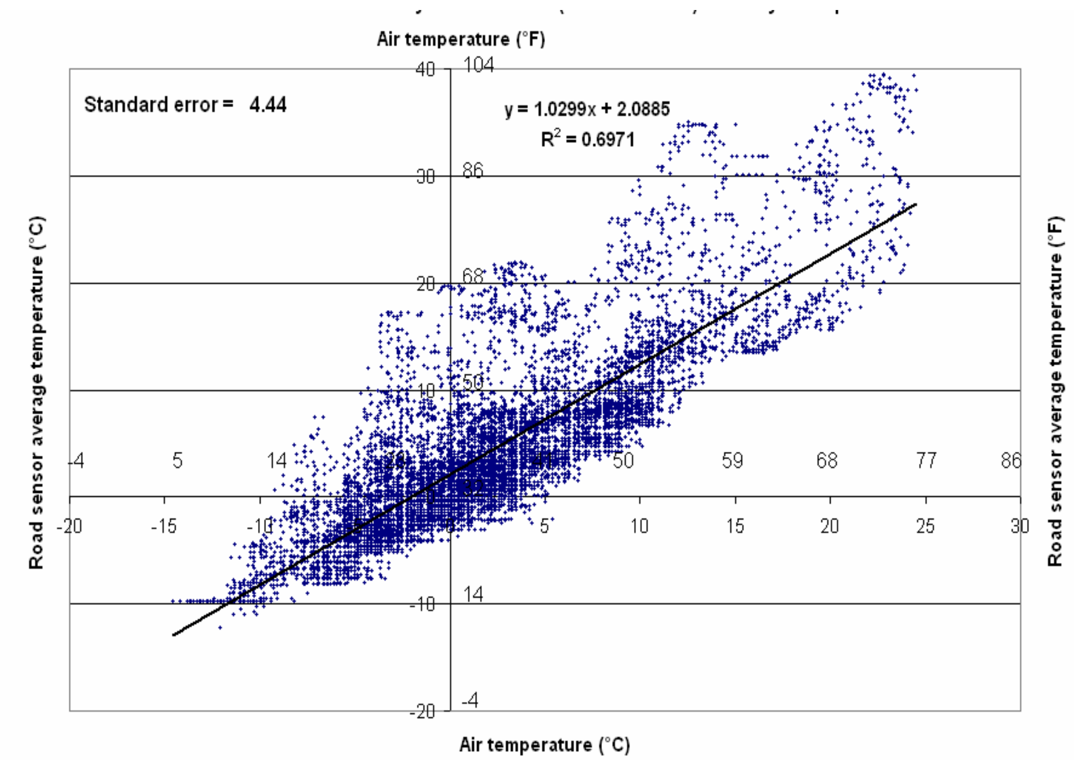



**Figure 79. Air versus road all-day temperature correlation graph for Site 68 I77 Summit County (Sensors 5 & 6) January 21 - April 5, 2005**

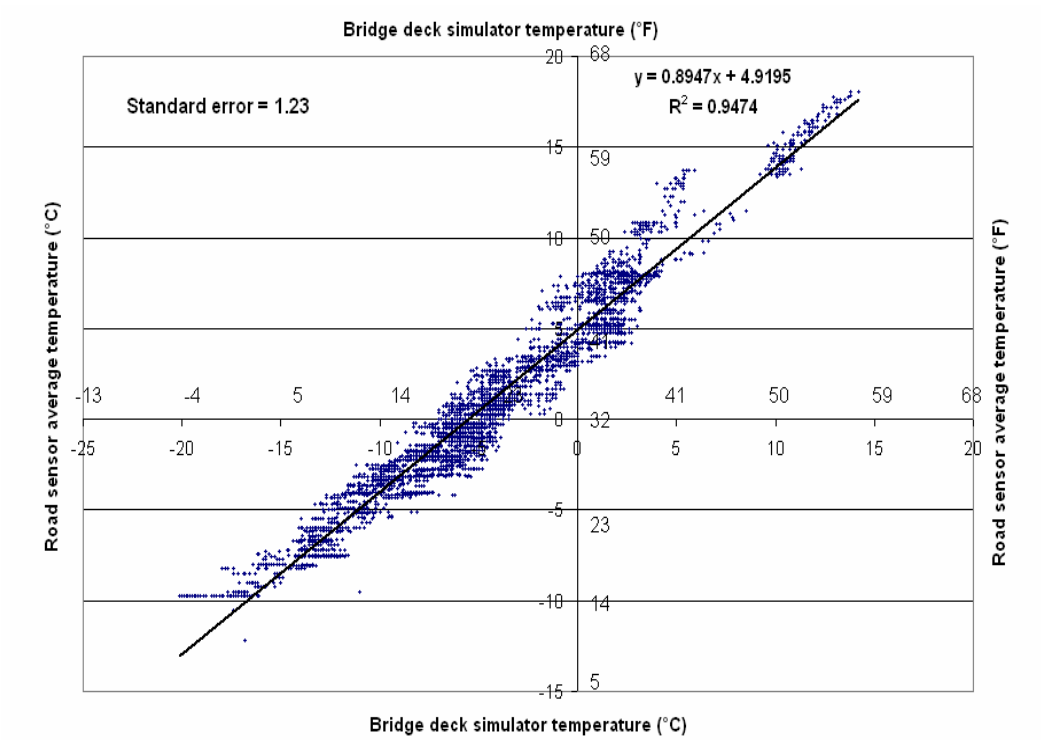



**Figure 80. BDS versus road all-day temperature correlation graph for Site 68 I77 Summit County Sensors 5 & 6) January 21-April 5, 2005**

## 9.5 Site 69 Hamilton County

### 9.5.1 Night time correlations

Figure 81 shows the correlation between the air temperature and the bridge deck simulator (BDS) temperature for Site 69 in Hamilton County. Figure 82 and Figure 83 respectively show the correlations of the air and BDS temperatures with the average bridge sensor temperature. Figure 84 and Figure 85 respectively show the correlations of the air and BDS temperature with the average of temperatures of the road sensors.

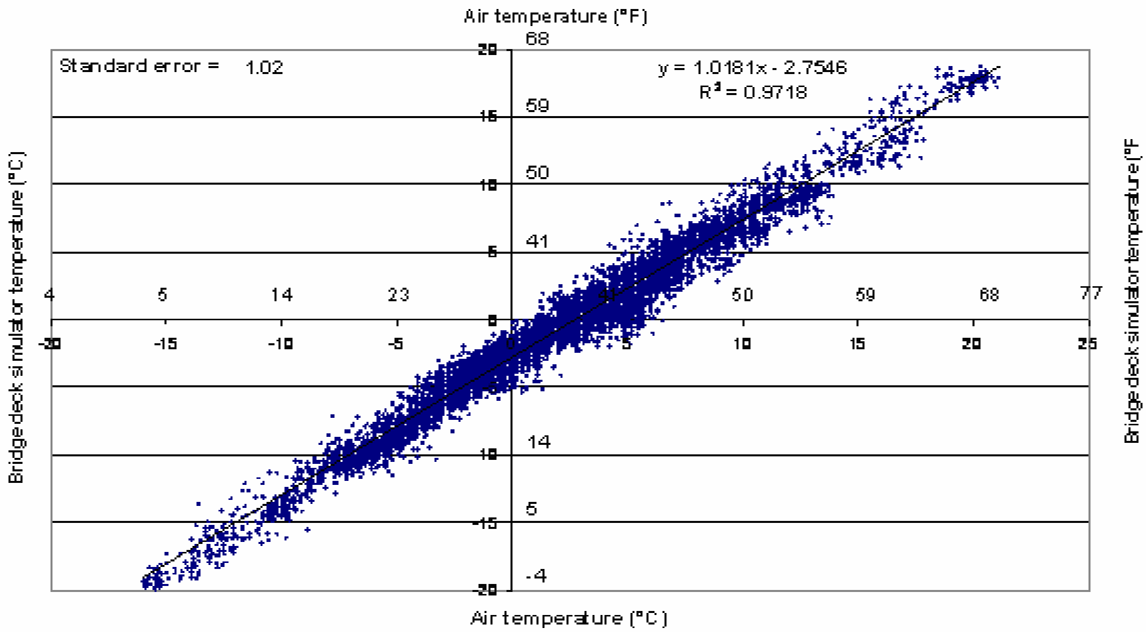



**Figure 81. Air versus BDS nighttime temperature correlation graph for Site 69 I275 Hamilton County, January 21 - April 5, 2005**

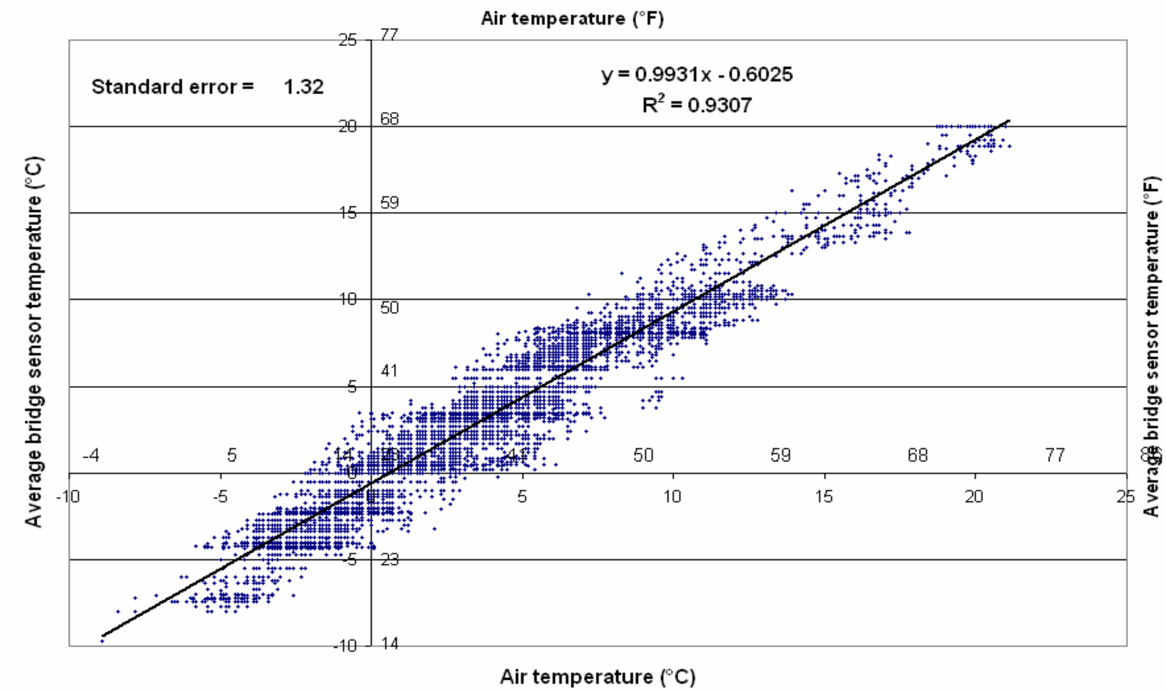



**Figure 82. Air versus bridge nighttime temperature correlation graph for Site 69 I275 Hamilton County, January 21-April 5, 2005**

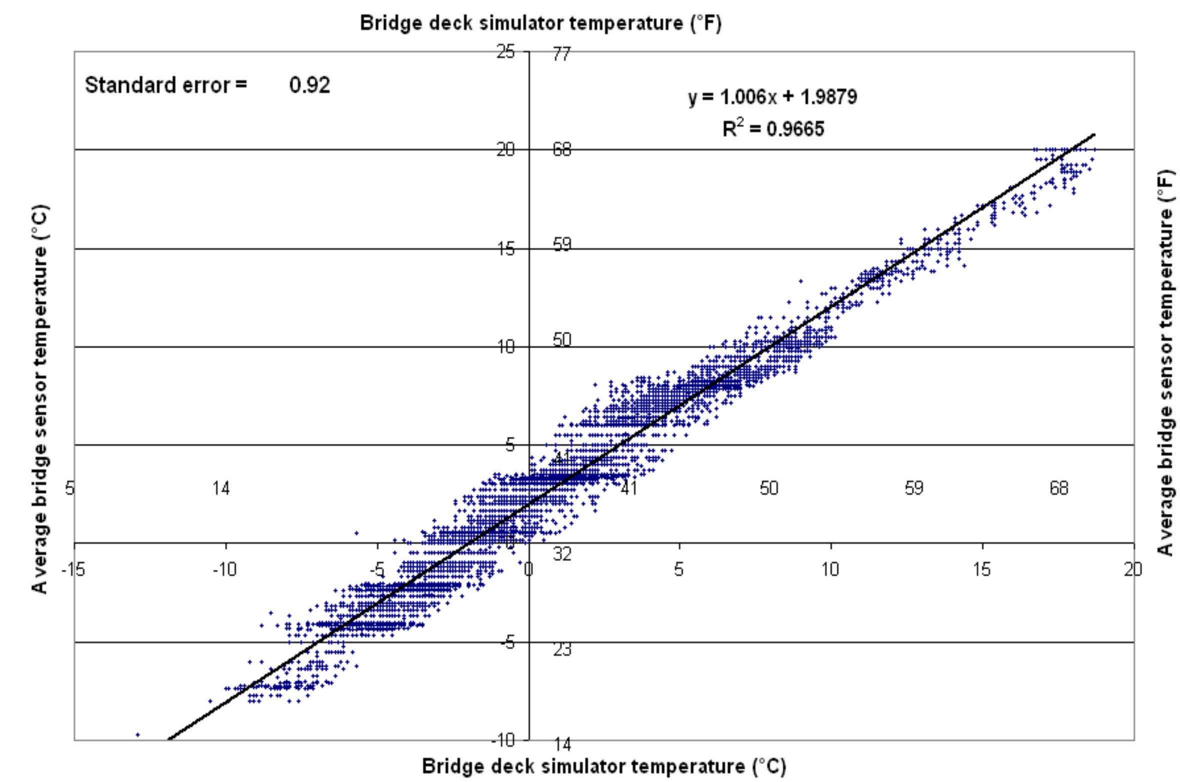



**Figure 83. BDS versus bridge nighttime temperature correlation graph for Site 69 I275 Hamilton County, January 21 - April 5, 2005**

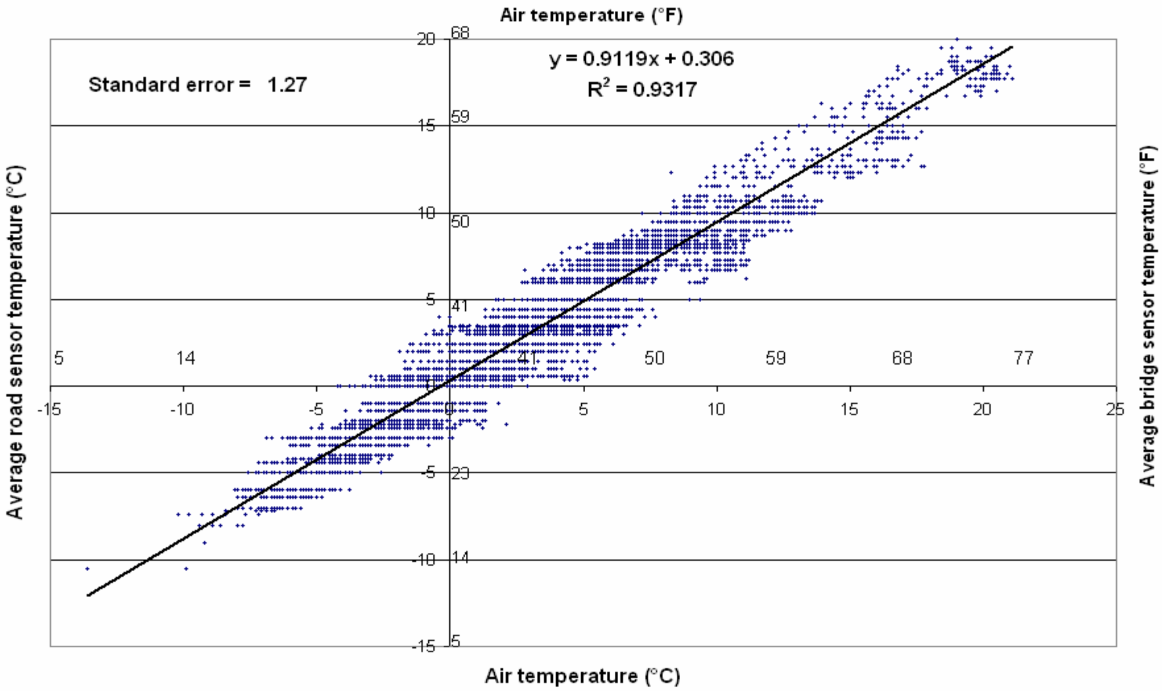



**Figure 84. Air versus road nighttime temperature correlation graph for Site 69 I275 Hamilton County, January 21 - April 5, 2005**

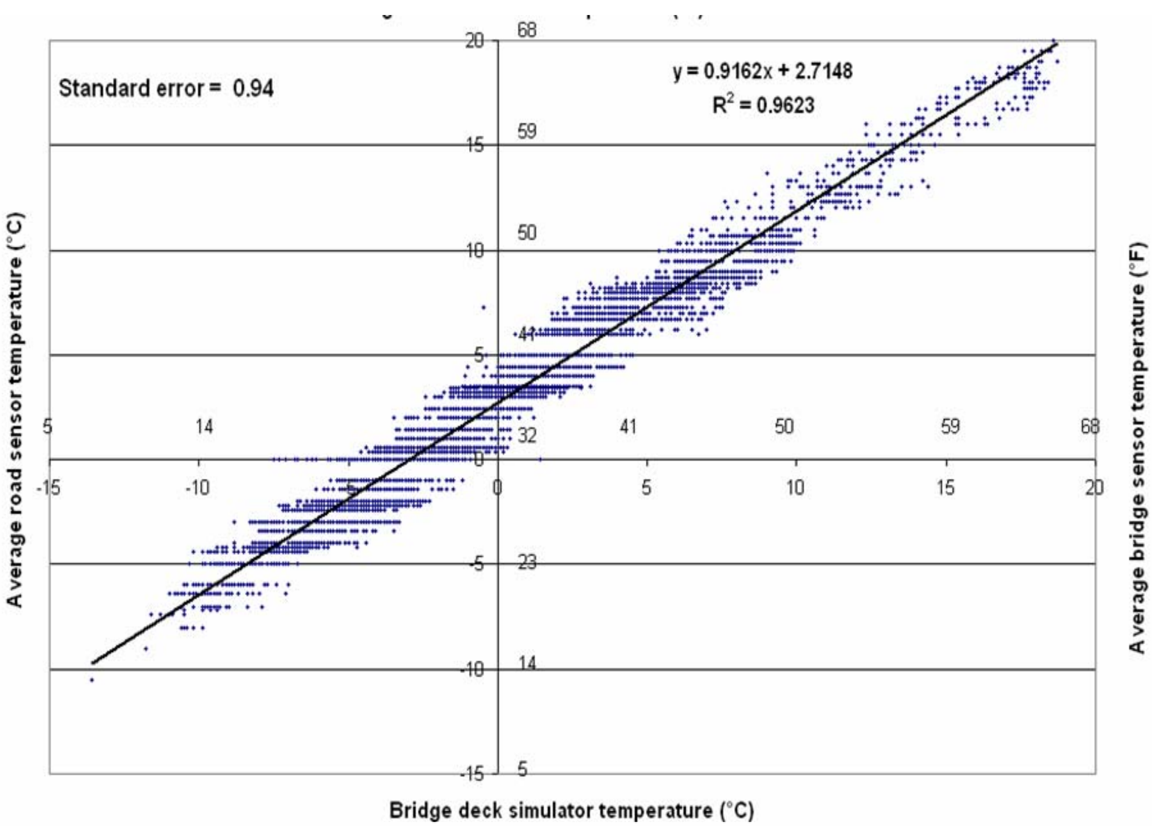



**Figure 85. BDS versus road nighttime temperature correlation graph for Site 69 I275 Hamilton County, January 21 - April 5, 2005**

### 9.5.2 Day Time Correlations

Figure 86 shows the air versus BDS temperature correlation for all day data for the entire data collection period of January 21, 2005-April 5, 2005. Figure 87 and Figure 88 show the air and BDS versus bridge all-day temperature correlations, respectively. Figure 89 and Figure 90 show the air and BDS versus average road all-day temperature correlations.

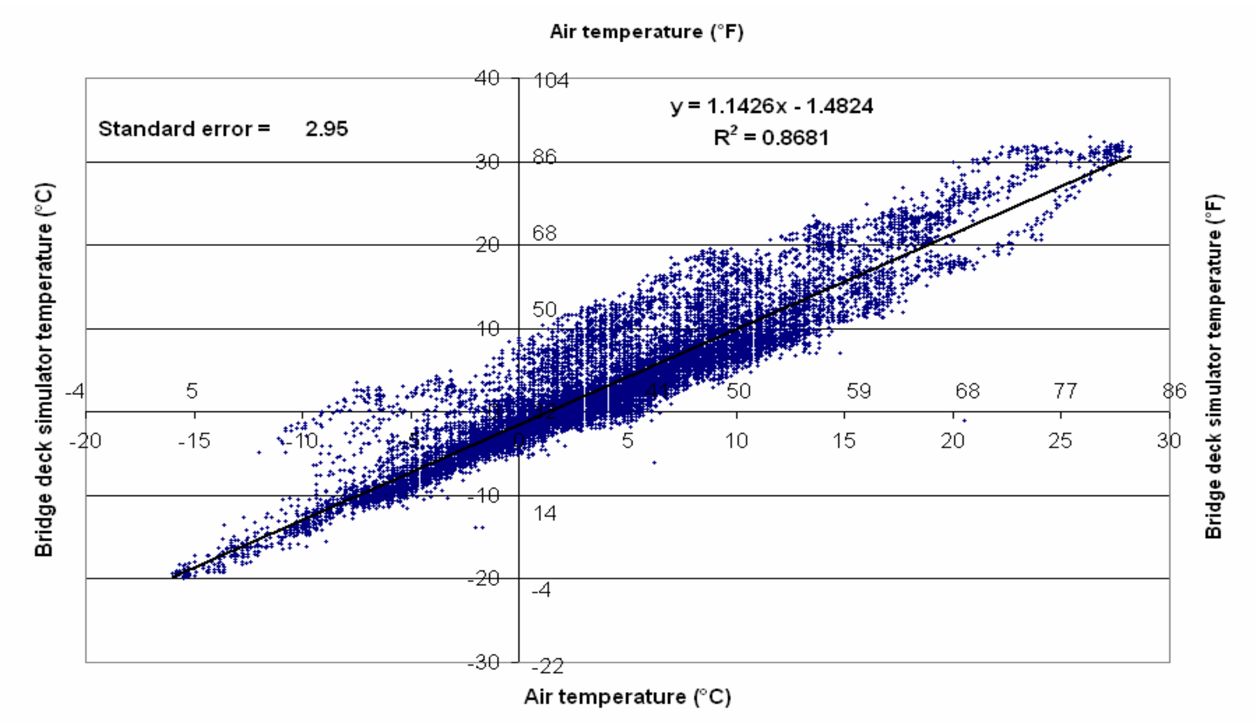



**Figure 86. Air versus BDS all-day temperature correlation graph for Site 69 I275 Hamilton County, January 21 - April 5, 2005**

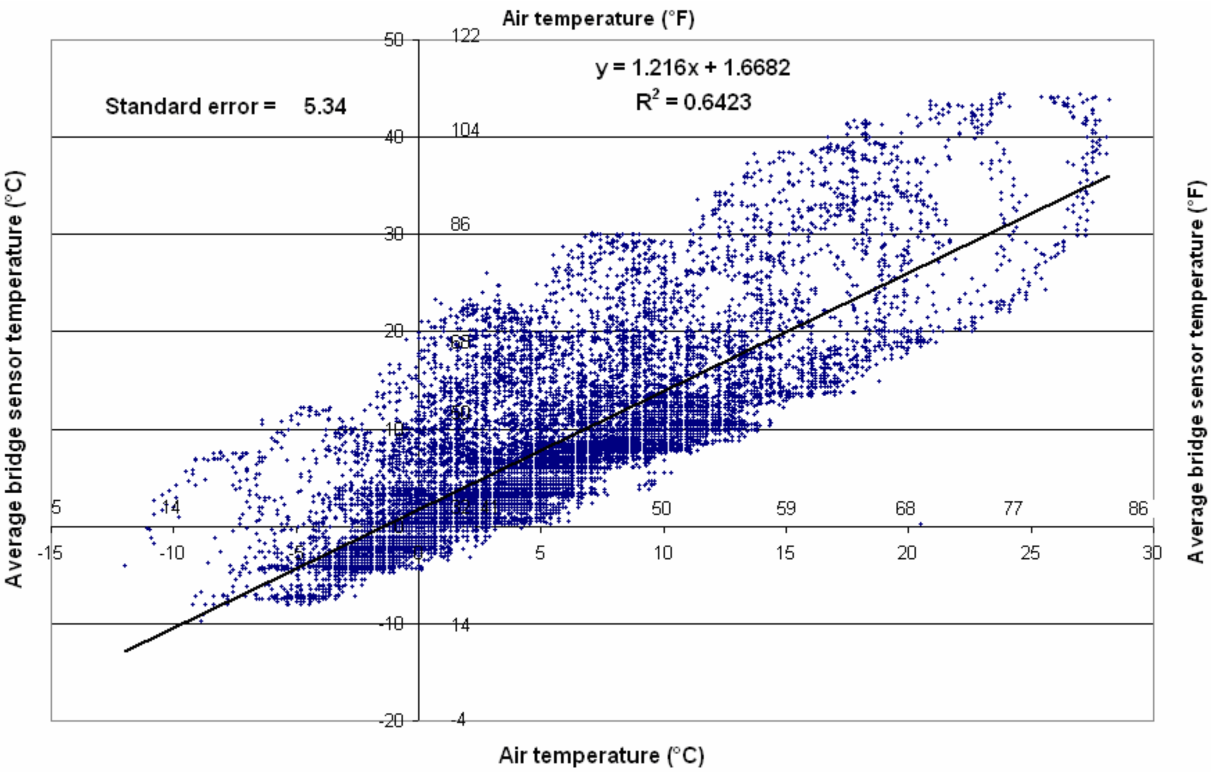



Figure 87. Air versus bridge all-day temperature correlation graph for Site 69 I275 Hamilton County, January 21-April 5, 2005

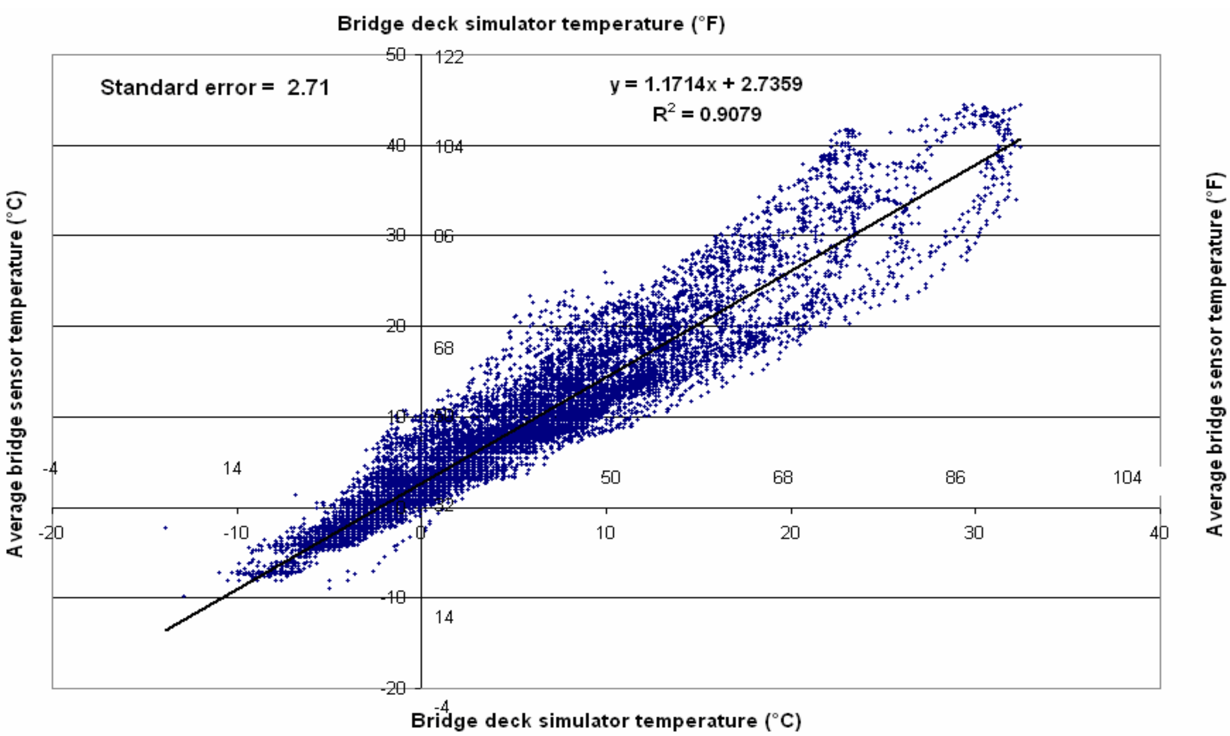



Figure 88. BDS versus bridge all-day temperature correlation graph for Site 69 I275 Hamilton County, January 21 - April 5, 2005

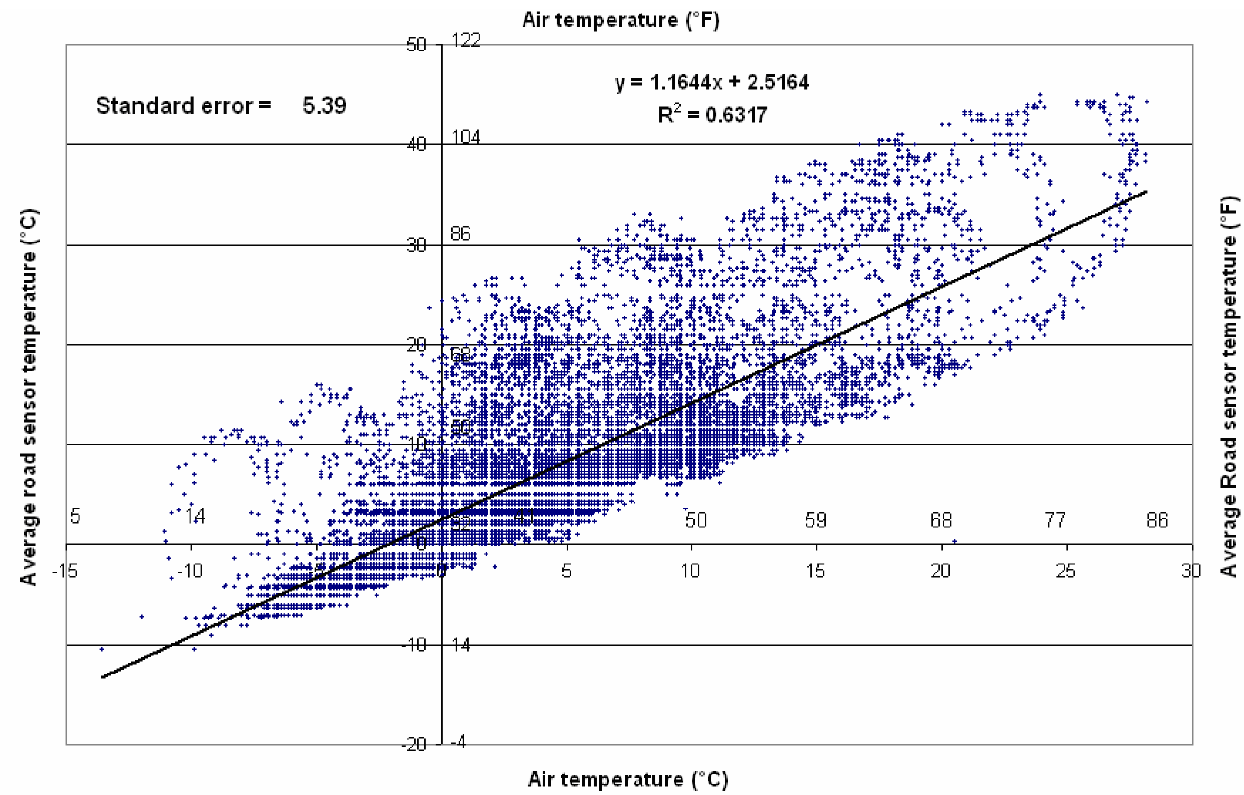



**Figure 89. Air versus road all-day temperature correlation graph for Site 69 I275 Hamilton County, January 21 - April 5, 2005**

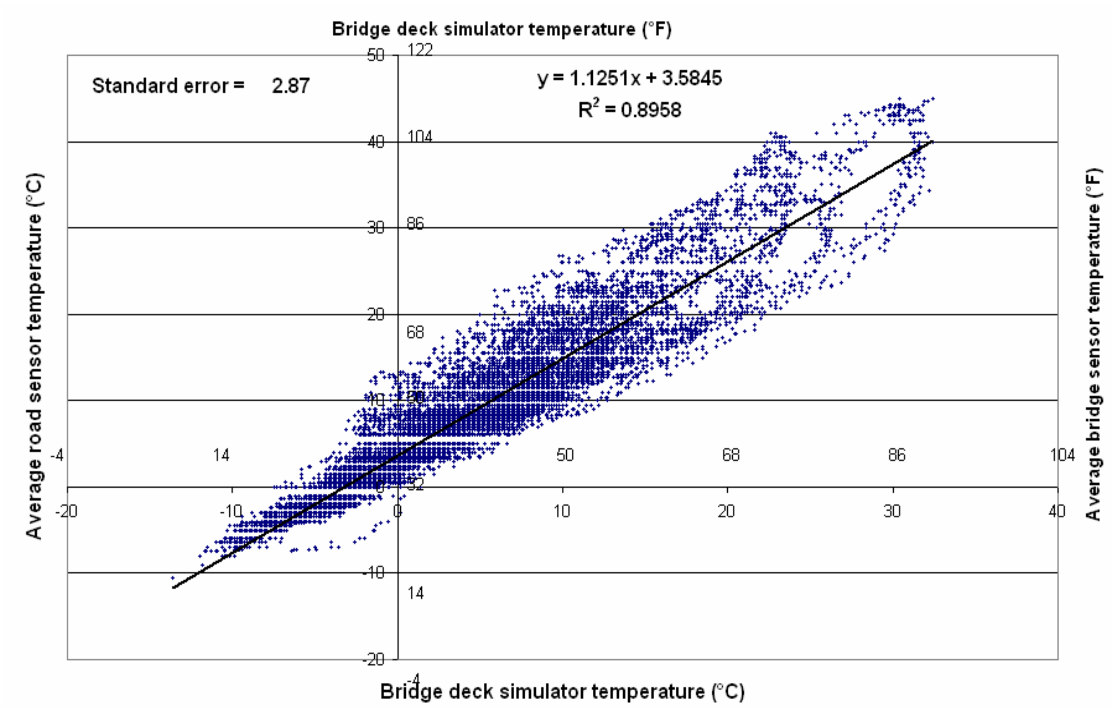



**Figure 90. BDS versus road all-day temperature correlation graph for Site 69 I275 Hamilton County, January 21 - April 5, 2005**

## 9.6 Site 70 Hamilton/Clermont County line

### 9.6.1 Night Time Correlations

Figure 91 shows the correlation between the air temperature and the bridge deck simulator (BDS) temperature for Site 70 at the Hamilton/Clermont County line. Figure 92 and Figure 93 respectively show the correlations of the air and BDS temperatures with the average bridge sensor temperature. Figure 94 and Figure 95 respectively show the correlations of the air and BDS temperature with the average of temperatures of the road sensors.

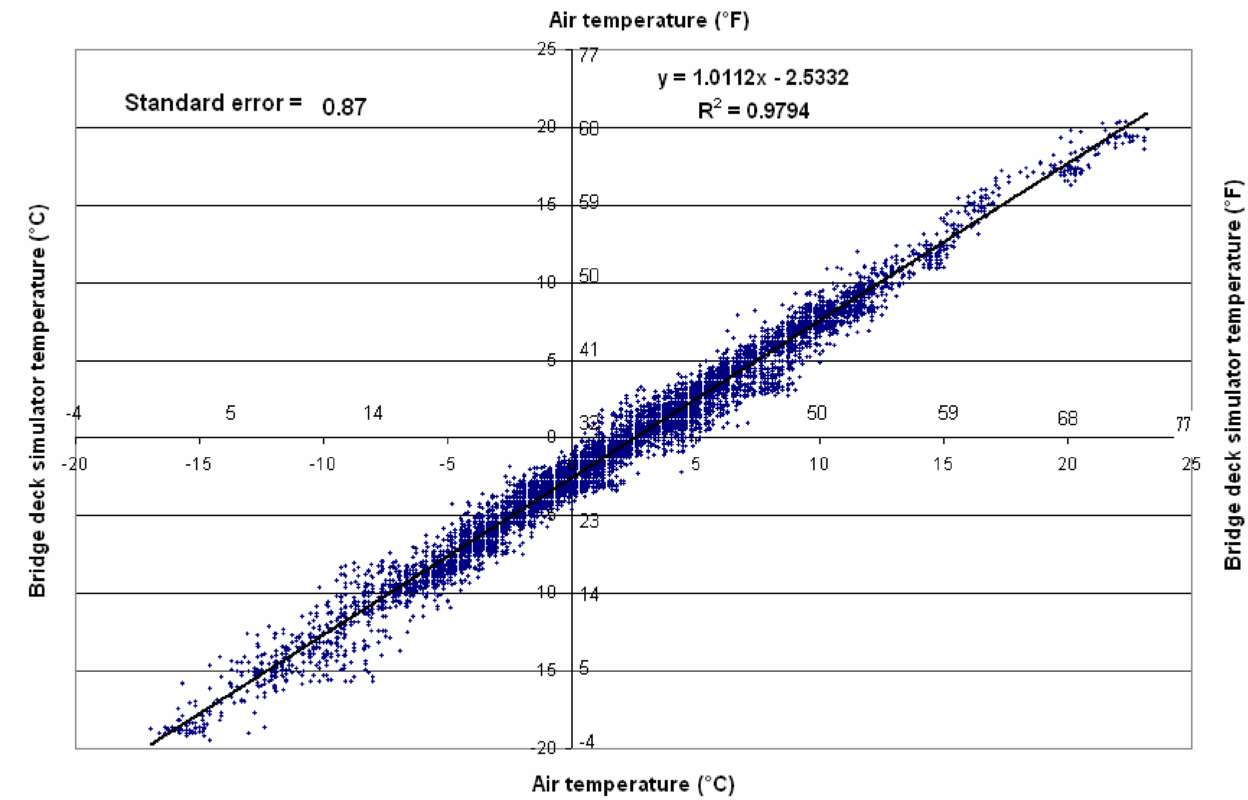



**Figure 91. Air versus BDS nighttime temperature correlation graph for Site 70 I275 Hamilton/Clermont County, January 21 - April 5, 2005**

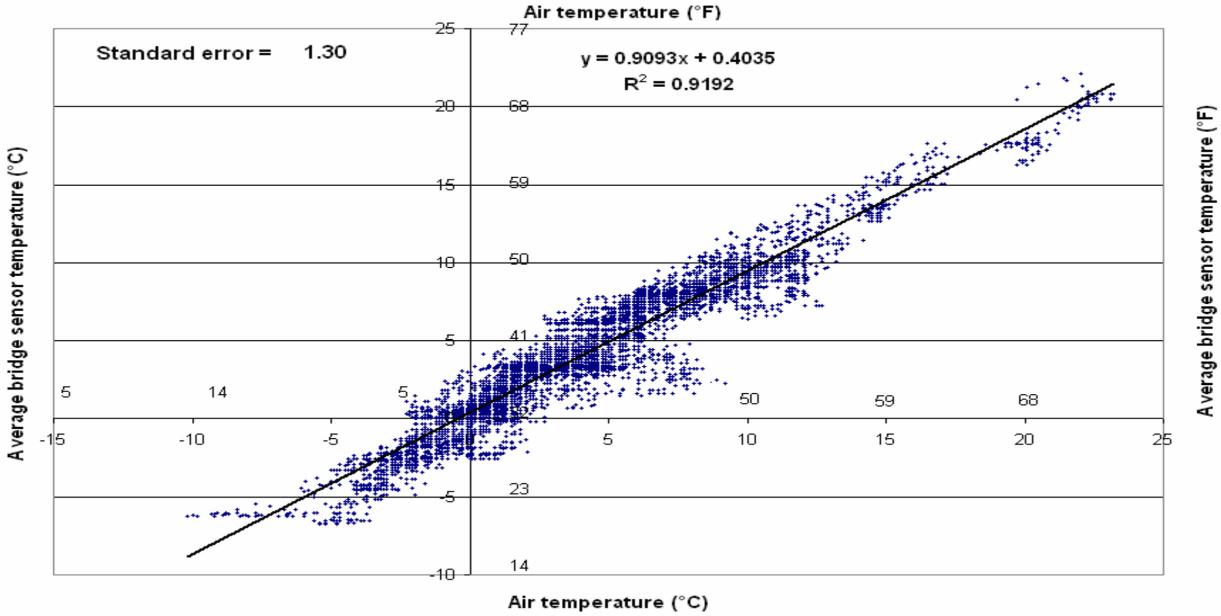



Figure 92. Air versus bridge nighttime temperature correlation graph for Site 70 I275 Hamilton/Clermont County, January 21-April 5, 2005

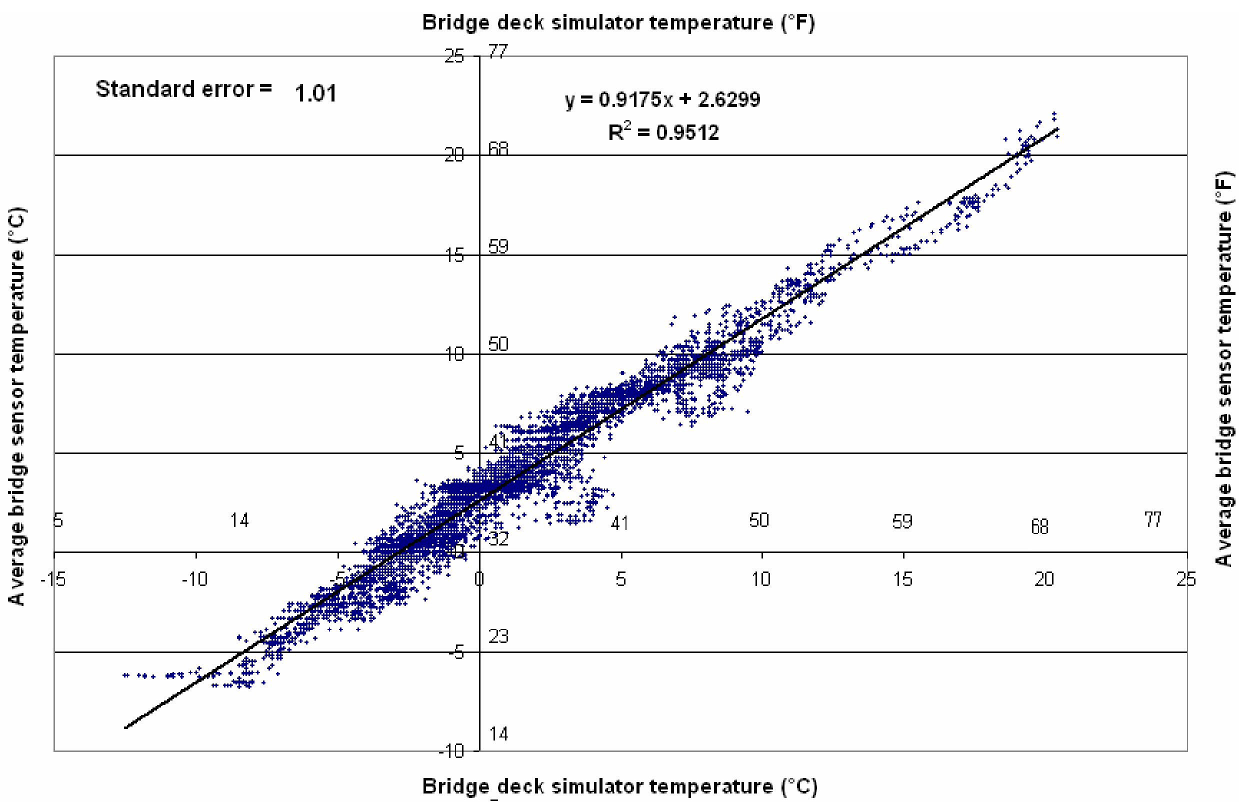



Figure 93. BDS versus bridge nighttime temperature correlation graph for Site 70 I275 Hamilton/Clermont County, January 21-April 5, 2005

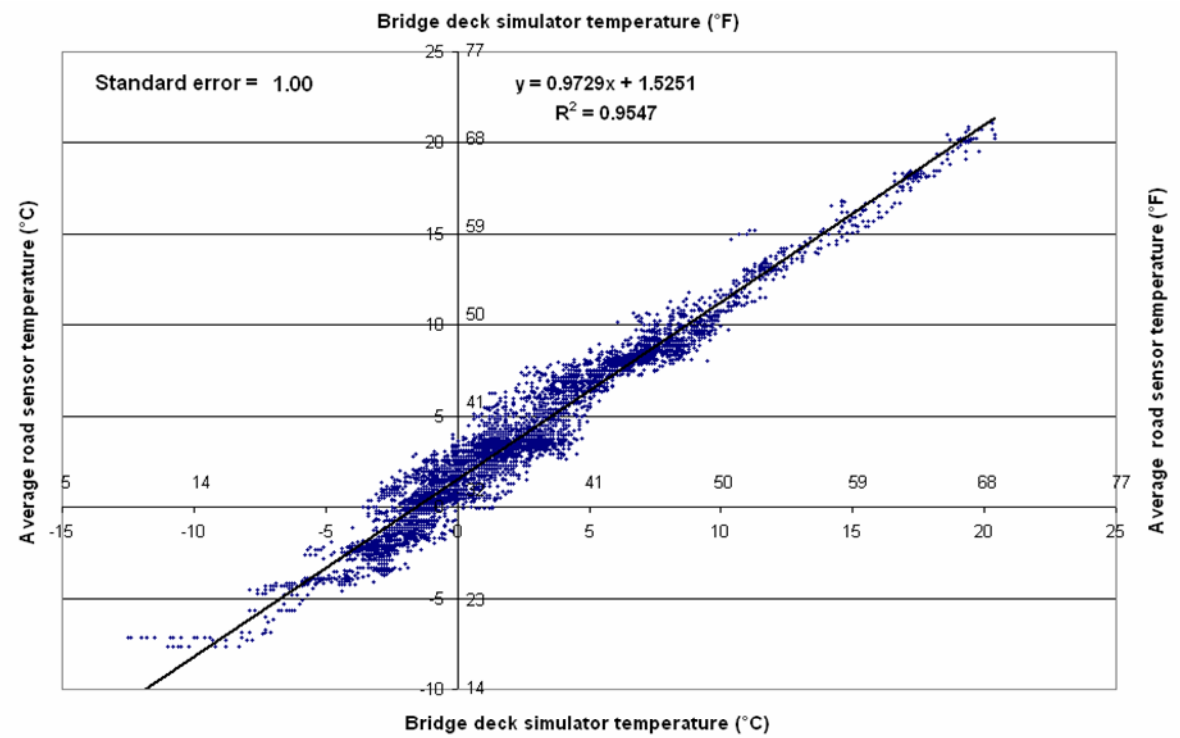



**Figure 94. Air versus road nighttime temperature correlation graph for Site 70 I275 Hamilton/Clermont County, January 21-April 5, 2005**

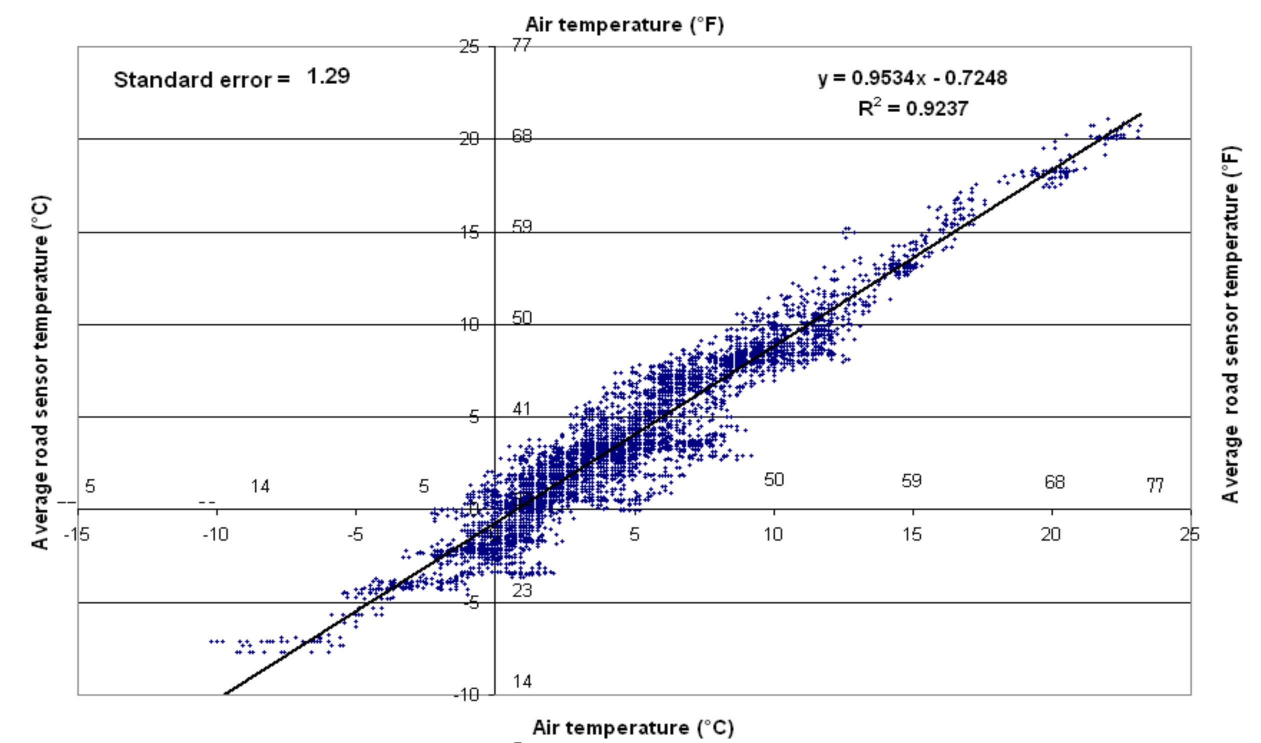



**Figure 95. BDS versus road nighttime temperature correlation graph for Site 70 I275 Hamilton/Clermont County, January 21-April 5, 2005**

## 9.6.2 Day Time Correlations

Figure 96 shows the air versus BDS temperature correlation for all day data for the entire data collection period of January 21, 2005-April 5, 2005. Figure 97 and Figure 98 show the air and BDS versus bridge all-day temperature correlations, respectively. Figure 99 and Figure 100 show the air and BDS versus average road all-day temperature correlations.

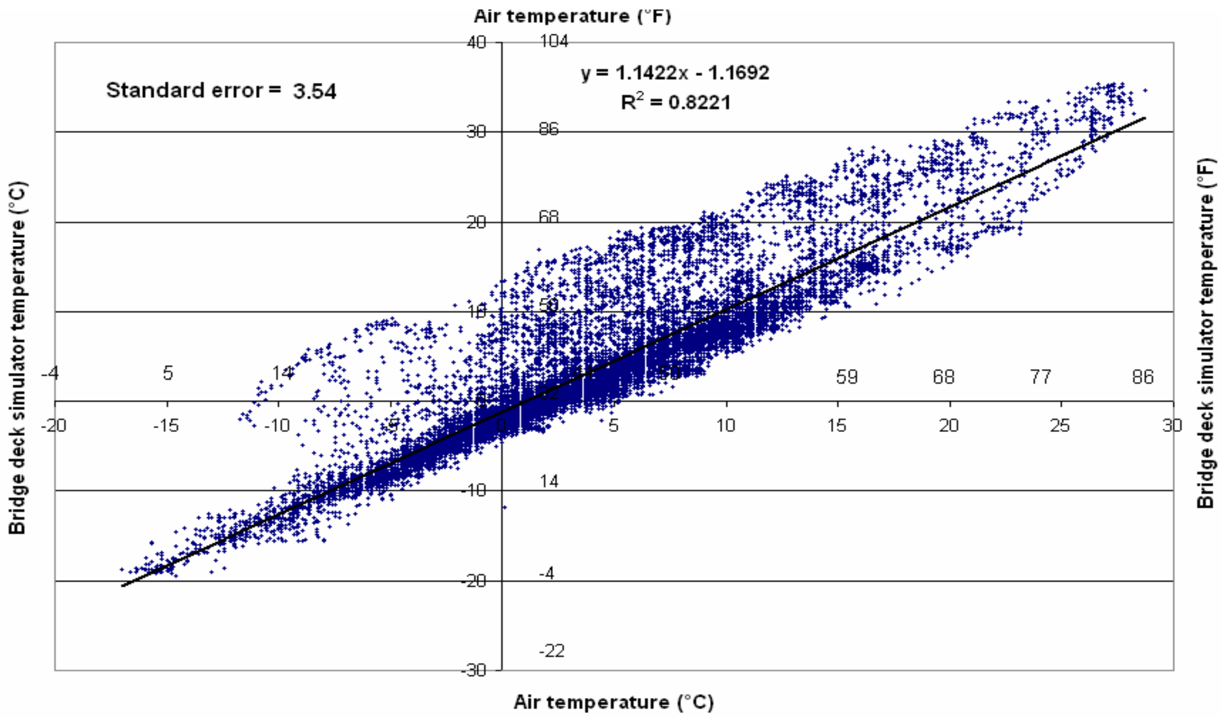



**Figure 96. Air versus BDS all-day temperature correlation graph for Site 70 I275 Hamilton/Clermont County, January 21-April 5, 2005**

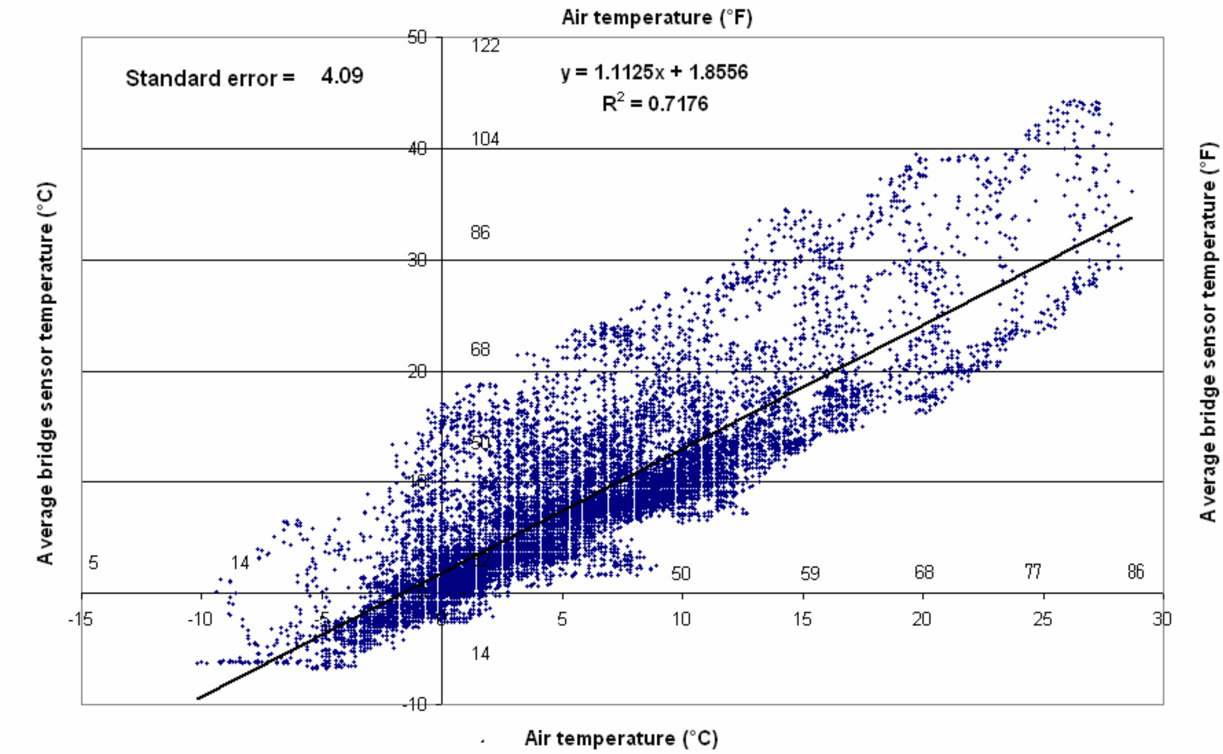



**Figure 97. Air versus bridge all-day temperature correlation graph for Site 70 I275 Hamilton/Clermont County, January 21-April 5, 2005**

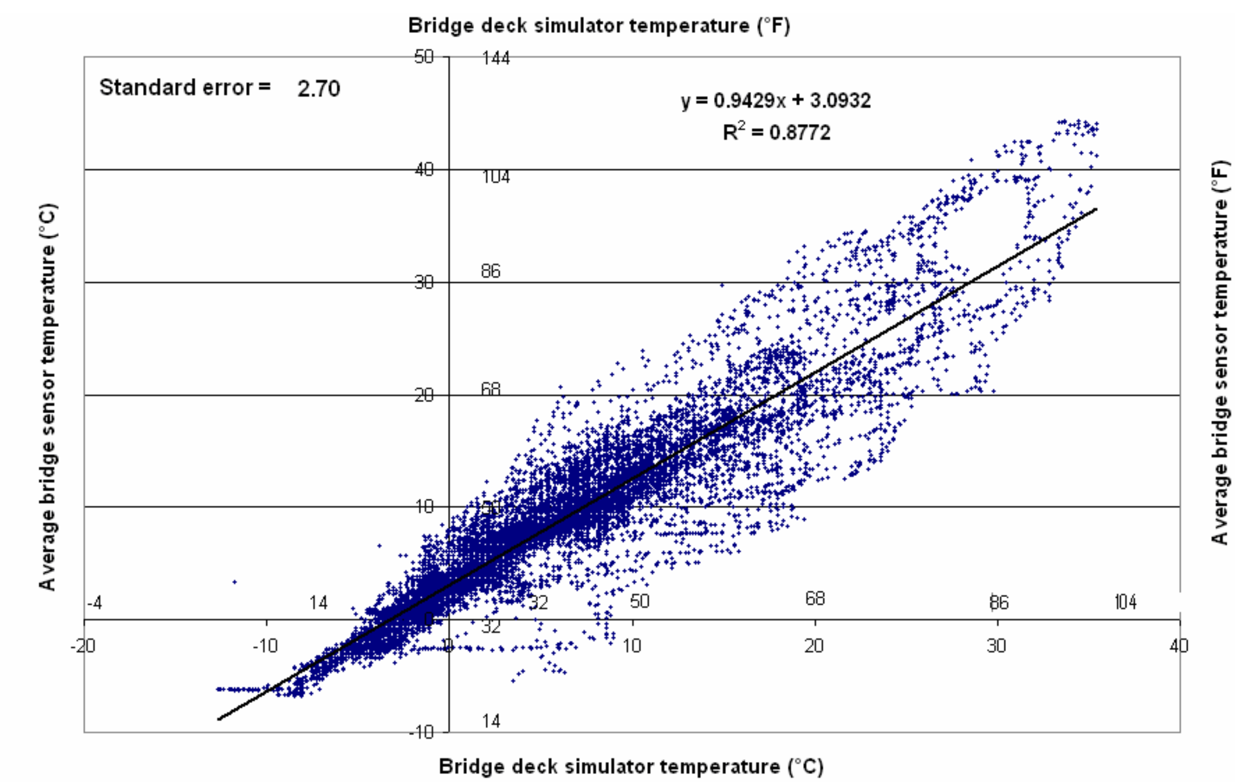



**Figure 98. BDS versus bridge all-day temperature correlation graph for Site 70 I275 Hamilton/Clermont County, January 21-April 5, 2005**

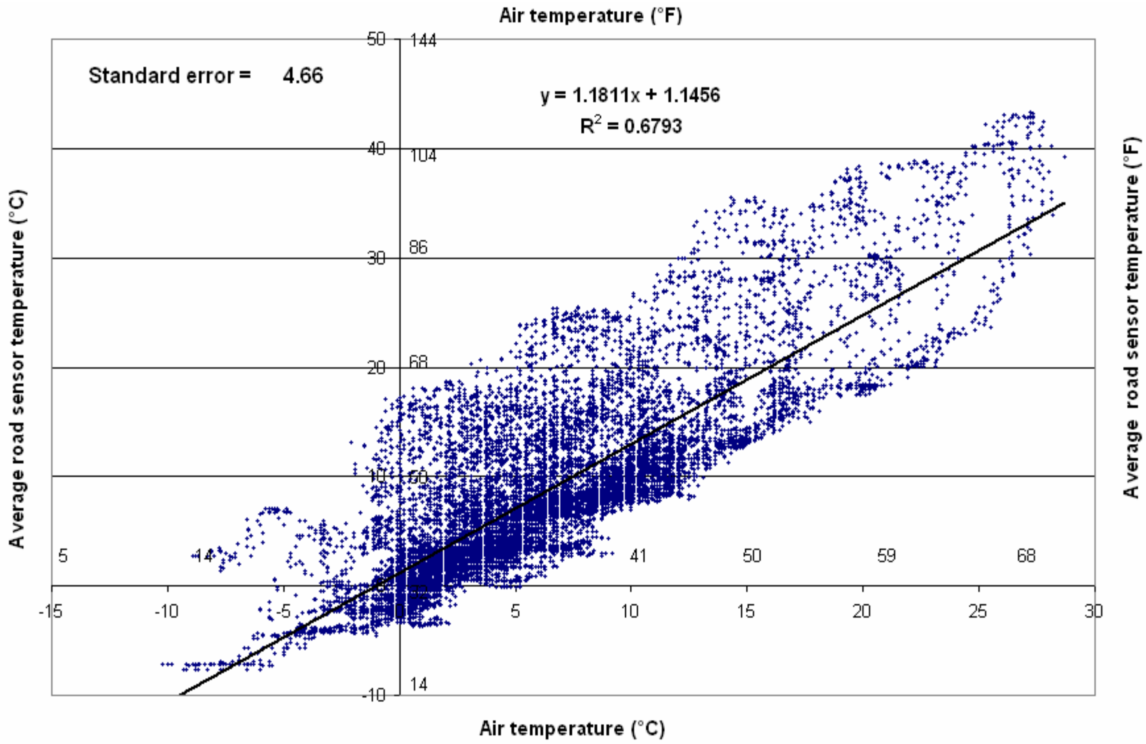



**Figure 99. Air versus road all-day temperature correlation graph for Site 70 I275 Hamilton/Clermont County, January 21-April 5, 2005**

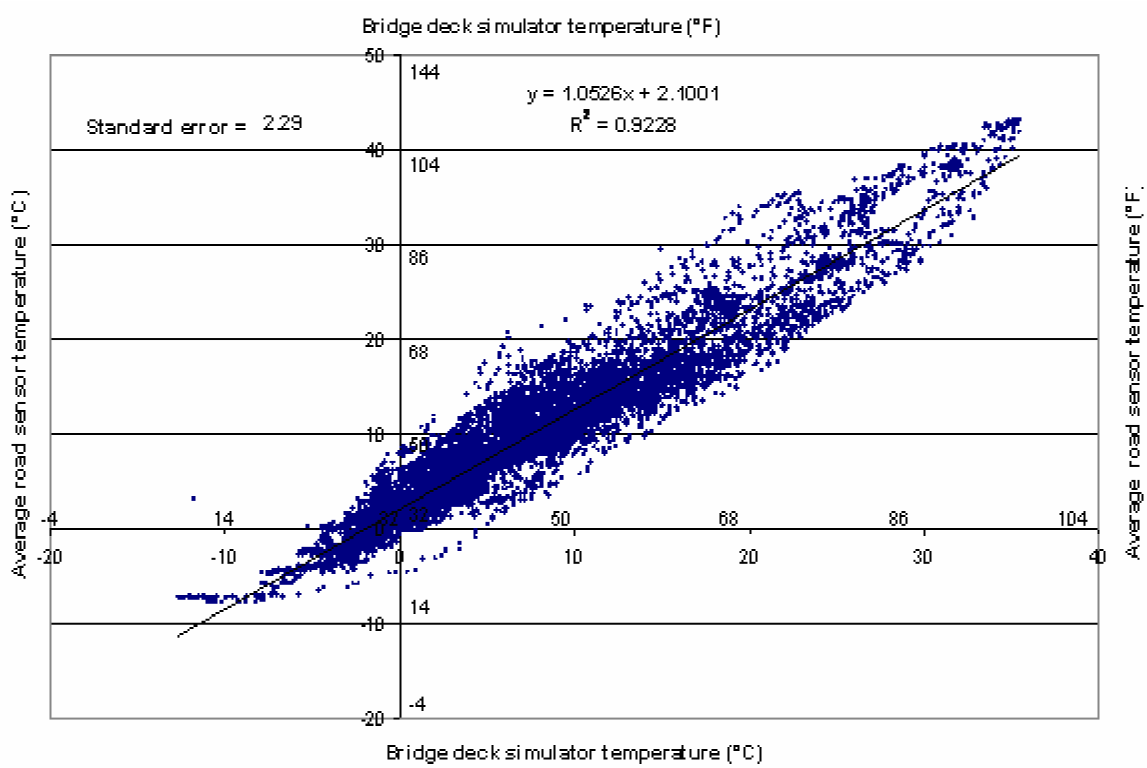



**Figure 100. BDS versus road all-day temperature correlation graph for Site 70 I275 Hamilton/Clermont County, January 21-April 5, 2005**

## 9.7 Site 86 Lorain County

### 9.7.1 Night time correlations

Figure 101 shows the correlation between the air temperature and the bridge deck simulator (BDS) temperature for Site 86 in Lorain County. Figure 102 and Figure 103 respectively show the correlations of the air and BDS temperatures with the average bridge sensor temperature. Figure 104 and Figure 105 respectively show the correlations of the air and BDS temperature with the average of temperatures of the road sensors.

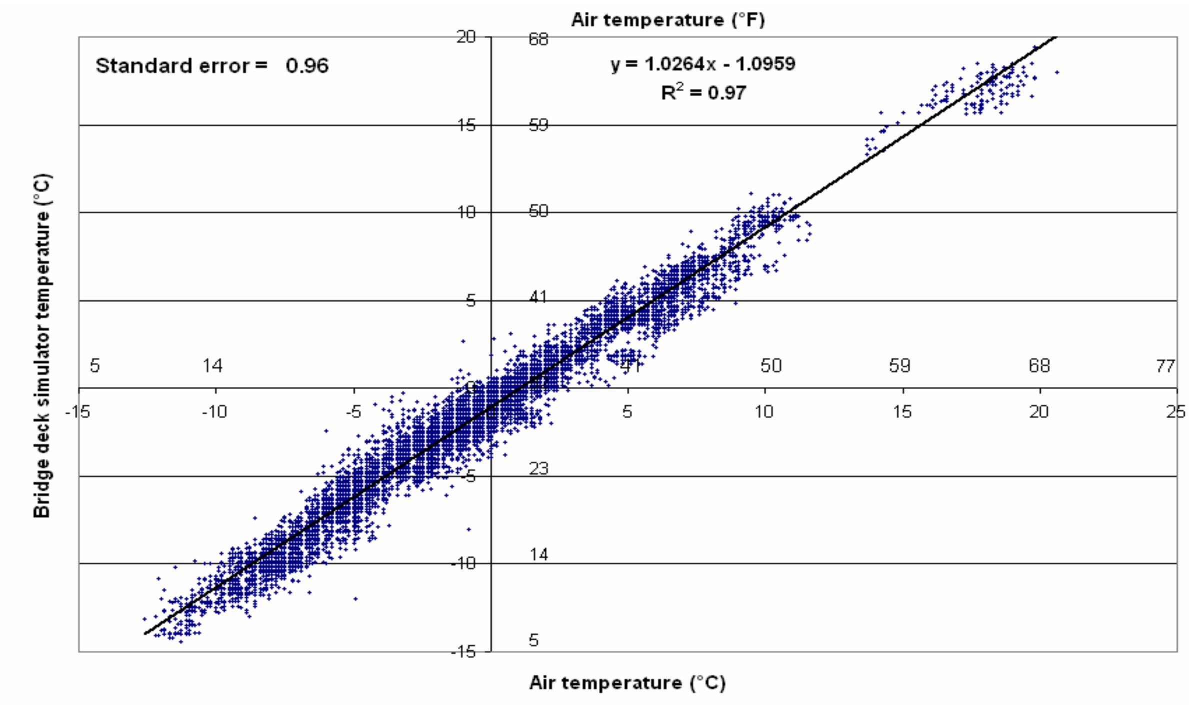



**Figure 101. Air versus BDS nighttime temperature correlation graph for Site 86 I90 Lorain County, January 21-April 5, 2005**

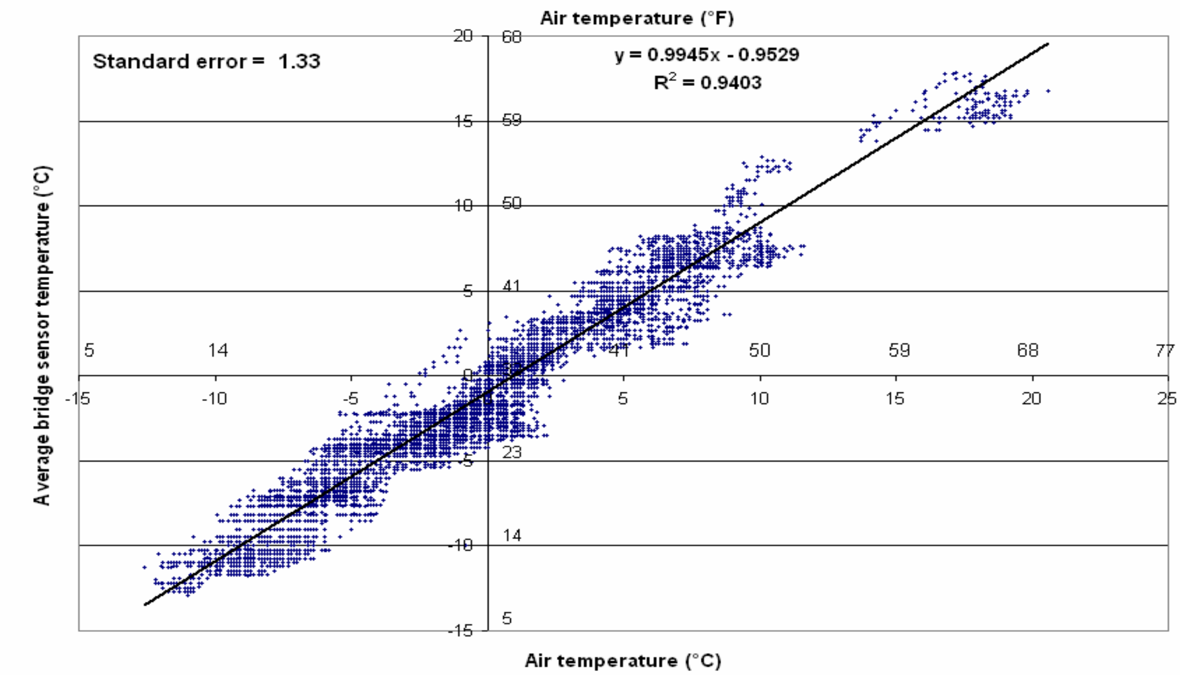



**Figure 102. Air versus bridge nighttime temperature correlation graph for Site 86 I90 Lorain County, January 21-April 5, 2005**

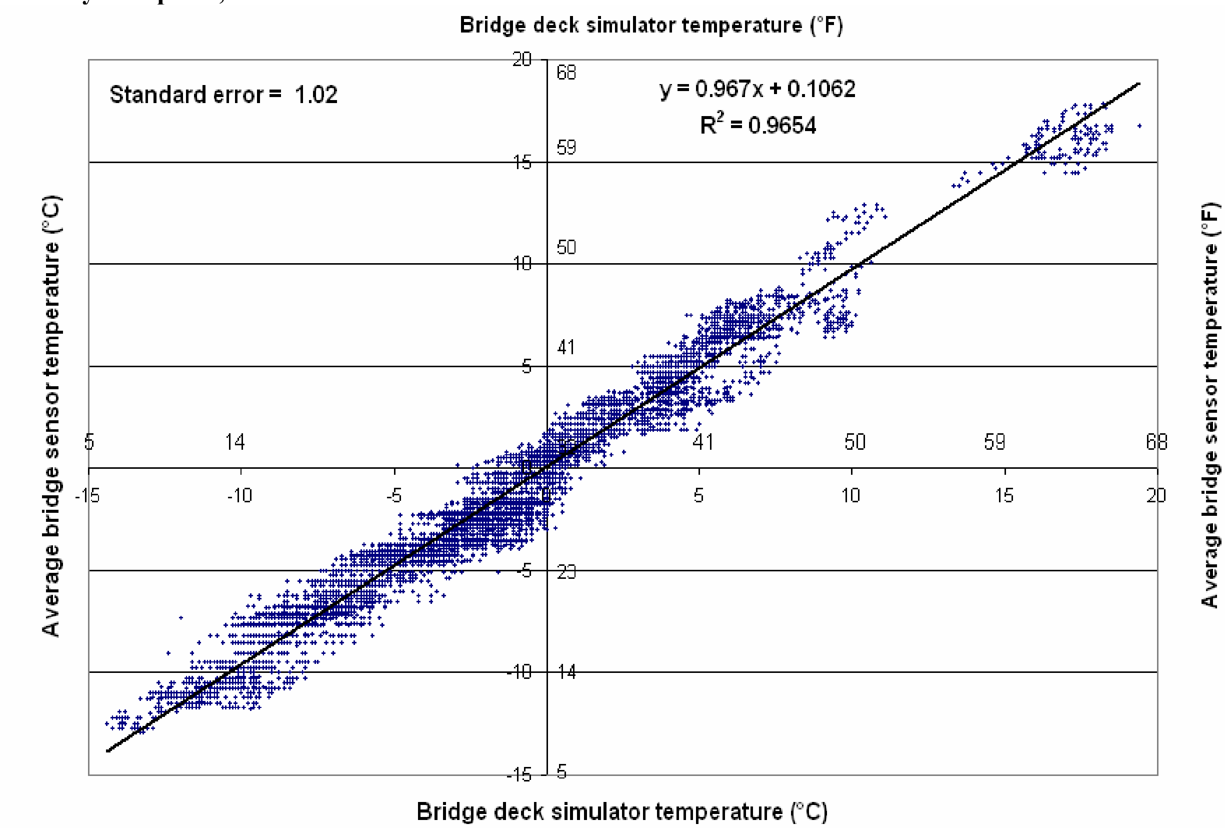



**Figure 103. BDS versus bridge nighttime temperature correlation graph for Site 86 I90 Lorain County, January 21-April 5, 2005**

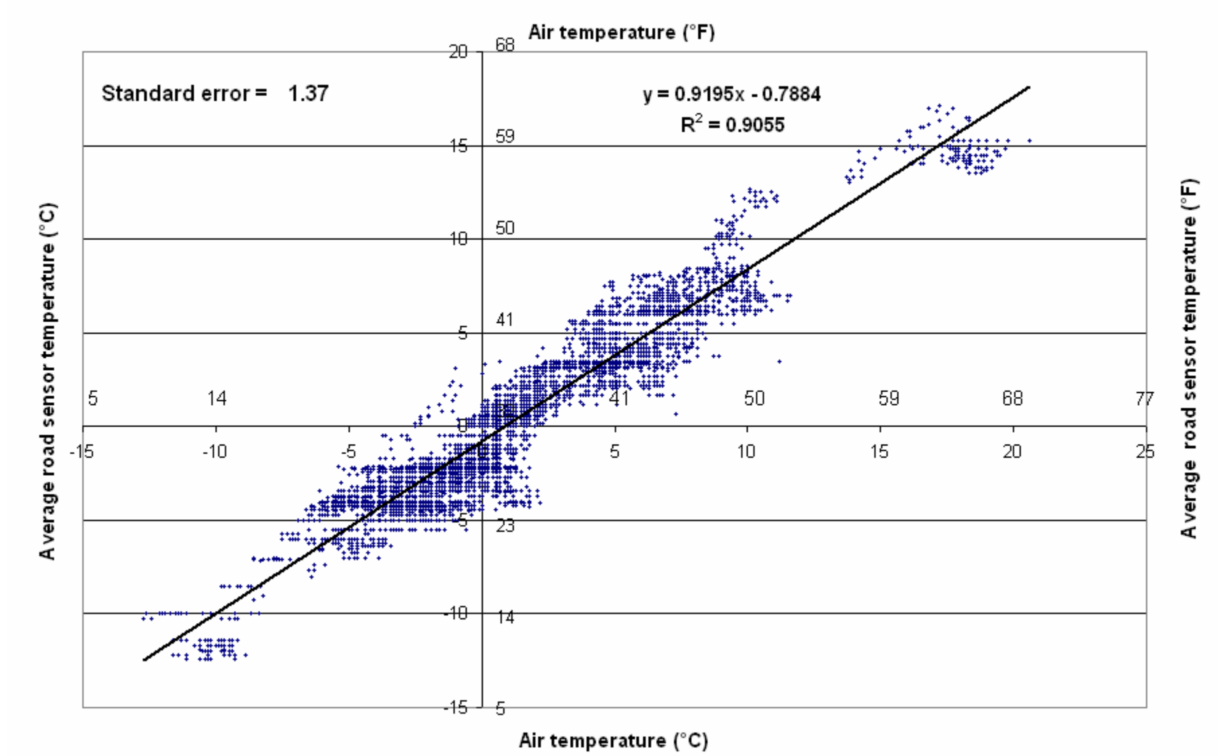



**Figure 104. Air versus road nighttime temperature correlation graph for Site 86 I90 Lorain County, January 21-April 5, 2005**

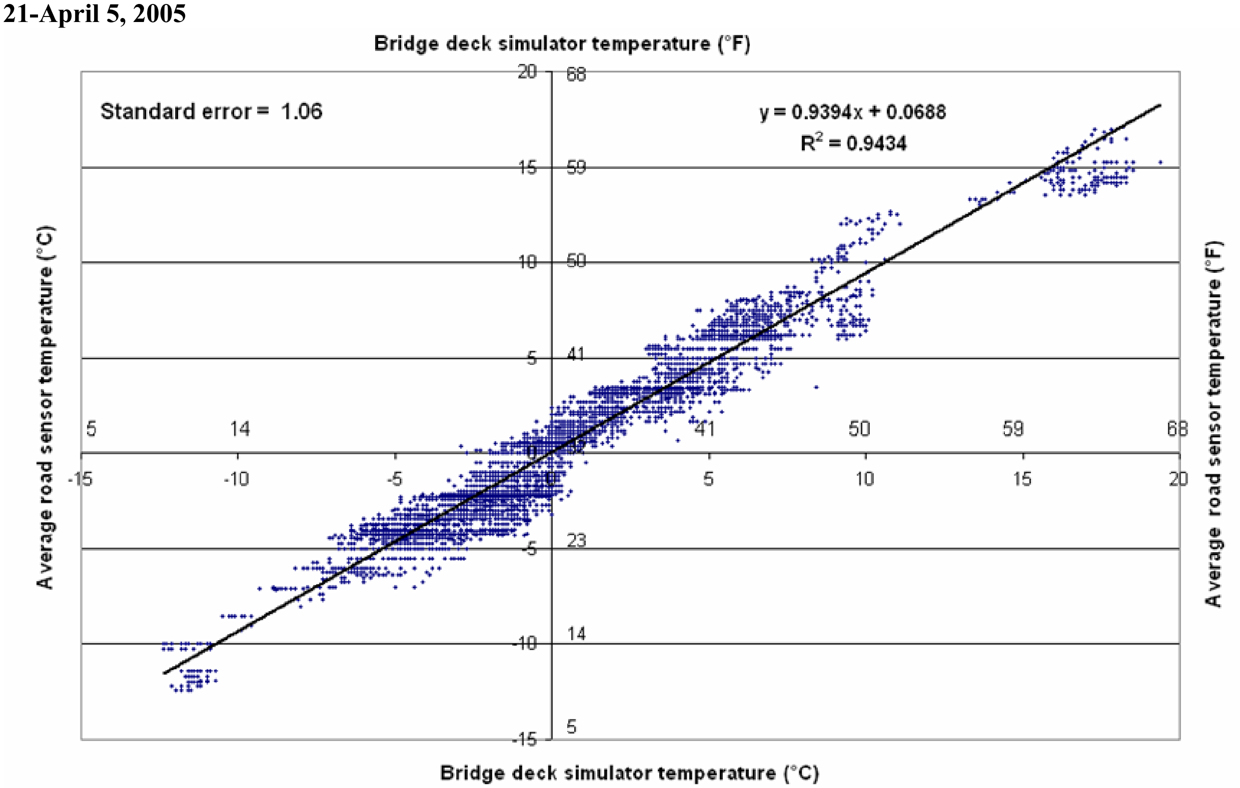



**Figure 105. BDS versus road nighttime temperature correlation graph for Site 86 I90 Lorain County, January 21-April 5, 2005**

## 9.7.2 Daytime Correlations

Figure 106 shows the air versus BDS temperature correlation for all day data for the entire data collection period of January 21, 2005-April 5, 2005. Figure 107 and Figure 108 show the air and BDS versus bridge all-day temperature correlations, respectively. Figure 109 and Figure 110 show the air and BDS versus average road all-day temperature correlations.

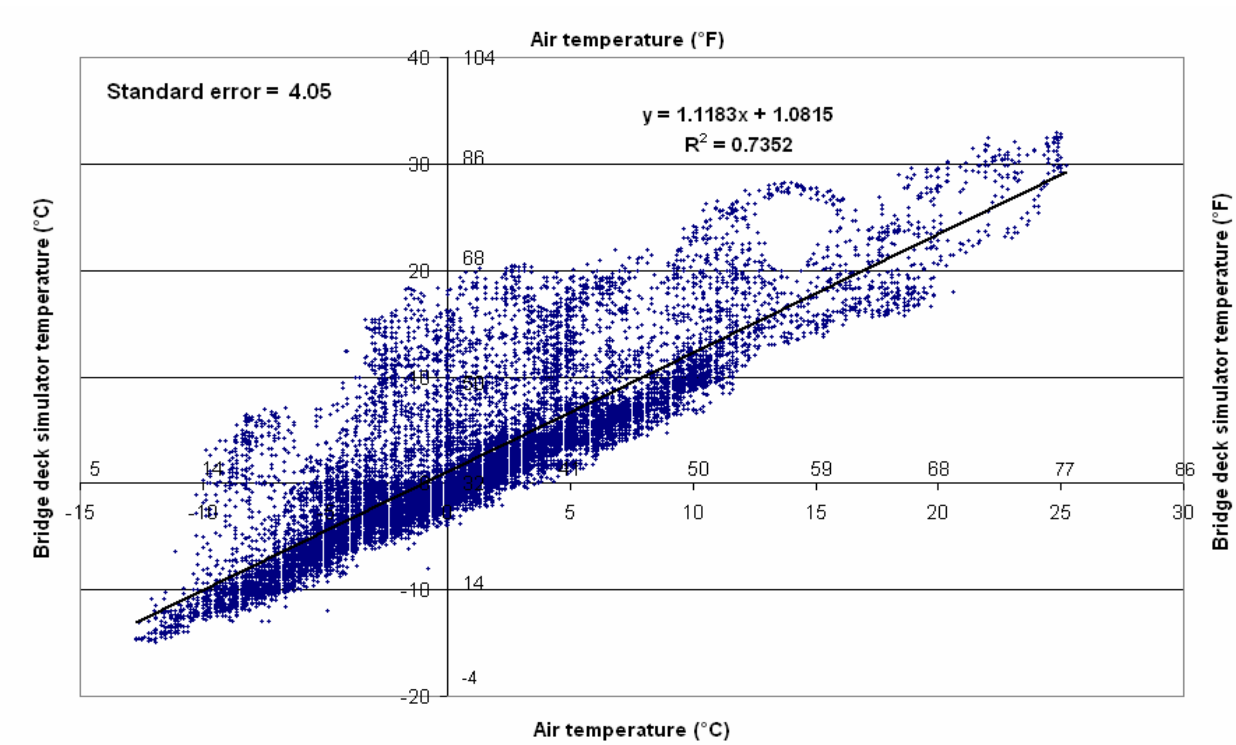



**Figure 106. Air versus BDS all-day temperature correlation graph for Site 86 I90 Lorain County, January 21-April 5, 2005**

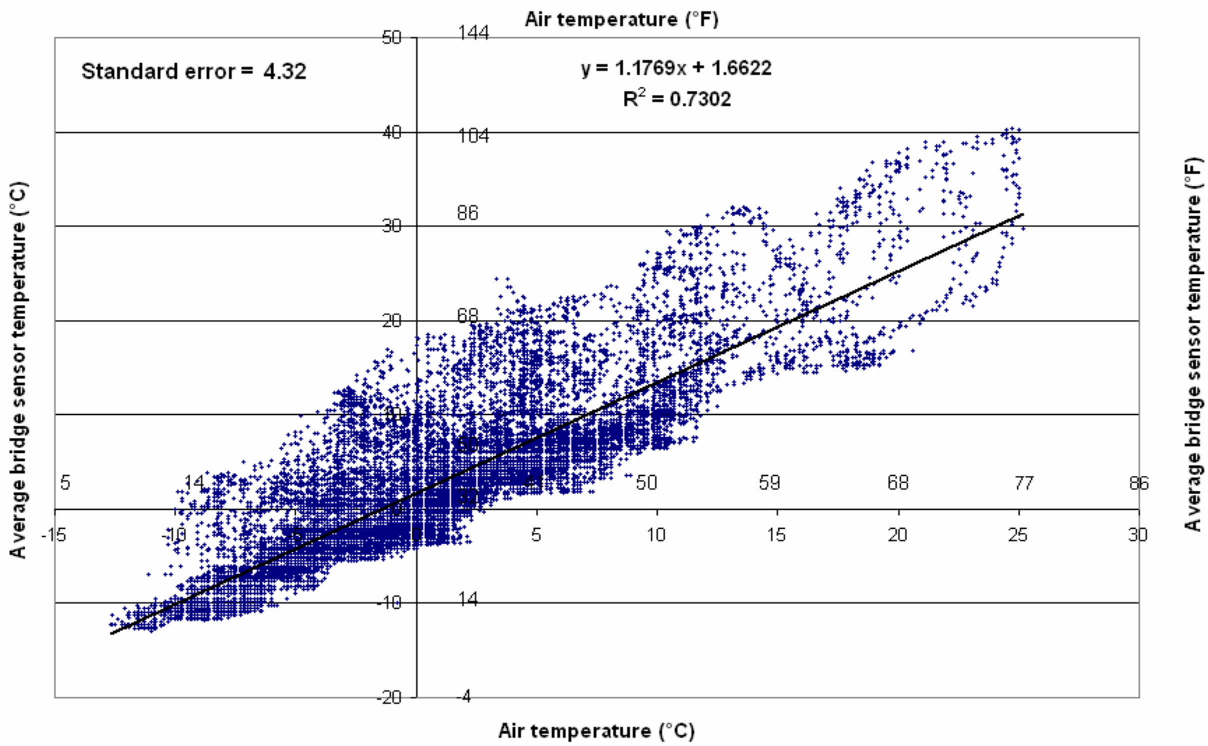



**Figure 107. Air versus bridge all-day temperature correlation graph for Site 86 I90 Lorain County, January 21-April 5, 2005**

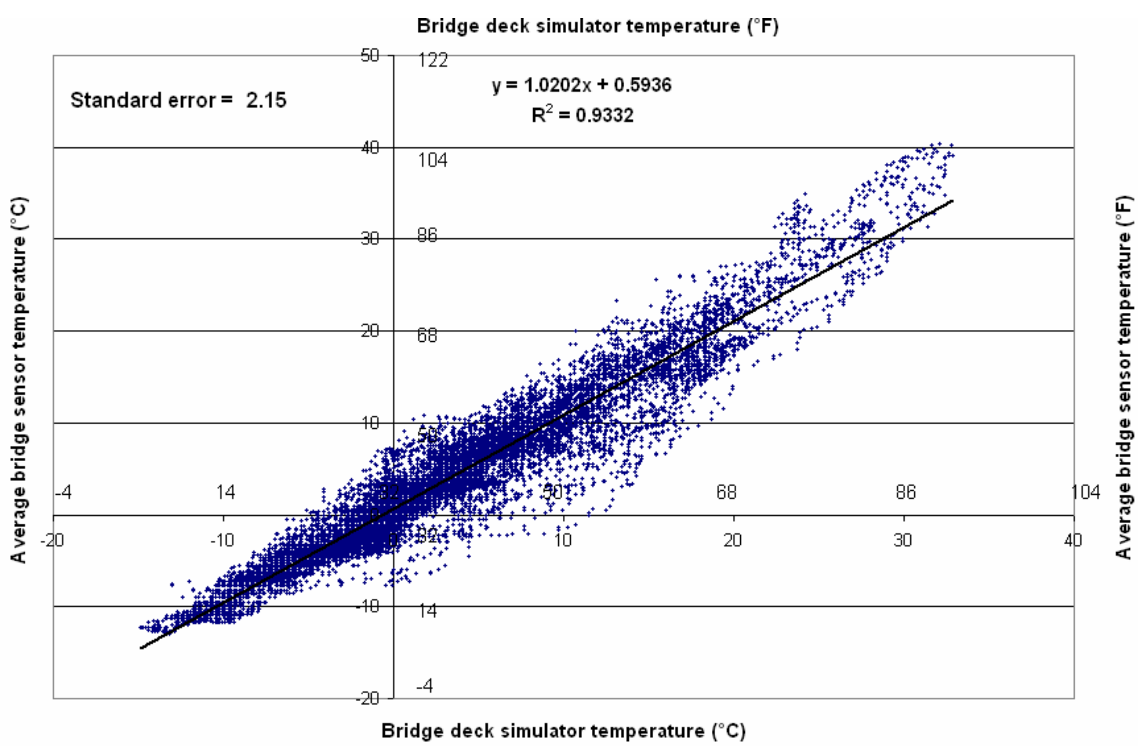



**Figure 108. BDS versus bridge all-day temperature correlation graph for Site 86 I90 Lorain County, January 21-April 5, 2005**

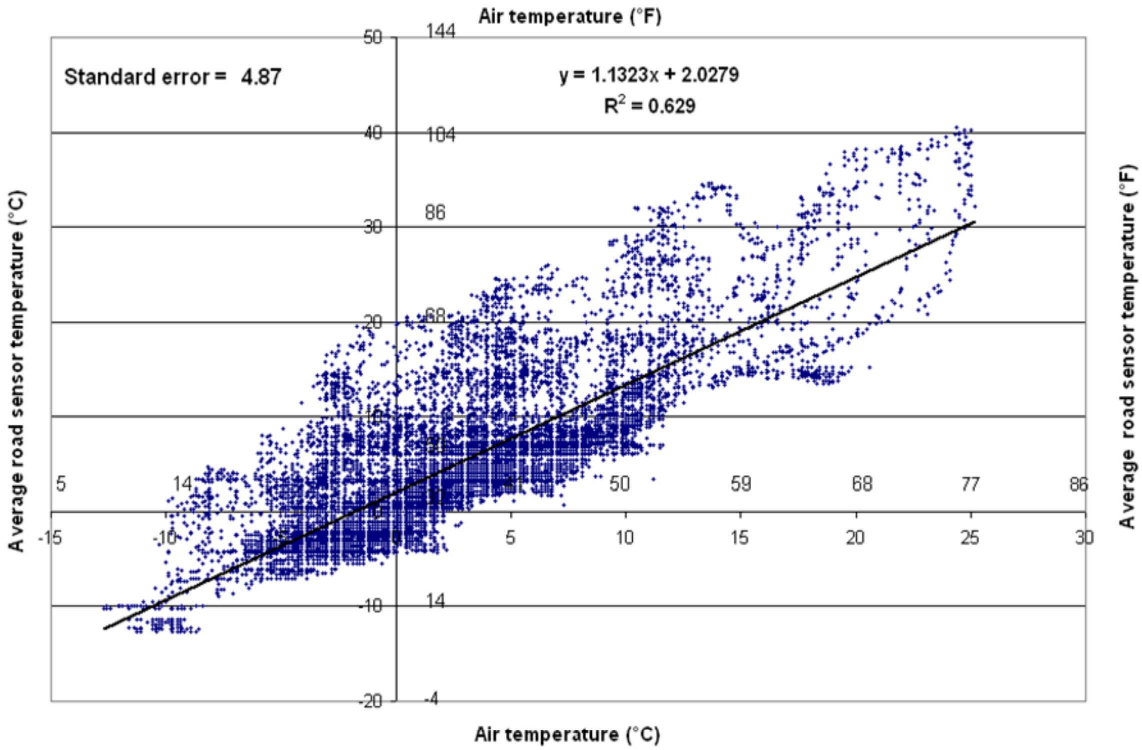



**Figure 109. Air versus road all-day temperature correlation graph for Site 86 I90 Lorain County, January 21-April 5, 2005**

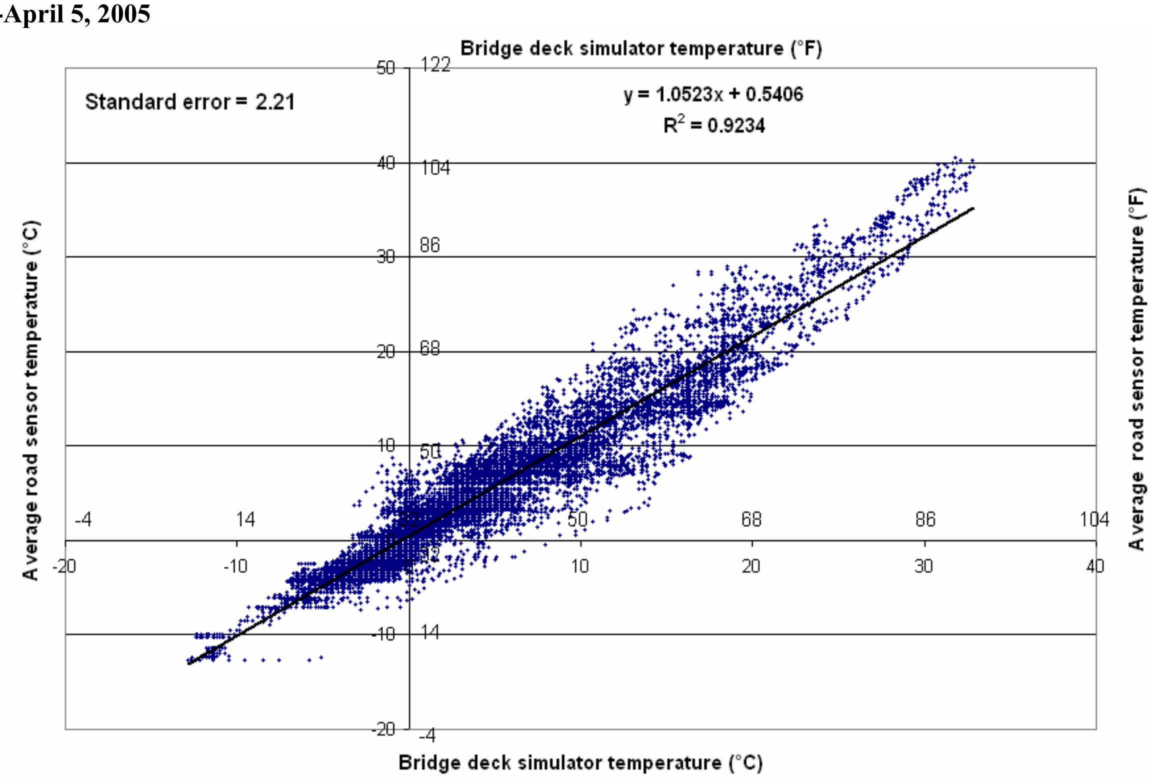



**Figure 110. BDS versus road correlation all-day temperature graph for Site 86 I90 Lorain County, January 21-April 5, 2005**

## 9.8 Site 88 Ashtabula County

### 9.8.1 Night time correlations

Figure 111 shows the correlation between the air temperature and the bridge deck simulator (BDS) temperature for Site 88 in Ashtabula County. Figure 112 and Figure 113 respectively show the correlations of the air and BDS temperatures with the bridge sensor temperature. Figure 114 and Figure 115 respectively show the correlations of the air and BDS temperature with the average of temperatures of the road sensors.

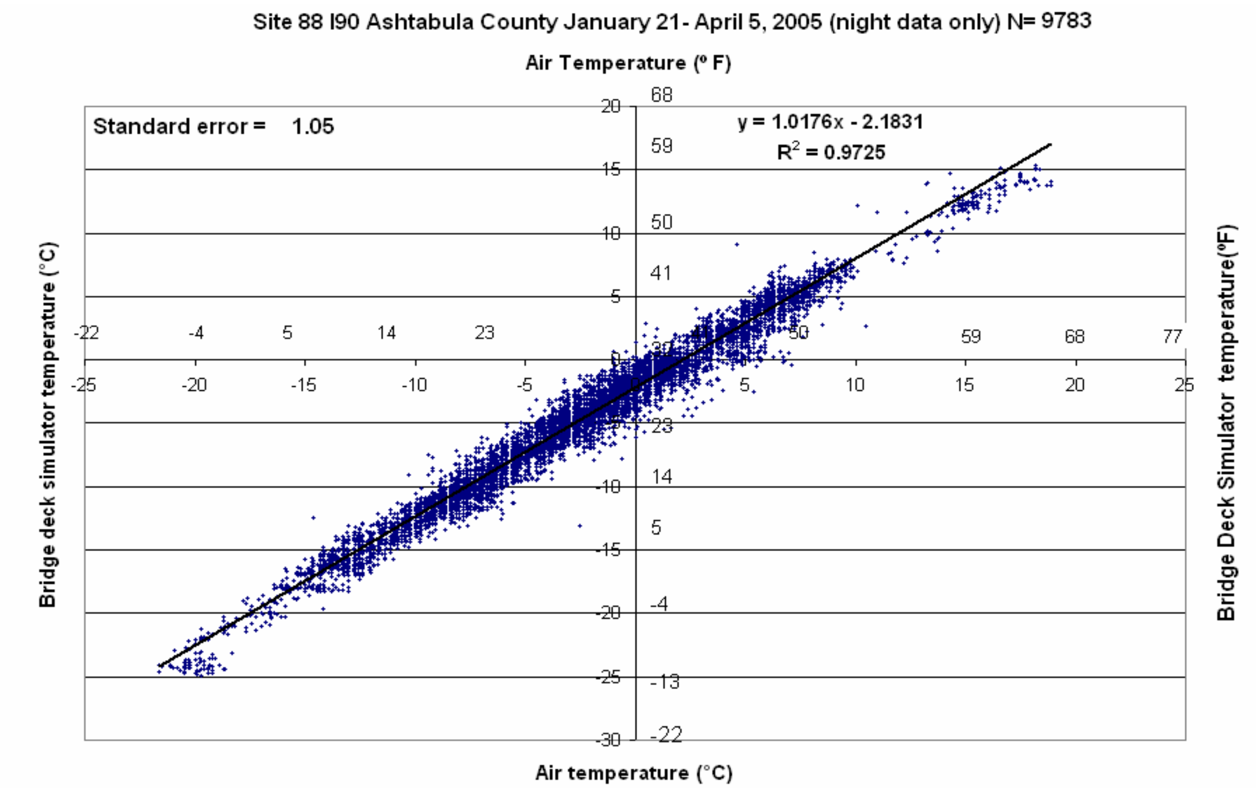



**Figure 111. Air versus BDS nighttime temperature correlation graph for Site 88 I90 Ashtabula County, January 21-April 5, 2005**

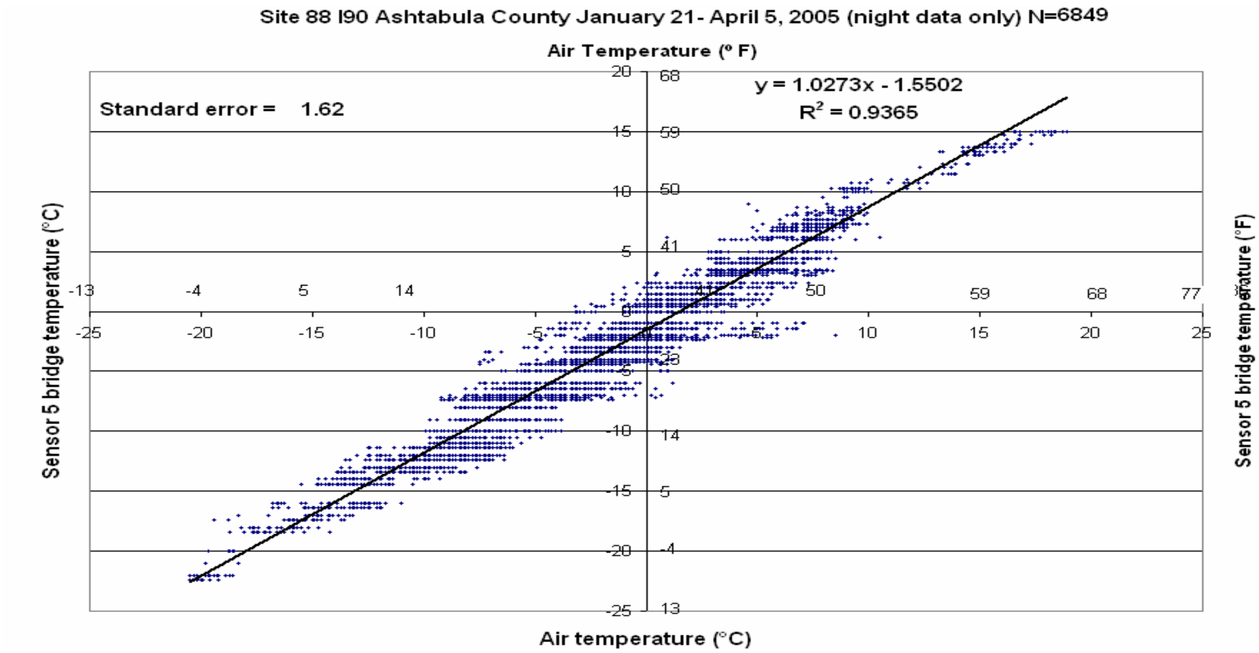



**Figure 112. Air versus bridge nighttime temperature correlation graph for Site 88 I90 Ashtabula County, January 21-April 5, 2005**

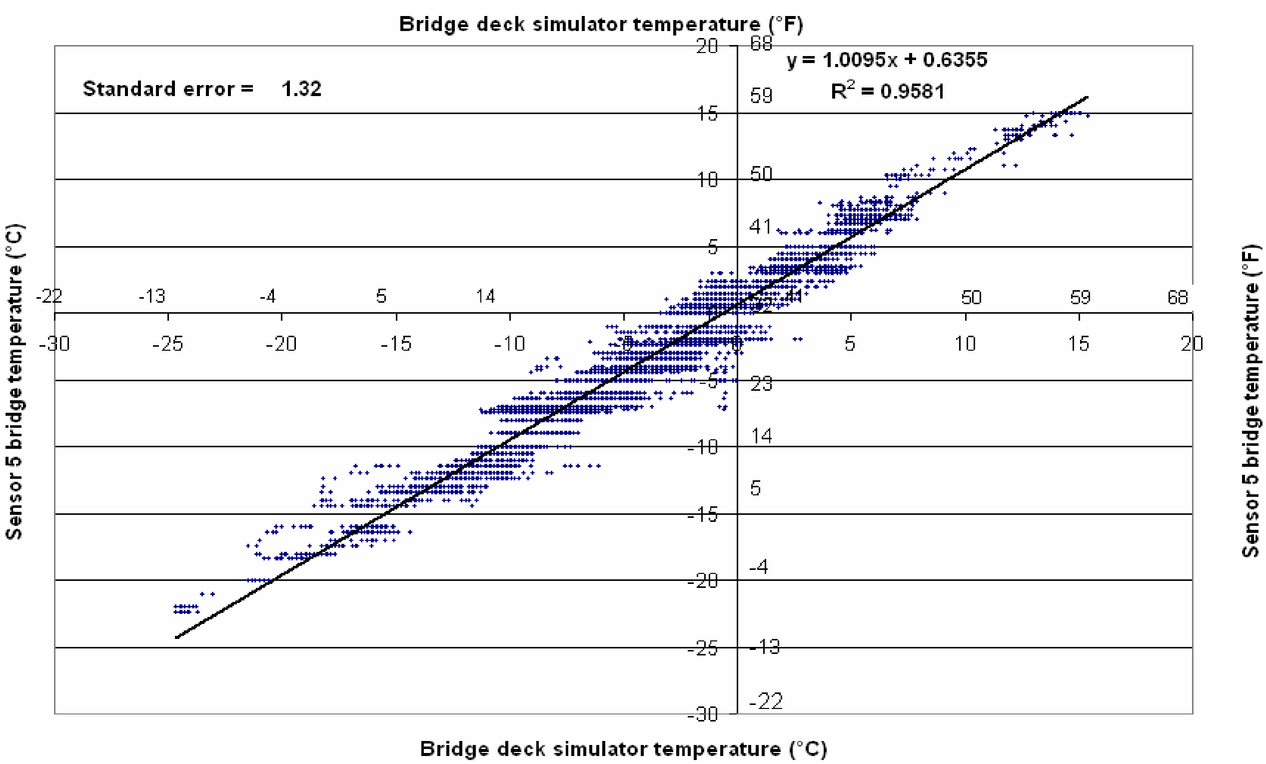



**Figure 113. BDS versus bridge nighttime temperature correlation graph for Site 88 I90 Ashtabula County, January 21-April 5, 2005**

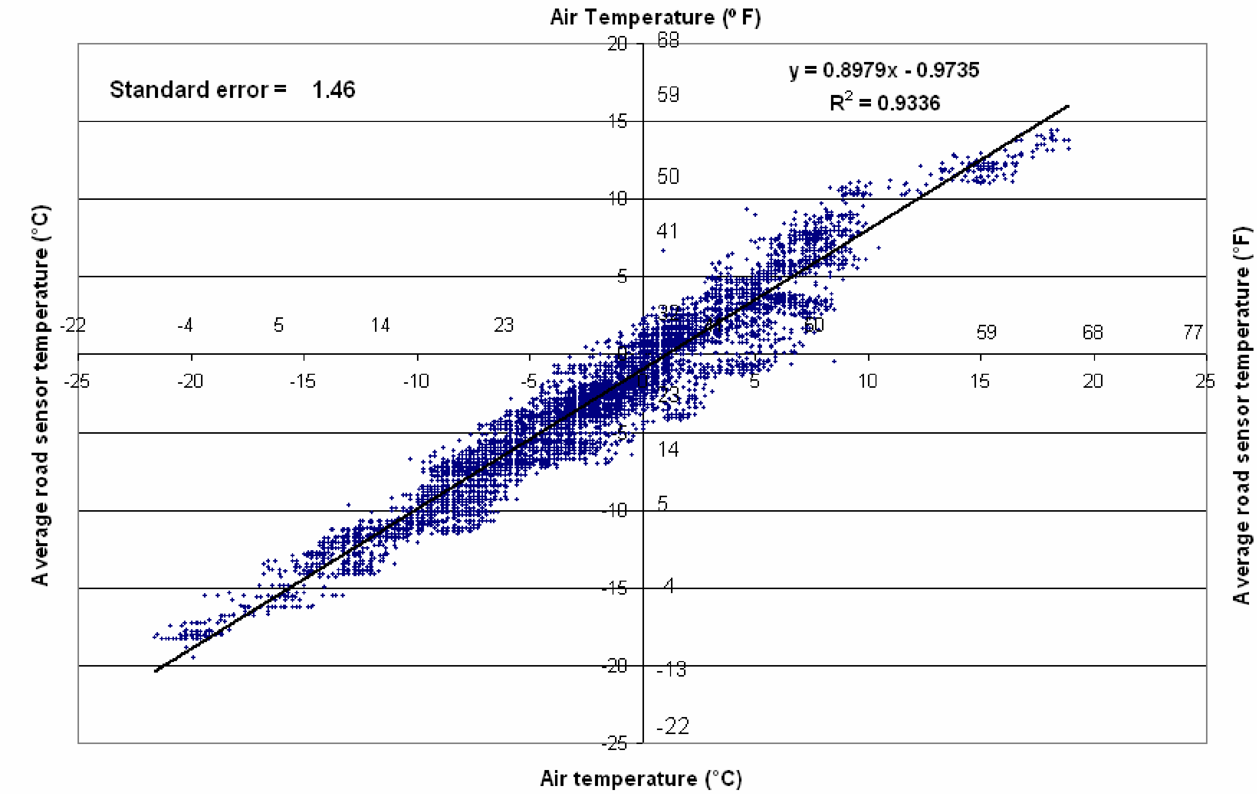



**Figure 114. Air versus road nighttime temperature correlation graph for Site 88 I90 Ashtabula County, January 21-April 5, 2005**

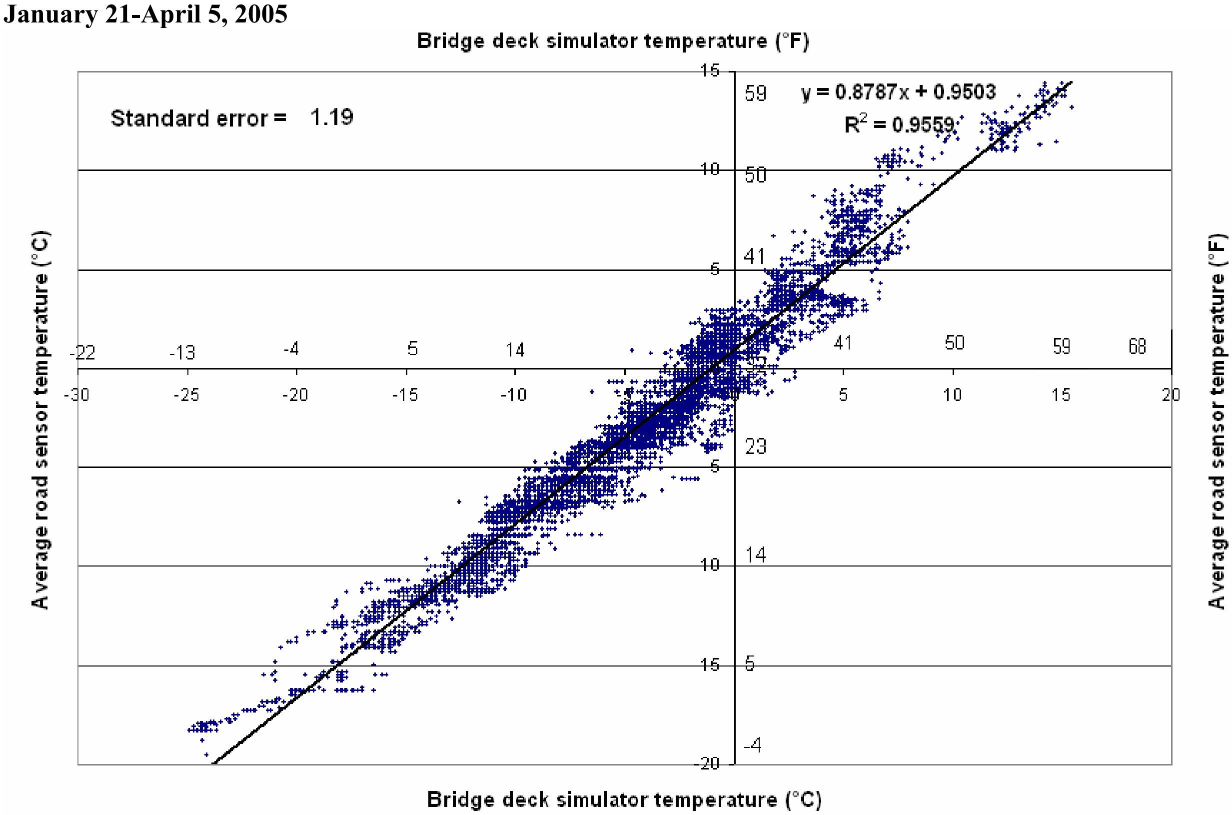



**Figure 115. BDS versus road nighttime temperature correlation graph for Site 88 I90 Ashtabula County, January 21-April 5, 2005**

## 9.8.2 Day time correlations

Figure 116 shows the air versus BDS temperature correlation for all day data for the entire data collection period of January 21, 2005-April 5, 2005. Figure 117 and Figure 118 show the air and BDS versus bridge all-day temperature correlations, respectively. Figure 119 and Figure 120 show the air and BDS versus average road all-day temperature correlations.

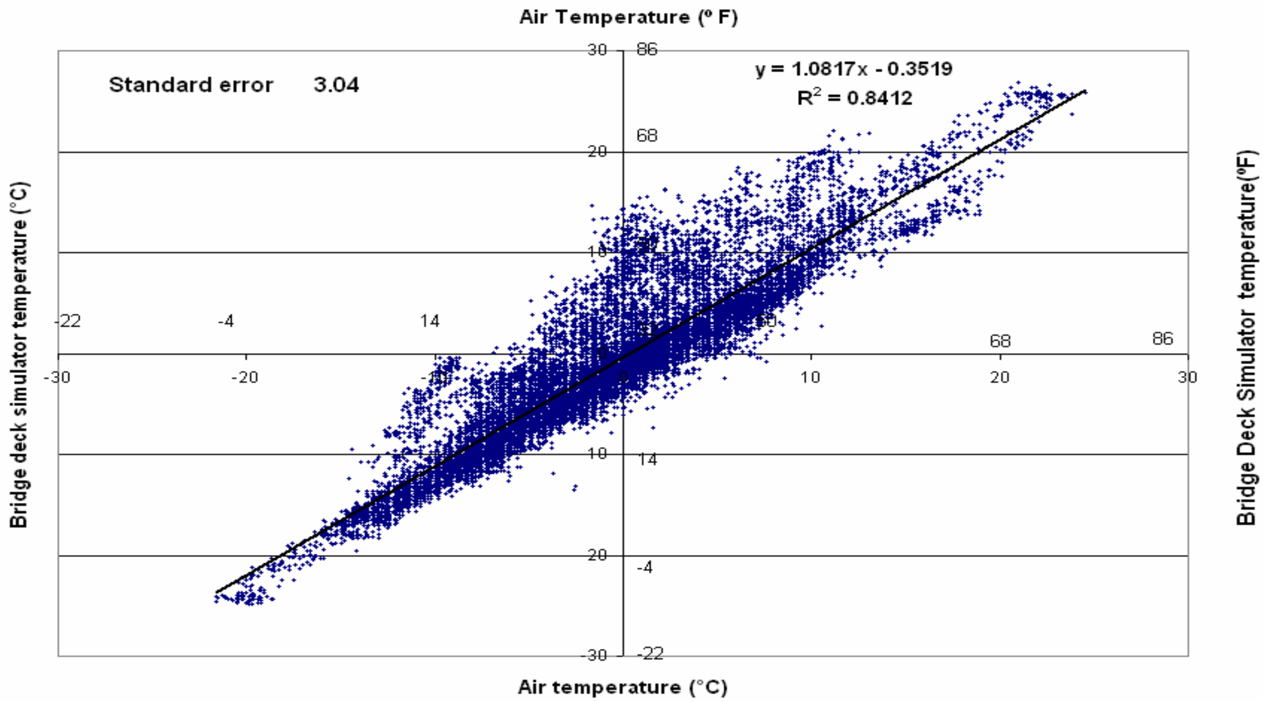



**Figure 116. Air versus BDS all-day temperature correlation graph for Site 88 I90 Ashtabula County, January 21-April 5, 2005**

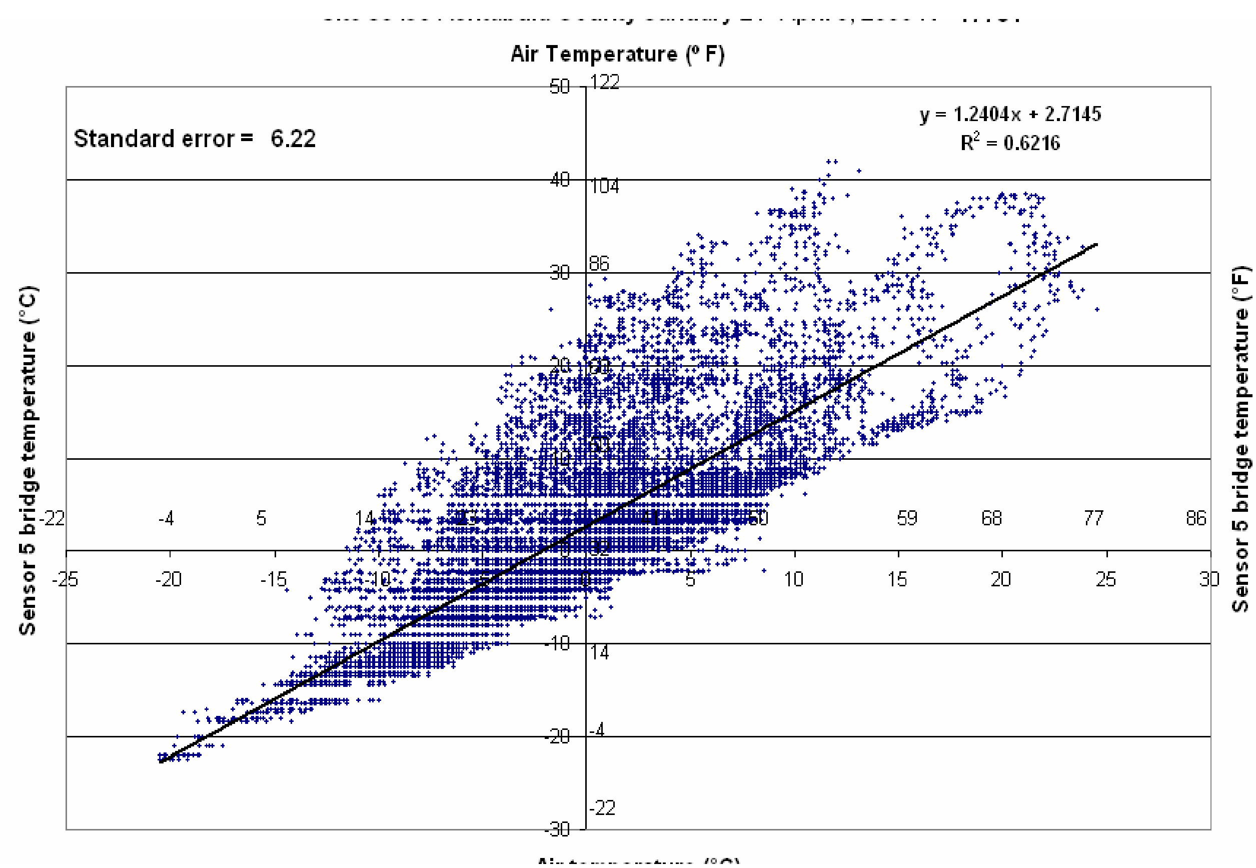


Figure 117. Air versus bridge all-day temperature correlation graph for Site 88 I90 Ashtabula County, January 21-April 5, 2005

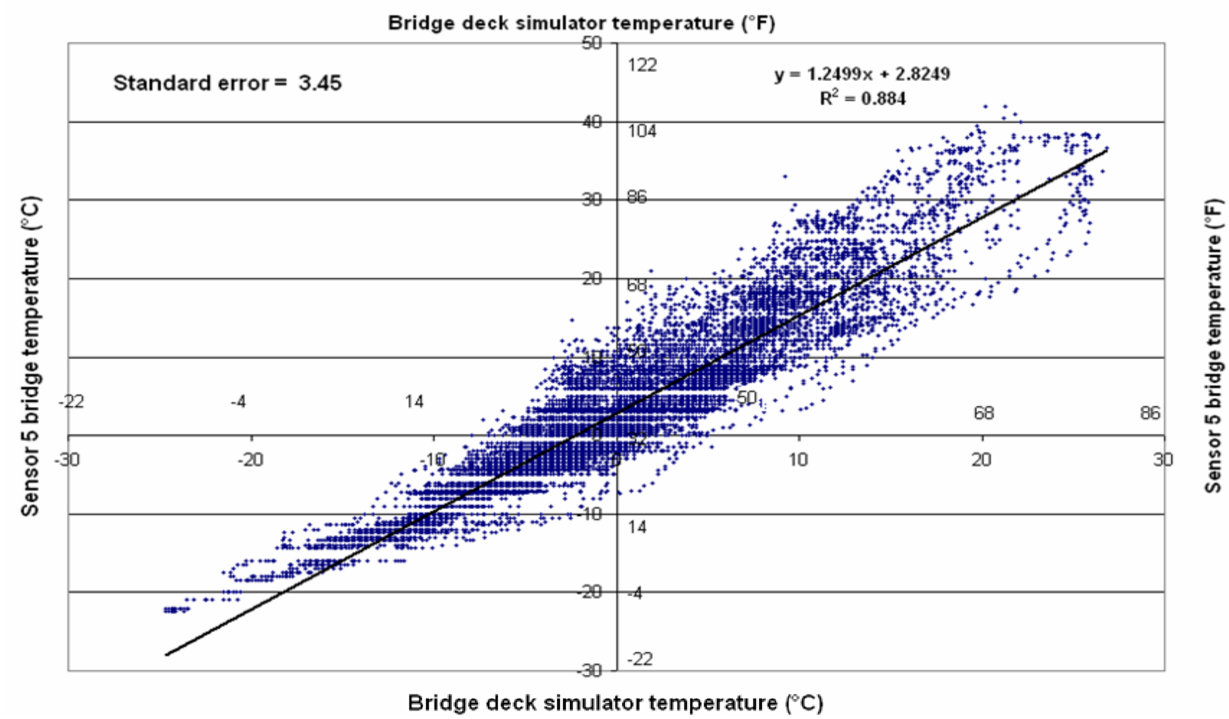


Figure 118. BDS versus bridge all-day temperature correlation graph for Site 88 I90 Ashtabula County, January 21-April 5, 2005

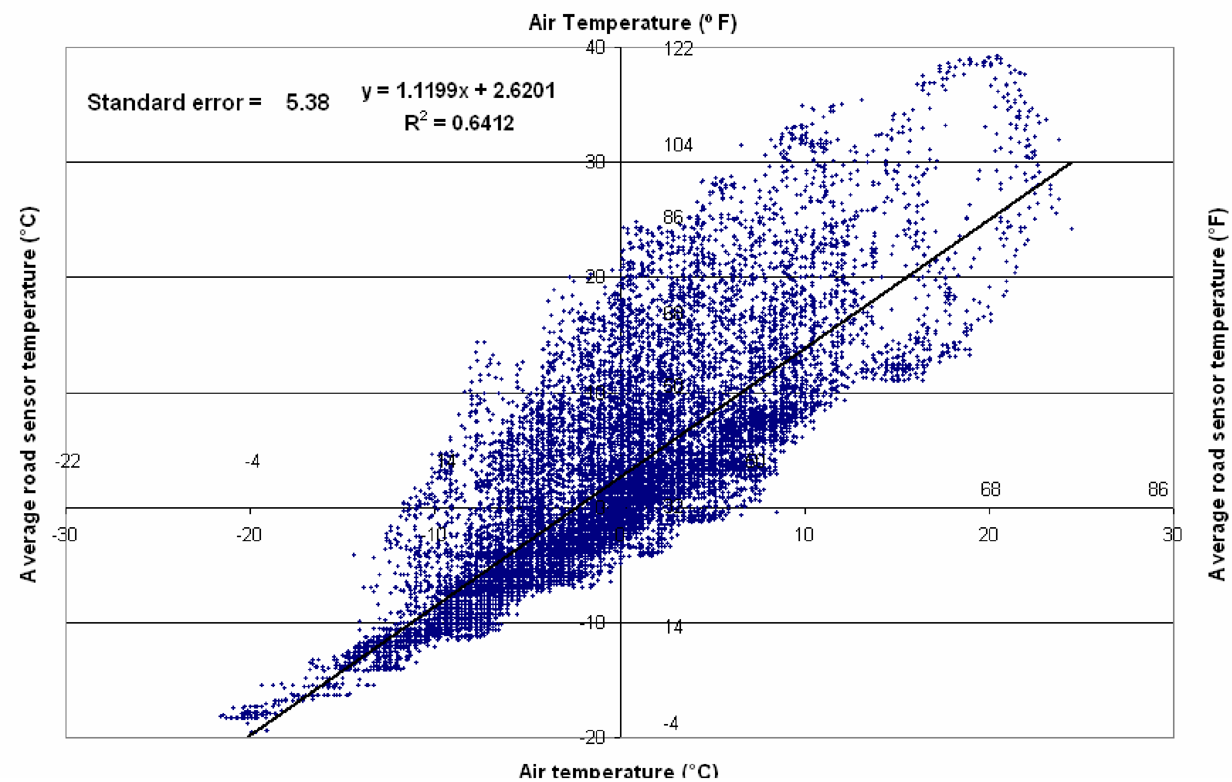



**Figure 119. Air versus road all-day temperature correlation graph for Site 88 I90 Ashtabula County, January 21-April 5, 2005**

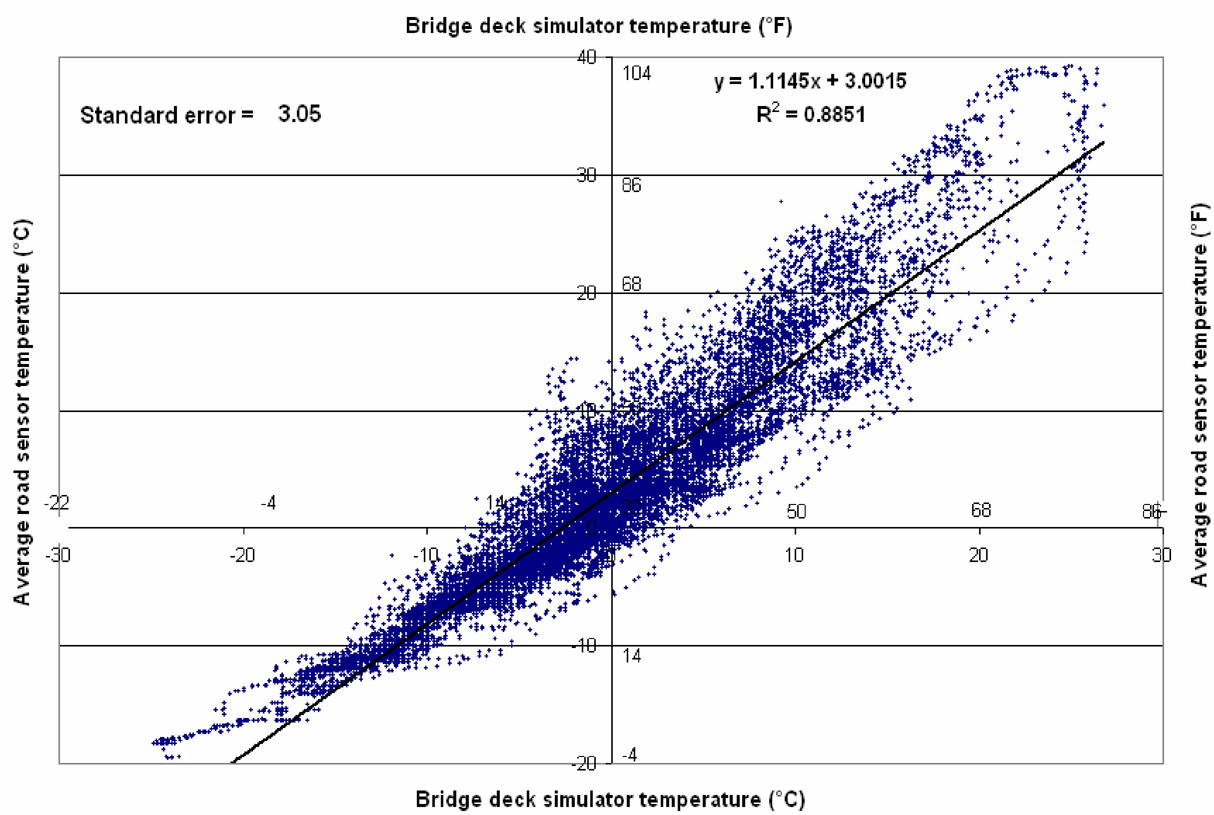



**Figure 120. BDS versus road all-day temperature correlation graph for Site 88 I90 Ashtabula County, January 21-April 5, 2005**

## 9.9 Site 91 Portage/Mahoning County line

### 9.9.1 Night time correlations

Figure 121 shows the correlation between the air temperature and the bridge deck simulator (BDS) temperature for Site 91 at the Portage/Mahoning County line. Figure 122 and Figure 123 respectively show the correlations of the air and BDS temperatures with the bridge sensor temperature. Figure 124 and Figure 125 respectively show the correlations of the air and BDS temperature with the average of temperatures of the road sensors.

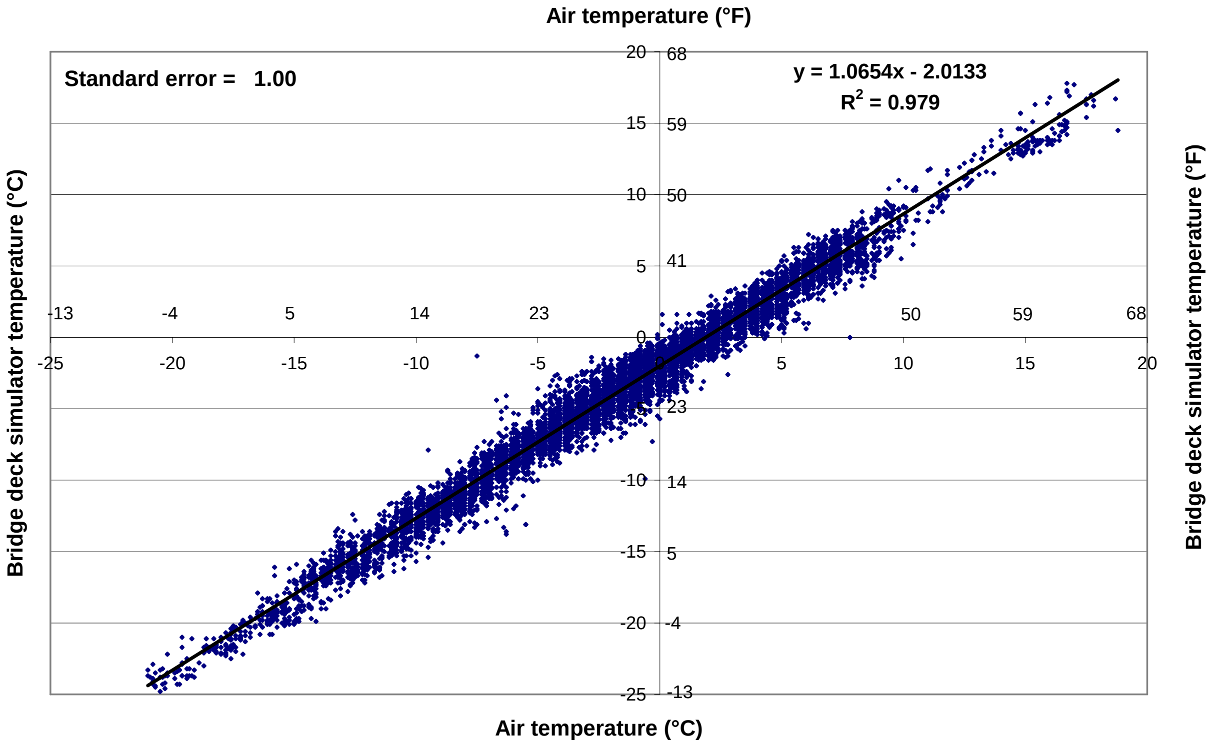



**Figure 121. Air versus BDS nighttime temperature correlation graph for Site 91 I76 Portage/Mahoning County, January 21-April 5, 2005**

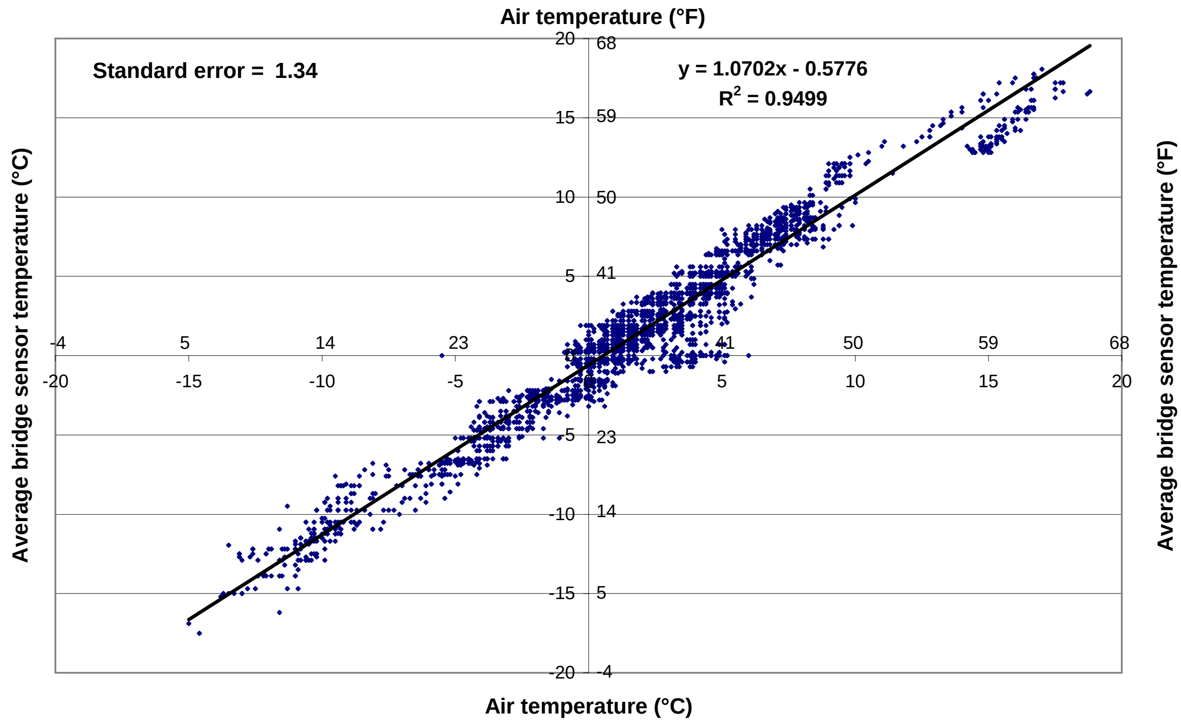



**Figure 122. Air versus bridge nighttime temperature correlation graph for Site 91 I76 Portage/Mahoning County, January 21-April 5, 2005**

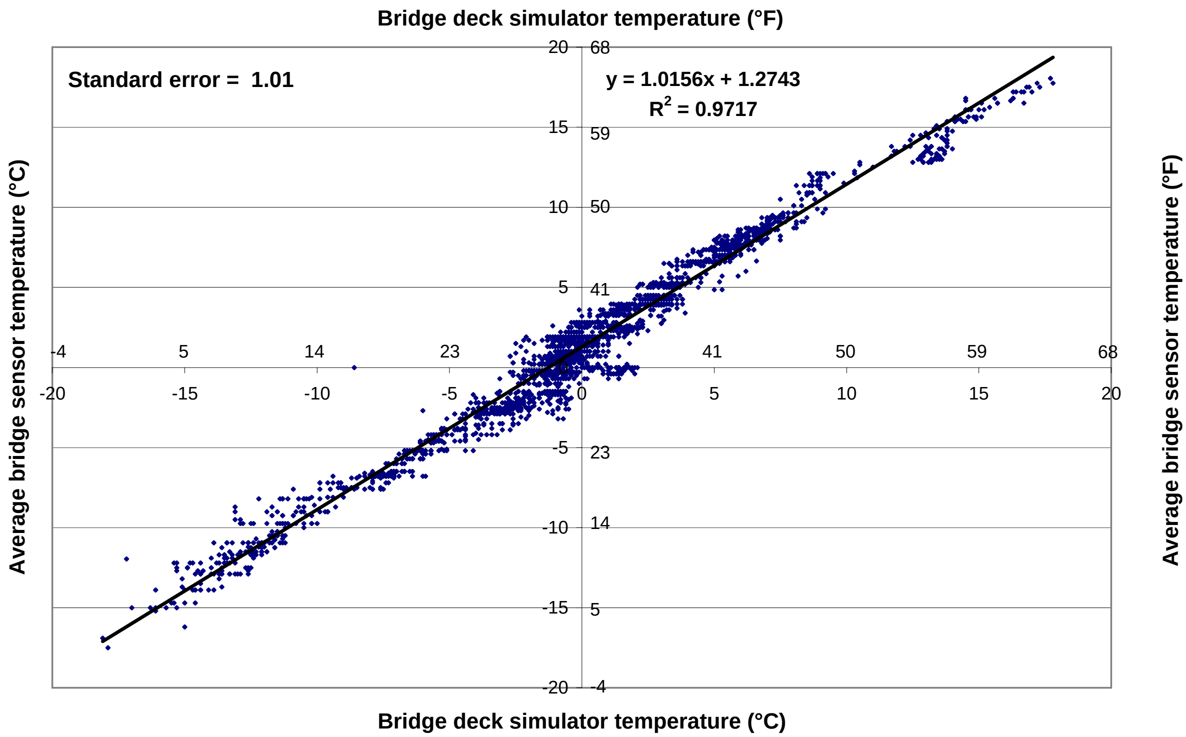



**Figure 123. BDS versus bridge nighttime temperature correlation graph for Site 91 I76 Portage/Mahoning County, January 21-April 5, 2005**

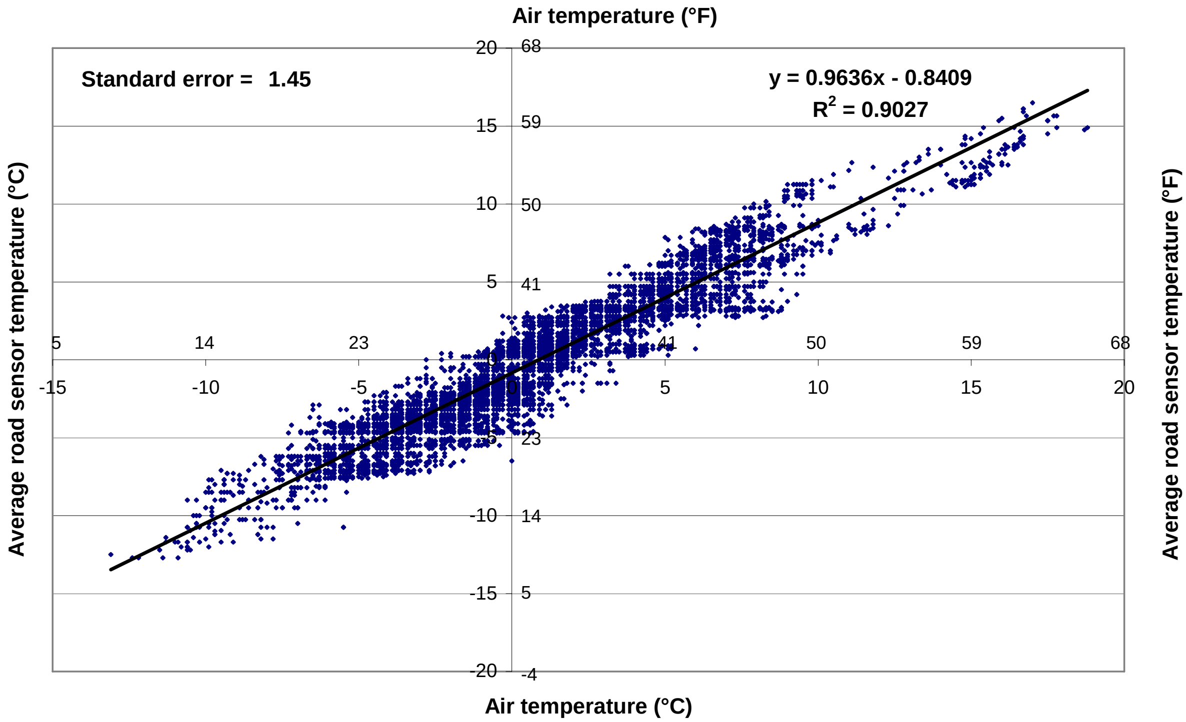



**Figure 124. Air versus road nighttime temperature correlation graph for Site 91 I76 Portage/Mahoning County, January 21-April 5, 2005**

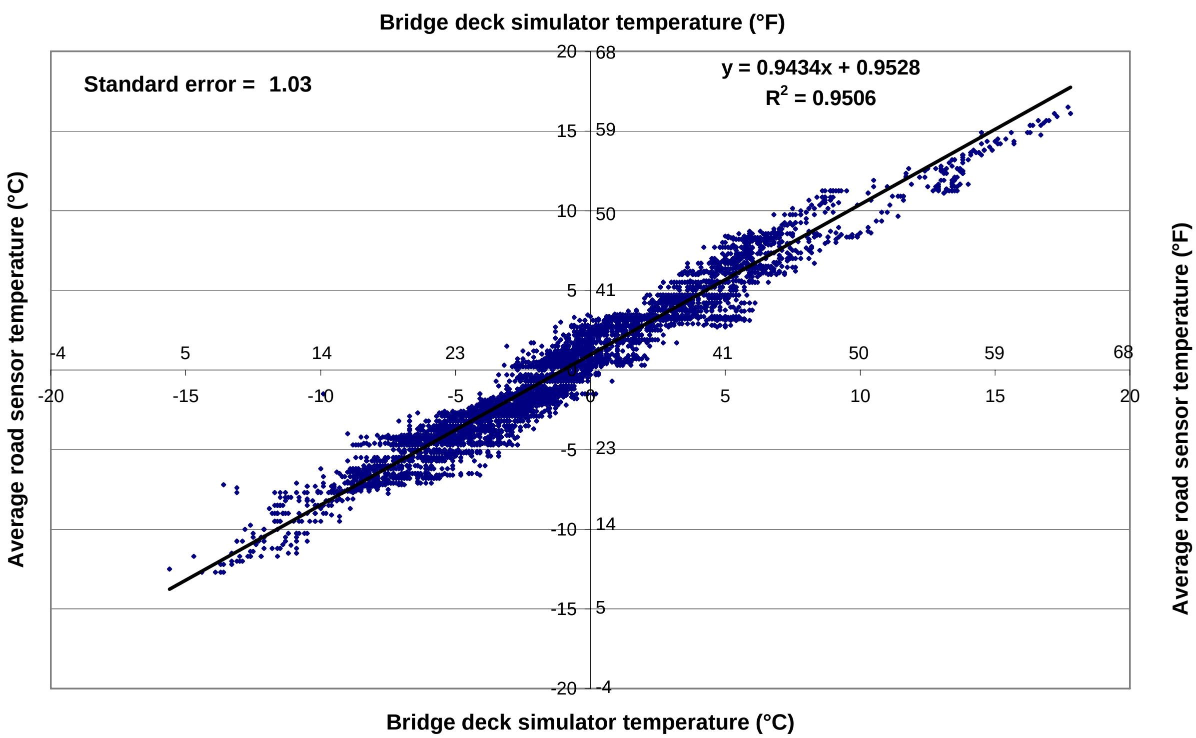



**Figure 125. BDS versus road nighttime temperature correlation graph for Site 91 I76 Portage/Mahoning County, January 21-April 5, 2005**

## 9.9.2 Day time correlations

Figure 126 shows the air versus BDS temperature correlation for all day data for the entire data collection period of January 21, 2005-April 5, 2005. Figure 127 and Figure 128 show the air and BDS versus bridge all-day temperature correlations, respectively. Figure 129 and Figure 130 show the air and BDS versus average road all-day temperature correlations.

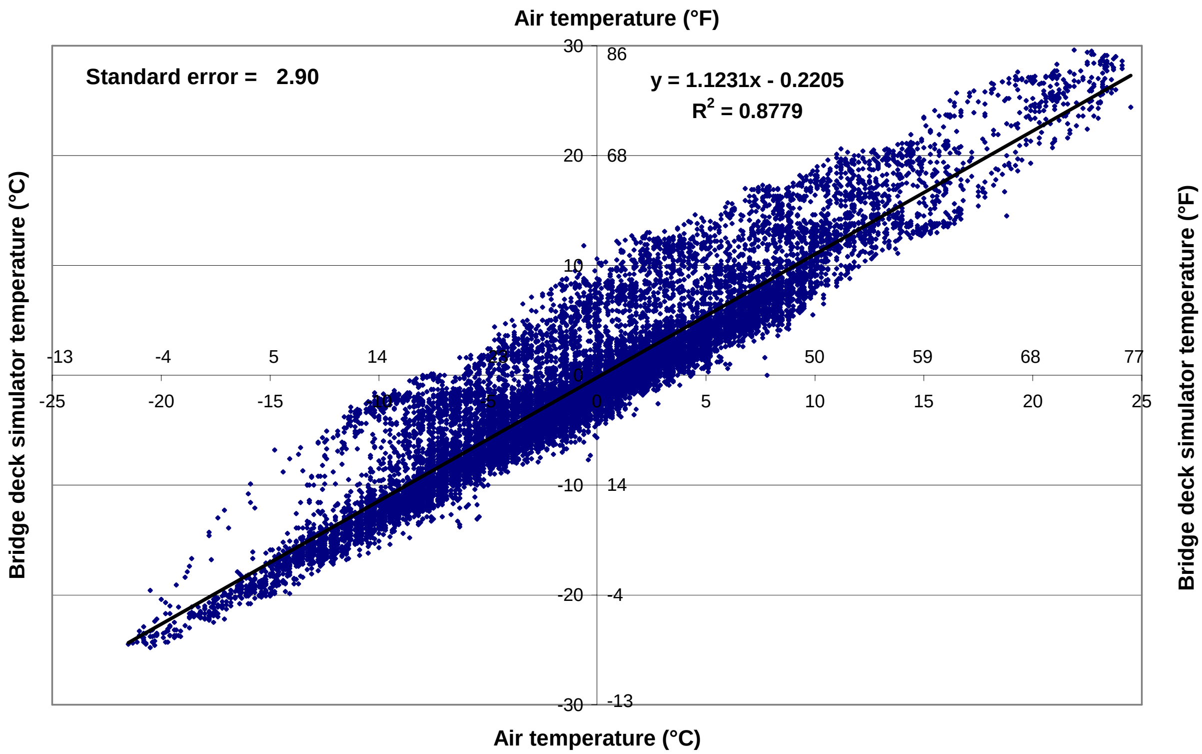



**Figure 126. Air versus BDS all-day temperature correlation graph for Site 91 I76 Portage/Mahoning County, January 21-April 5, 2005**

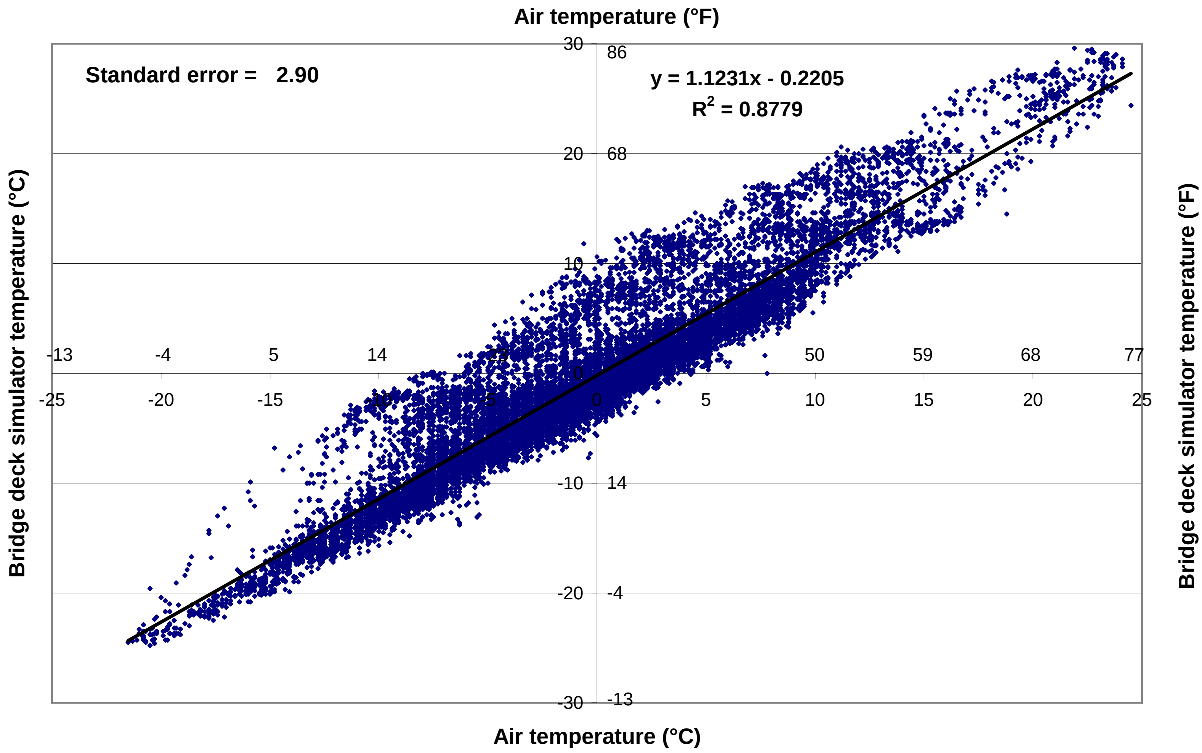



**Figure 127. Air versus bridge all-day temperature correlation graph for Site 91 I76 Portage/Mahoning County, January 21-April 5, 2005**

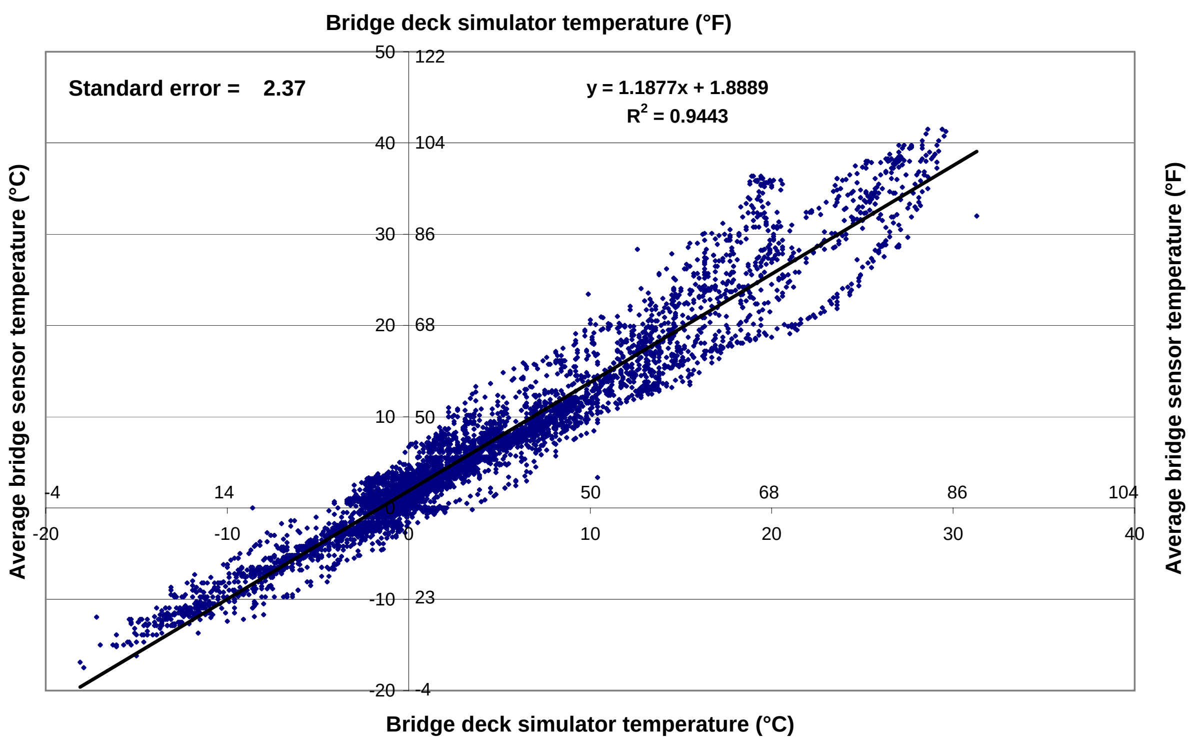



**Figure 128. BDS versus bridge all-day temperature correlation graph for Site 91 I76 Portage/Mahoning County, January 21-April 5, 2005**

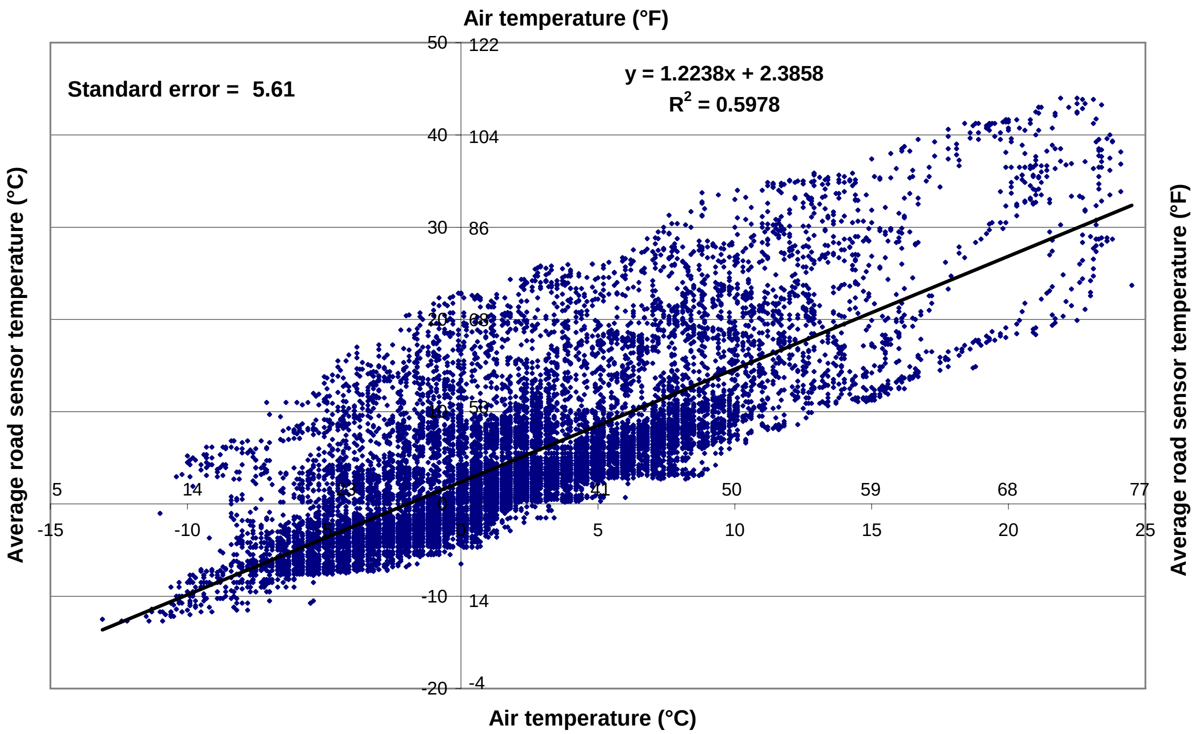



**Figure 129. Air versus road all-day temperature correlation graph for Site 91 I76 Portage/Mahoning County, January 21-April 5, 2005**

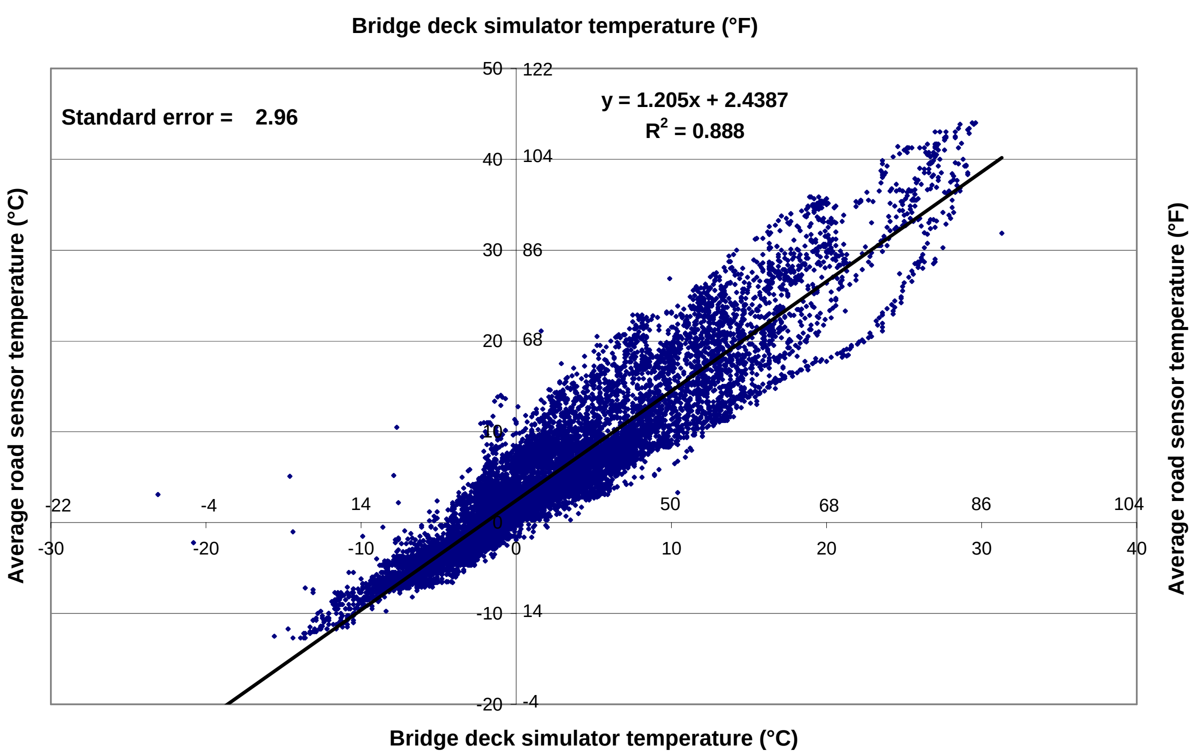



**Figure 130. BDS versus road all-day temperature correlation graph for Site 91 I76 Portage/Mahoning County, January 21-April 5, 2005**

## 9.10 Summary of Correlation results

The correlation results using all-day data for all sites are summarized in Table 15 (metric units) and Table 16 (English units). The tables are arranged as follows. Each site has a group of rows assigned to it, identified in the leftmost column. The dates during which data were collected from each site are indicated to the right of the site number. The individual rows are then assigned to the "dependent" sensor temperatures – the bridge deck simulator (BDS), bridge, and road; after each, the number of sensors of that type is indicated (e.g. "Bridge (2)" indicates there are two functioning pavement sensors installed in the bridge). The "independent" variables are the air temperature and the bridge deck simulator temperature, and each of these has a group of columns identified at the top. Under these headings, the parameters are listed: slope and intercept of the linear fit, the correlation coefficient, and the standard error. All of these values are taken from the graphs from each site in the previous sections. Note that for Sites 7 and 9, the data were split into two portions since there were too many data points for Excel to analyze in a single graph. The average and standard deviations of the fit parameters and statistics are shown in Table 17 (metric units) and Table 18 (English units). These are the averages and standard deviations across all the sites of the values in Table 15 and Table 16, respectively.

Table 15 and Table 16 both present the number of data points left for each correlation after the winnowing procedure described in Section 7.3, both as a number and as a percentage of the maximum possible (21,588 for the January 21-April 5 period used everywhere except for the first portions of Site 7 and Site 9, as indicated in the notes at the bottom of each table). The mean percentage of data points and standard deviations are given in Table 17 and Table 18, and are 96.59±1.36% for air-BDS correlations, 86.44±19.27% for bridge correlations, and 84.89±13.07% for road correlations. These latter two values were dragged down by a few sites that had a lot of data that had to be scrapped, namely Site 91 bridge data (31.63% kept) and Site 68 road data from I77 (54.86% kept).

Table 19 and Table 20 present the correlation results using nighttime data for all sites in metric and English units, respectively. The format is identical to that used for the daytime correlations in Table 15 and Table 16, with the difference that the values for the entire data collection period in Sites 7 and 9 could be plotted on a single graph. Table 21 (metric units) and Table 22 (English units) present the averages and standard deviations of the parameters combined for all sites, in analogy to Table 19 and Table 20 for the all-day data. While the number of data points retained in the analysis is recorded for each site in Table 15 and Table 16, no attempt was made to determine the percentage of "good" data points since estimating the maximum possible would be very difficult since the twilight and sunrise times vary from day to day and site to site. It should be noted that the number of points used for Sites 7 and 9 are especially high since for these two sites the data collection period ran from November 29 (Site 7) or November 1 (Site 9) through April 5, excluding January 20, about twice as many days as for the other sites.

There are some obvious patterns in the data if one looks closely at the nighttime fit parameters in Table 19 or Table 20. For instance, at each site, the air-BDS correlation coefficient ($R^2$) is the highest, except at Sites 59 and 68, where the bridge-BDS correlation coefficient was slightly higher and the air-BDS second highest. BDS-bridge correlation coefficients are always higher than air-bridge correlation coefficients, indicating that the BDS is a better approximation to the bridge temperature than is the air temperature at all sites. Similarly, BDS-road correlation coefficients are always higher than air-road correlation coefficients. Also, at all sites, correlation coefficients involving bridge temperature were higher than those with road temperature, for instance the bridge-air $R^2$ is higher than the road-air value. The only exceptions to this rule are Site 70 for where both road-BDS and road-air had slightly higher $R^2$ values than their bridge counterparts, and Site 69 where the road-air and bridge-air correlation coefficients were nearly equal. It is also worth noting that all the air-BDS correlations exceed 0.9612 (Site 68), while all the BDS-bridge correlations exceed 0.9512 (Site 70) and the BDS-road correlations exceed 0.9313 (Site 59). The lowest correlation is 0.8876 for air-road on I271 at Site 68.

If one looks at the all-day results in Table 15 and Table 16, most of the observations in the previous paragraph will carry over. For instance the BDS-bridge and BDS-road correlation coefficients are always greater than those for air-bridge and air-road. And road correlations are usually weaker than the corresponding bridge correlations, with some exceptions, namely Site 88 (both air and BDS), Site 70 (BDS only), and Site 68 (I77 versus bridge). The air-BDS correlations are always stronger than the air-road and air-bridge correlations, except for Site 59, where the air-road correlation is stronger than the air-BDS correlation. Lastly, in what is essentially a reversal of nighttime behavior, the correlations between the BDS and bridge or road sensors is always stronger than the correlation between the air and BDS temperatures. Correlation coefficient values are markedly lower than for the nighttime counterparts, as low as 0.5654 for air-road on Site 7 (January 21-April 5). The minimum air-BDS correlations are 0.7352 (Site 86) and 0.8145 (Site 9, January 21-April 5). In contrast, BDS-bridge correlations are at least 0.8772 (Site 70), and BDS-road correlations at least 0.8672 (Site 7 January 21-April 5).

The standard errors generally follow the reverse pattern of the correlation coefficients – if the correlation coefficient is high, the standard error is low and vice versa. Higher correlation is associated with a tighter relationship between the two temperatures, which implies a smaller spread, hence less error.

The line fit parameters, those are the slope (m) and intercept (b) also show some interesting patterns. Looking at the nighttime data summarized in Table 19 and Table 20, one sees that the slope can range from 0.8520 (Site 59 BDS-road) to 1.0719 (Site 9 air-BDS). The averages and standard deviations, from Table 21 and Table 22 are 1.0286±0.0305 for air-BDS, 1.0121±0.0536 for air-bridge, 0.9106±0.0376 for air-road, 0.9889±0.0369 for BDS-bridge, and 0.9108±0.0375 for BDS-road. These average±standard deviation ranges include 1 for the air-BDS, BDS-bridge, and air-bridge relationships, while the road averages are both clearly lower than the expected value of 1. Looking over the individual values for each site in Table 19 and Table 20 confirms this result – the slopes of all the road line fits, whether versus air or BDS temperature, are below 1.

The intercepts also show some deviations from the ideal value of 0. The averages and standard deviations for the intercepts displayed in Table 21 in Celsius (Table 22 in Fahrenheit) are -3.2289±1.4511°C (-6.7286±2.3411°F) for air-BDS, -1.3070±1.2915°C (-2.7390±2.8975°F) for air-bridge, -0.6030±1.0791°C (1.7746±2.7129°F) for air-road, 1.8682±1.6738°C (3.7190±2.7710°F) for BDS-bridge, and 2.5695±2.3516°C (7.4780±5.0378°F) for BDS-road. The relationship between intercept in Celsius and Fahrenheit is complicated as it involves multiplying by 9/5 (or 5/9 the other way) and a term that includes the slope. Since some of these slopes, particularly for road fits are clearly different from 1, a clearly nonzero intercept (that is one where even the standard deviation range does not include 0) may not indicate a built-in bias in one of the sensors relative to the other. That said, the strongly negative intercepts for the air-BDS relationships in both Celsius and Fahrenheit, which are also reflected in the fact that all the air-BDS intercepts for each site in both units are negative, indicate that the BDS is generally lower than the air temperature. One can see this in the nighttime air-BDS correlation graphs, where the cloud of data points typically skirts the Celsius origin (0°C, 0°C) ((32°F, 32°F)). Without going into such detail, the intercepts for BDS versus bridge or road are all positive, sometimes strongly so, while those for air versus road or bridge tend to be negative, but may be positive; they are also always greater than the strongly negative intercepts for air versus BDS.

For all-day data, the slope and intercept behavior is somewhat different. Looking at the averages and standard deviations of the slopes in Table 17 and Table 18, we see they are all greater than 1: 1.0952±0.0462 for air-BDS, 1.1739±0.0891 for air-bridge, 1.1038±0.0983 for air-road, 1.1086±0.0947 for BDS-bridge, and 1.0676±0.1110 for BDS-road. Except for the BDS-road, these ranges all exclude 1; the air-bridge relationship clearly has the highest average slope. These high slopes generally reflect the daytime behavior where sunlight warms the bridge or road surface to a much higher temperature than the air or BDS, which contributes to the upper portions of the data clouds in the correlation graphs and skews the line fits to higher slopes.

The intercepts also show some patterns. The air-BDS intercept for each site is negative in both Celsius and Fahrenheit, often markedly so for Fahrenheit because the slope that is larger than 1 depresses the Fahrenheit intercept at 0°F (-17.8°C) relative to the Celsius intercept at 0°C (32°F). Thus most of the air-bridge and air-road intercepts are also negative in Fahrenheit, and less so in Celsius. The BDS-bridge and BDS-road intercepts are all positive in Celsius and usually positive in Fahrenheit. Also, the air-BDS intercepts are always less than the other intercepts. The largest magnitude intercepts in Celsius are -5.1249°C (-12.9656°F) for Site 59 air-BDS and 7.2927°C (17.5973°F) for Site 59 air-road, which underscores the looseness of some of these fits.

**Table 15. Summary of correlation results with all-day data (metric units)**

| Site No. | Dates | Comparison (No. of reporting sensors) | Number of good data points N | Percentage of good data points (%) | Air Slope m | Air Intercept b (°C) | Air $R^2$ | Air Standard error (°C) | BDS Slope m | BDS Intercept b (°C) | BDS $R^2$ | BDS Standard error (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | Nov 29 – Jan 19 & Jan 21 – April 5 | BDS (1) | 14345 | 97.24% | 0.9939 | -1.8358 | 0.9005 | 2.55 | | | | |
| | | | 21382 | 99.05% | 1.0943 | -0.9683 | 0.8233 | 3.45 | | | | |
| | | Bridge (1) | 14345 | 97.24% | 1.0015 | -0.0111 | 0.8225 | 3.59 | 1.0222 | 1.8632 | 0.9401 | 2.09 |
| | | | 21382 | 99.05% | 1.2127 | 2.4773 | 0.6252 | 6.39 | 1.2050 | 3.6009 | 0.8979 | 3.33 |
| | | Road (4) | 13013 | 88.21% | 0.8957 | 0.4218 | 0.8084 | 3.42 | 0.9189 | 2.1602 | 0.9339 | 2.01 |
| | | | 20964 | 97.11% | 1.1394 | 2.6911 | 0.5654 | 6.81 | 1.1669 | 3.7810 | 0.8672 | 3.76 |
| 9 | Nov 1 – Jan 19 & Jan 21 – April 5 | BDS (1) | 21872 | 96.13% | 1.0375 | -1.6397 | 0.9200 | 2.16 | | | | |
| | | | 21144 | 97.94% | 1.1241 | -0.5416 | 0.8145 | 3.66 | | | | |
| | | Bridge (1) | 21872 | 96.13% | 1.0656 | 0.1585 | 0.8614 | 3.02 | 1.0306 | 1.8353 | 0.9426 | 1.95 |
| | | | 21144 | 97.94% | 1.2413 | 1.8488 | 0.7544 | 4.84 | 1.1137 | 2.4422 | 0.9422 | 2.35 |
| 59 | Jan 21 – April 5 | BDS (1) | 20544 | 95.16% | 1.1169 | -5.1249 | 0.8266 | 3.47 | | | | |
| | | Bridge (2) | 20544 | 95.16% | 1.2123 | 1.2702 | 0.7583 | 4.65 | 1.1048 | 6.8630 | 0.9503 | 2.11 |
| | | Road (2) | 20544 | 95.16% | 1.0039 | 2.7457 | 0.8450 | 2.92 | 0.8603 | 7.2927 | 0.9363 | 1.87 |
| 68 | Jan 21 – April 5 | BDS (1) | 20970 | 97.14% | 1.0725 | -4.2526 | 0.8405 | 3.14 | | | | |
| | | Bridge (2) | 18513 | 85.76% | 1.1255 | -1.0716 | 0.6518 | 5.36 | 1.1459 | 3.7282 | 0.8976 | 2.91 |
| | | Road (I271) (2) | 20551 | 95.20% | 1.1472 | 1.3392 | 0.6309 | 5.76 | 1.1608 | 6.1528 | 0.8865 | 3.19 |
| | | Road (I77) (2) | 11843 | 54.86% | 1.0299 | 2.0885 | 0.6971 | 4.44 | 1.0192 | 5.9047 | 0.8986 | 2.57 |
| 69 | Jan 21 – April 5 | BDS (1) | 20679 | 95.79% | 1.1426 | -1.4824 | 0.8681 | 2.95 | | | | |
| | | Bridge (2) | 18893 | 87.52% | 1.2160 | 1.6682 | 0.6423 | 5.34 | 1.1714 | 2.7359 | 0.9079 | 2.71 |
| | | Road (1) | 19574 | 90.67% | 1.1644 | 2.5164 | 0.6317 | 5.39 | 1.1251 | 3.5845 | 0.8958 | 2.87 |
| 70 | Jan 21 – April 5 | BDS (1) | 20910 | 96.86% | 1.1422 | -1.1692 | 0.8221 | 3.54 | | | | |
| | | Bridge (3) | 17734 | 82.15% | 1.1125 | 1.8556 | 0.7176 | 4.09 | 0.9429 | 3.0932 | 0.8772 | 2.70 |
| | | Road (3) | 16278 | 75.40% | 1.1811 | 1.1456 | 0.6793 | 4.66 | 1.0526 | 2.1001 | 0.9228 | 2.29 |
| 86 | Jan 21 – April 5 | BDS (1) | 20742 | 96.08% | 1.1183 | 1.0815 | 0.7352 | 4.05 | | | | |
| | | Bridge (2) | 20742 | 96.08% | 1.1769 | 1.6622 | 0.7302 | 4.32 | 1.0202 | 0.5936 | 0.9332 | 2.15 |
| | | Road (2) | 17728 | 82.12% | 1.1323 | 2.0279 | 0.6290 | 4.87 | 1.0523 | 0.5406 | 0.9234 | 2.21 |
| 88 | Jan 21 – April 5 | BDS (1) | 20954 | 97.06% | 1.0817 | -0.3519 | 0.8412 | 3.04 | | | | |
| | | Bridge (1) | 17731 | 82.13% | 1.2404 | 2.7145 | 0.6216 | 6.22 | 1.2499 | 2.8249 | 0.8840 | 3.45 |
| | | Road (4) | 20126 | 93.23% | 1.1199 | 2.6201 | 0.6412 | 5.38 | 1.1145 | 3.0015 | 0.8851 | 3.05 |
| 91 | Jan 21 – April 5 Excl. Feb 2-3 | BDS (1) | 19756 | 94.03% | 1.1231 | -0.2205 | 0.8779 | 2.90 | | | | |
| | | Bridge (2) | 6646 | 31.63% | 1.3081 | 1.6680 | 0.7802 | 4.72 | 1.1877 | 1.8889 | 0.9443 | 2.37 |
| | | Road (2) | 16166 | 76.94% | 1.2238 | 2.3858 | 0.5978 | 5.61 | 1.2050 | 2.4387 | 0.8880 | 2.96 |

N = number of data points after eliminating data where sensors were repeating data and times, sensor data were missing, or temperature values were extreme. Percentage is out of raw data which assumed all time slots were filled, excepting repeated data during daylight savings change. Thus percentages are out of 14752 for Site 7 Nov 29 (18:46)-Jan 19, 22753 for Site 9 Nov 1-Jan 19, 21588 for Jan 21-April 5 for Sites 7 & 9 and for all other sites except 91, which has 21012 for Jan 21-April 5 excepting Feb 2 & 3.

**Table 16. Summary of correlation results with all-day data (English units)**

| Site No. | Dates | Comparison (No. of reporting sensors) | Number of good data points N | Percentage of good data points (%) | Air Slope m | Air Intercept b (°F) | Air $R^2$ | Air Standard error (°F) | Bridge Deck Simulator (BDS) Slope m | BDS Intercept b (°F) | BDS $R^2$ | BDS Standard error (°F) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | Nov 29 – Jan 19 & Jan 21 – April 5 | BDS (1) | 14345 | 97.24% | 0.9939 | -3.1092 | 0.9005 | 4.59 | | | | |
| | | | 21382 | 99.05% | 1.0943 | -4.7605 | 0.8233 | 6.21 | | | | |
| | | Bridge (1) | 14345 | 97.24% | 1.0015 | -0.0680 | 0.8225 | 6.46 | 1.0222 | 2.6434 | 0.9401 | 3.762 |
| | | | 21382 | 99.05% | 1.2127 | -2.3473 | 0.6252 | 11.50 | 1.205 | -0.0784 | 0.8979 | 5.994 |
| | | Road (4) | 13013 | 88.21% | 0.8957 | 4.0968 | 0.8084 | 6.16 | 0.9189 | 6.4836 | 0.9339 | 3.618 |
| | | | 20964 | 97.11% | 1.1394 | 0.3832 | 0.5654 | 12.26 | 1.1669 | 1.4650 | 0.8672 | 6.768 |
| 9 | Nov 1 – Jan 19 & Jan 21 – April 5 | BDS (1) | 21872 | 96.13% | 1.0375 | -4.1515 | 0.9200 | 3.89 | | | | |
| | | | 21144 | 97.94% | 1.1241 | -4.9461 | 0.8145 | 6.59 | | | | |
| | | Bridge (1) | 21872 | 96.13% | 1.0656 | -1.8139 | 0.8614 | 5.44 | 1.0306 | 2.3243 | 0.9426 | 3.51 |
| | | | 21144 | 97.94% | 1.2413 | -4.3938 | 0.7544 | 8.71 | 1.1137 | 0.7576 | 0.9422 | 4.23 |
| 59 | Jan 21 – April 5 | BDS (1) | 20544 | 95.16% | 1.1169 | -12.9656 | 0.8266 | 6.25 | | | | |
| | | Bridge (2) | 20544 | 95.16% | 1.2123 | -4.5072 | 0.7583 | 8.37 | 1.1048 | 8.9998 | 0.9503 | 3.80 |
| | | Road (2) | 20544 | 95.16% | 1.0039 | 4.8175 | 0.8450 | 5.26 | 0.8603 | 17.5973 | 0.9363 | 3.37 |
| 68 | Jan 21 – April 5 | BDS (1) | 20970 | 97.14% | 1.0725 | -9.9747 | 0.8405 | 5.65 | | | | |
| | | Bridge (2) | 18513 | 85.76% | 1.1255 | -5.9449 | 0.6518 | 9.65 | 1.1459 | 2.0420 | 0.8976 | 5.24 |
| | | Road (I271) (2) | 20551 | 95.20% | 1.1472 | -2.2998 | 0.6309 | 10.37 | 1.1608 | 5.9294 | 0.8865 | 5.74 |
| | | Road (I77) (2) | 11843 | 54.86% | 1.0299 | 2.8025 | 0.6971 | 7.99 | 1.0192 | 10.0141 | 0.8986 | 4.63 |
| 69 | Jan 21 – April 5 | BDS (1) | 20679 | 95.79% | 1.1426 | -7.2315 | 0.8681 | 5.31 | | | | |
| | | Bridge (2) | 18893 | 87.52% | 1.2160 | -3.9092 | 0.6423 | 9.61 | 1.1714 | -0.5602 | 0.9079 | 4.88 |
| | | Road (1) | 19574 | 90.67% | 1.1644 | -0.7313 | 0.6317 | 9.70 | 1.1251 | 2.4489 | 0.8958 | 5.17 |
| 70 | Jan 21 – April 5 | BDS (1) | 20910 | 96.86% | 1.1422 | -6.6550 | 0.8221 | 6.37 | | | | |
| | | Bridge (3) | 17734 | 82.15% | 1.1125 | -0.2599 | 0.7176 | 7.36 | 0.9429 | 7.3950 | 0.8772 | 4.86 |
| | | Road (3) | 16278 | 75.40% | 1.1811 | -3.7331 | 0.6793 | 8.39 | 1.0526 | 2.0970 | 0.9228 | 4.12 |
| 86 | Jan 21 – April 5 | BDS (1) | 20742 | 96.08% | 1.1183 | -1.8389 | 0.7352 | 7.29 | | | | |
| | | Bridge (2) | 20742 | 96.08% | 1.1769 | -2.6688 | 0.7302 | 7.78 | 1.0202 | 0.4221 | 0.9332 | 3.87 |
| | | Road (2) | 17728 | 82.12% | 1.1323 | -0.5834 | 0.6290 | 8.77 | 1.0523 | -0.7005 | 0.9234 | 3.98 |
| 88 | Jan 21 – April 5 | BDS (1) | 20954 | 97.06% | 1.0817 | -3.2478 | 0.8412 | 5.47 | | | | |
| | | Bridge (1) | 17731 | 82.13% | 1.2404 | -2.8067 | 0.6216 | 11.20 | 1.2499 | -2.9120 | 0.8840 | 6.21 |
| | | Road (4) | 20126 | 93.23% | 1.1199 | 0.8794 | 0.6412 | 9.68 | 1.1145 | 1.7387 | 0.8851 | 5.49 |
| 91 | Jan 21 – April 5 Excl. Feb 2-3 | BDS (1) | 19756 | 94.03% | 1.1231 | -4.3361 | 0.8779 | 5.22 | | | | |
| | | Bridge (2) | 6646 | 31.63% | 1.3081 | -6.8568 | 0.7802 | 8.50 | 1.1877 | -2.6064 | 0.9443 | 4.27 |
| | | Road (2) | 16166 | 76.94% | 1.2238 | -2.8672 | 0.5978 | 10.10 | 1.2050 | -2.1703 | 0.8880 | 5.33 |

N = number of data points after eliminating data where sensors were repeating data and times, sensor data were missing, or temperature values were extreme. Percentage is out of raw data which assumed all time slots were filled, excepting repeated data during daylight savings change. Thus percentages are out of 14752 for Site 7 Nov 29 (18:46)-Jan 19, 22753 for Site 9 Nov 1-Jan 19, 21588 for Jan 21-April 5 for Sites 7 & 9 and for all other sites except 91, which has 21012 for Jan 21-April 5 excepting Feb 2 & 3

**Table 17. Averages and standard deviations of correlation results with all-day data (metric units)**

| Site No. | Dates | Comparison (Avg. no. of sensors) | Number of good data points N | Percentage of good data points (%) | Air Slope m | Air Intercept b (°C) | Air $R^2$ | Air Standard error (°C) | Bridge Deck Simulator (BDS) Slope m | BDS Intercept b (°C) | BDS $R^2$ | BDS Standard error (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Averages | Jan 21 – April 5 (mostly) | BDS (1) | 20299.8 | 96.59% | 1.0952 | -1.5005 | 0.8427 | 3.1736 | | | | |
| | | Bridge (1.78) | 18140.5 | 86.44% | 1.1739 | 1.2946 | 0.7241 | 4.7764 | 1.1086 | 2.8608 | 0.9198 | 2.5564 |
| | | Road (2.44) | 17678.7 | 84.89% | 1.1038 | 1.9982 | 0.6726 | 4.9260 | 1.0676 | 3.6957 | 0.9038 | 2.6780 |
| Standard Deviations | Jan 21 – April 5 (mostly) | BDS (1) | 2043.5 | 1.36% | 0.0462 | 1.7827 | 0.0496 | 0.5351 | | | | |
| | | Bridge (1.78) | 4399.6 | 19.27% | 0.0891 | 1.1422 | 0.0813 | 1.0267 | 0.0947 | 1.6030 | 0.0271 | 0.5092 |
| | | Road (2.44) | 3281.5 | 13.07% | 0.0983 | 0.7817 | 0.0896 | 1.1419 | 0.1110 | 2.1290 | 0.0237 | 0.5933 |

**Table 18. Averages and standard deviations of correlation results with all-day data (English units)**

| Site No. | Dates | Comparison (Avg. no. of sensors) | Number of good data points N | Percentage of good data points (%) | Air Slope m | Air Intercept b (°F) | Air $R^2$ | Air Standard error (°F) | Bridge Deck Simulator (BDS) Slope m | BDS Intercept b (°F) | BDS $R^2$ | BDS Standard error (°F) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Averages | Jan 21 – April 5 (mostly) | BDS (1) | 20299.8 | 96.59% | 1.0952 | -5.7470 | 0.8427 | 5.7125 | | | | |
| | | Bridge (1.78) | 18140.5 | 86.44% | 1.1739 | -3.2342 | 0.7241 | 8.5975 | 1.1086 | 1.6752 | 0.9198 | 4.6015 |
| | | Road (2.44) | 17678.7 | 84.89% | 1.1038 | 0.2765 | 0.6726 | 8.8668 | 1.0676 | 4.4903 | 0.9038 | 4.8204 |
| Standard Deviations | Jan 21 – April 5 (mostly) | BDS (1) | 2043.5 | 1.36% | 0.0462 | 3.2808 | 0.0496 | 0.9632 | | | | |
| | | Bridge (1.78) | 4399.6 | 19.27% | 0.0891 | 2.1464 | 0.0813 | 1.8481 | 0.0947 | 3.7110 | 0.0271 | 0.9166 |
| | | Road (2.44) | 3281.5 | 13.07% | 0.0983 | 2.9121 | 0.0896 | 2.0555 | 0.1110 | 5.8336 | 0.0237 | 1.0679 |

**Table 19. Summary of correlation results with nighttime data (metric units)**

| Site No. | Dates | Comparison (No. of reporting sensors) | Number of good data points N | Air | | | | Bridge Deck Simulator (BDS) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Slope m | Intercept b (°C) | $R^2$ | Standard error (°C) | Slope m | Intercept b (°C) | $R^2$ | Standard error (°C) |
| 7 | Nov 29 – April 5 Excl. Jan. 20 | BDS (1) | 17834 | 1.0659 | -2.9689 | 0.9810 | 1.05 | | | | |
| | | Bridge (1) | 17834 | 1.0499 | -1.5593 | 0.9550 | 1.61 | 0.9868 | 1.3717 | 0.9771 | 1.15 |
| | | Road (4) | 16990 | 0.9372 | -1.4407 | 0.9421 | 1.64 | 0.8843 | 1.1838 | 0.9698 | 1.19 |
| 9 | Nov 1 – April 5 Excl. Jan. 20 | BDS (1) | 21453 | 1.0719 | -2.6762 | 0.9813 | 1.02 | | | | |
| | | Bridge (1) | 21453 | 1.0659 | -1.4057 | 0.9544 | 1.60 | 0.9661 | 1.2579 | 0.9759 | 1.16 |
| 59 | Jan 21 – April 5 | BDS (1) | 9456 | 0.9916 | -6.7604 | 0.9788 | 0.94 | | | | |
| | | Bridge (2) | 9456 | 1.0410 | -1.1912 | 0.9657 | 1.26 | 1.0469 | 5.8906 | 0.9811 | 0.94 |
| | | Road (2) | 9456 | 0.8522 | 1.6481 | 0.9274 | 1.53 | 0.8520 | 7.4193 | 0.9313 | 1.49 |
| 68 | Jan 21 – April 5 | BDS (1) | 9810 | 0.9897 | -6.0741 | 0.9612 | 1.24 | | | | |
| | | Bridge (2) | 8720 | 0.9575 | -4.3268 | 0.9126 | 1.76 | 0.9844 | 1.6597 | 0.9662 | 1.09 |
| | | Road (I271) (2) | 9443 | 0.8942 | -2.1687 | 0.8876 | 1.91 | 0.9160 | 3.3907 | 0.9451 | 1.33 |
| | | Road (I77) (2) | 4856 | 0.8657 | -0.4443 | 0.9052 | 1.65 | 0.8947 | 4.9195 | 0.9474 | 1.23 |
| 69 | Jan 21 – April 5 | BDS (1) | 9675 | 1.0181 | -2.7546 | 0.9718 | 1.02 | | | | |
| | | Bridge (2) | 8281 | 0.9931 | -0.6025 | 0.9307 | 1.32 | 1.0060 | 1.9879 | 0.9665 | 0.92 |
| | | Road (1) | 8843 | 0.9119 | 0.3060 | 0.9317 | 1.27 | 0.9162 | 2.7148 | 0.9623 | 0.94 |
| 70 | Jan 21 – April 5 | BDS (1) | 9819 | 1.0112 | -2.5332 | 0.9794 | 0.87 | | | | |
| | | Bridge (3) | 7562 | 0.9093 | 0.4035 | 0.9192 | 1.30 | 0.9175 | 2.6299 | 0.9512 | 1.01 |
| | | Road (3) | 6638 | 0.9534 | -0.7248 | 0.9237 | 1.29 | 0.9729 | 1.5251 | 0.9547 | 1.00 |
| 86 | Jan 21 – April 5 | BDS (1) | 9499 | 1.0264 | -1.0959 | 0.9700 | 0.96 | | | | |
| | | Bridge (2) | 9499 | 0.9945 | -0.9529 | 0.9403 | 1.33 | 0.9670 | 0.1062 | 0.9654 | 1.02 |
| | | Road (2) | 7464 | 0.9195 | -0.7884 | 0.9055 | 1.37 | 0.9394 | 0.0688 | 0.9434 | 1.06 |
| 88 | Jan 21 – April 5 | BDS (1) | 9783 | 1.0176 | -2.1831 | 0.9725 | 1.05 | | | | |
| | | Bridge (1) | 6849 | 1.0273 | -1.5502 | 0.9365 | 1.62 | 1.0095 | 0.6355 | 0.9581 | 1.32 |
| | | Road (4) | 9111 | 0.8979 | -0.9735 | 0.9336 | 1.46 | 0.8787 | 0.9503 | 0.9559 | 1.19 |
| 91 | Jan 21 – April 5 Excl. Feb 2-3 | BDS (1) | 9123 | 1.0654 | -2.0133 | 0.9790 | 1.00 | | | | |
| | | Bridge (2) | 2748 | 1.0702 | -0.5776 | 0.9499 | 1.34 | 1.0156 | 1.2743 | 0.9717 | 1.01 |
| | | Road (2) | 6970 | 0.9636 | -0.8409 | 0.9027 | 1.45 | 0.9434 | 0.9528 | 0.9506 | 1.03 |

For Sites 7 and 9 no data were reported on January 20. For Site 91 there were no data from Feb 2 and 3.

Table 20. Summary of correlation results with nighttime data (English units)

| Site No. | Dates | Comparison (No. of reporting sensors) | Number of good data points N | Air | | | | Bridge Deck Simulator (BDS) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Slope m | Intercept b (°F) | $R^2$ | Standard error (°F) | Slope m | Intercept b (°F) | $R^2$ | Standard error (°F) |
| 7 | Nov 29 – April 5 Excl. Jan. 20 | BDS (1) | 17834 | 1.0659 | -7.4528 | 0.9810 | 1.89 | | | | |
| | | Bridge (1) | 17834 | 1.0499 | -4.4035 | 0.9550 | 2.90 | 0.9868 | 2.8915 | 0.9771 | 2.07 |
| | | Road (4) | 16990 | 0.9372 | -0.5837 | 0.9421 | 2.95 | 0.8843 | 5.8332 | 0.9698 | 2.14 |
| 9 | Nov 1 – April 5 Excl. Jan. 20 | BDS (1) | 21453 | 1.0719 | -7.1180 | 0.9813 | 1.84 | | | | |
| | | Bridge (1) | 21453 | 1.0659 | -4.6391 | 0.9544 | 2.88 | 0.9661 | 3.3490 | 0.9759 | 2.09 |
| 59 | Jan 21 – April 5 | BDS (1) | 9456 | 0.9916 | -11.8999 | 0.9788 | 1.69 | | | | |
| | | Bridge (2) | 9456 | 1.0410 | -3.4562 | 0.9657 | 2.27 | 1.0469 | 9.1023 | 0.9811 | 1.69 |
| | | Road (2) | 9456 | 0.8522 | 7.6962 | 0.9274 | 2.75 | 0.8520 | 18.0907 | 0.9313 | 2.68 |
| 68 | Jan 21 – April 5 | BDS (1) | 9810 | 0.9897 | -10.6038 | 0.9612 | 2.23 | | | | |
| | | Bridge (2) | 8720 | 0.9575 | -6.4282 | 0.9126 | 3.17 | 0.9844 | 3.4867 | 0.9662 | 1.96 |
| | | Road (I271) (2) | 9443 | 0.8942 | -0.5181 | 0.8876 | 3.44 | 0.9160 | 8.7913 | 0.9451 | 2.39 |
| | | Road (I77) (2) | 4856 | 0.8657 | 3.4979 | 0.9052 | 2.97 | 0.8947 | 12.2247 | 0.9474 | 2.21 |
| 69 | Jan 21 – April 5 | BDS (1) | 9675 | 1.0181 | -5.5375 | 0.9718 | 1.84 | | | | |
| | | Bridge (2) | 8281 | 0.9931 | -0.8637 | 0.9307 | 2.38 | 1.0060 | 3.3862 | 0.9665 | 1.66 |
| | | Road (1) | 8843 | 0.9119 | 3.3700 | 0.9317 | 2.29 | 0.9162 | 7.5682 | 0.9623 | 1.69 |
| 70 | Jan 21 – April 5 | BDS (1) | 9819 | 1.0112 | -4.9182 | 0.9794 | 1.57 | | | | |
| | | Bridge (3) | 7562 | 0.9093 | 3.6287 | 0.9192 | 2.34 | 0.9175 | 7.3738 | 0.9512 | 1.82 |
| | | Road (3) | 6638 | 0.9534 | 0.1866 | 0.9237 | 2.32 | 0.9729 | 3.6124 | 0.9547 | 1.80 |
| 86 | Jan 21 – April 5 | BDS (1) | 9499 | 1.0264 | -2.8174 | 0.9700 | 1.73 | | | | |
| | | Bridge (2) | 9499 | 0.9945 | -1.5392 | 0.9403 | 2.39 | 0.9670 | 1.2472 | 0.9654 | 1.84 |
| | | Road (2) | 7464 | 0.9195 | 1.1569 | 0.9055 | 2.47 | 0.9394 | 2.0630 | 0.9434 | 1.91 |
| 88 | Jan 21 – April 5 | BDS (1) | 9783 | 1.0176 | -4.4928 | 0.9725 | 1.89 | | | | |
| | | Bridge (1) | 6849 | 1.0273 | -3.6640 | 0.9365 | 2.92 | 1.0095 | 0.8399 | 0.9581 | 2.38 |
| | | Road (4) | 9111 | 0.8979 | 1.5149 | 0.9336 | 2.63 | 0.8787 | 5.5921 | 0.9559 | 2.14 |
| 91 | Jan 21 – April 5 Excl. Feb 2-3 | BDS (1) | 9123 | 1.0654 | -5.7167 | 0.9790 | 1.80 | | | | |
| | | Bridge (2) | 2748 | 1.0702 | -3.2861 | 0.9499 | 2.41 | 1.0156 | 1.7945 | 0.9717 | 1.82 |
| | | Road (2) | 6970 | 0.9636 | -0.3488 | 0.9027 | 2.61 | 0.9434 | 3.5262 | 0.9506 | 1.85 |

For Sites 7 and 9 no data were reported on January 20. For Site 91 there were no data from Feb 2 and 3.

**Table 21. Averages and standard deviations of correlation results with nighttime data (metric units)**

| Site No. | Dates | Comparison (Avg. no. of sensors) | Number of good data points N | Air | | | | Bridge Deck Simulator (BDS) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Slope m | Intercept b (°C) | $R^2$ | Standard error (°C) | Slope m | Intercept b (°C) | $R^2$ | Standard error (°C) |
| Averages | Jan 21 – April 5 (mostly) | BDS (1) | 11828.0 | 1.0286 | -3.2289 | 0.9750 | 1.0167 | | | | |
| | | Bridge (1.78) | 10266.9 | 1.0121 | -1.3070 | 0.9405 | 1.4600 | 0.9889 | 1.8682 | 0.9681 | 1.0689 |
| | | Road (2.44) | 8863.4 | 0.9106 | -0.6030 | 0.9177 | 1.5078 | 0.9108 | 2.5695 | 0.9512 | 1.1622 |
| Standard Deviations | Jan 21 – April 5 (mostly) | BDS (1) | 4746.1 | 0.0305 | 1.4511 | 0.0070 | 0.1045 | | | | |
| | | Bridge (1.78) | 5760.9 | 0.0536 | 1.2915 | 0.0176 | 0.1851 | 0.0369 | 1.6738 | 0.0095 | 0.1257 |
| | | Road (2.44) | 3415.9 | 0.0376 | 1.0791 | 0.0181 | 0.2027 | 0.0375 | 2.3516 | 0.0112 | 0.1751 |

**Table 22. Averages and standard deviations of correlation results with nighttime data (English units)**

| Site No. | Dates | Comparison (Avg. no. of sensors) | Number of good data points N | Air | | | | Bridge Deck Simulator (BDS) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Slope m | Intercept b (°F) | $R^2$ | Standard error (°F) | Slope m | Intercept b (°F) | $R^2$ | Standard error (°F) |
| Averages | Jan 21 – April 5 (mostly) | BDS (1) | 11828.0 | 1.0286 | -6.7286 | 0.9750 | 1.8300 | | | | |
| | | Bridge (1.78) | 10266.9 | 1.0121 | -2.7390 | 0.9405 | 2.6280 | 0.9889 | 3.7190 | 0.9681 | 1.9240 |
| | | Road (2.44) | 8863.4 | 0.9106 | 1.7746 | 0.9177 | 2.7140 | 0.9108 | 7.4780 | 0.9512 | 2.0920 |
| Standard Deviations | Jan 21 – April 5 (mostly) | BDS (1) | 4746.1 | 0.0305 | 2.3411 | 0.0070 | 0.1880 | | | | |
| | | Bridge (1.78) | 5760.9 | 0.0536 | 2.8975 | 0.0176 | 0.3332 | 0.0369 | 2.7710 | 0.0095 | 0.2263 |
| | | Road (2.44) | 3415.9 | 0.0376 | 2.7129 | 0.0181 | 0.3648 | 0.0375 | 5.0378 | 0.0112 | 0.3152 |

# 10 Solar radiation

A cursory examination of data recorded during sunny daytime hours quickly shows that the temperatures seen on pavement sensors and on bridge deck simulators is much higher than the air temperature. It is thus obvious that solar radiation is an important factor in determining pavement temperatures. Even low levels of solar radiation, such as those observed during cloudy skies preceding winter weather during daylight hours may have an effect. The effect may be different for bridge deck simulators than it is for bridge decks and may be different still for road surfaces off bridges, particularly when the road surface is asphalt and the bridge surface is concrete, as is the case for most of the sites in this study. The effect of solar radiation is thus an unquantified mystery affecting Ohio's RWIS system, and the data required to resolve the effects could not be directly obtained.

## 10.1 Kentucky's RWIS system

However, Kentucky's RWIS installations routinely include solar radiation monitoring. Since two of the sites in this study are in the suburban Cincinnati area, on the I275 beltway, an effort was made to see if any solar radiation data from nearby sites in Kentucky could be obtained and used to provide some handle on the effects of solar radiation. Glenn Anderson of the Kentucky Transportation Cabinet (KTC) provided information on the Kentucky installations and data covering the same period as this study. Current RWIS data from Kentucky's RWIS system may be obtained at http://transportation.ky.gov/rwis/ (accessed September 2, 2006), which is the KTC equivalent of ODOT's Buckeye Traffic (http://www.buckeyetraffic.org/rwis/nosvg/, accessed September 2, 2006). From an analysis of the data files provided, it was determined that Kentucky Sites 60 and 61 on the Kentucky portion of I275 were closest to Ohio Sites 70 and 69, respectively. The map in Figure 131 shows the locations and distances between corresponding Kentucky and Ohio RWIS sites.

Kentucky's RWIS system was designed by the KTC using various Campbell Scientific components and assembled by the KTC or contractors, rather than being an off-the-shelf system designed and built by a single outside vendor. Weather data from the Kentucky sites were recorded in the data files at five minute intervals, just as is the case with the ODOT data files, though the data reporting times were at minutes ending in 0 and 5 rather than those ending in 1 and 6. Solar radiation flux density is reported in $W/m^2$ and is measured with a Li-cor LI200X radiation meter. The KTC decided to include the solar radiation because they felt it would help accurately predict the pavement temperature.

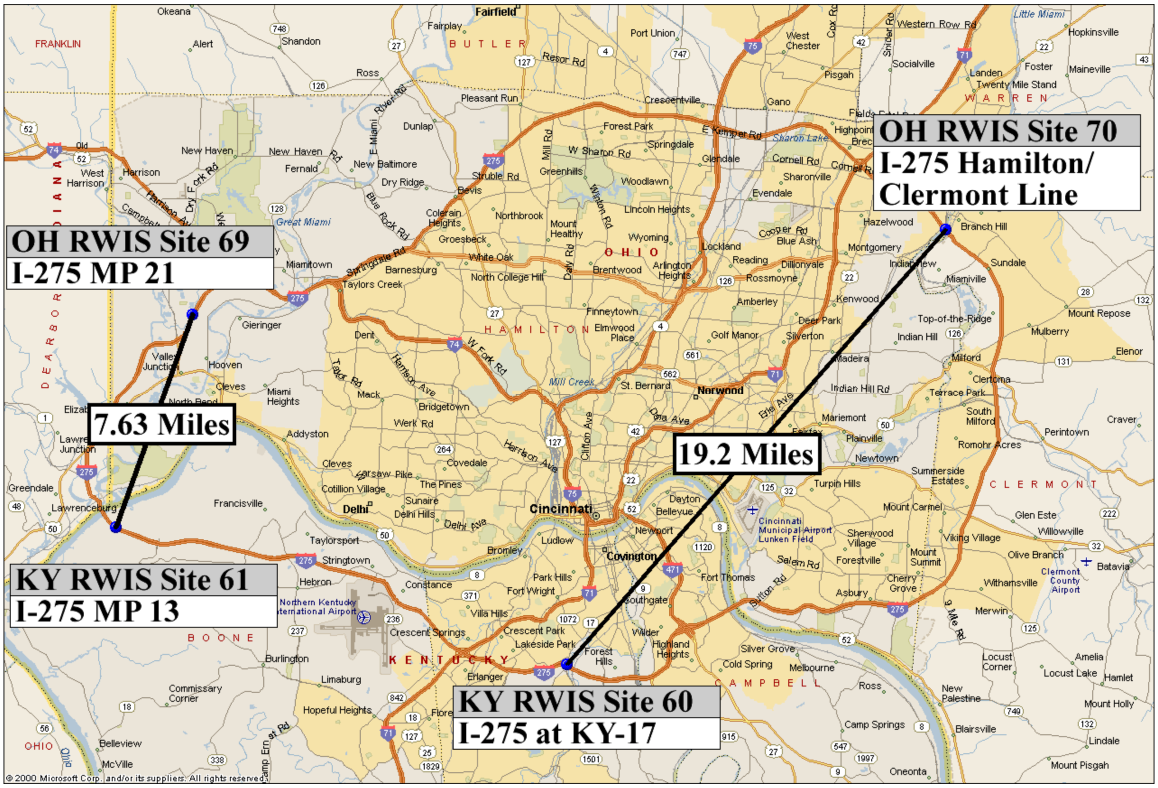


**Figure 131. Proximity map showing Kentucky RWIS Sites 60 & 61, and OH RWIS Sites 69 & 70.**

In looking at the solar radiation data from the two sites, it quickly became evident that Site 61 was reporting solar radiation levels consistently below those reported by Site 60. Solar radiation data from two other nearby KTC RWIS sites, Sites 63 and 64, were plotted with those of Site 60 and 61. It was quickly seen that even though there were minor differences between all the sites, Site 61 was clearly consistently under reporting solar radiation by a relatively constant factor. Figure 132 shows the time series plot of solar radiation flux density at four sites on the Kentucky Roadway Weather Information System (RWIS) during January 24-26, 2005. From the three days of data shown, it is clear that the maximum solar radiation flux density is observed at mid-day for each location. Readings from site 61 were observed to be consistently lower than those for site 60, 63 and 64 as can be seen in Figure 132. This indicates a systematic error in the data from site 61. Glenn Anderson was notified of this issue, and he said that he would report back when the contractor had visited the site on the next regularly scheduled maintenance stop. No word about the site had been received by the time this report was compiled.

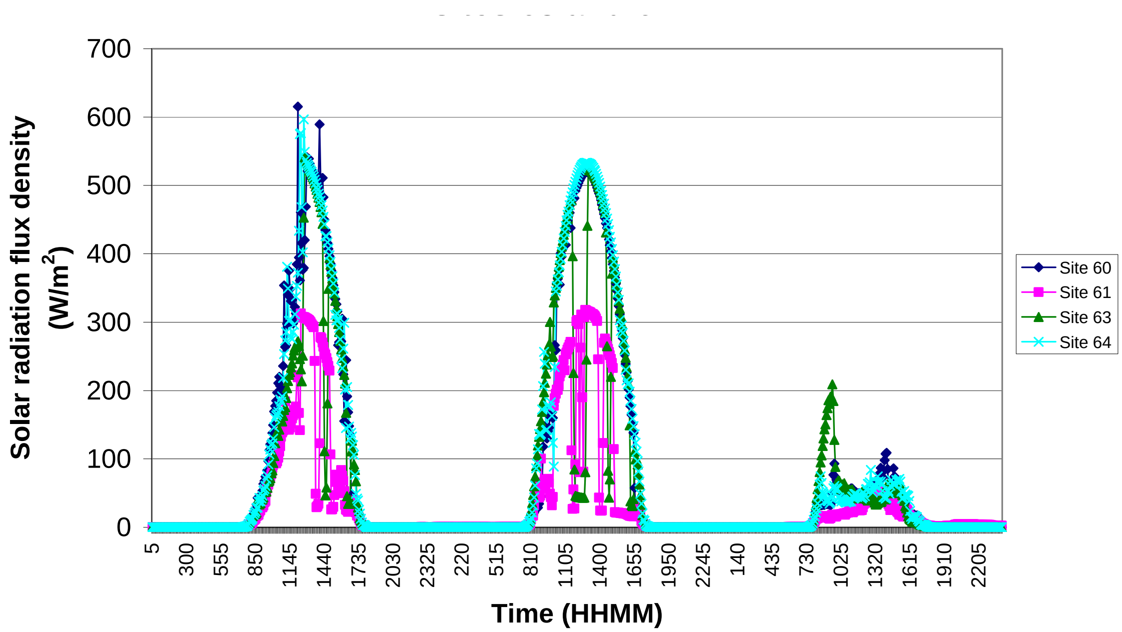



**Figure 132. Solar radiation flux density for Kentucky Sites 60, 61, 63 and 64 January 24-26 2005.**

## 10.2 Comparison of Kentucky solar radiation data with Ohio temperature data

Kentucky sites 60 and 61 were selected because they are close to Ohio sites 70 and 69 respectively, and the solar radiation measurements from the Kentucky sites provided the best available estimate of solar radiation at the Ohio sites. And because Site 61 was the closest to Site 69 and seemed to be off by a constant factor, it was decided that its solar data could be used with the understanding that the solar radiation values were proportionately higher than reported. The two sites were close enough that it was reasonable to assume that if conditions were generally sunny at the Kentucky site, the conditions would also be generally sunny at the corresponding Ohio site.

Figure 133 is a time series plot that shows the temperature of the air, bridge and bridge deck simulator for Ohio RWIS Site 69, and the solar flux density at Kentucky RWIS Site 61. From this plot, it is apparent that solar flux density has an impact on the temperature of both the bridge and bridge deck simulator. During the first two days, when solar flux density was high, the temperatures of the bridge and bridge deck simulator were much greater than the temperature of the air; however, on day three, when solar flux density was low, the three temperature readings were much closer. It can be inferred from this that solar flux density can have a major impact on the temperature of the bridge and bridge deck simulator. Figure 134 shows the time series graph for the same sensors from Ohio Site 70 and Kentucky Site 60. While the daytime temperature differences between the pavement and air temperatures were not as large as at Ohio Site 69, the differences could be due to some slight variations in local conditions or in the configuration of the site, such as the orientation of the bridge respective to the prevailing winds those days. The same general pattern of a large (nearly 10C° (18F°)) difference between bridge and air temperature during peak solar radiation still holds. No further analysis of this data is provided as the aim here is to demonstrate the importance of solar radiation as a factor in pavement temperatures during daytime.

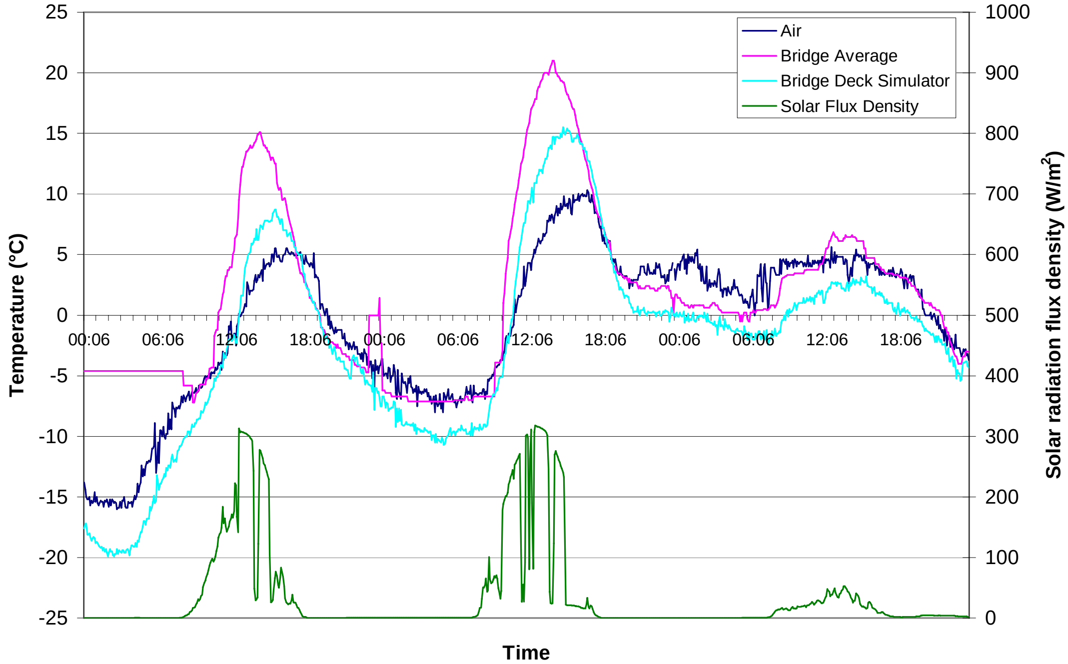



**Figure 133. Site 69 I275 MM21 bridge average January 24-26, 2005 plus KY Site 61 solar radiation.**

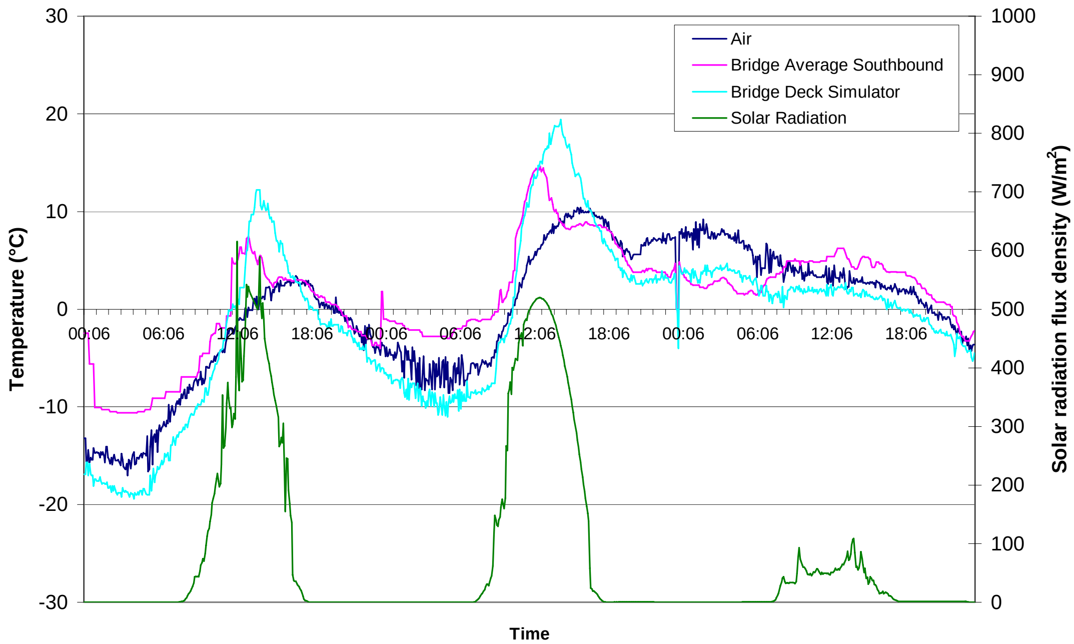



**Figure 134. Site 70, I275 Hamilton/Clermont County line bridge sensors January 24- 26, 2005 plus KY Site 60 solar radiation.**

# 11 Prediction Limits for Bridge Deck Temperatures

One objective of this research project is to determine how to use the bridge deck simulators to estimate bridge and road temperatures in the area of the simulator. To quantify this, a confidence limit was generated that represents temperature ranges within which one can be certain, up to a specified probability level, that, for example, the actual bridge temperature lies given the bridge deck simulator temperature. Confidence limits are generated assuming that the distribution of temperature differences is normal. In the case of the temperature data in this study, the data are clearly not normally distributed. However, the same idea is applied – using the actual temperature difference distribution to estimate a temperature range within which one may assume with a given level of certainty (90%, 95%, or 99%) the actual bridge temperature lies. In this report they are called prediction limits to distinguish them from normal-distribution-derived confidence limits.

The prediction limits were established for bridge deck simulator (BDS) temperature versus the bridge deck temperature regressions and also for the air temperature versus the bridge deck temperature regressions. Finally, the two sets of readings were compared to establish the closeness of readings indicated by the BDS sensor and the air temperature sensor to the actual bridge deck temperature reading. Additionally, prediction limits were also found for road temperature data in terms of bridge deck simulator and air temperatures.

## 11.1 Method

The method employed to determine the prediction limits was as follows.

1. Only nighttime readings were considered for these analyses. This was done to minimize the effects of solar radiation on the readings.

2. The results for the BDS temperature versus the bridge deck temperature were analyzed through regression analysis, as previously discussed in Chapter 9. From the scatter diagrams for each site, a regression equation was determined with the corresponding standard error. For instance, Figure 103 in Section 9.7.1 shows an example of the regression analysis with the relation between the BDS temperatures and the bridge deck temperatures for night time data, in this case for Site 86 on I90 in Lorain County. Figure 102 shows the regression between air and bridge deck temperatures obtained at the same site, which is used as an example in the following.

3. The ‘regression temperature’ $T_{BR}$ for each data point was computed using the appropriate regression equation.

4. The ‘delta’ value $\Delta T_B$ for each point was computed by finding the difference between the actual bridge deck temperature reading $T_B$ and the regression temperature $T_{BR}$ obtained in the previous step: $\Delta T_B = T_B - T_{BR}$ .

5. The delta values for each of the readings were then sorted in ascending order of their values (negative to positive).

6. Steps 3-5 were repeated using the regression between air temperature and bridge temperature. If the regression temperature in this case is designated $T_{AR}$, then one can generate the corresponding delta values as follows (the actual bridge temperature $T_B$ remains the same): $\Delta T_A = T_B - T_{AR}$ .

7. The initial plan for analyzing the temperatures for each of the nine sites was to sort the delta values into temperature bins and then test if the histogram obtained followed a standard normal distribution. The normal distribution for this comparison was obtained by multiplying the expected frequencies for each bin by the number of observations. Data from Site 86 (Lorain County) and Site 7 (Crawford County) were subjected to the chi-squared ($\chi^2$) test to verify if the histogram followed a normal distribution. The $\chi^2$ value obtained was much higher than the maximum value allowed from the chi-squared table for the specified degrees of freedom (DOF), meaning that the hypothesis that the histogram followed a normal curve had to be rejected. A quick examination for all the other sites showed that similar results would be obtained, and so an approach to use the overall standard deviation was adopted for all the nine sites. Figure 135 shows the histogram of the $\Delta T_B$ values for Site 86, which is highly skewed and visibly non-normal. Table 23 lists the data points plotted in the histogram in Figure 135. Figure 136 and Table 24 show the corresponding histogram and data table for the $\Delta T_A$ values at Site 86. Table 25 shows an excerpt of the Site 86 data sorted by bridge deck simulator temperature.

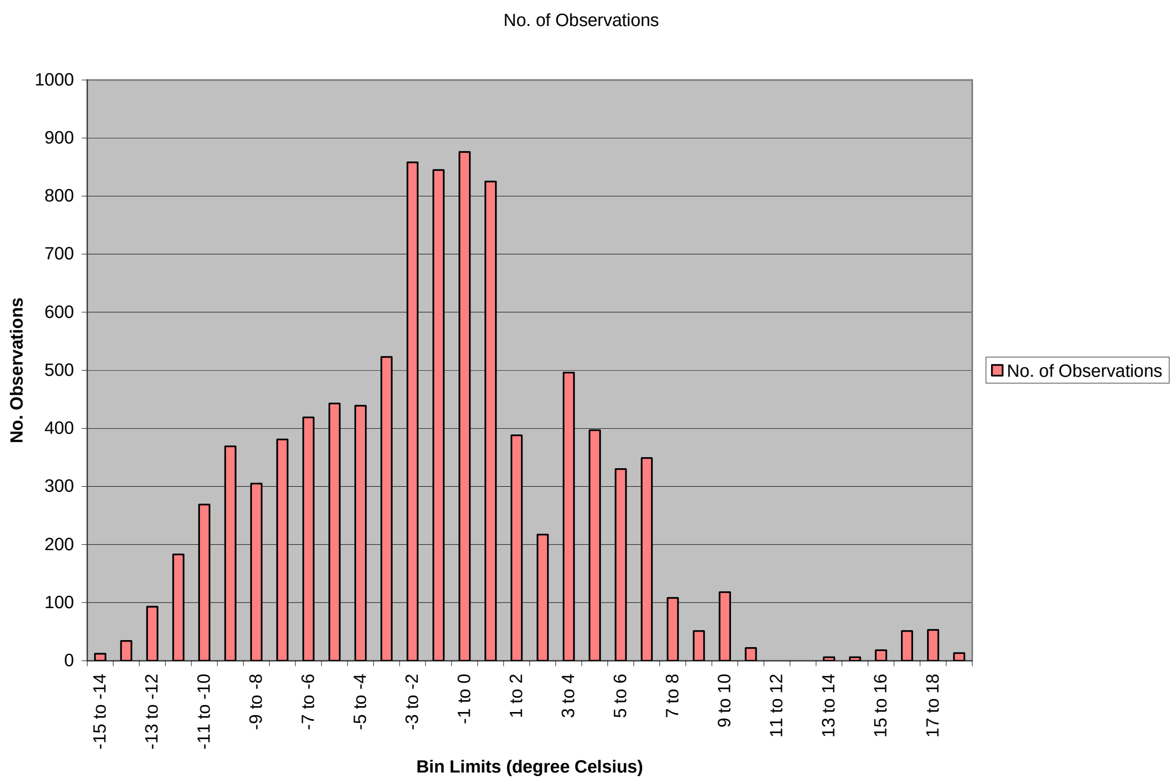



**Figure 135. Histogram of $\Delta T_B$ values for Site 86 in Lorain County used to check the distribution for normality (N = 9,499 total observations).**

Table 23. Data plotted in histogram in Figure 135.

| BDS temperature interval (°C) | BDS temperature interval (°F) | Number of observations Within range | Number of observations Cumulative |
|---|---|---|---|
| -15 to -14 | 5.0 to 6.8 | 12 | 12 |
| -14 to -13 | 6.8 to 8.6 | 34 | 46 |
| -13 to -12 | 8.6 to 10.4 | 93 | 139 |
| -12 to -11 | 10.4 to 12.2 | 183 | 322 |
| -11 to -10 | 12.2 to 14.0 | 269 | 591 |
| -10 to -9 | 14.0 to 15.8 | 369 | 960 |
| -9 to -8 | 15.8 to 17.6 | 305 | 1265 |
| -8 to -7 | 17.6 to 19.4 | 381 | 1646 |
| -7 to -6 | 19.4 to 21.2 | 419 | 2065 |
| -6 to -5 | 21.2 to 23.0 | 443 | 2508 |
| -5 to -4 | 23.0 to 24.8 | 439 | 2947 |
| -4 to -3 | 24.8 to 26.6 | 523 | 3470 |
| -3 to -2 | 26.6 to 28.4 | 858 | 4328 |
| -2 to -1 | 28.4 to 30.2 | 845 | 5173 |
| -1 to 0 | 30.2 to 32.0 | 876 | 6049 |
| 0 to 1 | 32.0 to 33.8 | 825 | 6874 |
| 1 to 2 | 33.8 to 35.6 | 388 | 7262 |
| 2 to 3 | 35.6 to 37.4 | 217 | 7479 |
| 3 to 4 | 37.4 to 39.2 | 496 | 7975 |
| 4 to 5 | 39.2 to 41.0 | 397 | 8372 |
| 5 to 6 | 41.0 to 42.8 | 330 | 8702 |
| 6 to 7 | 42.8 to 44.6 | 349 | 9051 |
| 7 to 8 | 44.6 to 46.4 | 108 | 9159 |
| 8 to 9 | 46.4 to 48.2 | 51 | 9210 |
| 9 to 10 | 48.2 to 50.0 | 118 | 9328 |
| 10 to 11 | 50.0 to 51.8 | 22 | 9350 |
| 11 to 12 | 51.8 to 53.6 | 0 | 9350 |
| 12 to 13 | 53.6 to 55.4 | 0 | 9350 |
| 13 to 14 | 55.4 to 57.2 | 6 | 9356 |
| 14 to 15 | 57.2 to 59.0 | 6 | 9362 |
| 15 to 16 | 59.0 to 60.8 | 18 | 9380 |
| 16 to 17 | 60.8 to 62.6 | 51 | 9431 |
| 17 to 18 | 62.6 to 64.4 | 53 | 9484 |
| 18 to 19 | 64.4 to 66.2 | 13 | 9497 |

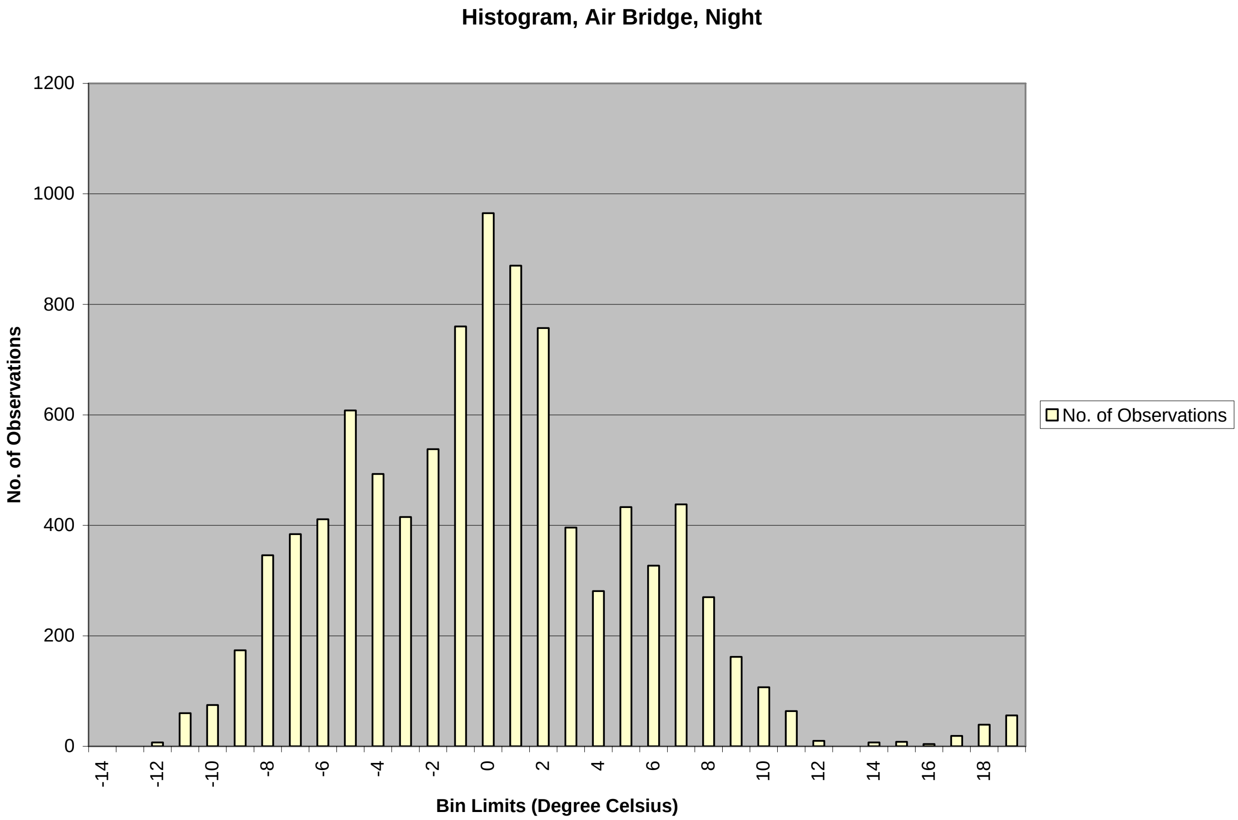



**Figure 136. Histogram of $\Delta T_A$ values for Site 86 in Lorain County used to check the distribution for normality (N = 9,499 total observations).**

**Table 24. Data plotted in histogram in Figure 136.**

| Upper Temperature (Air) | | Number of Observations | |
|---|---|---|---|
| (°C) | (°F) | Within range | Cumulative |
| -14 | 6.8 | 0 | 0 |
| -13 | 8.6 | 0 | 0 |
| -12 | 10.4 | 7 | 7 |
| -11 | 12.2 | 60 | 67 |
| -10 | 14.0 | 75 | 142 |
| -9 | 15.8 | 174 | 316 |
| -8 | 17.6 | 346 | 662 |
| -7 | 19.4 | 384 | 1046 |
| -6 | 21.2 | 411 | 1457 |
| -5 | 23.0 | 608 | 2065 |
| -4 | 24.8 | 493 | 2558 |
| -3 | 26.6 | 415 | 2973 |
| -2 | 28.4 | 538 | 3511 |
| -1 | 30.2 | 760 | 4271 |
| 0 | 32.0 | 965 | 5236 |
| 1 | 33.8 | 870 | 6106 |
| 2 | 35.6 | 757 | 6863 |
| 3 | 37.4 | 396 | 7259 |
| 4 | 39.2 | 281 | 7540 |
| 5 | 41.0 | 433 | 7973 |
| 6 | 42.8 | 327 | 8300 |
| 7 | 44.6 | 438 | 8738 |
| 8 | 46.4 | 270 | 9008 |
| 9 | 48.2 | 162 | 9170 |
| 10 | 50.0 | 107 | 9277 |
| 11 | 51.8 | 64 | 9341 |
| 12 | 53.6 | 10 | 9351 |
| 13 | 55.4 | 0 | 9351 |
| 14 | 57.2 | 7 | 9358 |
| 15 | 59.0 | 8 | 9366 |
| 16 | 60.8 | 4 | 9370 |
| 17 | 62.6 | 19 | 9389 |
| 18 | 64.4 | 39 | 9428 |
| 19 | 66.2 | 56 | 9484 |

**Table 25. Example of temperature values sorted by bridge deck simulator temperature, from Site 86 in Lorain County for temperature range -15 to -14°C (5.0 to 6.8°F). Top in metric units, bottom in English units.**

| BRIDGE AVG (°C) | BDS TEMP (°C) | Regression Temperature (°C) | Delta (C°) | Variance $(C°)^2$ | Std. Devn. (C°) | ANALYSIS | Prediction Limit Values (C°) |
|---|---|---|---|---|---|---|---|
| -12.5 | -14.4 | -13.82 | 1.32 | 0.08 | 0.282 | Bridge Temp. | 90% P.L. |
| -12.7 | -14.2 | -13.63 | 0.93 | | | Average (°C) | 0.134 |
| -12.2 | -14.2 | -13.63 | 1.43 | | | -12.42 | |
| -12.2 | -14.1 | -13.53 | 1.33 | | | BDS Temp. | 95% P.L. |
| -12.2 | -14.1 | -13.53 | 1.33 | | | Average (°C) | 0.16 |
| -12.5 | -14 | -13.43 | 0.93 | | | -14.08 | |
| -12.7 | -14 | -13.43 | 0.73 | | | Number of | 99% P.L. |
| -12.7 | -14 | -13.43 | 0.73 | | | Observations | 0.21 |
| -12.7 | -14 | -13.43 | 0.73 | | | 12 | |
| -11.9 | -14 | -13.43 | 1.53 | | | | |
| -12.2 | -14 | -13.43 | 1.23 | | | | |
| -12.5 | -14 | -13.43 | 0.93 | | | | |

| BRIDGE AVG (°F) | BDS TEMP (°F) | Regression Temperature (°F) | Delta (F°) | Variance $(F°)^2$ | Std. Devn. (F°) | ANALYSIS | Prediction Limit Values (F°) |
|---|---|---|---|---|---|---|---|
| 9.5 | 6.08 | 7.124 | 2.376 | 0.283 | 0.532 | Bridge Temp. | 90% P.L. |
| 9.14 | 6.44 | 7.466 | 1.674 | | | Average (°F) | 0.2412 |
| 10.04 | 6.44 | 7.466 | 2.574 | | | 9.65 | |
| 10.04 | 6.62 | 7.646 | 2.394 | | | BDS Temp. | 95% P.L. |
| 10.04 | 6.62 | 7.646 | 2.394 | | | Average (°F) | 0.288 |
| 9.5 | 6.8 | 7.826 | 1.674 | | | 6.65 | |
| 9.14 | 6.8 | 7.826 | 1.314 | | | Number of | 99% P.L. |
| 9.14 | 6.8 | 7.826 | 1.314 | | | Observations | 0.378 |
| 9.14 | 6.8 | 7.826 | 1.314 | | | 12 | |
| 10.58 | 6.8 | 7.826 | 2.754 | | | | |
| 10.04 | 6.8 | 7.826 | 2.214 | | | | |
| 9.5 | 6.8 | 7.826 | 1.674 | | | | |

8. For each of the two data comparisons, the delta values ($\Delta T_{AR}$ and $\Delta T_{BR}$) were sorted in ascending order and then analyzed to establish 90%, 95% and 99% prediction limits. For example, a 90% prediction limit would mean that the top and bottom five percentiles were eliminated and the readings corresponding to the 5th percentile and the 95th percentile were taken as the prediction limits $T_{A5\%}$ and $T_{A95\%}$, above and below the actual readings of the bridge deck. Thus for a given air temperature $T_A$, the actual bridge temperature $T_B$, should have a 90% chance of lying between $T_{A5\%}$ and $T_{A95\%}$, with the most likely value at the regression value $T_{AR}$. $T_{A5\%}$ is computed by adding the lower prediction value on the 90% row, which is negative, in Table 26 to $T_{AR}$. Similarly, $T_{A95\%}$ is computed by adding the upper prediction value on the 90% row in Table 26 to $T_{AR}$.

**Table 26. Prediction limits for Site 86 in Lorain County for predicting bridge temperature as a function of air temperature.**

| Prediction Limit | Lower observation number (9499 total observations) | Lower prediction value (C°) | Lower prediction value (F°) | Upper observation number | Upper prediction value (C°) | Upper prediction value (F°) |
|---|---|---|---|---|---|---|
| 90% | 475 | -2.35 | -4.23 | 9025 | 2.06 | 3.71 |
| 95% | 238 | -2.84 | -5.11 | 9262 | 2.52 | 4.54 |
| 99% | 47 | -3.61 | -6.50 | 9452 | 3.27 | 5.89 |

9. This method was repeated for all the nine sites, and for both the data sets. Finally the two sets of data were compared to check the closeness of the limits to the actual values. As expected, the BDS temperature performed better than the air temperature as a predictor of the bridge temperature, meaning in this case the prediction limits for the BDS values were narrower than for the air temperature. The metric used in the comparison was the ratio of the BDS bridge lower prediction limit expressed as a percentage of air bridge prediction limit. This included the lower prediction limit, the upper prediction limit as well as the entire range limit (upper prediction limit – lower prediction limit) at all three prediction levels (90%, 95% and 99%).

## 11.2 Results

The prediction limits for each site are presented in site number order in Table 27 through Table 35. Each table is formatted similarly, with rows grouped according to the temperatures being compared, in the order of bridge-BDS, bridge-air, road-BDS, and road-air comparisons. For each comparison, prediction limits of 90%, 95%, and 99% are tabulated, and in the columns to the right the lower and upper prediction values are given first in Celsius and then in Fahrenheit. Also, under the name of each comparison is the number of data points analyzed, which are the same as the number of good data points reported in Table 19 and Table 20 for bridge or road data.

The prediction values can be used as follows. Suppose one wants to use a BDS temperature to estimate a bridge temperature. For a selected site one first obtains the BDS temperature $T_{BDS}$ from the RWIS system. Then one computes the estimate of the bridge temperature using the slope and intercept of the line fit on Table 19 if one is working in Celsius or on Table 20 if one is working in Fahrenheit. Call this regression estimate $T_R$. One then selects the prediction limit one wants, then selects the corresponding lower prediction value (LPV) and upper prediction value (UPV). One can then be confident at the level of the prediction limit that the actual bridge temperature lies between $T_R$+LPV and $T_R$+UPV (note LPV<0). To make an example, suppose one wants to find the 90% prediction limits at Site 7 for road temperature given an air temperature of 24°F (-4.4°C). First we look up the nighttime air-road regression parameters m and b for Site 7 in Table 20 since we are working in Fahrenheit. These are m=0.9372 and b=-0.5837, so $T_R$ = 0.9372*24 -0.5837 = 21.91°F (-5.61°C). The 90% prediction limit values for road versus air at Site 7 are in the tenth row of numbers in Table 27, and they are LPV=-4.98F° and UPV=4.41F° (-2.76C° and 2.45C°). This gives a temperature range of $T_R$+LPV = 21.91 + -4.98 = 16.93°F (-8.37°C) to $T_R$+UPV = 21.91 + 4.41 = 26.32°F (-3.16°C). Thus based on the observed nighttime distribution of temperatures at Site 7 one can be 90% sure that if the air temperature is 24°F (-4.4°C) the bridge temperature is between 16.93°F (-8.37°C) and 26.32°F (-3.16°C).

As expected, the prediction limits using BDS temperatures are tighter than those using air temperatures. This follows from the higher correlations for BDS temperature relationships, such as bridge-BDS, than for air relationships, such as bridge-air, as can be seen in Table 19 and Table 20. Following the example above, but this time using a nighttime BDS temperature of 24°F (-4.4°C) at Site 7 to predict road temperature, one uses the regression relationship $T_R$=0.843*24+5.8322 in Table 20 to obtain a value of 27.06°F (-2.74°C). Then one can use the 90% BDS-road prediction limits in the seventh row of numbers in Table 27 to estimate that one can be 90% sure that the bridge temperature is between 23.42°F (-4.77°C) and 30.32°F (-0.93°C). The 6.90F° (3.83C°) range is indeed narrower than the 9.39F° (5.22C°) range from the earlier example, but the ranges do not overlap completely because the air temperature of 24°F (-4.4°C) in the first example does not correlate exactly to the 24°F (-4.4°C) BDS temperature used in the second.

**Table 27. Nighttime prediction limits for Site 07 in Crawford County.**

Nighttime Prediction Limits for Site 7, US30 Crawford County

For a given regression temperature reading $T_R$:
$T_U = T_R$ + Upper prediction value
$T_L = T_R$ + Lower prediction value (note lower prediction value is negative)

| Comparison | Prediction Limit | Lower Prediction Value (°C) | Upper Prediction Value (°C) | Lower Prediction Value (°F) | Upper Prediction Value (°F) |
|---|---|---|---|---|---|
| Bridge-BDS (N = 17,834) | 90% | -1.96 | 1.84 | -3.52 | 3.31 |
| | 95% | -2.32 | 2.23 | -4.18 | 4.02 |
| | 99% | -3.13 | 3.06 | -5.63 | 5.51 |
| Bridge-Air (N = 17,834) | 90% | -2.72 | 2.56 | -4.90 | 4.61 |
| | 95% | -3.17 | 3.07 | -5.70 | 5.53 |
| | 99% | -4.11 | 4.05 | -7.40 | 7.30 |
| Road-BDS (N = 16,990) | 90% | -2.02 | 1.81 | -3.64 | 3.26 |
| | 95% | -2.45 | 2.17 | -4.41 | 3.91 |
| | 99% | -3.45 | 2.87 | -6.21 | 5.17 |
| Road-Air (N = 16,990) | 90% | -2.76 | 2.45 | -4.98 | 4.41 |
| | 95% | -3.26 | 2.88 | -5.88 | 5.18 |
| | 99% | -4.82 | 3.78 | -8.68 | 6.80 |

Notes:
N=Number of observations
Regression temperatures based on parameters given in Table 19 and Table 20

**Table 28. Nighttime prediction limits for Site 09 in Stark County.**

| Nighttime Prediction Limits for Site 9, I77 Stark County | | | | | |
|---|---|---|---|---|---|
| For a given regression temperature reading $T_R$:<br>$T_U = T_R$ + Upper prediction value<br>$T_L = T_R$ + Lower prediction value (note lower prediction value is negative) | | | | | |
| Comparison | Prediction Limit | Lower Prediction Value (°C) | Upper Prediction Value (°C) | Lower Prediction Value (°F) | Upper Prediction Value (°F) |
| Bridge-BDS (N =21453 ) | 90% | -2.13 | 1.77 | -3.84 | 3.19 |
| | 95% | -2.57 | 2.10 | -4.62 | 3.79 |
| | 99% | -3.34 | 2.65 | -6.01 | 4.78 |
| Bridge-Air (N =21453 ) | 90% | -2.92 | 2.34 | -5.25 | 4.21 |
| | 95% | -3.46 | 2.71 | -6.22 | 4.88 |
| | 99% | -4.42 | 3.52 | -7.96 | 6.34 |
| Notes:<br>N=Number of observations<br>Regression temperatures based on parameters given in Table 19 and Table 20 | | | | | |

**Table 29. Nighttime prediction limits for Site 59 in Warren County.**

| Nighttime Prediction Limits for Site 59, I71 Warren County | | | | | |
|---|---|---|---|---|---|
| For a given regression temperature reading $T_R$:<br>$T_U = T_R$ + Upper prediction value<br>$T_L = T_R$ + Lower prediction value (note lower prediction value is negative) | | | | | |
| Comparison | Prediction Limit | Lower Prediction Value (°C) | Upper Prediction Value (°C) | Lower Prediction Value (°F) | Upper Prediction Value (°F) |
| Bridge-BDS (N =9456 ) | 90% | -1.60 | 1.49 | -2.89 | 2.69 |
| | 95% | -2.01 | 1.77 | -3.61 | 3.19 |
| | 99% | -2.52 | 2.28 | -4.53 | 4.10 |
| Bridge-Air (N = 9456) | 90% | -2.11 | 2.04 | -3.79 | 3.67 |
| | 95% | -2.55 | 2.44 | -4.60 | 4.39 |
| | 99% | -3.09 | 3.09 | -5.57 | 5.57 |
| Road-BDS (N =9456 ) | 90% | -2.57 | 2.18 | -4.62 | 3.92 |
| | 95% | -3.06 | 2.62 | -5.50 | 4.71 |
| | 99% | -4.42 | 3.87 | -7.96 | 6.97 |
| Road-Air (N = 9456) | 90% | -2.66 | 2.21 | -4.79 | 3.99 |
| | 95% | -3.11 | 2.66 | -5.59 | 4.78 |
| | 99% | -4.92 | 3.60 | -8.85 | 6.49 |
| Notes:<br>N=Number of observations<br>Regression temperatures based on parameters given in Table 19 and Table 20 | | | | | |

**Table 30. Nighttime prediction limits for Site 68 in Summit County.**

| Nighttime Prediction Limits for Site 68, I271 & I77 Summit County | | | | | |
|---|---|---|---|---|---|
| For a given regression temperature reading $T_R$:<br>$T_U = T_R$ + Upper prediction value<br>$T_L = T_R$ + Lower prediction value (note lower prediction value is negative) | | | | | |
| Comparison | Prediction Limit | Lower Prediction Value (°C) | Upper Prediction Value (°C) | Lower Prediction Value (°F) | Upper Prediction Value (°F) |
| Bridge-BDS (N =8720 ) | 90% | -1.86 | 1.80 | -3.35 | 3.23 |
| | 95% | -2.25 | 2.06 | -4.04 | 3.71 |
| | 99% | -2.91 | 2.57 | -5.23 | 4.63 |
| Bridge-Air (N = 8720) | 90% | -2.93 | 2.87 | -5.27 | 5.17 |
| | 95% | -3.48 | 3.40 | -6.26 | 6.11 |
| | 99% | -4.25 | 4.48 | -7.65 | 8.06 |
| I271 Road-BDS (N = 9443) | 90% | -0.79 | 6.57 | -1.42 | 11.82 |
| | 95% | -1.51 | 9.15 | -2.73 | 16.48 |
| | 99% | -3.67 | 13.52 | -6.61 | 24.34 |
| I271 Road-Air (N =9443 ) | 90% | -1.17 | 6.67 | -2.10 | 12.01 |
| | 95% | -1.99 | 8.26 | -3.58 | 14.88 |
| | 99% | -3.62 | 13.44 | -6.51 | 24.20 |
| I 77 Road-BDS (N =4856 ) | 90% | -1.92 | 2.18 | -3.46 | 3.92 |
| | 95% | -2.25 | 2.62 | -4.04 | 4.72 |
| | 99% | -2.90 | 3.43 | -5.22 | 6.17 |
| I77 Road-Air (N =4856 ) | 90% | -2.50 | 2.93 | -4.50 | 5.27 |
| | 95% | -2.95 | 3.84 | -5.31 | 6.91 |
| | 99% | -3.83 | 4.94 | -6.90 | 8.90 |
| Notes:<br>N=Number of observations<br>Regression temperatures based on parameters given in Table 19 and Table 20 | | | | | |

**Table 31. Nighttime prediction limits for Site 69 in Hamilton County.**

| Nighttime Prediction Limits for Site 69, I275 Hamilton County | | | | | |
|---|---|---|---|---|---|
| For a given regression temperature reading $T_R$:<br>$T_U = T_R$ + Upper prediction value<br>$T_L = T_R$ + Lower prediction value (note lower prediction value is negative) | | | | | |
| Comparison | Prediction Limit | Lower Prediction Value (°C) | Upper Prediction Value (°C) | Lower Prediction Value (°F) | Upper Prediction Value (°F) |
| Bridge-BDS (N =8281 ) | 90% | -1.49 | 1.51 | -2.68 | 2.73 |
| | 95% | -1.78 | 1.90 | -3.20 | 3.42 |
| | 99% | -2.27 | 2.61 | -4.08 | 4.69 |
| Bridge-Air (N = 8281) | 90% | -2.25 | 2.04 | -4.06 | 3.67 |
| | 95% | -2.77 | 2.51 | -4.99 | 4.52 |
| | 99% | -3.67 | 3.41 | -6.60 | 6.13 |
| Road-BDS (N =8843 ) | 90% | -1.52 | 1.54 | -2.74 | 2.77 |
| | 95% | -1.80 | 1.84 | -3.24 | 3.30 |
| | 99% | -2.32 | 2.35 | -4.18 | 4.24 |
| Road-Air (N = 8843) | 90% | -2.06 | 2.05 | -3.71 | 3.68 |
| | 95% | -2.47 | 2.42 | -4.44 | 4.36 |
| | 99% | -3.28 | 3.07 | -5.91 | 5.52 |
| Notes:<br>N=Number of observations<br>Regression temperatures based on parameters given in Table 19 and Table 20 | | | | | |

**Table 32. Nighttime prediction limits for Site 70 at Hamilton/Clermont County line.**

| Nighttime Prediction Limits for Site 70, I275 Hamilton/Clermont County line | | | | | |
|---|---|---|---|---|---|
| For a given regression temperature reading $T_R$:<br>$T_U = T_R$ + Upper prediction value<br>$T_L = T_R$ + Lower prediction value (note lower prediction value is negative) | | | | | |
| Comparison | Prediction Limit | Lower Prediction Value (°C) | Upper Prediction Value (°C) | Lower Prediction Value (°F) | Upper Prediction Value (°F) |
| Bridge-BDS (N =7562 ) | 90% | -1.77 | 1.48 | -3.18 | 2.67 |
| | 95% | -2.24 | 1.76 | -4.04 | 3.17 |
| | 99% | -3.63 | 2.39 | -6.54 | 4.29 |
| Bridge-Air (N = 7562) | 90% | -2.27 | 1.91 | -4.09 | 3.44 |
| | 95% | -3.07 | 2.22 | -5.53 | 3.99 |
| | 99% | -4.60 | 2.87 | -8.29 | 5.16 |
| Road-BDS (N =6638 ) | 90% | -1.58 | 1.74 | -2.85 | 3.14 |
| | 95% | -1.93 | 2.09 | -3.47 | 3.76 |
| | 99% | -2.52 | 2.88 | -4.54 | 5.19 |
| Road-Air (N =6638 ) | 90% | -2.31 | 2.05 | -4.16 | 3.68 |
| | 95% | -3.00 | 2.47 | -5.40 | 4.44 |
| | 99% | -3.93 | 3.12 | -7.08 | 5.61 |
| Notes:<br>N=Number of observations<br>Regression temperatures based on parameters given in Table 19 and Table 20 | | | | | |

**Table 33. Nighttime prediction limits for Site 86 in Lorain County.**

Nighttime Prediction Limits for Site 86, I90 Lorain County

For a given regression temperature reading $T_R$:

$T_U = T_R$ + Upper prediction value

$T_L = T_R$ + Lower prediction value (note lower prediction value is negative)

| Comparison | Prediction Limit | Lower Prediction Value (°C) | Upper Prediction Value (°C) | Lower Prediction Value (°F) | Upper Prediction Value (°F) |
|---|---|---|---|---|---|
| Bridge-BDS (N =9499 ) | 90% | -1.82 | 1.55 | -3.28 | 2.78 |
| | 95% | -2.19 | 1.77 | -3.94 | 3.19 |
| | 99% | -2.64 | 2.24 | -4.76 | 4.03 |
| Bridge-Air (N = 9499) | 90% | -2.35 | 2.06 | -4.22 | 3.72 |
| | 95% | -2.84 | 2.52 | -5.12 | 4.54 |
| | 99% | -3.61 | 3.27 | -6.50 | 5.89 |
| Road-BDS (N =7464 ) | 90% | -2.01 | 1.60 | -3.62 | 2.88 |
| | 95% | -2.36 | 1.86 | -4.24 | 3.35 |
| | 99% | -2.84 | 2.34 | -5.12 | 4.21 |
| Road-Air (N =7464 ) | 90% | -2.35 | 2.11 | -4.23 | 3.79 |
| | 95% | -2.90 | 2.60 | -5.23 | 4.68 |
| | 99% | -4.16 | 3.40 | -7.49 | 6.13 |

Notes:
N=Number of observations
Regression temperatures based on parameters given in Table 19 and Table 20

**Table 34. Nighttime prediction limits for Site 88 in Ashtabula County.**

| Nighttime Prediction Limits for Site 88, I90 and SR11 Ashtabula County | | | | | |
|---|---|---|---|---|---|
| For a given regression temperature reading $T_R$:<br>$T_U = T_R$ + Upper prediction value<br>$T_L = T_R$ + Lower prediction value (note lower prediction value is negative) | | | | | |
| Comparison | Prediction Limit | Lower Prediction Value (°C) | Upper Prediction Value (°C) | Lower Prediction Value (°F) | Upper Prediction Value (°F) |
| Bridge-BDS (N =6849 ) | 90% | -2.12 | 2.08 | -3.82 | 3.74 |
| | 95% | -2.59 | 2.58 | -4.66 | 4.64 |
| | 99% | -4.15 | 3.74 | -7.47 | 6.73 |
| Bridge-Air (N = 6849) | 90% | -2.76 | 2.39 | -4.97 | 4.31 |
| | 95% | -3.26 | 2.92 | -5.87 | 5.26 |
| | 99% | -5.18 | 4.21 | -9.32 | 7.58 |
| Road-BDS (N =9111 ) | 90% | -2.02 | 1.90 | -3.64 | 3.41 |
| | 95% | -2.42 | 2.33 | -4.35 | 4.20 |
| | 99% | -3.78 | 3.19 | -6.81 | 5.74 |
| Road-Air (N =9111 ) | 90% | -2.68 | 2.12 | -4.82 | 3.81 |
| | 95% | -3.37 | 2.51 | -6.07 | 4.51 |
| | 99% | -4.44 | 3.29 | -7.98 | 5.92 |
| Notes:<br>N=Number of observations<br>Regression temperatures based on parameters given in Table 19 and Table 20 | | | | | |

**Table 35. Nighttime prediction limits for Site 91 at Portage/Mahoning County line.**

| Nighttime Prediction Limits for Site 91, I76 Portage/Mahoning County line | | | | | |
|---|---|---|---|---|---|
| For a given regression temperature reading $T_R$:<br>$T_U = T_R$ + Upper prediction value<br>$T_L = T_R$ + Lower prediction value (note lower prediction value is negative) | | | | | |
| Comparison | Prediction Limit | Lower Prediction Value (°C) | Upper Prediction Value (°C) | Lower Prediction Value (°F) | Upper Prediction Value (°F) |
| Bridge-BDS (N =3597 ) | 90% | -1.81 | 1.44 | -3.26 | 2.59 |
| | 95% | -2.49 | 1.73 | -4.48 | 3.11 |
| | 99% | -3.10 | 2.20 | -5.58 | 3.95 |
| Bridge-Air (N =3597 ) | 90% | -2.38 | 1.83 | -4.29 | 3.29 |
| | 95% | -3.49 | 2.07 | -6.28 | 3.72 |
| | 99% | -4.35 | 2.58 | -7.82 | 4.65 |
| Road-BDS (N =6971 ) | 90% | -1.74 | 1.60 | -3.13 | 2.87 |
| | 95% | -2.13 | 1.84 | -3.83 | 3.31 |
| | 99% | -2.76 | 2.38 | -4.97 | 4.29 |
| Road-Air (N =6971 ) | 90% | -2.58 | 2.22 | -4.65 | 3.99 |
| | 95% | -3.09 | 2.56 | -5.56 | 4.61 |
| | 99% | -3.94 | 3.07 | -7.08 | 5.53 |
| Notes:<br>N=Number of observations<br>Regression temperatures based on parameters given in Table 19 and Table 20 | | | | | |

Table 36 includes the averages of the prediction limits from all sites. The averages for road-BDS and road-air do not include Site 9, which had no road sensors, and includes both I271 and I77 at Site 68. The pattern seen earlier applies here as well – the prediction limits based on BDS temperatures are tighter than those based on air temperatures. Standard deviations for the average prediction limits, again using the values from each site as a sample, are given in Table 37. With only one slight exception, these are between 10% and 20%, suggesting that there is not a wild variation in the quality of the fit of the regression from one site to another.

**Table 36. Average prediction limits based on results for all sites combined**

| Nighttime Prediction Limits averaged over all sites | | | | | |
|---|---|---|---|---|---|
| For a given regression temperature reading $T_R$:<br>$T_U = T_R$ + Upper prediction value<br>$T_L = T_R$ + Lower prediction value (note lower prediction value is negative) | | | | | |
| Comparison | Prediction Limit | Lower Prediction Value (°C) | Upper Prediction Value (°C) | Lower Prediction Value (°F) | Upper Prediction Value (°F) |
| Bridge-BDS | 90% | -1.84 | 1.66 | -3.31 | 2.99 |
| | 95% | -2.27 | 1.99 | -4.09 | 3.58 |
| | 99% | -3.08 | 2.64 | -5.54 | 4.75 |
| Bridge-Air | 90% | -2.52 | 2.23 | -4.54 | 4.01 |
| | 95% | -3.12 | 2.65 | -5.62 | 4.77 |
| | 99% | -4.14 | 3.50 | -7.46 | 6.30 |
| Road-BDS | 90% | -1.96 | 1.84 | -3.52 | 3.32 |
| | 95% | -2.33 | 2.22 | -4.19 | 3.99 |
| | 99% | -3.16 | 2.99 | -5.69 | 5.37 |
| Road-Air | 90% | -2.58 | 2.33 | -4.65 | 4.20 |
| | 95% | -3.11 | 2.82 | -5.60 | 5.07 |
| | 99% | -4.24 | 3.61 | -7.64 | 6.50 |

**Table 37. Standard deviations of prediction limits based on all sites. Percentages are relative to average values in Table 36**

| Nighttime Prediction Limits - standard deviations over all sites | | | | | | | |
|---|---|---|---|---|---|---|---|
| Comparison | Prediction Limit | Lower Prediction Value (°C) | Upper Prediction Value (°C) | Lower Prediction Value (°F) | Upper Prediction Value (°F) | Lower Prediction Value % | Upper Prediction Value % |
| Bridge-BDS | 90% | 0.21 | 0.22 | 0.38 | 0.39 | 11.59% | 13.07% |
| | 95% | 0.26 | 0.28 | 0.48 | 0.51 | 11.64% | 14.24% |
| | 99% | 0.58 | 0.49 | 1.05 | 0.89 | 18.95% | 18.70% |
| Bridge-Air | 90% | 0.31 | 0.34 | 0.56 | 0.61 | 12.37% | 15.24% |
| | 95% | 0.34 | 0.42 | 0.61 | 0.76 | 10.88% | 15.90% |
| | 99% | 0.61 | 0.64 | 1.11 | 1.14 | 14.83% | 18.18% |
| Road-BDS | 90% | 0.32 | 0.25 | 0.58 | 0.45 | 16.37% | 13.54% |
| | 95% | 0.37 | 0.34 | 0.66 | 0.60 | 15.87% | 15.14% |
| | 99% | 0.67 | 0.56 | 1.21 | 1.01 | 21.17% | 18.88% |
| Road-Air | 90% | 0.36 | 0.34 | 0.64 | 0.62 | 13.87% | 14.78% |
| | 95% | 0.37 | 0.49 | 0.67 | 0.88 | 11.98% | 17.42% |
| | 99% | 0.56 | 0.63 | 1.01 | 1.13 | 13.17% | 17.44% |

The size of the prediction limit intervals in relationship to each other can be determined from Table 38 through Table 46, where all the prediction limit values in Table 27 through Table 35 are expressed in terms of those for the bridge-BDS values at each percentage level. Table 47 takes the average values from Table 36 and expresses those as a percentage of the bridge-BDS average values.

**Table 38. Nighttime prediction limits for Site 07 in Crawford County in terms of bridge-BDS values.**

| Nighttime Prediction Limits for Site 7, US30 Crawford County in terms of Bridge-BDS values | | | |
|---|---|---|---|
| Comparison | Prediction Limit | Lower Prediction Value | Upper Prediction Value |
| Bridge-BDS | 90% | 100% | 100% |
| | 95% | 100% | 100% |
| | 99% | 100% | 100% |
| Bridge-Air | 90% | 139.1% | 139.1% |
| | 95% | 136.2% | 137.4% |
| | 99% | 131.4% | 132.4% |
| Road-BDS | 90% | 103.5% | 98.3% |
| | 95% | 105.4% | 97.4% |
| | 99% | 110.3% | 93.9% |
| Road-Air | 90% | 141.3% | 133.1% |
| | 95% | 140.4% | 128.7% |
| | 99% | 154.1% | 123.5% |

**Table 39. Nighttime prediction limits for Site 09 in Stark County in terms of bridge-BDS values.**

| Nighttime Prediction Limits for Site 9, I77 Stark County in terms of Bridge-BDS values | | | |
|---|---|---|---|
| Comparison | Prediction Limit | Lower Prediction Value | Upper Prediction Value |
| Bridge-BDS | 90% | 100% | 100% |
| | 95% | 100% | 100% |
| | 99% | 100% | 100% |
| Bridge-Air | 90% | 136.8% | 132.1% |
| | 95% | 134.7% | 128.8% |
| | 99% | 132.4% | 132.7% |

**Table 40. Nighttime prediction limits for Site 59 in Warren County in terms of bridge-BDS values.**

| Nighttime Prediction Limits for Site 59, I71 Warren County in terms of Bridge-BDS values | | | |
|---|---|---|---|
| Comparison | Prediction Limit | Lower Prediction Value | Upper Prediction Value |
| Bridge-BDS | 90% | 100% | 100% |
| | 95% | 100% | 100% |
| | 99% | 100% | 100% |
| Bridge-Air | 90% | 131.2% | 136.6% |
| | 95% | 127.3% | 137.6% |
| | 99% | 122.9% | 135.8% |
| Road-BDS | 90% | 159.9% | 145.6% |
| | 95% | 152.3% | 147.5% |
| | 99% | 175.6% | 170.2% |
| Road-Air | 90% | 166.0% | 148.2% |
| | 95% | 154.9% | 149.8% |
| | 99% | 195.3% | 158.2% |

**Table 41. Nighttime prediction limits for Site 68 in Summit County in terms of bridge-BDS values.**

| Nighttime Prediction Limits for Site 68, I271 & I77 Summit County in terms of Bridge-BDS values | | | |
|---|---|---|---|
| Comparison | Prediction Limit | Lower Prediction Value | Upper Prediction Value |
| Bridge-BDS | 90% | 100% | 100% |
| | 95% | 100% | 100% |
| | 99% | 100% | 100% |
| Bridge-Air | 90% | 157.5% | 159.8% |
| | 95% | 154.9% | 164.8% |
| | 99% | 146.3% | 174.1% |
| I271 Road-BDS | 90% | 42.3% | 365.4% |
| | 95% | 67.4% | 444.2% |
| | 99% | 126.3% | 525.7% |
| I271 Road-Air | 90% | 62.8% | 371.4% |
| | 95% | 88.6% | 401.1% |
| | 99% | 124.5% | 522.7% |
| I77 Road-BDS | 90% | 103.4% | 121.1% |
| | 95% | 99.9% | 127.3% |
| | 99% | 99.7% | 133.2% |
| I77 Road-Air | 90% | 134.4% | 162.9% |
| | 95% | 131.4% | 186.4% |
| | 99% | 131.9% | 192.2% |

**Table 42. Nighttime prediction limits for Site 69 in Hamilton County in terms of bridge-BDS values.**

| Nighttime Prediction Limits for Site 69, I275 Hamilton County in terms of Bridge-BDS values | | | |
|---|---|---|---|
| Comparison | Prediction Limit | Lower Prediction Value | Upper Prediction Value |
| Bridge-BDS | 90% | 100% | 100% |
| | 95% | 100% | 100% |
| | 99% | 100% | 100% |
| Bridge-Air | 90% | 151.4% | 134.8% |
| | 95% | 155.8% | 132.3% |
| | 99% | 161.9% | 130.7% |
| Road-BDS | 90% | 102.3% | 101.5% |
| | 95% | 101.2% | 96.7% |
| | 99% | 102.6% | 90.3% |
| Road-Air | 90% | 138.5% | 135.2% |
| | 95% | 138.8% | 127.5% |
| | 99% | 144.9% | 117.7% |

**Table 43. Nighttime prediction limits for Site 70 at Hamilton/Clermont County line in terms of bridge-BDS values.**

| Nighttime Prediction Limits for Site 70, I275 Hamilton/Clermont County line in terms of Bridge-BDS values | | | |
|---|---|---|---|
| Comparison | Prediction Limit | Lower Prediction Value | Upper Prediction Value |
| Bridge-BDS | 90% | 100% | 100% |
| | 95% | 100% | 100% |
| | 99% | 100% | 100% |
| Bridge-Air | 90% | 128.4% | 128.7% |
| | 95% | 136.8% | 125.7% |
| | 99% | 126.7% | 120.1% |
| Road-BDS | 90% | 89.5% | 117.4% |
| | 95% | 85.9% | 118.5% |
| | 99% | 69.5% | 120.9% |
| Road-Air | 90% | 130.7% | 137.9% |
| | 95% | 133.7% | 139.9% |
| | 99% | 108.3% | 130.6% |

**Table 44. Nighttime prediction limits for Site 86 in Lorain County in terms of bridge-BDS values.**

| Nighttime Prediction Limits for Site 86, I90 Lorain County in terms of Bridge-BDS values | | | |
|---|---|---|---|
| Comparison | Prediction Limit | Lower Prediction Value | Upper Prediction Value |
| Bridge-BDS | 90% | 100% | 100% |
| | 95% | 100% | 100% |
| | 99% | 100% | 100% |
| Bridge-Air | 90% | 128.8% | 133.5% |
| | 95% | 129.9% | 142.3% |
| | 99% | 136.6% | 146.1% |
| Road-BDS | 90% | 110.4% | 103.4% |
| | 95% | 107.6% | 105.0% |
| | 99% | 107.6% | 104.4% |
| Road-Air | 90% | 128.9% | 136.2% |
| | 95% | 132.7% | 146.6% |
| | 99% | 157.3% | 152.1% |

**Table 45. Nighttime prediction limits for Site 88 in Ashtabula County in terms of bridge-BDS values.**

| Nighttime Prediction Limits for Site 88, I90 & SR11 Ashtabula County in terms of Bridge-BDS values | | | |
|---|---|---|---|
| Comparison | Prediction Limit | Lower Prediction Value | Upper Prediction Value |
| Bridge-BDS | 90% | 100% | 100% |
| | 95% | 100% | 100% |
| | 99% | 100% | 100% |
| Bridge-Air | 90% | 130.0% | 115.3% |
| | 95% | 126.0% | 113.5% |
| | 99% | 124.7% | 112.7% |
| Road-BDS | 90% | 95.3% | 91.3% |
| | 95% | 93.4% | 90.5% |
| | 99% | 91.2% | 85.3% |
| Road-Air | 90% | 126.1% | 102.0% |
| | 95% | 130.3% | 97.3% |
| | 99% | 106.9% | 88.0% |

**Table 46. Nighttime prediction limits for Site 91 at Portage/Mahoning County line in terms of bridge-BDS values.**

| Nighttime Prediction Limits for Site 91, I76 Portage/Mahoning County line in terms of Bridge-BDS values | | | |
|---|---|---|---|
| Comparison | Prediction Limit | Lower Prediction Value | Upper Prediction Value |
| Bridge-BDS | 90% | 100% | 100% |
| | 95% | 100% | 100% |
| | 99% | 100% | 100% |
| Bridge-Air | 90% | 131.4% | 126.7% |
| | 95% | 140.1% | 119.5% |
| | 99% | 140.1% | 117.7% |
| Road-BDS | 90% | 95.9% | 110.8% |
| | 95% | 85.6% | 106.4% |
| | 99% | 88.9% | 108.6% |
| Road-Air | 90% | 142.3% | 153.7% |
| | 95% | 124.1% | 148.1% |
| | 99% | 126.8% | 140.0% |

**Table 47. Average nighttime prediction limits combining all sites, expressed as percentage of the bridge-BDS values.**

| Nighttime Prediction Limits averaged over all sites Expressed in terms of bridge-BDS values | | | |
|---|---|---|---|
| Comparison | Prediction Limit | Lower Prediction Value | Upper Prediction Value |
| Bridge-BDS | 90% | 100% | 100% |
| | 95% | 100% | 100% |
| | 99% | 100% | 100% |
| Bridge-Air | 90% | 136.9% | 134.0% |
| | 95% | 137.5% | 133.2% |
| | 99% | 134.6% | 132.7% |
| Road-BDS | 90% | 106.2% | 110.9% |
| | 95% | 102.5% | 111.4% |
| | 99% | 102.8% | 113.2% |
| Road-Air | 90% | 140.3% | 140.3% |
| | 95% | 137.0% | 141.5% |
| | 99% | 137.9% | 137.0% |

# 12 Long Distance Correlations and Prediction Limits

If the BDS is to work as designed as a substitute for pavement sensors and is to cover an extended area as well as the immediate neighborhood, it is important to see how well BDS temperatures compare with pavement sensor temperatures at an extended distance. This exploratory analysis gives an insight into how well the temperature of the bridge deck at one RWIS site can be predicted using the temperature of the bridge deck simulator of another nearby RWIS site. The three sites in southwest Ohio were close enough to each other that such an analysis was likely to be of practical interest. These sites were Site 59 (Warren County), Site 69 (Hamilton County) and Site 70 (Hamilton/Clermont County). They are fairly close to each other which are shown in Figure 137. The maximum distance was 40.54 mi (65.23 km) from Site 59 to Site 69, and the minimum was 19.81 mi (31.87 km) from Site 59 to Site 70; the distance from Site 69 to Site 70 was in between at 27.90 mi (44.89 km). In comparison, a communication with an SSI vendor cited in [1] stated that a single RWIS station was "representative of a 25 mile radius or area" (25 mi = 40.2 km).

For a given instant of time, temperature data from the air, bridge, and the bridge deck simulator from all three sites were chosen for analysis. After the data reduction procedure described in Chapter 7, Site 59 had 9456 good nighttime data points, Site 69 had 8280 good nighttime data points and Site 70 had 7560 good nighttime data points; these points were not all concurrent, however. The first month of cleaned data from each site (January 22-February 21) was selected to reduce the data selection effort as it was not feasible to go through the complete set of data by hand. From this set, those entries that had a common time stamp temperature data for three sites were retained for the analysis, providing a total of 2016 data points. Correlation plots were drawn using the data from three sites to obtain the prediction limits for different combinations which are tabulated in Table 48. Then 90%, 95%, and 99% prediction limits were obtained for two distant sites at a time in accordance to the procedure described in Section 11.1. The obtained prediction limits were then compared to the prediction limits for the home sites based on the same set of 2016 data points, which are slightly different than those previously obtained for each site in Section 11.2. These new home site prediction limits were made to guarantee comparability between the home and away data.

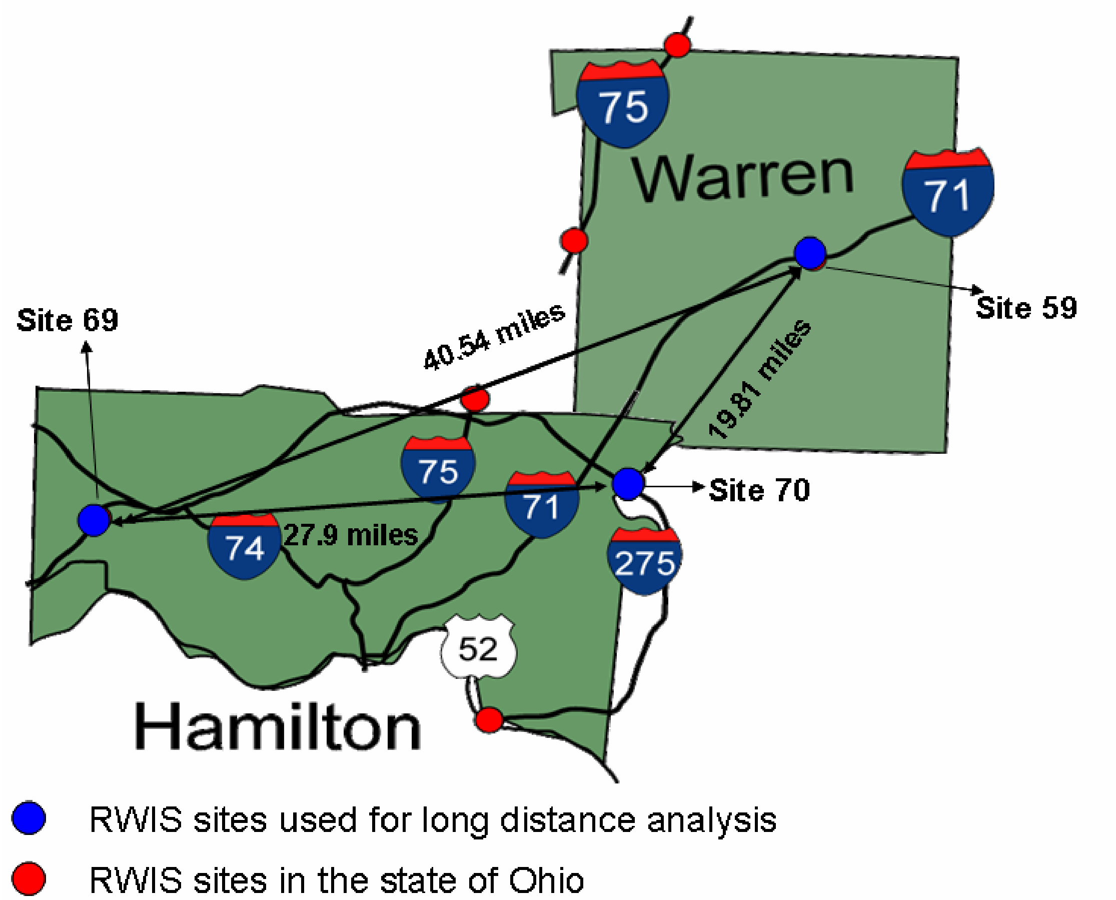



**Figure 137: Map showing the RWIS sites used for long distance analysis in Warren and Hamilton counties.**

**Table 48: Summary of the correlation plots obtained for the long distance analysis for the three sites.**

| BDS \ Bridge | Site 59 | Site 69 | Site 70 |
|---|---|---|---|
| **Site 59** | X | X | X |
| **Site 69** | X | X | X |
| **Site 70** | X | X | X |

Figure 138, Figure 139, Figure 140 show all six BDS-bridge prediction limit ranges as percentages of the home site BDS-bridge prediction limit ranges at the 90%, 95%, and 99% levels, respectively. For purposes of this analysis, the home site is defined as the one where the BDS is located, thus the Site 59 BDS-Site 69 bridge prediction limit range is expressed as a percentage of the corresponding Site 59 BDS-bridge prediction limit range. The home site prediction limit ranges for each site are printed on the graph. These ranges are the difference between the upper prediction limit and the (negative) lower prediction limit and they describe the total range around the predicted value bounded by the two limits.

It can be seen from Figure 138 that the 90% prediction limit ranges for prediction of a bridge deck temperature using a BDS at a distant site is larger than the corresponding prediction limit range obtained for the prediction of the bridge deck temperature at home site. Similar trends can be seen from Figure 139 and Figure 140 for the 95% and 99% ranges. Thus the long distance predictions are even less certain than those at the home site – if the 90% prediction limits at Site 59 are 2.99C° (5.38 F°), then the corresponding prediction limit range using the Site 70 BDS will be about 140% of that or 4.19C° (7.53F°). The long-distance prediction limit ranges lie anywhere from about 100% up to 175%, and generally increase with distance. The relationship is especially bad between Site 59 BDS and Site 69 bridge, which could be seen as upholding the 25 mi (40 km) criterion given by SSI or perhaps Site 69 simply had smaller home site prediction limit ranges to begin with, at least at the 95% and 99% levels.

The home site prediction limits were already so broad as to make the BDS predictions or bridge temperature only mildly useful, and distance only exacerbates the situation. However, it is likely that if the relationship between BDS and bridge temperature can be tightened, e.g. through better quality control and calibration of field sensors or through adoption of a higher mass simulator, the quality of long distance predictions is also very likely to improve. Additionally, it should be noted that solar radiation during daytime is likely to make these relationships much more tentative, as the sun conditions at one site may be very different than at the other, though this can be verified by looking at measures of cloud cover or at radar maps as is appropriate, including recent history in the event of changing weather.

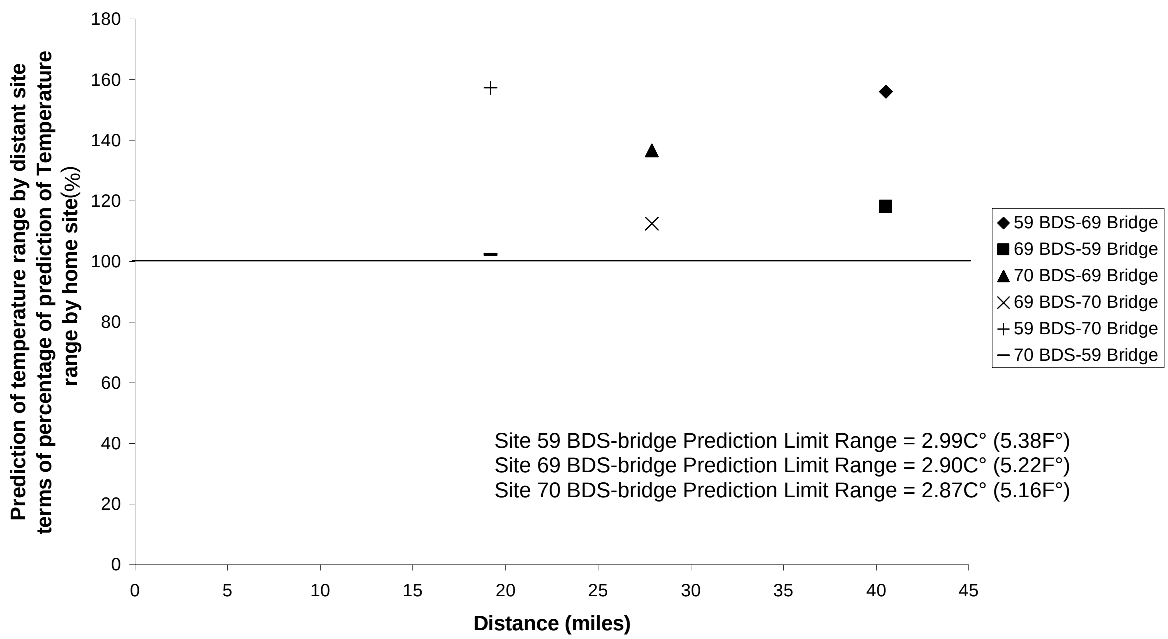



**Figure 138: Prediction of temperature range by BDS at distant site in terms of the percentage of prediction of temperature range by BDS at home site for 90% confidence level for night time only. (1 mile = 1.609 km)**

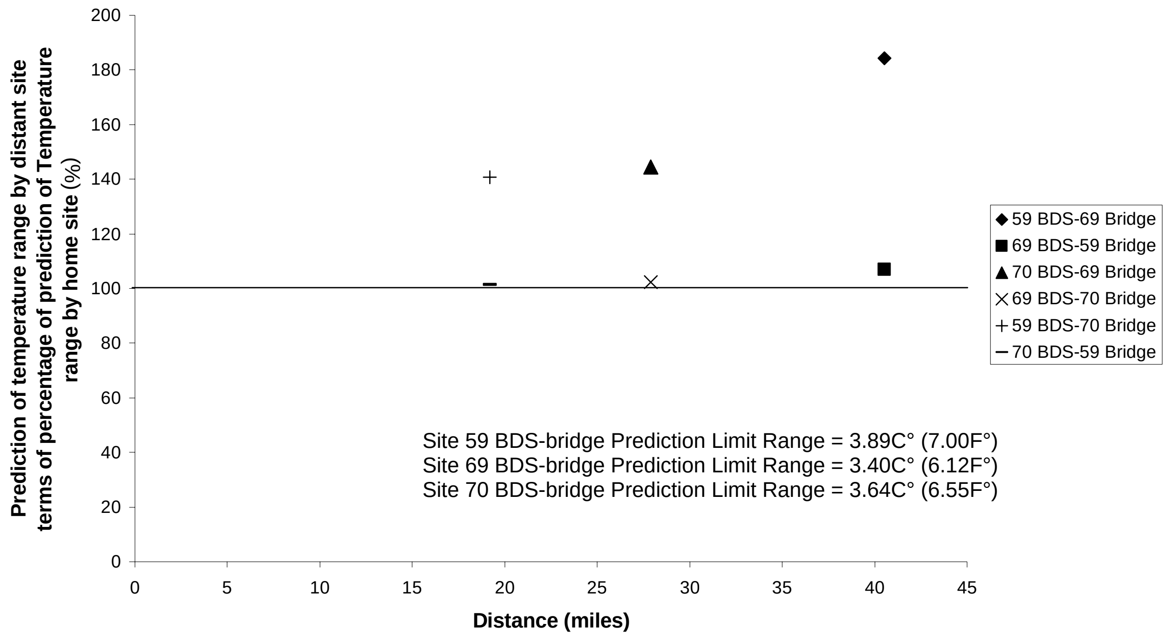



**Figure 139: Prediction of temperature range by BDS at distant site in terms of the percentage of prediction of temperature range by BDS at home site for 95% confidence level for night time only. (1 mile = 1.609 km)**

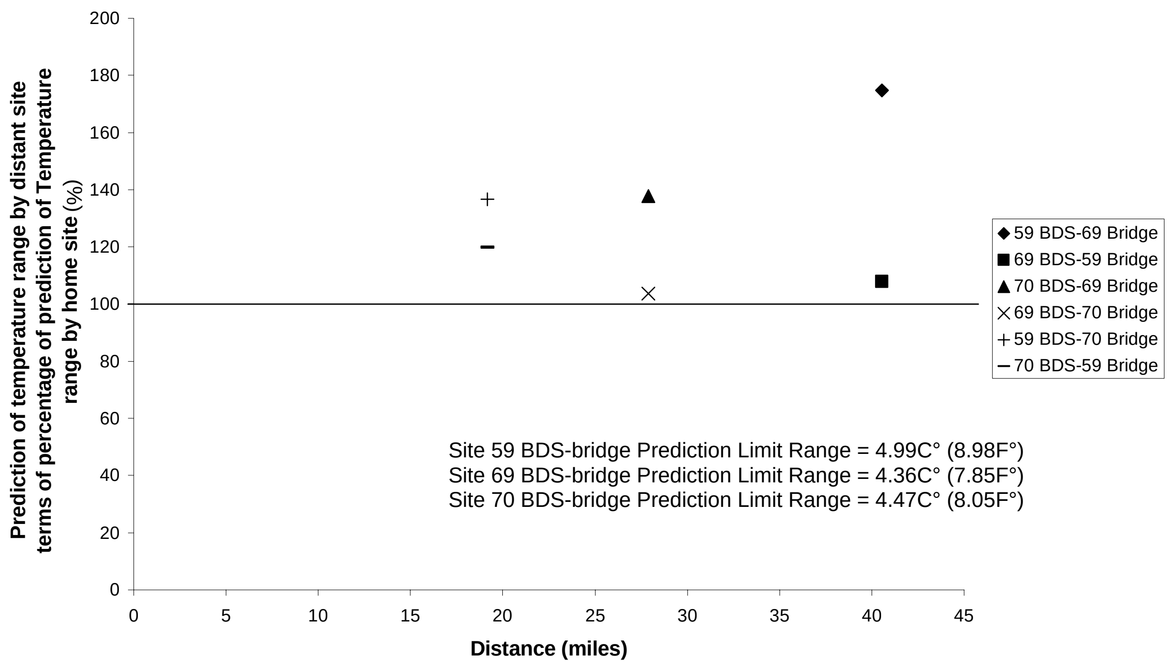



**Figure 140: Prediction of temperature range by BDS at distant site in terms of the percentage of prediction of temperature range by BDS at home site for 99% confidence level for night time only. (1 mile = 1.609 km)**

# 13 Procedure for Finite Element Analysis

The finite element analysis was conducted using the following steps:

1. Select the modeling approach.
2. Select the finite element modeling software.
    2.1. ALGOR V18 was selected.
3. Set up the model for finite element analysis.
    3.1. Create the drawings using CAD (Computer aided drawing) tool.
    3.2. Create an IGES (Initial graphics exchange specification) file.
    3.3. Import the files into ALGOR V18.
    3.4. Generate the mesh.
4. Select thermal loads and set up the parameters for analysis.
5. Validate the simulations done by using ALGOR V18 with the climatic chamber experiment data.
6. Determine hourly air temperature gradients at each site.
    6.1. Create histogram of temperature gradients
    6.2. Select maximum positive and negative gradients at each site with at least five hours of data.
7. Perform finite element model simulations for the nine sites undergoing maximum positive and negative temperature gradients.

## 13.1 Selection of Modeling Approach

Heat transfer problems in engineering are governed by differential equations. Solving these differential equations provides an exact solution for the problem being studied, but this is not always possible. The complex geometry, material properties, and boundary conditions of real world problems make it necessary to seek numerical or computational solutions.

The Finite Element Method (FEM) is a computational approach which provides an approximate solution in a reasonable amount of time. In the FEM a continuous body is discretized into smaller elements of simple geometric form, such as tetrahedrons or hexagons, and each element is analyzed under the same governing equation. An assembly of all the values obtained at the vertices (nodes) of these elements links every element to the entire system. When load and boundary conditions are considered, a system of linear and non linear algebraic equations is obtained. Solution of these equations gives the approximate behavior of the entire system. The FEM can be easily applied to a system having a complex geometry, composed of different materials and experiencing varied boundary conditions. The FEM has become widespread in engineering for modeling bridges and other engineering structures for stress analysis and for heat analysis, so FEM was a logical choice for the problem of modeling heating and cooling of bridges for winter maintenance, even though this problem had not been widely approached through FEM.

## 13.2 Selection of FEM software

Various FEM software programs are available in the market. MSC.PATRAN/NASTRAN, MSC.MARC and ALGOR V18 are the packages that were available in the engineering center at Ohio University. MSC PATRAN is considered one of the most powerful preprocessing tools and which easily handles complex geometries. However, there were several issues related with the licensing for MSC.PATRAN/NASTRAN and also the lack of availability of computers due to several research groups working on the single licensed copy at the university made the process of using MSC.PATRAN/NASTRAN impractical.

MSC.MARC was tried as a second option but due to a lack of tutorials for transient heat transfer modeling and insufficient online help MSC.MARC could not be used.

ALGOR V18 is an industry renowned FEM package which is capable of handling transient heat transfer cases with varying load inputs including convective and radiation loads. Also the software is available in all the public computer labs in the engineering center. The software comes with a well documented set of tutorials and online help to successfully model the behavior of most real world problems. Thus, ALGOR V18 was used for performing the finite element analysis.

### 13.2.1 Description of ALGOR V18

The ALGOR V18 includes technology for direct CAD/CAE data exchange with most CAD software, including Autodesk Inventor, Pro/ENGINEER, Solid Edge, and SolidWorks [21]. Analysis capabilities for ALGOR V18 include consideration of conduction, convection, heat flux, heat generation, radiation, and thermal contact. Users can specify material properties, steady-state heat transfer boundary conditions, initial temperatures, and time-dependent heat flow. They can stipulate transient parameters such as the time-step size and the use of variable heat transfer boundary elements, which control temperature at specific points. They can apply multiple load curves having different arrival times and heat rate loadings at specific points in conjunction with other thermal loads. Variable material properties are automatically handled.

The extensive results evaluation and presentation capabilities of ALGOR V18 include transparent display options, fast dynamic viewing controls and customization options. All analysis results can be [21]:

- Displayed graphically as contours or plots
- Output in the BMP, JPG, TIF, PNG, PCX and TGA formats
- Animated with AVI creation and display tools
- Presented in text or HTML reports

But ALGOR V18 has a few restrictions:

- It is incapable of handling wind direction and varying wind speed
- It has restricted options for mesh generation on complex geometries
- It is a slow program.

To account for the restrictions on wind direction and speed, the programmer input a value for convective heat transfer coefficient (h) which accounts for all the variable parameters including mass density and thermal conductivity of air. The convective heat transfer coefficient is a validated value.

The restriction on mesh generation is not an issue for the relatively simple geometries of the bridges and block. The hexagonal mesh settings worked effectively.

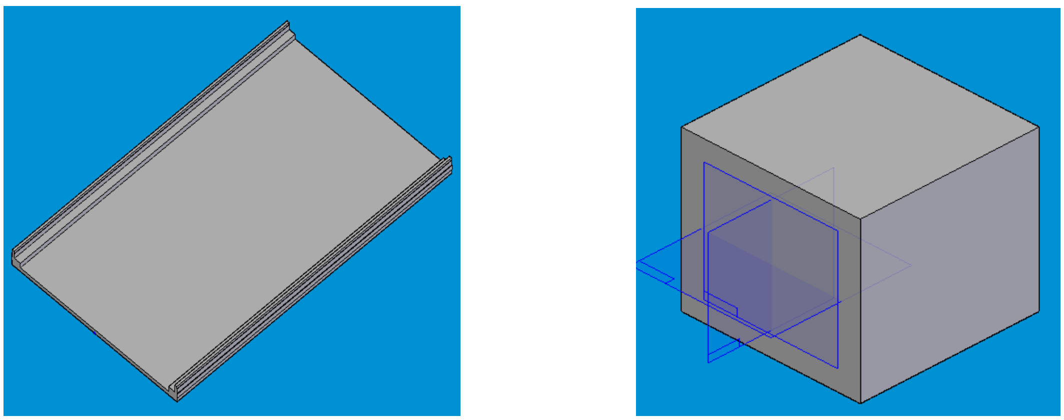
As for program speed, a Xeon processor with 2GB RAM took about 1.5 hours to run a simulation. A computer with a Centrino processor and 512 MB RAM required 2.5 to 3 hours for a simulation. But the availability of multiple licenses meant that the inconveniences of long computing times could be mitigated by running multiple simulations on different computers available in the public computer labs in the Stocker Engineering Center at Ohio University during off-peak hours.

## 13.3 Setting up the Model for Finite Element Analysis

Following is the general approach used for setting up the model for thermal analysis.

### 13.3.1 Creating the drawing using CAD tool

The dimensions for the bridge to be drawn were taken from the bridge plan for the site. The bridge deck simulator is modeled as a 6 in (15.2 cm) cube. Drawings using Solid Edge V14 for the Ashtabula County bridge (Site 88) and a bridge deck simulator are shown in Figure 141.



a) b)

**Figure 141. a) Drawing for Site 88 Ashtabula County bridge b) The bridge deck simulator. Both are drawn using Solid Edge V14.**

### 13.3.2 Creating an IGES File

IGES format serves as a neutral data format to transfer a three dimensional model with associated drawing views and dimensions using a CAD system to another dissimilar system. A translator was used to export the Solid Edge drawings for bridges and bridge deck simulators into an IGES file (extension ".igs" [22]) that could be imported into ALGOR V18.

### 13.3.3 Mesh Generation

The geometry imported into ALGOR V18 through the IGES file was then divided into a mesh of finite elements through a process of discretization. This meshing process is one of the most important steps which govern the final result to a large extent. If the mesh generated is too coarse it gives inaccurate results since the number of elements is too small to truly represent the geometry. On the other hand, if the mesh size is too fine the results are not accurate because round off errors in calculation at every node during analysis will add together and compromise the result.

Thus, there is a need to define an optimum mesh size, which means making a trade-off between minimizing round-off errors and having enough elements so that the geometry is well represented. For this modeling a 70% fine mesh was used for the block which creates about 24000 elements. For modeling bridges the finest mesh size used was a 10% fine mesh. The number of elements generated varied with the dimensions of the bridge. These optimized mesh sizes were obtained by comparing the temperature results at different mesh sizes, decreasing the mesh size by 10% each time. The optimum mesh size was found when the results were similar for two consecutive mesh sizes. Figure 142 illustrates a bridge deck simulator with 70% fine mesh.

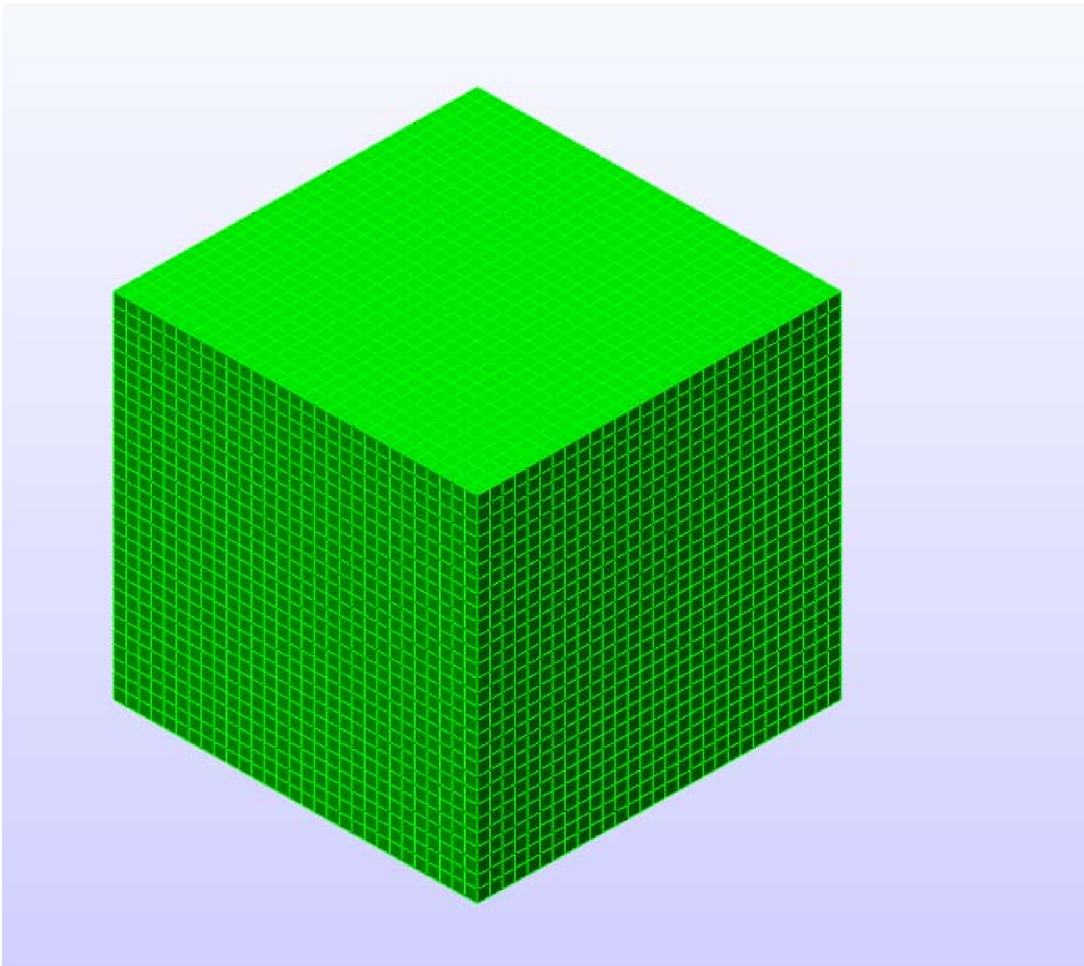


**Figure 142. bridge deck simulator with 70% fine mesh in ALGOR V18.**

## 13.4 Selecting Loads and Setting up the Model for Analysis

To proceed towards analysis, the units for the parameters that are used in calculations must be defined. All parameters were defined and computations performed using English units.

The material of the bridge also needs to be defined. For these simulations the block and all the bridges except the Lorain County (Site 86) bridge were assumed to be made of concrete with the following properties [23]:

Mass density = $2.25 \times 10^{-4}$ lb*(s$^2$/in)/in$^3$ = 2400 kg/m$^3$
Thermal conductivity = $5.32 \times 10^{-5}$ BTU/(sec*in*F°) = 3.98 J/(s*m*C°)
Specific heat = 70 BTU/(lb*(s$^2$/in)*F°) = 760 J/(kg*C°)

The Lorain County (Site 86) bridge has an asphalt overlay; the structure was estimated to be a 9 in (22.9 cm) thick concrete bridge deck with an asphalt overlay of 3 in (7.6 cm). In the simulation the bridge was modeled as a uniform structure with material properties that were a weighted average of the properties of cement and asphalt. These weighted material properties are as follows [23]:

Mass density = $2.045 \times 10^{-4}$ lb*(s$^2$/in)/in$^3$ = 2181 kg/m$^3$
Thermal conductivity = $5.08 \times 10^{-5}$ BTU/(sec*in*F°) = 3.80 J/(s*m*C°)
Specific heat = 84 BTU/(lb*(s$^2$/in)*F°) = 912 J/(kg*C°)

The units for the above material properties are as defined in the ALGOR V18 material properties library.

Once the material properties have been defined the thermal loads are to be defined for the geometry, starting with the convective heat transfer coefficient h. The value for h was input as $1.2 \times 10^{-5}$ BTU/(s*in$^2$*F°) (35.3 J/(s*m$^2$*C°)) which was validated on the Lorain County (Site 86) bridge and block. Various values of h were assigned and bridge and block were simulated for this value of h ranging from $0.42 \times 10^{-5}$ BTU/(s*in$^2$*F°) (12.4 J/(s*m$^2$*C°)) to $1.2 \times 10^{-5}$ BTU/(s*in$^2$*F°) (35.3 J/(s*m$^2$*C°)). The best fit value of h was then used for all the simulations for all the sites. Figure 143 shows the simulation results for the different values of h. It can be noted that the value of $1.2 \times 10^{-5}$ BTU/(s*in$^2$*F°) (35.3 J/(s*m$^2$*C°)) best fits the actual data from the bridge deck simulator sensor.

It should be noted that the temperatures obtained in the simulation results are taken at specific locations designed to approximate actual conditions in the field. The simulated BDS temperature is that computed at a distance of 0.5 in (1.27 cm) beneath the center of the top surface, while the simulated bridge surface temperatures are for a point located at the center of the top surface.

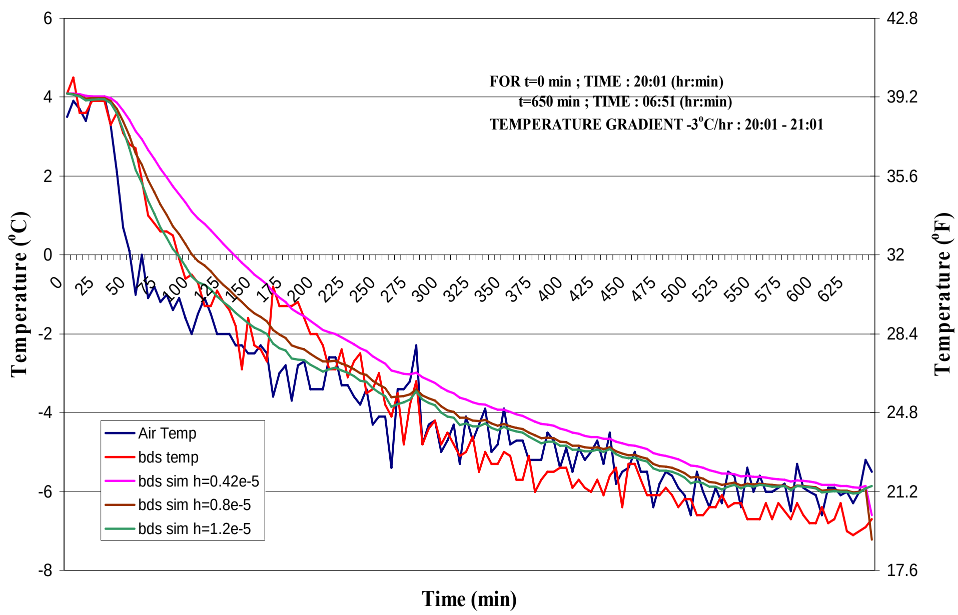



**Figure 143. Validation of h value for BDS – Lorain County (Site 86) for temperature gradient of -3.5°C/hr 3/7/05 20:01 – 3/8/05 06:51.**

It is also necessary to assign a number for the load curve for ambient air temperature. The load curve accounts for the varying ambient air temperature. The value for air temperatures in this load curve are assigned later in the ‘analysis parameters section’. In the ‘analysis parameters section’ a ‘default nodal temperature’ is also assigned, which represents the value of the bridge/block at the beginning (time = 0) of the simulation.

Once all inputs are defined, the program is run and the solver generates a result. This result in graphical form illustrated in Figure 144. It can be also exported as a text file and is saved as a data file which can be opened through Microsoft Excel. The results are obtained for half an inch below the center of the top surface for the block by defining a plane half an inch below the top surface as in Figure 144.

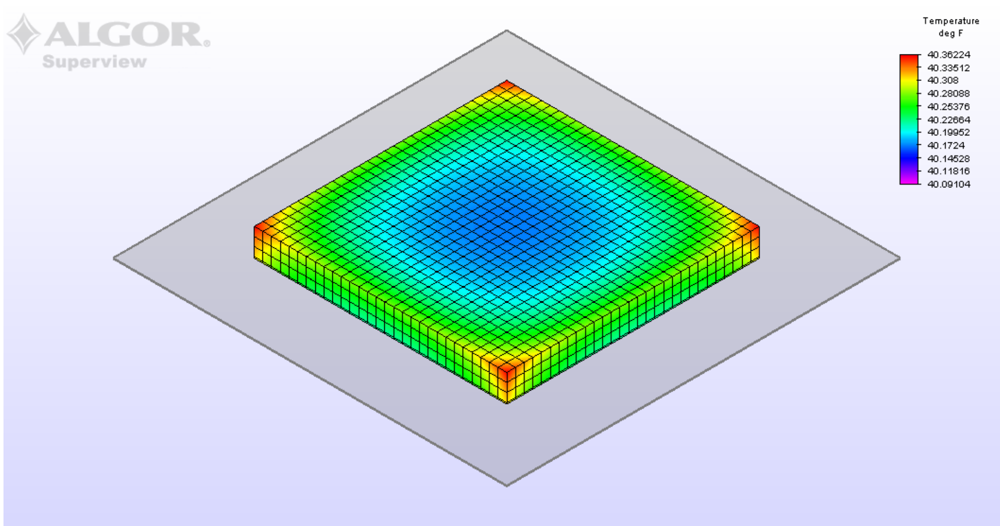



**Figure 144. Graphical representation of results for bridge deck simulator from ALGOR V18.**

This result in graphical form illustrated in Figure 144. It can be also exported as a text file and is saved as a data file which can be opened through Microsoft Excel. The results are obtained for half an inch below the center of top surface for the block by defining a slice plane half an inch below the top surface as shown in the above figure.

## 13.5 Validation of ALGOR V18

Before analyzing the bridge structures using ALGOR V18 the results from the FEA software were validated by comparing the results of the software with the experimental results obtained from a climate chamber.

In the climate chamber experiment a 6” x 6” x 6” (15.2 cm x 15.2 cm x 15.2 cm) concrete block was placed in a controlled environment where ambient air temperature was varied in a controlled manner. The ambient air temperature in the climate chamber was dropped from 20°C (68°F) to 15°C (59°F) as rapidly as the chamber could cool and maintained at 15°C (59°F) for a certain time period. After this the ambient air temperature was suddenly dropped to 10°C (50°F). This was continued in steps of 5°C (9°F) until a temperature of -10°C (14°F) was attained.

The same methodology was used to heat the ambient air temperature from -10°C (14°F) to 20°C (68°F) in steps of 5°C (9°F). The results from the climate chamber for an h value of $0.42x10^{-5}$ BTU/(s*$in^2$*°F) (12.4 J/(s*$m^2$*C°)) are shown in Figure 145 through Figure 150, each of which simulates a selected period of 5C° (9F°) cooling or warming in the chamber using as input the air temperature recorded in the chamber. Some of the simulations were not run through the entire experimental time period to save simulation time. The simulations were run long enough to get an idea of the accuracy of the results. The spikes in the temperature readings in Figure 146, Figure 147, and Figure 148 can be attributed to opening of the experimental chamber door while the experiment was still in progress. As can be seen in Figure 145 through Figure 150, ALGOR V18 gives fairly accurate results for the climate chamber experiment.

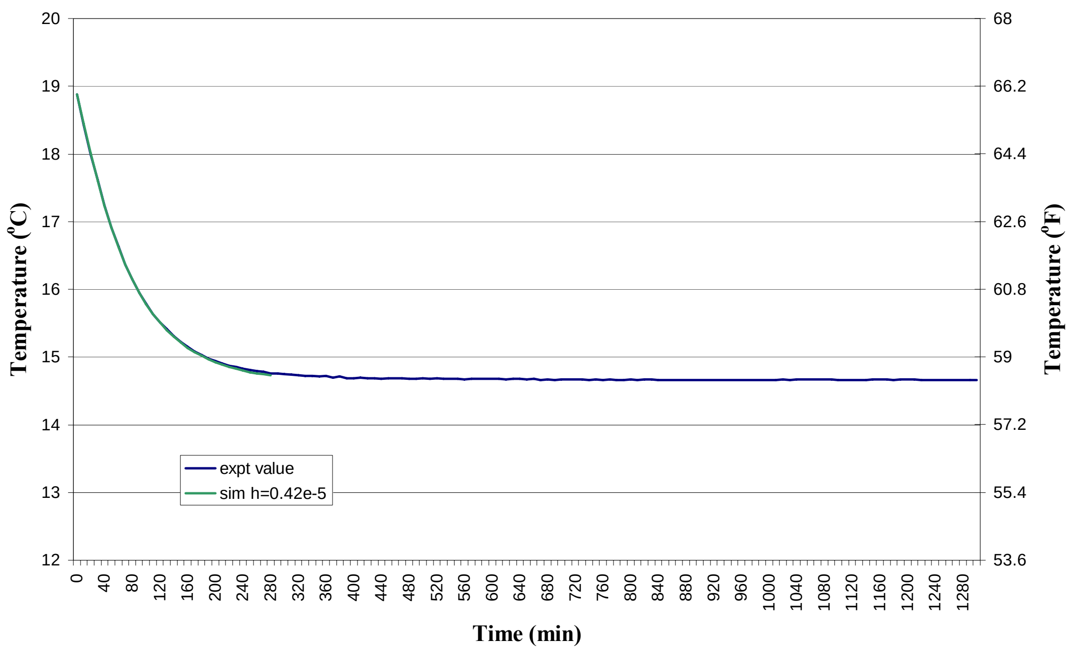



**Figure 145. Validation of h value for climate chamber with temperature decreasing from 20°C (68°F) to 15°C (59°F).**

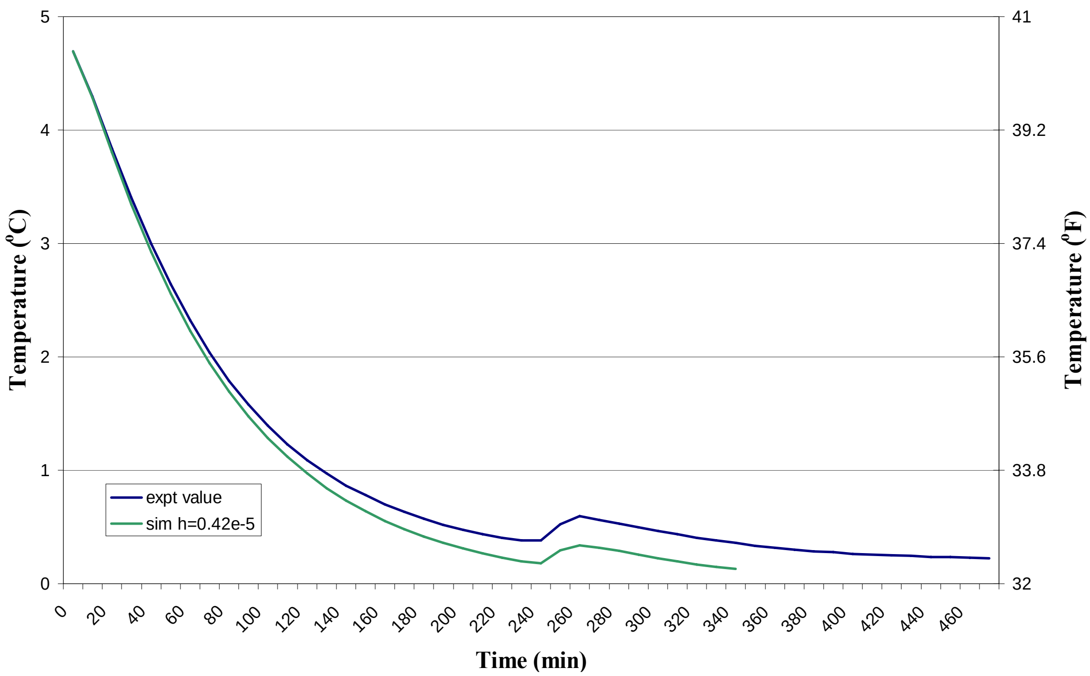



Figure 146. Validation of h value for climate chamber with temperature decreasing from 5°C (41°F) to 0°C (32°F).

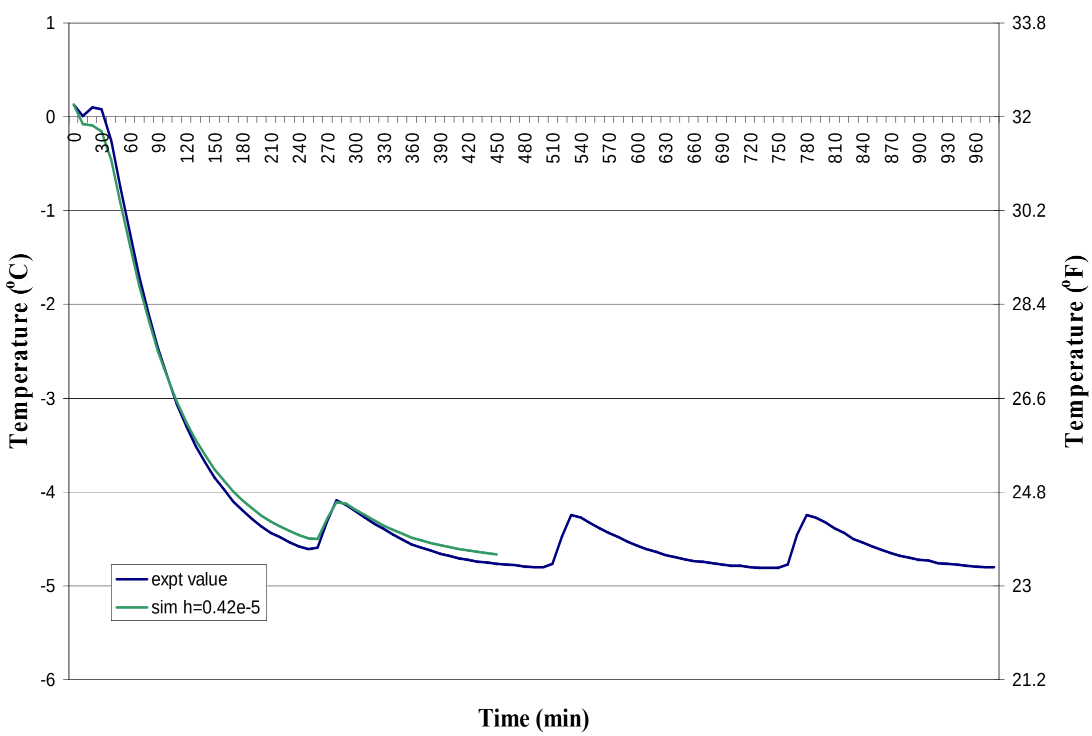



Figure 147. Validation of h value for climate chamber with temperature decreasing from 0°C (32°F) to -5°C (23°F).

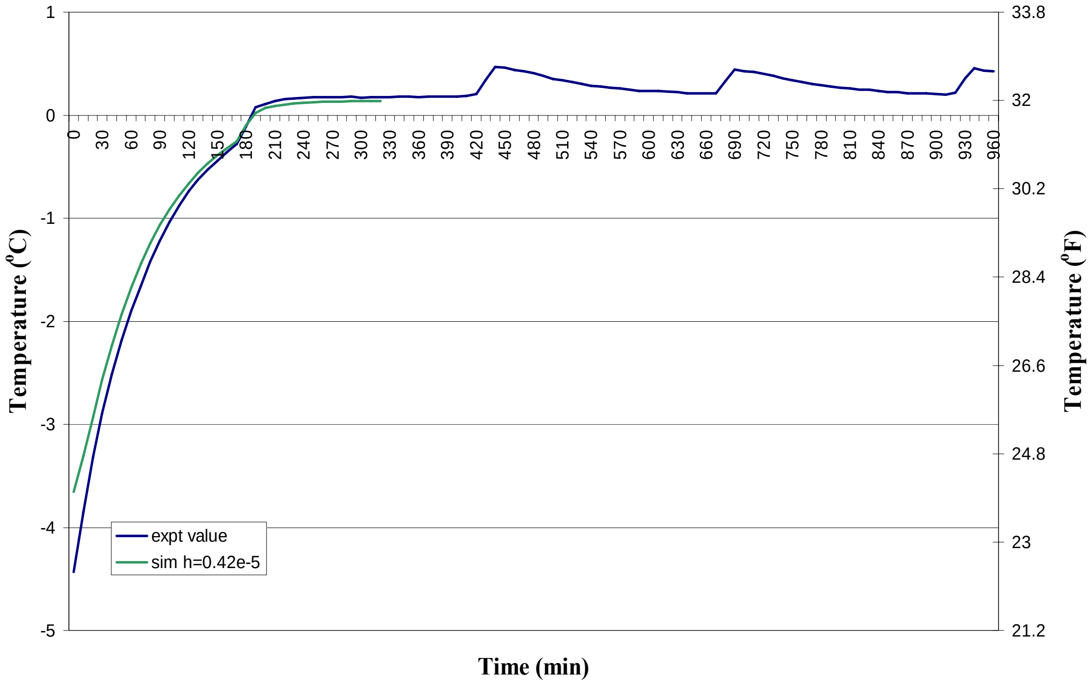



**Figure 148. Validation of h value for climate chamber with temperature increasing from -5°C (23°F) to 0°C (32°F)**

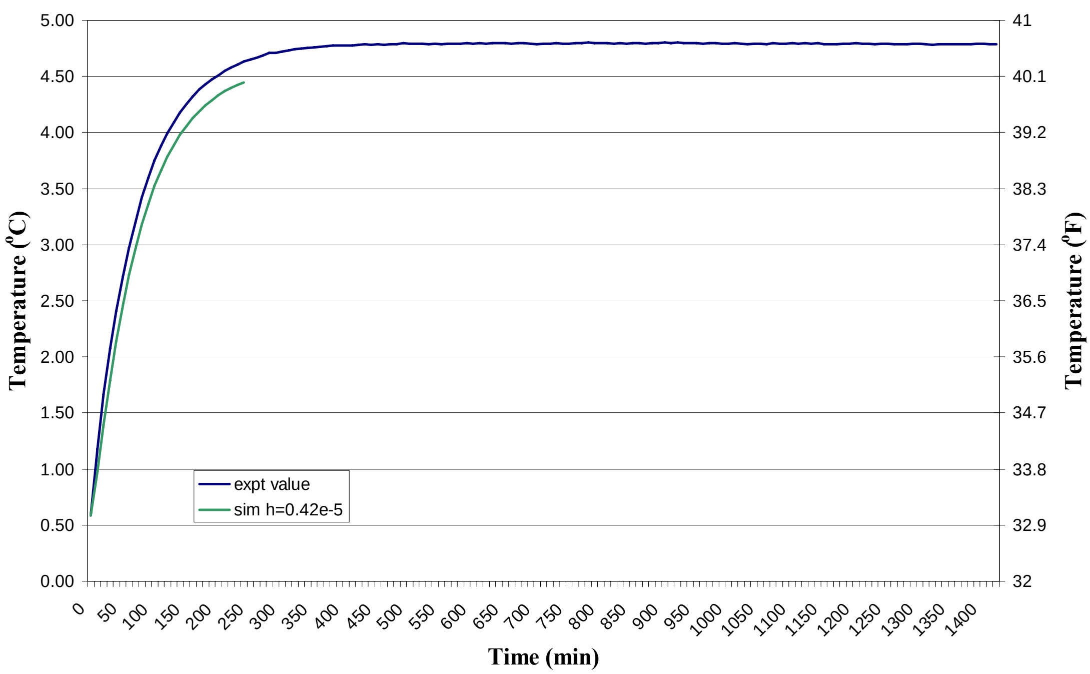



**Figure 149. Validation of h value for climate chamber with temperature increasing from 0°C (32°F) to 5°C (41°F).**

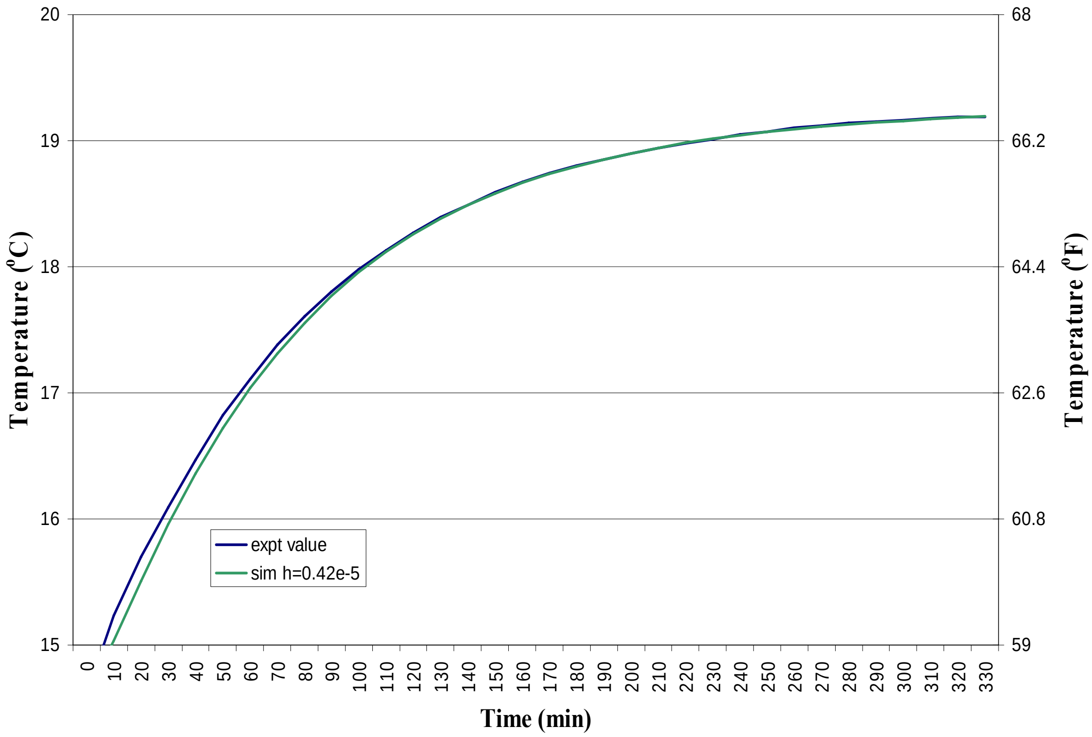



**Figure 150. Validation of h value for climate chamber with temperature increasing from 15°C (59°F) to 20°C (68°F).**

## 13.6 Determination of Air Temperature Gradients

The nighttime temperature records for each site were analyzed for large changes in air temperature. The maximum air temperature changes per hour, or maximum air temperature gradients, were determined for these night time recorded air temperatures. Daytime readings were not considered since for most sites there were no data that could be used to assess the impact of solar radiation. The air temperature gradient was calculated only for continuous data over an hour. If there were any missing temperature values during that hour, that hour of data was not considered and the next hourly temperature gradient was examined.

When all full-hour air temperature gradients had been determined from the night data at a site, a histogram of the gradients was plotted. The histogram for Lorain County (Site 86) is shown in Figure 151. From the histogram the maximum cooling and warming gradients were identified; in Figure 151 these are -3.5C°/hr (-6.3F°/hr) and +2.9C°/hr (-5.2F°/hr), respectively.

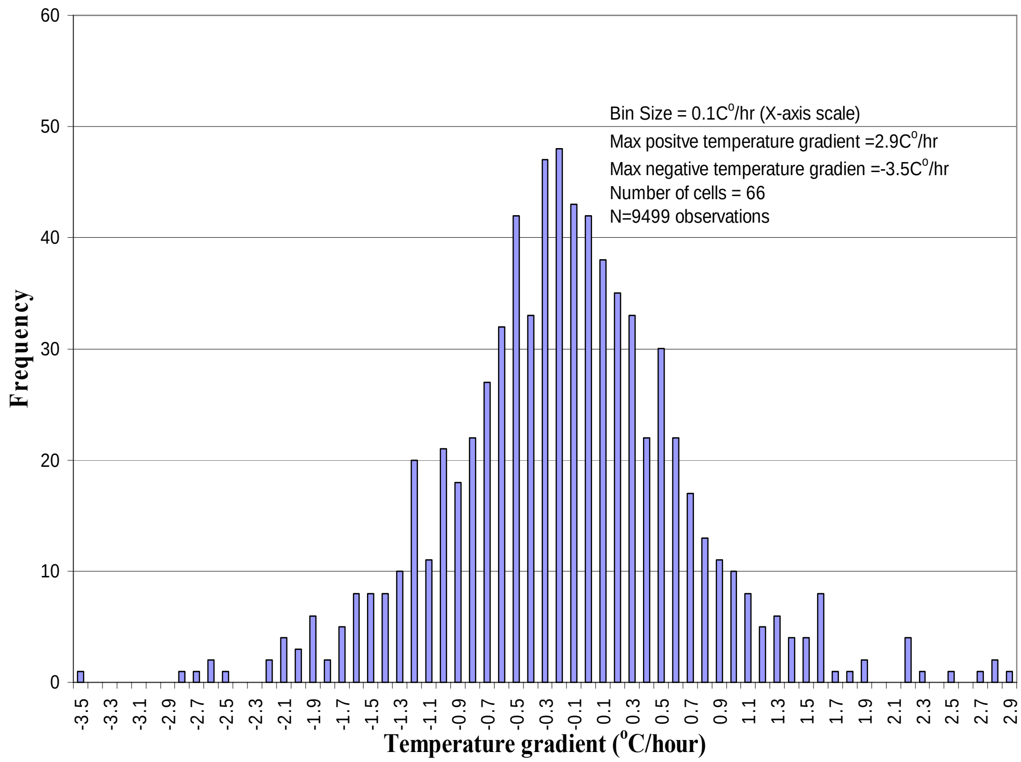



**Figure 151. Hourly temperature gradient for Site 86 – Lorain County (Night time data only) from January 21 – April 5, 2005.**

The air temperature for the periods ranging from about 2-3 hours before and after the maximum cooling and warming gradient were used as the boundary condition inputs for the thermal analysis in ALGOR V18. That is, 5-7 hours of actual air temperature values centered around the maximum positive and negative temperature gradients were used as the input ambient temperature profile for the ALGOR V18 simulation.

In cases where there were insufficient data before and after the maximum cooling and warming gradients the next maximum gradient was considered. Also, gradients that were actually fortuitous combinations of spikes were not considered.

### 13.6.1 Temperature bias adjustments

At many sites a modified value of bridge deck simulator temperature data was used to compensate for bias. If one looks at some of the nighttime correlation graphs in Chapter 9, one can see where the cloud of data points clearly avoids the origin, suggesting that there is a consistent difference between the two temperatures being plotted. While some of this difference could be explained by, for instance, a tendency for ground or concrete to retain heat after dark that tends to warm road surfaces relative to air, some may also be caused by a constant bias built into one or more of the sensors. To compensate for this, modifications have been made in the temperature data used in the FEM simulation. The compensation procedure for bridge deck simulator (BDS) temperatures consists of averaging the air and BDS temperatures over the period of the simulation, and adding the difference of the averages to the BDS temperature so that the average of the modified BDS temperature is the same as the average air temperature. A similar compensation process is also applied at some sites to bridge sensor temperature data relative to air temperature data. For instances where the air and BDS or bridge temperatures crossed or clearly varied over time, no bias adjustment was made. Also, different bias adjustments were used for the simulations of cooling and warming temperature gradients at the same site. In the plots of the temperature gradient data below, the actual and modified BDS and bridge temperatures are shown and the bias adjustments printed on the graph, e.g. "MODIFIED BDS TEMP = ACTUAL BDS TEMP + 2.19°C (+3.94°F)", where 2.19°C (+3.94°F) is the bias adjustment. These bias adjustments were used to make it easier to compare results in the simulation, and may not agree with either intercepts recorded in Table 19 and Table 20 or with differences in temperature values recorded during site visits in Chapter 6.

## 13.7 FEM Results

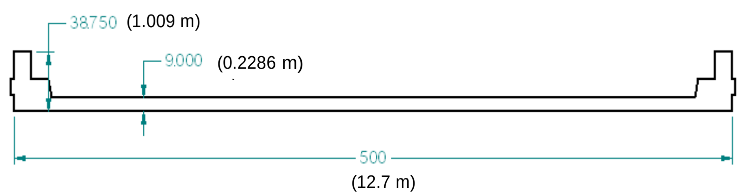
The results from the FEM simulation analysis for each individual site are represented below in order of increasing ODOT RWIS site number. The first site, Site 7 in Crawford County is presented in full detail, followed by the other sites with the essential results only and the other plots relegated to Electronic Appendix B. The essential results shown for each site include the histogram of temperature gradients, time series graphs, one for the extended time period that includes the steepest cooling gradient followed by one for the steepest warming gradient. These time series plots each include the air temperature, the BDS temperature, and the bridge temperature. If a nonzero bias correction was made, the modified BDS and bridge temperatures are shown, as appropriate. The horizontal time axis is marked in clock time recorded in the RWIS system. This is followed by time series graphs showing the air temperature, the BDS simulation with the chosen value of h ($1.2 \times 10^{-5}$) and the modified actual BDS temperature (or unmodified actual BDS temperature if the bias was zero), one for the modeling of the cooling gradient and one for the modeling of the warming gradient. The horizontal time axis is marked in minutes from the beginning of the simulation, which typically covered 300 minutes (5 hours) or longer. The clock time for the beginning and end of the simulation period are also printed on each graph. These are followed by a corresponding pair of time series graphs of the simulation of the bridge deck temperature, including the air temperature, simulated bridge temperature, and modified actual bridge temperature (unmodified actual bridge temperature if the bias was zero). Additional graphs relegated to Electronic Appendix B (and shown below for Site 7 as an example) include bridge cross-section with dimensions and values of average and maximum wind speeds during time periods in the simulation, the temperature difference between the simulated bridge and simulated BDS temperatures – first for the steepest cooling gradient then for the steepest warming gradient, then a similar pair of graphs featuring the difference between the actual bridge and BDS temperatures.

### 13.7.1 Crawford County (Site 7)

Figure 152 shows the cross-section view of the Crawford County bridge. The dimensions on the drawing are given in inches with their equivalents in meters. The length and orientation of the bridge are also listed in the figure, along with the average and maximum wind speeds recorded by the RWIS system during the periods including the maximum warming and cooling gradients that are the basis for the simulations.

## BRIDGE NO: CRA-30N-0711

**Average Wind Speed: Max Cooling Gradient = 0.807 mph - 1.298 kmph(14.2 in/sec)**
**Max Warming Gradient = 1.08 mph - 1.737 kmph (19 in/sec)**
**Maximum Wind Speed :Max Cooling Gradient =1.7 mph - 2.735 kmph (29.92 in/sec)**
**Direction :40$^o$ (NE)**
**Maximum Wind Speed :Max Warming gradient = 2.4 mph - 3.861 kmph (42.24 in/sec)**
**Direction :190$^o$ (S)**




**ALL DIMENSIONS ARE IN INCHES**

**Length of bridge = 129.74' (39.54 m)**
**Orientation: 89$^o$40'17" (NE)**

**Figure 152: Cross-Section view of Crawford County Bridge (Site 7).**

Figure 153 shows the histogram plot for temperature gradients at night time.

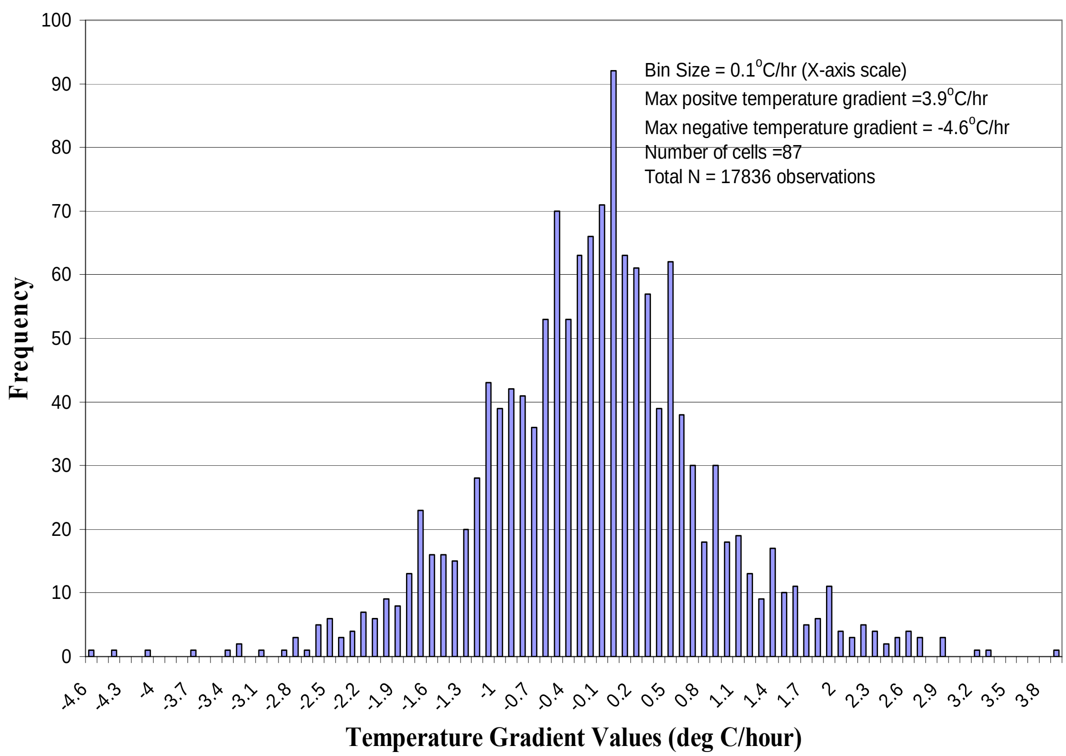



**Figure 153. Hourly temperature gradient for Site 7 – Crawford County (Night time data only) from November 29 – April 5, 2005.**

Figure 154 and Figure 155 show actual recorded temperature data for the maximum cooling and warming periods. The only temperature modification is the addition of 2.19C° (3.94F°) to the BDS temperature during the warming gradient. The simulation period during the cooling gradient is from 19:26 to 7:41, or 725 minutes. For the warming gradient the simulation lasted from 0:11 to 7:46, or 455 minutes.

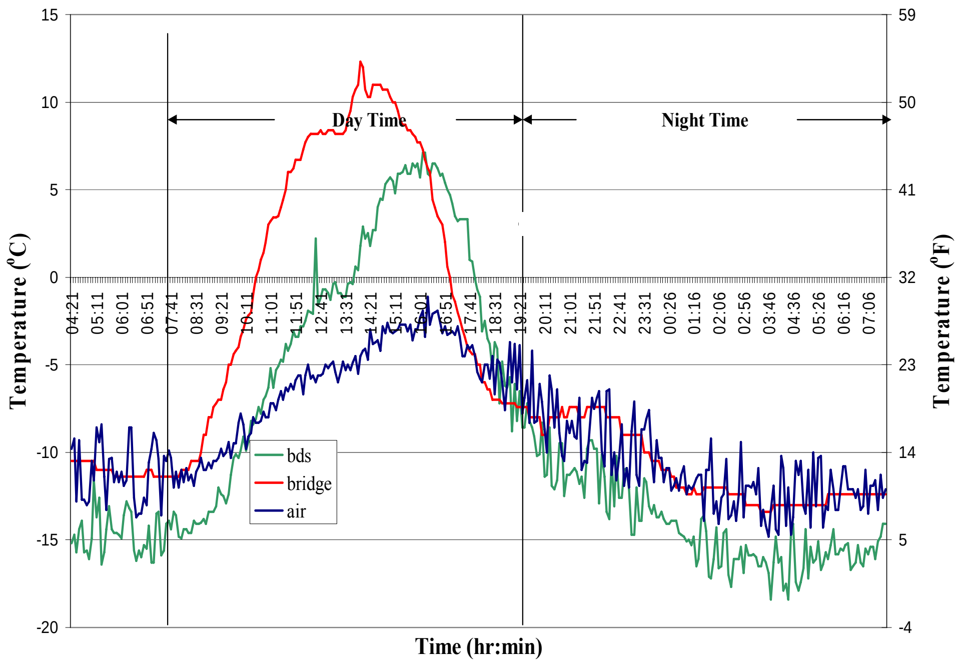



**Figure 154. Data containing the -4.6C°/hr (-8.3F°/hr) temperature gradient for Crawford County (Site 7) from 2/1/05 04:21 – 2/2/05 07:41.**

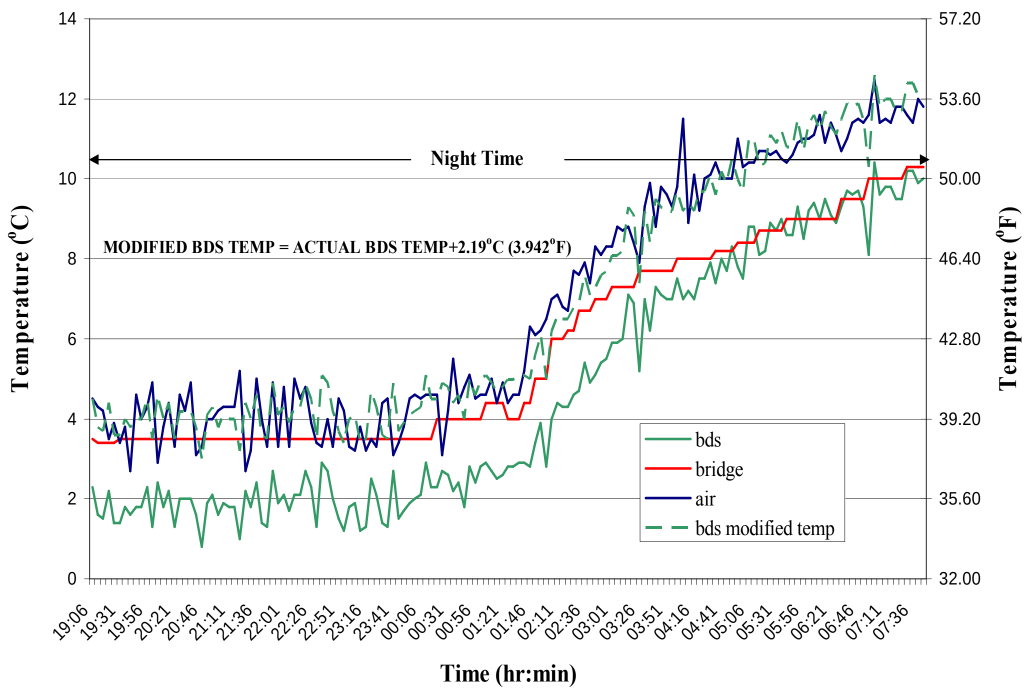



**Figure 155. Data containing the 2.7C°/hr (4.9F°/hr) temperature gradient for Crawford County (Site 7) from 1/11/05 19:06 – 1/12/05 07:46.**

Figure 156 and Figure 157 show the simulation results for the BDS.

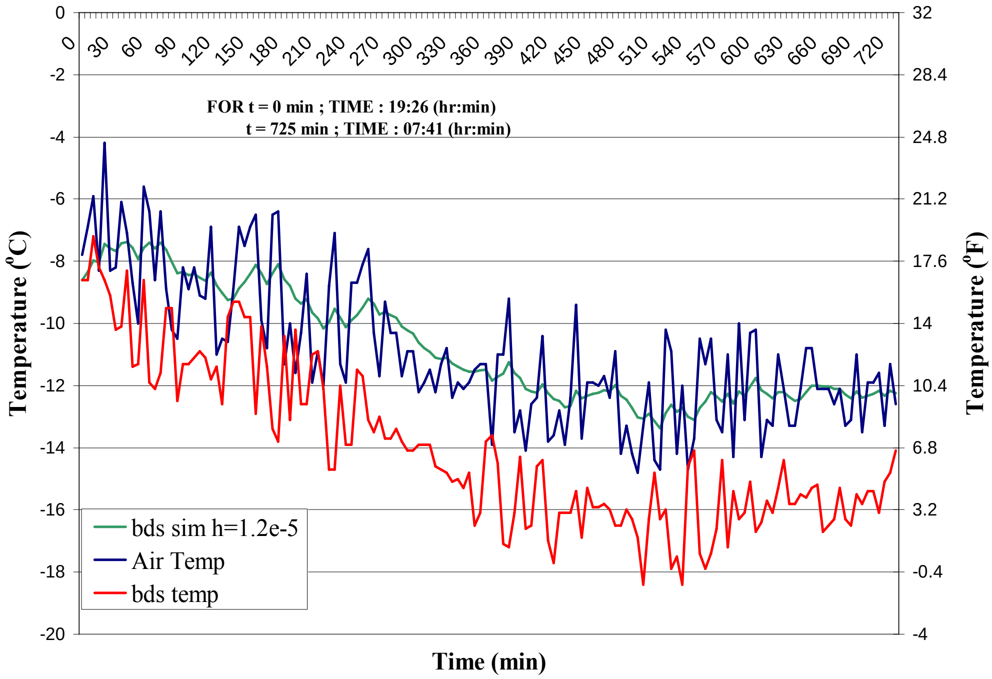



**Figure 156. Validation of h value of BDS-Crawford County (Site 7) for -4.6C°/hr (-8.3F°/hr) temperature gradient from 2/1/05 19:26 – 2/2/05 07:41.**

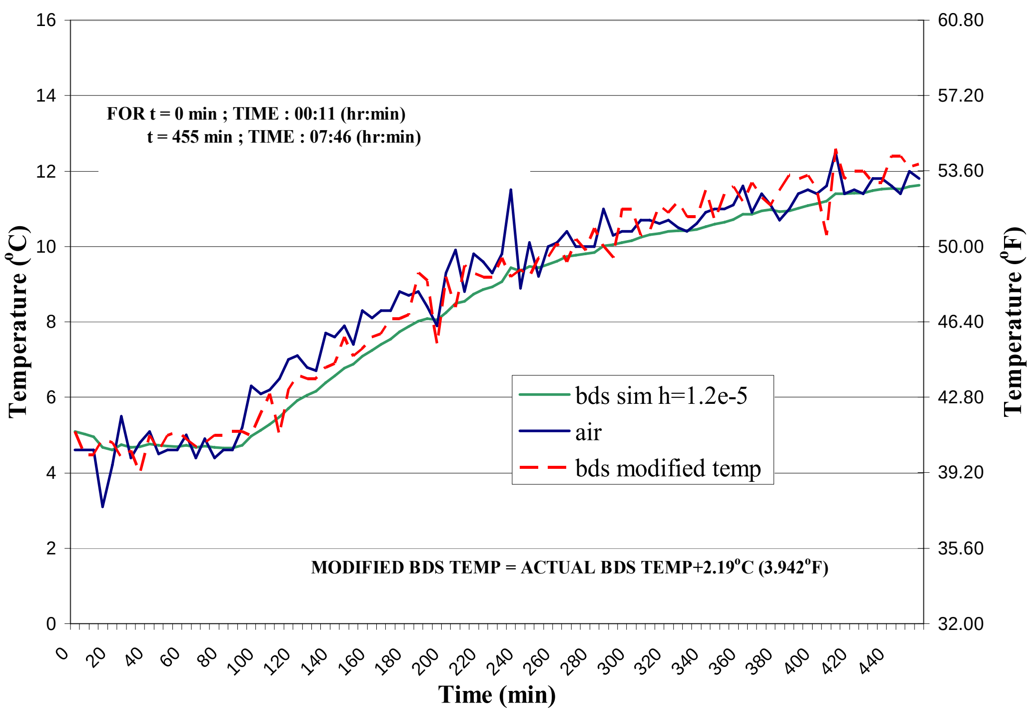



**Figure 157. Validation of h value of BDS-Crawford County (Site 7) for 2.7C°/hr (4.9F°/hr) temperature gradient from 1/12/05 00:11 – 1/12/05 07:46.**

Figure 158 and Figure 159 show the simulation results for the bridge.

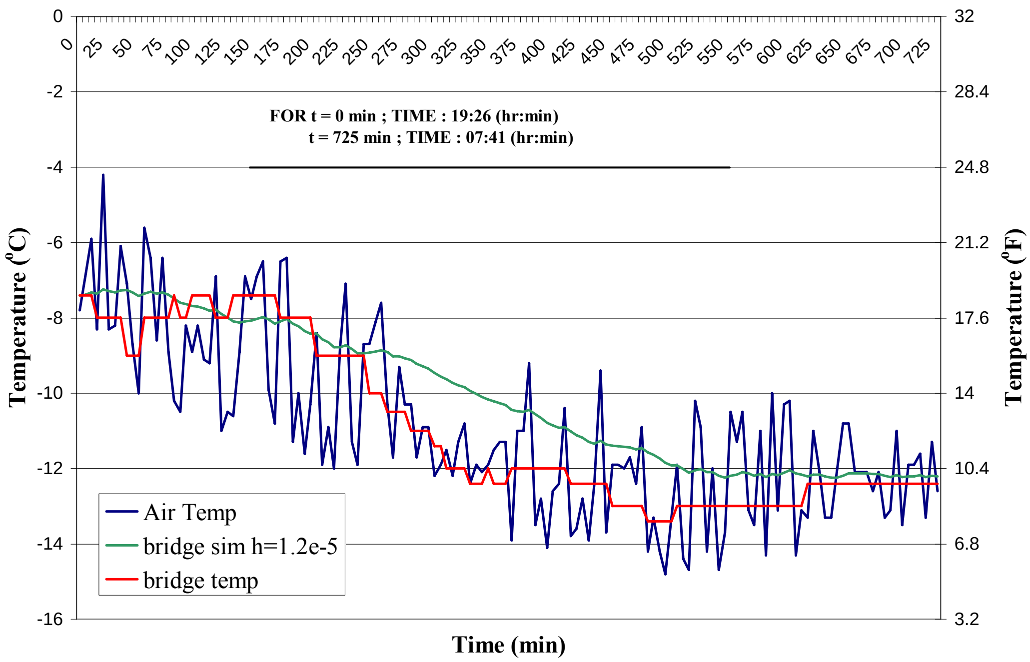



**Figure 158. Validation of h value of bridge-Crawford County (Site 7) for -4.6C°/hr (-8.3F°/hr) temperature gradient from 2/1/05 19:26 – 2/2/05 07:41.**

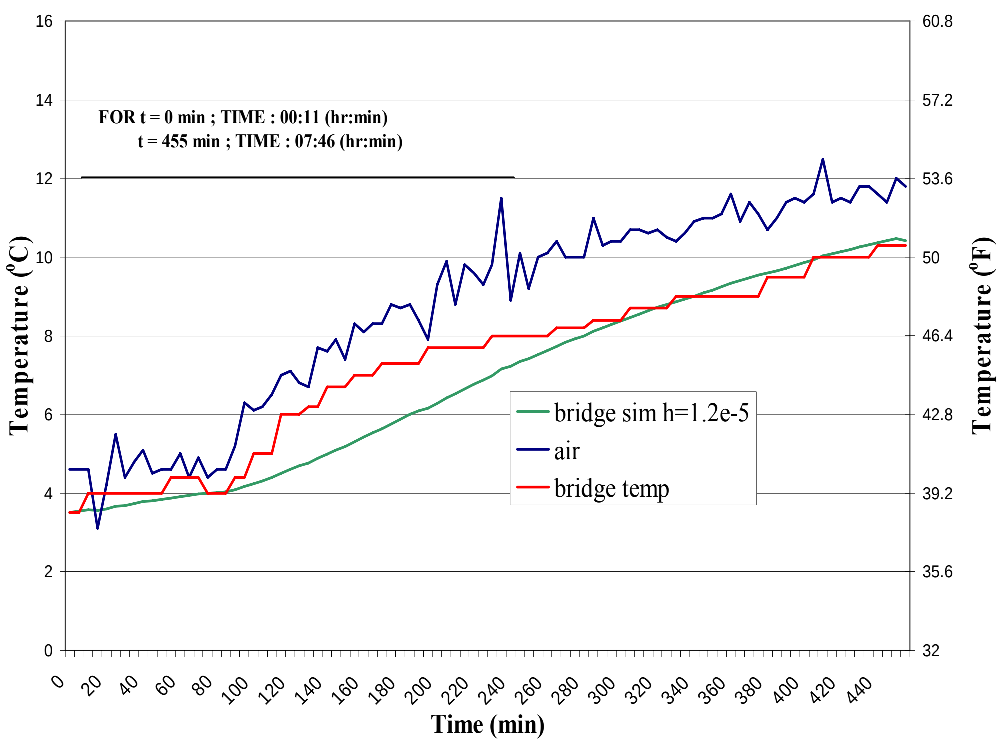



**Figure 159. Validation of h value of bridge-Crawford County (Site 7) for 2.7C°/hr (4.9F°/hr) temperature gradient from 1/12/05 00:11 – 1/12/05 07:46.**

Figure 160 illustrates the temperature difference between the simulated bridge deck temperature and the simulated bridge deck simulator block temperature during the steepest cooling temperature gradient at Site 7. Figure 161 shows the temperature difference between the actual bridge deck temperature and the actual bridge deck simulator block temperature during the same period.

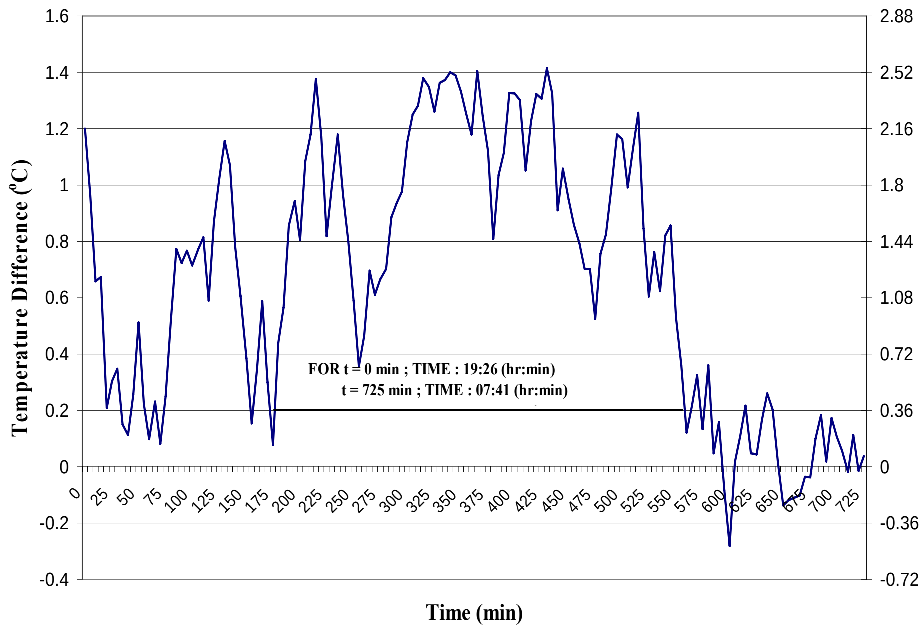



**Figure 160. Temperature difference between simulated values for bridge and block for Site 7 – Crawford County for delta = -4.6C°/hr (-8.3F°/hr): 2/1/05 19:26 – 2/2/05 07:41.**

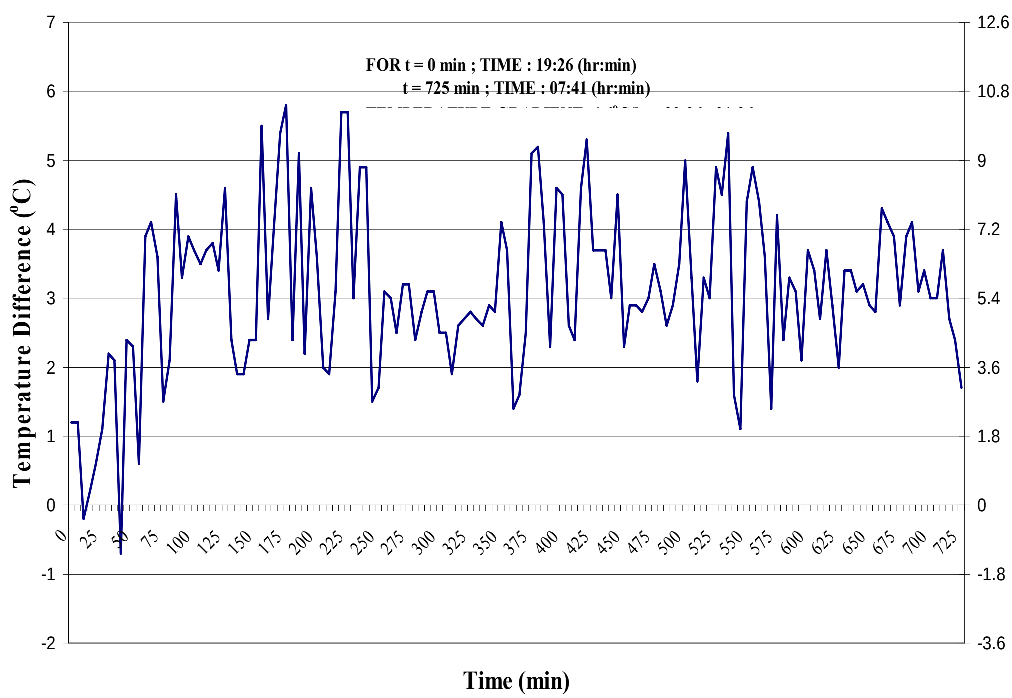



**Figure 161. Temperature difference between actual values for bridge deck and block for Site 7 – Crawford County for delta = -4.6C°/hr (-8.3F°/hr): 2/1/05 19:26 – 2/2/05 07:41.**

Figure 162 illustrates the temperature difference between the simulated bridge deck temperature and the simulated bridge deck simulator block temperature during the steepest warming temperature gradient at Site 7. Figure 163 shows the temperature difference between the actual bridge deck temperature and the actual bridge deck simulator block temperature during the same period.

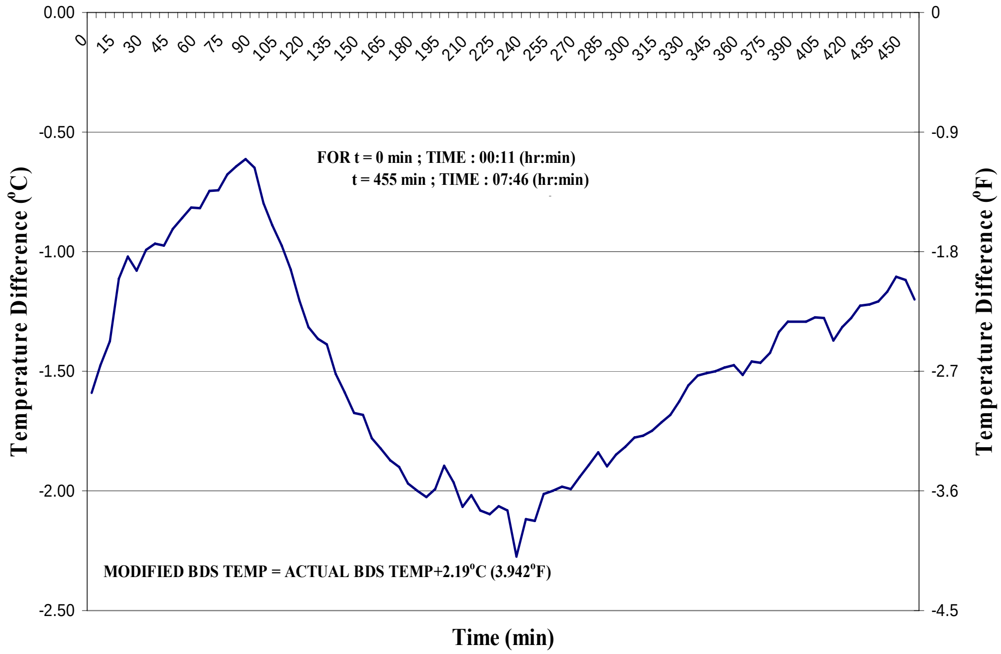



**Figure 162. Temperature difference between simulated values for bridge and block for Site 7 – Crawford County for delta = 2.7C°/hr (4.9F°/hr): 1/12/05 00:11 – 1/12/05 07:46.**

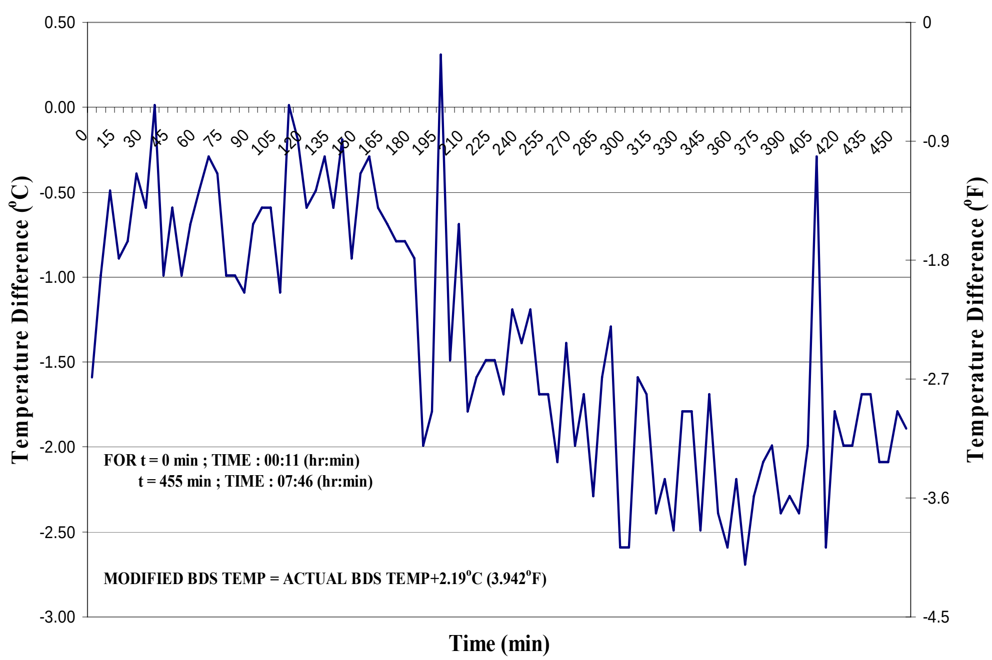



**Figure 163. Temperature difference between actual values for bridge deck and block for Site 7 – Crawford County for delta = 2.7C°/hr (4.9F°/hr): 1/12/05 00"11 – 1/12/05 07:46.**

### 13.7.2 Stark County

The cross-section and dimensions of the bridge as used in the simulation along with average and maximum wind speed values are given in Electronic Appendix B. Figure 164 shows the histogram plot for temperature gradients at nighttime.

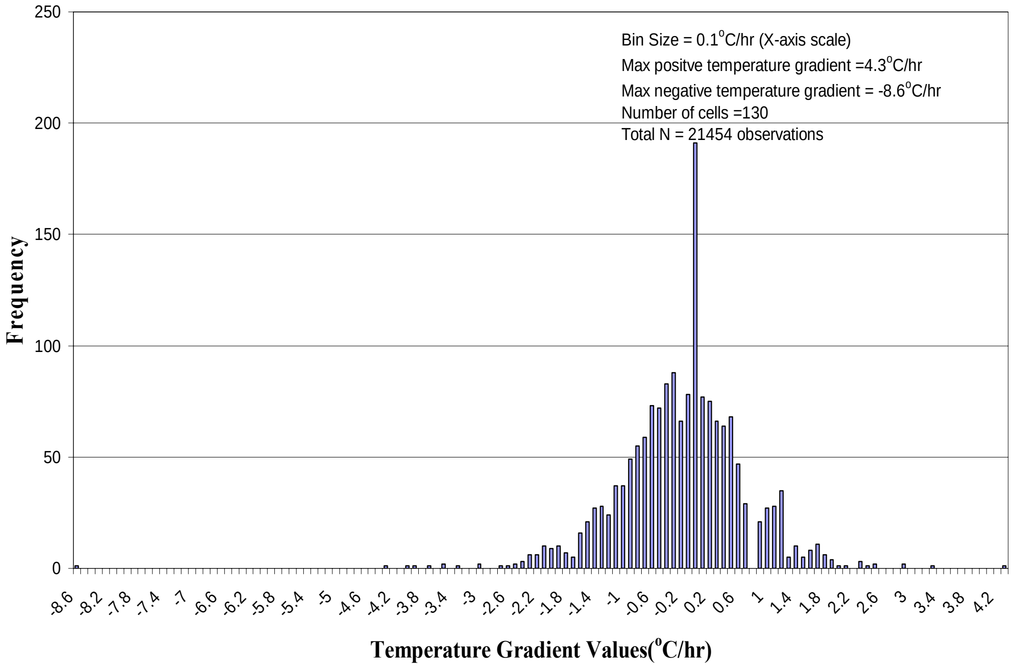



**Figure 164. Hourly temperature gradient for Site 9 – Stark County (Night time data only) from November 29 – April 5, 2005.**

Figure 165 and Figure 166 show actual recorded temperature data for -8.6C°/hr (-15.5F°/hr) temperature gradient for cooling and 4.3C°/hr (7.7F°/hr) temperature gradient for warming, respectively. For the warming gradient, both the BDS and bridge temperature have been modified by adding 3C° (5.4F°). The simulation of the cooling gradient covers the 270 minutes from 19:01 to 23:31. For the warming gradient the simulation lasted from 1:01 to 7:46, or 405 minutes.

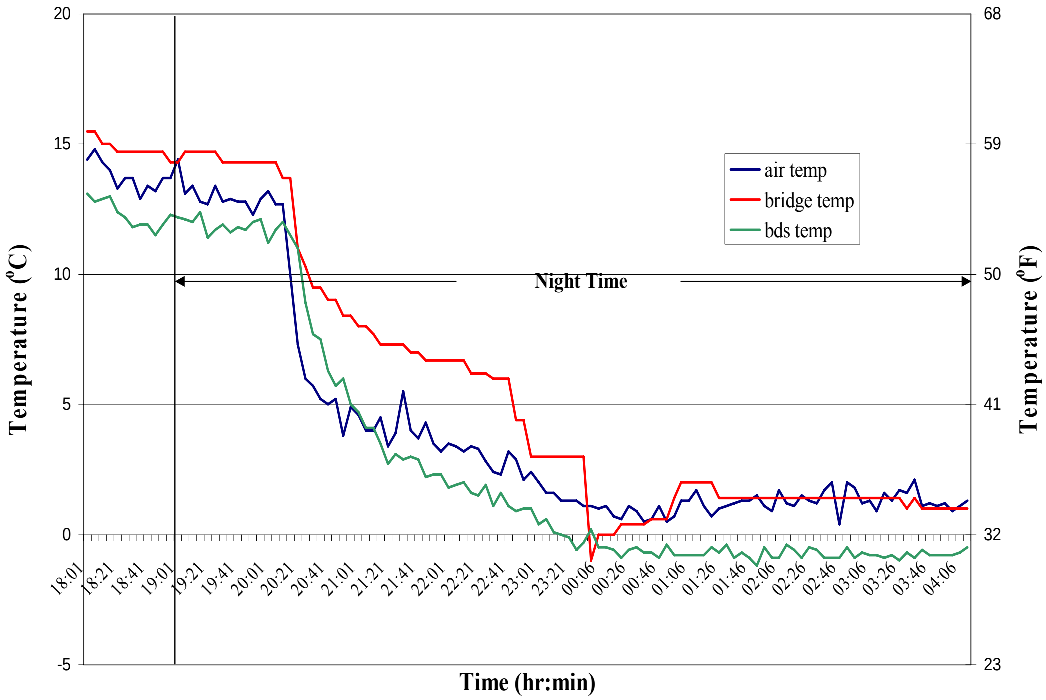



**Figure 165. Data containing the -8.6C°/hr (-15.5F°/hr) temperature gradient for Stark County (Site 9) from 1/13/05 18:01 – 1/14/05 04:16.**

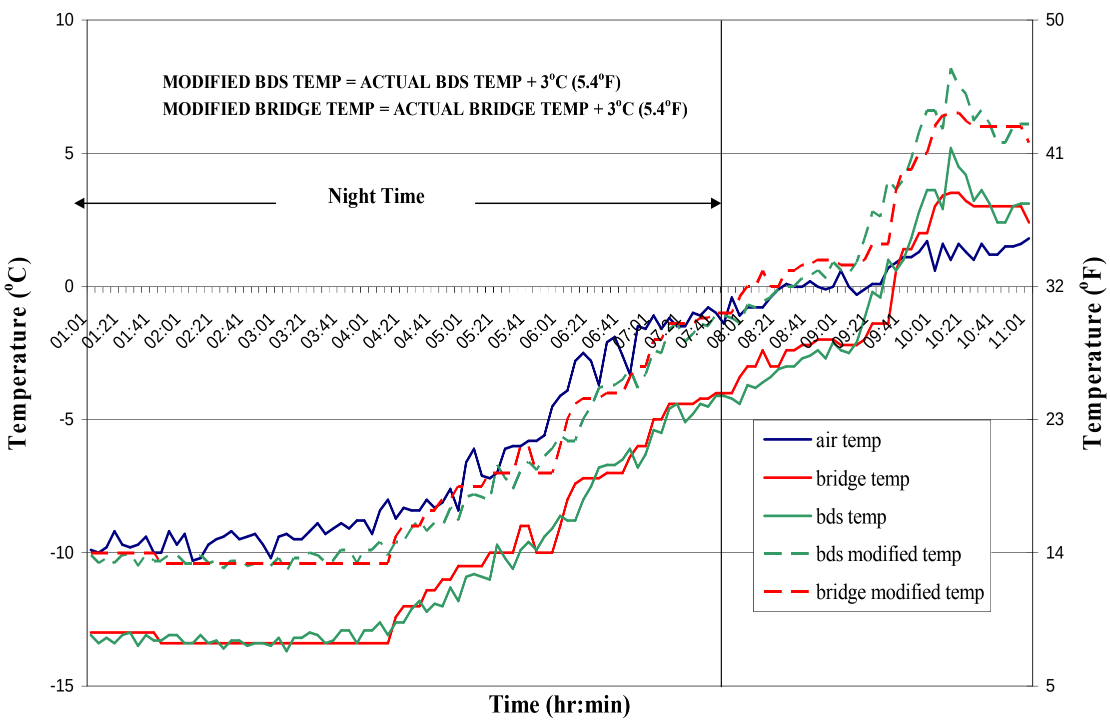



**Figure 166. Data containing the 4.3C°/hr (7.7F°/hr) temperature gradient for Stark County (Site 9) from 12/21/05 01:01 – 12/21/05 11:01.**

Figure 167 and Figure 168 show the simulation results for the BDS during the -8.6C°/hr (-15.5F°/hr) temperature gradient for cooling and the 4.3C°/hr (7.7F°/hr) temperature gradient for warming, respectively.

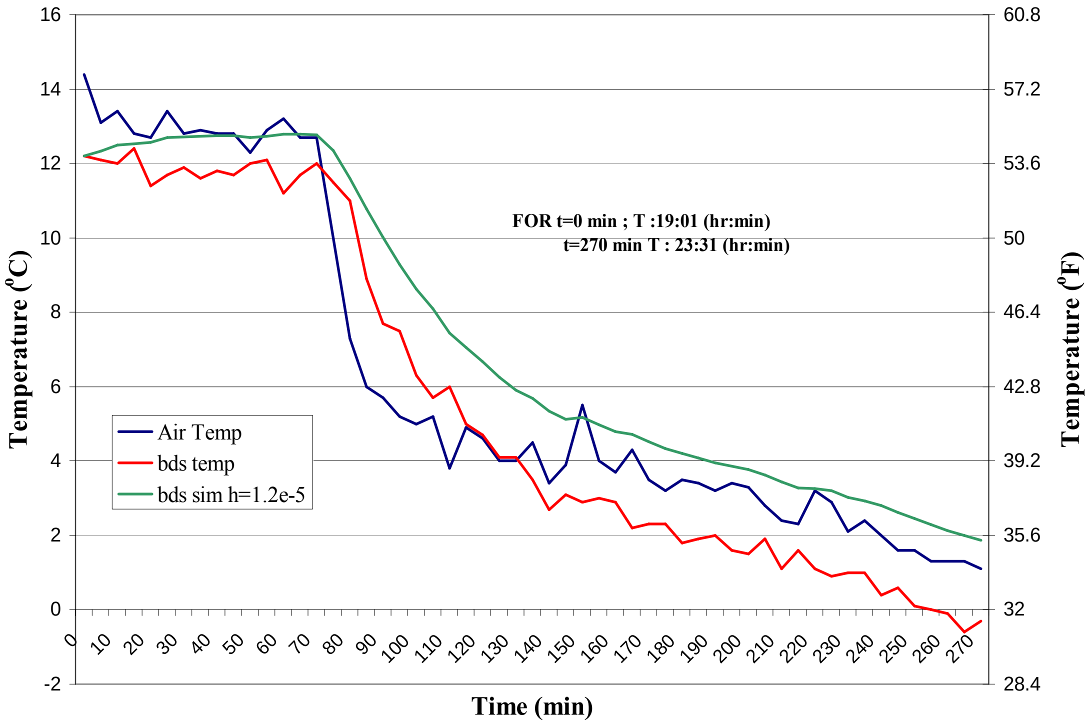



**Figure 167. Validation of h value of BDS-Stark County (Site 9) for -8.6C°/hr (-15.5F°/hr) temperature gradient from 1/13/05 19:01 – 1/13/05 23:31.**

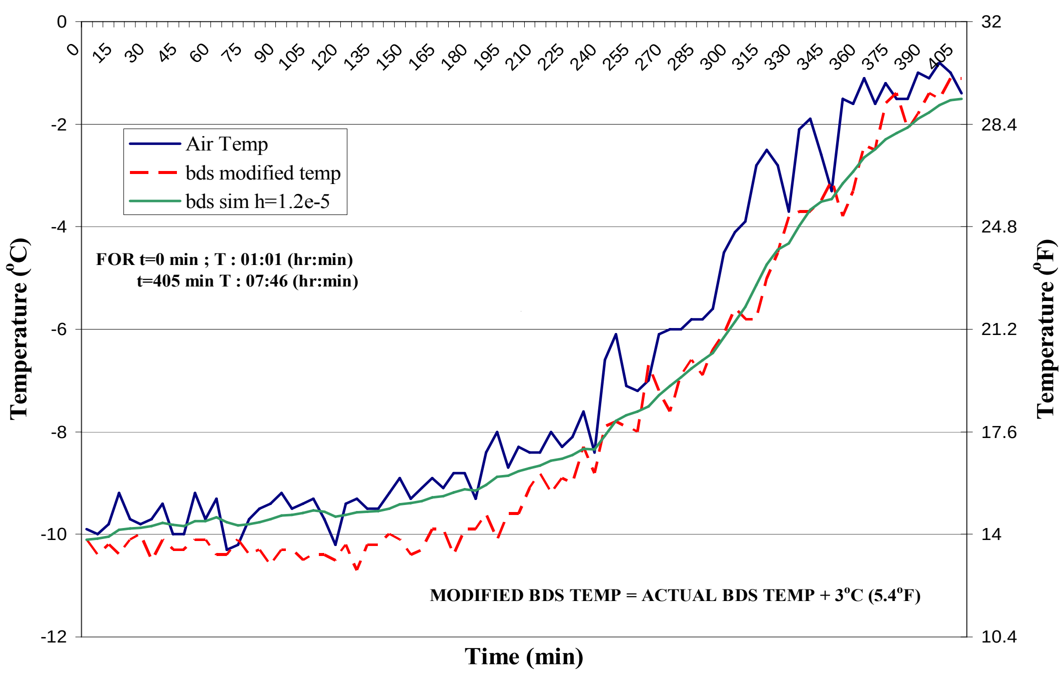



**Figure 168. Validation of h value of BDS-Stark County (Site 9) for 4.3C°/hr (7.7F°/hr) temperature gradient from 12/21/05 01:01 – 12/21/05 07:46.**

Figure 169 and Figure 170 show the simulation results for the bridge during the -8.6C°/hr (-15.5F°/hr) temperature gradient for cooling and the 4.3C°/hr (7.7F°/hr) temperature gradient for warming, respectively.

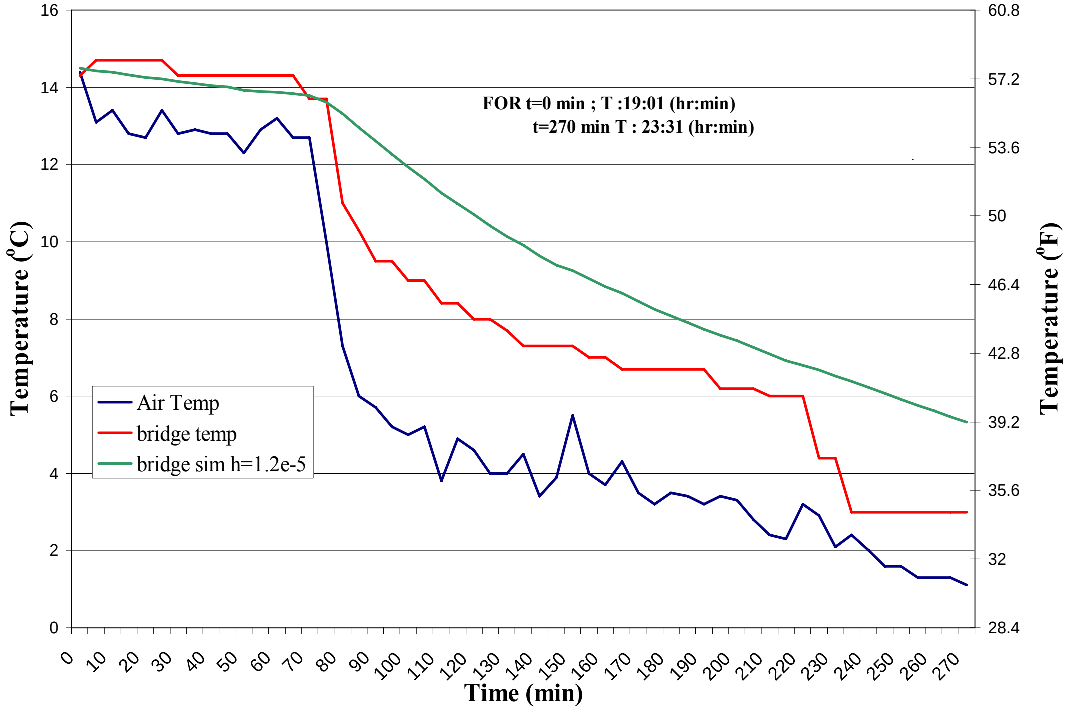



**Figure 169. Validation of h value of bridge-Stark County (Site 9) for -8.6C°/hr (-15.5F°/hr) temperature gradient from 1/13/05 19:01 – 1/13/05 23:31.**

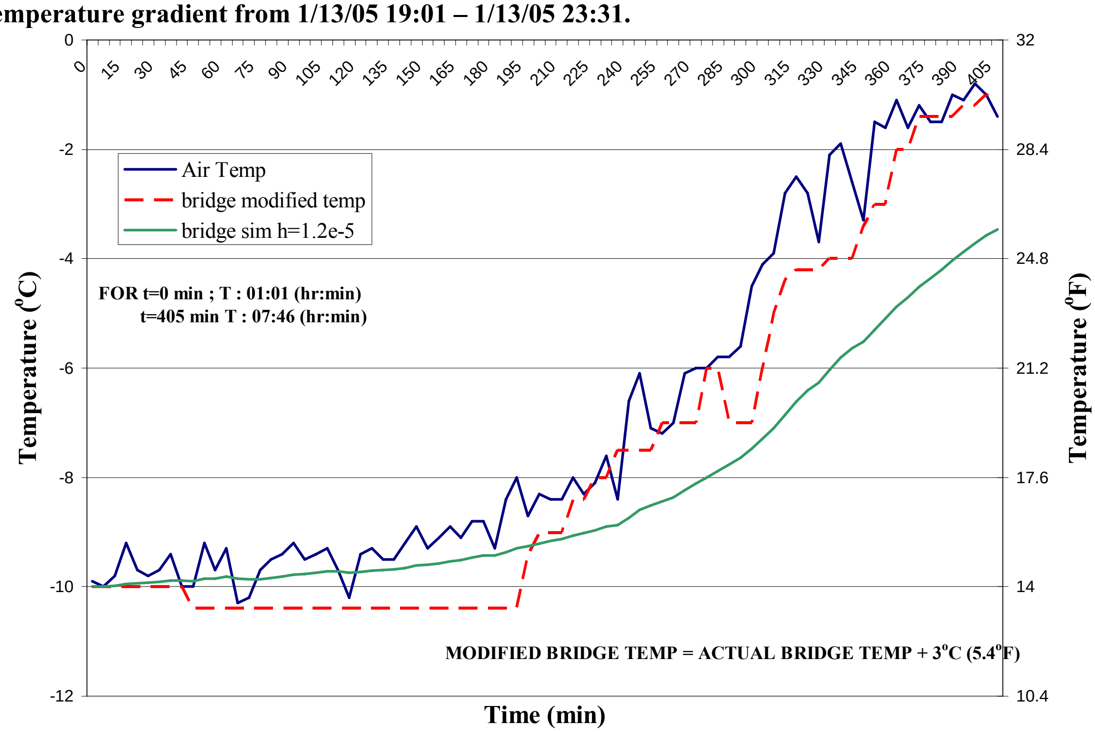



**Figure 170. Validation of h value of bridge-Stark County (Site 9) for 4.3C°/hr (-7.7F°/hr) temperature gradient from 12/21/05 01:01 – 12/21/05 07:46.**

### 13.7.3 Warren County (Site 59)

Figure 171 shows the histogram plot for temperature gradients at night time.

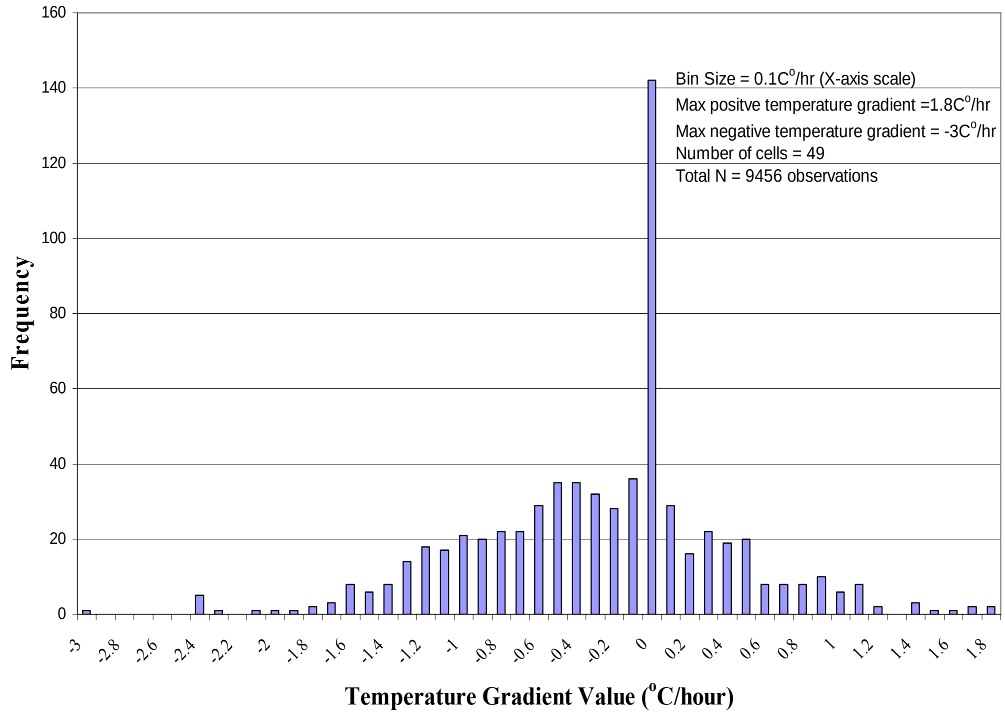



**Figure 171. Hourly temperature gradient for Site 59 – Warren County (Night time data only) from January 21 – April 5, 2005.**

Figure 172 and Figure 173 present actual recorded temperature data for -3C°/hr (-5.6F°/hr) temperature gradient for cooling and 1.4C°/hr (2.5F°/hr) temperature gradient for warming respectively. During the negative temperature gradient, the bridge deck simulator temperature was modified by adding 7.42C° (13.37F°) and the bridge temperature was modified by adding 1.57C° (2.83F°). During the warming gradient, the modification amounts were 6.00C° (10.80F°) and 1.50C° (2.70F°) for BDS and bridge, respectively. The simulation during the cooling gradient lasted from 1:01 to 6:21, or 320 minutes. The simulation during the warming gradient covered the 360 minutes from 19:46 to 1:46.

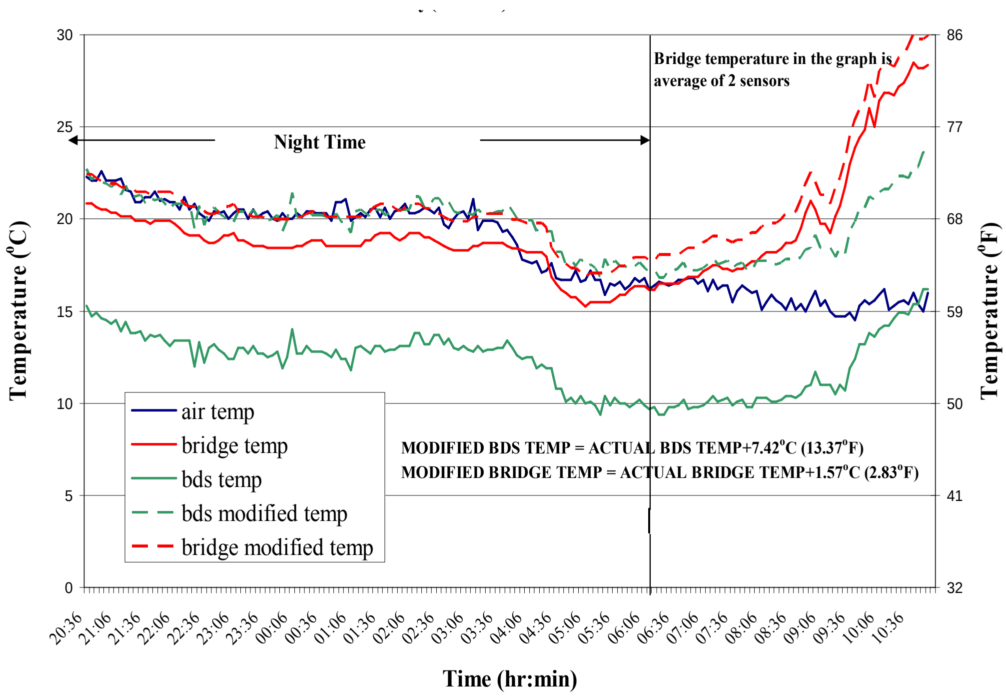



**Figure 172. Data containing the -3C°/hr (-5.6F°/hr) temperature gradient for Warren County (Site 59) from 3/30/05 20:36 – 3/31/05 11:01.**

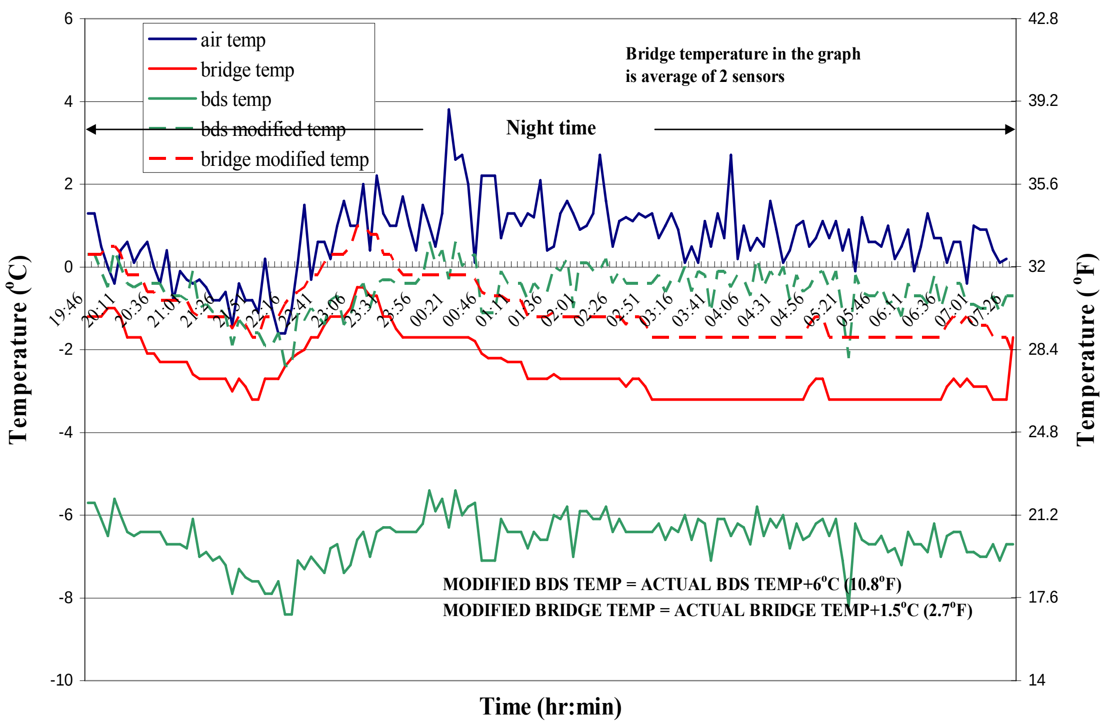



**Figure 173. Data containing the 1.4C°/hr (2.5F°/hr) temperature gradient for Warren County (Site 59) from 2/11/05 19:46 – 2/12/05 07:36.**

Figure 174 and Figure 175 show the simulation results for -3C°/hr (-5.6F°/hr) temperature gradient for cooling and 1.4C°/hr (2.5F°/hr) temperature gradient for warming for the BDS.

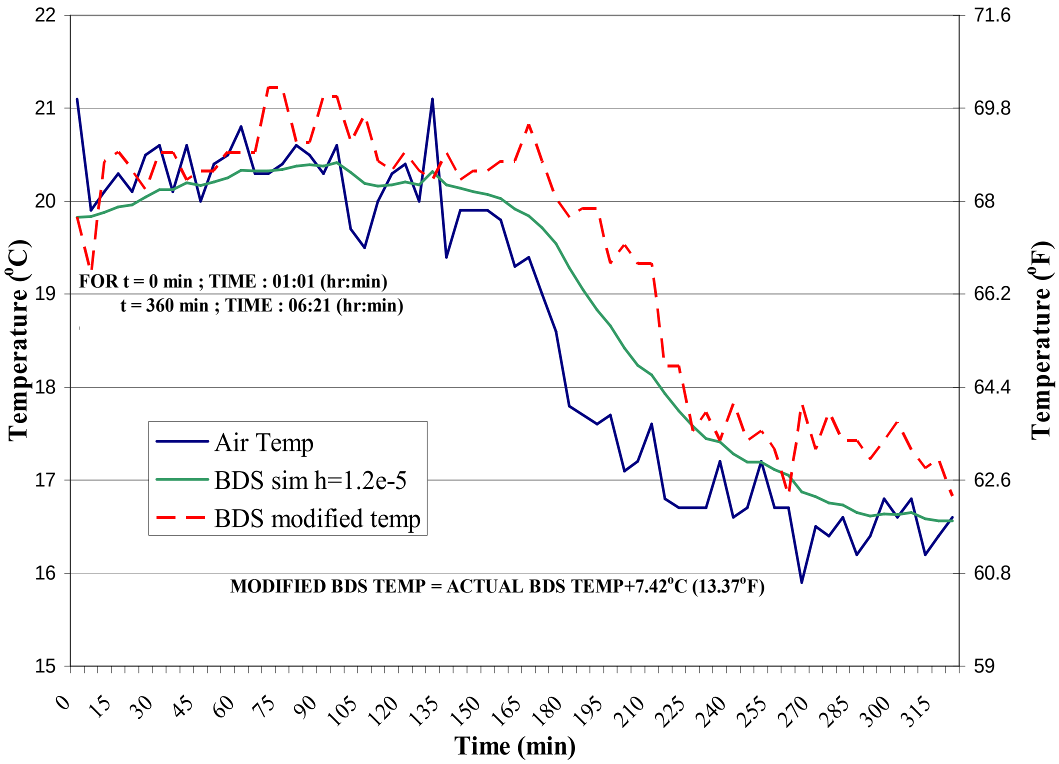



**Figure 174. Validation of h value of BDS-Warren County (Site 59) for -3C°/hr (-5.6F°/hr) temperature gradient from 3/31/05 01:01 – 3/31/05 06:21.**

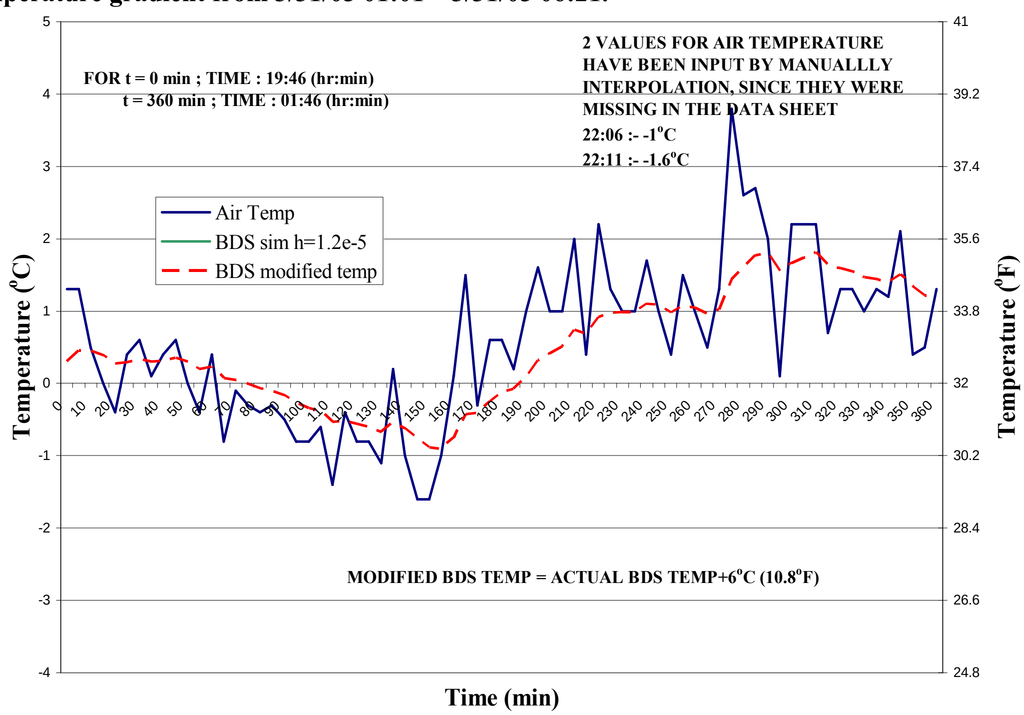



**Figure 175. Validation of h value of BDS-Warren County (Site 59) for 1.4C°/hr (2.5F°/hr) temperature gradient from 2/11/05 19:46 – 2/12/05 01:46.**

Figure 176 and Figure 176 show the simulation results for -3C°/hr (-5.6F°/hr) temperature gradient for cooling and 1.4C°/hr (2.5F°/hr) temperature gradient for warming for the bridge.

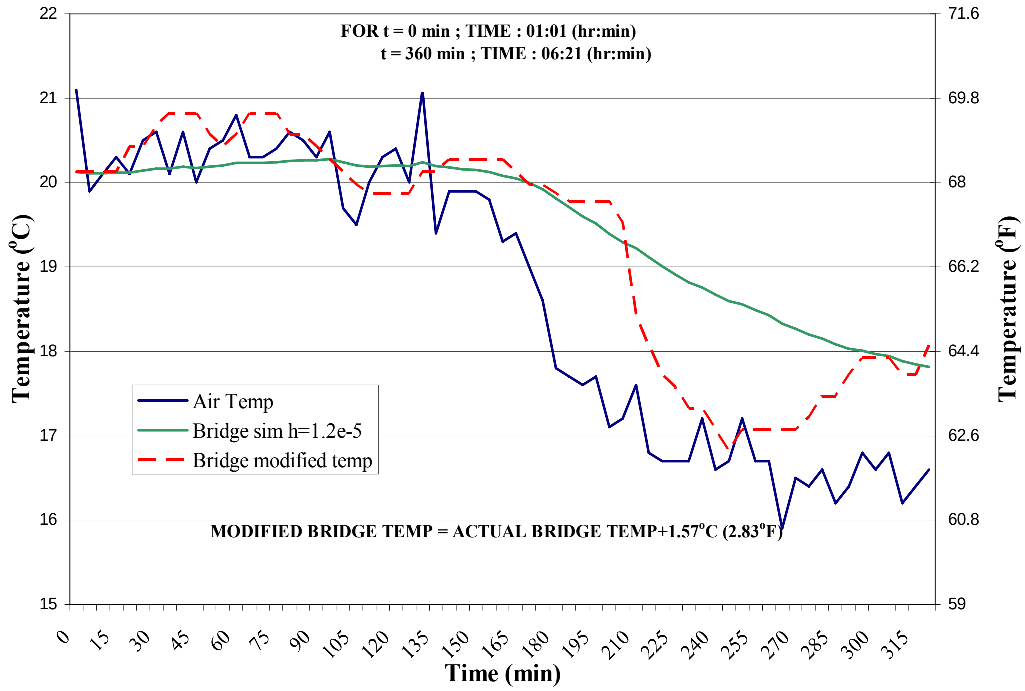



**Figure 176. Validation of h value for bridge-Warren County (Site 59) for -3C°/hr (-5.6F°/hr) temperature gradient from 3/31/05 01:01 – 3/31/05 06:21.**

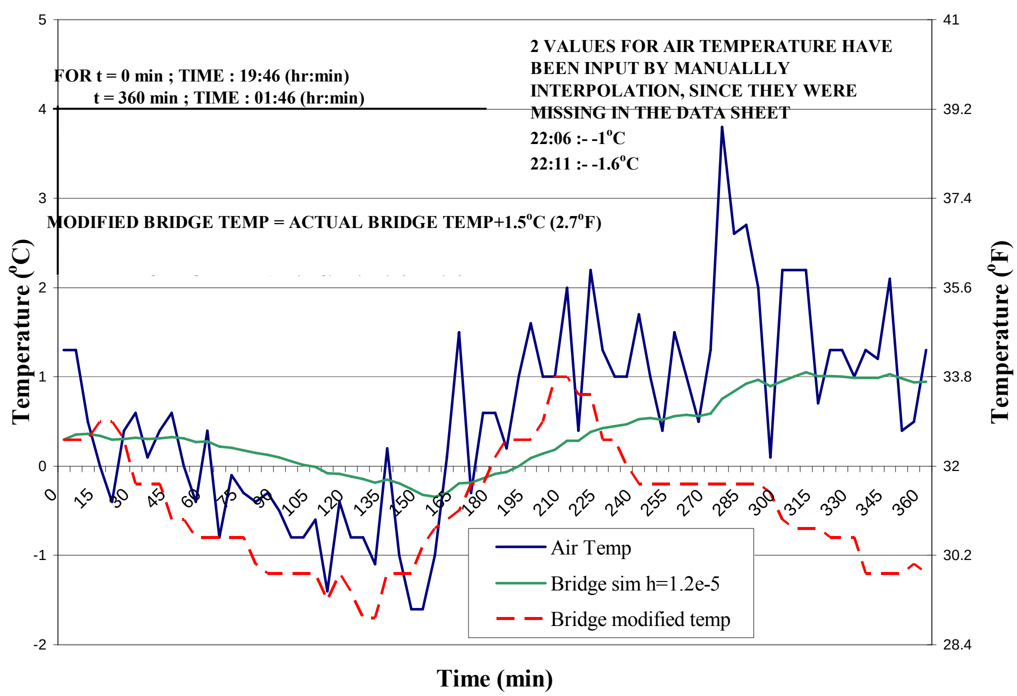



**Figure 177. Validation of h value for bridge-Warren County (Site 59) for 1.4C°/hr (2.5F°/hr) temperature gradient from 2/11/05 19:46 – 2/12/05 01:46.**

### 13.7.4 Summit County (Site 68)

Figure 178 shows the histogram plot for temperature gradients at night time.

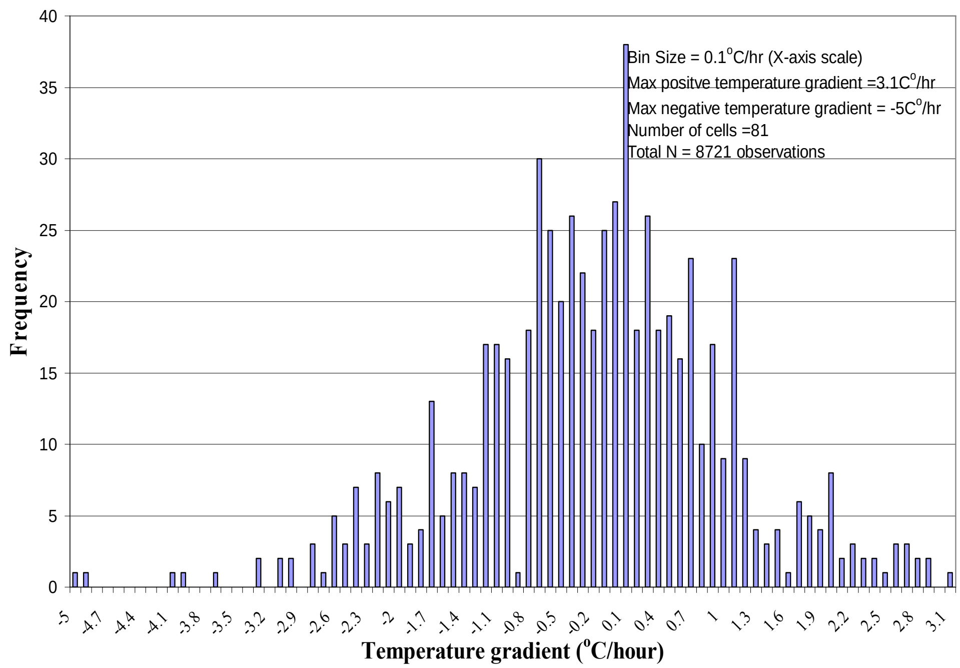



**Figure 178. Hourly temperature gradient for Site 68 – Summit County (Night time data only) from January 21 – April 5, 2005.**

Figure 179 and Figure 180 show actual recorded temperature data for -4.9C°/hr (-8.8F°/hr) temperature gradient for cooling and 2.9C°/hr (5.2F°/hr) temperature gradient for warming respectively. During the cooling gradient, the bridge deck simulator temperature was modified by adding 2.50C° (4.50F°), and the bridge temperature was not modified. The BDS and bridge temperatures during simulation of the warming gradient were modified by adding 6.50C° (11.70F°) and 4.50C° (8.10F°), respectively. The cooling gradient simulation period was from 19:56 to 4:56, or 540 minutes, while that for the warming gradient was from 20:01 to 1:26, or 325 minutes.

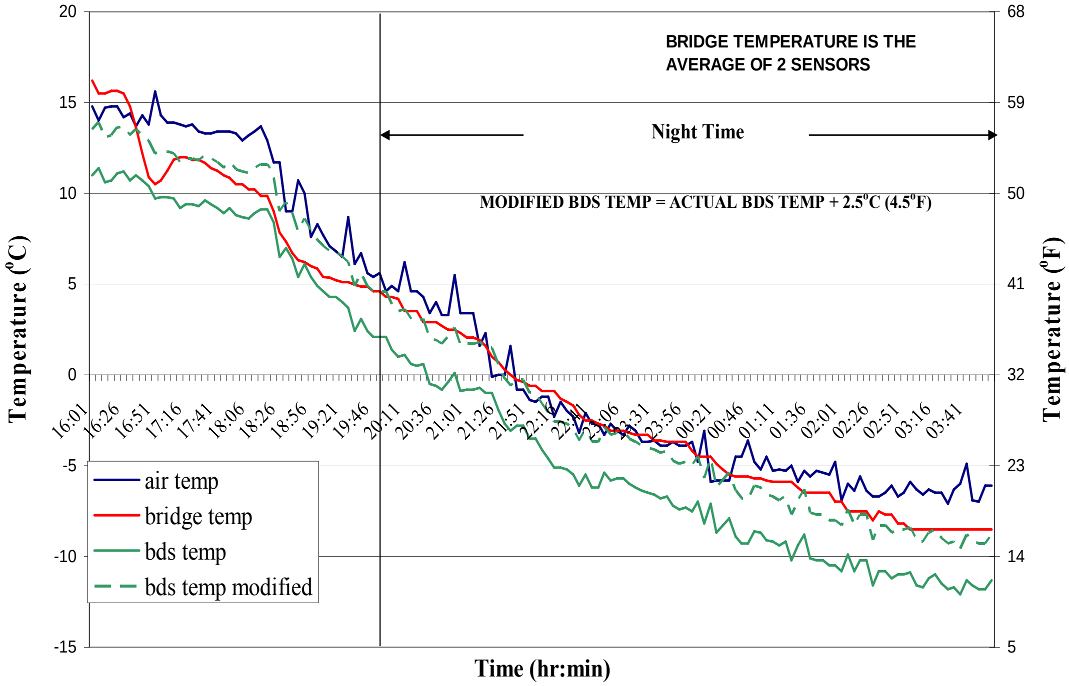



**Figure 179. Data containing the -4.9C°/hr (-8.8F°/hr) temperature gradient for Summit County (Site 68) from 3/7/05 16:01 – 3/8/05 04:01.**

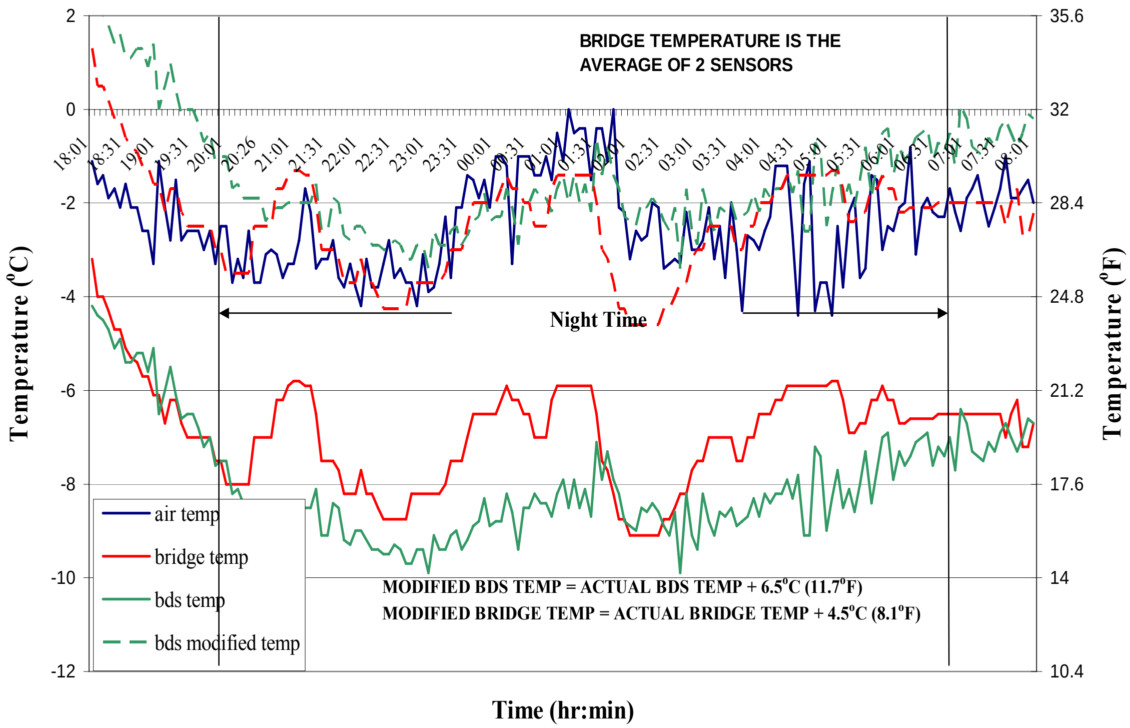



**Figure 180. Data containing the 2.9C°/hr (5.2F°/hr) temperature gradient for Summit County (Site 68) from 3/11/05 18:01 – 3/12/05 08:01.**

Figure 181 and Figure 182 show the simulation results for -4.9C°/hr (-8.8F°/hr) temperature gradient for cooling and 2.9C°/hr (5.2F°/hr) temperature gradient for warming for the BDS.

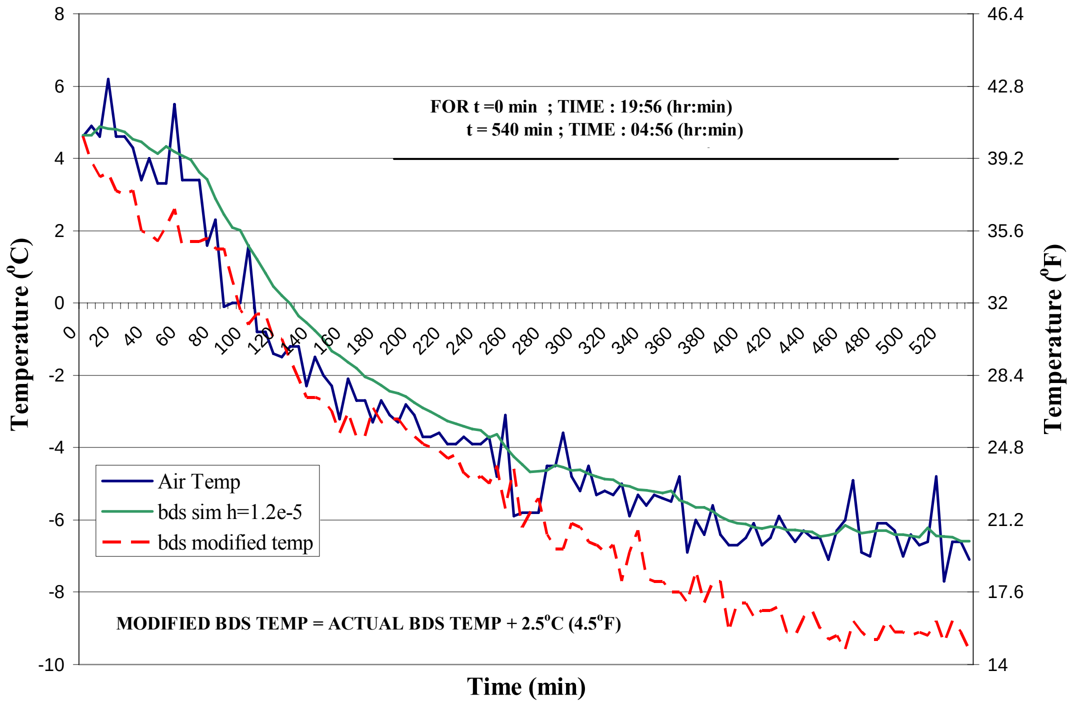



**Figure 181. Validation of h value of BDS-Summit County (Site 68) for -4.9C°/hr (-8.8F°/hr) temperature gradient from 3/7/05 19:56 – 3/8/05 04:56.**

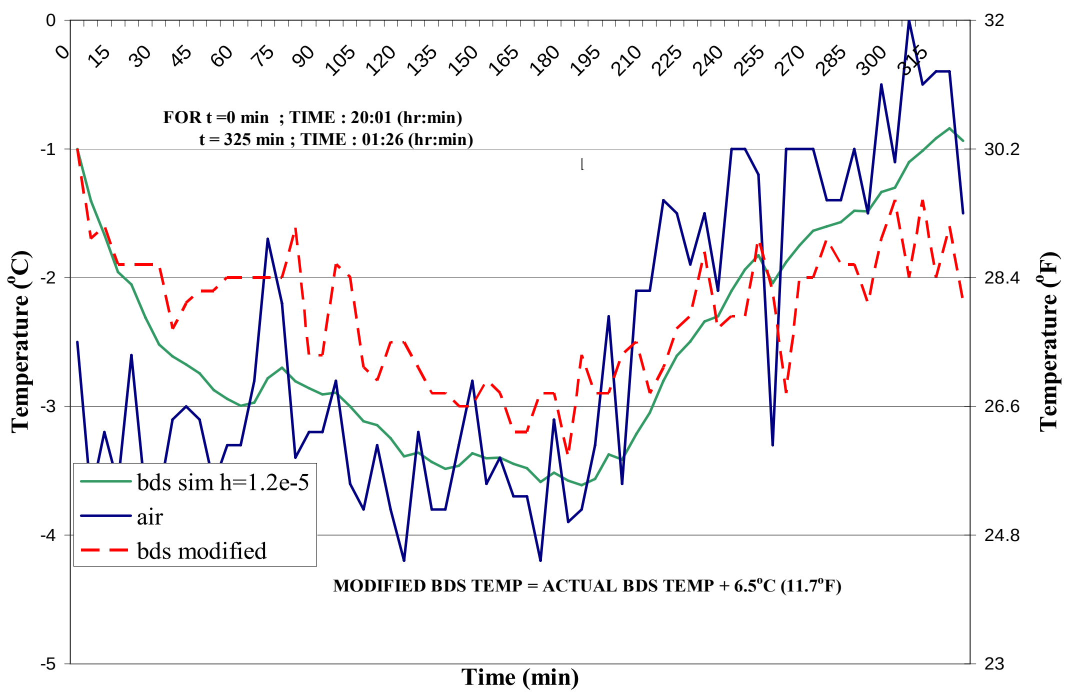



**Figure 182. Validation of h value of BDS-Summit County (Site 68) for 2.9C°/hr (5.2F°/hr) temperature gradient from 3/11/05 20:01 – 3/12/05 01:26.**

Figure 183 and Figure 184 show the simulation results for -4.9C°/hr (-8.8F°/hr) temperature gradient for cooling and 2.9C°/hr (5.2F°/hr) temperature gradient for warming of the bridge.

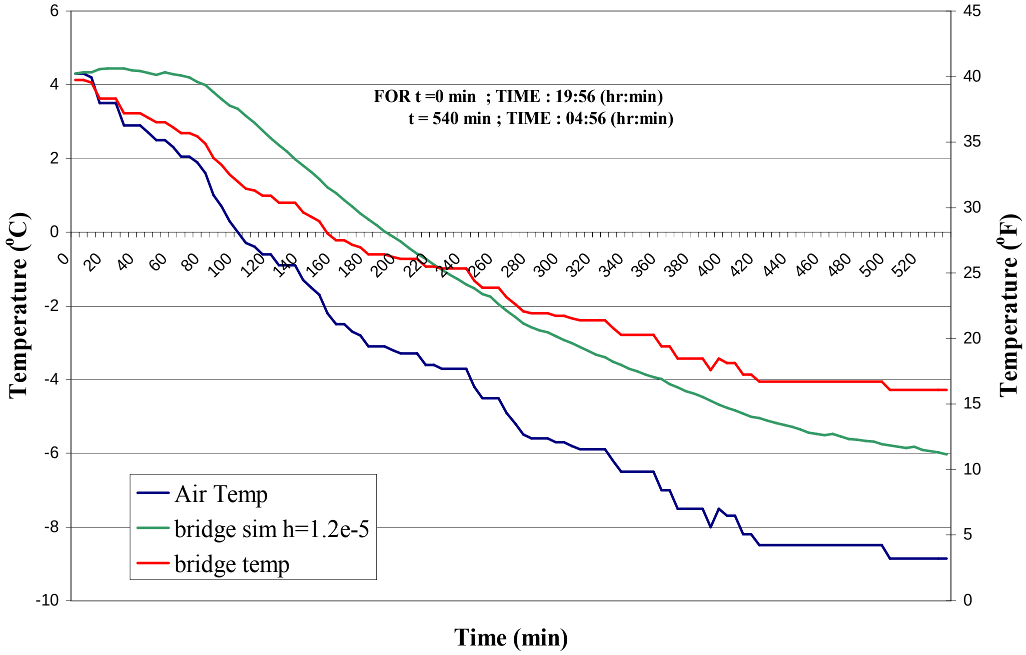



**Figure 183. Validation of h value of bridge-Summit County (Site 68) for -4.9C°/hr (-8.8F°/hr) temperature gradient from 3/7/05 19:36 – 3/8/05 04:56.**

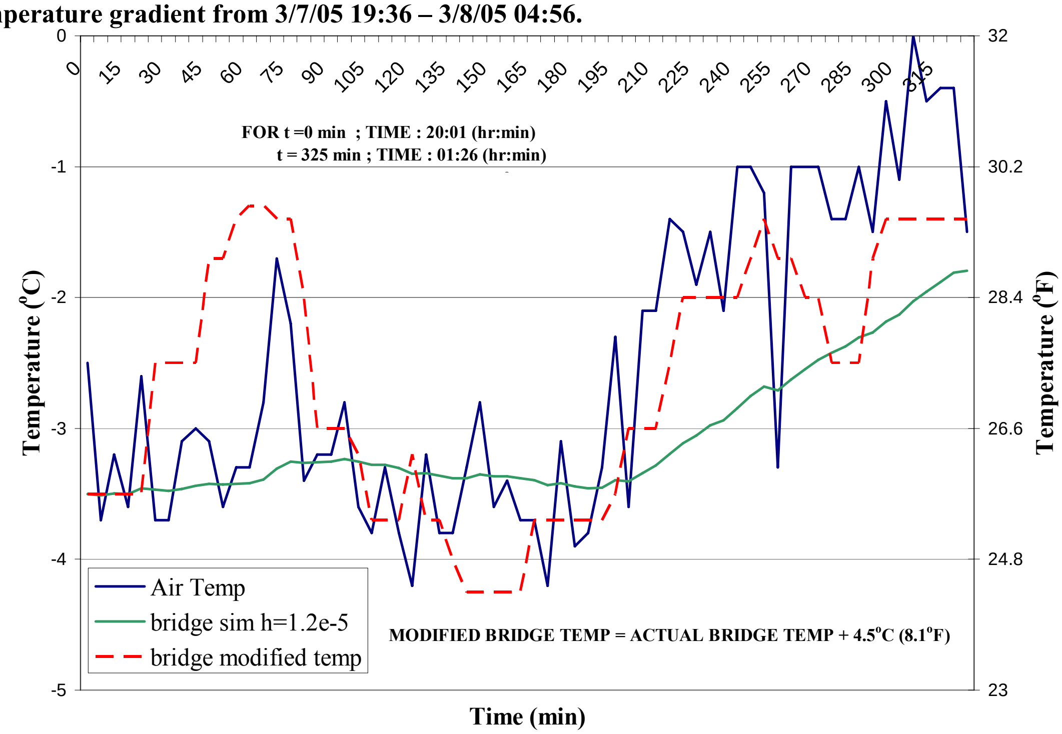



**Figure 184. Validation of h value of bridge-Summit County (Site 68) for 2.9C°/hr (5.2F°/hr) temperature gradient.**

### 13.7.5 Hamilton County (Site 69)

Figure 185 shows the histogram plot for temperature gradients at night time.

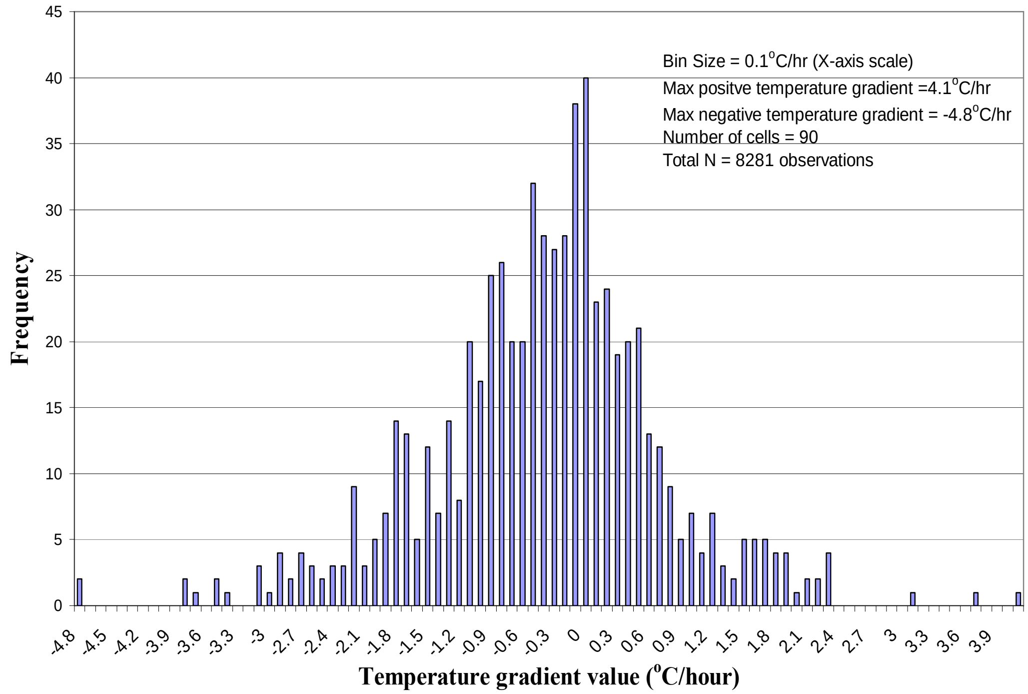



**Figure 185. Hourly temperature gradient for Site 69 – Hamilton County (Night time data only) from January 21 – April 5, 2005.**

Figure 185 and Figure 187 show actual recorded temperature data for -4.8C°/hr (-8.4F°/hr) temperature gradient for cooling and 4.1C°/hr (7.4F°/hr) temperature gradient for warming respectively. During the cooling gradient the temperatures were used without modification, while for the warming gradient the BDS and bridge temperatures were modified by adding 3.90C° (7.02F°) and 2.68C° (4.84F°), respectively. The simulation during the cooling gradient lasted from 1:56 to 6:16,or 260 minutes, while that for the warming gradient lasted from 0:11 to 6:21, or 370 minutes.

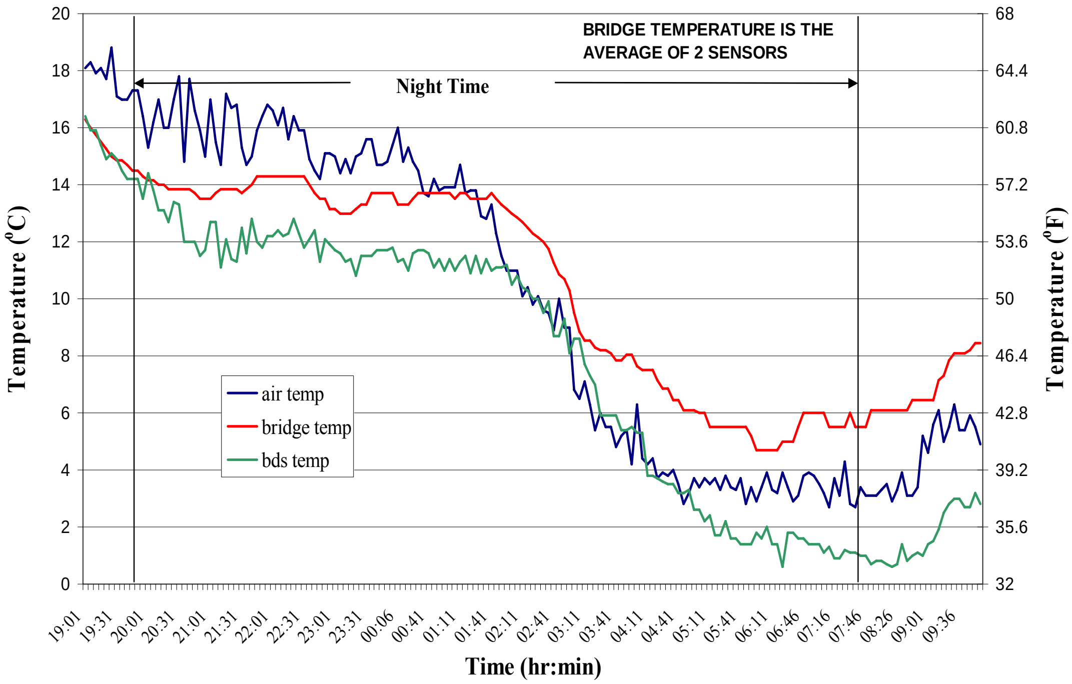



**Figure 186. Data containing the -4.8C°/hr (-8.4F°/hr) temperature gradient for Hamilton County (Site 69) from 2/15/05 19:01 – 2/16/05 09:56.**

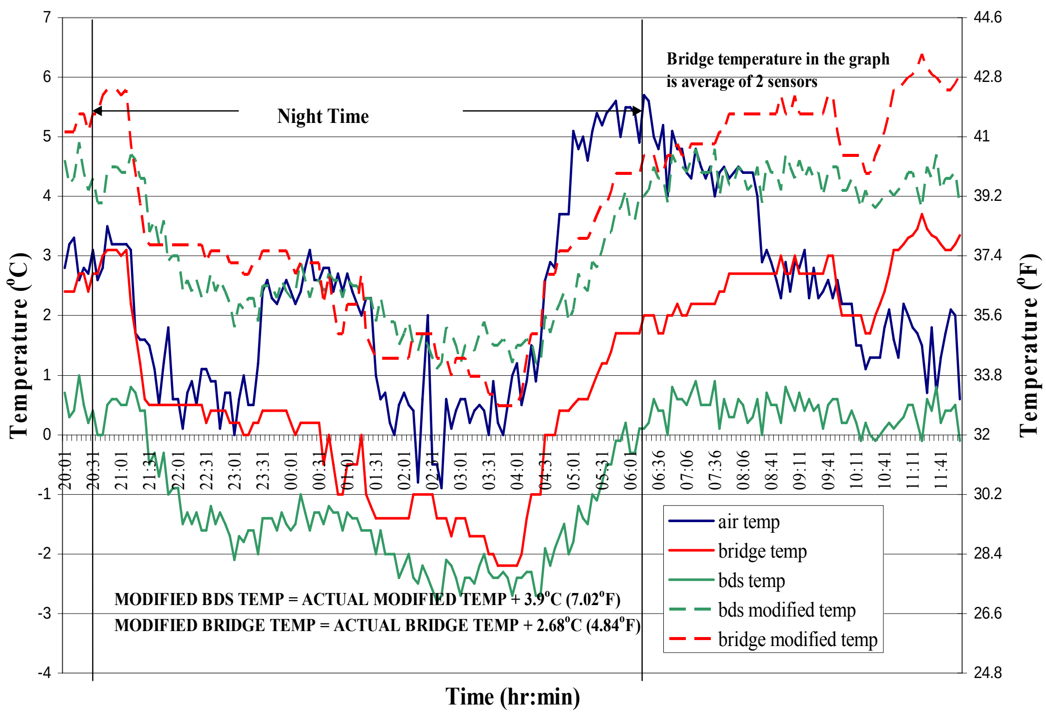



**Figure 187. Data containing the 4.1C°/hr (7.4F°/hr) temperature gradient for Hamilton County (Site 69) from 3/10/05 20:01 – 3/11/05 12:01.**

Figure 188 and Figure 189 show the simulation results for -4.8C°/hr (-8.4F°/hr) temperature gradient for cooling and 4.1C°/hr (7.4F°/hr) temperature gradient for warming for the BDS.

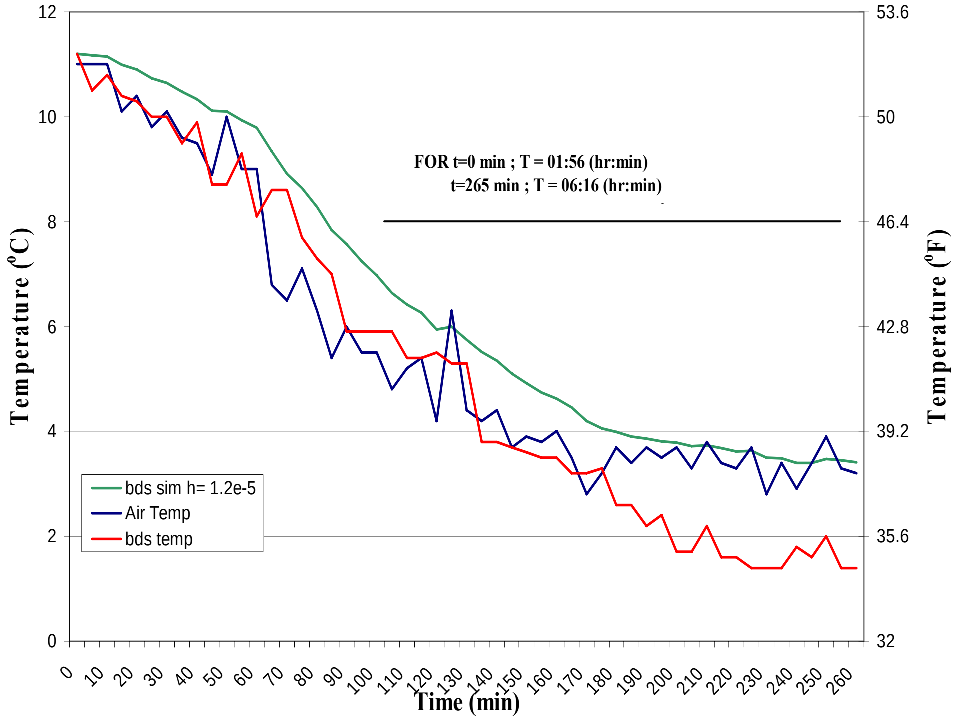



**Figure 188. Validation of h value of BDS- Hamilton County (Site 69) for -4.8C°/hr (-8.4F°/hr) temperature gradient from 2/16/05 01:56 – 2/16/05 06:16.**

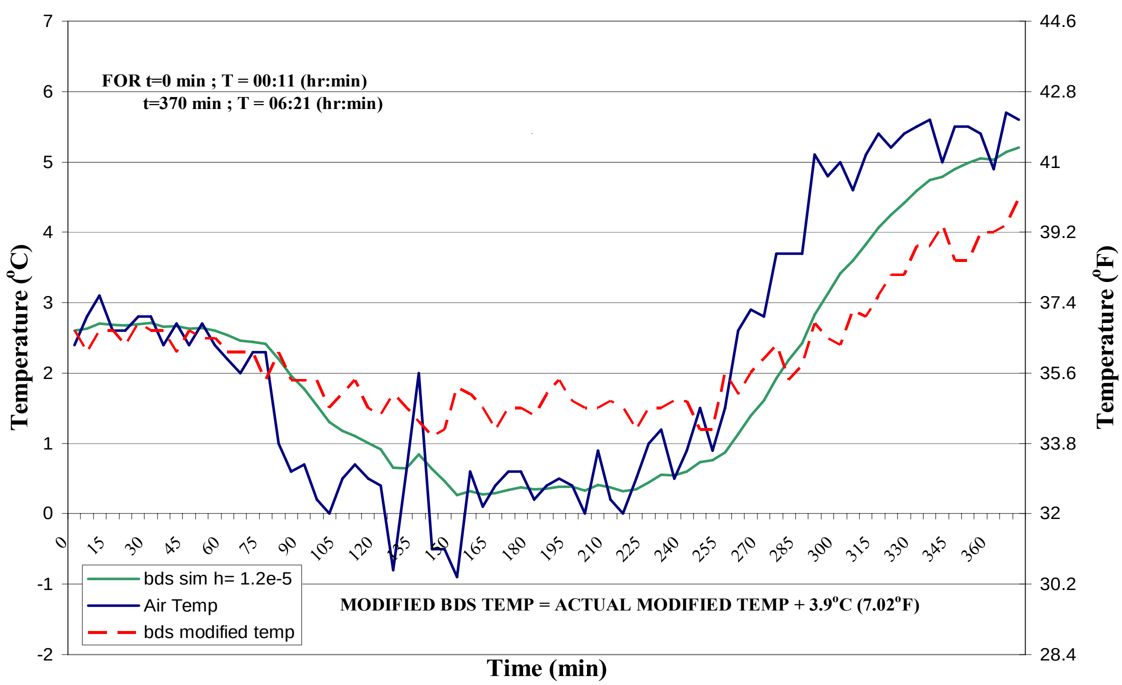



**Figure 189. Validation of h value of BDS- Hamilton County (Site 69) for 4.1C°/hr (7.4F°/hr) temperature gradient from 3/11/05 00:11 – 3/11/05 06:21.**

Figure 190 and Figure 191 show the simulation results for -4.8C°/hr (-8.4F°/hr) temperature gradient for cooling and 4.1C°/hr (7.4F°/hr) temperature gradient for warming for the bridge.

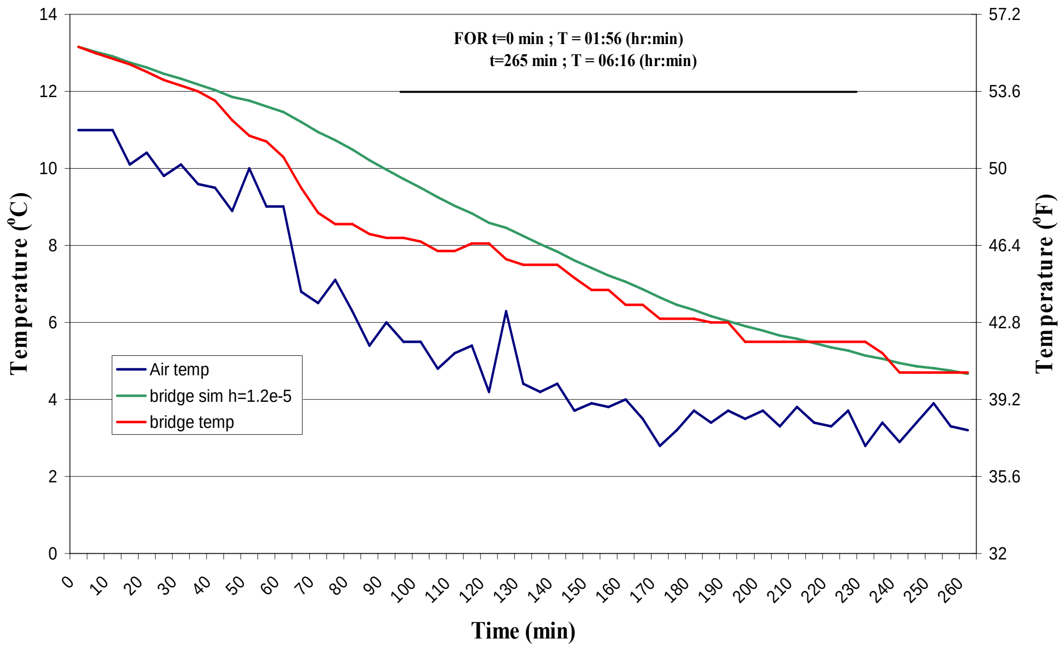



**Figure 190. Validation of h value for bridge- Hamilton County (Site 69) for -4.8C°/hr (-8.4F°/hr) temperature gradient from 2/16/05 01:56 – 2/16/05 06:16.**

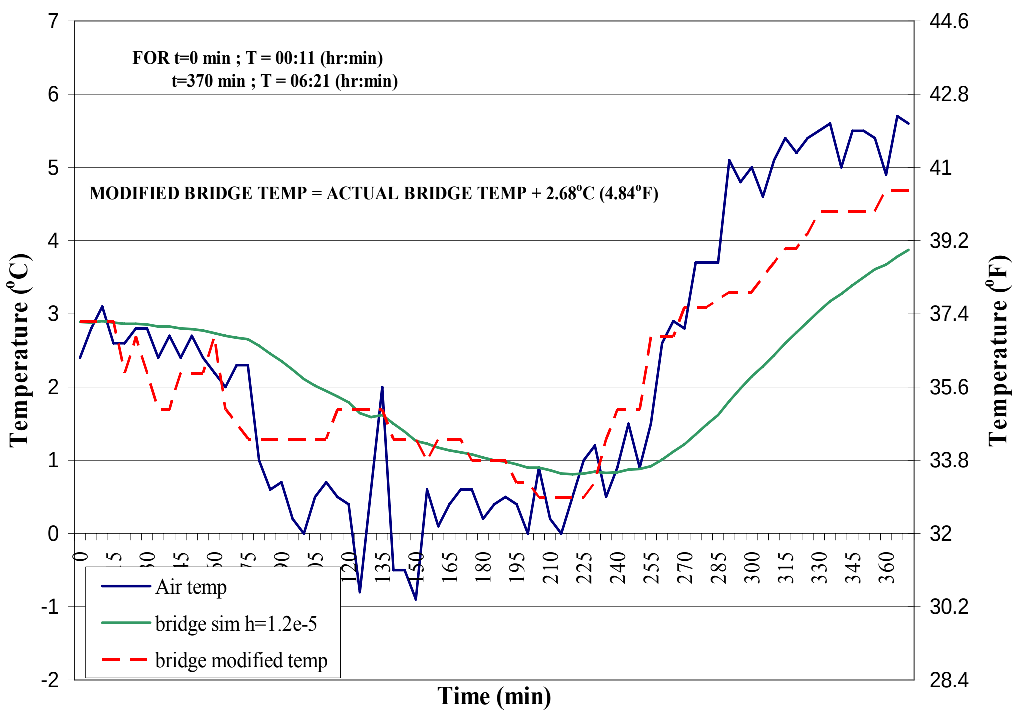



**Figure 191. Validation of h value for bridge- Hamilton County (Site 69) for 4.1C°/hr (7.4F°/hr) temperature gradient from 3/11/05 00:11 – 3/11/05 06:26.**

### 13.7.6 Hamilton/Clermont County line (Site 70)

Figure 192 shows the histogram plot for temperature gradients at night time.

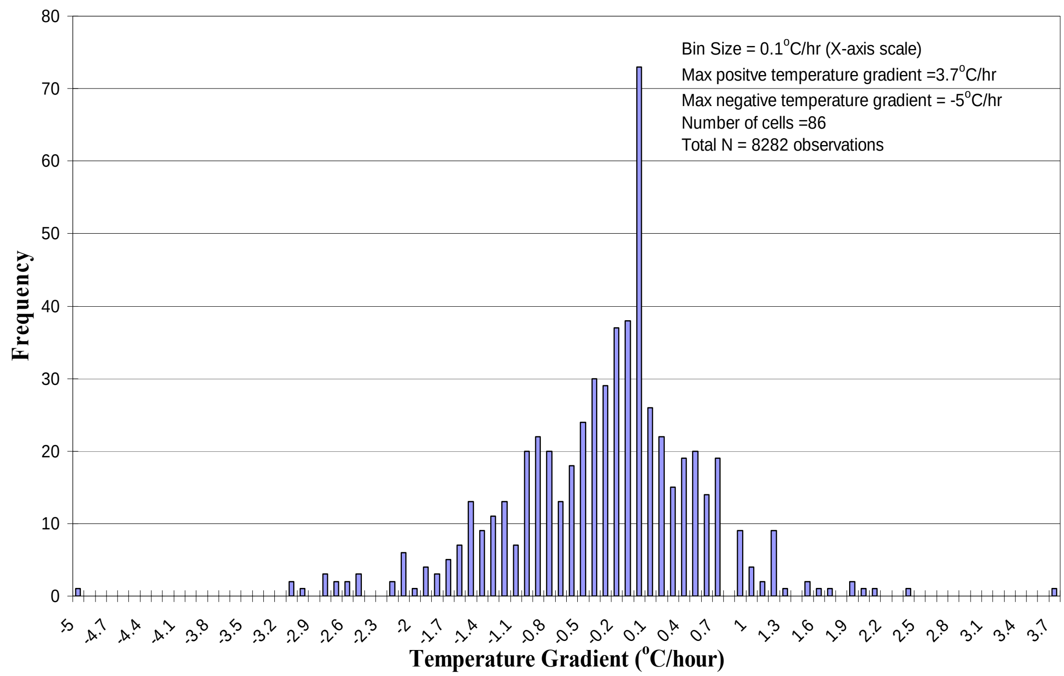



**Figure 192. Hourly temperature gradient for Site 70 – Hamilton County (Night time data only) from January 21 – April 5, 2005.**

Figure 193 and Figure 194 show actual recorded temperature data for -5C°/hr (-9F°/hr) temperature gradient for cooling and 3.7C°/hr (6.7F°/hr) temperature gradient for warming respectively. During the cooling gradient, the temperature modifications for BDS and bridge are 2.88C° (5.20F°) and 1.33C° (2.39F°), respectively. During the warming gradient the BDS temperature was modified by adding 2.01C° (3.62F°) and the bridge temperature was unmodified. The simulation during the cooling gradient encompassed the 240 minutes from 1:56 to 5:56, while that for the warming gradient covered the 390 minutes from 0:11 to 6:41.

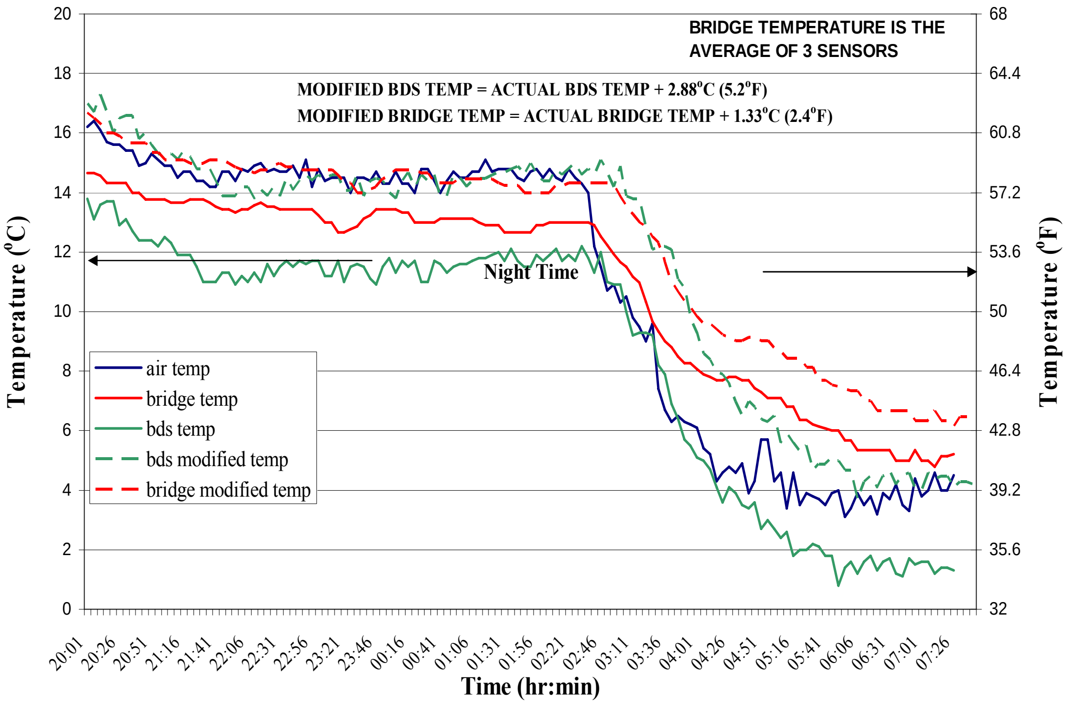



**Figure 193. Data containing the -5C°/hr (-9F°/hr) temperature gradient for Hamilton County (Site 70) from 2/15/05 19:46 – 2/16/05 07:26.**

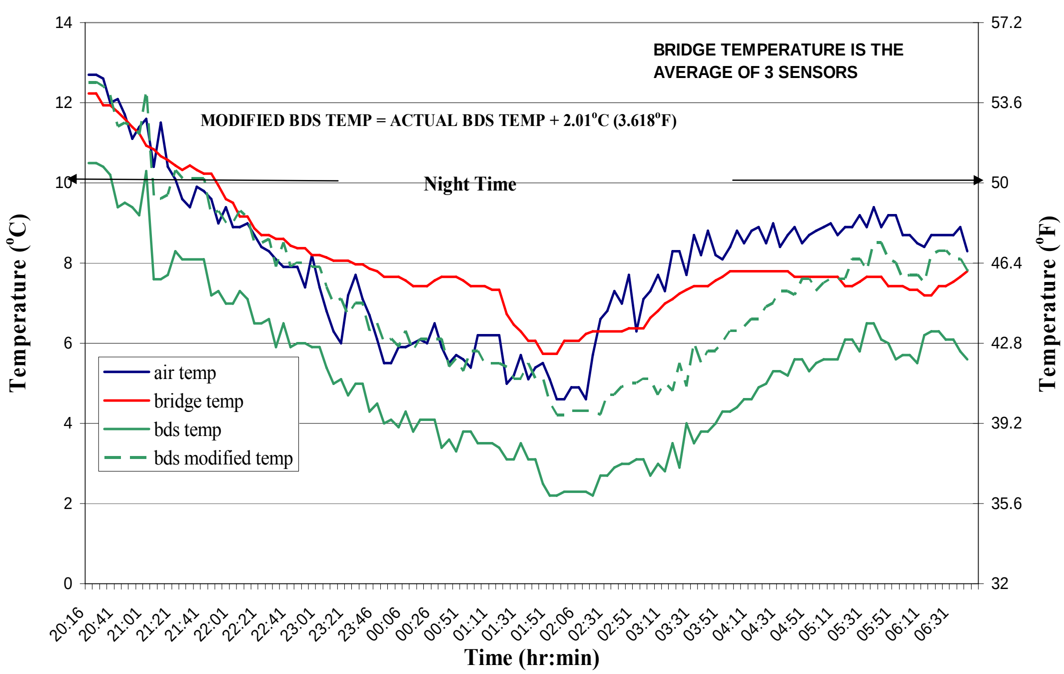



**Figure 194. Data containing the 3.7C°/hr (6.7F°/hr) temperature gradient for Hamilton County (Site 70) from 3/18/06 20:16 – 3/19/05 06:41.**

Figure 195 and Figure 196 show the simulation results for -5C°/hr (-9F°/hr) temperature gradient for cooling and 3.7C°/hr (6.7F°/hr) temperature gradient for warming for the BDS.

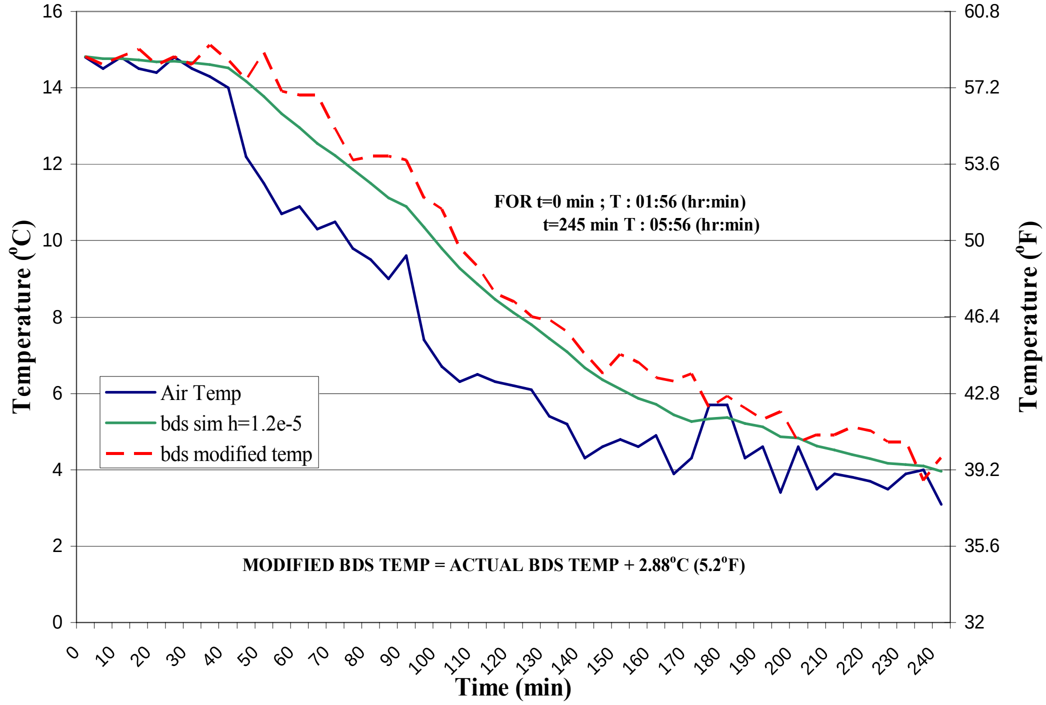



**Figure 195. Validation of h value for BDS-Hamilton County (Site 70) for -5C°/hr (-9F°/hr) temperature gradient from 2/16/05 01:56 – 2/16/05 05:56.**

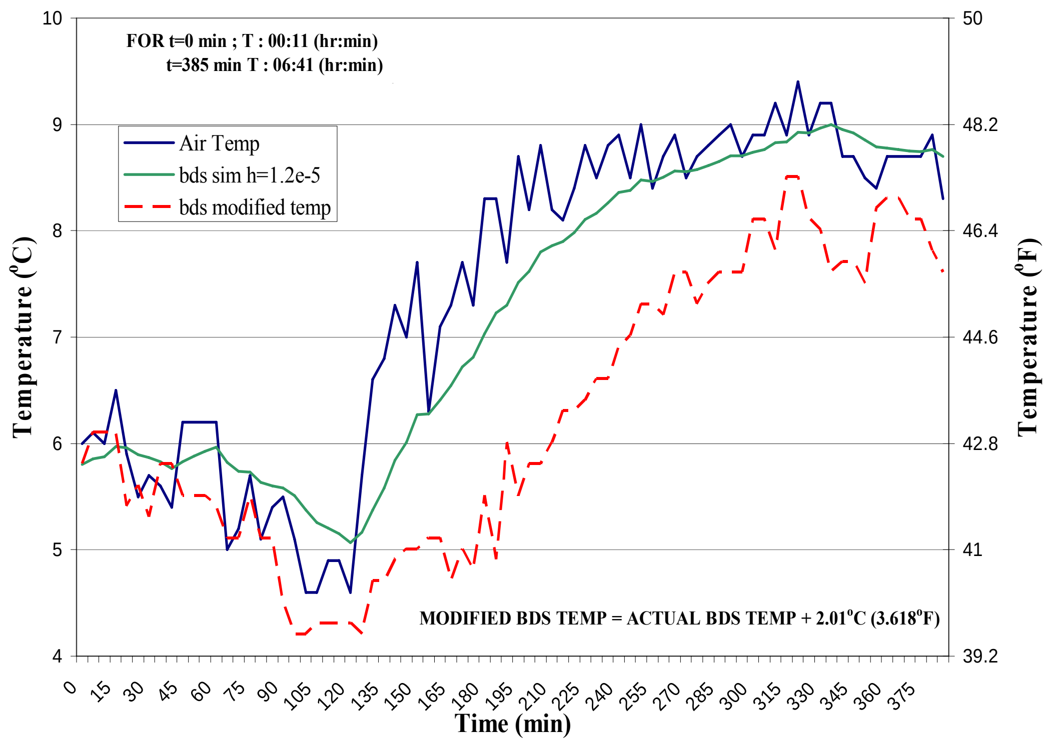



**Figure 196. Validation of h value for BDS-Hamilton County (Site 70) for 3.7C°/hr (6.7F°/hr) temperature gradient from 3/19/05 00:11 – 3/19/05 06:41.**

Figure 197 and Figure 198 show the simulation results for the -5C°/hr (-9F°/hr) temperature gradient for cooling and the 3.7C°/hr (6.7F°/hr) temperature gradient for warming for the bridge.

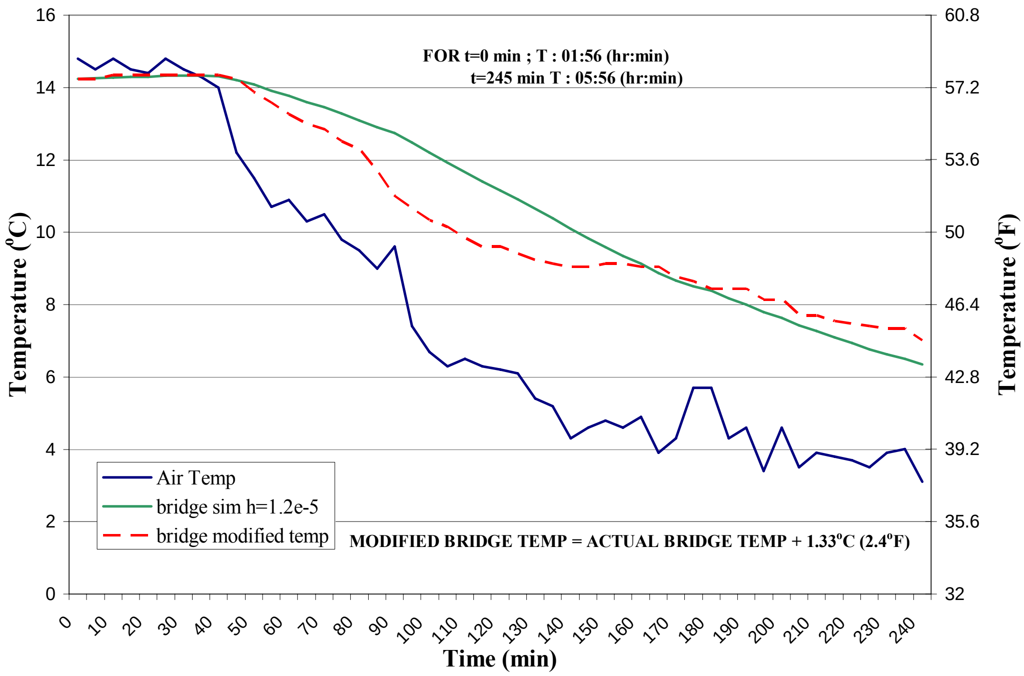



**Figure 197. Validation of h value for bridge-Hamilton County (Site 70) for -5C°/hr (-9F°/hr) temperature gradient from 2/16/05 01:56 – 2/16/05 05:56.**

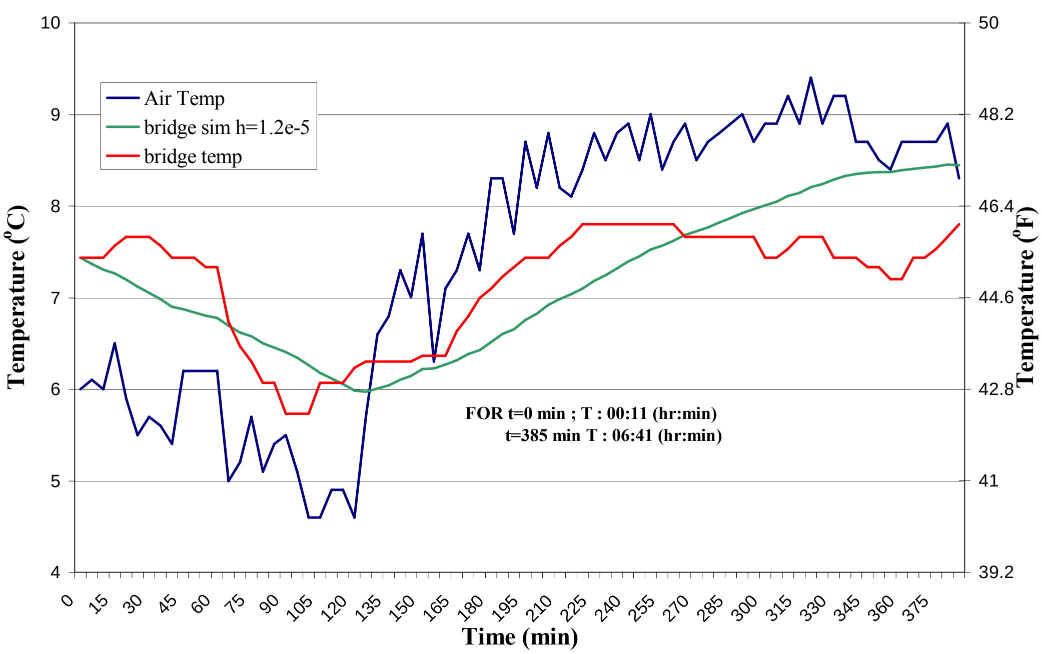



**Figure 198. Validation of h value for bridge-Hamilton County (Site 70) for 3.7C°/hr (6.7F°/hr) temperature gradient from 3/19/05 00:11 – 3/19/05 06:41.**

## 13.7.7 Lorain County

Figure 199 shows the histogram plot for temperature gradients at night time at Site 86 in Lorain County.

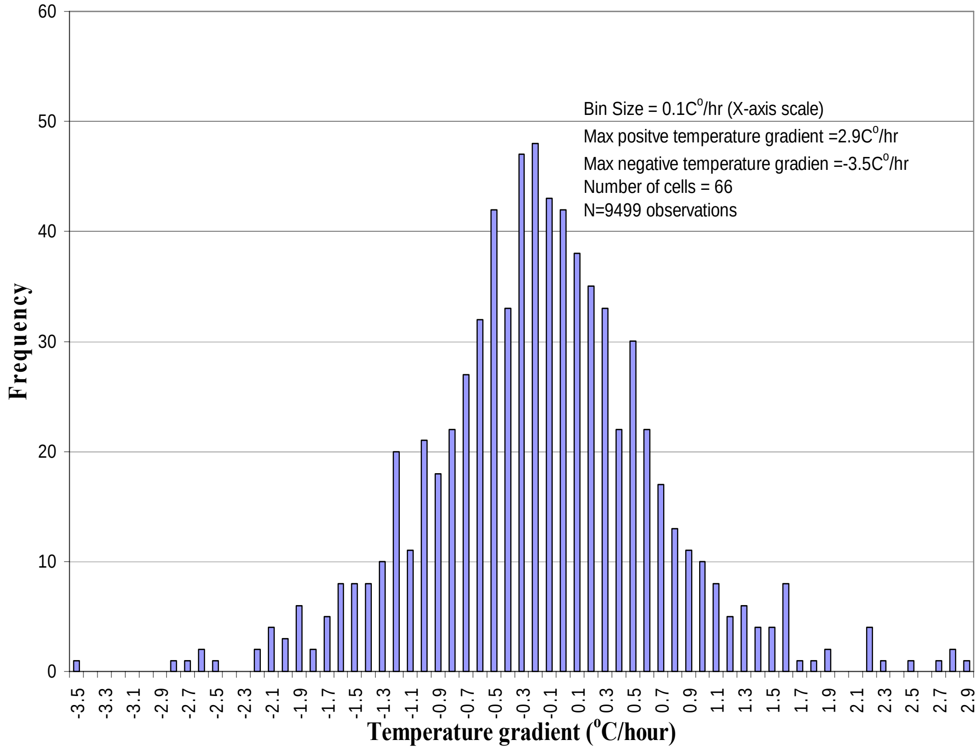



**Figure 199. Hourly temperature gradient for Site 86 – Lorain County (Night time data only) from January 21 – April 5, 2005.**

Figure 200 and Figure 201 show actual recorded temperature data for -3.5C°/hr (-6.3F°/hr) temperature gradient for cooling and 2.9C°/hr (5.2F°/hr) temperature gradient for warming respectively. None of the temperatures were modified. The simulation during the cooling gradient lasted from 20:01 to 6:51, or 650 minutes; that for the warming gradient lasted from 22:21 to 5:21, or 420 minutes (it is incorrectly reported in the figure).

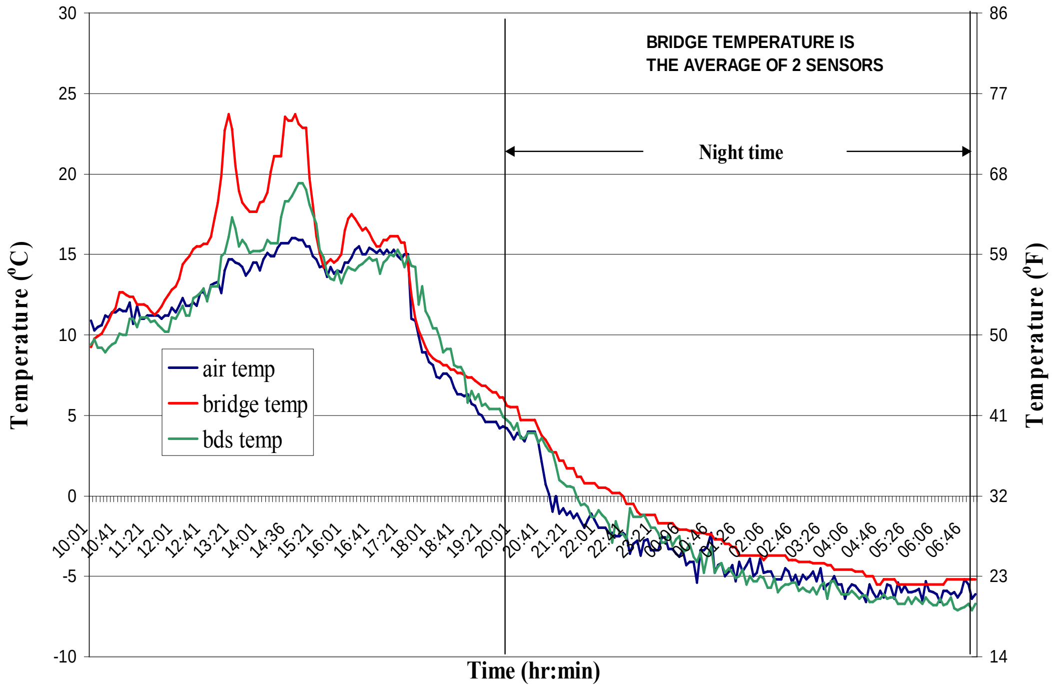



**Figure 200. Data containing the -3.5C°/hr (-6.3F°/hr) temperature gradient for Lorain County (Site 86) from 3/7/05 10:01 – 3/8/05 07:01.**

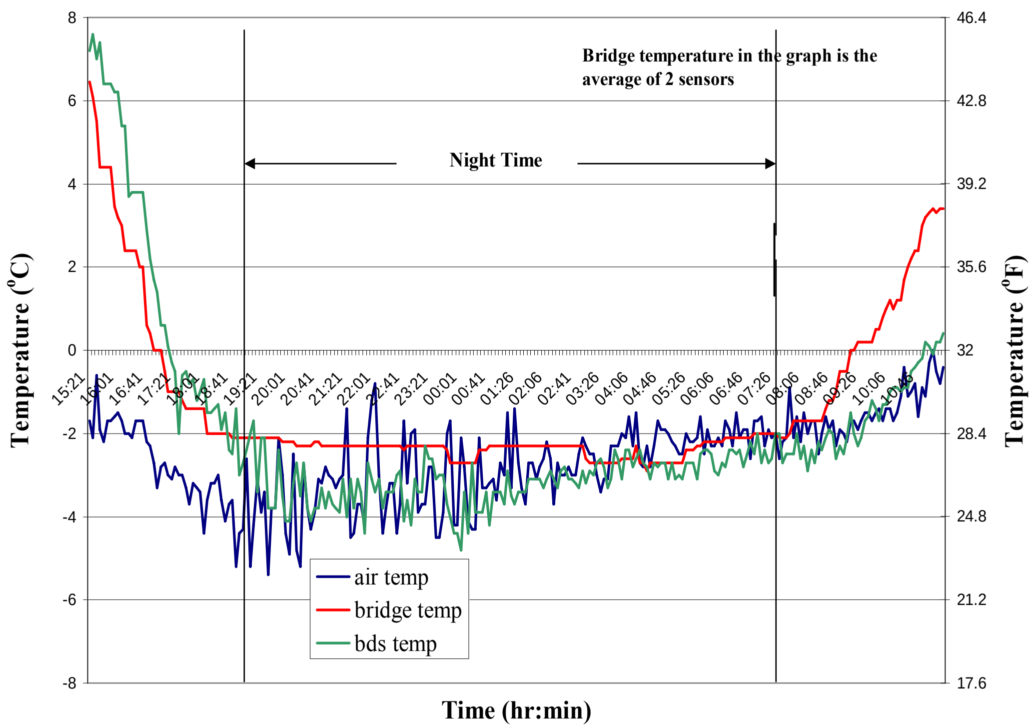



**Figure 201. Data containing the 2.9C°/hr (5.2F°/hr) temperature gradient for Lorain County (Site 86) from 2/2/05 15:21 – 2/3/05 11:21.**

Figure 202 and Figure 203 show the simulation results for -3.5C°/hr (-6.3F°/hr) temperature gradient for cooling and 2.9C°/hr (5.2F°/hr) temperature gradient for of warming for the BDS.

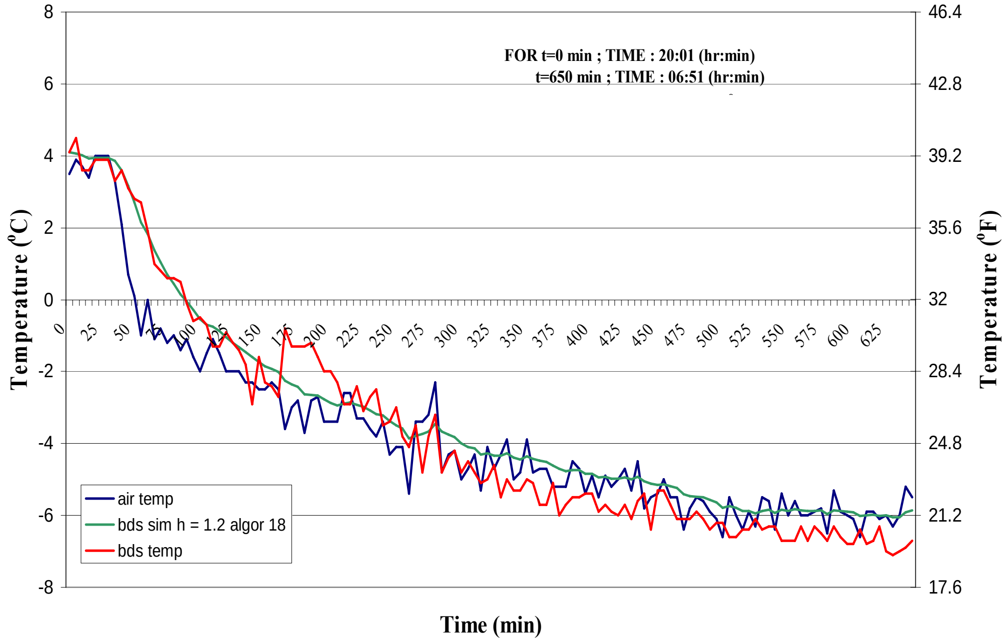



**Figure 202. Validation of h value of BDS-Lorain County (Site 86) for -3.5C°/hr (-6.3F°/hr) temperature gradient from 3/7/05 20:01 – 3/8/05 06:51.**

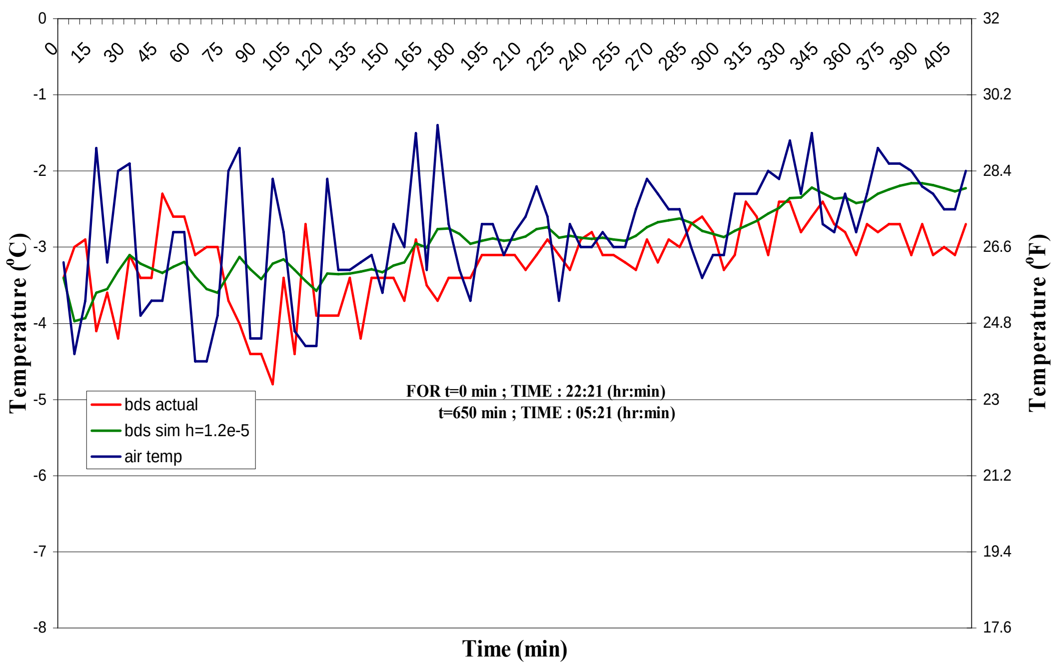



**Figure 203. Validation of h value of BDS-Lorain County (Site 86) for 2.9C°/hr (5.2F°/hr) temperature gradient from 2/2/05 22:21 – 2/3/05 05:21.**

Figure 204 shows the simulation results for 2.9C°/hr (5.2F°/hr) temperature gradient for warming of the bridge.

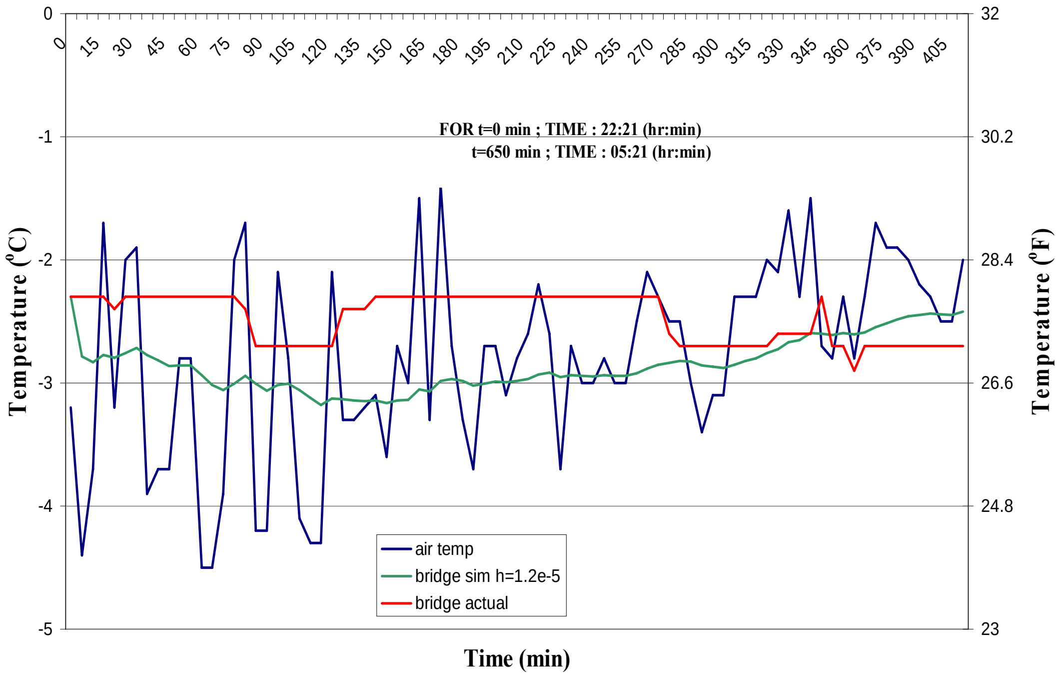



**Figure 204. Validation of h value of bridge-Lorain County (Site 86) for 2.9C°/hr (5.2F°/hr) temperature gradient from 2/2/05 22:21 – 2/3/05 05:21.**

### 13.7.8 Ashtabula County

Figure 205 shows the histogram plot for temperature gradients at nighttime for Site 88 in Ashtabula County.

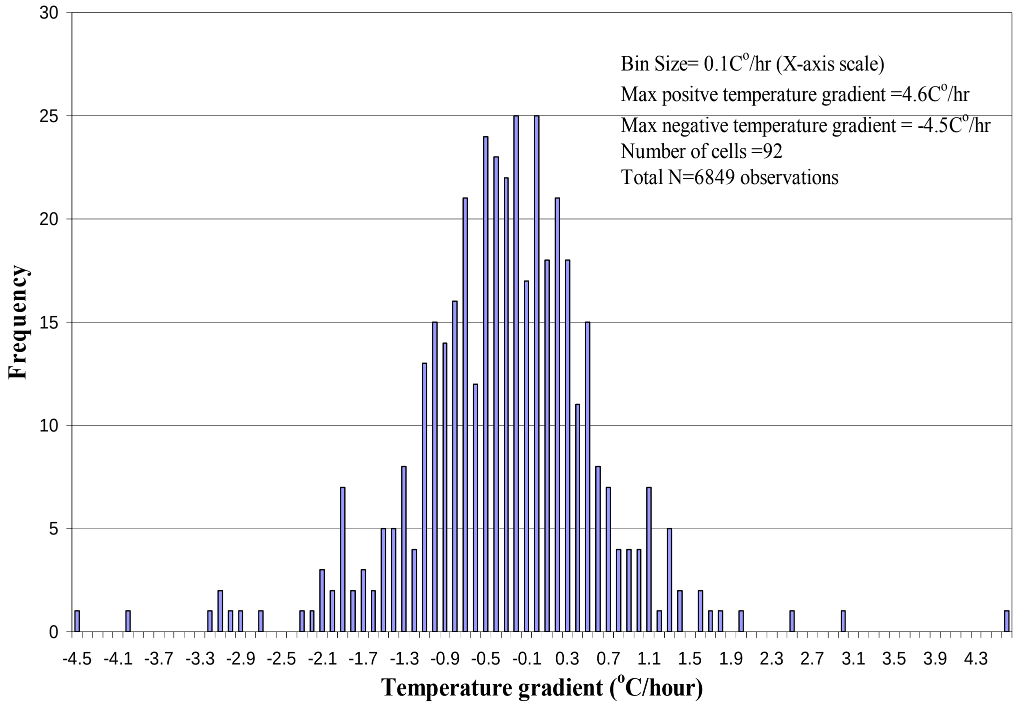



**Figure 205. Hourly temperature gradient for Site 88 – Ashtabula County (Night time data only) from January 21 – April 5, 2005.**

Figure 206 and Figure 207 show actual recorded temperature data for -4.5C°/hr (-8.1F°/hr) temperature gradient for cooling and 3C°/hr (5.4F°/hr) temperature gradient for warming respectively. The only temperature modification used was the addition of 2.50C° (4.50F°) to the BDS temperature during the warming gradient. The simulation during the cooling gradient covered the 250 minutes from 19:56 to 0:06, while the warming gradient simulation lasted from 22:06 to 2:21, or 255 minutes.

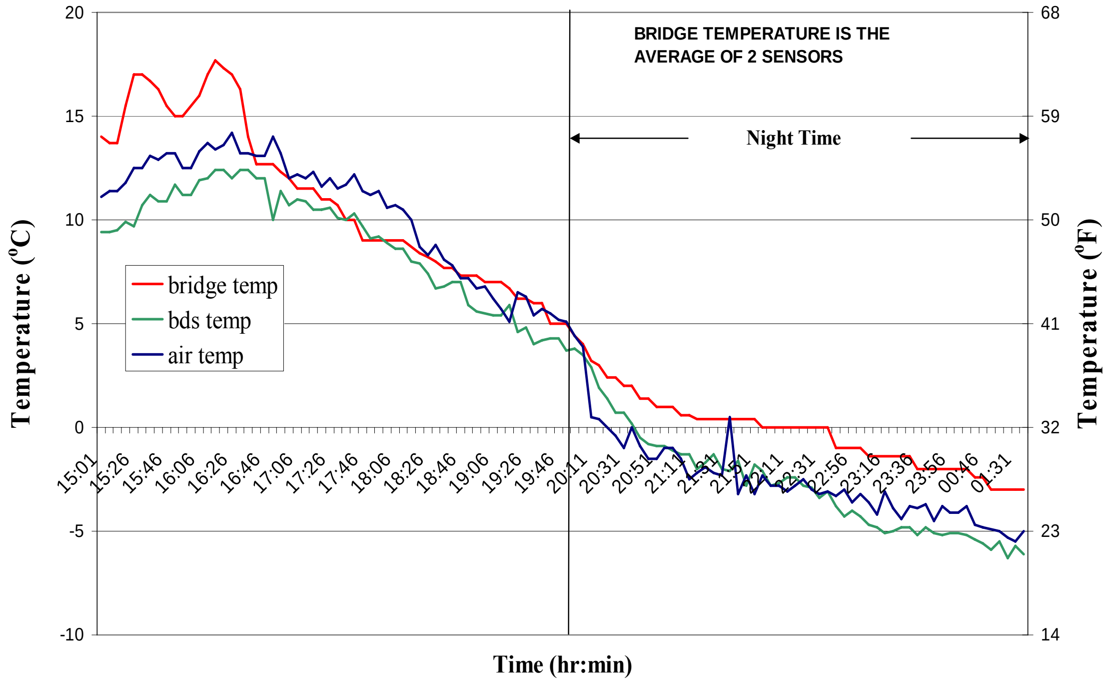



**Figure 206. Data containing the -4.5C°/hr (-8.1F°/hr) temperature gradient for Ashtabula County (Site 88) from 3/7/05 15:01 – 3/8/05 01:36.**

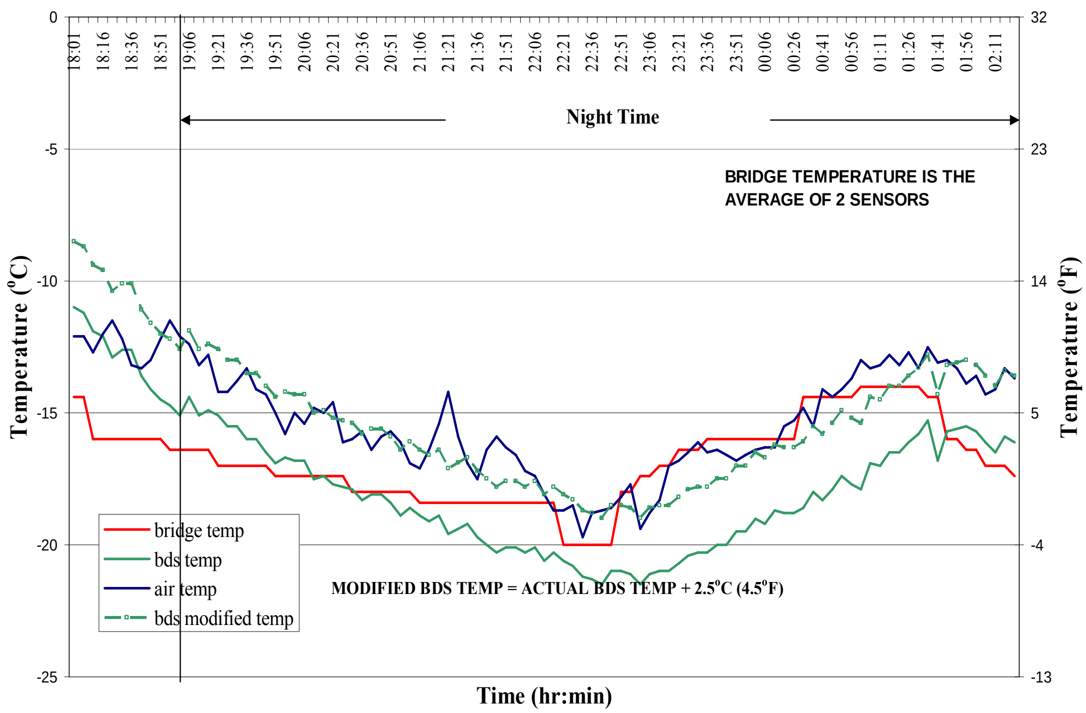



**Figure 207. Data containing the 3C°/hr (5.4F°/hr) temperature gradient for Ashtabula County (Site 88) from 1/23/05 18:01 – 1/24/05 02:21.**

Figure 208 and Figure 209 show the simulation results for -4.5C°/hr (-8.1F°/hr) temperature gradient for cooling and 3C°/hr (5.4F°/hr) temperature gradient for warming for the BDS.

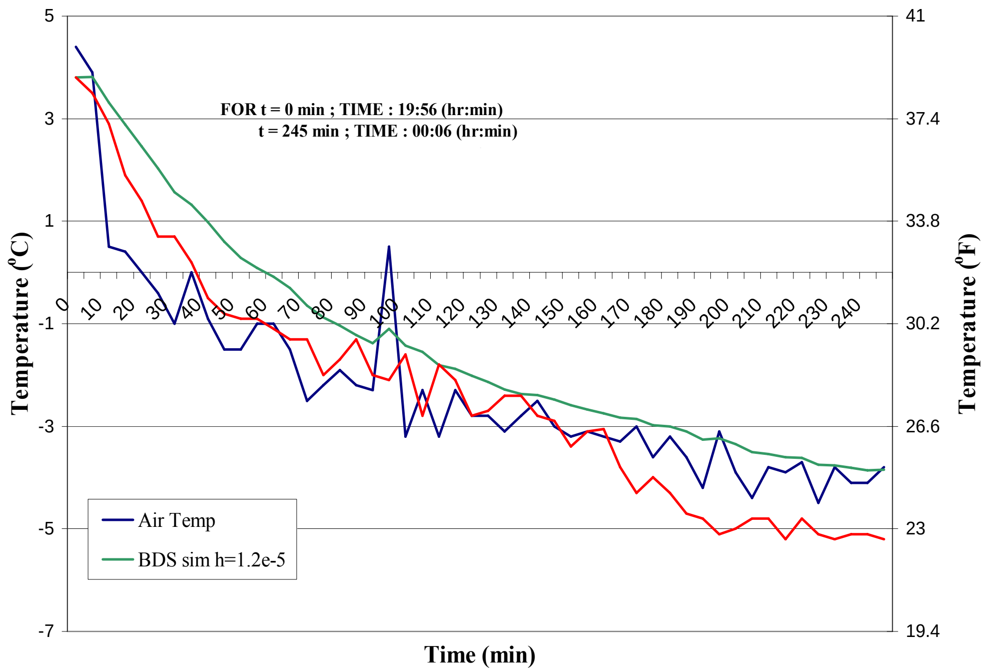



**Figure 208. Validation of h value of BDS-Ashtabula County (Site 88) for -4.5C°/hr (-8.1F°/hr) temperature gradient from 3/7/05 19:56 – 3/8/05 00:06.**

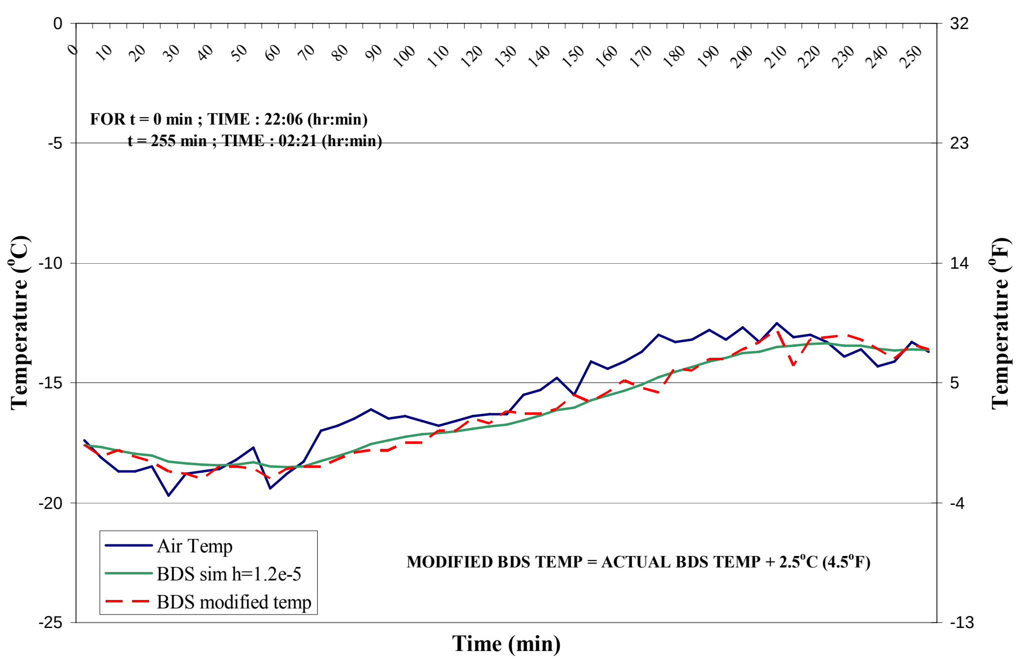



**Figure 209. Validation of h value of BDS-Ashtabula County (Site 88) for 3C°/hr (5.4F°/hr) temperature gradient from 1/23/05 22:06 – 1/24/05 02:21.**

Figure 210 and Figure 211 show the simulation results for -4.5C°/hr (-8.1F°/hr) temperature gradient for cooling and 3C°/hr (5.4F°/hr) temperature gradient for warming for the bridge.

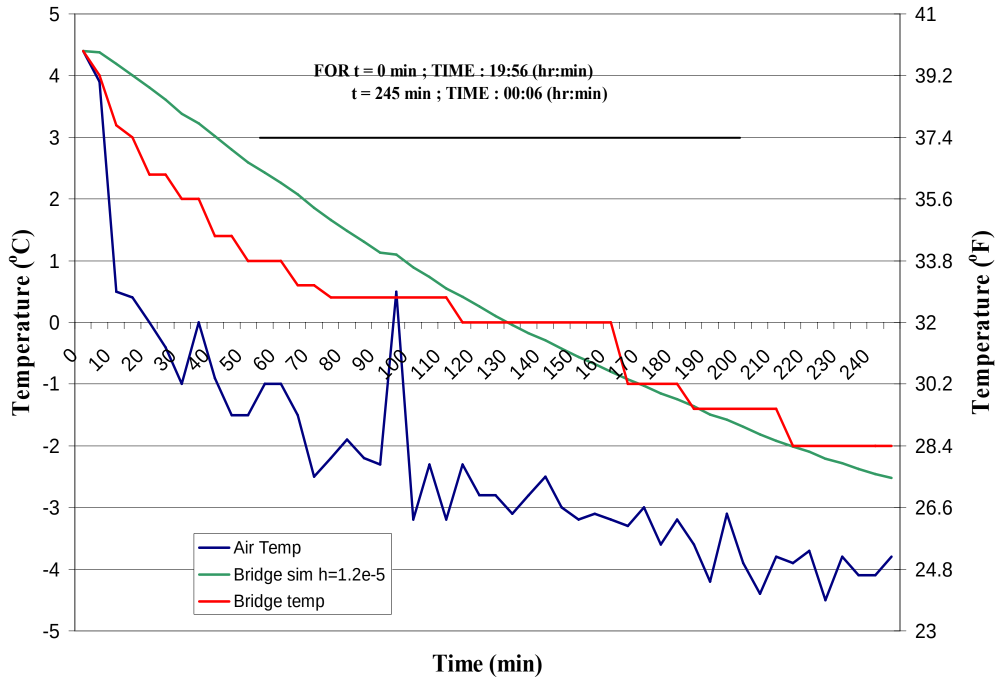



**Figure 210. Validation of h value of bridge-Ashtabula County (Site 88) for -4.5C°/hr (-8.1F°/hr) temperature gradient from 3/7/05 19:56 – 3/8/05 00:06.**

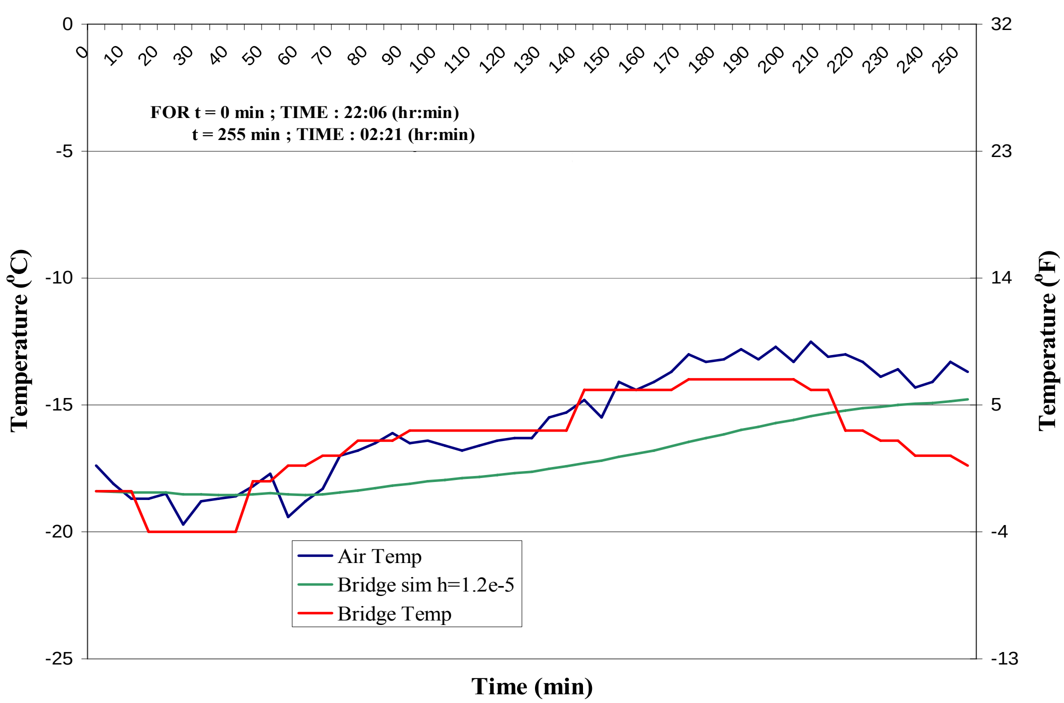



**Figure 211. Validation of h value of bridge-Ashtabula County (Site 88) for 3C°/hr (5.4F°/hr) temperature gradient from 1/23/05 22:06 – 1/24/05 00:06.**

### 13.7.9 Portage County

Figure 212 shows the histogram plot for temperature gradients at nighttime.

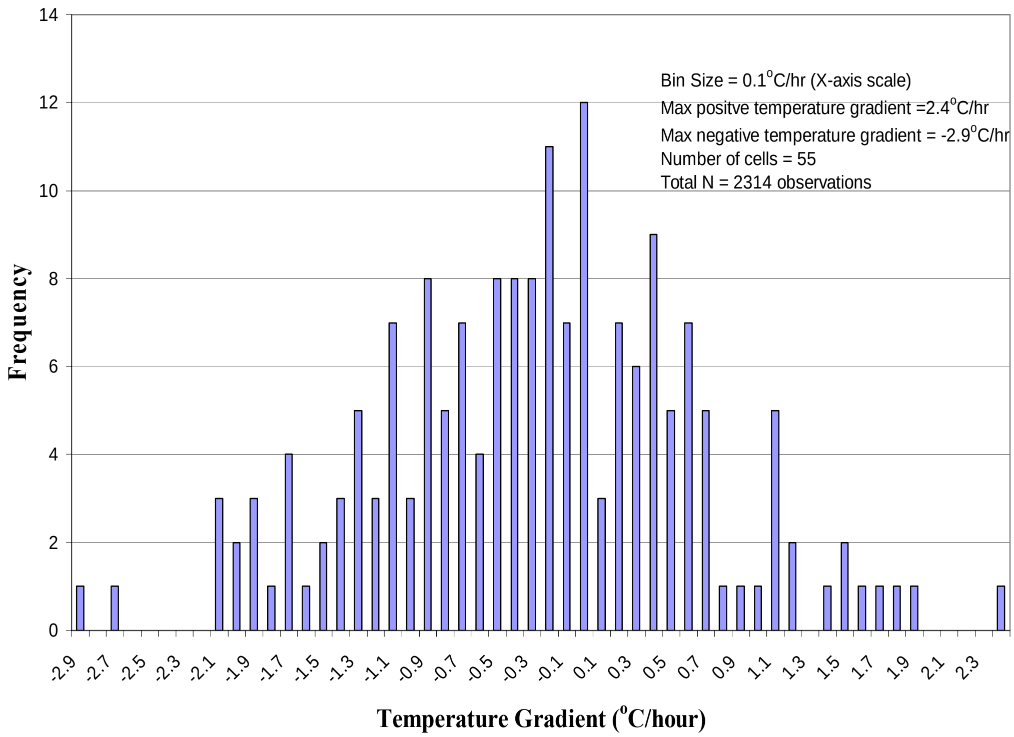



**Figure 212. Hourly temperature gradient for Site 91 – Portage County (Night time data only) from January 21 – April 5, 2005.**

Figure 213 and Figure 214 shows the actual recorded temperature data for -2.7C°/hr (-4.9F°/hr) temperature gradient for cooling and 2.4C°/hr (4.3F°/hr) temperature gradient for warming respectively. The BDS temperature during the warming gradient was modified by adding 2.15C° (3.87F°) during the warming gradient. Otherwise, all temperatures were unmodified. The simulation during the cooling gradient encompassed the 520 minutes from 20:16 to 4:56, while that for the warming gradient included 240 minutes from 1:16 to 5:16.

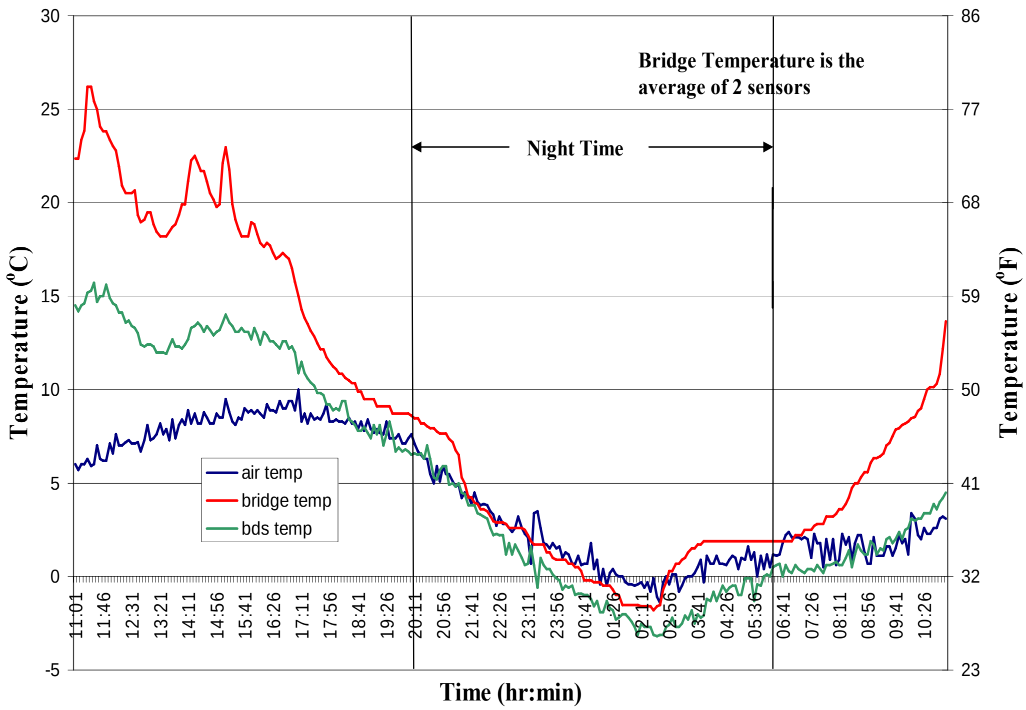



**Figure 213. Data containing the -2.7C°/hr (-4.9F°/hr) temperature gradient for Portage County (Site 91) from 3/26/05 11:01 – 3/27/05 11:01.**

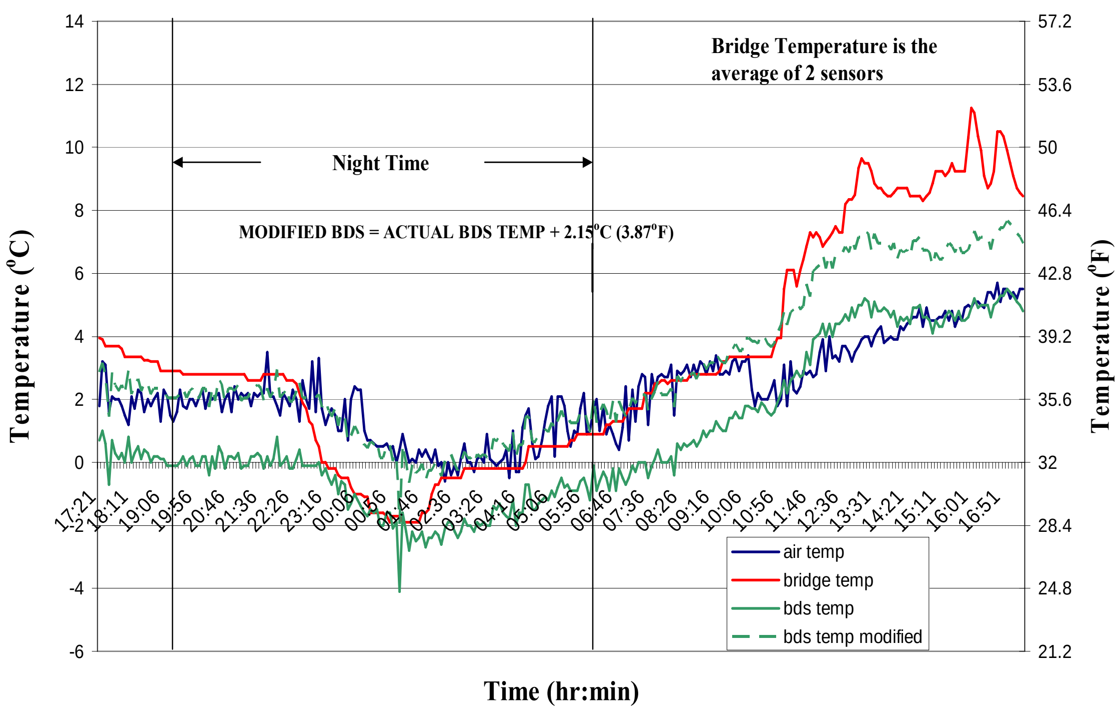



**Figure 214. Data containing the 2.4C°/hr (4.3F°/hr) temperature gradient for Portage County (Site 91) from 3/24/05 17:21 – 3/25/05 17:21.**

Figure 215 and Figure 216 show the simulation results for -2.7C°/hr (-4.9F°/hr) temperature gradient for cooling and 2.4C°/hr (4.3F°/hr) temperature gradient for warming for the BDS.

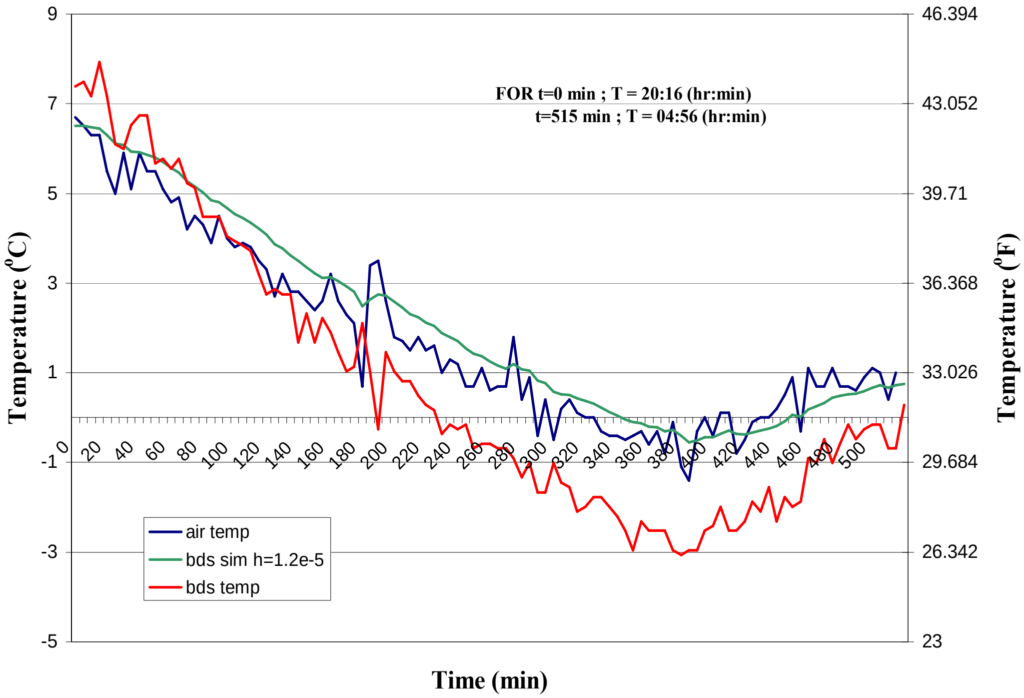



**Figure 215. Validation of h value of BDS-Portage County (Site 91) for -2.7C°/hr (-4.9F°/hr) temperature gradient from 3/26/05 20:16 – 3/27/05 04:56.**

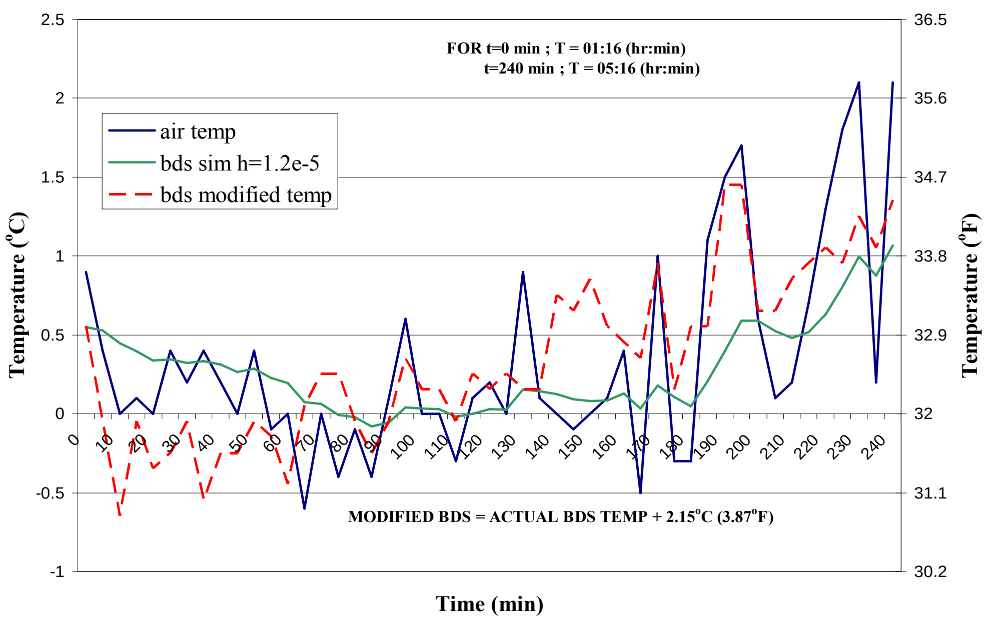



**Figure 216. Validation of h value of BDS-Portage County (Site 91) for 2.4$^{C°/hr}$ temperature gradient from 3/25/05 01:16 – 3/25/05 05:16.**

Figure 217 and Figure 218 show the simulation results for -2.7C°/hr (-4.9F°/hr) temperature gradient for cooling and 2.4C°/hr (4.3F°/hr) temperature gradient for warming for the bridge.

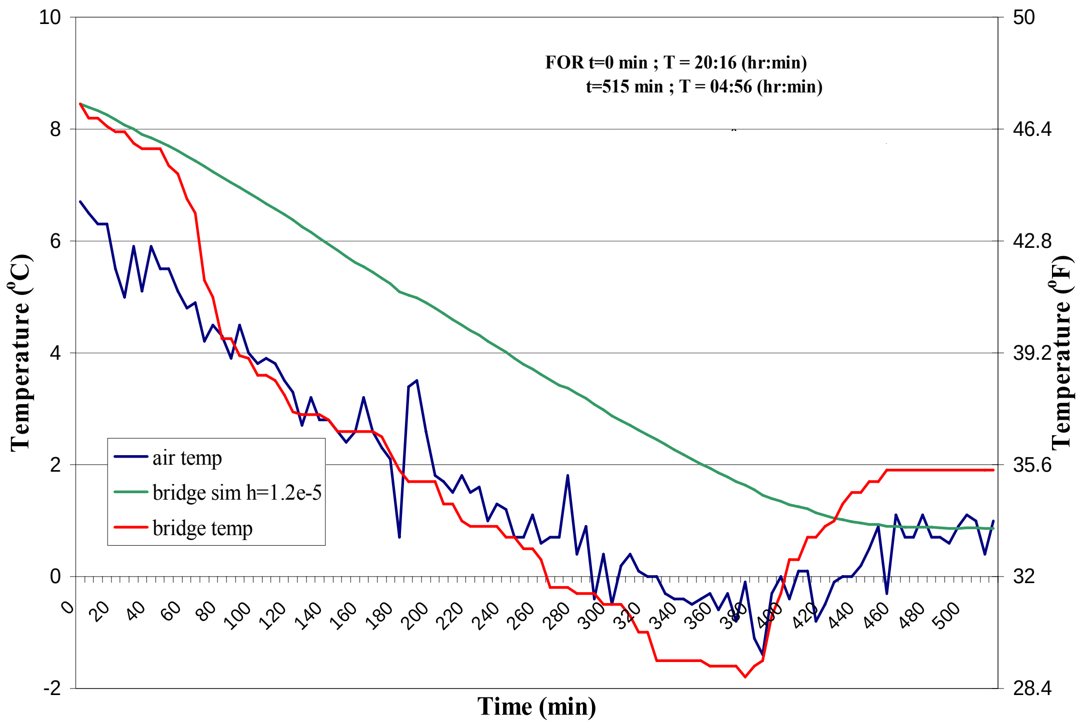



**Figure 217. Validation of h value of bridge-Portage County (Site 91) for -2.7C°/hr (-4.9F°/hr) temperature gradient from 3/26/05 20:16 – 3/27/05 04:56.**

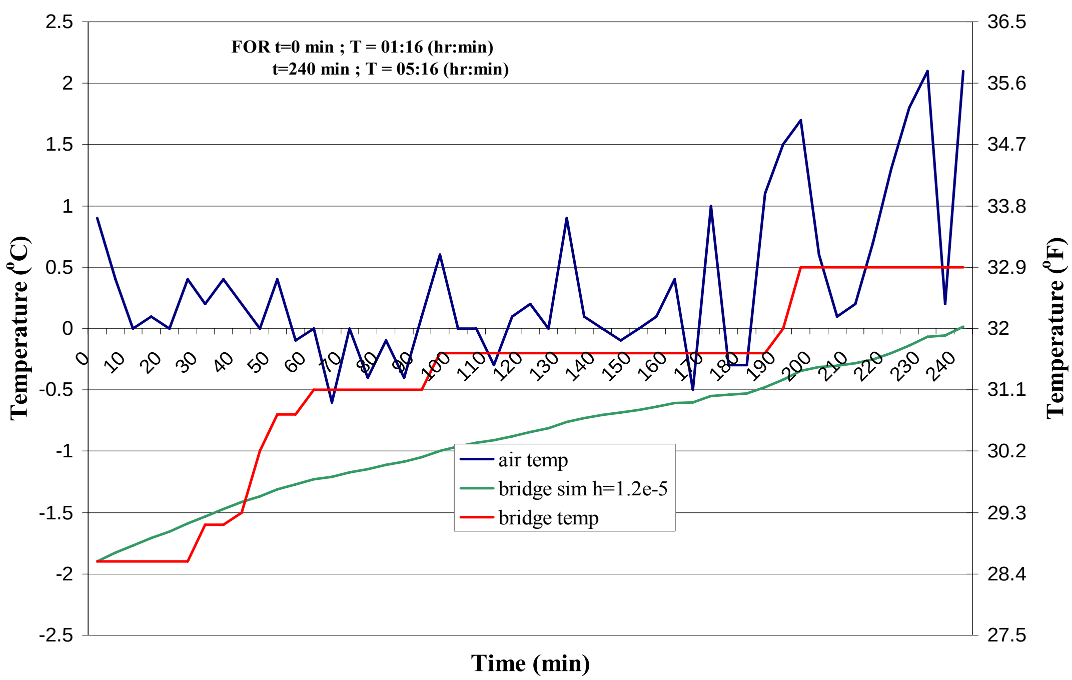



**Figure 218. Validation of h value of bridge-Portage County (Site 91) for 2.4C°/hr (4.3F°/hr) temperature gradient from 3/25/05 01:16 – 3/25/05 05:16.**

## 13.8 Summary of Results

The results from the simulation at all the sites are summarized in Table 49, Table 50, and Table 51. Table 49 summarizes the maximum warming and cooling air temperature gradient and associated time period for each site. The average maximum magnitude cooling gradient was -2.43C°/hr (-4.37F°/hr) and the average maximum warming gradient was 1.73C°/hr (3.11F°/hr). Table 50 provides temperature gradient and time period of cooling and warming from the FEM simulation of the bridge deck simulator block at each site. The temperature gradients and time periods are also calculated as a percentage of air temperature parameters. The average simulated cooling gradient was -2.02C°/hr (-3.63F°/hr) or 83.1% of the average maximum magnitude cooling air temperature gradient and the average simulated warming gradient was 1.29C°/hr (2.32F°/hr) or 74.6% of the average maximum warming air temperature gradient. Table 51 shows temperature gradient and time period of cooling and warming for the FEM simulation of the bridge deck. The temperature gradients and time periods are also calculated as a percentage of air parameters. The average cooling gradient was -1.58C°/hr (-2.84F°/hr) or 65.0% of the average maximum magnitude cooling air temperature gradient and the average warming gradient was 0.89C°/hr (1.60F°/hr) or 51.4% of the average maximum warming air temperature gradient.

**Table 49. Maximum cooling and warming air temperature gradients at all sites.**

| | AIR TEMPERATURE GRADIENT | | | | | |
|---|---|---|---|---|---|---|
| | COOLING | | | WARMING | | |
| **LOCATION AND SITE NUMBER** | INITIAL TEMP | TEMP GRADIENT | TIME PERIOD | INITIAL TEMP | TEMP GRADIENT | TIME PERIOD |
| **CRAWFORD COUNTY (007)** | -6.4°C<br>20.5°F | -1.58C°/hr<br>-2.83F°/hr | 320 min | 4.6°C<br>40.3°F | 1.33C°/hr<br>2.40F°/hr | 310 min |
| **STARK COUNTY (009)** | 12.7°C<br>54.9°F | -5.01C°/hr<br>-9.01F°/hr | 110 min | -9.3°C<br>15.3°F | 2.55C°/hr<br>4.60F°/hr | 190 min |
| **WARREN COUNTY (059)** | 20.4°C<br>68.7°F | -1.58C°/hr<br>-2.85F°/hr | 140 min | -1.6°C<br>29.1°F | 1.42C°/hr<br>2.56F°/hr | 160 min |
| **SUMMIT COUNTY (068)** | 3.4°C<br>38.1°F | -1.80C°/hr<br>-3.24F°/hr | 330 min | -3.9°C<br>25.0°F | 1.50C°/hr<br>2.70F°/hr | 140 min |
| **HAMILTON COUNTY (069)** | 9.0°C<br>48.2°F | -2.65C°/hr<br>-4.77F°/hr | 120 min | 0.0°C<br>32.0°F | 2.71C°/hr<br>4.88F°/hr | 115 min |
| **HAMILTON / CLERMONT (070)** | 14.8°C<br>58.6°F | -4.02C°/hr<br>-7.24F°/hr | 170 min | 4.7°C<br>33.5°F | 1.77C°/hr<br>3.20F°/hr | 135 min |
| **LORAIN COUNTY (086)** | 4.0°C<br>39.2°F | -1.25C°/hr<br>-2.25F°/hr | 480 min | -4.5°C<br>23.9°F | 0.55C°/hr<br>1.00F°/hr | 215 min |
| **ASHTABULA COUNTY (088)** | 4.4°C<br>39.9°F | -2.80C°/hr<br>-5.04F°/hr | 165 min | -19.4°C<br>-2.9°F | 2.76C°/hr<br>4.97F°/hr | 150 min |
| **PORTAGE COUNTY (091)** | 6.3°C<br>43.3°F | -1.20C°/hr<br>-2.16F°/hr | 335 min | -0.4°C<br>31.3°F | 0.96C°/hr<br>1.74F°/hr | 155 min |
| **AVERAGE** | | **-2.43C°/hr<br>-4.37F°/hr** | **241.11 min** | | **1.73C°/hr<br>3.11F°/hr** | **174.44 min** |
| **STANDARD DEVIATION** | | **1.32C°/hr<br>2.38F°/hr** | **128.90 min** | | **0.79C°/hr<br>1.42F°/hr** | **58.86 min** |

**Table 50. Simulated BDS block temperature gradient at all sites.**

| | SIMULATED BDS TEMPERATURE GRADIENT | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | COOLING | | | | | WARMING | | | | |
| LOCATION AND SITE NUMBER | INITIAL TEMP | TEMP GRADIENT | % OF AIR | TIME PERIOD | % OF AIR | INITIAL TEMP | TEMP GRADIENT | % OF AIR | TIME PERIOD | % OF AIR |
| **CRAWFORD COUNTY (007)** | -8.10°C 17.42°F | -1.00C°/hr -1.80F°/hr | 63.60% | 295 min | 92.18% | 4.65°C 40.37°F | 1.24C°/hr 2.24F°/hr | 93.23% | 325 min | 104.83% |
| **STARK COUNTY (009)** | 12.70°C 54.86°F | -4.04C°/hr -7.28F°/hr | 80.63% | 135 min | 122.72% | -8.87°C 16.03°F | 2.00C°/hr 3.60F°/hr | 78.43% | 220 min | 115.78% |
| **WARREN COUNTY (059)** | 20.17°C 68.30°F | -1.26C°/hr -2.27F°/hr | 79.74% | 170 min | 121.42% | -0.88°C 30.41°F | 1.01C°/hr 1.82F°/hr | 70.80% | 160 min | 100.00% |
| **SUMMIT COUNTY (068)** | 3.61°C 38.49°F | -1.58C°/hr -2.85F°/hr | 87.77% | 380 min | 115.15% | -3.50°C 25.70°F | 1.14C°/hr 2.05F°/hr | 76.00% | 140 min | 100.00% |
| **HAMILTON COUNTY (069)** | 9.78°C 49.60°F | -2.51C°/hr -4.52F°/hr | 94.71% | 145 min | 120.83% | 0.35°C 32.63°F | 2.14C°/hr 3.86F°/hr | 78.96% | 130 min | 113.04% |
| **HAMILTON/ CLERMONT (070)** | 14.50°C 58.10°F | -3.16C°/hr -5.69F°/hr | 78.60% | 200 min | 117.64% | 5.16°C 41.29°F | 1.58C°/hr 2.85F°/hr | 89.26% | 125 min | 92.59% |
| **LORAIN COUNTY (086)** | 3.95°C 39.11°F | -1.2C°/hr -2.16F°/hr | 96.00% | 490 min | 102.08% | -3.50°C 25.70°F | 0.22C°/hr 0.4F°/hr | 40.00% | 220 min | 102.32% |
| **ASHTABULA COUNTY (088)** | 3.815°C 38.86°F | -2.30C°/hr -4.13F°/hr | 81.96% | 185 min | 112.12% | -18.52°C -1.34°F | 1.85C°/hr 3.32F°/hr | 66.92% | 165 min | 110.00% |
| **PORTAGE COUNTY (091)** | 6.44°C 43.60°F | -1.13C°/hr -2.03F°/hr | 94.16% | 370 min | 110.44% | -0.08°C 31.86°F | 0.44C°/hr 0.79F°/hr | 45.83% | 155 min | 100.00% |
| **AVERAGE** | | **-2.02C°/hr -3.64F°/hr** | **83.13%** | **263.33 min** | **109.10%** | | **1.29C°/hr 2.32F°/hr** | **74.65%** | **182.22 min** | **104.40%** |
| **STANDARD DEVIATION** | | **1.05C°/hr 1.89F°/hr** | **51.98%** | **125.84 min** | **47.79%** | | **0.67 C°/hr 1.21F°/hr** | **51.94%** | **63.79 min** | **35.00%** |

**Table 51. Simulated bridge temperature gradient at all sites.**

| | SIMULATED BRIDGE TEMPERATURE GRADIENT | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | COOLING | | | | | WARMING | | | | |
| **LOCATION AND SITE NUMBER** | INITIAL TEMP | TEMP GRADIENT | % OF AIR | TIME PERIOD | % OF AIR | INITIAL TEMP | TEMP GRADIENT | % OF AIR | TIME PERIOD | % OF AIR |
| **CRAWFORD COUNTY (007)** | -8.15°C 17.33°F | -0.71C°/hr -1.28F°/hr | 45.04% | 335 min | 104.68% | 4.02°C 39.23°F | 1.04C°/hr 1.88F°/hr | 78.19% | 370 min | 112.12% |
| **STARK COUNTY (009)** | 13.51°C 56.32°F | -2.95C°/hr -5.31F°/hr | 58.88% | 180 min | 163.63% | -9.29°C 15.27°F | 1.55C°/hr 2.80F°/hr | 60.78% | 225 min | 118.42% |
| **WARREN COUNTY (059)** | 20.13°C 68.25°F | -0.78C°/hr -1.40F°/hr | 49.05% | 160 min | 114.28% | -0.31°C 31.43°F | 0.48C°/hr 0.86F°/hr | 33.40% | 160 min | 100.00% |
| **SUMMIT COUNTY (068)** | 4.20°C 39.56°F | -1.32C°/hr -2.37F°/hr | 73.22% | 465 min | 140.9% | -3.40°C 25.88°F | 0.80C°/hr 1.44F°/hr | 53.33% | 120 min | 85.71% |
| **HAMILTON COUNTY (069)** | 11.46°C 52.63°F | -2.10C°/hr -3.78F°/hr | 79.24% | 190 min | 158.33 | 0.88°C 33.58°F | 1.44C°/hr 2.59F°/hr | 53.13% | 125 min | 108.69% |
| **HAMILTON/ CLERMONT (070)** | 14.23°C 57.63°F | -2.48C°/hr -4.47F°/hr | 61.69% | 190 min | 111.76% | 5.97°C 42.75°F | 0.66C°/hr 1.19F°/hr | 37.34% | 215 min | 159.25% |
| **LORAIN COUNTY (086)** | 4.95°C 40.91°F | -1.17C°/hr -2.11F°/hr | 93.52% | 545 min | 113.54% | -3.15°C 26.33°F | 0.16C°/hr 0.30F°/hr | 29.09% | 195 min | 90.69% |
| **ASHTABULA COUNTY (088)** | 4.37°C 39.86°F | -1.71C°/hr -3.09F°/hr | 61.07% | 240 min | 145.45% | -18.46°C -1.23°F | 1.44C°/hr 2.59F°/hr | 52.21% | 165 min | 110.00% |
| **PORTAGE COUNTY (091)** | 8.25°C 46.85°F | -1.00C°/hr -1.81F°/hr | 83.58% | 440 min | 131.34% | -1.83°C 28.71°F | 0.47C°/hr 0.85F°/hr | 48.95% | 235 min | 151.61% |
| **AVERAGE** | | **-1.58C°/hr -2.84F°/hr** | **65.02%** | **305.00 min** | **175.28%** | | **0.893C°/hr 1.61F°/hr** | **51.60%** | **201.11min** | **115.28%** |
| **STANDARD DEVIATION** | | **0.78 C°/hr 1.40F°/hr** | **49.37%** | **145.62 min** | **47.74%** | | **0.52C°/hr 0.94F°/hr** | **58.23%** | **75.69 min** | **37.64%** |

## 13.9 Modeling arbitrary gradients

One can use ALGOR V18 to help model the behavior of bridge deck when the air temperature changes linearly over a period of 1 hour and then stays constant for a period of time after that. For this purpose a theoretical air temperature profile was developed with various temperature gradients for cooling and warming conditions, which will serve as an input for the model. The modeling approach, constants used, and analysis is otherwise the same as applied earlier. Figure 219 and Figure 220 show examples of the theoretical air temperature profile that was used for simulations for cooling and warming respectively.

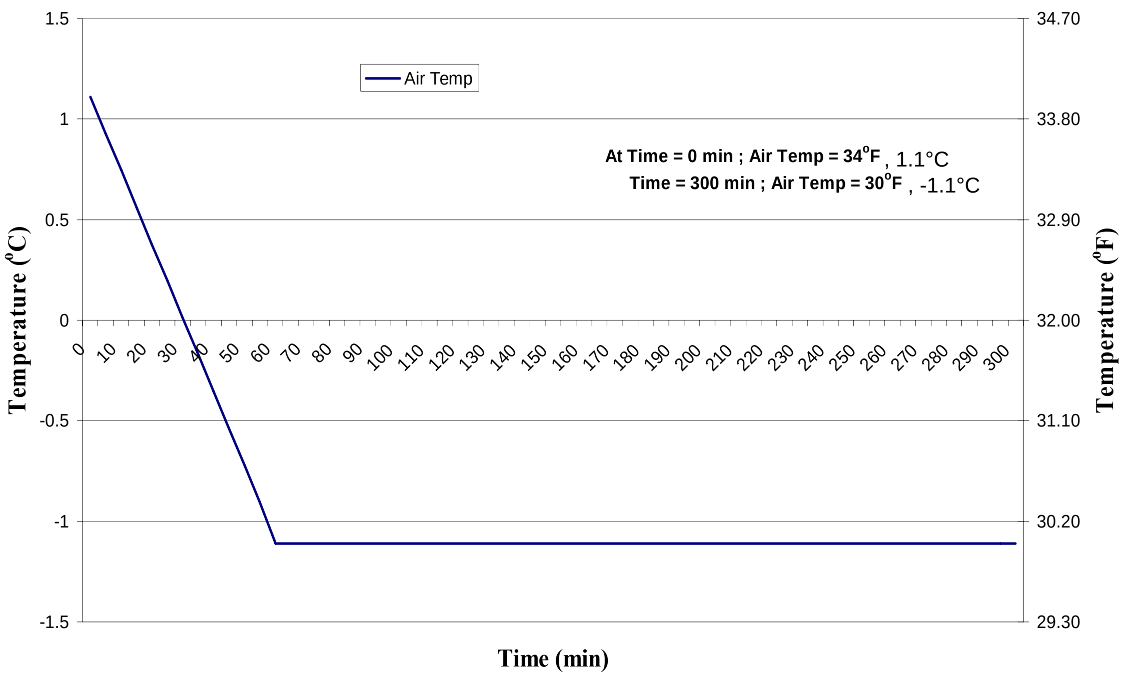



**Figure 219. Theoretical air temperature gradient of -4F° (-2.2C°) for one hour followed by constant temperature for four hours used for simulation. The initial temperature was 34°F (1.1°C).**

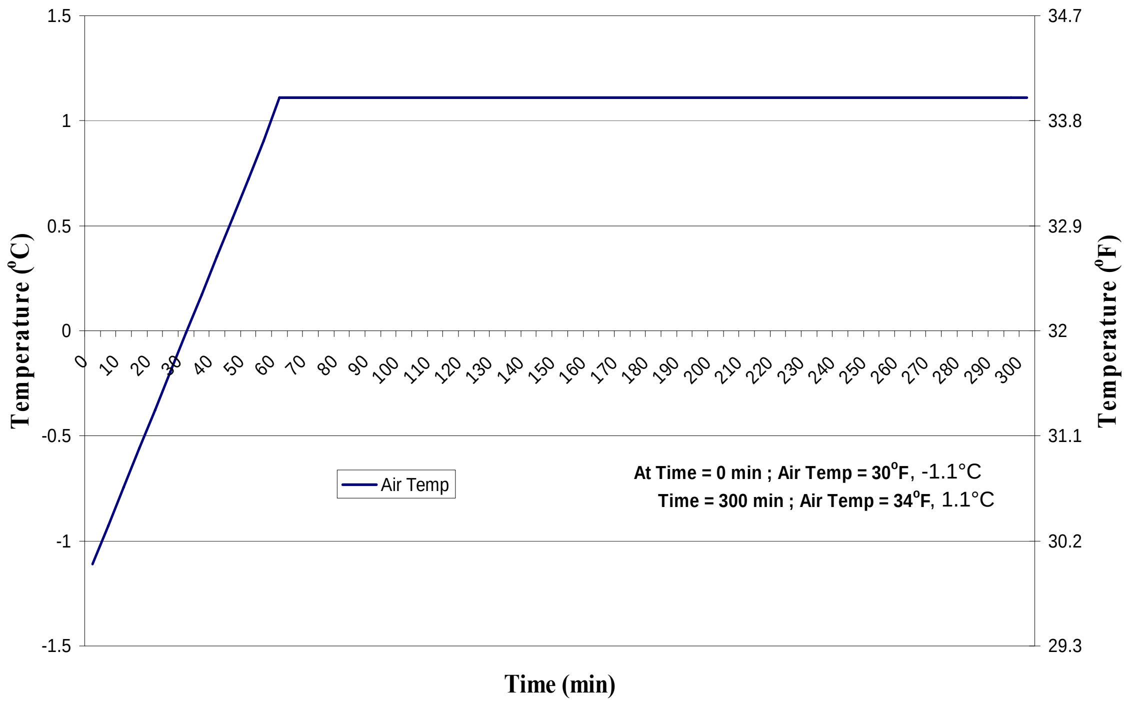



**Figure 220. Theoretical air temperature gradient of +4F° (+2.2C°) for one hour followed by constant temperature for four hours used for simulation. The initial temperature was 30°F (-1.1°C).**

### 13.9.1 Validation of ALGOR V18

Consider a practical case from the data that was already provided for the 9 sites, which was fairly close to the theoretical case for validation. Figure 221 shows the temperature data for a selected time including a temperature gradient of -2.1C°/hr (-3.8F°/hr) from Site 69 in Hamilton County. The bridge temperature has been modified by adding 0.9C° (1.6F°) to compensate for bias.

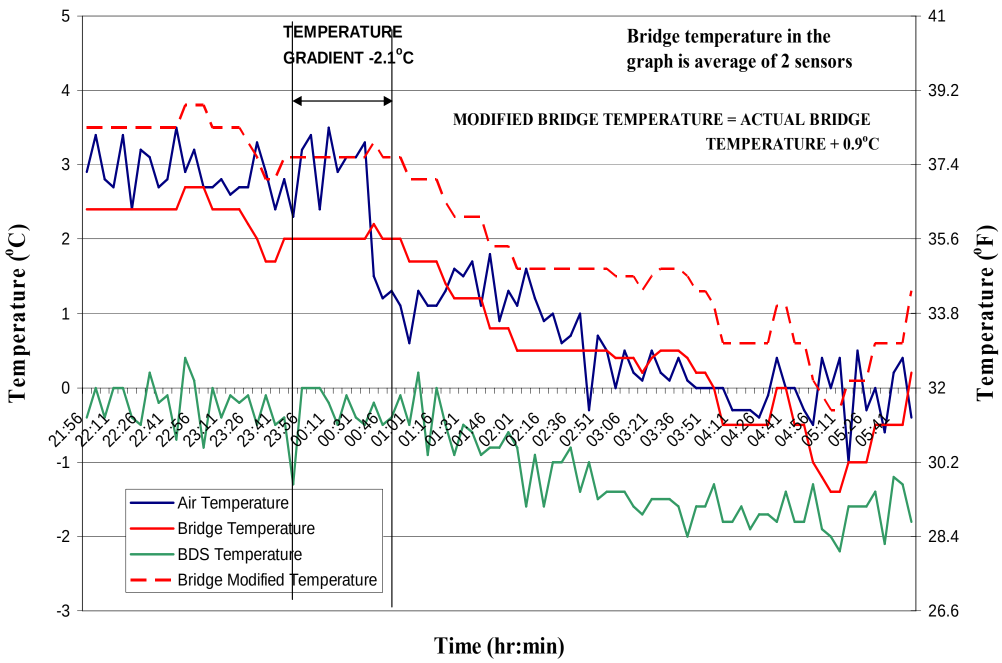



**Figure 221. Data containing the –2.1C°/hr (-3.8F°/hr) temperature gradient for Hamilton County (Site 69) from 2/23/05 21:56 – 2/24/05 05:51.**

The air temperature used for simulation is shown in Figure 222. The air temperature profile for the simulation is shown as a dashed line, and has been smoothed compared to the actual air temperature (solid line). The simulation period runs from 23:56 to 5:26, or 330 minutes.

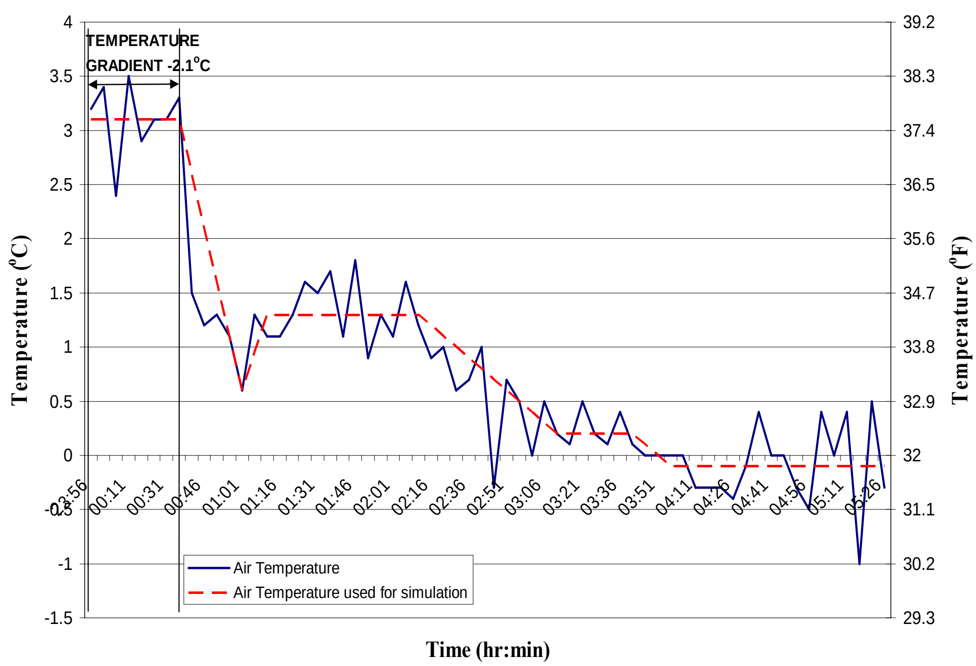



**Figure 222. Averaged air temperature data for the Site 69 Hamilton County bridge deck containing a -2.1C°/hr (-3.8F°/hr) temperature gradient from 2/23/05 23:56 – 2/24/05 05:26 used for simulation.**

Figure 223 shows the result of the analysis for the bridge deck after the modeling, with the smoothed air temperature profile from Figure 222, the simulated bridge deck temperature, and the modified bridge temperature from Figure 221. ALGOR V18 gives a fairly accurate reading for the bridge deck, within 1C° (1.8F°) of the actual bridge deck reading. Some of the differences may be due to the smoothing of the air temperature profile.

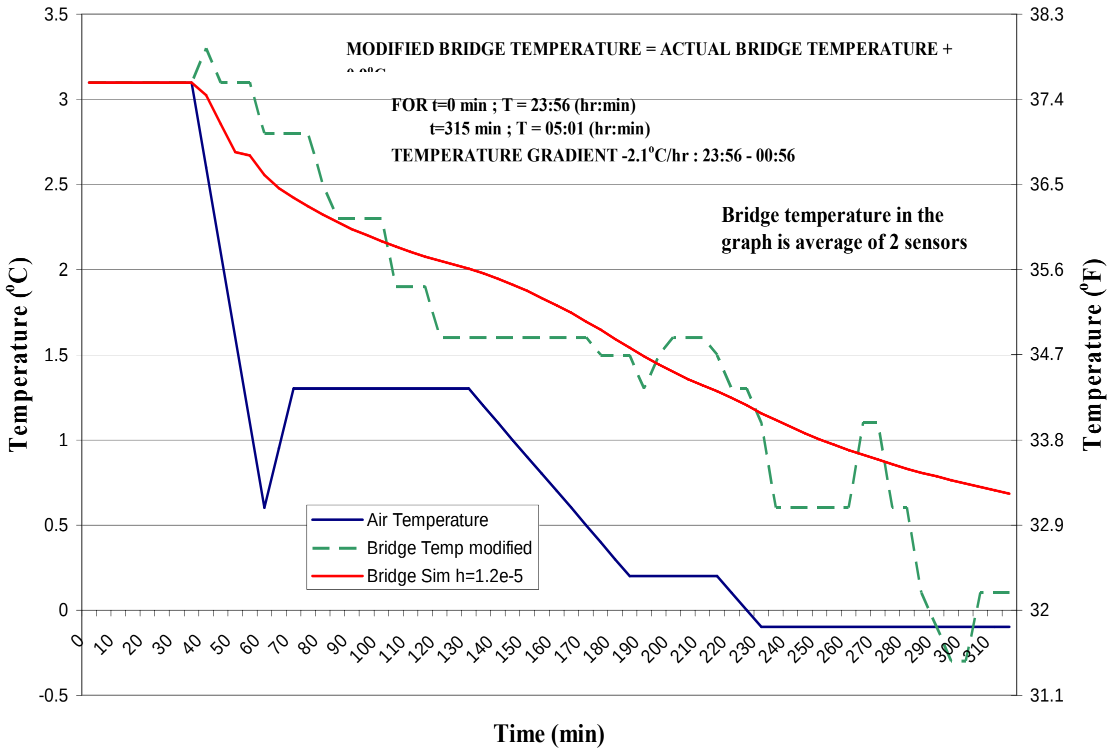



**Figure 223. Validation of ALGOR V18 for Site 69 Hamilton County bridge deck for the data from 2/23/05 23:56 – 2/24/05 05:01.**

## 13.9.2 Validation with different air temperature gradients

The results from simulations for the different air temperature gradients are shown below. Hamilton County (Site 69) bridge cross-section was used for simulation of bridge deck temperatures. Figure 224, Figure 225, Figure 226, and Figure 227 respectively show the FEM simulation results obtained for the bridge deck and the BDS for air temperature gradients of -8F˚/hr (-4.4C°/hr), -6F˚/hr (-3.3C°C/hr), -4F˚/hr (-2.2C°/hr) and -2F˚/hr (-1.1C°/hr) for a period of one hour and held constant for four hours.

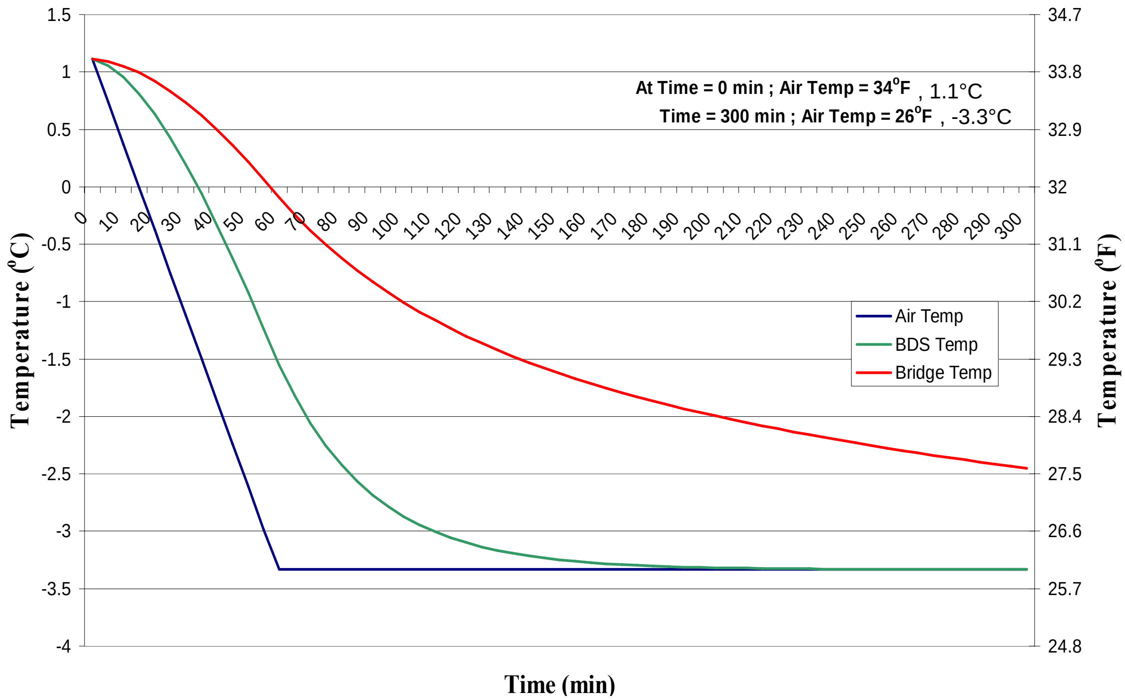



**Figure 224. Results for bridge deck and block temperatures for an air temperature gradient of -8˚F/hr (-4.4C°/hr) for a period of one hour and held constant for four hours. The initial temperature was 34°F (1.1°C) and the final air temperature was 26°F (-3.3°C).**

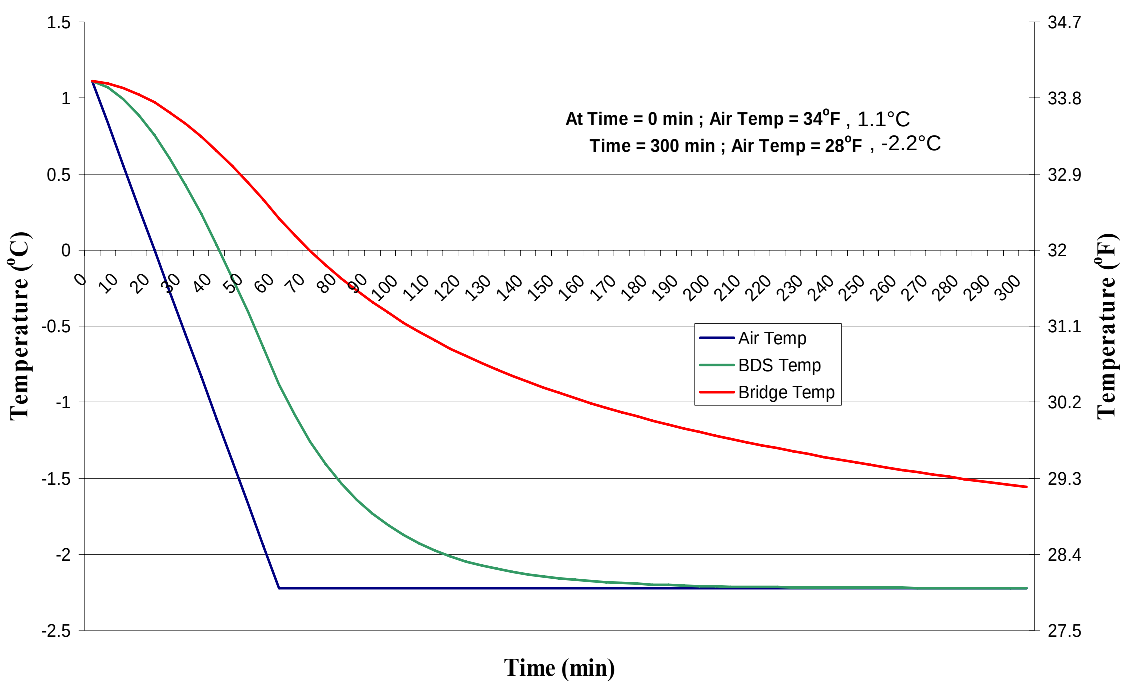



**Figure 225. Results for bridge deck and block temperatures for an air temperature gradient of -6F°/hr (-3.3C°C/hr) for a period of one hour and held constant for four hours. The initial temperature was 34°F (1.1°C) and the final air temperature was 28°F (-2.2°C).**

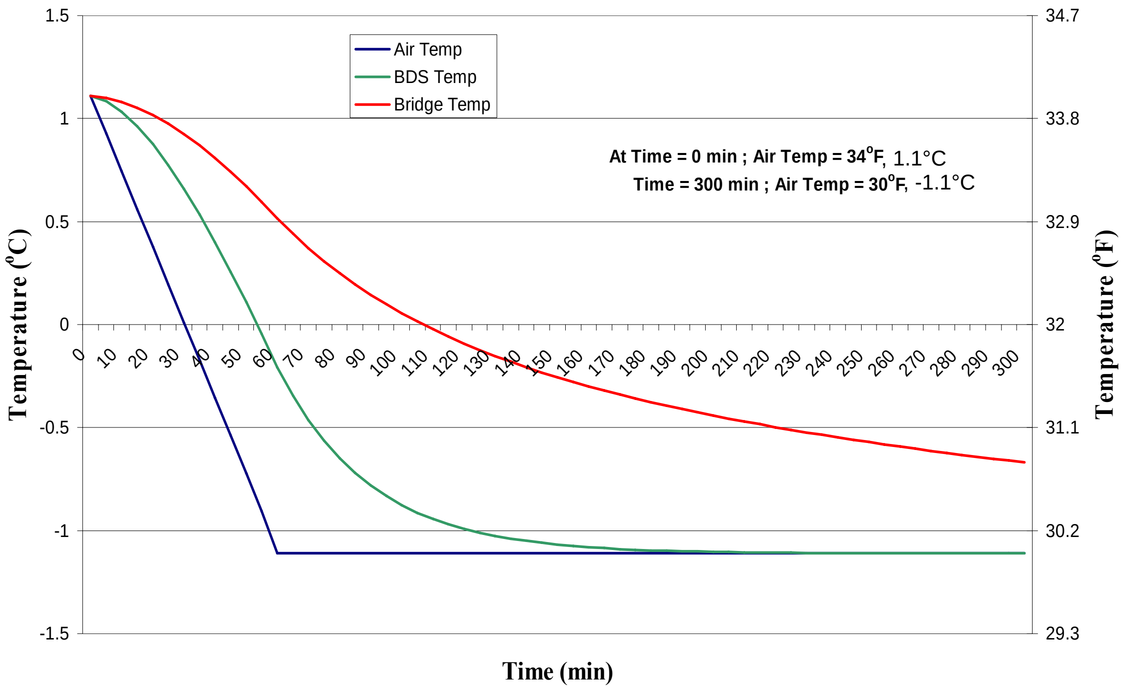



**Figure 226. Results for bridge deck and block temperatures for an air temperature gradient of -4F°/hr (-2.2C°/hr) for a period of one hour and held constant for four hours. The initial temperature was 34°F (1.1°C) and the final air temperature was 30°F (-1.1°C).**

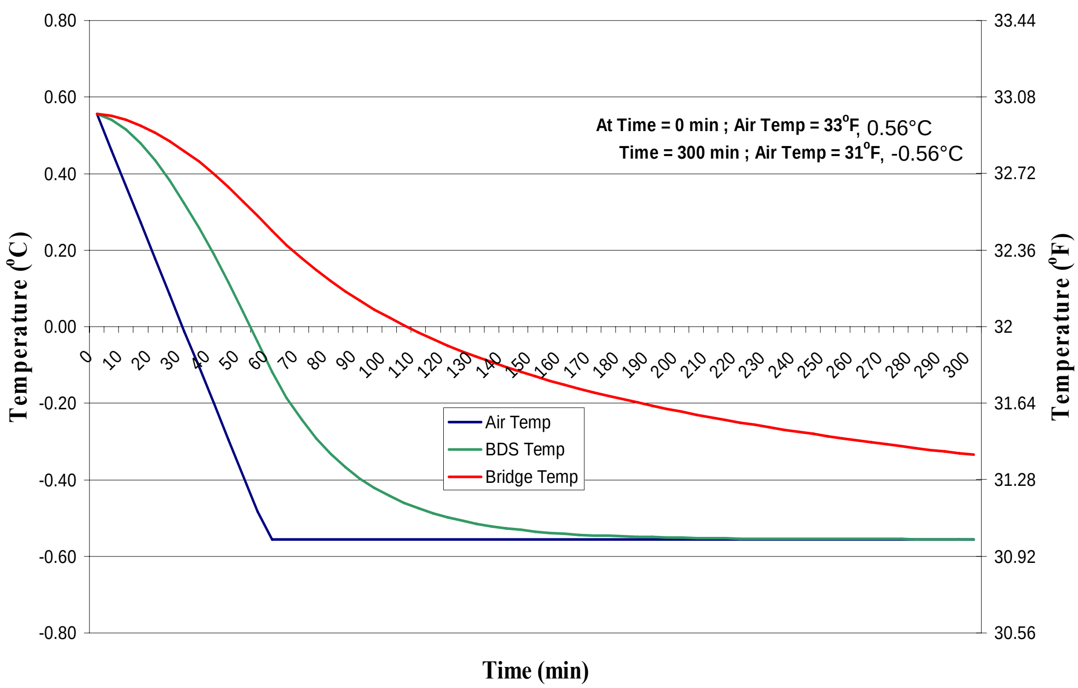



**Figure 227. Results for bridge deck and block temperatures for an air temperature gradient of -2°F/hr (-1.1C°/hr) for a period of one hour and held constant for four hours. The initial temperature was 33°F (0.56°C) and the final air temperature was 31°F (-0.56°C).**

Figure 228 and Figure 229 have the same temperature gradient of +2F˚/hr (+1.1C°/hr) for a period of one hour and held constant for four hours but different starting temperatures.

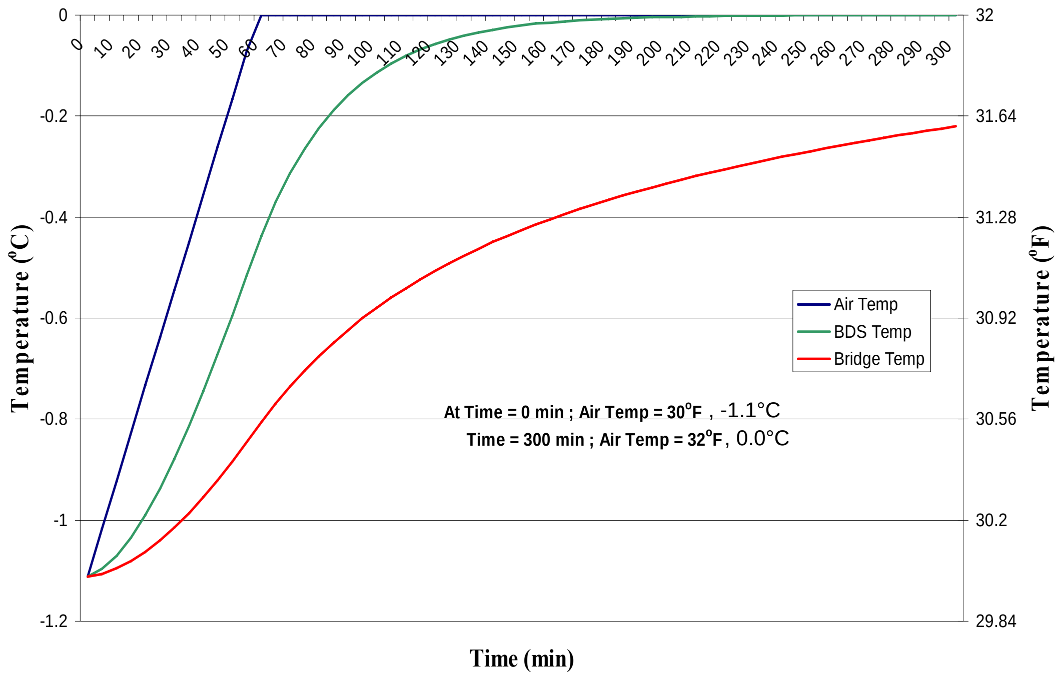



**Figure 228. Results for bridge deck and block temperatures for an air temperature gradient of +2˚F/hr (+1.1C°/hr) for a period of one hour and held constant for four hours. The initial temperature was 30°F (-1.1°C) and the final air temperature was 32°F (0.0°C).**

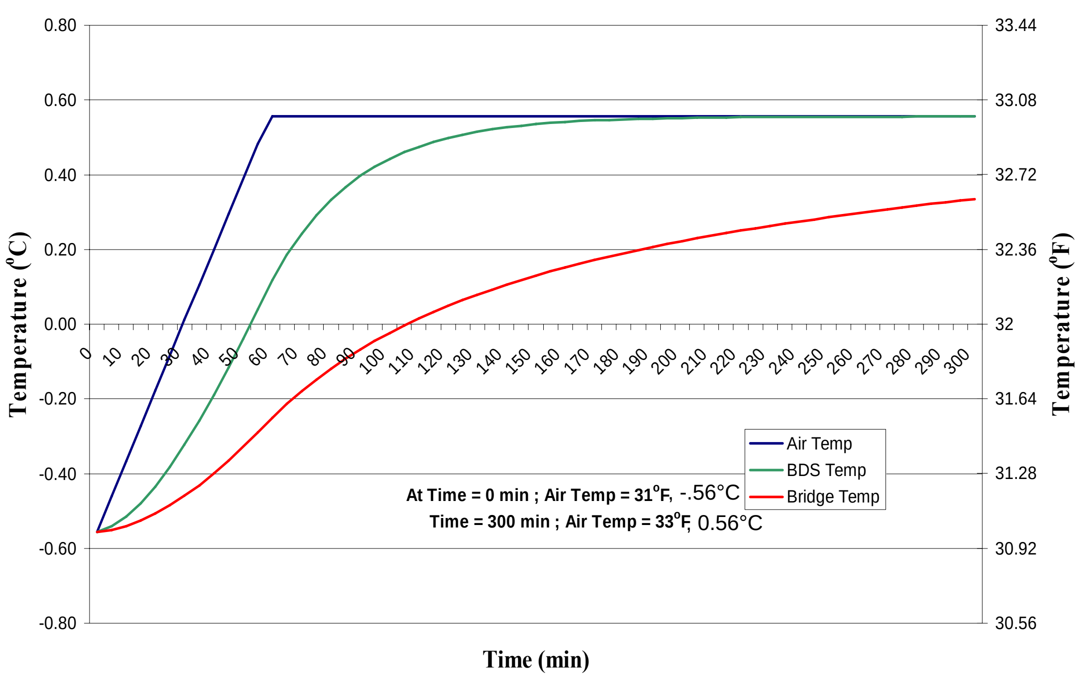



**Figure 229. Results for bridge deck and block temperatures for an air temperature gradient of +2˚F/hr (+1.1C°/hr) for a period of one hour and held constant for four hours. The initial temperature was 31°F (-0.56°C) and the final air temperature was 33°F (0.56°C).**

Figure 230 and Figure 231 show the results obtained for an air temperature gradient of +4F˚/hr (+2.2C°/hr) and +6F˚/hr (+3.3C°/hr) for a period of one hour and then held constant for four hours, respectively.

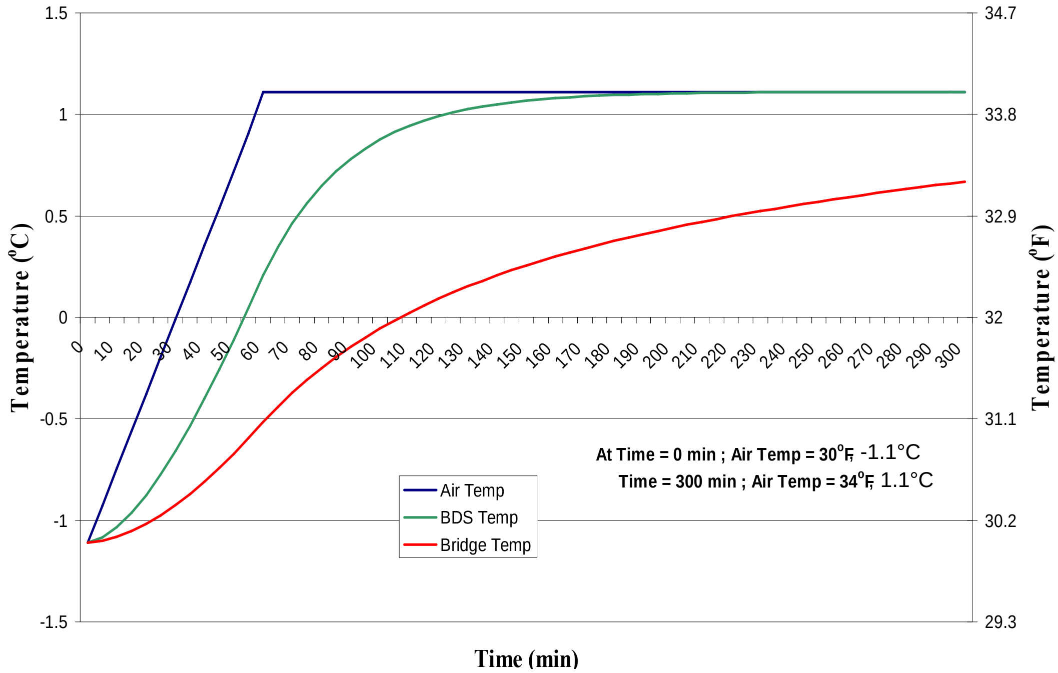



**Figure 230. Results for bridge deck and block temperatures for an air temperature gradient of +4F˚/hr (+2.2C°/hr) for a period of one hour and held constant for four hours. The initial temperature was 30°F (-1.1°C) and the final air temperature was 34°F (1.1°C).**

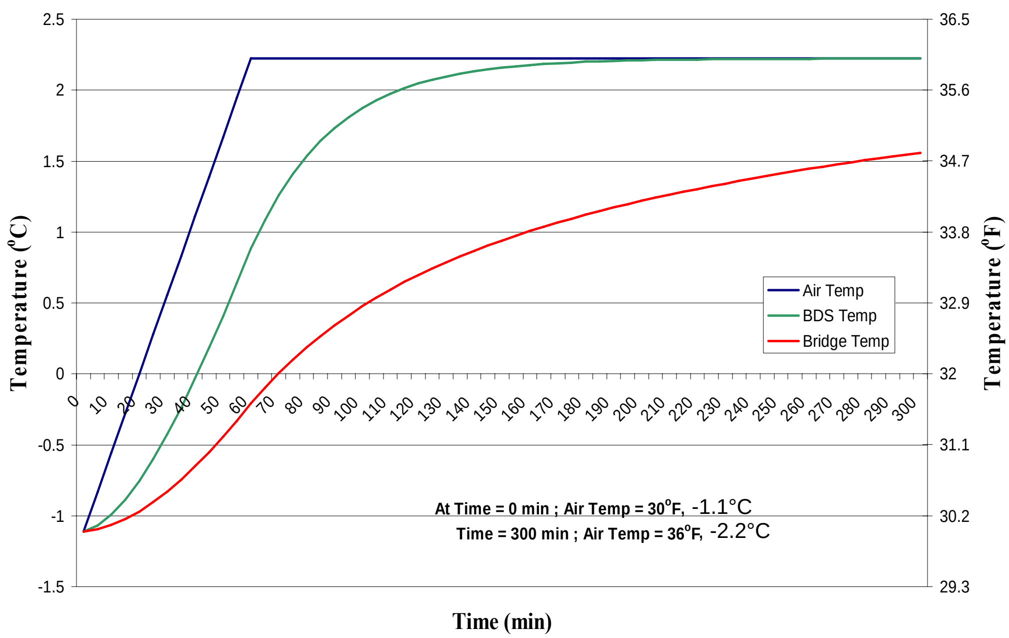



**Figure 231. Results for bridge deck and block temperatures for an air temperature gradient of +6F˚/hr (+3.3C°/hr) for a period of one hour and held constant for four hours. The initial temperature was 30°F (-1.1°C) and the final air temperature was 36°F (2.2°C).**

## 13.10 Simulation of high-mass bridge deck simulators

To see the effect of special high-mass bridge deck simulator which will allow us to determine to what extent the mass of the simulator matters in determining the validity of the simulator measurements, simulations were performed with different sizes of BDS blocks for an assumed air temperature gradients of -8F˚/hr (-4.4C°/hr), -6F˚/hr (-3.3C°/hr), -4F˚/hr (-2.2C°/hr), -2F˚/hr (-1.1C°/hr), 6F˚/hr (3.3C°/hr), and 4F˚/hr (2.2C°/hr) for a period of one hour and held constant for four hours respectively. The simulations were run for cubical block sizes of 6 in (15.24 cm), 9 in (22.86 cm), 12 in (30.48 cm), and 24 in (60.96 cm). In each case, the simulated BDS temperature represents a point 0.5 in (1.27 cm) beneath the center of the top surface of the block, regardless of the size or mass.

Figure 232, Figure 233, Figure 234, and Figure 235 show the results obtained for the prediction of BDS and bridge deck temperature for an assumed air temperature gradients of -8F˚/hr (-4.4C°/hr), -6F˚/hr (-3.3C°/hr), -4F˚/hr (-2.2C°/hr), -2F˚/hr (-1.1C°/hr) for a period of one hour and held constant for four hours respectively. Figure 236 and Figure 237 show the results obtained for the prediction of BDS and bridge deck temperature for an assumed air temperature gradients of 6F˚/hr (3.3C°/hr) and 4F˚/hr (2.2C°/hr)for a period of one hour and held constant for four hours for warming respectively. It can be seen from the graphs that the BDS temperature for a block size of 24 in (60.96 cm) matches almost exactly with the bridge deck temperatures showing that the size of the block does have an effect of how well it actually simulates the bridge deck temperatures.

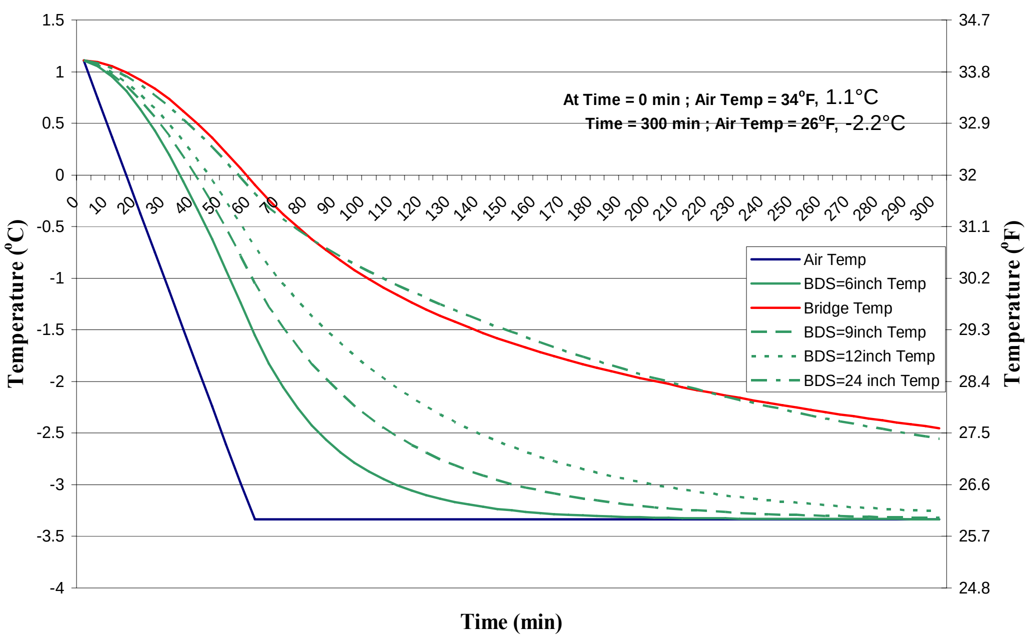



**Figure 232. Prediction of BDS and bridge temperature for an air temperature gradient of -8F°/hr (-4.4C°/hr) for a period of one hour and held constant for four hours for different sizes of the block. The initial temperature was 34°F (1.1°C) and the final air temperature was 26°F (-3.3°C). 6 in = 15.24 cm.**

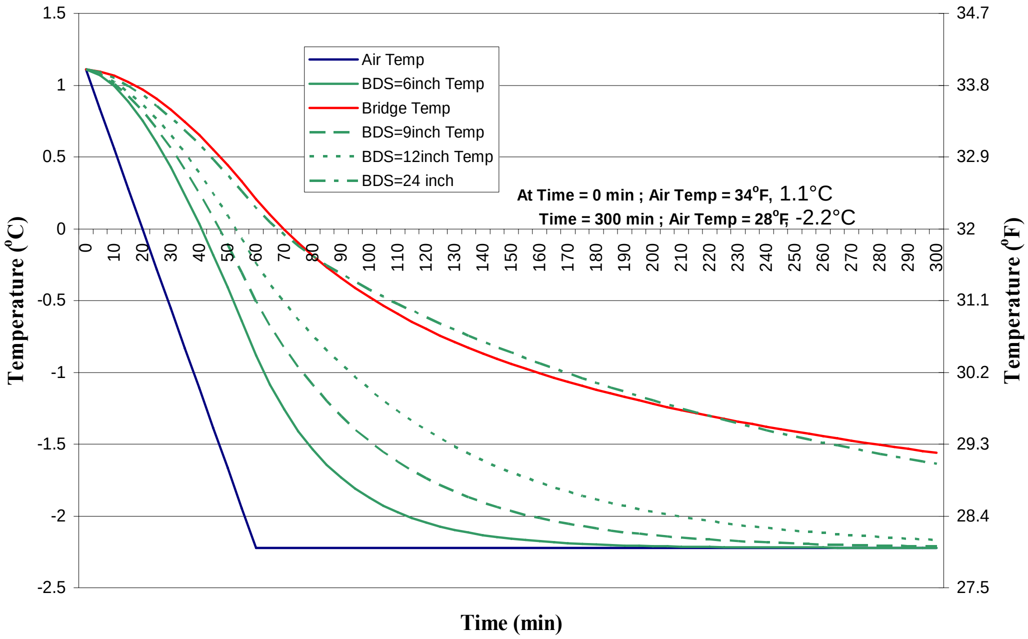



**Figure 233. Prediction of BDS and bridge temperature for an air temperature gradient of -6F°/hr (-3.3 C°/hr) for a period of one hour and held constant for four hours for different sizes of the block. The initial temperature was 34°F (1.1°C) and the final air temperature was 28°F (-2.2°C). 6 in = 15.24 cm.**

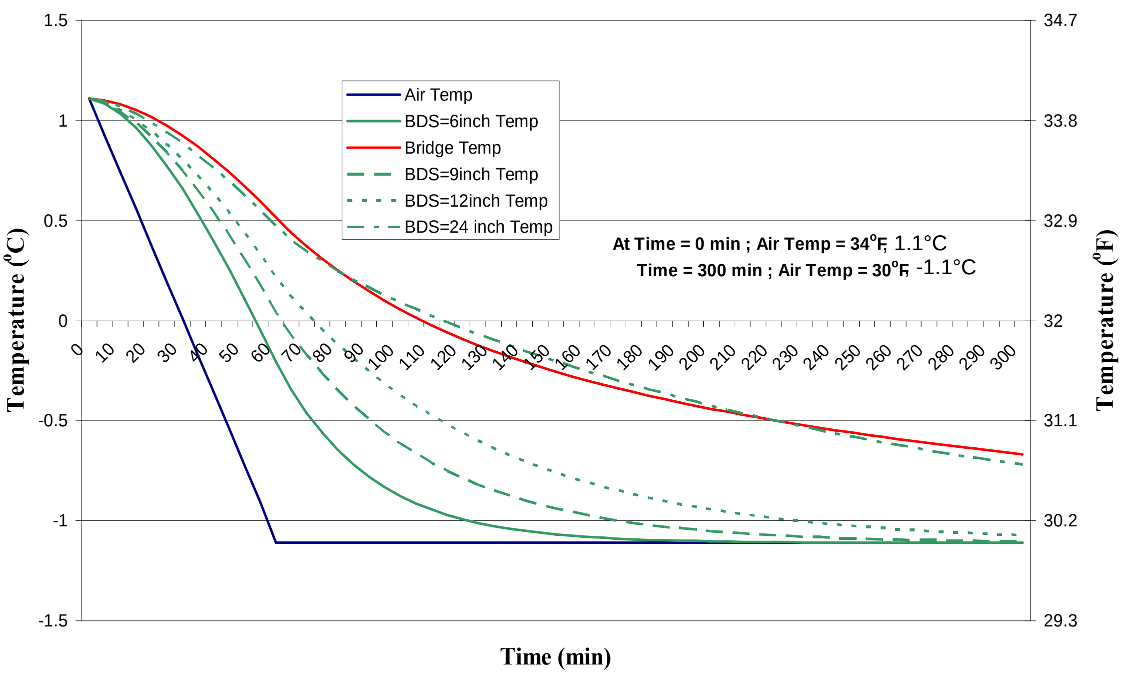



**Figure 234. Prediction of BDS and bridge temperature for an air temperature gradient of -4F°/hr (-2.2 C°/hr) for a period of one hour and held constant for four hours for different sizes of the block. The initial temperature was 34°F (1.1°C) and the final air temperature was 30°F (-1.1°C). 6 in = 15.24 cm.**

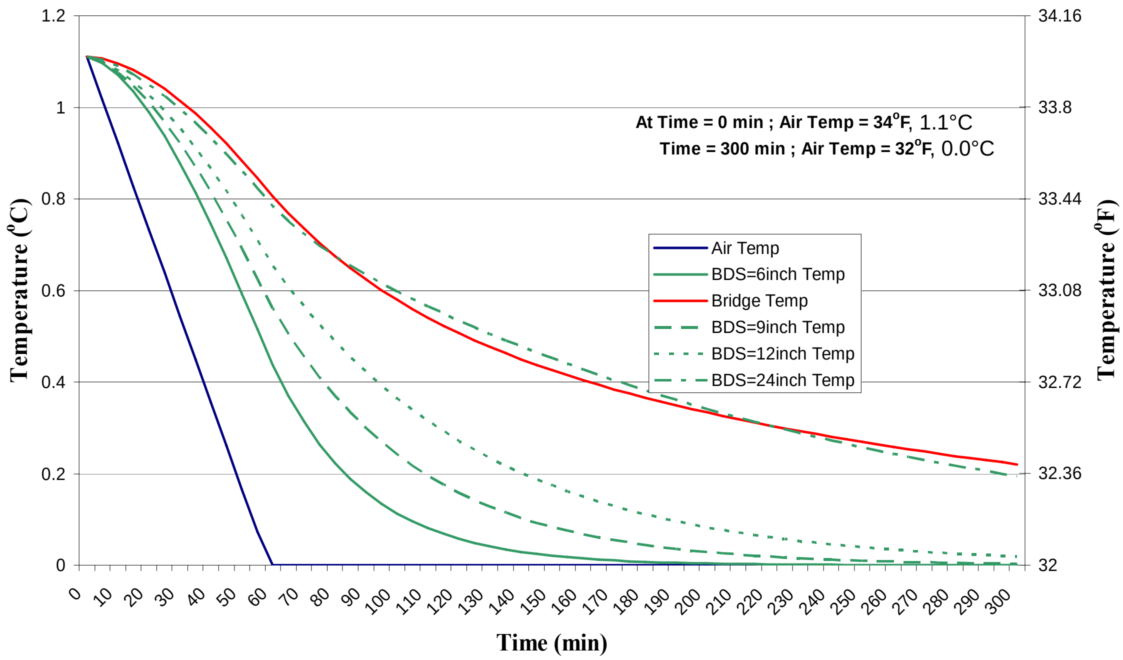



**Figure 235. Prediction of BDS and bridge temperature for an air temperature gradient of -2F°/hr (-1.1C°/hr) for a period of one hour and held constant for four hours for different sizes of the block. The initial temperature was 34°F (1.1°C) and the final air temperature was 32°F (0.0°C). 6 in = 15.24 cm.**

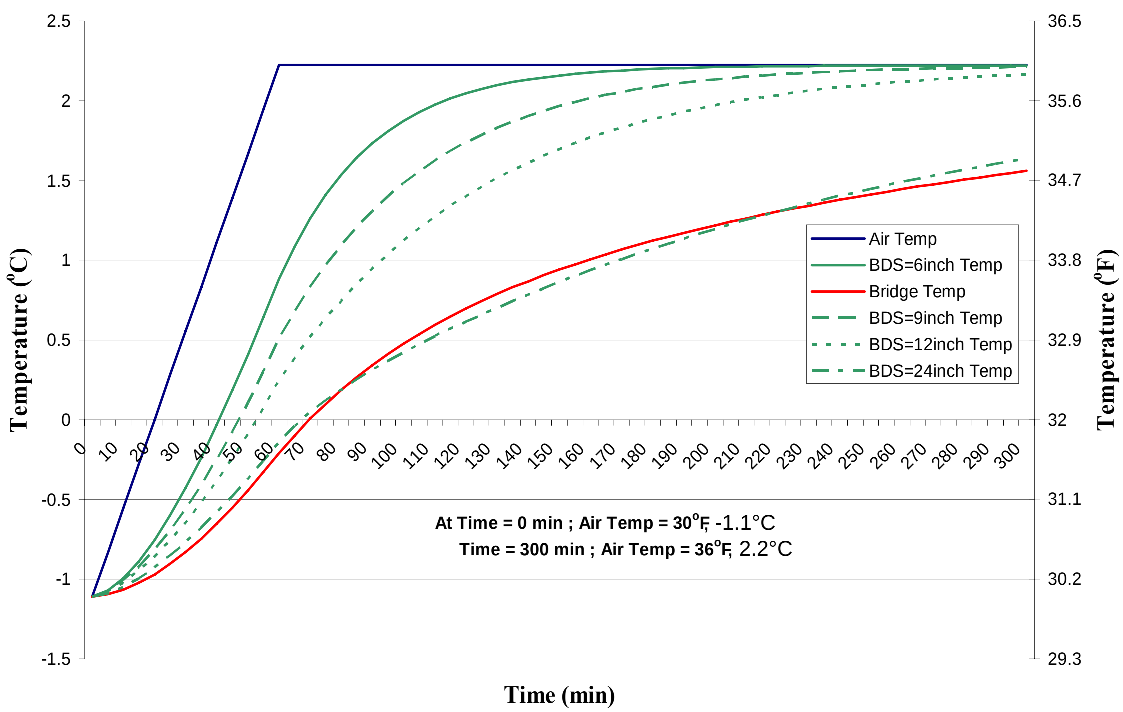



**Figure 236. Prediction of BDS and bridge temperature for an air temperature gradient of +6F°/hr (+3.3 C°/hr) for a period of one hour and held constant for four hours for different sizes of the block. The initial temperature was 30°F (-1.1°C) and the final air temperature was 36°F (2.2°C). 6 in = 15.24 cm.**

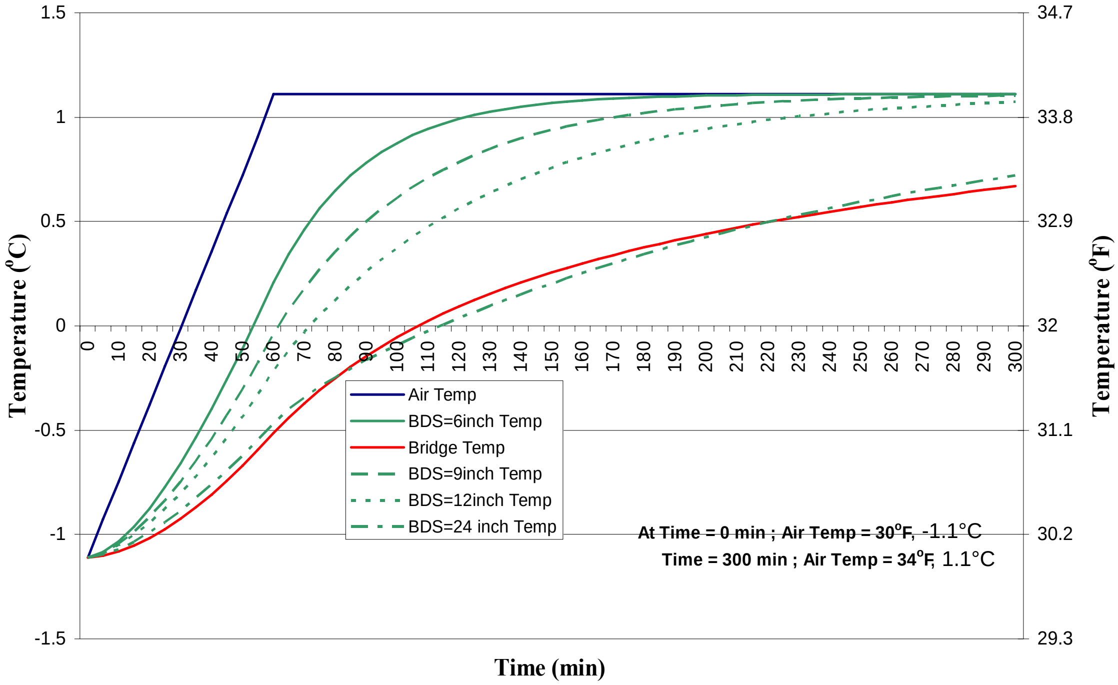



**Figure 237. Prediction of BDS and bridge temperature for an air temperature gradient of +4F°/hr (+2.2C°/hr) for a period of one hour and held constant for four hours for different sizes of the block. The initial temperature was 30°F (-1.1°C) and the final air temperature was 34°F (1.1°C). 6 in = 15.24 cm.**

# 14 Conclusions and recommendations

In order to evaluate the effectiveness of the RWIS bridge temperature simulators, the BDS temperatures were compared to air, bridge deck sensor, and road sensor temperatures, first by correlating the data, then by generating prediction limits for bridge deck and road temperatures based on their best-fit relationships with BDS data. Finite element simulations were conducted to determine the predictive value of BDS readings. The FEM results were compared to those of a hypothetical heavier mass BDS. Finally BDS temperatures at one location were compared to bridge deck temperatures at a second location as a way to gauge the long-distance effectiveness of BDS readings. The conclusions and recommendations for each of these analyses follows.

## 14.1 Correlations

- A significant portion of the data collected for the correlation data had to be rejected due to data integrity problems, as much as 69% (Site 91 bridge sensors) but more typically around 15%. Most of this may be due to intermittent communication problems between the pavement sensors and the RPU, though on average about 3.5% of air and BDS data were discarded before pavement sensor data were considered. These communication problems in turn may be related to weather, but no attempt was made to study the potential relationship as it was outside the scope of the project.

- It is apparent from a visual inspection of the correlation graphs that the BDS temperatures at most sites have a bias relative to the bridge and road temperatures. These can be several degrees Celsius. While the amount of bias, as indicated by the intercepts of the correlation graphs, varies from site to site, the intercepts are always positive.

- The regression slopes also varied from site to site. Since the slopes and intercepts (biases) varied from site to site, it was not possible to generate a meaningful average relationship between BDS and bridge deck or road temperature that could be applied across the state.

- Nighttime air-BDS and BDS-bridge sample coefficient of determination ($R^2$, square of correlation coefficient R) exceeded 0.95 for all sites. This means that the BDS temperature explains at least 95% of the observed temperature behavior of the nearby bridge decks.

- Correlations of BDS temperatures with bridge deck temperatures are clearly higher than correlations between air and bridge temperatures for both nighttime and all-day data. Thus, the BDS temperature does give a better estimate of bridge temperature than does the air temperature. The same observation holds regarding BDS-road versus air-road temperature relationships.

- The BDS temperatures do not always closely predict the bridge deck temperatures when a rapid change in air temperature is taking place.

- Temperatures during daytime may be strongly affected by solar radiation, which is not measured by Ohio's RWIS stations. Solar radiation seemed to affect BDS simulators a bit differently than bridge decks, thus reducing the correlation during daytime. It may be worth looking further into the experiences Kentucky has had using the solar radiation data their system gets to determine if the added measurements enhance the value of the RWIS results to make the expense worthwhile.

## 14.2 Prediction Limits

- For instantaneous prediction of nighttime bridge deck temperature based on the BDS temperature, the prediction limit values were on the average 73.3% of those based on air temperature at the 90% level. At the 95% and 99% level, the BDS temperature based prediction limit values are 74.0% and 75.7% of those for based on air temperature. Thus the BDS helps to reduce the prediction limit ranges for the bridge deck temperature by about 25% from those based on air temperature.

- The prediction limit values for the different sites are fairly close, so that the average prediction limits can be considered to be applicable anywhere in the state. However, the regression relationships between BDS and bridge or road temperatures are site-specific, and the regression relationship needs to be known in order to use the prediction limits. Once a regression relationship at a site is determined, then the average prediction limits can be used.

## 14.3 Finite Element Analysis

- Finite Element Analysis can be used to predict when a bridge freezes or thaws out based on the assumption of a future air temperature profile with no solar radiation. If one adds assumptions about how fast a weather front moves through and how quickly the deicing chemicals work, then one could determine a "treatment window" within which brine or salt must be applied in order to effect anti-icing before onset of winter conditions.

- Finite Element Analysis could help to determine the influence of solar radiation. However there is no solar radiation measurement equipment on Ohio's RWIS stations.

- Finite Element Analysis of bridge decks is possible but is not a real-time solution. Since it takes at least one hour and a half to run one simulation on a fast PC, an FEA model can not be used to make real-time maintenance decisions by field personnel.

## 14.4 High Mass Bridge Deck Simulator

- Additional research is needed to study the effect of mass and size of the bridge deck simulator on how well it follows actual bridge deck temperature behavior. From the exploratory simulations performed using the 24 in (61 cm) block it is evident that the accuracy of simulations of the BDS relative to a bridge increases as the mass of the BDS block increases.

- A 6 in (15 cm) BDS block responds to rapid air temperature changes, such as those accompanying an advancing cold front, much more quickly than an actual bridge deck does. The present BDS configuration does a better job tracking slower changes in air temperature.

## 14.5 Long-distance Prediction Limits

- An exploratory prediction limit range analysis was conducted using the nighttime BDS temperatures from one RWIS station to predict the prediction limit ranges for a bridge deck at another RWIS station. As expected, the prediction limit ranges increase by up to 75% under long distance conditions making the installation of one BDS for predicting bridge deck temperatures 20 to 40 miles (32 to 64 km) from the home site questionable. This was particularly true for the largest separation distance. Thus the range over which a BDS can predict bridge and road temperatures is limited. Local variations in weather conditions, such as cloud cover, may account for much of the difference.

## 14.6 System maintenance, use, and upgrades

- The survey results indicate that county personnel appear to be not always cognizant of the availability of RWIS data, including BDS and/or pavement temperatures, and that some do not use the system because it is not perceived to be useful.

# 15 Implementation

- For ODOT's investment in the RWIS system with BDS to be fully realized and for ODOT to truly make itself "second to none in snow and ice control", annual training of all winter maintenance personnel at the district and county level is imperative, including county managers and other supervisory personnel. This includes familiarizing winter maintenance decision makers with the BDS and making sure that they know how to use it in conjunction with the RWIS system data and other weather information to make winter maintenance decisions. This annual training will also serve as an opportunity for ODOT to reinforce the importance of "weather consciousness" in personnel and to encourage the use of anti-icing techniques.

- A second step to enhance use of the system would be for ODOT to actively and periodically solicit user feedback on how to improve the system, at the very least how to improve the configuration and presentation of RWIS and BDS data so that they are of maximum utility to end users.

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