CIVIL ENGINEERING STUDIES
Illinois Center for Transportation Series No. 16-020
UILU-ENG-2016-2020
ISSN: 0197-9191

EVALUATION OF SOFTWARE SIMULATION OF ROAD WEATHER INFORMATION SYSTEM

Prepared By
William R. Vavrik, Ph.D., P.E.
Carmine E. Dwyer, P.E.
Wouter C. Brink, Ph.D.
Gregg Larson
Applied Research Associates, Inc.

Research Report No. FHWA-ICT-16-018

A report of the findings of

ICT PROJECT R27-142
Evaluation of Software Simulation of Road Weather Information System

Illinois Center for Transportation

September 2016

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-ICT-16-018		

4. Title and Subtitle
Evaluation of Software Simulation of Road Weather Information System

5. Report Date
September 2016

6. Performance Organization Code

7. Author(s)
William R. Vavrik, Carmine E. Dwyer, Wouter C. Brink, Gregg Larson

8. Performing Organization Report No.
ICT-16-020
UILU-ENG-2016-2020

9. Performing Organization Name and Address
Applied Research Associates, Inc.
100 Trade Centre Dr., Suite 200
Champaign, IL 61820

10. Work Unit No.

11. Contract or Grant No.
R27-142

12. Sponsoring Agency Name and Address
Illinois Department of Transportation (SPR)
Bureau of Materials and Physical Research
126 East Ash Street
Springfield, IL 62704

13. Type of Report and Period Covered
Oct. 1, 2014–Sep. 30, 2016

14. Sponsoring Agency Code
FHWA

15. Supplementary Notes
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

A road weather information system (RWIS) is a combination of technologies that collects, transmits, models, and disseminates weather and road condition information. Sensors measure a range of weather-related conditions, including pavement temperature and status (wet, dry, snow), subsurface pavement temperature, wind speed and direction, precipitation, water level conditions, humidity, and visibility. These data are transmitted to automated warning systems, traffic operations centers, emergency operations centers, and road maintenance facilities for decision support. The Enhanced Integrated Climatic Model (EICM) is a computerized heat and moisture flow model that simulates changes in pavement and subgrade properties. It has evolved over the past 40 years and is a key module in the American Association of State Highway and Transportation Officials (AASHTO) Pavement ME Design software. Using the EICM as a software-based RWIS can "virtualize" the data that would be gathered by conventional RWIS hardware and software systems. The software-based RWIS stations would provide current conditions as well as pavement temperature forecasts to supplement or replace hardware in the RWIS network.

The objective of this study was to evaluate the use of the EICM to determine pavement surface temperature for winter maintenance operations. Detailed pavement information at Illinois Department of Transportation, Illinois Tollway, and McHenry County RWIS locations was collected and used to model pavement surface temperatures with the EICM. The modeled pavement surface temperatures were compared with the measured pavement surface temperatures from the RWIS sensors.

Data analysis showed that, when the pavement materials are used at the correct thickness and recommended default values are used for material types, a reasonable pavement surface temperature prediction can be obtained. Using these recommended default values for thermal conductivity, heat capacity, and shortwave absorptivity results in a reasonable modeled pavement temperature that can be used for understanding future snow and ice potential from forecast weather data.

17. Key Words	18. Distribution Statement
Roadway, weather, RWIS, vRWIS, EICM, pavement, surface temperature, thermal conductivity, heat capacity, thermal absorptivity, icing, precipitation, freezing	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	34 pp.	

ACKNOWLEDGMENT, DISCLAIMER, MANUFACTURERS' NAMES

This publication is based on the results of **ICT-R27-142, Evaluation of Software Simulation of Road Weather Information System**. ICT-R27-142 was conducted in cooperation with the Illinois Center for Transportation; the Illinois Department of Transportation (IDOT); and the U.S. Department of Transportation, Federal Highway Administration (FHWA). Additional cooperation was provided by the Illinois Tollway and McHenry County.

Members of the technical review panel (TRP) were the following:

- Derek Parish, TRP Chair
- Rick Walker, TRP Past Chair, IDOT D6 retired
- Llyle Barker, National Weather Service
- Rueben Boehler, IDOT
- Ryan Culton, IDOT
- Brent Gronewold, IDOT D6
- Scott Kapton, Illinois Tollway
- Edward Markison, McHenry County
- Dean Mentjes, FHWA
- Tim Peters, IDOT BLRS

EXECUTIVE SUMMARY

Over the past 40+ years, a computerized climatic model has evolved that can accurately predict the temperature in pavement systems based on atmospheric weather data inputs and pavement materials. This model is the Enhanced Integrated Climatic Model (EICM). The EICM started as the University of Illinois Heat Transfer Model in 1969 and has undergone continuous improvement, allowing it to be used with current pavement materials and structure data, historical weather data, and forecast atmospheric weather data to forecast pavement temperature and moisture conditions. When used as a real-time monitoring tool, the EICM can evaluate the probability of icing conditions at the pavement surface. The five weather-related parameters that are required to run the EICM are air temperature, wind speed, percentage of sunshine, precipitation, and relative humidity. These inputs are used to estimate the heat transfer between the road and the atmosphere. Using the EICM allows pavement surface conditions to be monitored on a frequent basis, identifying times of high probability of surface ice formation.

The EICM was used to model measured pavement temperatures. The objective of this project was to evaluate the use of the EICM for determining pavement surface temperature for winter maintenance operations. Modeling the pavement temperatures could provide virtual RWIS data at a cost that is considerably less than the cost of physical sensors and systems. The study involved collecting pavement material information, modeling the pavements over the past 5 years at these locations with actual atmospheric weather data, and evaluating the difference between actual and EICM modeled pavement temperatures.

Comparisons between the measured and predicted pavement temperature were made by collecting measured pavement temperatures and pavement structure information for various sites across the State of Illinois. A total of 38 sites was selected, which consisted of 25 Illinois Department of Transportation (IDOT) sites, 11 Illinois Tollway sites, and two McHenry County sites. The temperature data were compared using the Pavement ME default parameters for thermal conductivity, heat capacity, and absorptivity. Additionally, the model was calibrated for each site by adjusting the parameters discussed above.

Two different climate datasets were used to model the predicted pavement temperatures. Both climate datasets showed very good results when comparing the measured and predicted pavement temperatures ($R^2 >$ 0.8). The average mean temperature difference among all sites was 2.5°F for all temperatures and 1.1°F for both ±10°F and ±5°F from freezing (32°F). The calibration process was completed by running a design matrix of different thermal conductivity, heat capacity, and absorptivity values. The matrix consisted of 27 total combinations for both flexible and rigid pavements. The EICM was executed for each combination, and the root mean square error (RMSE) and mean error were determined. The top ten combinations based on the ±5°F RMSE were used to determine the new recommended values for Illinois pavements. Based on the results, the recommended values for thermal conductivity, heat capacity, and absorptivity of pavements with a PCC surface were 1.5, 0.3, and 0.85, respectively. The values were 1.0, 0.25, and 0.85 for flexible and composite pavements.

Using the recommended thermal inputs and the actual in-place pavement structure (material types and layer thicknesses) as inputs to the EICM yields reasonable model accuracy with a mean error that is generally less than 2°F. Understanding that the model error is a function of the quality of the weather data, the quality of the sensor data, and the validity of the model, an error of less than 2°F is considered reasonable and is appropriate for use in a virtual RWIS.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

Over the past 40+ years, a computerized climatic model has evolved that can accurately predict the temperature in pavement systems based on atmospheric weather data inputs and pavement materials. This model is the Enhanced Integrated Climatic Model (EICM). The EICM started as the University of Illinois Heat Transfer Model in 1969 and has undergone continuous improvement, allowing it to be used with current pavement materials and structure data, historical weather data, and forecast atmospheric weather data to forecast pavement temperature and moisture conditions. When used as a real-time monitoring tool, the EICM can evaluate the probability of icing conditions at the pavement surface.

Historically, the EICM has been used for pavement performance research and as a key component in pavement performance modeling and pavement design. The EICM is one of the key modules in the American Association of State Highway and Transportation Officials (AASHTO) Pavement ME Design software, which is the commercial version of the Mechanistic-Empirical Pavement Design Guide (MEPDG). The EICM has been demonstrated in the literature to be used for:

- Soil properties—shrinkage, suction, moisture, and temperature, freeze-thaw damage
- Unbound materials—resilient modulus, moisture, freeze-thaw damage, frost penetration, seasonal variation of moduli
- Thermal stresses in concrete pavements—warping, curling, performance modeling, cracking
- Thermal cracking and thermal engineering properties of asphalt pavements

WHAT IS THE EICM?

The EICM is a one-dimensional forward finite difference heat and moisture flow model that simulates changes in pavement and subgrade properties. It incorporates patterns of rainfall, solar radiation, cloud cover, wind speed, and air temperature at the pavement surface. The five weather-related parameters that are required to run the EICM include air temperature, wind speed, percentage of sunshine, precipitation, and relative humidity. These inputs are used to estimate the heat transfer between the road and the atmosphere, as shown in Figure 1.

The EICM is made up of three main components: the climate-materials structural model (CMS model) developed at the University of Illinois, the frost-heave and settlement model (CRREL model) developed at the United States Army Cold Regions Research and Engineering Laboratory, and the infiltration-drainage model (ID model) developed at Texas A&M University’s Texas Transportation Institute. The EICM predicts temperature, resilient modulus adjustment factors, pore water pressure, water content, frost and thaw depths, and frost heave throughout the complete pavement and subgrade profile for the entire design life of the pavement structure.

One of the limitations of the current models in the EICM is the treatment of precipitation when determining the pavement surface conditions. Currently, precipitation data are used to determine infiltration of moisture into the pavement, not to impact the surface temperature of the pavement.

This limitation will be explored and reviewed to determine how best to change the model inputs or the model formulation so that precipitation is taken into account in the heat balance at the pavement surface.

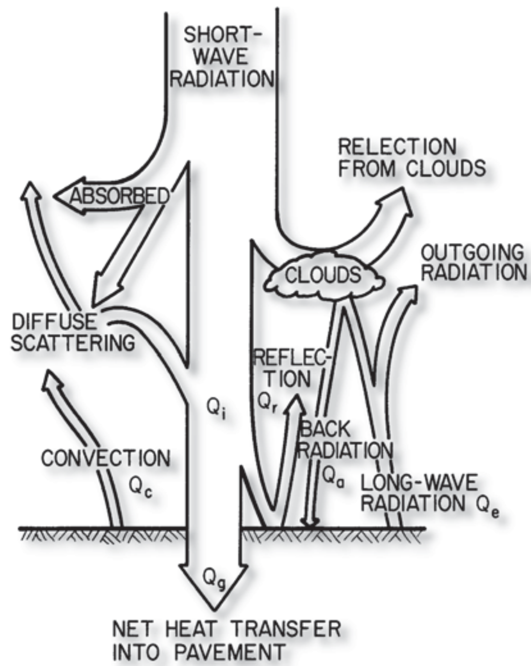


Figure 1. Schematic of heat transfer at the pavement surface.

1.2 APPLICABILITY OF EICM TO ROAD WEATHER FORECASTING

The EICM can easily accommodate hourly or more frequent weather data inputs, thereby making it adaptable to real-time prediction of pavement temperatures and precipitation conditions. Using the EICM allows pavement surface conditions to be monitored on a frequent basis, identifying times of high probability of surface ice formation.

An advantage of using the EICM-based pavement forecast is that a history of the pavement surface temperatures can be maintained so that conditions that lead to icing can be readily identified. One of these conditions could occur, for example, in situations where extreme cold spells are followed by precipitation at temperatures just above freezing. In those situations, the pavement surface and temperatures as a function of depth will often remain below freezing, and ice forms when rainfall occurs just above the freezing temperature.

Because using the EICM-based pavement forecast requires no physical hardware installation, EICM-based pavement temperature and forecast stations for road weather applications would be considered software-based or virtual road weather information systems. It is anticipated that software-based systems would have significant advantages in an overall winter maintenance program.

1.3 ROAD WEATHER INFORMATION SYSTEMS

A road weather information system (RWIS) is a combination of technologies that collects, transmits, models, and disseminates weather and road condition information. The component of an RWIS that collects weather data is the environmental sensor station (ESS). An ESS is a suite of sensors that collects and transmits pavement and meteorological data. Sensors measure a range of weather-related conditions, including pavement temperature and status (wet, dry, snow), subsurface pavement temperature, wind speed and direction, precipitation (amount, occurrence, type), water level conditions, humidity, and visibility. These data are transmitted to automated warning systems, traffic operations centers, emergency operations centers, and road maintenance facilities for decision support. Weather service providers also use the data to develop tailored road weather products (for example, pavement temperature forecasts). All of these activities make for safer roadway conditions for motorists.

In the past, RWIS were used almost exclusively by state and local transportation maintenance departments to make better operational decisions. The collected weather data allowed agencies to coordinate anti-icing practices; efficiently plan winter maintenance routes; reduce the amount of chemicals, sand, and salt used in roadway clearing operations; and reduce wear and tear on maintenance vehicles. Now, state and local transportation agencies are sharing weather data with a broader audience of weather data users, recognizing the inherent value of a better-informed traveling public.

1.4 CURRENT USE/COST OF RWIS?

The cost to procure, implement, and maintain an RWIS is a significant investment. A single RWIS station can have an initial cost of $20,000 to $50,000 per station, depending on the location and the number of sensors used. The software and hardware to run the RWIS can be an additional $20,000. Telephone and other communication lines are required to transmit the data to the RWIS. The computers and hardware have a limited useful life and need to be updated approximately every 5 years. Annual system maintenance can cost $1,000 or more per station per year. Reducing these costs to a uniform equivalent annual cost brings the cost of ownership in a range from $1,000 to $10,000 per station per year.

1.5 PROJECT OPPORTUNITY STATEMENT

Using the EICM as a software-based RWIS can "virtualize" the data that would be gathered by conventional RWIS hardware and software systems. Software-based RWIS stations would provide current conditions as well as pavement temperature forecasts to supplement or replace hardware in the RWIS network. The ability to have a software-based RWIS every 10 miles on every interstate in Illinois and have stations in every county would provide improved road weather maintenance decision support to the Illinois Department of Transportation (IDOT) and local agencies.

1.6 PROBLEM STATEMENT

Using the EICM to model pavement conditions and provide a pavement forecast requires that the modeled pavement conditions mimic the actual observed pavement conditions. The accuracy of the model relates directly to the applicability of using it for winter maintenance opportunities.

The accuracy an EICM-based weather station depends on the quality of the model, the quality of the atmospheric weather data and forecast, and the pavement properties. Because the quality of the model is high and well documented in the literature, and the quality of atmospheric weather data and forecasts is covered in other disciplines, this study focused on understanding how the pavement material properties impact the model accuracy.

The pavement property inputs for the EICM include heat capacity, thermal conductivity, shortwave absorptivity, porosity, unit weight, and permeability. Very few of these pavement properties are measured in the pavement design or construction process. This project determined the best EICM model inputs using data available from design or construction that minimize model error. The study involved collecting pavement material information, modeling the pavements over the last 5 years at these locations with actual atmospheric weather data, and evaluating the difference between actual and modeled pavement temperatures.

1.7 PROJECT OBJECTIVE

The research team evaluated the use of the EICM to determine pavement surface temperature for winter maintenance operations. Detailed pavement information was collected at IDOT, Illinois Tollway, and McHenry County RWIS locations and used to model pavement surface temperatures with the EICM. The modeled pavement surface temperatures were compared with the measured pavement surface temperatures from the RWIS sensors. The ultimate goal of the project was to determine whether appropriate EICM inputs to minimize model error can be determined from readily available data.

CHAPTER 2: RWIS DATA COLLECTION AND SITE SELECTION

2.1 GATHERING DATA FROM ILLINOIS RWIS SITES

To compare measured and predicted pavement surface temperatures, the researchers gathered all historical RWIS data from the study participants (IDOT, Illinois Tollway, and McHenry County). RWIS stations can have many different sensors providing weather-related data. This study was primarily concerned with temperature data from pavement surface sensors, such as the one shown in Figure 2.

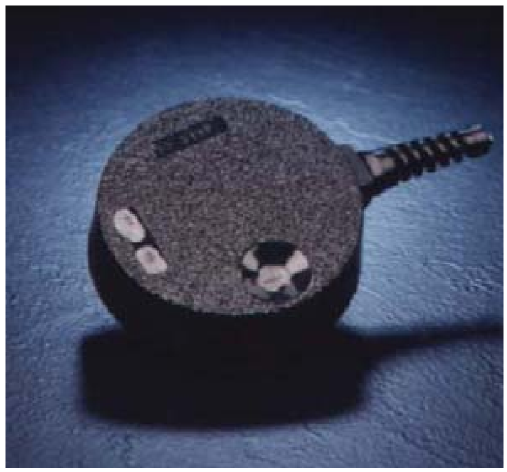


Figure 2. Pavement surface sensor.

After the research team received the datasets, the data fields were reviewed to determine which stations had pavement surface sensors. Some stations had multiple pavement surface sensors, some had no surface sensors, and others had only bridge deck surface sensors. Table 1 reports the total number of RWIS stations for each participating agency, as well as the number of stations with pavement (non-bridge deck) surface sensors. The number of RWIS sites with pavement surface sensors represents the potential sites to be included in the measured versus predicted comparisons.

Table 1. Number of Potential RWIS Study Sites

Participating Agency	Total Number of RWIS Sites	Number of RWIS Sites with Pavement Surface Sensors
Illinois Department of Transportation	58	49
Illinois Tollway	17	13
McHenry County	6	6

2.2 SELECTING RWIS SITES FOR STUDY ANALYSIS

There were 68 potential study sites with pavement surface sensors. Because sensors can malfunction, be damaged, or go missing, the researchers analyzed the historical pavement surface temperature data from each site for completeness and reasonable value ranges. Because predicted pavement surface temperatures for this study were based on current pavement structures (current material properties and layer thicknesses), only the five most recent, full-year datasets (2009 to 2014) were reviewed. The goal of this review was to eliminate sites with too much missing data, particularly in the months in which freezing and icing surface conditions can exist, and to eliminate sites with outlier data.

Figure 3 is an example of one site with a considerable amount of missing data for a given winter month of one year. Figure 4 is an example of two sites with good data—a complete set of data with expected, reasonable values for a given colder month.

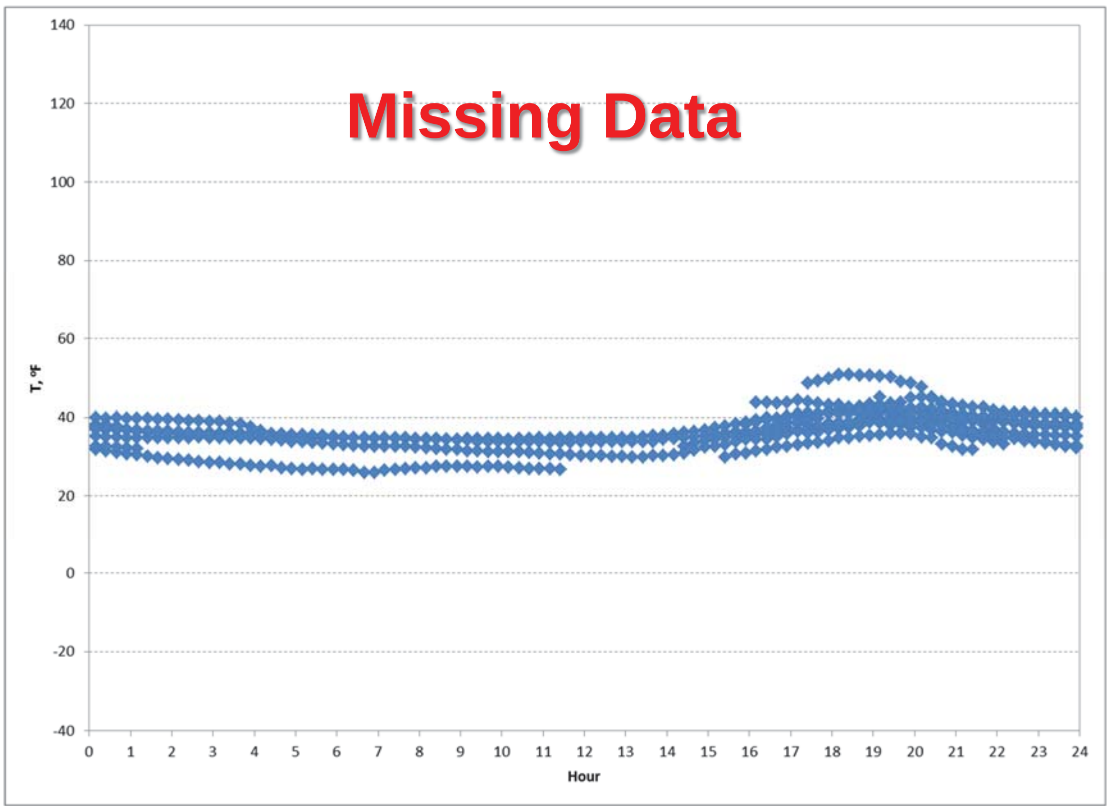
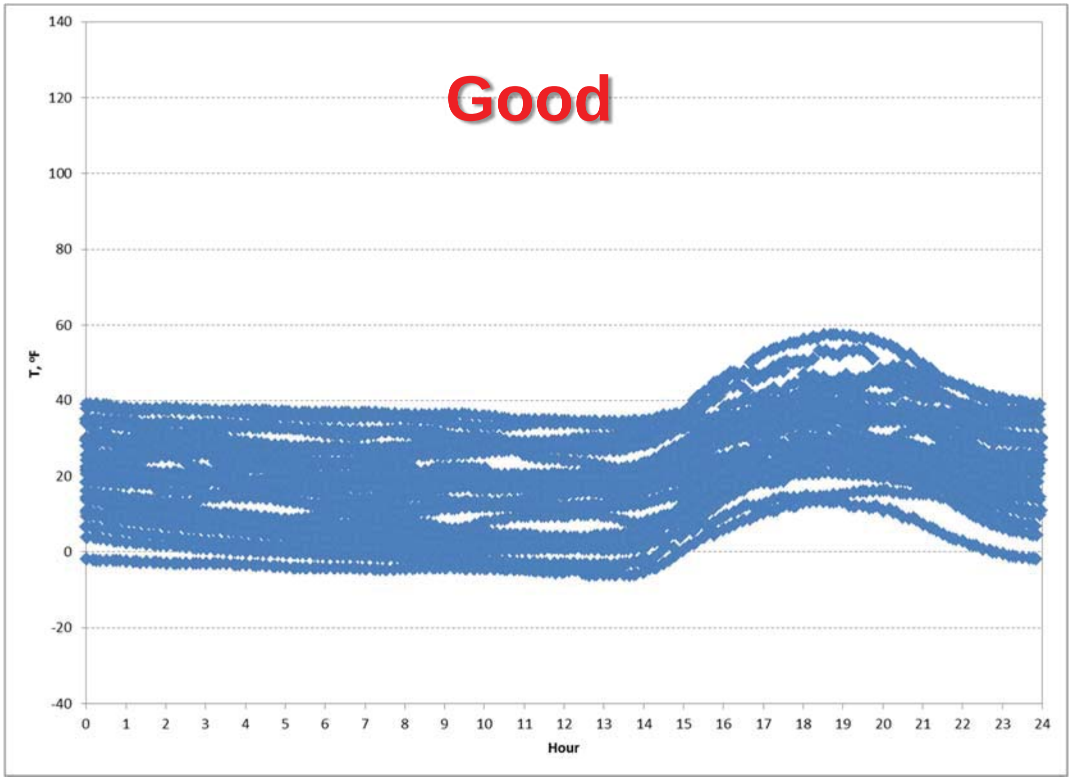


Figure 3. One winter month's hourly temperatures for one RWIS site with missing data.



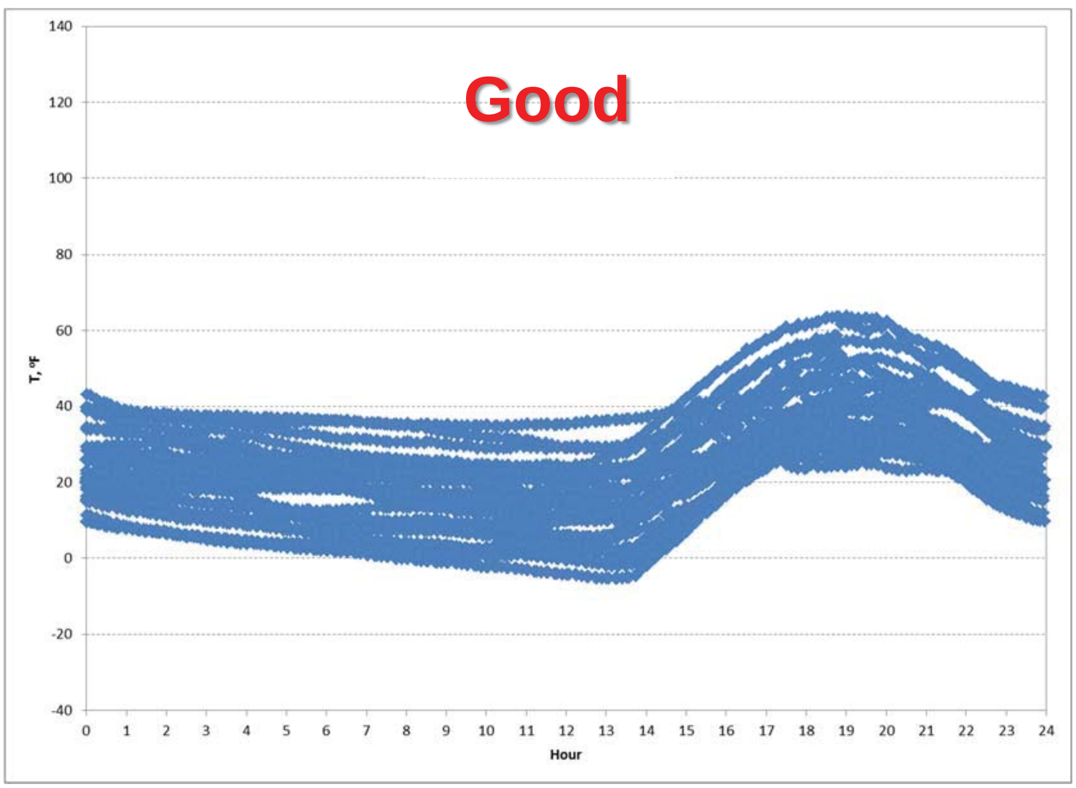


Figure 4. One winter month's hourly temperatures for two RWIS sites with complete data.

When RWIS sites were selected for prediction comparisons, a representative distribution of other factors was considered. These factors included the following:

- Locations throughout the state
- Pavement type (asphalt concrete, portland cement concrete, composite)
- Pavement thickness
- Traffic volume

At the conclusion of the measured temperature data analysis, 38 RWIS pavement surface sensor sites were selected. The number of sites selected, by agency, was as follows:

- Illinois Department of Transportation: 25
- Illinois Tollway: 11
- McHenry County: 2

Figure 5 is a map of the 38 sites and shows the distribution of site locations across Illinois.

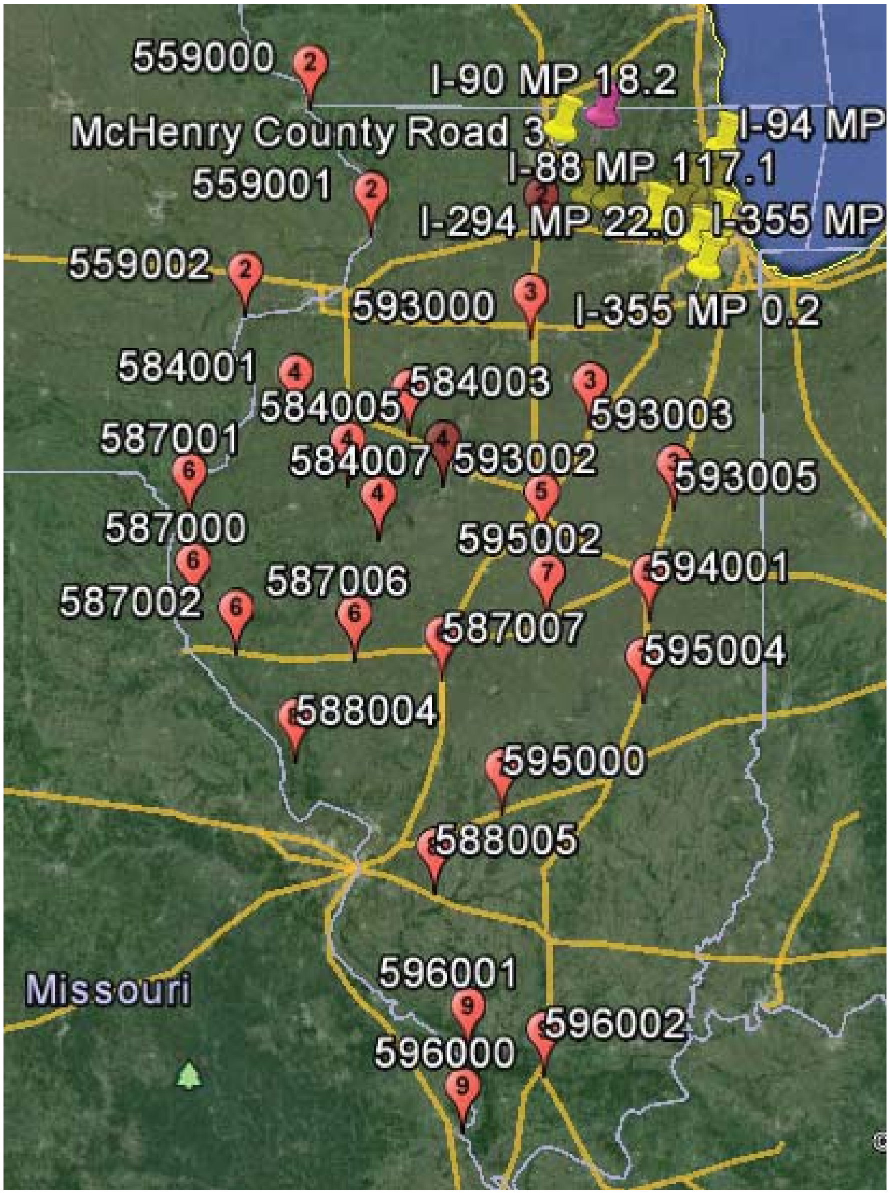


Figure 5. Illinois RWIS sites selected for measured versus predicted analysis.

CHAPTER 3: CREATION OF PREDICTED DATA

3.1 PAVEMENT DATA COLLECTION

Pavement Coring

To ensure the predicted pavement surface temperatures were developed based on the current, in-place pavement structure, the researchers sent a field crew to each of the 38 selected RWIS sites to collect pavement data. Data collection included the following:

- Coring the pavement structure to determine pavement layer thicknesses
- Augering the base course to determine base layer thickness and material type
- Measuring pavement surface color

Figure 5 depict the coring and auguring processes, respectively.

Figure 6. Pavement coring.

Figure 7. Removing base course material.

The core logs from the RWIS sites are presented in Appendix A of this report. These logs note the core location and thickness of the pavement layers. Core photographs are also provided.

Pavement Color

Five pavement surface color measurements were recorded in each location for potential correlation between surface color and pavement thermal absorptivity. Measurements were taken with a spectrophotometer, like the one shown in Figure 8. All measurements were taken prior to coring. One was taken in the center of the core location, and the remaining four were taken around the perimeter of the core location.

Figure 8. Konica Minolta CM-2500c spectrophotometer.

The pavement colors from the RWIS sites are presented in Appendix B of this report. These logs note the location where the color measurement was taken and the measured pavement color. Photographs are also provided with a standard grayscale color band.

3.2 VIRTUAL RWIS SITE CREATION

The collected pavement data were used to create input files for the EICM for each of the 38 sites. The EICM input file was then used to create the respective virtual RWIS sites. Figure 9 shows a map of all 38 sites in the virtual RWIS program. During the creation of these sites, the five most recent years of historical data (2009 to 2014) were generated for comparison to the measured data.

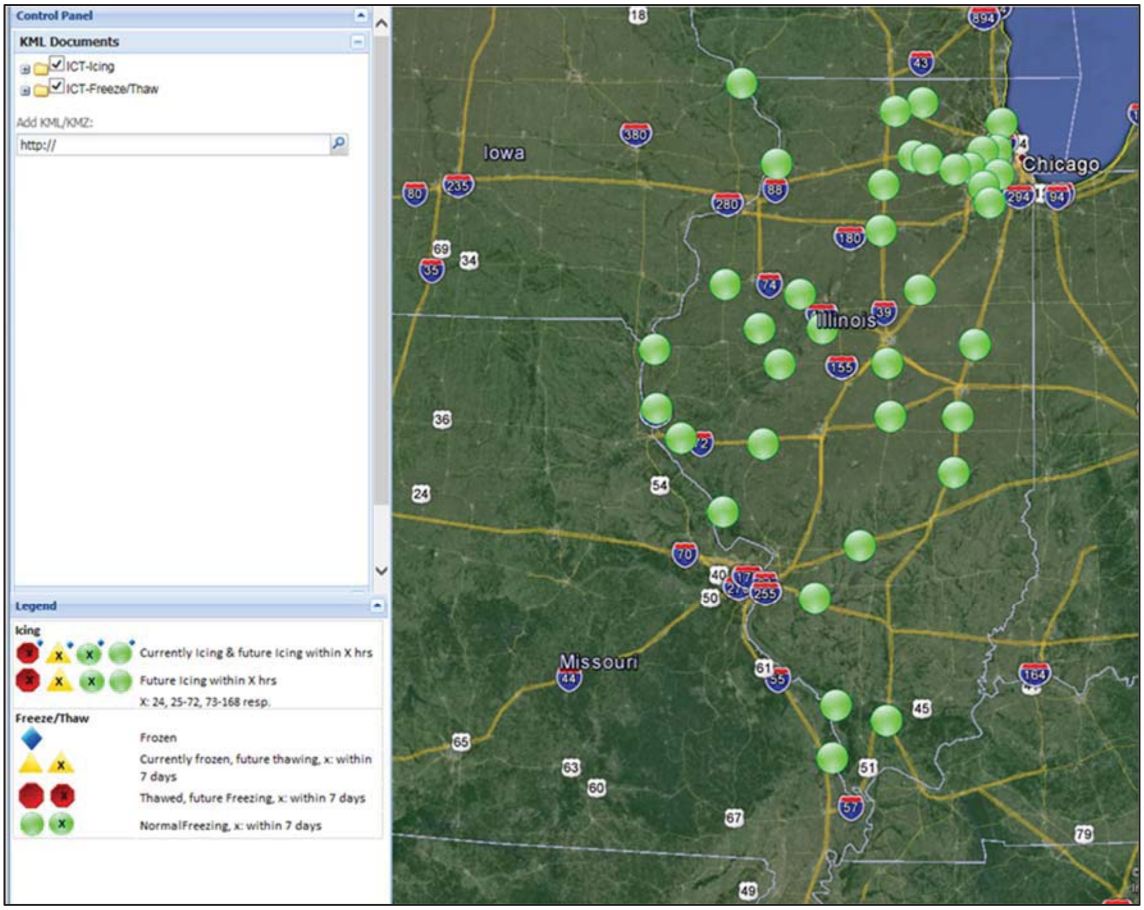


Figure 9. The 38 selected sites shown in ARA's Virtual RWIS program.

CHAPTER 4: ANALYSIS OF PREDICTED VERSUS MEASURED DATA

4.1 DATA PREPARATION

Table 2 provides summary information on the 38 sites included in the study. The raw measured pavement temperature data were extracted from the various IDOT, Illinois Tollway, and McHenry County databases for processing prior to comparing the measured and predicted data.

Figure 10 shows the geographical distribution of the project sites throughout Illinois. The different colors represent the different data sources.

Table 2. Project Sites

Site Number	Station	SiteID_ SensID	Lat	Long	Pavement Type
Site 1	Tollway_I-355 @ Des Plains River - MP 9.5	5_0	41.66389	–88.02479	PCC
Site 2	Tollway_I-355 @ I-80 - MP 0.2	6_0	41.53845	–87.96227	PCC
Site 3	Tollway_I-294 @ Mile Long Bridge - MP 22.0	2_0	41.75408	–87.87294	PCC
Site 4	Tollway_I-294 @ Bensenville RR Bridge - MP 36.9	1_0	41.94062	–87.89380	PCC
Site 5	Tollway_I-94 @ Edens Spur - MP 27.2	17_0	42.14887	–87.84001	Composite
Site 6	Tollway_I-88 @ Fox River Bridge - MP 117.1	8_0	41.79595	–88.32345	PCC
Site 7	Tollway_I-88 @ County Line Road - MP 100.7	7_0	41.8745	–88.60807	Composite
Site 8	Tollway_I-88 @ Route 23 - MP 92.5	9_0	41.90289	–88.75318	Composite
Site 9	McHenry_CH30 @ Westbound	665001_1	42.31308	–88.66394	AC
Site 10	McHenry_CH30 @ Eastbound	665001_5	42.31303	–88.66390	AC
Site 11	Tollway_I-90 Kishwaukee River - MP 18.2	13_0	42.24713	–88.94598	AC
Site 12	Tollway_I-355 @ Army Trail - MP 29.8	4_0	41.93167	–88.03780	PCC
Site 13	Tollway_I-88 @ Winfield Road - MP 125.2	12_0	41.80652	–88.16683	PCC
Site 14	IDOT_I-57 @ IL-9 Paxton	593005_2	40.45452	–88.11241	Composite
Site 15	IDOT_I-39 @ Lincoln Bridge	593000_0	41.32918	–89.07495	PCC
Site 16	IDOT_I-39 @ Lee County - MP 81	559004_1	41.67969	–89.05265	Composite
Site 17	IDOT_US20 @ near East Dubuque	559000_0	42.46255	–90.57733	Composite
Site 18	IDOT_US30 @ Clinton	559001_0	41.8379	–90.17255	PCC
Site 19	IDOT_IL-9 @ McNaughton Bridge	584002_2	40.5725	–89.65180	PCC
Site 20	IDOT_I-74 @ Brimfield Rd	584003_2	40.83507	–89.88917	Composite
Site 21	IDOT_IL-9 @ Spoon River	584005_2	40.56775	–90.29451	AC
Site 22	IDOT_US-136 @ Lacy Ditch	584007_2	40.29575	–90.07898	Composite
Site 23	IDOT_US-136 @ Mississippi River	587001_2	40.38905	–91.36910	AC
Site 24	IDOT_I-172_IL-104 @ Quincy	587000_0	39.93503	–91.32418	Composite
Site 25	IDOT_I-72 @ Barry	587002_0	39.71471	–91.06354	AC
Site 26	IDOT_I-72_US-67 @ Jacksonville	587006_0	39.68697	–90.22854	Composite
Site 27	IDOT_IL-100 @ Joe Page Bridge	588004_0	39.16033	–90.61611	Composite
Site 28	IDOT_I-64 @ IL-160	588005_0	38.51710	–89.68644	AC
Site 29	IDOT_SR-3 @ Gorham	596001_2	37.70056	–89.47248	Composite
Site 30	IDOT_SR-146 @ East Cape Girardeau	596000_0	37.29577	–89.50499	AC
Site 31	IDOT_I-24 @ Pulleys Mill	596002_0	37.59015	–88.97875	Composite
Site 32	IDOT_I-70 @ IL-140	595000_0	38.92359	–89.2463	Composite
Site 33	IDOT_I-57 @ IL-16	594003_1	39.48346	–88.32161	Composite
Site 34	IDOT_I-72 @ US-36 US-51	594000_0	39.9083	–88.9553	Composite
Site 35	IDOT_US-34 @ Monmouth	584001_2	40.90331	–90.6626	AC
Site 36	IDOT_US-51 @ Heyworth	593002_0	40.31149	–88.98928	PCC
Site 37	IDOT_IL-116 @ I-55	593003_0	40.87355	–88.67050	Composite
Site 38	IDOT_I-57 @ US-45	594001_1	39.90551	–88.27932	Composite

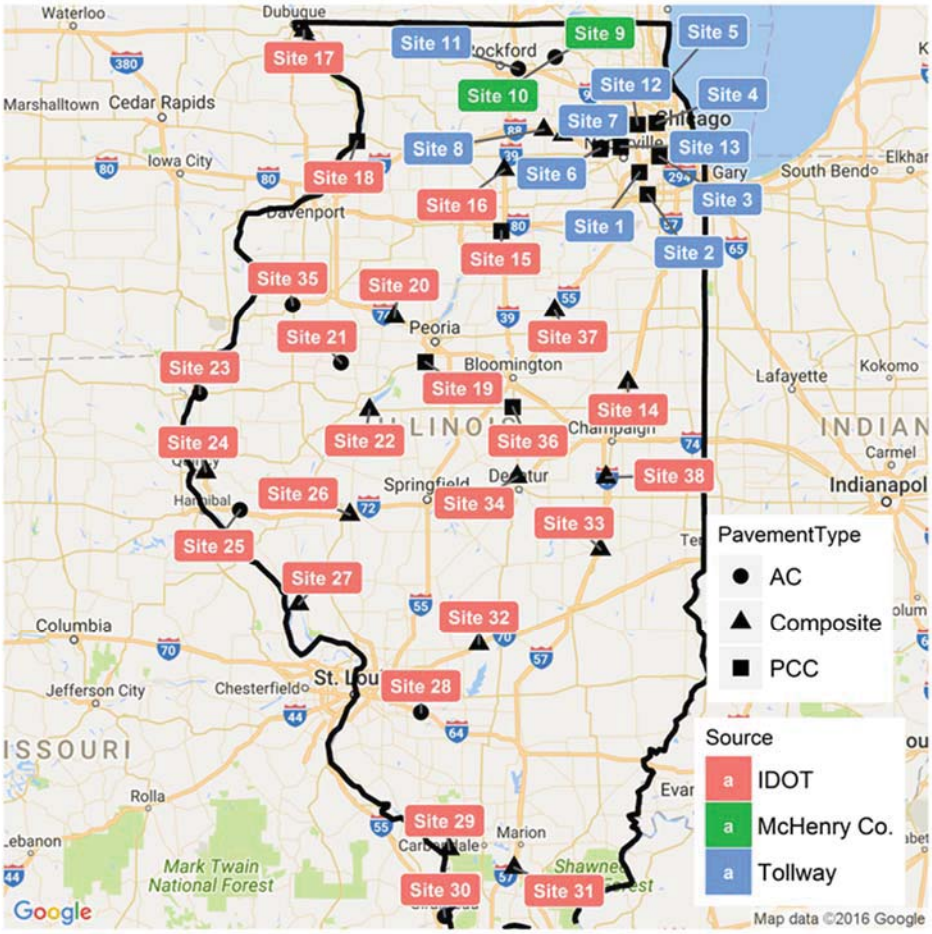


Figure 10. Site locations.

4.1.1 Measured Data

The participating agencies provided the measured data to the research team, and the team internally processed the data for each site to meet hourly formatting needs. The number of data points for each site was significant and varied from every 8 to 12 minutes. Overall, more than 7.3 million data entries were available for the 38 sites. These values were reduced to every hour to be consistent with the predicted values in the Pavement ME Design software. After the data were formatted to hourly measurements, the number of observations decreased to 1.12 million.

Some sites had more data than others. Generally speaking, the IDOT sites had more measured data than the Illinois Tollway and McHenry County sites did.

4.1.2 Predicted Data

The predicted data were obtained by generating an EICM input file using the actual pavement thickness and material information and executing the analysis software to run the EICM. The predicted pavement temperature data were extracted from the EICM output files and stored for further analysis.

4.2 DATA COMPARISON

The data comparison consisted of two different climate datasets. The first dataset consisted of the existing climate stations in the Pavement ME Design software. The second comparison used the North American Regional Reanalysis (NARR) dataset to create new climate files. The details for each climate dataset are discussed briefly below.

4.2.1 Pavement ME Design Climate Files

The original hourly climate database (HCD) was compiled in late 1990s from the National Centers for Environmental Information (NCEI), which was formerly the National Climatic Data Center (NCDC), to support the Federal Highway Administration (FHWA) Integrated Climatic Model (ICM). Originally it contained just 3 years' worth of data. The length of the dataset was limited by what was available for electronic download from the NCEI. The ICM (and, therefore, the Pavement ME Design analyses dependent on the ICM) requires complete input data over the design period to properly execute. The Unedited Local Climatological Data (ULCD) by design is a raw dataset with minimal quality control; data fields with missing data are left blank. The ULCD also contains a small quantity of erroneous data. Early use of the HCD required user input to fix missing or obviously incorrect climatic data.

In 2001, additional data were added to the climatic database, extending the period covered to 6 years. Because the original MEPDG software did not have a utility to edit the climate files, it was determined that all missing data would be filled prior to delivery to the user. A software utility was developed to programmatically fill in missing data and correct bad data. A multi-step process was deployed that identified missing and erroneous data and created a log file of changes made to the ULCD to create the HCD. This utility has been used to fill and correct all currently published climate data files.

The previous method for fixing the files consisted of the following steps:

1. Find missing data.
2. Interpolate missing data, if less than 12 hours.
3. If more than 12 hours, repeat the day from previous good day.
4. If more than a week is missing, mark the month as incomplete.
5. Check for values out of range (relative humidity of over 100, temperatures over 130°F, etc.).
6. Create a log file of any interpolations or corrections.

Stations with incomplete months are available to be used in analyses but require interpolation between nearby stations to complete the missing months. The HCD has been improved at different times to increase the amount of time series data and reduce inconsistencies and anomalies in the dataset. The following is a short description of the dates the HCD was modified, and how:

- In 2006, the HCD was updated using the method described above for the United States and Canada to include climatic data up to December 31, 2005. At that time, the HCD was recompiled with the raw data starting from 1995.
- In 2013, the Canadian stations in the HCD were updated using data from Environment Canada, which added data from the 1940s to December 2012.

The HCD accompanying the Pavement ME Design software includes some missing and/or erroneous data. Some of these anomalies have been identified and flagged. Once they have been flagged, the missing and/or erroneous data can be populated and/or replaced to provide a more representative and accurate dataset. The climate files included in the Pavement ME Design software were populated using data starting in 1995 and ending in 2005 (U.S. sections). Some climate files have more data than others. The current dataset consists of 1,083 climate files for the United States and Canada. Additionally, only climate stations that have complete monthly data are available as a preset station in the software. A complete dataset for all monthly climate measurements is available for 870 climate stations in the United States and Canada.

Original Climate Data Comparison

Figure 11 shows the time-series data for Site 1. This Illinois Tollway portland cement concrete (PCC) site is located on I-355 at Des Plaines River milepost (MP) 9.5. As shown in the figure, the measured temperature data range from 2012 to 2014. For this particular location, data are missing for a few months in 2013. There may have been errors in the sensors, or perhaps data were not collected during that timeframe. The figure also shows the predicted pavement temperature for the dates and times when measured observations were available, as well as the residual error between the measured and predicted pavement temperatures. Based on the residual plot, the error is less for colder temperatures than for warmer temperatures. The lower errors at colder temperatures are beneficial for this project because determining when freezing will occur in the pavement is important.

Such figures were created for all sites included in the study. The rest of these figures using the original climate data are presented in Appendix C.

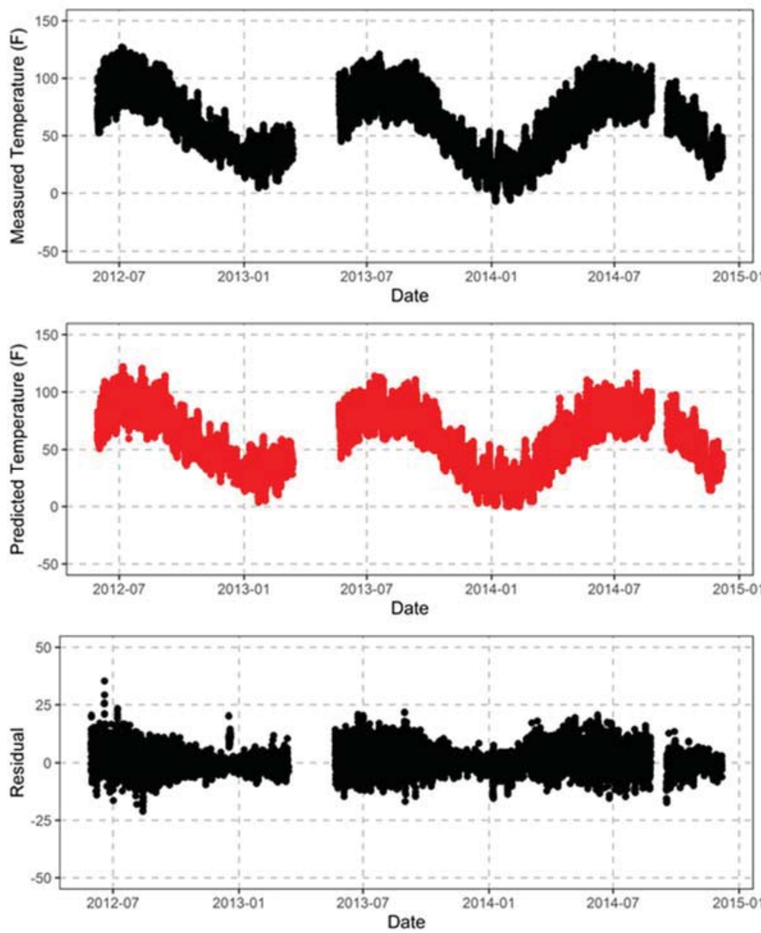


Figure 11. Site 1 time-series pavement temperature data.

Additionally, for each site, a one-to-one comparison plot shows how well the predicted pavement temperatures compare to the measured pavement temperatures. Figure 12 shows an example of the one-to-one plot for Site 1. The figure shows a very good correlation between the predicted and measured temperatures with an R^2 of 0.97 for 18,606 data points. Appendix C contains the measured versus predicted pavement temperature figures for the remaining sites.

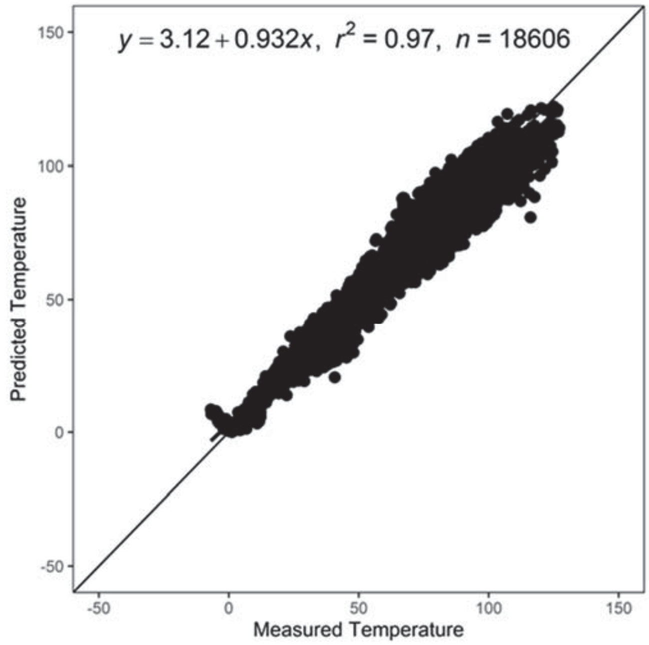
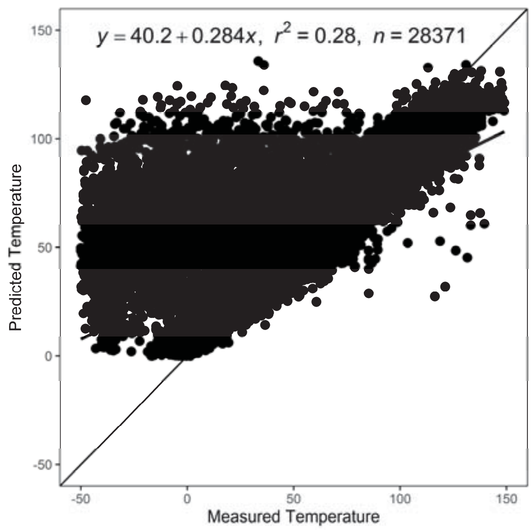


Figure 12. Site 1 measured versus predicted pavement temperature data.

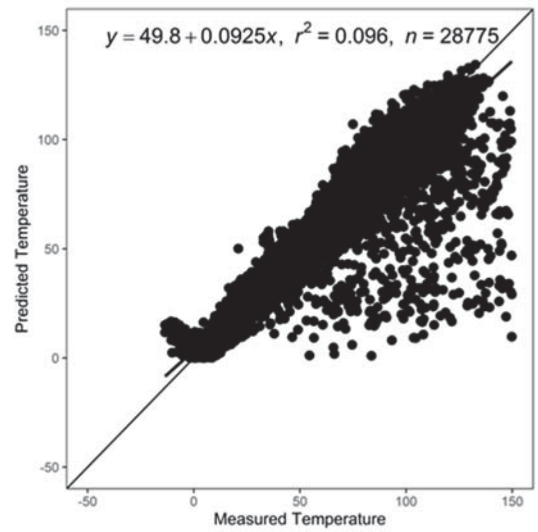
Overall, the majority of the sites showed very good R^2 results. However, some did not. Particularly notable are Site 16 (IDOT I-39 at Lee County) and Site 18 (IDOT US-30 at Clinton). Figure 13 shows the measured versus predicted temperature one-to-one plots for these sites. The R^2 values for those two sites were 0.28 and 0.096, respectively. Site 16 exhibited warmer predicted temperatures compared with the corresponding measured temperatures (over-prediction). Alternatively, Site 18 showed an under-prediction of the measured temperature—the measured temperatures were warmer than the predicted temperatures.

To determine the cause for the over- or under-prediction, the time-series data were observed. Figure 14 illustrates the time-series curves for Site 16 and Site 18. The figures show abnormal temperature measurements for both sites. There does not seem to be a consistent hourly trend in the abnormal data. The causes for these measured temperature anomalies are unknown. Therefore, these values were excluded from the final analysis comparisons.

Similar analysis was performed on the other sites for consistency. Based on the findings from using the original climate data and the measured data, data cleaning was performed to ensure reasonable and accurate data were used in the analysis. Additionally, a different dataset for hourly climate data was used to improve the accuracy of the predicted pavement temperatures. The climate data details and the comparison between measured and predicted pavement temperature results are presented and discussed in the next section.

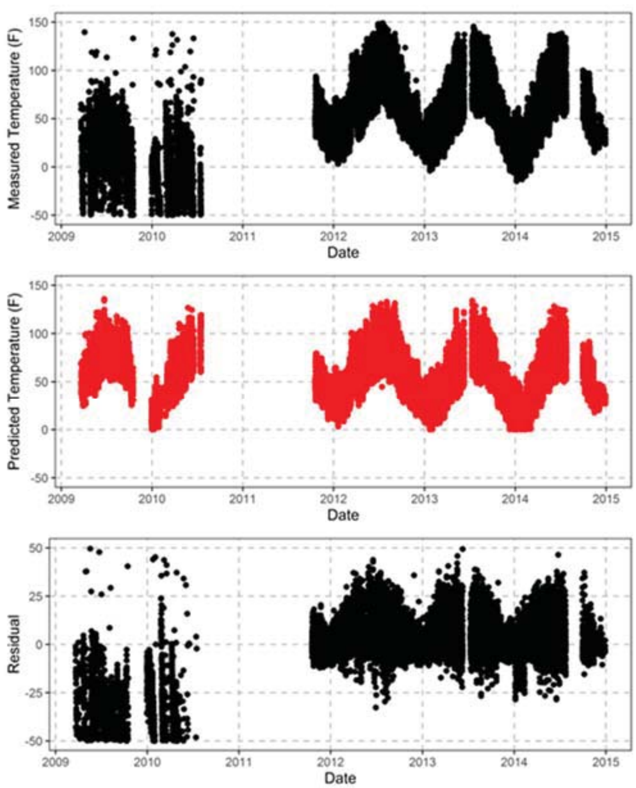


(a) Site 16 measured versus predicted pavement temperature

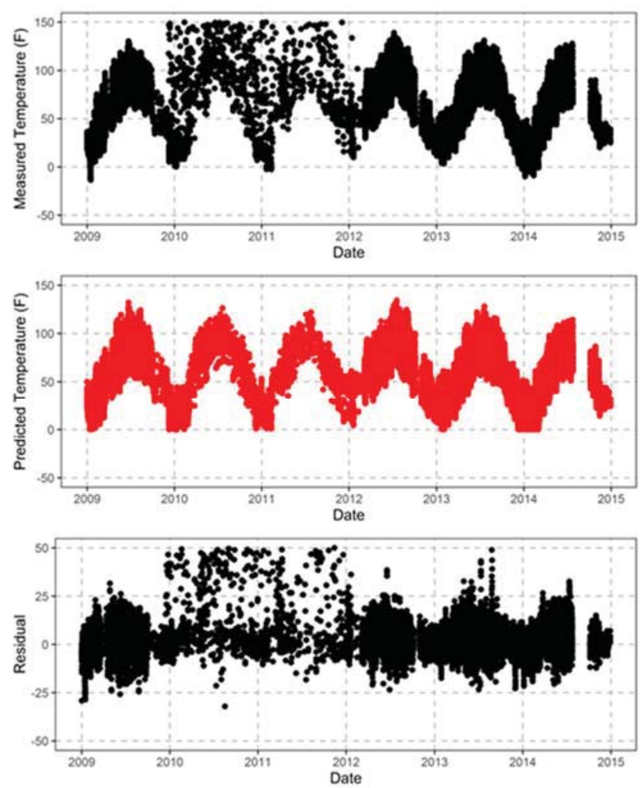


(b) Site 18 measured versus predicted pavement temperature

Figure 13. Measured versus predicted pavement temperature comparisons.



(a) Site 16 time-series pavement temperature data



(b) Site 18 time-series pavement temperature data

Figure 14. Site 16 and Site 18 time-series pavement temperature data.

4.2.2 North American Regional Reanalysis Database Generated Climate Files

The NARR database is used primarily for atmospheric research requiring historical atmospheric conditions and to study the variability of climate conditions. The database was developed by the National Centers for Environmental Predictions to model or assimilate observational data to produce a long-term overview of weather over North America. The model is initialized by using real-world temperature, wind, precipitation, and moisture conditions from surface observations.

Many different sources were used to develop the NARR database. Some of these sources were also used in a global reanalysis, along with a variety of additional sources. These sources include the following:

- National Centers for Environmental Prediction
- National Center for Atmospheric Research
- Global Reanalysis
- Climate Prediction Center
- National Environmental Satellite, Data, and Information Service
- Environmental Modeling Center
- Center for Ocean-Land-Atmosphere Studies
- Great Lakes Environmental Research Laboratory
- Lawrence Livermore National Laboratory

Additional details about which datasets were used for each source can be found in the article titled "North American Regional Reanalysis" by Mesinger et al. (http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-87-3-343).

The NARR data are available for a 32 × 32 km (20 × 20 mile) grid across North America. The data are available in 3-hour, daily, and monthly values from 1979 to present. The longer timeframe of available climate data is a significant improvement over the ranges currently available in the Pavement ME Design software. The 37 years of continuous data are significant because the climate of a location is defined based on the weather data from the previous 30 years. Therefore, the NARR data provide a more accurate representation of climate for any location in North America.

The NARR dataset has gone through several quality control checks and does not need further data smoothing or quality assurance and control. This is a large advantage, given the amount of climate data needed for the Pavement ME Design climate files. Additionally, a climate file can be generated for any latitude or longitude across North America because the NARR dataset is based on a grid system, which eliminates the use of a physical climate station that may not be close to the actual pavement location. It should be noted that the assimilation process in the NARR uses the available observed values in a particular 32 × 32 km grid. The number of available observed values and the topography can affect the assimilation results and impact the quality of the model for some locations.

NARR-Generated Climate Data Comparison

The NARR-generated climate data compilation uses the nearest grid point to the location of each project site. These sites may be different from the nearest climate station. Therefore, there are some differences between the original Pavement ME Design climate file and the NARR-generated climate file. Overall, the NARR database produces a better estimate of a region's climate because it assimilates climate data using many different sources over a longer time period.

The one-to-one plots and time-series plots were also created for the NARR-generated climate data. The results were similar to the results for the original climate data. Figure 15 shows the measured versus predicted pavement temperature for Site 1. The results show a very good correlation (R^2 = 0.95) between the measured and predicted pavement temperature. The scatter around the line of equality was less at colder temperatures than at warmer temperatures. Figure 16 shows the time-series temperature curves and the residual plot for Site 1. The figure indicates that there is a similar trend between the measured and predicted temperatures. Additionally, the residual plot shows that there is a range between -25 and 20 °F for the difference between the measured and predicted pavement temperatures. The larger differences occurred during the summer months.

Appendix B includes the measured versus predicted and time-series figures for the other sites.

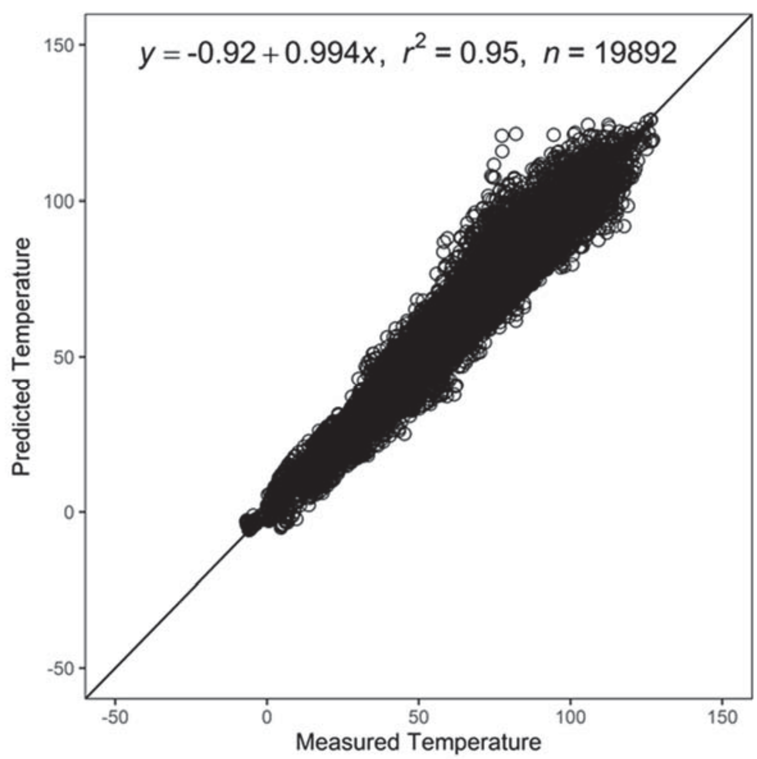


Figure 15. Site 1 measured versus predicted pavement temperature using NARR-generated climate data.

iv

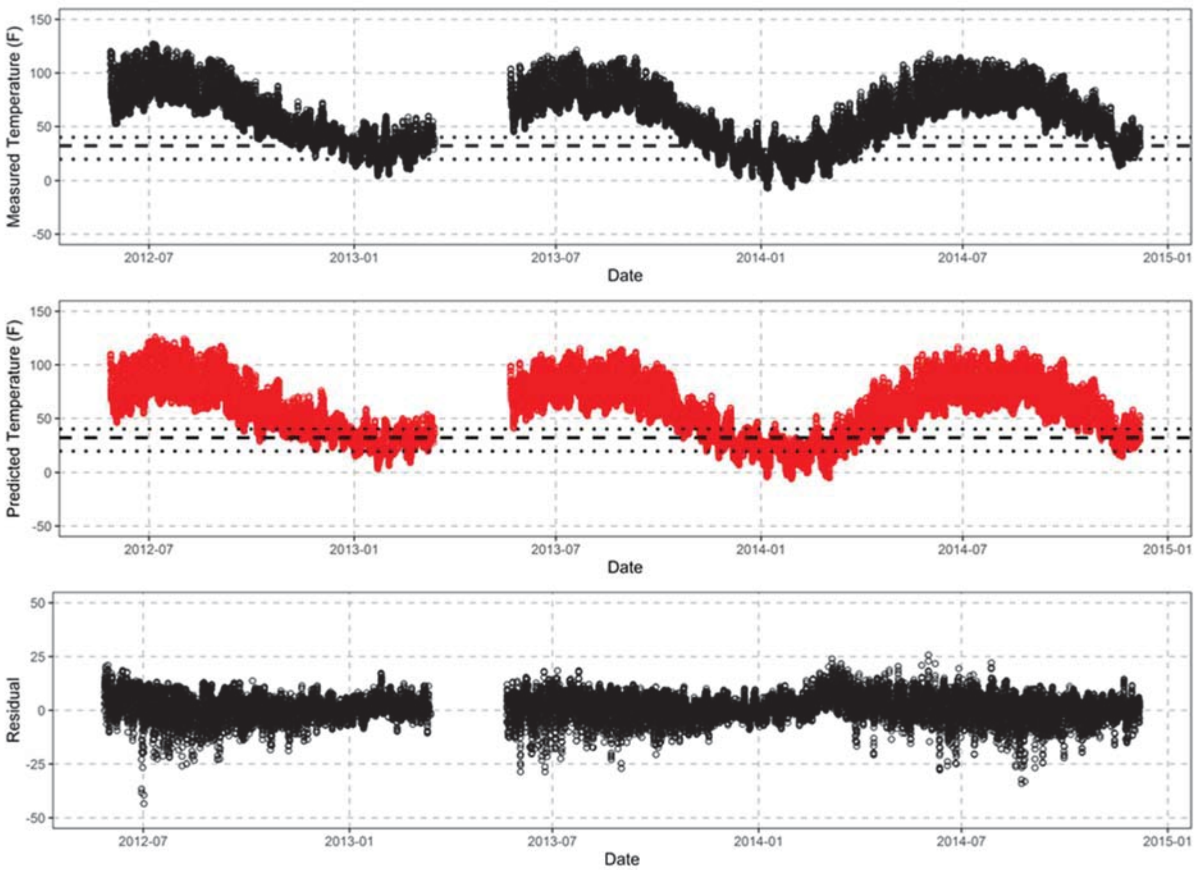


Figure 16. Site 1 time-series pavement temperature data using NARR climate files.

To study the differences between the measured and predicted pavement temperatures, a histogram was created to visually see the spread of the residual error. Figure 17 shows the histogram for Site 1. The results show that the mean difference between the measured and predicted pavement temperature was 1.3°F, with a standard deviation of 6°F. The histogram makes it easier to see how many data points lie closer to zero. If a data point is close to zero, it means there is almost no difference between the measured and predicted pavement temperature.

Appendix D contains histograms for the other sites.

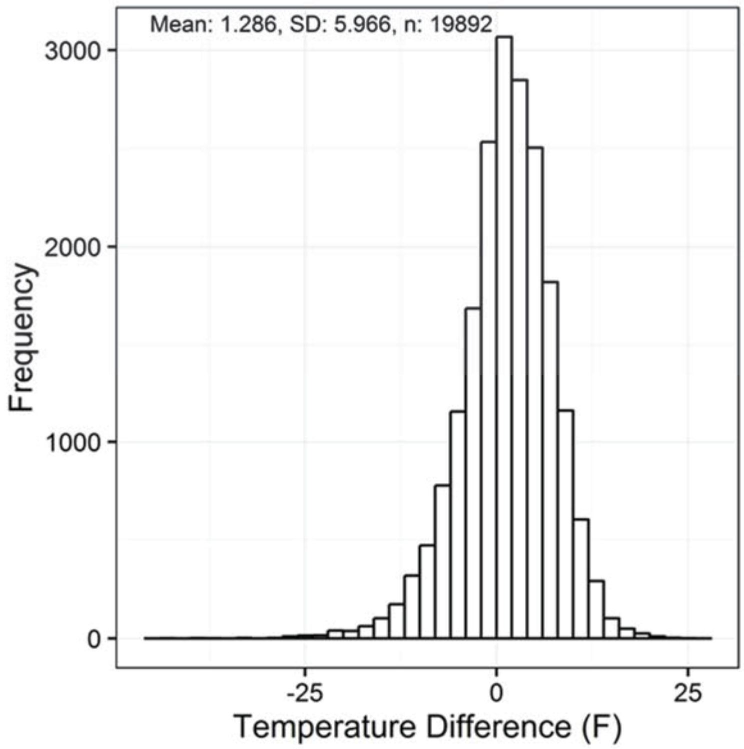


Figure 17. Temperature difference histogram.

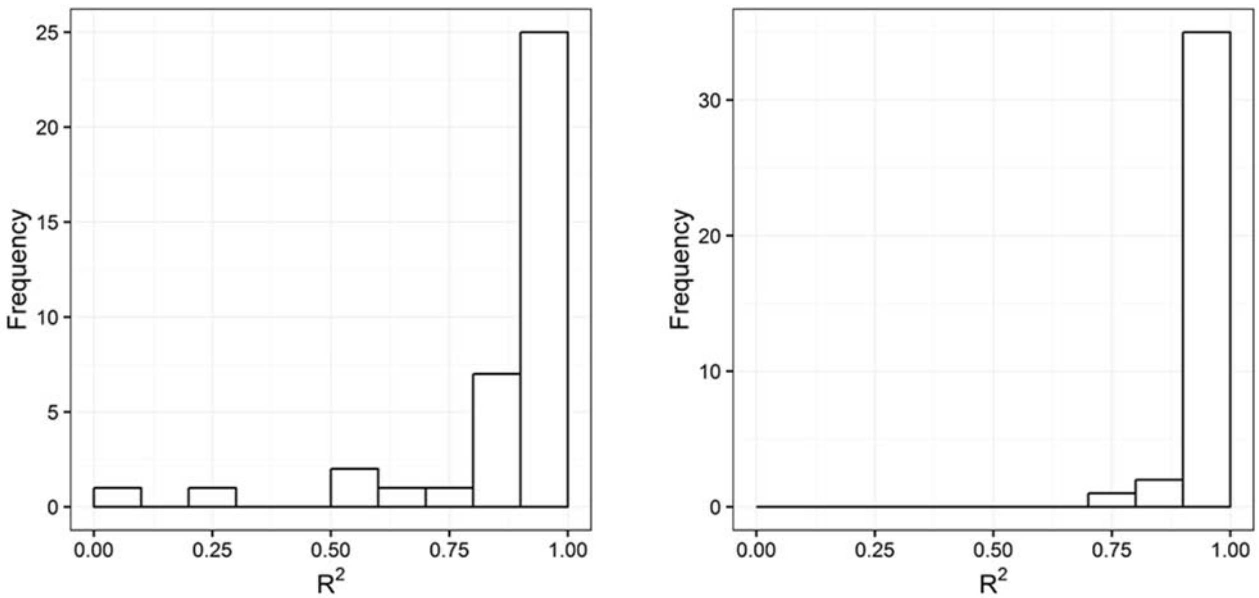
4.3 ANALYSIS SUMMARY

Both the original and NARR-generated climate files showed adequate comparisons between the measured and predicted pavement temperatures. Many of the pavement sites were missing measured data, especially the Illinois Tollway sites. The missing data do not affect the analysis because the predicted data were matched only when measured temperatures were available.

Figure 18 shows the comparison of R^2 for the original and NARR database climate files. The results show that there is a wider spread of R^2 for the predicted pavement temperatures when using the original climate files. Overall, the majority of the sites showed a very good R^2. All of the R^2 values were greater than 0.75 when using the NARR-generated climate files.

Even though there seems to be a good correlation between the predicted and measured pavement temperatures, the research team needed to determine whether the error could be reduced further.

Table 3 summarizes the averages of the mean temperature differences for all sites, as well as the averages for the three different pavement types. The hot-mix asphalt (HMA) pavement sites showed the lowest mean difference for the temperatures ±5 and ±10 °F from freezing. The details on the calibration of the pavement temperature predictions are discussed in Chapter 5. Only the NARR-generated climate data were used in the model calibration review.



(a) Original climate files

(b) NARR database climate files

Figure 18. Summary of R^2 values for all project sites.

Table 3. Average Mean Temperature Differences

Dataset	All	±10 °F	±5°F
Average Among All Sites	2.51	1.13	1.19
PCC Only	2.18	1.35	1.48
HMA Only	2.80	0.91	0.87
Composite Only	2.59	1.09	1.15

CHAPTER 5: CALIBRATION OF MODEL INPUTS

5.1 INTRODUCTION

Chapter 4 presented the comparison between the measured and predicted pavement temperatures for the 38 sites included in this study. Based on the results presented in Chapter 4, the researchers established a process to attempt to reduce the error between the measured and predicted pavement temperatures.

5.2 CALIBRATION PROCESS

The process for calibrating the prediction models consisted of changing the input variables in the Pavement ME Design software that affect the pavement temperature predictions—absorptivity, heat capacity, and thermal conductivity. The absorptivity affects how much of the solar radiation is absorbed into the pavement material. The heat capacity is equal to the ratio of the heat added to/removed from an object to the resulting temperature change. The thermal conductivity is used to determine the properties of a material to conduct heat. These three values can be changed to study the effects on predicted pavement temperature.

5.3 CALIBRATION DESIGN MATRIX

Each of the three input variables was adjusted to three different levels. The levels were selected based on the default values in the Pavement ME Design software and a realistic upper and lower value for each variable. All combinations were analyzed, and the error was determined for each combination.

The thermal conductivity and heat capacity for PCC and HMA pavements do not vary significantly because they depend on the material. Therefore, a value of ±0.5 was used for thermal conductivity and a value of ±0.05 was used for heat capacity. The absorptivity values were selected based on the defaults in the Pavement ME Design software with a difference of ±0.1.

Table 4 summarizes the full design matrix for PCC and HMA pavements. All 27 combinations were analyzed for each of the 38 selected sites. The analysis results were summarized to determine a rank order of the lowest error for each site. Additionally, the results were shown for three different temperature criteria. The three different criteria consisted of the following:

- All pavement temperatures
- Pavement temperatures ±10°F from freezing (32°F)
- Pavement temperatures ± 5°F from freezing

The results for the various combinations are summarized and discussed after the table.

Table 4. Design Matrix for PCC and HMA Pavements

Pavement Surface	Thermal Conductivity	Heat Capacity	Absorptivity 0.75	Absorptivity 0.85	Absorptivity 0.95
PCC	0.75	0.23	1	2	3
		0.28	4	5	6
		0.33	7	8	9
	1.25	0.23	10	11	12
		0.28	13	14	15
		0.33	16	17	18
	1.75	0.23	19	20	21
		0.28	22	23	24
		0.33	25	26	27
HMA	0.17	0.18	1	2	3
		0.23	4	5	6
		0.28	7	8	9
	0.67	0.23	10	11	12
		0.28	13	14	15
		0.33	16	17	18
	1.17	0.23	19	20	21
		0.28	22	23	24
		0.33	25	26	27

5.3 CALIBRATION RESULTS

The results of the calibration runs were summarized by calculating the root mean squared error (RMSE) for each combination (thermal conductivity, heat capacity, and absorptivity) and site. The results were also summarized by pavement type. In total, 1,026 EICM runs were analyzed. Sites 6, 7, and 11 were excluded from the analysis because they did not have measured temperatures during cold months.

Pavement ME Design Default Values

The RMSE was calculated for all the sites and data subsets. The results are shown in Figure 19. The results show a large difference in RMSE when comparing the three different temperature categories. These differences indicate that the model is more accurate at colder temperatures than at warmer temperatures, as discussed previously. Additionally, there is no distinguishable difference in RMSE when comparing the sites from IDOT, McHenry County, and the Illinois Tollway, or when comparing PCC and HMA pavements.

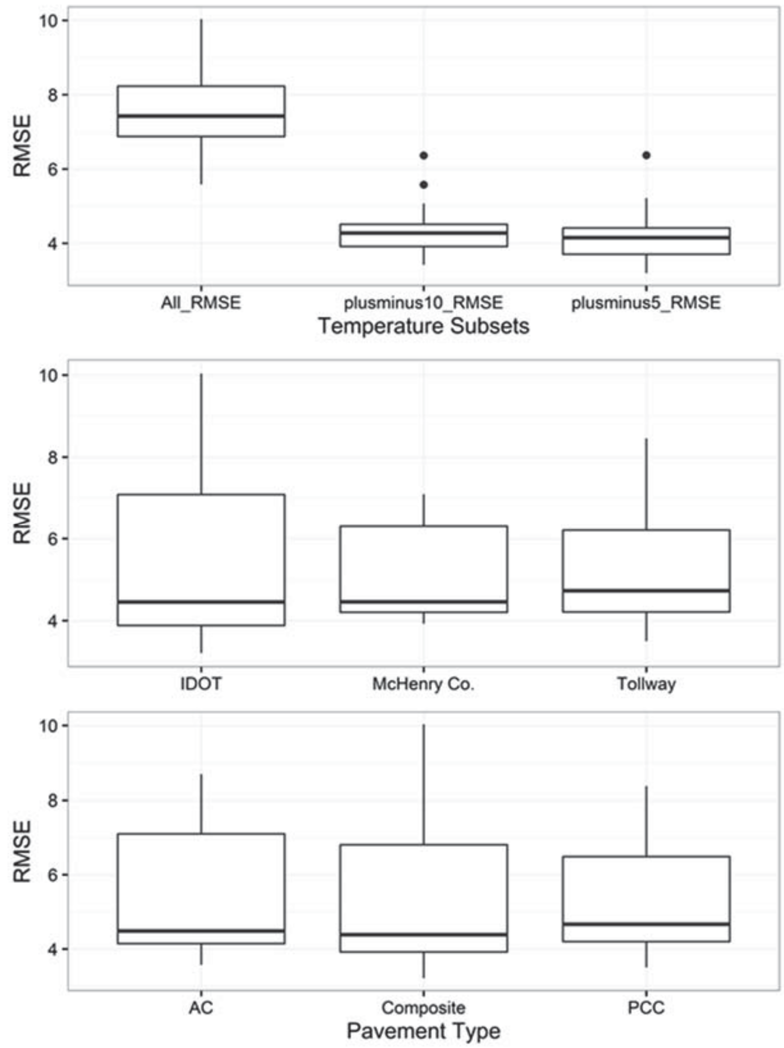


Figure 19. Root mean squared error comparison for the Pavement ME Design defaults.

Concrete Pavement Sections

Table 5 summarizes the PCC calibration results. The top ten results based on the RMSE for the ±5°F category are shown. Based on these results, the average thermal conductivity values among all sites was 1.5, 2.9, and 0.89. The RMSE did not vary significantly among the top ten for any of the three temperatures. Therefore, it is recommended that the following values be used for PCC pavements:

- Thermal conductivity: 1.50
- Heat capacity: 0.30
- Absorptivity: 0.85

The Pavement ME Design default absorptivity value is recommended because of its low impact at colder temperatures.

Table 5. PCC Pavement Calibration Results—Top Ten

	Rank	Site 1			Site 2			Site 3			Site 4			Site 12		
PCC	1	1.75	0.33	0.95	1.75	0.33	0.95	1.75	0.33	0.95	1.75	0.33	0.95	1.75	0.33	0.95
	2	1.75	0.33	0.85	1.75	0.28	0.95	1.75	0.28	0.95	1.75	0.28	0.95	1.75	0.28	0.95
	3	1.75	0.28	0.95	1.25	0.33	0.95	1.25	0.33	0.95	1.75	0.23	0.95	1.75	0.23	0.75
	4	1.75	0.28	0.85	1.75	0.33	0.85	1.75	0.33	0.85	1.25	0.33	0.95	1.75	0.28	0.85
	5	1.25	0.33	0.95	1.75	0.23	0.95	1.75	0.28	0.85	1.25	0.28	0.95	1.75	0.33	0.85
	6	1.25	0.33	0.85	1.25	0.28	0.95	1.25	0.28	0.95	1.75	0.33	0.85	1.75	0.23	0.85
	7	1.25	0.28	0.85	1.25	0.33	0.85	1.25	0.33	0.85	1.75	0.23	0.85	1.25	0.33	0.95
	8	1.25	0.28	0.95	1.75	0.28	0.85	1.25	0.23	0.95	1.75	0.28	0.85	1.25	0.28	0.95
	9	1.75	0.33	0.75	1.75	0.23	0.85	0.75	0.33	0.95	1.25	0.23	0.95	1.25	0.28	0.85
	10	1.25	0.33	0.75	1.25	0.28	0.85	1.25	0.28	0.85	0.75	0.33	0.95	1.75	0.28	0.75
	Rank	Site 13			Site 15			Site 18			Site 19				Average	Standard Deviation
PCC	1	1.75	0.33	0.95	1.75	0.33	0.95	1.75	0.33	0.95	1.25	0.23	0.75			
	2	1.75	0.33	0.85	1.75	0.28	0.95	1.25	0.33	0.95	0.75	0.23	0.75	Thermal Conductivity	1.50	0.19
	3	1.75	0.28	0.85	1.25	0.33	0.95	1.75	0.28	0.95	0.75	0.28	0.75			
	4	1.25	0.33	0.85	1.25	0.28	0.95	1.25	0.33	0.85	1.25	0.28	0.75			
	5	1.25	0.33	0.95	1.25	0.23	0.95	1.25	0.28	0.85	1.75	0.28	0.75	Heat Capacity	0.30	0.02
	6	1.75	0.28	0.95	1.75	0.28	0.85	1.25	0.28	0.95	1.25	0.23	0.85			
	7	1.25	0.28	0.85	1.75	0.33	0.85	1.75	0.28	0.85	0.75	0.33	0.75			
	8	1.75	0.23	0.75	0.75	0.33	0.95	1.75	0.33	0.85	0.75	0.23	0.85	Absorptivity	0.90	0.05
	9	1.25	0.28	0.95	0.75	0.28	0.95	1.25	0.23	0.85	0.75	0.28	0.85			
	10	1.75	0.28	75	0.75	0.23	0.95	0.75	0.33	0.95	1.25	0.28	0.85			

Full-Depth HMA Pavement Sections

Table 7 summarizes the full-depth HMA pavement calibration results. The top ten combinations of thermal conductivity, heat capacity, and absorptivity are shown. The ranking is also based on the RMSE for the ±5 °F data subset. The results show that the averages for thermal conductivity, heat capacity, and absorptivity were 1.08, 0.25, and 0.83, respectively. Based on engineering judgement and experience, the recommended values for these three inputs are as follows:

- Thermal conductivity: 1.00
- Heat capacity: 0.25
- Absorptivity: 0.85

The Pavement ME Design default absorptivity value is recommended because of its low impact at colder temperatures, similar to PCC pavements.

Composite Pavement Sections

Table 8 summarizes the composite pavement calibration results. The top 10 combinations are presented similar to the AC and PCC datasets. The average thermal conductivity, heat capacity, and absorptivity for the composite pavement sections were 0.96, 0.24, and 0.86, respectively. The recommended values for composite pavements are the same as for AC pavements because the surface layer is also AC.

5.4 SUMMARY

The calibration process involves changing the thermal conductivity, heat capacity, and absorptivity in the EICM. A calibration matrix was developed to determine the effects of these three input variables on the pavement temperature predictions. The EICM was executed for all the selected sites. Based on the results, a recommended value for each parameter was established based on the pavement type:

- PCC pavements
  - Thermal conductivity: 1.50
  - Heat capacity: 0.30
  - Absorptivity: 0.85
- AC pavements (including composite)
  - Thermal conductivity: 1.00
  - Heat capacity: 0.25
  - Absorptivity: 0.85

The Pavement ME Design default absorptivity value was selected for both surface types because of its minimal impact at cold temperatures. Overall, the Pavement ME Design default values provided a very good initial prediction of pavement temperatures for the selected pavement sites. Additionally, all sites were analyzed using the updated values. The results are summarized in Table 6 and shows on average minimal error between the measured and predicted pavement temperatures. The average errors are also lower compared with the default values presented in Table 3.

Table 6. Error Results After Calibration

Error type	Agency	AC	Composite	PCC
Root Mean Square Error (°F)	IDOT	3.9	3.9	4.8
	McHenry Co.	3.8	—	—
	Illinois Tollway	—	4.8	4.1
	Average	3.9	4.0	4.4
Mean Error (°F)	IDOT	0.7	0.9	1.0
	McHenry Co.	0.8		
	Illinois Tollway		2.4	1.7
	Average	0.8	1.1	1.4

Table 7. HMA Pavement Calibration Results—Top Ten

		Site 9			Site 10			Site 21			Site 23			Site 25			Site 30			Site 35		
AC	1	1.17	0.28	0.85	1.17	0.28	0.75	1.17	0.28	0.75	1.17	0.28	0.75	1.17	0.28	0.95	1.17	0.28	0.95	1.17	0.28	0.85
	2	1.17	0.28	0.95	1.17	0.23	0.75	1.17	0.23	0.75	1.17	0.23	0.75	1.17	0.23	0.95	1.17	0.28	0.85	1.17	0.18	0.85
	3	1.17	0.28	0.75	1.17	0.28	0.85	1.17	0.28	0.85	0.67	0.28	0.75	1.17	0.28	0.85	1.17	0.23	0.95	1.17	0.23	0.85
	4	1.17	0.23	0.85	0.67	0.28	0.75	1.17	0.23	0.85	1.17	0.18	0.75	1.17	0.23	0.85	1.17	0.23	0.85	1.17	0.28	0.95
	5	1.17	0.23	0.75	1.17	0.18	0.75	1.17	0.18	0.75	0.67	0.23	0.75	1.17	0.18	0.95	0.67	0.28	0.95	1.17	0.18	0.75
	6	1.17	0.23	0.95	1.17	0.23	0.85	1.17	0.28	0.95	0.67	0.18	0.75	0.67	0.28	0.95	0.67	0.28	0.85	1.17	0.23	0.95
	7	1.17	0.18	0.75	0.67	0.23	0.75	0.67	0.28	0.75	1.17	0.28	0.85	1.17	0.18	0.85	1.17	0.28	0.75	1.17	0.23	0.75
	8	0.67	0.28	0.85	1.17	0.28	0.95	0.67	0.23	0.75	1.17	0.23	0.85	0.67	0.23	0.95	1.17	0.18	0.85	0.67	0.28	0.85
	9	0.67	0.28	0.75	0.67	0.28	0.85	0.67	0.28	0.85	0.67	0.28	0.85	1.17	0.28	0.75	1.17	0.23	0.75	1.17	0.28	0.75
	10	1.17	0.18	0.85	0.67	0.18	0.75	1.17	0.18	0.85	1.17	0.18	0.85	1.17	0.23	0.75	1.17	0.18	0.95	0.67	0.23	0.85

	Average	Standard Deviation
Thermal Conductivity	1.08	0.04
Heat Capacity	0.25	0.01
Absorptivity	0.83	0.05

Table 8. Composite Pavement Calibration Results—Top Ten

Composite	Site 5			Site 8			Site 14			Site 16			Site 17			Site 20			Site 22			Site 24			Site 26		
1	1.17	0.28	0.95	1.17	0.18	0.85	0.67	0.18	0.75	0.17	0.23	0.75	1.17	0.28	0.95	1.17	0.28	0.95	1.17	0.28	0.95	1.17	0.28	0.85	1.17	0.23	0.95
2	1.17	0.23	0.95	1.17	0.23	0.85	0.67	0.23	0.75	0.17	0.28	0.75	1.17	0.23	0.95	1.17	0.23	0.95	1.17	0.23	0.95	1.17	0.23	0.85	1.17	0.18	0.95
3	0.67	0.28	0.95	0.67	0.28	0.85	1.17	0.18	0.75	0.17	0.18	0.75	0.67	0.28	0.95	1.17	0.18	0.95	1.17	0.28	0.85	1.17	0.18	0.75	1.17	0.28	0.95
4	1.17	0.18	0.95	1.17	0.28	0.85	0.67	0.28	0.75	0.17	0.28	0.85	1.17	0.18	0.95	0.67	0.28	0.95	1.17	0.23	0.85	1.17	0.23	0.75	0.67	0.28	0.95
5	1.17	0.28	0.85	0.67	0.23	0.85	1.17	0.23	0.75	0.17	0.23	0.85	0.67	0.23	0.95	0.67	0.23	0.95	0.67	0.28	0.95	0.67	0.28	0.75	0.67	0.23	0.95
6	0.67	0.23	0.95	1.17	0.18	0.75	1.17	0.28	0.75	0.67	0.18	0.75	1.17	0.28	0.85	1.17	0.18	0.85	0.67	0.28	0.85	1.17	0.28	0.75	0.67	0.18	0.95
7	1.17	0.23	0.85	0.67	0.23	0.75	0.17	0.28	0.75	0.67	0.18	0.85	1.17	0.23	0.85	1.17	0.23	0.85	1.17	0.18	0.95	0.67	0.23	0.75	1.17	0.18	0.85
8	0.67	0.28	0.85	0.67	0.18	0.75	0.17	0.23	0.75	0.17	0.18	0.85	0.67	0.28	0.85	1.17	0.28	0.85	1.17	0.18	0.85	0.67	0.28	0.85	1.17	0.23	0.85
9	0.67	0.18	0.95	0.67	0.28	0.75	1.17	0.18	0.85	0.67	0.23	0.85	1.17	0.18	0.85	0.67	0.28	0.85	1.17	0.28	0.75	1.17	0.18	0.85	0.67	0.23	0.85
10	1.17	0.18	0.85	0.67	0.18	0.85	1.17	0.23	0.85	0.67	0.23	0.75	0.67	0.23	0.85	0.67	0.23	0.85	0.67	0.23	0.85	0.67	0.18	0.75	0.67	0.18	0.85

Composite	Site 27			Site 29			Site 31			Site 32			Site 33			Site 34			Site 37			Site 38		
1	1.17	0.28	0.95	1.17	0.28	0.95	1.17	0.28	0.95	1.17	0.28	0.95	1.17	0.18	0.75	1.17	0.28	0.95	0.67	0.18	0.75	1.17	0.28	0.75
2	1.17	0.28	0.85	1.17	0.23	0.95	1.17	0.28	0.85	1.17	0.28	0.85	1.17	0.23	0.75	1.17	0.23	0.95	0.17	0.28	0.75	1.17	0.23	0.75
3	1.17	0.23	0.95	1.17	0.28	0.85	1.17	0.23	0.95	1.17	0.23	0.95	0.67	0.28	0.75	1.17	0.23	0.85	0.67	0.18	0.85	1.17	0.18	0.75
4	1.17	0.23	0.85	0.67	0.28	0.95	1.17	0.23	0.85	1.17	0.23	0.85	1.17	0.28	0.85	1.17	0.18	0.85	0.17	0.23	0.75	0.67	0.28	0.75
5	1.17	0.28	0.75	1.17	0.18	0.95	0.67	0.28	0.95	0.67	0.28	0.95	0.67	0.23	0.75	0.67	0.28	0.85	0.67	0.23	0.75	1.17	0.28	0.85
6	1.17	0.23	0.75	1.17	0.23	0.85	1.17	0.18	0.95	0.67	0.28	0.85	1.17	0.23	0.85	1.17	0.28	0.85	0.67	0.23	0.85	0.67	0.23	0.75
7	0.67	0.28	0.85	0.67	0.23	0.95	0.67	0.28	0.85	1.17	0.18	0.95	1.17	0.28	0.75	0.67	0.23	0.85	1.17	0.18	0.85	1.17	0.23	0.85
8	1.17	0.18	0.85	0.67	0.28	0.85	1.17	0.18	0.85	1.17	0.28	0.75	0.67	0.18	0.75	1.17	0.18	0.95	1.17	0.18	0.75	0.67	0.18	0.75
9	0.67	0.28	0.95	1.17	0.18	0.85	1.17	0.28	0.75	1.17	0.18	0.85	0.67	0.28	0.85	0.67	0.28	0.95	0.67	0.28	0.85	0.67	0.28	0.85
10	1.17	0.18	0.95	1.17	0.28	0.75	0.67	0.23	0.95	0.67	0.23	0.95	1.17	0.18	0.85	0.67	0.18	0.85	0.17	0.18	0.75	1.17	0.18	0.85

	Average	Standard Deviation
Thermal Conductivity	0.96	0.22
Heat Capacity	0.24	0.01
Absorptivity	0.86	0.07

CHAPTER 6: RECOMMENDATIONS AND CONCLUSIONS

The objective of this project was to evaluate the use of the EICM for determining pavement surface temperature for winter maintenance operations. Modeling the pavement temperatures could provide virtual RWIS data at a cost that is considerably less than the cost of physical sensors and systems. By having a winter operations system that includes both physical sensors and virtual stations, an agency could reduce costs while maintaining a high level of data density and quality.

Through a data comparison and calibration process, the research team attempted to determine the pavement materials and thermal inputs that should be used in establishing a virtual RWIS station so that the total error is minimized. Table 9 lists the recommended thermal property inputs.

Table 9. Recommended Thermal Inputs for the EICM in a Virtual RWIS

	Concrete Materials	Asphalt Materials
Thermal Conductivity	1.50	1.00
Heat Capacity	0.30	0.25
Short Wave Absorptivity	0.85	0.85

Using the recommended thermal inputs and the actual in-place pavement structure (material types and layer thicknesses) as inputs to the EICM yields reasonable model accuracy with a mean error that is generally less than 2°F. Understanding that the model error is a function of the quality of the weather data, the quality of the sensor data, and the validity of the model, an error of less than 2°F is considered reasonable and is appropriate for use in a virtual RWIS. Because the virtual RWIS will use forecast atmospheric weather data, it is anticipated that the error in the model will be more of a function of an error in the forecast data than an error in the EICM model for determining pavement surface temperatures.