# IDAHO TRANSPORTATION DEPARTMENT

# RESEARCH REPORT

# Development of Pavement Temperature Prediction Model

RP 279

By


Emad Kassem
Fouad M.S. Bayomy
Christopher Williams
Eric Saasita
Simpson Lamichane
Dio D. Permadi

University of Idaho


Prepared for

Idaho Transportation Department

ITD Research Program, Contracting Services

Highways Construction and Operations

August 2020

YOUR Safety • • • ▶ YOUR Mobility • • • ▶ YOUR Economic Opportunity

# Disclaimer

# Technical Report Documentation Page

| 1. Report No. FHWA-ID-20-279 | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 4. Title and Subtitle Development of Pavement Temperature Prediction Model | | 5. Report Date August 2020 |
| | | 6. Performing Organization Code |
| 7. Author(s) Emad Kassem, https://orcid.org/0000-0002-4331-6692 Fouad M.S. Bayomy, Christopher Williams, Eric Saasita, Simpson Lamichane, and Dio D. Permadi | | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address University of Idaho 875 Perimeter Drive MS 1022, Moscow, ID 83844-1022 | | 10. Work Unit No. (TRAIS) |
| | | 11. Contract or Grant No. UI-EN3238 |
| 12. Sponsoring Agency Name and Address Idaho Transportation Department (SPR) Highways Construction and Operations, Contracting Services, Research Program PO Box 7129 Boise, ID 83707-7129 | | 13. Type of Report and Period Covered Final Report 01/01/2019 - 08/31/2020 |
| | | 14. Sponsoring Agency Code RP 279 |
| 15. Supplementary Notes Project performed in cooperation with the Idaho Transportation Department and U.S. Department of Transportation, Federal Highway Administration. | | |

16. Abstract

Pavement temperature has a significant effect on the deflection measured using the falling weight deflectometer (FWD) or traffic speed deflectometer (TSD). Pavement temperature is used to adjust the backcalculated asphalt concrete moduli or deflection at a reference temperature. The current practice is to drill holes at the mid-depth of the top asphalt layer and filling the holes with mineral oil. The temperature of the mineral oil is measured at the time of FWD testing to reflect mid-depth pavement temperature. These holes are drilled every three miles along the FWD survey. Drilling holes before FWD testing requires traffic control that causes traffic delays and puts the Idaho Transportation Department (ITD) crew in the line of traffic. In addition, although this procedure provides accurate measurements for the mid-depth pavement temperature at the locations of the holes, temperature interpolation is used to estimate the temperature at locations between holes. TSD measures pavement deflection at highway speed and drilling holes is not feasible while performing the TSD evaluations. Alternatively, pavement temperature can be estimated using prediction models. This study examined the feasibility of predicting pavement temperature as a function of pavement surface temperature, average air temperature the day before testing, depth, and time of testing. Several existing models were examined along with considering new prediction models. Based on the statistical analysis, the researchers selected and recommended two models: the calibrated BELLS2 model and Idaho 7-Term model for predicting pavement temperature. Both models can predict pavement temperature with good accuracy and low bias. ITD can utilize the prediction models to predict pavement temperature without the need to drill holes which can save time and resources and improve the safety of the ITD FWD crew in the field.

| 17. Key Words Pavement, Temperature, BELLS model, FWD, TSD | | 18. Distribution Statement Copies available from the ITD Research Program | |
|---|---|---|---|
| 19. Security Classification (of this report) Unclassified | 20. Security Classification (of this page) Unclassified | 21. No. of Pages 62 | 22. Price None |

## Acknowledgments

This project is funded by Idaho Transportation Department (ITD) from SPR funds. It is performed in cooperation with ITD. The authors would like to acknowledge all members of the research project Technical Advisory Committee (TAC) for their valuable feedback and cooperation all over the project tasks. The authors would like also to acknowledge the support from the National Institute for Advanced Transportation Technology (NIATT) and the Department of Civil and Environmental Engineering at the University of Idaho. The authors would also like to acknowledge the help from Dr. Ahmed Muftah and Mr. Austin Corley in this study.

## Technical Advisory Committee

Each research project is overseen by a Technical Advisory Committee (TAC). The TAC is responsible for monitoring project progress, reviewing deliverables, ensuring that study objectives are met, and facilitating implementation of research recommendations, as appropriate. ITD's Research Program Manager appreciates the work of the following TAC members in guiding this research study.

- Project Sponsor: Mark Snyder, P.E.
- Project Manager: James Poorbaugh, P.E.
- TAC Members: James Poorbaugh, Trek Pallister, Ned Parrish
- FHWA-Idaho Advisor: Kyle Holman, P.E.

# Table of Contents

## List of Tables

## List of Figures

## List of Abbreviations and Acronyms

FWD ………………………… Falling Weight Deflectometer

TSD …………………………… Traffic Speed Deflectometer

ITD …………………………… Idaho Transportation Department

FHWA ………………………. Federal Highway Administration

LTPP ………………………… Long-Term Pavement Performance

UI ……………………………… University of Idaho

TxDOT ……………………… Texas Department of Transportation

TAC ………………………… Technical Advisory Committee

# Executive Summary

Pavement temperature has a significant effect on the deflection measured using the falling weight deflectometer (FWD) or traffic speed deflectometer (TSD). Pavement temperature is used to adjust the backcalculated asphalt concrete moduli or deflection at a reference temperature. The current practice at Idaho Transportation Department (ITD) and other transportation agencies is to drill holes at the mid-depth of the top asphalt layer and filling the holes with mineral oil. The temperature of the mineral oil is measured at the time of FWD testing to reflect mid-depth pavement temperature. These holes are drilled every three miles along the FWD survey. Drilling holes before FWD testing requires traffic control that causes traffic delays and puts the ITD crew in the line of traffic. In addition, although this procedure provides accurate measurements for the mid-depth pavement temperature at the locations of the holes, temperature interpolation is used to estimate the temperature at locations between holes since they are drilled every three miles. This may result in inaccurate pavement temperature predictions. Furthermore, ITD recently adapted the use of TSD is evaluating the structural conditions of pavements. TSD measures pavement deflection at highway speeds and drilling holes is not feasible while performing the TSD evaluations. Alternatively, pavement temperature can be estimated using prediction models.

This study aimed to develop a procedure that can be used by ITD crew to predict the mid-depth pavement temperature as a function of pavement surface temperature, previous day's average air temperature, depth, and time of testing. An infrared thermometer is installed on the FWD trailer to measure the pavement surface temperature during testing. In addition, the location of the measurements was also documented. The location was used to determine the previous day's average air temperature from the weather records using online resources such as Weather Underground website. The researchers used the pavement temperature data collected by the ITD FWD crew in the past four years (i.e., 2016, 2017, 2018, and 2019) during the FWD testing in the six districts of the state. A total number of 454 measurements were collected in the field. Most of the pavement temperature measurements collected by FWD crew were obtained at a fixed depth of three inches from the pavement surface. Therefore, the researchers collected additional measurements (142 measurements) at two different depths (i.e., three inches and five inches) at two sites on campus at the University of Idaho. A total number of 596 pavement temperature measurements were used in this study to develop pavement temperature prediction models or calibrate existing ones. The researchers evaluated seven models to obtain a pavement temperature prediction model with good accuracy and low bias. These seven cases included:

- Case 1: BELLS2 model with the national coefficient estimates
- Case 2: BELLS3 model with the national coefficient estimates
- Case 3: Calibrated BELLS2 model with calibrated (Idaho) coefficient estimates
- Case 4: Alternative Texas model with Texas coefficient estimates
- Case 5: Calibrated Alternative Texas model with calibrated (Idaho) coefficient estimates
- Case 6: Idaho First Order Model
- Case 7: Idaho 7-Term Model

The results revealed that the calibration process improved the accuracy of the BELLS2 model and reduced the bias in pavement temperature prediction. There was a reduction of 12.5% in Root-Mean-Square Error (RMSE) using the calibrated BELLS2 model compared to the original BELLS2 model. The calibrated BELLS2 model and Idaho 7-Term model were found to provide the highest adjusted $R^2$ and lowest RMSE. An adjusted $R^2$ of 0.913 was obtained for the calibrated BELLS2 model and 0.919 for Idaho 7-Term model, while an RMSE of 3.3 °C was associated with the calibrated BELLS2 model and 3.2 °C for the Idaho 7-Term model. Both models (i.e., Idaho 7-Term and calibrated BELLS2) are highly correlated ($R^2$ of 0.99). It should be noted that BELLS2 model was originally developed using over 10,000 observations and the measurements used in this study (596 observations) were used to calibrate the model and provide the calibrated BELLS2 model. Whereas the Idaho 7-Term model was developed based on the data collected in Idaho (596 observations). The Idaho 7-Term model provided comparable $R^2$ to that of calibrated BELLS2 model but a slightly lower RMSE.

The results of this study clearly demonstrate that pavement temperature can be estimated as a function or pavement surface temperature, previous day's average air temperature, depth, and time of testing. Based on the statistical analysis, the researchers selected and recommended two models: the calibrated BELLS2 model and Idaho 7-Term model for predicting pavement temperature. Both models can predict pavement temperature with good accuracy and low bias. ITD can utilize the prediction models to predict pavement temperature without the need to drill holes which can save time and resources. In addition, this procedure improves the safety of ITD crew and the accuracy of mid-depth pavement temperature at locations where no holes are drilled or can be drilled such as when TSD is used.

# 1. Introduction

## Background and Problem Statement

The falling weight deflectometer (FWD) is used to assess the structural capacity of pavement systems. The moduli of asphalt layers are highly affected by pavement temperature; therefore, pavement temperature is measured during FWD testing. It is used to adjust the backcalculated asphalt concrete moduli at a reference temperature. The current practice at ITD is to drill holes at the mid-depth of the top asphalt layer (around 3 inches) every three miles along the testing route a day before FWD testing. Then, mineral oil is added before covering the hole. ITD crew measures the temperature of the mineral oil in the holes at the time of FWD testing using a temperature probe. Drilling holes before FWD testing requires traffic control that often causes traffic delays and puts the ITD crew in the line of traffic. In addition, although this procedure provides accurate measurements for pavement temperature at the locations of the holes, the crew uses interpolation to predict the temperature at locations between holes since they are drilled every three miles. This may result in inaccurate pavement temperature predictions. Furthermore, ITD recently adapted the use of traffic speed deflectometer (TSD) in evaluating the structural conditions of pavements. TSD measures pavement deflection at highway speed and drilling holes is not feasible while performing the TSD evaluations. Alternatively, pavement temperature can be estimated using prediction models.

This research study aimed to expedite the FWD testing and operations by eliminating the need for drilling holes for measuring mid-depth pavement temperature. This study evaluated and developed statistical-based models that are used to predict the mid-depth of pavement temperature as a function of pavement surface temperature, previous day's average air temperature, depth, and time of testing. This procedure can be used to save time and resources currently spent by ITD on traffic control and drilling holes before FWD testing. In addition, this procedure improves the safety of ITD crew and the accuracy of mid-depth pavement temperature at locations where no holes are drilled or can be drilled such as when TSD is used.

The use of FWD non-destructive testing is one of the primary means of determining in situ structural capacities of existing pavements. The FWD deflection data are used to backcalculate the moduli of each layer of the pavement system. It can be also used to estimate the remaining service life of a given pavement and identify locations for further sampling and testing (FHWA 1998). The nondestructive testing is quick and inexpensive, less invasive to pavements, and cause less traffic interruptions. The FWD is designed to simulate deflection of a pavement surface caused by a fast-moving truck. It applies transient impulse force to the pavement structure and measures the corresponding pavement deflections using a set of velocity transducers (geophones) placed at fixed distances from the loading plate to measure the shape of the deflection basin. Several factors affect the pavement deflections including applied load, pavement distresses and conditions, climatic conditions (e.g., pavement temperature, subgrade moisture variation, etc.). As the pavement temperature increases, the deflection of asphalt layers increases. Therefore, the use of FWD deflection measurements in flexible pavement analysis and design requires the adjustment of the deflections to a reference temperature (Lytton et. al. 1990).

The BELLS2 and BELLS3 models are the most common models used to estimate the pavement temperature as a function of pavement surface temperature, previous day's average air temperature, depth, and time of testing (Lukanen et. al. 2000). The BELLS2 model was developed based on the FWD testing protocol followed in the Long-Term Pavement Performance (LTPP) program while the BELLS3 model considers the shade effect to suit the routine FWD testing operation followed by various transportation agencies. Both the BELLS2 and BELLS3 models have the same mathematical expression but different calibration coefficients. Research studies showed that local calibration of the BELLS models may be necessary to improve the accuracy of pavement temperature prediction (Fernando et. al. 2001). In addition to the BELLS2 and BELLS3 models, researchers at Texas A&M University proposed an alternative model that provided a 7% reduction in the Root-Mean-Square Error (RMSE) between predicted and measured values.

## Project Goal and Objectives

The FWD is used by ITD to measure the structural capacity and stiffness of pavements. The FWD testing involves applying loads and measuring the corresponding deflections from the center of loading plate using geophones which is referred to as deflection basin. Pavement temperature (often mid-depth) is used to adjust the backcalculated moduli from the deflection basin. The ITD FWD crew measures the mid-depth pavement temperature by drilling holes and filling them with mineral oil before the FWD testing. This practice requires additional resources from ITD and extends the road closure time required for drilling the holes. This project aims to assist the ITD crew with a procedure to eliminate the need for site preparation prior to FWD data collection. In addition, the proposed method would improve the accuracy of estimated mid-depth pavement temperature at locations where no holes are drilled. In addition, when the TSD is used, drilling holes is not feasible while performing the TSD evaluations. The project has three main objectives as follows:

- Review and select proper methods/models used for predicting mid-depth pavement temperature using pavement surface temperature, previous day's average air temperature, depth, and time of testing.
- Validate and revise existing models or develop new models for predicting mid-depth pavement temperature and develop a simple excel-based utility that can be used by ITD crew to facilitate the calculations.
- Develop recommendations and guideline on a revised practice for measuring pavement temperature during FWD testing.

## Research Tasks

Several tasks were performed to achieve the above-mentioned research objectives. The tasks performed in the study are described in the following section.

## Task 1: Literature Review

Under this task, the research team conducted a literature review to collect pertinent information on current practices, methods, and models used to predict mid-depth pavement temperature. These methods include the BELLS2 and BELLS3 models as well as an alternative model developed at Texas A&M University. In addition, the researchers reviewed the statistical analysis parameters used to evaluate the accuracy of various prediction models. The outcome of the literature review guided the researchers to identify proper models used to predict mid-depth pavement temperature as a function of pavement surface temperature, previous day's average air temperature, depth, and time of testing.

## Task 2: Review ITD Measured Mid-Depth Pavement Temperature Data

Under this task, the research team reviewed the mid-depth pavement temperature data collected by the ITD FWD crew. The mid-depth pavement temperature measurements were collected by ITD crew in 2016, 2017, 2018, and 2019 during their annual FWD testing and operations. The collected data include the following:

- Location: highway number and mile post.
- Depth: the depth at which the temperature was measured from the surface.
- Pavement Surface temperature: the surface temperature is measured using an infrared thermometer mounted on the FWD trailer.
- Pavement temperature at a given depth (e.g., three inches): the pavement temperature is measured by drilling holes and filling them with mineral oil. A fluke meter is used to measure the temperature of the mineral oil inside the holes.
- Air temperature: the previous day's average air temperature can be obtained from the weather records using online resources such as Weather Underground website.
- Time of measurements: the time at which the temperature was measured.

The research team reviewed the collected data provided by ITD FWD crew. In addition, the team collected additional data at two sites on campus at the University of Idaho (U of I). It should be noted that pavement temperature collected by ITD crew is often measured at a depth of three inches from the pavement surface. The researchers collected temperature data at both three inches and five inches from the surface of pavement sections at U of I.

## Task 3: Validate Existing Mid-Depth Pavement Temperature Models

Under this task, the researchers analyzed the mid-depth pavement temperature data collected by ITD FWD crew as well as the data collected at U of I. The researchers validated and calibrated the BELLS models and an alternative model proposed by Texas A&M University. In addition, the researchers proposed and developed two new models for Idaho. These models predict pavement temperature as a function of pavement surface temperature pavement surface temperature, previous day's average air temperature, depth, and time of testing.

### Task 4: Develop Excel–Based Utility

Under this task the research team developed a simple Excel-based utility that summarizes the mathematical relationships and models that were developed under Task 3 to predict the mid-depth pavement temperature. The inputs for this utility include the following information:

- Pavement surface temperature measured using an infrared thermometer mounted on the FWD trailer.
- Previous day's average air temperature obtained from climate and weather data records.
- Depth at which the temperature is needed.
- Time of testing.

The output of the software is a predicted mid-depth pavement temperature at the specified time using two models: the calibrated BELLS2 model and Idaho 7-Term model. This Excel-based utility is simple to use by the ITD FWD crew to predict mid-depth pavement temperature.

### Task 5: Develop Recommendations on Revised Practice for Pavement Temperature Measurement

Under this task, the research team provided recommendations based on the calibrated BELLS2 model and proposed new Idaho models to predict mid-depth pavement temperature. Such noninvasive methods can be used to predict pavement temperature with adequate accuracy, assist ITD FWD crew to improve their operations, speed up the testing, improve the FWD crew's safety, and reduce the amount of time needed for traffic control.

## Report Organization

This report documents research methodology, presents the results and analysis, summarizes the findings, and provides recommendations. The report has four chapters and one appendix. Chapter 1 provides background and problem statement, project goal and objectives, research tasks, and report organization. Chapter 2 presents a review of current methods and models used to predict pavement temperature during the FWD testing and previous studies conducted to validate these models.

Chapter 3 provides an overview of the data collection and discusses in detail the statistical analysis used to evaluate the accuracy of various prediction models examined in this study. Based on the results, the researchers selected and recommended the proper statistical-based models to predict pavement temperature without the need to drill holes. In addition, it presented the developed Excel-based utility to facilitate the pavement temperature calculations. Finally, Chapter 4 summarizes the research methodology and findings and provides recommendations on measuring pavement temperature. Appendix A provides all the data used in this study.

# 2. Literature Review

## Introduction

ITD conducts FWD testing to evaluate and assess the structural capacity of pavement systems. The results are used in overlay design to determine the proper overlay thickness and detect possible pavement failure due to insufficient structural support (ITD Pavement Performance Report, 2015). The FWD trailer is towed behind an ITD truck (Figure 1). It is designed to simulate deflection of a pavement surface caused by a fast-moving truck. The FWD applies transient impulse force to the pavement structure and measures the corresponding pavement deflections using a set of velocity transducers (geophones) placed at fixed distances from the loading plate to measure the shape of the deflection basin (Figure 2). The force is applied through lifting a weight to a given height and releasing it to drop on the loading plate placed on the pavement surface. The applied force can be varied by changing the falling weight and/or the drop height. The magnitude of the applied force and its duration have significant effect on pavement deflection (FHWA 1998). Using the applied force, corresponding deflections, and pavement structure (e.g., number of layer and thickness of each layer), various computational methods can be used to estimate the modulus of each pavement layer.

**Figure 1: ITD's FWD Truck and Trailer**

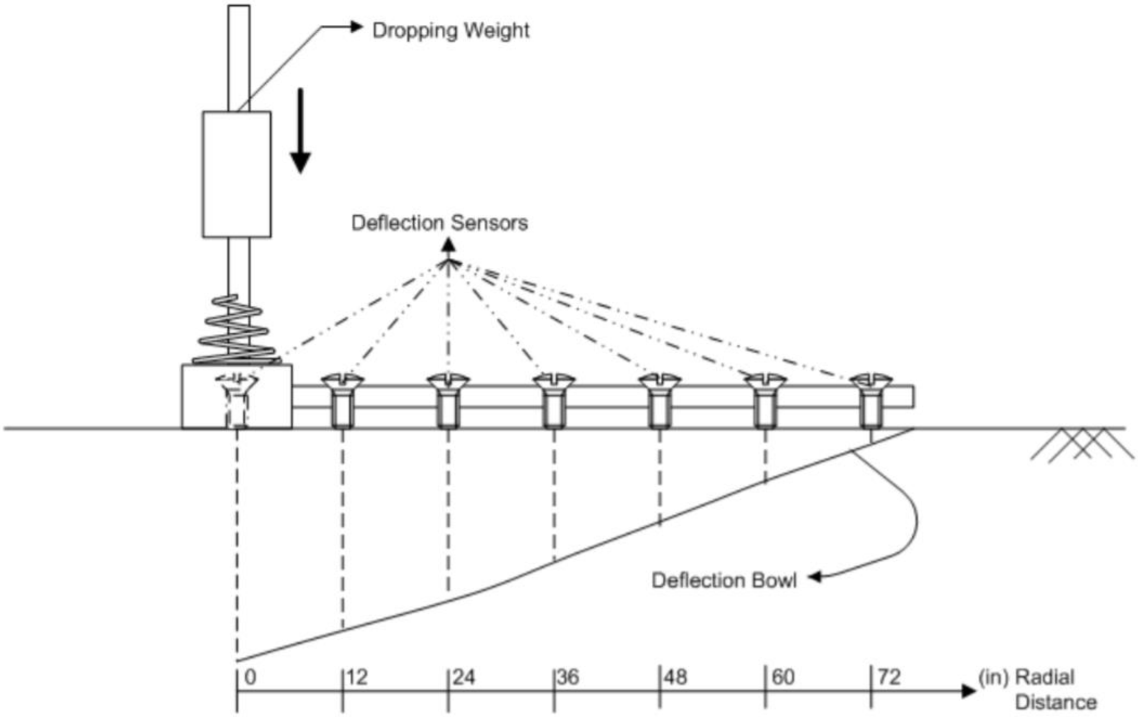


**Figure 2. FWD Deflection Basin (Tutumluer and Sarker 2015)**

The deflection basin is affected by several factors including applied load, pavement distresses and conditions, climatic conditions (e.g., pavement temperature, subgrade moisture variation, etc.) (FHWA 1998). The deflection increases with the applied load; however, such relationship is nonlinear. Also, shorter load pulse, simulating faster vehicle, results in smaller deflection (FHWA 1998). Pavement deflection near distressed or cracked areas is often greater than non-distressed areas. Pavement temperature has a significant impact on the deflection. Inge and Kim (1995) demonstrated that pavement temperature changes with the depth of pavements and time of testing (Figure 3). The variation in temperature decreases as the depth increases away from the surface (Inge and Kim 1995). As the pavement temperature increases, the deflection of asphalt layers increases (Figure 4) since asphalt binders are softer at higher temperatures. Therefore, the use of FWD deflection measurements in flexible pavement analysis and design requires the adjustment of deflections to a reference temperature (Lytton et al. 1990).

The current practice at ITD is to drill holes at a depth of three inches from the surface and filling it with mineral oil before covering the hole. ITD FWD crew measures the temperature of the mineral oil inside the hole at the time of FWD testing. Such information is used to adjust the FWD deflection measurements. Drilling holes requires traffic control that may cause traffic delays and put the ITD crew in the line of traffic. In addition, since these holes are drilled every three miles, temperature interpolation is often used to estimate pavement temperature at the locations of testing between two consecutive holes which may result in inaccurate pavement temperature predictions. Alternatively, statistical-based models such as the

BELLS2 and BELLS3 models are often used to predict pavement temperature as a function of pavement surface temperature, previous day's average air temperature, depth, and time of testing.

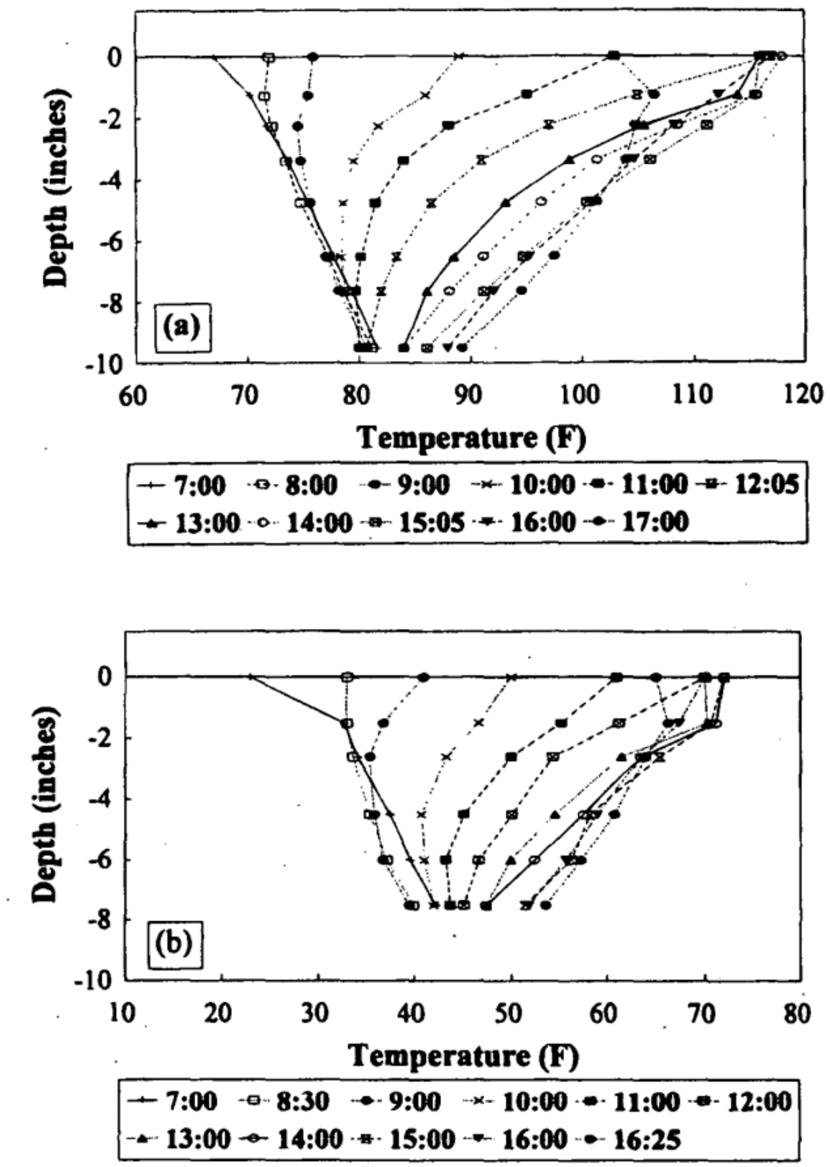


**Figure 3. Temperature Change as a Function of Pavement Depth and Time of Measurement: (a) Section 20 in September; (b) Section 13 in February 7 (Inge and Kim 1995)**

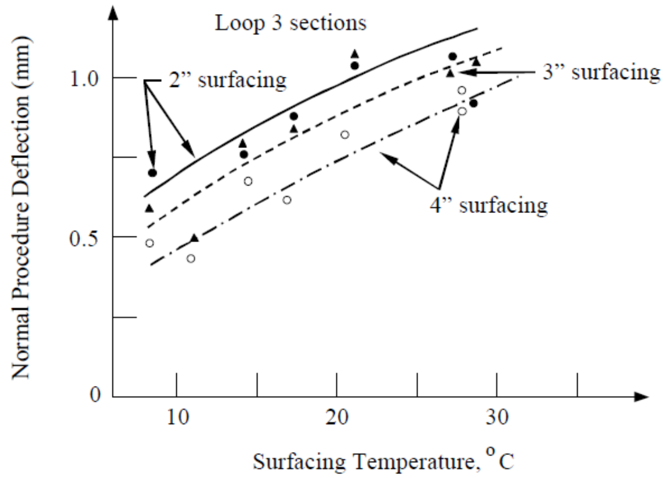


**Figure 4. Influence of Temperature on Flexible Pavement Deflection (Johnson et al. 1990)**

# Temperature Prediction Models

## BELLS Models

The BELLS2 and BELLS3 models are the primary models used to estimate pavement temperature without the need for drilling holes. The BELLS2 model was developed based on the FWD testing protocol followed in the LTPP program while the BELLS3 model considers the shade effect to suit the routine FWD testing operations followed by various transportation agencies. The time required to complete the FWD testing at a given location may affect the surface temperature of pavement if shaded for an extended period of time. The shading allows the surface to cool down. The testing location was shaded for about six min. in the LTPP testing protocol. Meanwhile, the routine FWD testing can be completed in a shorter time at a given location. The LTPP surface temperature data were adjusted to account for the cooling effects. The BELLS2 model (based on the LTPP testing protocol) has the same mathematical equation as the BELLS3 model (that considers the shade effect to suit the routine FWD testing operation) except the regression coefficients are different. The values of the regression coefficients for both BELLS models are presented in Table 1. The BELLS2 and BELLS3 models were developed using 10,304 observations. The BELLS2 model provided an adjusted $R^2$ of 0.977 and standard error of 1.8 °C, while the BELLS3 model provided adjusted $R^2$ of 0.975 and standard error of 1.9 °C. The equation of BELLS Models is as follows:

$$T_d = \beta_0 + \beta_1 \, IR + [\log(d) - 1.25]\,[\beta_2 IR + \beta_3 T_{(1-day)} + \beta_4 \sin(hr_{18} - 15.5)] + \beta_5 IR \sin(hr_{18} - 13.5)$$

… … … Eqn. 1

where,

$T_d$ = pavement temperature at depth d, °C

IR = pavement surface temperature measured using an infrared gauge, °C

d = depth at which the temperature is predicted, mm

$T_{(1\text{-day})}$ = average air temperature of the previous day (average of high and low temperatures), °C

$hr_{18}$ = time of the day, in a 24-hr system but calculated using an 18-hr asphalt concrete temperature rise- and fall-time cycle (Figure 5).

**Table 1 Coefficients of BELLS Equations**

| Coefficient | BELLS2 | BELLS3 |
|---|---|---|
| $\beta_0$ | +2.780 | +0.950 |
| $\beta_1$ | +0.912 | +0.892 |
| $\beta_2$ | -0.428 | -0.448 |
| $\beta_3$ | +0.553 | +0.621 |
| $\beta_4$ | +2.630 | +1.830 |
| $\beta_5$ | +0.027 | +0.042 |

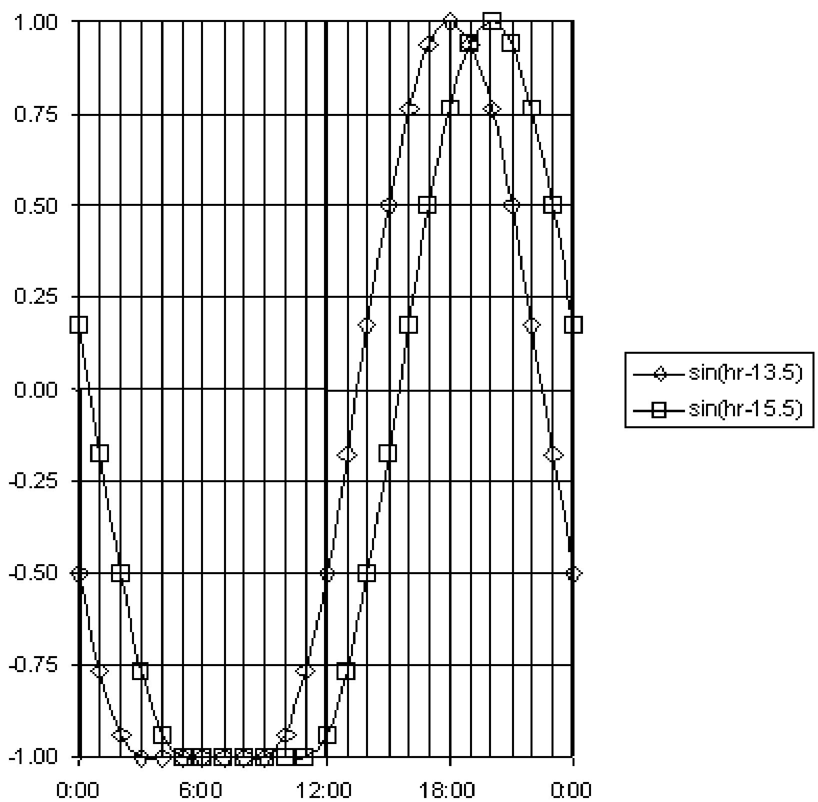


**Figure 5. 18-hr Sine Function Used in BELLS Equations (Lukanen et al. 2000)**

## Alternative (Texas A&M) Prediction Model

The Texas Department of Transportation (TxDOT) uses the FWD to evaluate the structural capacity of pavements. They use MODULUS program to estimate of pavement layer moduli and use the modulus values in other applications (e.g., pavement design, loading analysis) (Fernando et al. 2001). The backcalculated moduli are corrected or adjusted at reference conditions (e.g., temperature and loading frequency). TxDOT recommends recoding the pavement temperature at the beginning and end of FWD survey and interpolation is used to estimate the temperature at stations between the start and end locations (Fernando et. al 2001). Since measuring the pavement temperature at every station is not feasible, Fernando et al. (2001) conducted a study to evaluate the BELLS equations and developed an alternative equation that can be used to estimate pavement temperature without the need to drill holes (Fernando et al. 2001). The BELLS2 equation provided an adjusted $R^2$ of 0.878 and RMSE of 7.4 °C for 1575 observations used by Fernando et al. (2001). However, the researchers reported that there was noticeable bias from the equality line as shown in Figure 6. Based on the results, Fernando et al. (2001) calibrated the BELLS2 model and provided new values for the regression coefficients as presented in Table 2. The calibrated BELLS2 model provided improved adjusted $R^2$ of 0.92 and smaller RMSE of 6.0 °C.

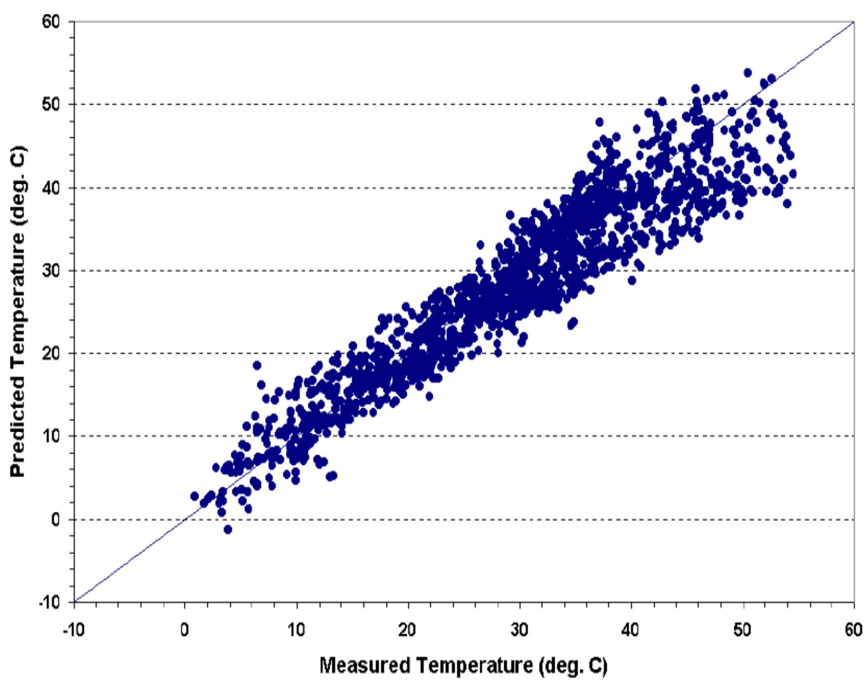


**Figure 6. Comparison of Predicted Temperatures from BELLS2 with Measured Temperatures (Fernando et al. 2011)**

**Table 2. Coefficients of Calibrate BELLS Equation after Fernando et al. (2001) (Fernando et al. 2011)**

| Coefficient | Value |
| --- | --- |
| $\beta_0$ | +1.472 |
| $\beta_1$ | +1.079 |
| $\beta_2$ | -0.924 |
| $\beta_3$ | +0.979 |
| $\beta_5$ | +0.065 |

Note: β4 coefficient in the original BELLS2 model was found insignificant; therefore, it was omitted from the calibrated model

Fernando et al. (2001) also proposed an alternative model. This model is referred to as alternative Texas model in the study herein. The alternative Texas equation considers the climatic conditions in Texas. This model uses the same parameters used in the BELLS2 model. Equation 2 presents the proposed alternative Texas model. Table 3 presents the values of regressions coefficients of the alternative Texas model. This model provided an adjusted $R^2$ of 0.93 and RMSE of 5.6 °C (Table 4). Although the adjusted $R^2$ of the alternative Texas model was close to the calibrated BELLS2 model (adjusted $R^2$ = 0.92), the RMSE was reduced by 7 percent compared to BELLS2 model (RMSE = 6.0 °C).

$$T_d = \beta_0 + \beta_1 (IR + 2)^{1.5} + \log_{10}(d) \times \{\beta_2 (IR + 2)^{1.5} + \beta_3 \sin^2(hr_{18} - 15.5) + \beta_4 \sin^2(hr_{18} - 13.5) + \beta_5 [T_{(1-day)} + 6)^{1.5}\} + \beta_6 \sin^2(hr_{18} - 15.5) \sin^2(hr_{18} - 13.5)$$

… … … Eqn. 2

**Table 3. Coefficients of the Alternative Model for Predicting Pavement Temperature (Liao et al. 2009)**

| Coefficient | Alternative Texas A&M model Estimate |
| --- | --- |
| $\beta_0$ | +6.460 |
| $\beta_1$ | +0.199 |
| $\beta_2$ | -0.083 |
| $\beta_3$ | -0.692 |
| $\beta_4$ | 1.875 |
| $\beta_5$ | +0.059 |
| $\beta_6$ | -6.784 |

**Table 4. Comparison of Predictive Accuracy of Models Evaluated by Fernando et al. (2001) (Fernando et al. 2011)**

| Model | Adjusted $R^2$ | Root-Mean-Square Error, $^{\circ}C$ |
|---|---|---|
| BELLS2 | 0.878 | 7.410 |
| Calibrated BELLS2 | 0.920 | 5.998 |
| Alternative Texas Model | 0.931 | 5.584 |

## Validation of BELLS Models

Several studies have been conducted in the literature to validate and calibrate the BELLS models. Inge and Kim (1995) demonstrated that BELLS models underpredict pavement temperatures at higher temperatures (Figure 7) (Inge and Kim 1995). These results demonstrate that model calibration is needed to improve the accuracy of the BELLS prediction models. Inge and Kim (1995) also proposed the inclusion of temperature gradients as a function of the testing time along with the depth to predict pavement temperature. Meanwhile, the number of test sections included in their study was limited.

Recently, Solatifar et al. (2018) evaluated the BELLS equation which was found to provided very good correlation with measured pavement temperature ($R^2$ was greater than 0.96) and it was even slightly improved with model calibration (Figure 8) (Solatifar et al. 2018).

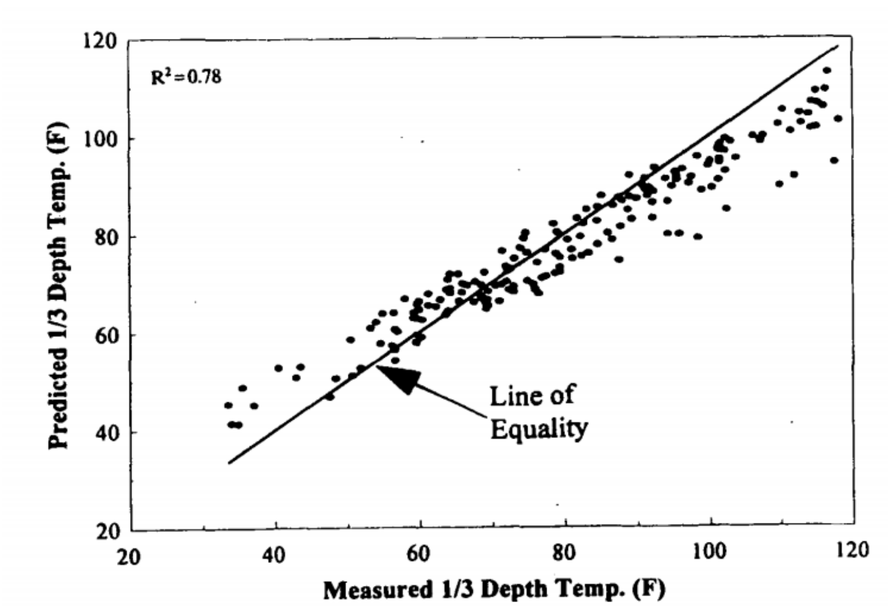


**Figure 7. Validation of the BELLS Equation using Temperatures Measured from Pavements in North Carolina (Inge and Kim 1995)**

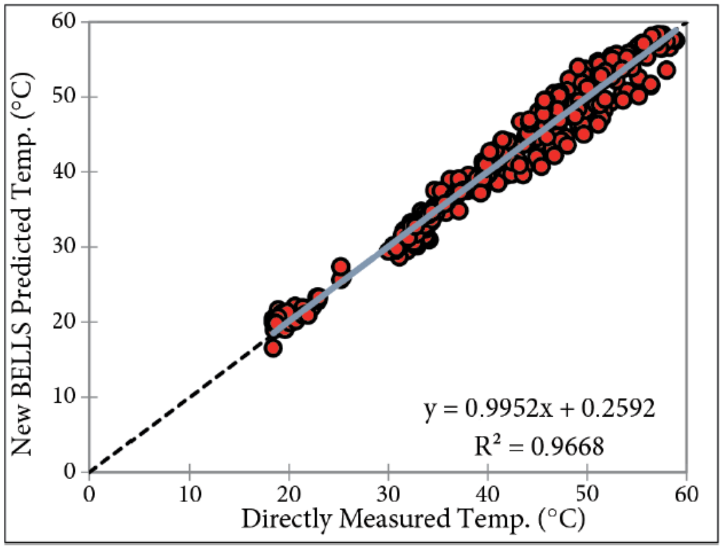


**Figure 8. Measured versus Predicted Pavement Temperature using Calibrated BELLS model (Solatifar et al. 2018)**

Liao et al. (2009) collected pavement temperature data from three pavement sections and compared predicted pavement temperature using the BELLS3 model with the measured pavement temperature at various depths (i.e., 0.79, 1.59, 2.36, 3.15, 3.93 inches) (Figure 9). The results demonstrated that a linear relationship between measured pavement temperature and predicted temperature using the BELLS3 model ($R^2$ = 0.8848); however, the BELLS3 model tended to underestimate pavement temperatures at temperatures above 40 °C. Based on the results, the researchers developed an alternative model that provided improved correlation between measured and predicted pavement temperature (Liao et al. 2009).

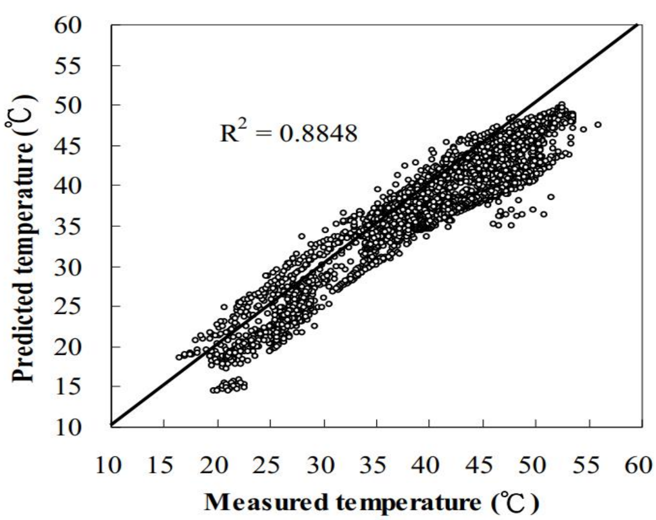


**Figure 9. Measured versus predicted pavement temperature using BELLS3 model (Liao et al. 2009)**

# 3. Data Collection and Statistical Analysis

## Introduction

The current practice at ITD is to drill holes and measure pavement temperature every three miles during the FWD testing. Although such practice provides accurate pavement temperature measurements at the location of drilled holes, interpolation is used to predict pavement temperature at the FWD testing locations between the holes. In addition, such practice requires additional resources (traffic control and staff time) and may put the crew in line with the traffic. The primary objective of this study was to utilize the ITD collected data over the past few years (2016, 2017, 2018, and 2019) available to the researchers to examine the feasibility of predicting pavement temperature using the data collected in Idaho. Most of the ITD pavement temperature measurements were collected a depth of three inches from the surface. A total number of 454 measurements were collected in the field. These measurements were obtained from sites distributed over the six districts of the state of Idaho. In addition to the field data, the team collected 142 measurements at two sites on campus at the University of Idaho at two different depths (i.e., three inches and five inches) to complement the measurements collected by ITD crew. A total number of 596 pavement temperature measurements were used in this study. This chapter discusses the data collection and analysis.

## ITD Data Collection

The research team carefully reviewed the mid-depth pavement temperature data collected by the ITD FWD crew for the last four years. The ITD FWD crew collected comprehensive amount of mid-depth pavement temperature during their annual FWD testing and operations. The collected data included highway location, the depth at which the temperature was measured from the surface, pavement temperature, surface temperature, air temperature, and the time and date of measurements. The pavement temperature data were collected for four consecutive years: 2016, 2017, 2018, and 2019. The data were in MDB formats, and the researchers processed the data and exported the MDB files created from FWD to generate Excel tables with the needed information. Table 5 presents an example of the processed data collected in 2016. Appendix A provides all the pavement temperature measurements used in this study. The selected sections covered all six districts, and geographic locations of these sections are shown in Figure 10. The researchers obtained the previous day’s average air temperature from the weather records using online resources such as Weather Underground website.

**Table 5. Example of the Measured Pavement Temperature Data by ITD**

| Highway | Station ID | Station | Pavement Temp. at 3 in. | Surface Temp. (°F) | Air Temp. (°F) | Date | Time |
|---|---|---|---|---|---|---|---|
| SH06 | 1 | 35.06 | 56.50 | 59.60 | 54.40 | 5/19/2016 | 8:48:09 AM |
| | 68 | 29.00 | 65.30 | 61.70 | 53.10 | 5/19/2016 | 10:54:25 AM |
| SH-41 | 1 | 37.34 | 53.10 | 53.50 | 50.30 | 5/11/2016 | 8:00:05 AM |
| | 61 | 32.00 | 61.60 | 64.50 | 57.90 | 5/11/2016 | 9:45:16 AM |
| | 159 | 23.00 | 77.90 | 82.70 | 74.40 | 5/11/2016 | 12:46:32 PM |
| | 192 | 20.00 | 82.50 | 83.50 | 74.50 | 5/11/2016 | 1:41:33 PM |
| SH-53 | 1 | 9.67 | 55.10 | 50.60 | 47.60 | 5/12/2016 | 5:26:08 AM |
| | 27 | 12.00 | 53.80 | 48.00 | 43.70 | 5/12/2016 | 6:04:45 AM |
| | 50 | 14.00 | 57.50 | 49.60 | 45.90 | 5/12/2016 | 6:38:01 AM |
| US-02-A0009 | 1 | 9.70 | 89.30 | 84.20 | 70.10 | 5/10/2016 | 2:30:23 PM |
| | 27 | 12.00 | 95.80 | 92.10 | 78.50 | 5/10/2016 | 3:20:16 PM |
| | 60 | 15.00 | 74.00 | 64.90 | 54.10 | 5/10/2016 | 5:18:14 PM |
| | 104 | 19.00 | 79.70 | 72.20 | 64.80 | 5/10/2016 | 7:38:58 PM |
| US-02-D0020 | 1 | 19.01 | 52.80 | 50.50 | 45.10 | 5/10/2016 | 7:29:07 AM |
| | 25 | 17.00 | 56.20 | 55.00 | 49.90 | 5/10/2016 | 9:01:13 AM |
| | 57 | 14.00 | 73.50 | 73.60 | 59.20 | 5/10/2016 | 10:45:33 AM |
| | 90 | 11.00 | 72.80 | 80.60 | 69.20 | 5/10/2016 | 12:24:53 PM |
| | 104 | 9.70 | 89.50 | 89.80 | 73.90 | 5/10/2016 | 1:08:03 PM |
| US-95-A0393 | 1 | 393.80 | 71.70 | 84.40 | 78.50 | 5/18/2016 | 11:02:15 AM |
| | 34 | 397.00 | 81.30 | 82.90 | 77.30 | 5/18/2016 | 11:55:27 AM |
| | 45 | 398.00 | 74.00 | 84.20 | 79.80 | 5/18/2016 | 12:09:56 PM |
| US-95-A0429 | 1 | 429.03 | 77.00 | 68.60 | 66.50 | 7/26/2016 | 5:43:30 AM |
| | 17 | 430.60 | 77.30 | 70.10 | 67.40 | 7/26/2016 | 6:10:10 AM |

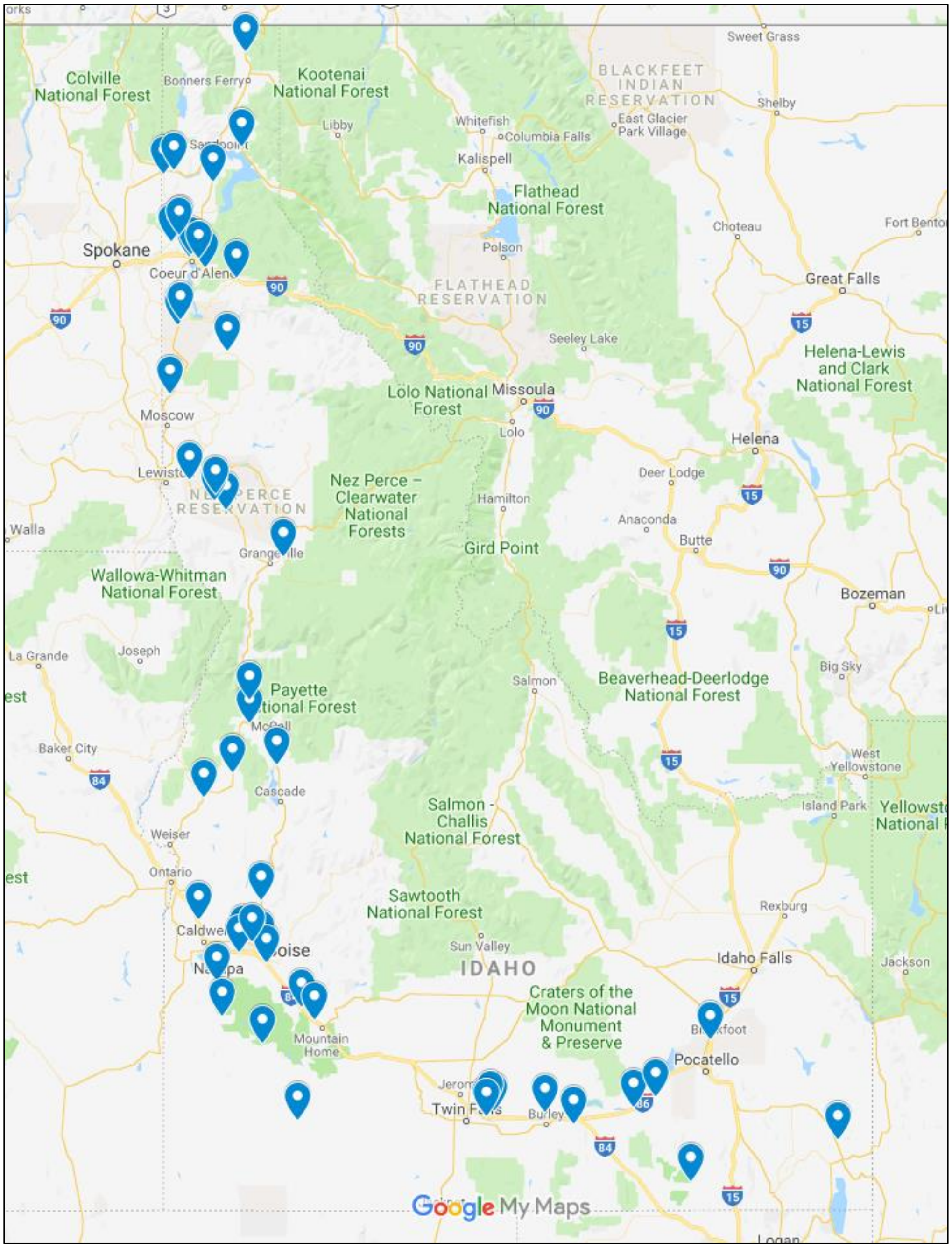


**Figure 10. Locations of selected sections**

Typical materials used during hole drilling in the field included:

- Cleaning duster
- Duct tape
- Spray paint

- Mineral oil
- Hammer drill with and a 0.5-inch drill bit
- Fluke Meter
- Caulk Gun
- Blacktop repair (Siliconized acrylic latex for flexible, durable seal)

The process of hole drilling included the following steps:

- Use the spray paint to mark the measurement location.
- Drill a hole using a 0.5-drill bit.
- Clean out the hole using the cleaning duster and clean around the hole.
- Pour in the mineral oil in the hole all the way to the top.
- Cover the hole with duct tape and spray a circle around the temp hole to mark it.
- Before the FWD testing, peel back tape and insert the fluke meter wire to gather the temperature. Wait for the temperature to stabilize before recording.
- Mark down the temperature and put it in the system.
- When the temperature hole is no longer needed, fill the hole with the blacktop repair using the caulk gun.

Figure 11 shows the items used in measuring pavement temperature in the field.

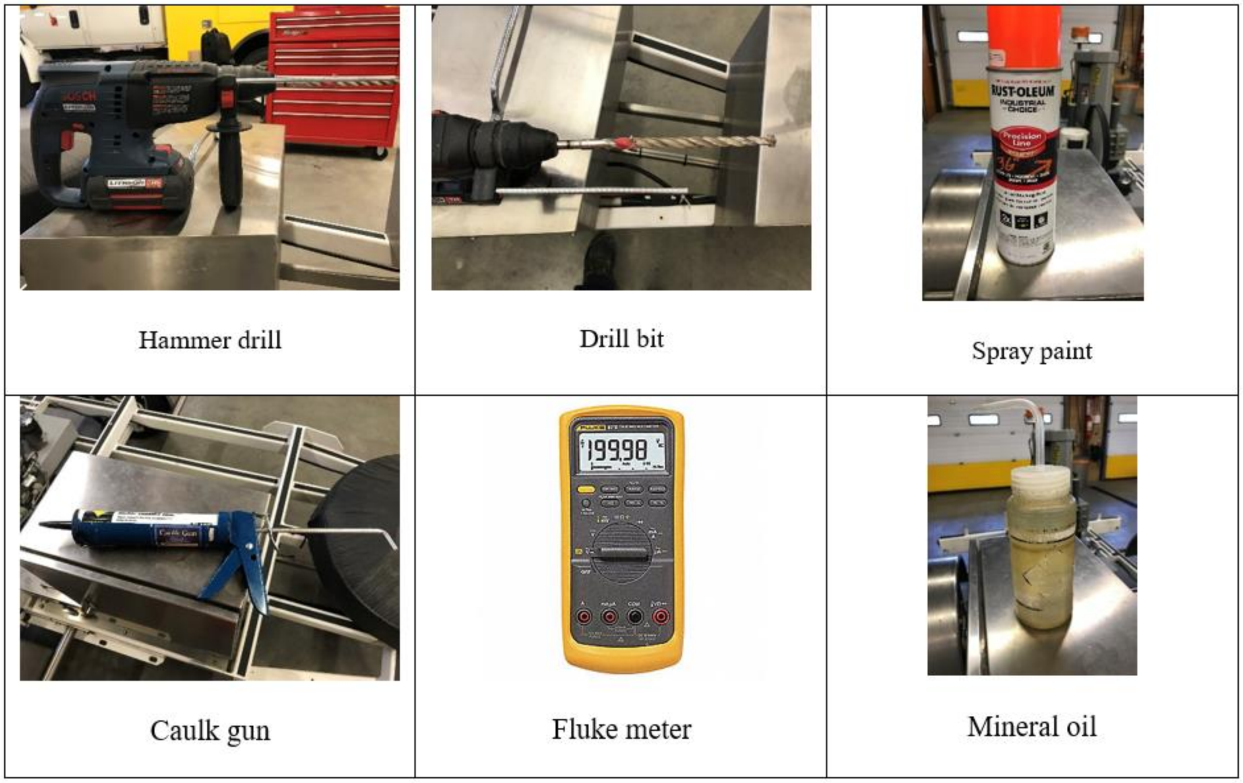


**Figure 11. Items and materials used in Measuring Pavement Temperature in the Field**

## Data Collection on Campus

A similar procedure was followed to collect additional pavement temperature data on campus at the University of Idaho. The temperature data were collected at two sites at different depths (i.e., three inches and five inches from the surface). Two holes were drilled at each site. Since most of the ITD pavement temperature data were collected at three inches from the surface, which is the practice at ITD, the researchers collected pavement temperatures at various depths (i.e., three and five inches) since the depth in an important parameter in the prediction models. Figure 12 shows the location of the two sites (i.e., Site A and Site B) on campus.

The following data were obtained at the sites of U of I:

- Pavement surface temperature recorded by an infrared thermometer.
- Pavement temperature at three inches and five inches from the surface recorded using a fluke meter.
- Previous day’s average air temperature obtained from the “Weather Underground” website.
- Time and date of pavement temperature measurements.

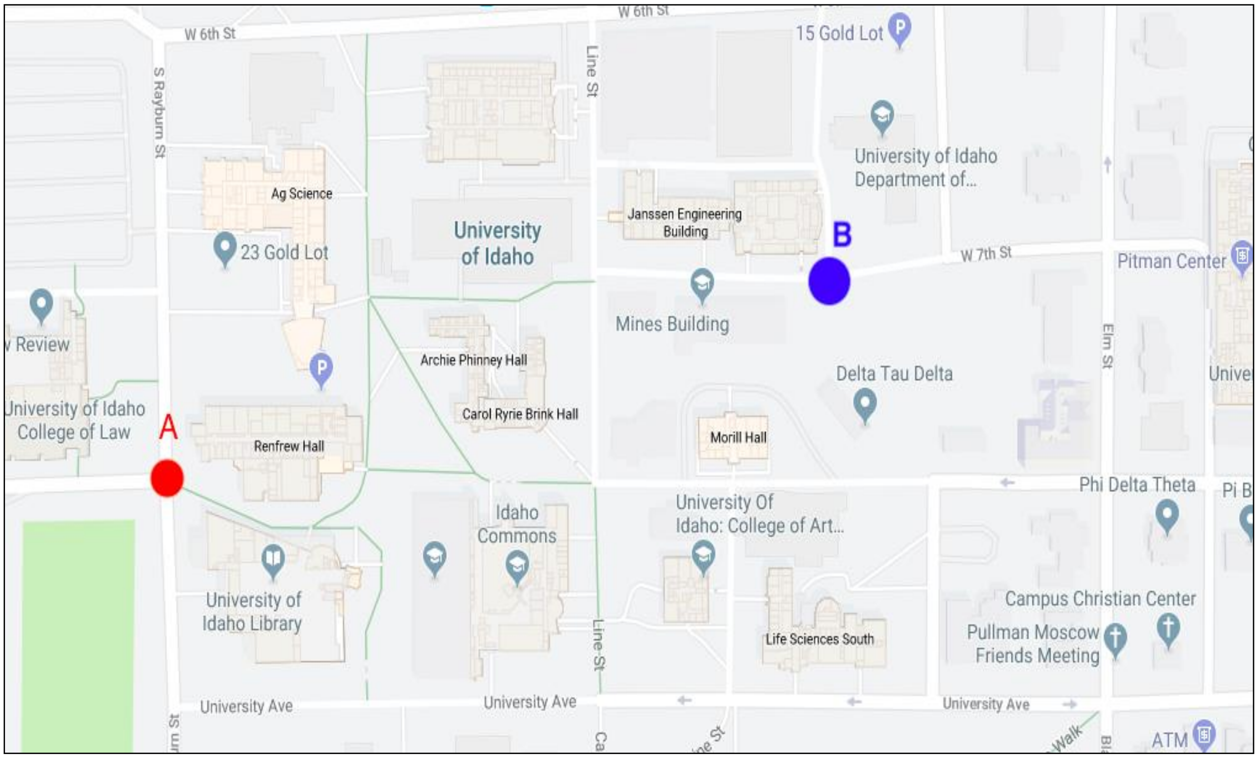


**Figure 12. Location of Test Sites at U of I**

## Statistical Analysis of Pavement Temperature Data

The researchers used statistical software SAS and R to conduct the statistical analysis and model development and calibration in this study (SAS 2013; R Core Team 2013). Based on the literature review, the BELLS models (i.e., BELLS2 and BELLS3) are commonly used to estimate the pavement temperature as a function of pavement surface temperature, depth, average air temperature of the previous day of testing, and time of testing. Both BELLS2 and BELLS3 have the same mathematical expression (Equation 1) but different calibration coefficients (Table 1). Research studies showed that local calibration of BELLS model may be necessary to improve its prediction accuracy (Fernando et al. 2001). In addition, the researchers at Texas A&M University proposed an alternative model (i.e., alternative Texas model), which provided 7% reduction in RMSE between predicted and measured values (Fernando et al. 2001).

In addition to the above-mentioned pavement temperature prediction models, the researchers explored new alternative models to improve accuracy of pavement temperature prediction compared to existing models. Seven cases were considered for evaluating and selecting proper prediction models that suit Idaho conditions. These seven cases are as follows:

- Case 1: BELLS2 model with the national coefficient estimates
- Case 2: BELLS3 model with the national coefficient estimates

- Case 3: Calibrated BELLS2 model with calibrated (Idaho) coefficient estimates
- Case 4: Alternative Texas model with Texas coefficient estimates
- Case 5: Calibrated Alternative Texas model with calibrated (Idaho) coefficient estimates
- Case 6: Idaho First Order Model
- Case 7: Idaho 7-Term Model

The statistical analysis of these cases and models are discussed in detail the following section.

## BELLS2 Model

Figure 13 shows the predicted pavement temperature versus measured temperature in this study using the BELLS2 model (Equation 1) using the national coefficient estimates (Table 1). Such correlation (Figure 13) provides an adjusted $R^2$ of 0.886 and RMSE of 3.7 °C (Table 6). It can be observed that the BELLS2 model tends to underpredict the pavement temperature especially at higher temperatures which is consistent with the findings of previous studies (Fernando et al. 2001; Inge and Kim 1995; Liao et al. 2009). Such correlation can be further improved by calibrating the model coefficient estimates to suit Idaho conditions. It should be noted that the BELLS2 model was developed based on 10,304 observations that covered different climatic conditions across the Unites States.

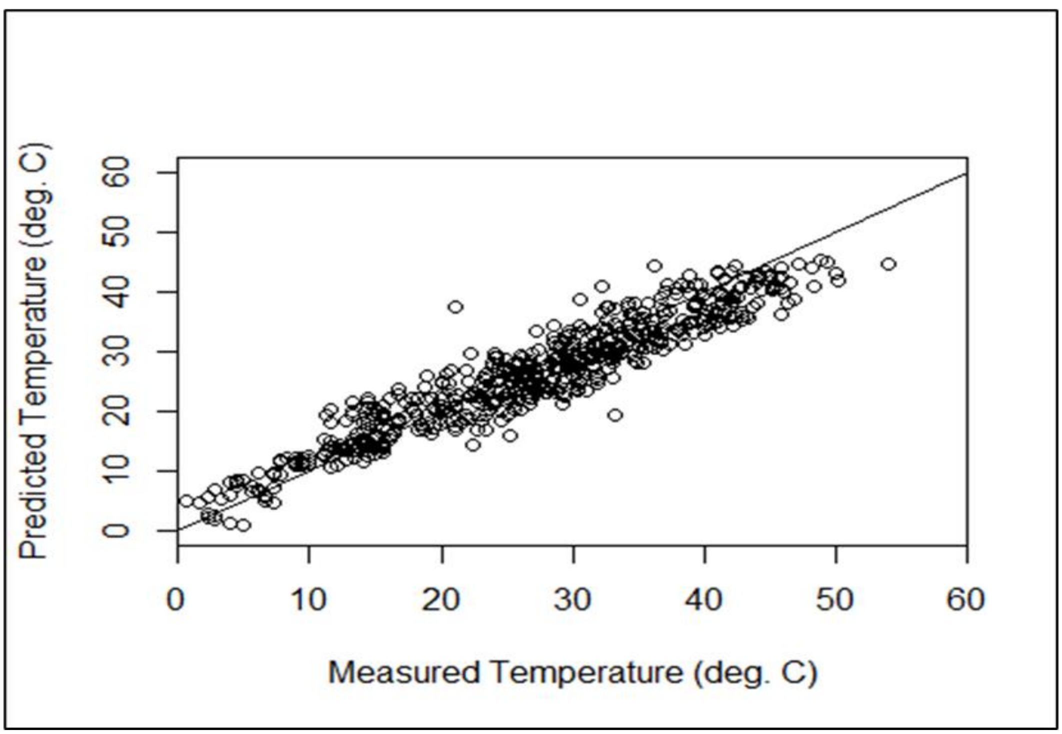


**Figure 13. Predicted Temperature vs. Measured Temperature using the BELLS2 Model with National Parameter Estimates**

**Table 6. Statistical Analysis of BELLS2 Model using National Parameter Estimates**

| N | Standard error of residuals | $R^2$ | Adjusted $R^2$ | Root-mean-square error |
|---|---|---|---|---|
| 596 | 3.729 | 0.887 | 0.886 | 3.73 |

## BELLS3 Model

Similarly, Figure 14 shows the predicted pavement temperature versus measured temperature in this study using the BELLS3 model (Equation 1) using the national coefficient estimates (Table 1). Such comparison provides an adjusted $R^2$ of 0.834 and RMSE of 4.5 °C (Table 7). The BELLS3 model provided slightly lower $R^2$ and higher RMSE compared to the BELLS2 model, which means that the BELLS2 model provided slightly better pavement temperature prediction when compared to the BELLS3 model.

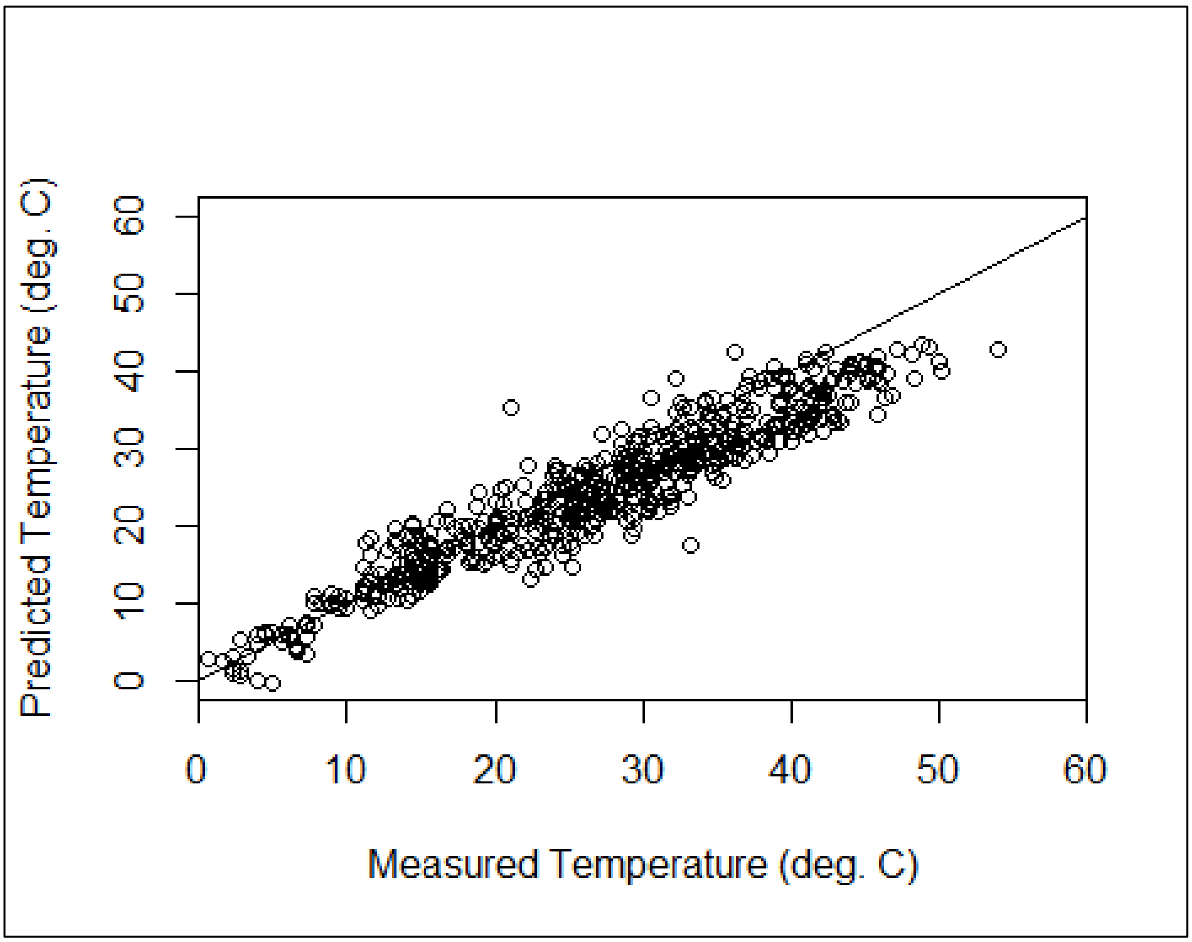


**Figure 14. Predicted Temperature vs. Measured Temperature using the BELLS3 Model with National Parameter Estimates**

**Table 7. Statistical Analysis of BELLS3 Model using National Parameter Estimates**

| N | Standard error of residuals | $R^2$ | Adjusted $R^2$ | Root-mean-square error |
|---|---|---|---|---|
| 596 | 4.503 | 0.835 | 0.834 | 4.503 |

## Calibrated BELLS2 Model

The researchers calibrated the BELLS2 model by calculating the model coefficient estimates to suit Idaho conditions. It should be noted that the BELLS2 and BELLS3 model have the same mathematical expression (Equation 1) but different coefficient estimates (Table 1). Researchers used statistical software SAS and R to calibrate the coefficients of the BELLS2 model (SAS 2013; R Core Team 2013). The significance of model parameters or independent variables (i.e., $\beta_0$, $\beta_1$, $\beta_2$, $\beta_3$, $\beta_4$, and $\beta_5$) was examined using the t-test. The t-test is used to determine whether the null hypothesis (no significant effect of a model parameter) should be supported or rejected. The model parameter is significant if the associated p-value is less than 0.05. The significance of model parameters increases as the p-value decreases. Table 8 summarizes the statistical analysis and p-value for the calibrated BELLS2 model. The results demonstrate that all model coefficients (i.e., $\beta_0$, $\beta_1$, $\beta_2$, $\beta_3$, $\beta_4$, and $\beta_5$) are significant. Meanwhile, $\beta_4$ coefficient was less significant when compared to the other model coefficients.

Figure 15 shows the predicted pavement temperature using the calibrated BELLS2 model versus the measured temperatures. Such model provided improved adjusted $R^2$ of 0.913 and reduced RMSE of 3.3 °C (Table 9) compared to $R^2$ of 0.886 and RMSE of 3.7 °C for the BELLS2 model before calibration. These results show that the calibration process improved the accuracy of the BELLS2 model and reduced the RMSE by 12.5%. In addition, such calibration reduced the bias in the model prediction (i.e., improved the predicted pavement temperature at higher temperatures). It should be noted that the calibration of the BELLS3 model would provide the same results as the calibrated BELLS2 model since both the BELLS2 and BELLS3 models have the same equation but different model coefficients.

**Table 8. Coefficients of Calibrated BELLS2 Model**

| Variable | Coefficient estimate | *t*-value | *p*-value |
|---|---|---|---|
| Intercept | 1.5008 ($\beta_0$) | 3.545 | 0.0004 |
| IR | 1.2919 ($\beta_1$) | 37.927 | 0.0000 |
| [$\log_{10}$(d)-1.25]IR | -0.8750 ($\beta_2$) | -16.492 | 0.0000 |
| [$\log_{10}$(d)-1.25] $T_{(1\text{-day})}$ | 0.5300 ($\beta_3$) | 12.061 | 0.0000 |
| [$\log_{10}$(d)-1.25] x sin ($hr_{18}$ – 15.5) | 1.4128 ($\beta_4$) | 3.018 | 0.0026 |
| IR sin ($hr_{18}$- 13.5) | 0.0447 ($\beta_5$) | 3.699 | 0.0002 |

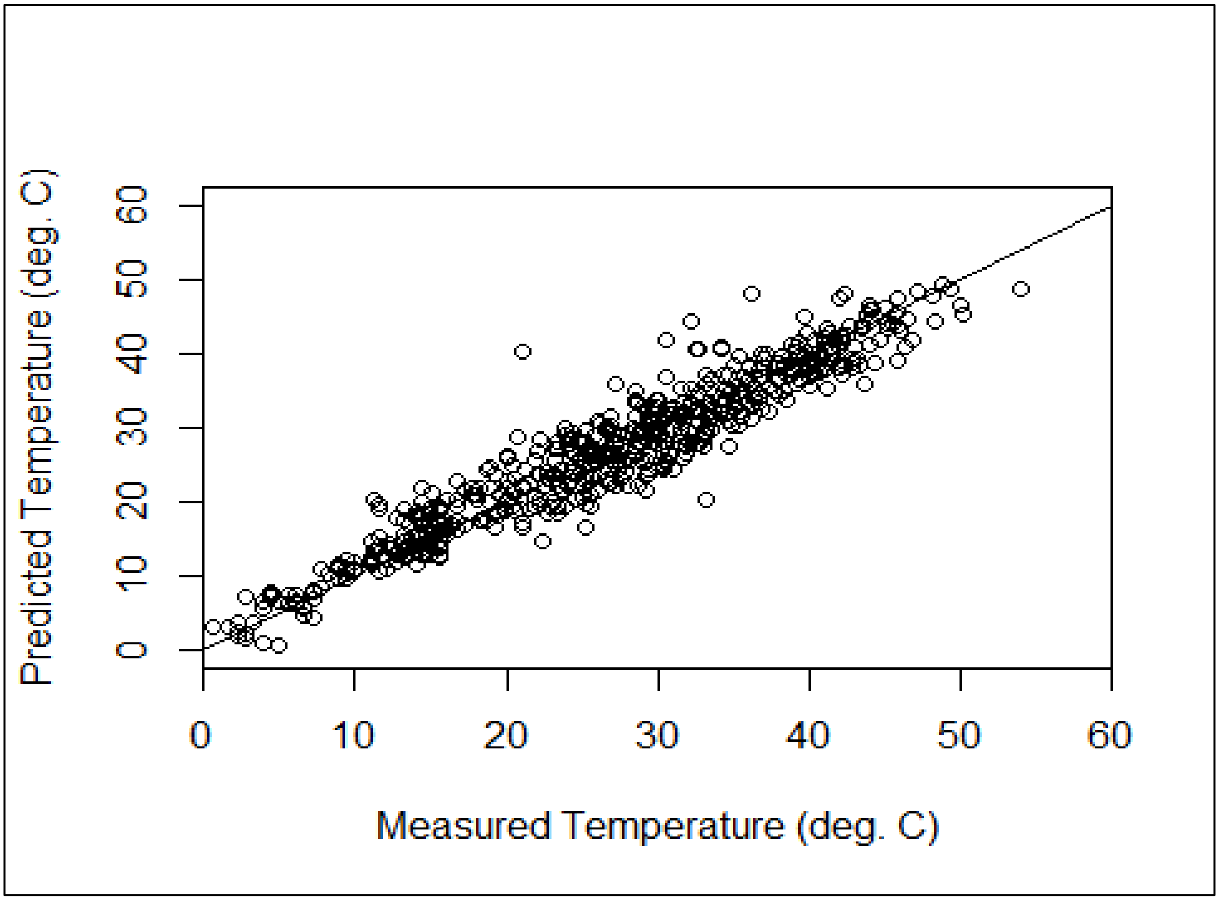


**Figure 15. Predicted Temperature vs. Measured Temperature using the Calibrated BELLS2 Model with Idaho Parameter Estimates**

**Table 9. Statistical Analysis of Calibrated BELLS2 Model using Idaho Parameter Estimates**

| N | Standard error of residuals | $R^2$ | Adjusted $R^2$ | Root-mean-square error |
|---|---|---|---|---|
| 596 | 3.264 | 0.914 | 0.913 | 3.265 |

# Alternative Texas Model

In addition to the BELLS models, the researchers evaluated an alternative model proposed by Fernando et al. (2001) which is referred to as alternative Texas model in this study. The equation for this model is presented in Equation 2 and the coefficient of the model is presented in Table 3. Figure 16 shows the predicted versus the measured pavement temperature using the alternative Texas model and the model coefficients proposed by Fernando et al. (2001) previously presented in Table 3. An adjusted $R^2$ of 0.796 and RMSE of 5.0 °C were obtained for the correlation between measured versus predicted pavement temperature using the alternative Texas model (Table 10). It should be noted that this model was developed based on the pavement temperature data obtained from various sites in Texas to suit the climatic conditions in Texas. Therefore, the researchers attempted to improve accuracy of the alternative Texas model through calibrating the coefficients of the model to suit the conditions in Idaho.

Table 11 shows the alternative Texas model coefficients after calibration. The calibrated model provided improved correlation between measured and predicted pavement temperature and reduced bias (Figure 13). The adjusted $R^2$ was improved from 0.796 to 0.90 and RMSE was reduced from 5.0 °C to 3.5 °C using the calibrated model (Table 12). However, two parameters (i.e., $\beta_4$ and $\beta_6$) were found to be insignificant in the alternative Texas model where the p-values are greater than 0.05 (Table 11). Comparing the calibrated alternative Texas model to the calibrated BELLS2 model, the latter has higher adjusted $R^2$ (0.913) and lower RMSE (3.3 °C) compared to adjusted $R^2$ (0.90) and RMSE (3.5 °C) of the former. These results demonstrate that the calibrated BELLS2 model provided more accurate prediction when compared to the calibrated Texas model.

The researchers also examined further improvements to the prediction of pavement temperature by developing new statistical-based models using the data collected and distributed over the state of Idaho. Two new models were developed and proposed: the Idaho First Order model and Idaho 7-Term model. These two models are discussed in detail in the following section.

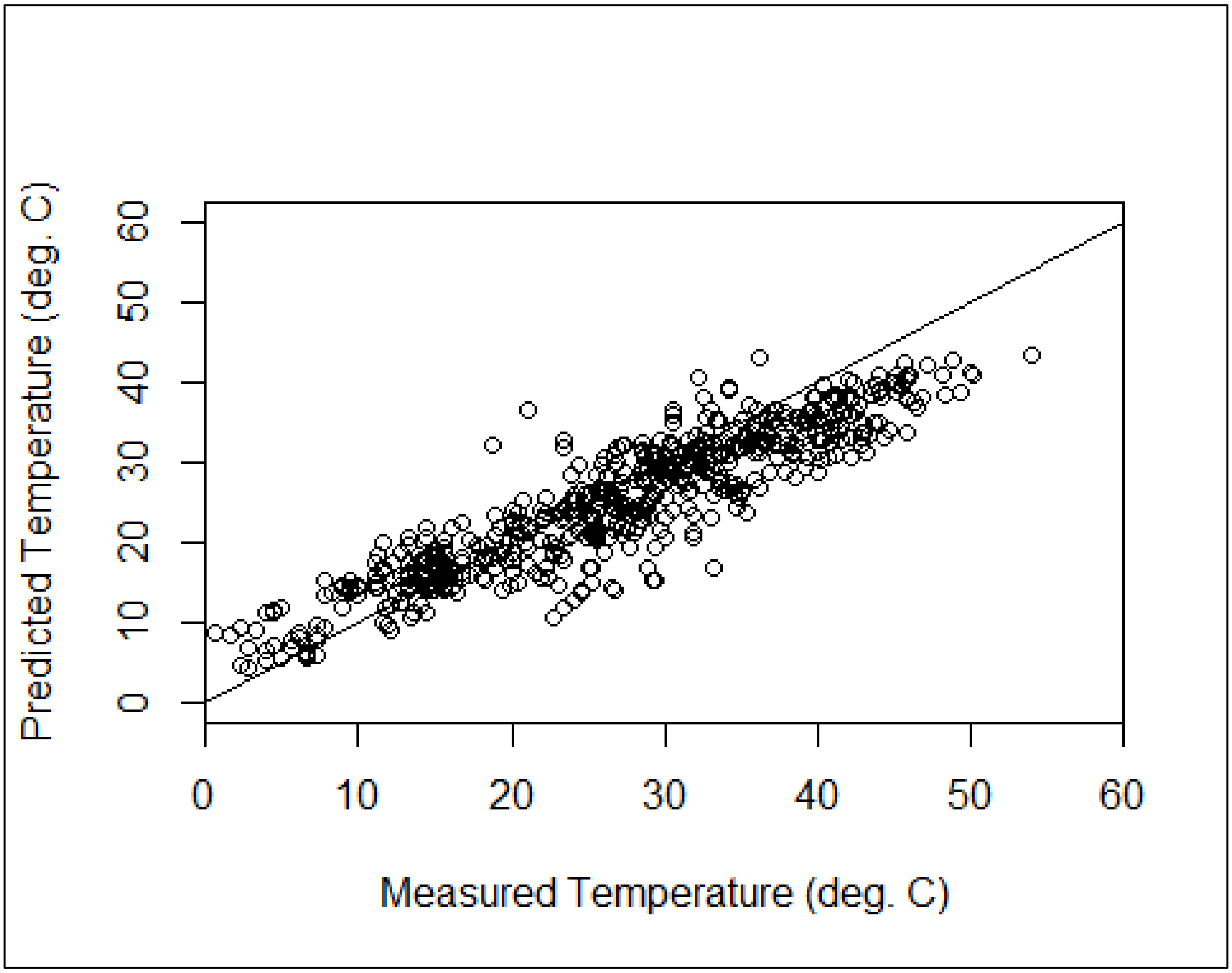


**Figure 16. Predicted Temperature vs. Measured Temperature using Alternative Texas Model with Texas Parameter Estimates**

**Table 10. Statistical Analysis of Alternative Texas Model using Texas Parameter Estimates**

| N | Standard error of residuals | $R^2$ | Adjusted $R^2$ | Root-mean-square error |
|---|---|---|---|---|
| 596 | 4.993 | 0.798 | 0.796 | 4.993 |

**Table 11. Coefficients of Calibrated Alternative Texas Model for Predicting Pavement Temperature**

| Calibration Coefficients | Estimate | *t*-value | *p*-value |
|---|---|---|---|
| $\beta_0$ | 7.2397 | 10.377 | 0.0000 |
| $\beta_1$ | 0.2796 | 19.073 | 0.0000 |
| $\beta_2$ | -0.1027 | -13.834 | 0.0000 |
| $\beta_3$ | -1.1464 | -2.554 | 0.0109 |
| $\beta_4$ | 0.7471 | 1.732 | 0.0838 |
| $\beta_5$ | 0.0306 | 13.503 | 0.0000 |
| $\beta_6$ | -2.4508 | -1.837 | 0.0668 |

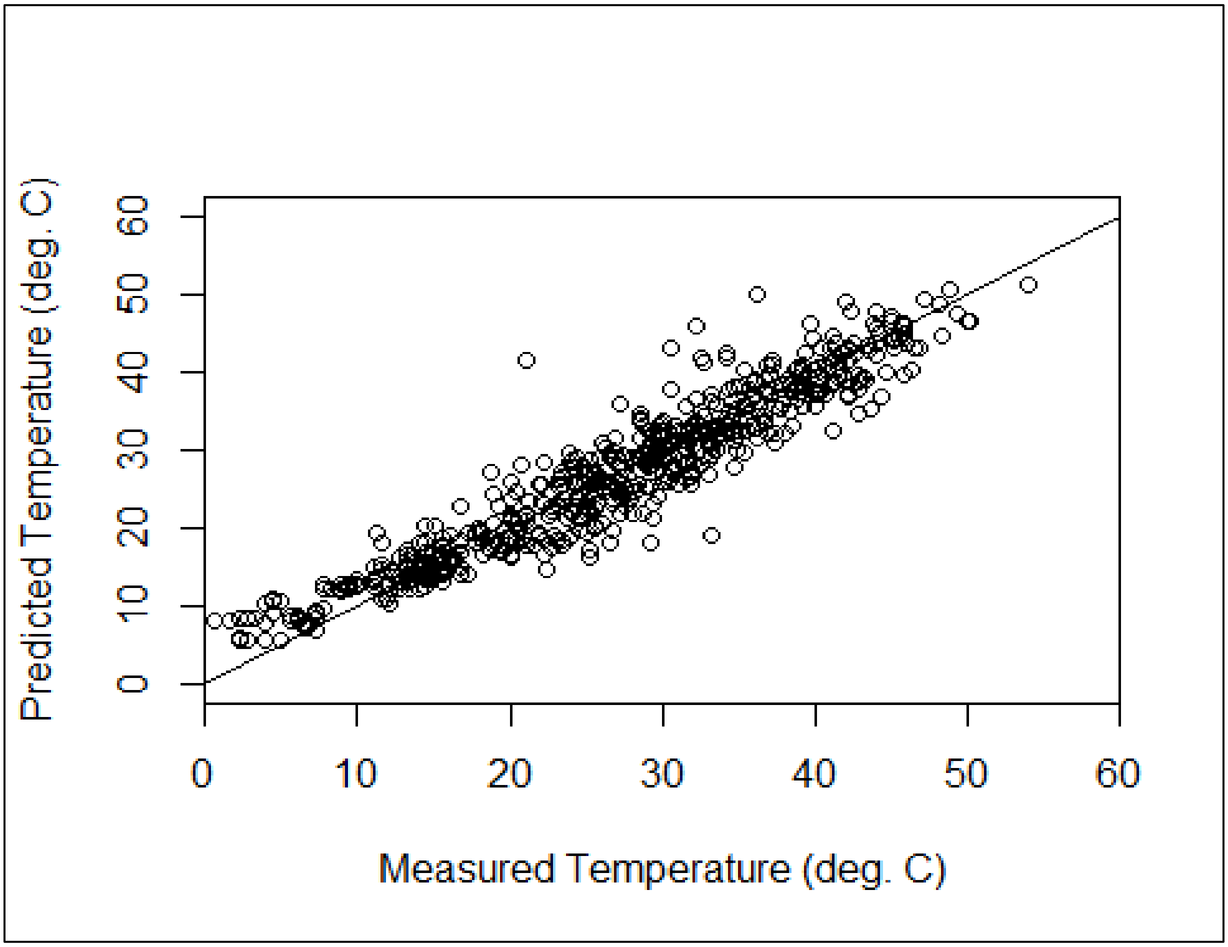


**Figure 17. Predicted Temperature vs. Measured Temperature using Alternative Texas Model with ID parameter estimates and ID data**

**Table 12. Statistical Analysis of Calibrated Alternative Texas Model using Idaho Parameter Estimates**

| N | Standard error of residuals | $R^2$ | Adjusted $R^2$ | Root-mean-square error |
|---|---|---|---|---|
| 596 | 3.504 | 0.9 | 0.9 | 3.504 |

## Idaho First Order Model

The researchers used the pavement temperature data collected in this study and developed a new model as presented in Equation 3. This model is referred to as Idaho First Order model. Table 13 summarizes the coefficients of the model and estimate and p-value of each parameter. The results showed that all the model parameters were significant (i.e., p-value < 0.05). Good correlation between the measured and predicted pavement temperature was obtained as shown in Figure 20. The model provided adjusted $R^2$ of

0.906 and RMSE of 3.4 °C (Table 14). The Idaho First Order model is a simple equation compared to other models, meanwhile the calibrated BELLS2 model provided slightly better adjusted $R^2$ of 0.913 and RMSE of 3.3 °C when compared to the Idaho First Order model.

$$T_d = \beta_0 + \beta_1 \, IR + \beta_2 \log_{10}(d) + \beta_3 \, T_{(1\ day)} + \beta_4 \sin(hr_{18} - 13.5) + \beta_5 \sin(hr_{18} - 15.5)$$

… … … Eqn. 3

where,

$T_d$ = pavement temperature at depth d, °C

IR = pavement surface temperature measured using an infrared gauge, °C

d = depth at which the temperature is predicted, mm

$T_{(1\text{-}day)}$ = average air temperature of previous day (average of high and low temperatures), °C

$hr_{18}$ = time of the day, in a 24-hr system but calculated using an 18-hr asphalt concrete temperature rise- and fall-time cycle (Figure 5).

**Table 13. Coefficients of Idaho First Order Model**

| **Variable** | **Coefficient** | **Coefficient Estimate** | ***t*-value** | ***p*-value** |
|---|---|---|---|---|
| Intercept | $\beta_0$ | 30.6716 | 10.605 | 0.0000 |
| IR | $\beta_1$ | 0.7488 | 37.022 | 0.0000 |
| $\log_{10}(d)$ | $\beta_2$ | -14.6048 | -9.982 | 0.0000 |
| $T_{(1\text{-}day)}$ | $\beta_3$ | 0.2612 | 7.630 | 0.0000 |
| $\sin(hr_{18} – 13.5)$ | $\beta_4$ | -1.4134 | -2.598 | 0.0096 |
| $\sin(hr_{18} - 15.5)$ | $\beta_5$ | 3.3316 | 6.065 | 0.0000 |

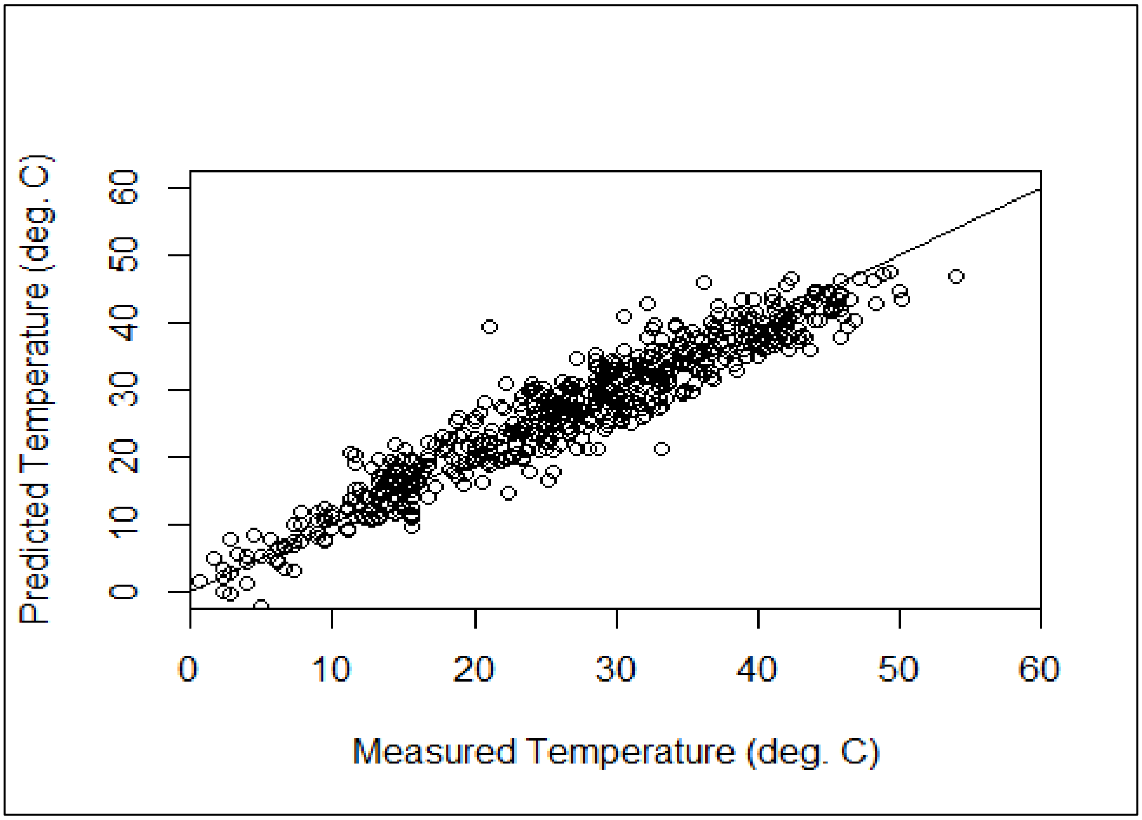


**Figure 18. Predicted Temperature vs. Measured Temperature using the Idaho First Order Model**

**Table 14. Statistical Analysis of Idaho First Order Model**

| N | Standard error of residuals | $R^2$ | Adjusted $R^2$ | Root-mean-square error |
|---|---|---|---|---|
| 596 | 3.382 | 0.907 | 0.906 | 3.382 |

## Idaho 7-Term Model

The researchers developed another model that utilizes the pavement temperature collected across the state. This term has seven terms in addition to the intercept (Equation 4) so it is referred to as the Idaho 7-Term model. Table 15 presents the model parameters, estimate of each parameter, and p-value to assess the significance of each parameter. The results demonstrate that all the model parameters are significant (p-value < 0.05). This model provides very good correlation between measured pavement temperatures and predicted ones as shown in Figure 19. This model provides the highest adjusted $R^2$ of 0.919 and lowest RMSE of 3.2 °C when compared to all other models examined in this study (Table 16 and Table 17).

$$T_d = \beta_0 + \beta_1 IR + \beta_2 T_{(1\ day)} + \beta_3 \sin(hr_{18} - 13.5) + \beta_4 \sin(hr_{18} - 15.5) + \beta_5 IR \log_{10}(d) + \beta_6 IR \sin(hr_{18} - 13.5) + \beta_7 \log_{10}(d)\ T_{(1\ day)}$$

… … … Eqn. 4

where,

$T_d$ = pavement temperature at depth d, °C

IR = pavement surface temperature measured using an infrared gauge, °C

d = depth at which the temperature is predicted, mm

$T_{(1\text{-}day)}$ = average air temperature of previous day (average of high and low temperatures), °C

$hr_{18}$ = time of the day, in a 24-hr system but calculated using an 18-hr asphalt concrete temperature rise- and fall-time cycle (Figure 5).

**Table 15. Coefficients of the Idaho 7-Term Model**

| Variable | Coefficient | Coefficient estimate | *t*-value | *p*-value |
|---|---|---|---|---|
| Intercept | $\beta_0$ | 1.7569 | 4.246 | 0.0000 |
| IR | $\beta_1$ | 2.6607 | 9.348 | 0.0000 |
| $T_{(1\ day)}$ | $\beta_2$ | -1.1392 | -2.350 | 0.0191 |
| $\sin(hr_{18} - 13.5)$ | $\beta_3$ | -3.9043 | -6.499 | 0.0000 |
| $\sin(hr_{18} - 15.5)$ | $\beta_4$ | 3.6932 | 7.137 | 0.0000 |
| $IR \log_{10}(d)$ | $\beta_5$ | -0.9829 | -6.743 | 0.0000 |
| $IR \sin(hr_{18} - 13.5)$ | $\beta_6$ | 0.0901 | 6.305 | 0.0000 |
| $\log_{10}(d)\ T_{(1\ day)}$ | $\beta_7$ | 0.7303 | 2.911 | 0.0038 |

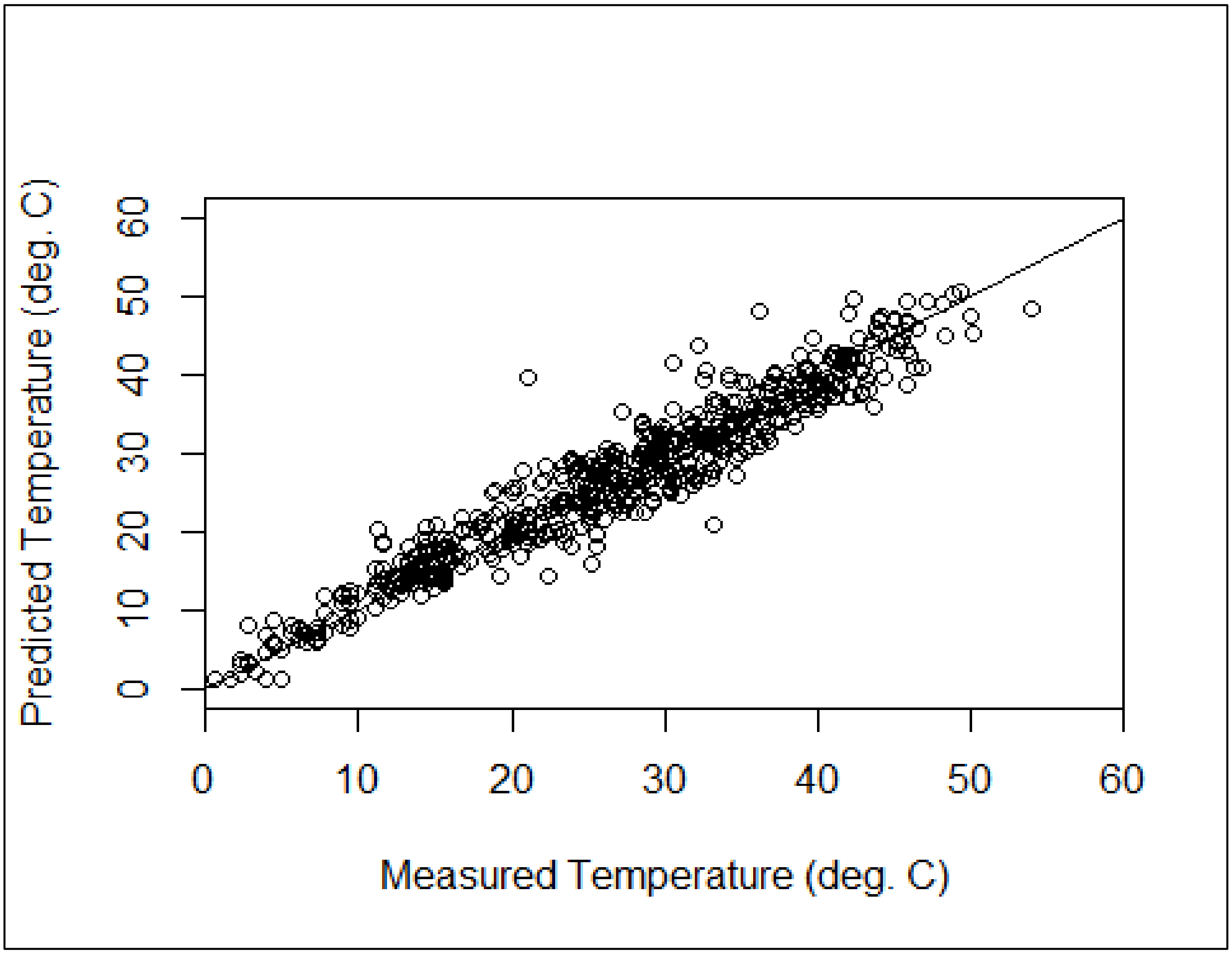


**Figure 19. Predicted Temperature vs. Measured Temperature using the Idaho 7-Term Model**

**Table 16. Statistical Analysis of the Idaho 7-Term Model**

| N | Standard error of residuals | $R^2$ | Adjusted $R^2$ | Root-mean-square error |
|---|---|---|---|---|
| 596 | 3.154 | 0.92 | 0.919 | 3.154 |

## Summary of Prediction Models

The researchers examined seven models to obtain pavement temperature predictions with good accuracy and low bias. These seven cases included:

- Case 1: BELLS2 model with the national coefficient estimates
- Case 2: BELLS3 model with the national coefficient estimates

- Case 3: Calibrated BELLS2 model with calibrated (Idaho) coefficient estimates
- Case 4: Alternative Texas model with Texas coefficient estimates
- Case 5: Calibrated Alternative Texas model with calibrated (Idaho) coefficient estimates
- Case 6: Idaho First Order Model
- Case 7: Idaho 7-Term Model

Table 17 summarizes the adjusted $R^2$ and RMSE for all cases evaluated in this study. The results demonstrate that the calibrated BELLS2 model and Idaho 7-Term model provide higher $R^2$ and lower RMSE compared to other models evaluated in this study. The Idaho 7-Term model provides the highest $R^2$ (0.919) and lowest RMSE (3.2 °C); therefore, it recommended in this study. However, the calibrated BELLS2 model still provides good adjusted $R^2$ of 0.913 and low RMSE of 3.3 °C. The original BELLS2 model was developed based on a larger data set (over 10,000 observations) compared to the Idaho 7-Term model (total of 596 data points); therefore, both models are recommended and used in the Excel-based utility developed in this study to assist in ITD engineers in predicting pavement temperature as discussed in the following section. The data used in the development of Idaho 7-Term model were collected in Idaho, while the observations used in the development of BELLS2 model were collected across the US. The calibrated BELLS2 model, recommended in this study, used the data collected in Idaho to estimate the model coefficients to improve model prediction and reduce the bias. Both models (i.e., the Idaho 7-Term model and the calibrated BELLS2 model) are highly correlated ($R^2$ of 0.99) as shown in Figure 20.

The statistical analysis clearly demonstrated that pavement temperature can be predicted with reasonable accuracy without the need of hole drilling. Pavement temperature can be predicted by measuring pavement surface temperature, previous day's average air temperature, time of testing, and depth at which pavement temperature is needed. ITD measures pavement surface temperature during the routine FWD or TSD testing using infrared sensors mounted on the FWD or TSD trailers. Previous day's average temperature can be obtained from the weather records using online resources such as Weather Underground website where the user enters the geographic location of the site and select the date. ITD can use the recommended models to predict pavement temperature without the need to drill holes and employ temperature interpolations to correct the backcalculated moduli in case of FWD testing. Also, the recommended models can be used to estimate pavement temperature needed to correct the TSD deflection measurements. The use of these models will also greatly improve the accuracy of pavement evaluation and assessment processes using FWD and TSD that require pavement temperature corrections.

**Table 17. Summary Results from all models**

| Model | Parameter Estimates | Data | Adjusted $R^2$ | RMSE |
|---|---|---|---|---|
| BELLS2 | National | Idaho | 0.886 | 3.73 |
| BELLS3 | National | Idaho | 0.834 | 4.503 |
| Calibrated BELLS2 | Idaho | Idaho | 0.913 | 3.265 |
| Alternative | Texas | Idaho | 0.796 | 4.993 |
| Alternative | Idaho | Idaho | 0.90 | 3.504 |
| Idaho First Order | Idaho | Idaho | 0.906 | 3.382 |
| Idaho 7-Term Model | Idaho | Idaho | 0.919 | 3.154 |

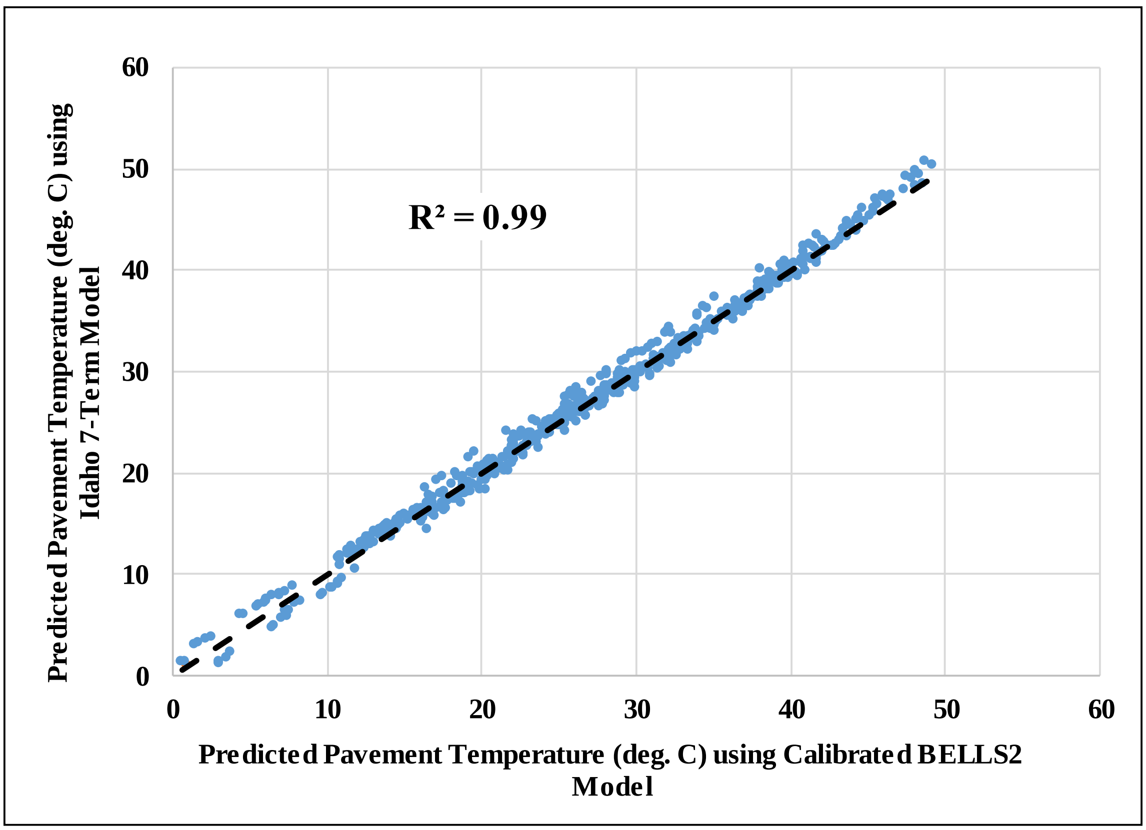


**Figure 20. Predicted Pavement Temperature using the Calibrated BELLS Model vs. Idaho 7-Term Model**

## Excel-Based Utility for Pavement Temperature Prediction

The researchers developed an Excel-based utility to facilitate the calculations of pavement temperature using the selected models and recommended in this study. This excel-based visual basic application can assist ITD crew to perform the analysis in a simple way. The user interface of this utility is shown in Figure 21. The inputs of this utility include previous day's average air temperature, pavement surface temperature, time of the measurement, and depth. The outputs of the excel utility is the predicted pavement temperature using two selected models: the calibrated BELLS2 model and the Idaho 7-Term model. The user enters the inputs and selects the model to use to predict the pavement temperature. Table 18 summarizes the inputs and outputs of the developed Excel-based utility. The user has the choice to determine the pavement temperature based on the calibrated BELLS2 model or Idaho 7-Term model. Both modes are highly correlated ($R^2$ of 0.99) as discussed earlier. The function of each command button in the user interface (Figure 21) is described in Table 18.

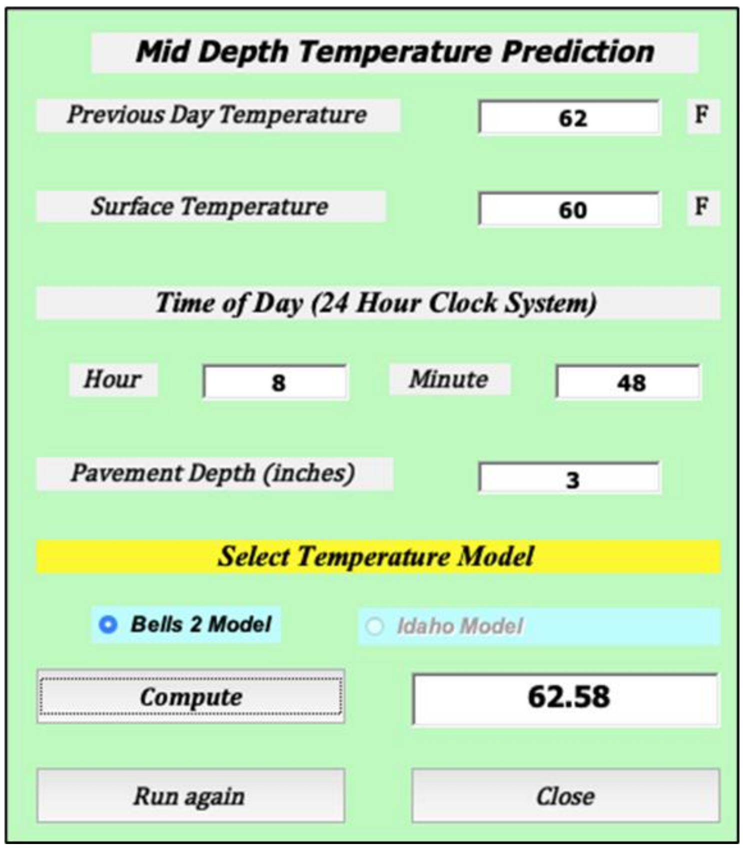


**Figure 21. Excel–Based Utility for Pavement Temperature Prediction**

**Table 18. Command Buttons and Their Function**

| Commands | Functions |
|---|---|
| Previous Day Temperature (°F) | Enter the previous day average air temperature |
| Surface Temperature (°F) | Enter the pavement surface temperature using infrared sensor installed on the FWD trailer |
| Time | Enter the time (hour and minutes) of measuring pavement surface temperature on 24-hour clock system |
| Pavement Depth (inches) | Enter pavement depth at which temperature is needed |
| BELLS Model | Provide the pavement temperature prediction using the calibrated BELLS2 model |
| Idaho Model | Provide the pavement temperature prediction using the Idaho 7-Term model |
| Compute | Provide the pavement temperature prediction either using the calibrated BELLS2 model or the Idaho 7-Term model |
| Run Again | Clear all the commands and inputs and restore the software to the initial status to start new runs |
| Close | Close the program |

# 4. Conclusions and Recommendations

Currently ITD measures the pavement temperature during FWD testing by drilling holes every three-mile interval. Although this practice provides an accurate pavement temperature at the locations of drilled holes, it requires additional resources (e.g., traffic control and staff time), causes traffic delays, and may put the crew in line with traffic. In addition, pavement temperature interpolation is used to estimate the temperature at locations between two consecutive holes since there are drilled every three miles. Pavement temperature interpolation may not always provide accurate measurements. Furthermore, ITD recently adapted the use of TSD in evaluating the structural conditions of pavements. TSD measures pavement deflection at highway speed and drilling holes is not feasible while performing the TSD evaluations. Alternatively, pavement temperature can be estimated using prediction models.

The study herein was initiated to examine the feasibility of predicting pavement temperature using data collected in Idaho. The pavement temperature data were collected by ITD FWD crew during their FWD testing. The data were collected in 2016, 2017, 2018, and 2019 in the six districts of the state. Most of pavement temperatures were measured at three inches from the surface (the current practice at ITD). An infrared thermometer is mounted on the FWD trailer to measure the pavement surface temperature during testing. In addition, the location of the measurements was also documented. The location was used to determine the previous day's average air temperature from the weather records using online resources such as Weather Underground website. A total number of 454 measurements were collected in the field. The team also collected additional 142 measurements at two sites on campus at the University of Idaho at two different depths (i.e., three inches and five inches). A total number of 596 observations or pavement temperature were used in the model development and calibration in this study.

The researchers evaluated seven cases to obtain a pavement temperature prediction model with good accuracy and low bias. These seven cases included:

- Case 1: BELLS2 model with the national coefficient estimates
- Case 2: BELLS3 model with the national coefficient estimates
- Case 3: Calibrated BELLS2 model with calibrated (Idaho) coefficient estimates
- Case 4: Alternative Texas model with Texas coefficient estimates
- Case 5: Calibrated Alternative Texas model with calibrated (Idaho) coefficient estimates
- Case 6: Idaho First Order Model
- Case 7: Idaho 7-Term Model

The results revealed that the calibrated BELLS2 model and Idaho 7-Term model provide the highest $R^2$ and lowest RMSE. An adjusted $R^2$ of 0.913 was obtained for the calibrated BELLS2 model and 0.919 for the Idaho 7-Term model, while RMSE of 3.3 °C was associated with the calibrated BELLS2 model and 3.2 °C for the Idaho 7-Term model. Both models (i.e., the Idaho 7-Term model and the calibrated BELLS2 model) are highly correlated ($R^2$ of 0.99). It should be noted that BELLS2 model was originally developed using over 10,000 observations and the measurements used in this study (596 observations) were used to calibrate the model and provide the calibrated BELLS2 model. Whereas Idaho 7-Term model was developed based on the data collected in Idaho (596 observations). The Idaho 7-Term model provided comparable $R^2$ to that of the calibrated BELLS2 model but a slightly lower RMSE.

The results of this study demonstrated the feasibility of predicting pavement temperature as a function of pavement surface temperature, previous day's average air temperature, depth, and time of testing. The results also demonstrated the need to calibrate the BELLS models for improved accuracy and reduce bias. The adjusted $R^2$ of the BELLS2 model improved from 0.886 to 0.913 and RMSE was reduced from 3.7 °C to 3.3 °C after calibration. Based on the statistical analysis, the researchers selected and recommended two models: the calibrated BELLS2 model and Idaho 7-Term model for predicting pavement temperature. Both models can predict pavement temperature with good accuracy and low bias. These models are calibrated and developed based on the data collected in Idaho. ITD can utilize the prediction models to estimate pavement temperature without the need to drill holes, which saves time and resources and improves the safety of the ITD FWD crew in the field.

# 5. References


Federal Highway Administration (FHWA). 1998. *Techniques for Pavement Rehabilitation*. FHWA-NHI-131008.

National Cooperative Highway Research Program (NCHRP). 1990. *Determining Asphaltic Concrete Pavement Structural Properties by Nondestructive Testing*. Lytton, Robert L., F. P. Germann, Eddie Y. J. Chou, and Shelley Stoffels. NCHRP Report No. 327, Texas Transportation Institute, Texas A&M University System, College Station, TX.

Federal Highway Administration (FHWA). 2000. *Temperature Predictions and Adjustment Factors for Asphalt Pavement.* Lukanen, Erland O., Richard N. Stubstad, and Robert Briggs. FHWA-RD-98-085.

Federal Highway Administration (FHWA). 2001. *Development of a Procedure for Temperature Correction of Backcalculated AC Modulus*. Fernando, Emmanuel G., Wenting Liu, and Duchwan Ryu. FHWA/TX-02/1863-1, Texas Transportation Institute, Texas A&M University System, College Station, TX.

Idaho Transportation Department. 2015. *Idaho Transportation System Pavement Performance Report.* Idaho Transportation Department, Boise, Idaho.

United States Department of Transportation (USDOT). 2015. *Development of Improved Pavement Rehabilitation Procedures Based on FWD Backcalculation.* Tutumluer, Erol, and Priyanka Sarker. USDOT Region V Regional University Transportation Center Final Report, NEXTRANS Project No. 094IY04, University of Illinois at Urbana-Champaign, IL.

Inge Jr, Earl H., and Richard Kim. 1995. "Prediction of Effective Asphalt Layer Temperature." *Transportation Research Record* ,1473: 93-100.

Illinois Department of Transportation. 1990. Johnson, Kurt D., Elias H. Rmeili, and Michael I. Darter. *Development of Maintenance and Rehabilitation Strategies—Northern Illinois Toll Highway, East-West Tollway Extension.* Phase II Final Report, Illinois State Toll Highway Authority.

Solatifar, Nader, Mojtaba Abbasghorbani, Amir Kavussi, and Henrikas Sivilevičius. 2018. "Prediction of Depth Temperature of Asphalt layers in Hot Climate Areas*." Journal of Civil Engineering and management*, 24(7): 516-525.

Liao, Chi-Chou, Bo-Ruei Chen, Shun-Hsing Chen, and Wei-Hsing Huang. 2009. "Temperature Prediction Model for Flexible Pavements in Taiwan." Presented at GeoHunan International Conference, Changsha, Hunan, China, August 3-6, 2009.

SAS. 2013. SAS Software, SAS Institute Inc.

R Core Team. 2013*. R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org

# Appendix A. Test Data

## Table A.1 Data Collection

| Date | Time | Surf. Temp (°F) | Prev. Day's Avg. Temp. | Depth (mm) | Measured Pavement. Temp. (°F) |
|---|---|---|---|---|---|
| 19/05/2016 | 08:48:09 | 59.60 | 62.00 | 76.20 | 56.50 |
| 19/05/2016 | 10:54:25 | 61.70 | 62.00 | 76.20 | 65.30 |
| 11/05/2016 | 08:00:05 | 53.50 | 52.00 | 76.20 | 53.10 |
| 11/05/2016 | 09:45:16 | 64.50 | 52.00 | 76.20 | 61.60 |
| 11/05/2016 | 12:46:32 | 82.70 | 52.00 | 76.20 | 77.90 |
| 11/05/2016 | 13:41:33 | 83.50 | 52.00 | 76.20 | 82.50 |
| 12/05/2016 | 05:26:08 | 50.60 | 54.00 | 76.20 | 55.10 |
| 12/05/2016 | 06:04:45 | 48.00 | 54.00 | 76.20 | 53.80 |
| 12/05/2016 | 06:38:01 | 49.60 | 54.00 | 76.20 | 57.50 |
| 10/05/2016 | 14:30:23 | 84.20 | 50.00 | 76.20 | 89.30 |
| 10/05/2016 | 15:20:16 | 92.10 | 50.00 | 76.20 | 95.80 |
| 10/05/2016 | 17:18:14 | 64.90 | 49.00 | 76.20 | 74.00 |
| 10/05/2016 | 19:38:58 | 72.20 | 48.00 | 76.20 | 79.70 |
| 10/05/2016 | 07:29:07 | 50.50 | 48.00 | 76.20 | 52.80 |
| 10/05/2016 | 09:01:13 | 55.00 | 48.00 | 76.20 | 56.20 |
| 10/05/2016 | 10:45:33 | 73.60 | 48.00 | 76.20 | 73.50 |
| 10/05/2016 | 12:24:53 | 80.60 | 48.00 | 76.20 | 72.80 |
| 10/05/2016 | 13:08:03 | 89.80 | 48.00 | 76.20 | 89.50 |
| 18/05/2016 | 11:02:15 | 84.40 | 62.00 | 76.20 | 71.70 |
| 18/05/2016 | 11:55:27 | 82.90 | 62.00 | 76.20 | 81.30 |
| 18/05/2016 | 12:09:56 | 84.20 | 62.00 | 76.20 | 74.00 |
| 26/07/2016 | 05:43:30 | 68.60 | 72.00 | 76.20 | 77.00 |
| 26/07/2016 | 06:10:10 | 70.10 | 72.00 | 76.20 | 77.30 |

| Date | Time | Surf. Temp (°F) | Prev. Day's Avg. Temp. | Depth (mm) | Measured Pavement. Temp. (°F) |
|---|---|---|---|---|---|
| 18/05/2016 | 09:26:51 | 64.80 | 62.00 | 76.20 | 57.40 |
| 18/05/2016 | 10:28:36 | 69.60 | 62.00 | 76.20 | 64.30 |
| 18/05/2016 | 10:50:46 | 85.90 | 62.00 | 76.20 | 73.80 |
| 26/07/2016 | 06:19:28 | 70.70 | 72.00 | 76.20 | 77.20 |
| 26/07/2016 | 06:47:15 | 69.10 | 72.00 | 76.20 | 75.40 |
| 14/09/2016 | 11:05:43 | 75.90 | 48.00 | 76.20 | 64.40 |
| 14/09/2016 | 12:26:24 | 81.90 | 48.00 | 76.20 | 73.80 |
| 14/09/2016 | 14:20:20 | 94.70 | 48.00 | 76.20 | 80.30 |
| 14/09/2016 | 16:19:07 | 89.10 | 48.00 | 76.20 | 84.10 |
| 14/09/2016 | 17:36:59 | 86.90 | 48.00 | 76.20 | 86.20 |
| 15/09/2016 | 09:06:18 | 49.90 | 53.00 | 76.20 | 48.00 |
| 15/09/2016 | 11:34:18 | 68.70 | 53.00 | 76.20 | 53.00 |
| 15/09/2016 | 14:27:04 | 99.30 | 61.00 | 76.20 | 91.00 |
| 15/09/2016 | 15:54:32 | 105.40 | 61.00 | 76.20 | 95.10 |
| 13/09/2016 | 10:21:02 | 69.00 | 60.00 | 76.20 | 52.40 |
| 13/09/2016 | 11:45:32 | 78.50 | 60.00 | 76.20 | 70.20 |
| 13/09/2016 | 13:04:14 | 88.90 | 60.00 | 76.20 | 84.10 |
| 13/09/2016 | 13:16:19 | 93.00 | 52.00 | 76.20 | 83.40 |
| 13/09/2016 | 13:35:56 | 63.70 | 52.00 | 76.20 | 57.50 |
| 15/09/2016 | 11:52:40 | 76.30 | 61.00 | 76.20 | 66.60 |
| 15/09/2016 | 13:09:53 | 87.00 | 61.00 | 76.20 | 69.30 |
| 06/06/2016 | 11:48:55 | 96.50 | 80.00 | 76.20 | 92.50 |
| 06/06/2016 | 12:33:25 | 98.40 | 80.00 | 76.20 | 97.00 |
| 06/06/2016 | 13:14:59 | 107.20 | 80.00 | 76.20 | 93.70 |
| 06/06/2016 | 13:31:36 | 107.80 | 80.00 | 76.20 | 93.70 |
| 06/06/2016 | 14:00:37 | 108.50 | 80.00 | 76.20 | 104.50 |

| Date | Time | Surf. Temp (°F) | Prev. Day's Avg. Temp. | Depth (mm) | Measured Pavement. Temp. (°F) |
|---|---|---|---|---|---|
| 06/06/2016 | 09:27:46 | 82.60 | 80.00 | 76.20 | 78.70 |
| 06/06/2016 | 10:12:27 | 88.40 | 80.00 | 76.20 | 83.30 |
| 06/06/2016 | 10:56:42 | 90.30 | 80.00 | 76.20 | 90.80 |
| 06/06/2016 | 11:25:54 | 90.70 | 80.00 | 76.20 | 89.70 |
| 29/06/2016 | 00:26:19 | 84.20 | 82.00 | 76.20 | 96.00 |
| 29/06/2016 | 01:33:06 | 79.30 | 82.00 | 76.20 | 91.60 |
| 29/06/2016 | 02:18:55 | 77.90 | 82.00 | 76.20 | 87.00 |
| 29/06/2016 | 03:20:08 | 77.40 | 82.00 | 76.20 | 86.80 |
| 27/06/2016 | 09:18:43 | 85.60 | 75.00 | 76.20 | 82.40 |
| 27/06/2016 | 10:08:08 | 94.00 | 75.00 | 76.20 | 85.70 |
| 27/06/2016 | 10:54:38 | 99.60 | 75.00 | 76.20 | 94.90 |
| 27/06/2016 | 11:16:37 | 106.10 | 75.00 | 76.20 | 102.00 |
| 23/06/2016 | 00:33:18 | 79.50 | 75.00 | 76.20 | 86.60 |
| 23/06/2016 | 00:49:04 | 79.70 | 75.00 | 76.20 | 85.50 |
| 23/06/2016 | 01:24:58 | 76.00 | 75.00 | 76.20 | 83.40 |
| 04/05/2016 | 23:10:32 | 76.00 | 67.00 | 76.20 | 78.00 |
| 04/05/2016 | 23:21:26 | 75.40 | 67.00 | 76.20 | 79.20 |
| 04/05/2016 | 23:31:59 | 74.60 | 67.00 | 76.20 | 78.80 |
| 22/06/2016 | 23:45:57 | 83.40 | 72.00 | 76.20 | 89.70 |
| 23/06/2016 | 00:15:17 | 80.40 | 72.00 | 76.20 | 83.80 |
| 04/05/2016 | 23:44:37 | 75.50 | 67.00 | 76.20 | 78.30 |
| 05/05/2016 | 00:02:27 | 70.30 | 67.00 | 76.20 | 77.30 |
| 23/08/2016 | 09:08:37 | 72.60 | 72.00 | 76.20 | 72.10 |
| 23/08/2016 | 09:18:38 | 74.10 | 72.00 | 76.20 | 74.50 |
| 23/08/2016 | 09:29:12 | 72.20 | 72.00 | 76.20 | 73.40 |
| 21/06/2016 | 08:57:09 | 70.90 | 60.00 | 76.20 | 67.20 |

| Date | Time | Surf. Temp (°F) | Prev. Day's Avg. Temp. | Depth (mm) | Measured Pavement. Temp. (°F) |
|---|---|---|---|---|---|
| 21/06/2016 | 10:17:13 | 85.90 | 60.00 | 76.20 | 77.70 |
| 21/06/2016 | 11:22:28 | 87.80 | 60.00 | 76.20 | 86.00 |
| 21/06/2016 | 12:45:31 | 92.40 | 60.00 | 76.20 | 94.70 |
| 21/06/2016 | 14:02:23 | 102.90 | 60.00 | 76.20 | 104.10 |
| 20/07/2016 | 10:45:50 | 90.40 | 75.00 | 76.20 | 88.60 |
| 20/07/2016 | 11:42:16 | 96.50 | 75.00 | 76.20 | 97.60 |
| 20/07/2016 | 09:25:31 | 78.80 | 75.00 | 76.20 | 80.70 |
| 20/07/2016 | 10:24:59 | 86.30 | 75.00 | 76.20 | 85.40 |
| 07/09/2016 | 07:18:46 | 54.40 | 56.00 | 76.20 | 54.50 |
| 07/09/2016 | 08:37:32 | 59.50 | 56.00 | 76.20 | 60.90 |
| 07/09/2016 | 09:07:43 | 61.60 | 56.00 | 76.20 | 61.30 |
| 07/09/2016 | 09:53:53 | 64.40 | 56.00 | 76.20 | 60.70 |
| 07/09/2016 | 10:38:13 | 69.20 | 56.00 | 76.20 | 72.00 |
| 07/09/2016 | 11:44:11 | 86.10 | 56.00 | 76.20 | 80.20 |
| 07/09/2016 | 12:42:23 | 82.20 | 56.00 | 76.20 | 82.90 |
| 07/09/2016 | 13:07:59 | 86.50 | 56.00 | 76.20 | 91.40 |
| 07/09/2016 | 13:52:54 | 85.80 | 56.00 | 76.20 | 89.30 |
| 07/09/2016 | 14:40:32 | 98.00 | 56.00 | 76.20 | 89.20 |
| 07/09/2016 | 15:21:23 | 103.80 | 56.00 | 76.20 | 100.10 |
| 08/09/2016 | 08:27:51 | 58.20 | 59.00 | 76.20 | 57.50 |
| 08/09/2016 | 09:08:02 | 63.20 | 59.00 | 76.20 | 57.90 |
| 08/09/2016 | 09:53:52 | 69.80 | 59.00 | 76.20 | 64.40 |
| 08/09/2016 | 10:42:11 | 72.70 | 59.00 | 76.20 | 78.80 |
| 08/09/2016 | 11:05:44 | 81.70 | 59.00 | 76.20 | 81.00 |
| 01/08/2017 | 21:26:44 | 92.60 | 72.00 | 76.20 | 106.00 |
| 01/08/2017 | 22:19:14 | 87.00 | 72.00 | 76.20 | 99.20 |

| Date | Time | Surf. Temp (°F) | Prev. Day's Avg. Temp. | Depth (mm) | Measured Pavement. Temp. (°F) |
|---|---|---|---|---|---|
| 01/08/2017 | 23:03:01 | 86.50 | 75.00 | 76.20 | 99.20 |
| 01/08/2017 | 23:15:22 | 82.00 | 75.00 | 76.20 | 91.70 |
| 02/08/2017 | 00:05:13 | 76.70 | 74.00 | 76.20 | 80.20 |
| 02/08/2017 | 00:57:25 | 75.00 | 74.00 | 76.20 | 89.10 |
| 02/08/2017 | 01:48:18 | 67.00 | 74.00 | 76.20 | 80.30 |
| 02/08/2017 | 02:36:24 | 69.70 | 74.00 | 76.20 | 84.70 |
| 02/08/2017 | 02:59:39 | 72.40 | 74.00 | 76.20 | 88.00 |
| 02/08/2017 | 20:44:55 | 97.80 | 74.00 | 76.20 | 109.20 |
| 02/08/2017 | 21:31:54 | 90.00 | 74.00 | 76.20 | 100.60 |
| 02/08/2017 | 22:22:10 | 85.40 | 74.00 | 76.20 | 89.20 |
| 02/08/2017 | 23:11:08 | 80.00 | 74.00 | 76.20 | 83.60 |
| 02/08/2017 | 23:55:29 | 81.90 | 74.00 | 76.20 | 91.60 |
| 31/07/2017 | 13:46:10 | 115.40 | 70.00 | 76.20 | 108.60 |
| 31/07/2017 | 15:09:26 | 108.30 | 70.00 | 76.20 | 107.50 |
| 31/07/2017 | 16:07:33 | 114.60 | 70.00 | 76.20 | 119.10 |
| 29/08/2017 | 14:14:47 | 111.80 | 66.00 | 76.20 | 91.00 |
| 29/08/2017 | 14:22:24 | 114.90 | 78.00 | 76.20 | 90.00 |
| 29/08/2017 | 15:13:20 | 121.70 | 78.00 | 76.20 | 97.10 |
| 29/08/2017 | 16:05:52 | 109.00 | 78.00 | 76.20 | 113.30 |
| 29/08/2017 | 10:23:47 | 83.60 | 78.00 | 76.20 | 76.00 |
| 29/08/2017 | 11:31:19 | 88.30 | 78.00 | 76.20 | 80.40 |
| 29/08/2017 | 12:31:25 | 100.70 | 78.00 | 76.20 | 87.00 |
| 29/08/2017 | 13:22:22 | 107.80 | 78.00 | 76.20 | 90.50 |
| 23/05/2017 | 12:08:45 | 103.50 | 57.00 | 76.20 | 94.20 |
| 23/05/2017 | 12:43:11 | 102.40 | 57.00 | 76.20 | 95.10 |
| 24/05/2017 | 22:58:27 | 63.50 | 56.00 | 76.20 | 73.20 |

| Date | Time | Surf. Temp (°F) | Prev. Day's Avg. Temp. | Depth (mm) | Measured Pavement. Temp. (°F) |
|---|---|---|---|---|---|
| 24/05/2017 | 23:41:15 | 59.20 | 56.00 | 76.20 | 69.80 |
| 24/05/2017 | 23:48:02 | 57.60 | 56.00 | 76.20 | 69.80 |
| 24/05/2017 | 23:54:57 | 60.40 | 56.00 | 76.20 | 65.20 |
| 23/05/2017 | 11:13:38 | 89.20 | 57.00 | 76.20 | 81.10 |
| 23/05/2017 | 11:37:45 | 97.70 | 57.00 | 76.20 | 87.00 |
| 25/05/2017 | 21:03:24 | 71.90 | 45.00 | 76.20 | 84.50 |
| 25/05/2017 | 21:31:08 | 67.70 | 45.00 | 76.20 | 77.40 |
| 14/06/2017 | 11:06:15 | 71.50 | 59.00 | 76.20 | 59.20 |
| 14/06/2017 | 12:23:20 | 84.50 | 59.00 | 76.20 | 75.70 |
| 14/06/2017 | 13:19:01 | 94.50 | 59.00 | 76.20 | 91.70 |
| 14/06/2017 | 15:16:26 | 96.20 | 59.00 | 76.20 | 101.40 |
| 14/06/2017 | 16:05:48 | 92.60 | 59.00 | 76.20 | 92.60 |
| 14/06/2017 | 16:48:25 | 92.50 | 59.00 | 76.20 | 92.50 |
| 14/06/2017 | 17:28:03 | 82.00 | 59.00 | 76.20 | 88.90 |
| 14/06/2017 | 18:23:56 | 79.90 | 59.00 | 76.20 | 85.60 |
| 15/06/2017 | 08:58:49 | 58.70 | 48.00 | 76.20 | 56.50 |
| 15/06/2017 | 09:49:21 | 55.80 | 48.00 | 76.20 | 57.90 |
| 23/05/2017 | 06:50:32 | 59.40 | 57.00 | 76.20 | 58.60 |
| 23/05/2017 | 06:51:34 | 59.60 | 57.00 | 76.20 | 58.60 |
| 23/05/2017 | 08:01:52 | 63.50 | 57.00 | 76.20 | 65.00 |
| 23/05/2017 | 08:17:37 | 67.40 | 57.00 | 76.20 | 70.90 |
| 23/05/2017 | 08:51:07 | 71.30 | 57.00 | 76.20 | 91.70 |
| 23/05/2017 | 10:09:10 | 80.20 | 57.00 | 76.20 | 73.00 |
| 23/05/2017 | 10:41:40 | 86.70 | 57.00 | 76.20 | 79.50 |
| 19/09/2017 | 13:37:01 | 70.60 | 57.00 | 76.20 | 74.80 |
| 19/09/2017 | 14:20:52 | 57.70 | 57.00 | 76.20 | 66.70 |

| Date | Time | Surf. Temp (°F) | Prev. Day's Avg. Temp. | Depth (mm) | Measured Pavement. Temp. (°F) |
|---|---|---|---|---|---|
| 19/09/2017 | 14:51:33 | 65.30 | 57.00 | 76.20 | 66.00 |
| 19/09/2017 | 08:45:21 | 52.90 | 58.00 | 76.20 | 52.30 |
| 19/09/2017 | 09:30:37 | 57.70 | 58.00 | 76.20 | 56.70 |
| 19/09/2017 | 10:35:28 | 55.50 | 58.00 | 76.20 | 72.40 |
| 19/09/2017 | 11:10:43 | 60.20 | 58.00 | 76.20 | 77.40 |
| 19/09/2017 | 11:42:16 | 62.30 | 58.00 | 76.20 | 65.70 |
| 18/09/2017 | 09:45:18 | 68.10 | 51.00 | 76.20 | 67.00 |
| 18/09/2017 | 10:06:35 | 70.00 | 51.00 | 76.20 | 67.90 |
| 18/09/2017 | 10:11:54 | 71.10 | 51.00 | 76.20 | 68.70 |
| 18/09/2017 | 10:32:17 | 74.30 | 51.00 | 76.20 | 71.40 |
| 20/09/2017 | 19:34:03 | 50.40 | 42.00 | 76.20 | 53.90 |
| 20/09/2017 | 19:58:50 | 52.10 | 42.00 | 76.20 | 53.60 |
| 18/07/2017 | 12:20:24 | 109.20 | 73.00 | 76.20 | 104.10 |
| 18/07/2017 | 12:59:17 | 106.60 | 73.00 | 76.20 | 109.00 |
| 18/07/2017 | 13:45:01 | 105.50 | 69.00 | 76.20 | 109.00 |
| 18/07/2017 | 13:52:04 | 112.90 | 69.00 | 76.20 | 111.20 |
| 18/07/2017 | 09:15:19 | 80.10 | 73.00 | 76.20 | 78.20 |
| 18/07/2017 | 09:50:58 | 87.30 | 73.00 | 76.20 | 85.20 |
| 18/07/2017 | 10:34:23 | 94.50 | 73.00 | 76.20 | 91.00 |
| 17/07/2017 | 11:38:42 | 99.30 | 69.00 | 76.20 | 93.70 |
| 17/07/2017 | 12:26:45 | 103.80 | 69.00 | 76.20 | 100.40 |
| 17/07/2017 | 13:15:59 | 107.30 | 69.00 | 76.20 | 110.00 |
| 17/07/2017 | 14:02:38 | 107.10 | 69.00 | 76.20 | 114.40 |
| 17/07/2017 | 14:57:07 | 105.10 | 69.00 | 76.20 | 106.80 |
| 19/07/2017 | 09:24:42 | 75.10 | 65.00 | 76.20 | 77.90 |
| 19/07/2017 | 10:19:37 | 81.90 | 65.00 | 76.20 | 79.50 |

| Date | Time | Surf. Temp (°F) | Prev. Day's Avg. Temp. | Depth (mm) | Measured Pavement. Temp. (°F) |
|---|---|---|---|---|---|
| 19/07/2017 | 11:00:17 | 92.40 | 65.00 | 76.20 | 84.60 |
| 19/07/2017 | 11:32:05 | 95.50 | 65.00 | 76.20 | 87.50 |
| 19/07/2017 | 12:51:11 | 112.00 | 65.00 | 76.20 | 105.40 |
| 19/07/2017 | 13:37:47 | 111.90 | 65.00 | 76.20 | 106.80 |
| 12/07/2018 | 10:23:58 | 82.10 | 68.00 | 76.20 | 79.70 |
| 12/07/2018 | 11:09:12 | 87.80 | 68.00 | 76.20 | 88.90 |
| 12/07/2018 | 11:23:34 | 91.90 | 68.00 | 76.20 | 88.50 |
| 12/07/2018 | 12:17:47 | 94.20 | 68.00 | 76.20 | 90.30 |
| 12/07/2018 | 06:47:34 | 62.70 | 68.00 | 76.20 | 67.70 |
| 12/07/2018 | 07:43:36 | 62.70 | 68.00 | 76.20 | 60.20 |
| 12/07/2018 | 05:30:06 | 62.90 | 68.00 | 76.20 | 71.50 |
| 12/07/2018 | 05:50:10 | 62.00 | 68.00 | 76.20 | 69.70 |
| 11/07/2018 | 09:39:05 | 69.60 | 66.00 | 76.20 | 68.60 |
| 11/07/2018 | 10:53:49 | 90.30 | 66.00 | 76.20 | 79.90 |
| 10/07/2018 | 14:11:11 | 92.60 | 65.00 | 76.20 | 98.40 |
| 10/07/2018 | 15:01:11 | 83.00 | 65.00 | 76.20 | 86.30 |
| 10/07/2018 | 16:31:33 | 85.10 | 65.00 | 76.20 | 85.10 |
| 11/07/2018 | 13:14:02 | 103.30 | 66.00 | 76.20 | 96.60 |
| 11/07/2018 | 13:58:03 | 108.50 | 66.00 | 76.20 | 104.20 |
| 11/07/2018 | 15:18:12 | 96.30 | 66.00 | 76.20 | 100.90 |
| 11/07/2018 | 16:16:35 | 97.90 | 66.00 | 76.20 | 92.50 |
| 11/07/2018 | 16:45:39 | 101.80 | 66.00 | 76.20 | 107.80 |
| 09/07/2018 | 11:13:55 | 87.80 | 72.00 | 76.20 | 75.10 |
| 09/07/2018 | 11:58:38 | 95.50 | 72.00 | 76.20 | 89.90 |
| 09/07/2018 | 13:59:08 | 104.90 | 72.00 | 76.20 | 104.30 |
| 09/07/2018 | 14:17:33 | 107.70 | 72.00 | 76.20 | 105.20 |

| Date | Time | Surf. Temp (°F) | Prev. Day's Avg. Temp. | Depth (mm) | Measured Pavement. Temp. (°F) |
|---|---|---|---|---|---|
| 09/07/2018 | 15:30:06 | 110.40 | 72.00 | 76.20 | 107.90 |
| 09/07/2018 | 16:04:29 | 116.40 | 72.00 | 76.20 | 111.00 |
| 09/07/2018 | 16:33:32 | 117.50 | 72.00 | 76.20 | 113.00 |
| 16/08/2018 | 09:21:50 | 77.80 | 63.00 | 76.20 | 76.70 |
| 16/08/2018 | 10:11:43 | 78.80 | 63.00 | 76.20 | 77.10 |
| 16/08/2018 | 10:55:38 | 83.60 | 63.00 | 76.20 | 83.10 |
| 22/06/2018 | 02:32:47 | 72.70 | 73.00 | 76.20 | 86.80 |
| 22/06/2018 | 02:45:16 | 75.10 | 73.00 | 76.20 | 86.60 |
| 21/06/2018 | 22:05:06 | 87.90 | 82.00 | 76.20 | 98.20 |
| 21/06/2018 | 22:12:09 | 86.60 | 82.00 | 76.20 | 98.20 |
| 21/06/2018 | 22:49:55 | 83.60 | 82.00 | 76.20 | 95.10 |
| 21/06/2018 | 23:29:23 | 81.80 | 82.00 | 76.20 | 92.00 |
| 21/06/2018 | 23:55:41 | 81.00 | 82.00 | 76.20 | 90.90 |
| 22/06/2018 | 03:57:12 | 70.20 | 73.00 | 76.20 | 80.20 |
| 22/06/2018 | 04:18:53 | 70.80 | 73.00 | 76.20 | 78.30 |
| 22/06/2018 | 02:15:55 | 75.20 | 73.00 | 76.20 | 87.10 |
| 22/06/2018 | 02:29:52 | 73.30 | 73.00 | 76.20 | 86.80 |
| 22/06/2018 | 00:21:02 | 78.90 | 73.00 | 76.20 | 90.80 |
| 22/06/2018 | 01:00:44 | 76.10 | 73.00 | 76.20 | 85.00 |
| 22/06/2018 | 01:38:22 | 75.20 | 73.00 | 76.20 | 84.50 |
| 22/06/2018 | 02:04:05 | 75.80 | 73.00 | 76.20 | 87.10 |
| 22/06/2018 | 05:15:43 | 68.40 | 74.00 | 76.20 | 75.30 |
| 20/06/2018 | 21:42:11 | 87.30 | 79.00 | 76.20 | 96.00 |
| 20/06/2018 | 22:28:54 | 80.70 | 79.00 | 76.20 | 85.50 |
| 20/06/2018 | 23:15:05 | 71.50 | 79.00 | 76.20 | 87.20 |
| 20/06/2018 | 23:59:03 | 69.80 | 79.00 | 76.20 | 81.30 |

| Date | Time | Surf. Temp (°F) | Prev. Day's Avg. Temp. | Depth (mm) | Measured Pavement. Temp. (°F) |
|---|---|---|---|---|---|
| 21/06/2018 | 00:45:40 | 62.60 | 79.00 | 76.20 | 74.20 |
| 21/06/2018 | 01:26:53 | 66.00 | 79.00 | 76.20 | 74.00 |
| 21/06/2018 | 02:16:41 | 70.00 | 79.00 | 76.20 | 65.80 |
| 19/06/2018 | 10:26:28 | 72.60 | 61.00 | 76.20 | 69.80 |
| 19/06/2018 | 11:58:23 | 72.50 | 61.00 | 76.20 | 69.80 |
| 19/06/2018 | 12:19:04 | 71.70 | 61.00 | 76.20 | 68.00 |
| 19/06/2018 | 13:18:43 | 74.70 | 61.00 | 76.20 | 71.60 |
| 19/06/2018 | 14:21:46 | 77.20 | 61.00 | 76.20 | 73.90 |
| 19/06/2018 | 15:11:14 | 82.10 | 61.00 | 76.20 | 76.60 |
| 25/06/2018 | 10:49:43 | 99.80 | 63.00 | 76.20 | 95.00 |
| 18/06/2018 | 10:22:48 | 76.80 | 34.00 | 76.20 | 72.90 |
| 18/06/2018 | 11:22:58 | 76.50 | 34.00 | 76.20 | 74.20 |
| 18/06/2018 | 11:36:29 | 85.30 | 34.00 | 76.20 | 76.20 |
| 18/06/2018 | 12:33:16 | 79.40 | 34.00 | 76.20 | 76.20 |
| 18/06/2018 | 12:46:31 | 92.80 | 34.00 | 76.20 | 83.90 |
| 18/06/2018 | 17:30:39 | 80.80 | 34.00 | 76.20 | 85.00 |
| 18/06/2018 | 17:45:33 | 77.50 | 34.00 | 76.20 | 80.10 |
| 18/06/2018 | 18:10:38 | 77.00 | 34.00 | 76.20 | 75.40 |
| 28/06/2018 | 08:42:00 | 71.60 | 57.00 | 76.20 | 77.20 |
| 28/06/2018 | 09:42:02 | 84.60 | 57.00 | 76.20 | 81.90 |
| 28/06/2018 | 10:25:13 | 81.50 | 57.00 | 76.20 | 85.00 |
| 23/07/2018 | 12:38:46 | 104.50 | 76.00 | 76.20 | 107.50 |
| 23/07/2018 | 13:37:50 | 111.20 | 76.00 | 76.20 | 116.40 |
| 23/07/2018 | 15:31:30 | 115.30 | 76.00 | 76.20 | 122.30 |
| 23/07/2018 | 16:48:15 | 116.20 | 76.00 | 76.20 | 122.10 |
| 25/07/2018 | 08:33:42 | 77.30 | 76.00 | 76.20 | 76.30 |

| Date | Time | Surf. Temp (°F) | Prev. Day's Avg. Temp. | Depth (mm) | Measured Pavement. Temp. (°F) |
|---|---|---|---|---|---|
| 25/07/2018 | 09:16:17 | 81.80 | 76.00 | 76.20 | 81.10 |
| 25/07/2018 | 09:43:38 | 88.40 | 76.00 | 76.20 | 86.50 |
| 25/07/2018 | 10:56:38 | 99.30 | 76.00 | 76.20 | 96.10 |
| 25/07/2018 | 11:36:52 | 98.40 | 76.00 | 76.20 | 99.90 |
| 25/07/2018 | 12:05:05 | 103.30 | 76.00 | 76.20 | 102.00 |
| 24/07/2018 | 14:08:40 | 125.20 | 79.00 | 76.20 | 129.30 |
| 24/07/2018 | 14:53:04 | 111.80 | 79.00 | 76.20 | 114.60 |
| 24/07/2018 | 15:46:08 | 108.20 | 79.00 | 76.20 | 114.90 |
| 24/07/2018 | 16:21:48 | 112.90 | 79.00 | 76.20 | 114.30 |
| 24/07/2018 | 17:25:09 | 101.60 | 79.00 | 76.20 | 107.30 |
| 24/07/2018 | 09:37:37 | 82.70 | 65.00 | 76.20 | 80.50 |
| 24/07/2018 | 10:21:49 | 91.50 | 65.00 | 76.20 | 83.00 |
| 25/06/2018 | 13:04:23 | 105.80 | 70.00 | 76.20 | 105.80 |
| 25/06/2018 | 13:22:54 | 109.40 | 70.00 | 76.20 | 105.60 |
| 25/06/2018 | 13:31:44 | 109.50 | 70.00 | 76.20 | 104.30 |
| 25/06/2018 | 13:50:18 | 111.30 | 70.00 | 76.20 | 106.40 |
| 25/06/2018 | 09:04:35 | 87.20 | 65.00 | 76.20 | 74.20 |
| 25/06/2018 | 09:20:33 | 87.10 | 65.00 | 76.20 | 77.30 |
| 25/06/2018 | 09:28:15 | 89.40 | 65.00 | 76.20 | 80.60 |
| 25/06/2018 | 09:46:15 | 90.60 | 65.00 | 76.20 | 80.10 |
| 25/06/2018 | 11:51:19 | 102.70 | 71.00 | 76.20 | 97.20 |
| 25/06/2018 | 12:07:39 | 104.50 | 71.00 | 76.20 | 104.00 |
| 18/06/2018 | 14:58:39 | 95.90 | 67.00 | 76.20 | 83.40 |
| 18/06/2018 | 15:22:25 | 97.70 | 67.00 | 76.20 | 81.00 |
| 18/06/2018 | 13:54:27 | 82.00 | 50.00 | 76.20 | 78.00 |
| 18/06/2018 | 14:11:17 | 85.80 | 50.00 | 76.20 | 77.30 |

| Date | Time | Surf. Temp (°F) | Prev. Day's Avg. Temp. | Depth (mm) | Measured Pavement. Temp. (°F) |
|---|---|---|---|---|---|
| 18/06/2018 | 13:52:06 | 82.40 | 50.00 | 76.20 | 78.00 |
| 18/06/2018 | 14:21:25 | 87.20 | 50.00 | 76.20 | 78.00 |
| 18/06/2018 | 14:35:18 | 91.40 | 50.00 | 76.20 | 77.30 |