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Final Report

Test and Validation of a Model for Forecasting Frost on Bridges

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16. Abstract (Limit: 200 words)

Frost frequently forms on roads and bridges during winters when the pavement temperature is at or below 273 K and below the dew-point temperature. Accurate forecasts of frost onset times, frost intensity, and frost disappearance help roadway maintenance personnel decide when, where, and how much frost-suppression chemicals should be used.

A finite-difference program has been developed that predicts bridge surface temperature by simulating vertical heat transfer in a bridge in response to evolving weather conditions. A vapor flux calculation uses the bridge surface temperature and concurrent meteorological variables from a weather forecast model to produce forecasts of depth of frost deposited, melted, or sublimed.

Comparisons of model results with measured surface temperatures from a Roadway Weather Information Systems (RWIS) station have demonstrated that the model realistically represents early-morning low temperatures and temperature trends when run with input from current observations. Average surface temperature error using observations was 0.25 K. Some of the error can be attributed to spatial separation of the bridge site and the radiation observation site. BridgeT is capable of supplying surface temperatures within 1K of measured values over a 40-hour forecast period if it is supplied with accurate weather forecasts.

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Executive Summary

Frost frequently forms on roads and bridges during Iowa winters when the pavement temperature is at or below 273 K and below the dew-point temperature. Previous research has shown that there are about 20 roadway frost events and 12 to 58 bridge frost events in Iowa each year. Frost on roadways and bridges can present hazardous conditions to motorists, especially when it occurs in patches or on bridges when adjacent roadways are clear of frost. The Iowa Department of Transportation (IaDOT) chemically treats roadways and bridges to prevent frost formation to maintain safe driving conditions during the frost season. To minimize negative environmental impacts, vehicle corrosion, and materials cost, frost-suppression chemicals should be applied only when, where, and in amounts needed to maintain roadways in a safe condition for motorists. Accurate forecasts of frost onset times, frost intensity, and frost disappearance are needed to help roadway maintenance personnel decide when, where, and how much frost-suppression chemicals should be used.

Accurate frost forecasts rely on accurate forecasts of bridge surface temperature and ambient atmospheric conditions (i.e., air temperature, humidity, precipitation, and wind speed). All these factors, except bridge surface temperature, are routinely calculated by weather forecast models such as the Pennsylvania State University/ National Center for Atmospheric Research (PSU/NCAR) mesoscale model (MM5) or the NCAR Road Weather Forecast System (RWFS). Although numerical weather models do not forecast bridge temperature, many models calculate the ambient parameters needed to derive the temperature of a bridge that is being influenced by the predicted weather.

A finite-difference program (BridgeT) has been developed that predicts bridge surface temperature by simulating vertical heat transfer in a bridge in response to evolving weather conditions produced by a forecast model. A vapor flux calculation within BridgeT uses the bridge surface temperature and concurrent meteorological variables from the forecast model to produce forecasts of incremental volume per unit area (i.e., depth) of frost deposited, melted, or sublimed.

A physically based method was chosen for this bridge condition model because the necessary information to derive the heat and vapor fluxes to the bridge is already available through mesoscale forecasting models. Statistically based methods require large amounts of accurate observations for model training which may not be available for certain sites. Additionally, frost and observations of other bridge conditions may not be regularly or reliably collected due to the effects of chemical treatment, irregular observing schedules and locations, or inaccurate observation practice. Physically based models do not need lengthy training data and may be better at forecasting bridge condition during periods of abrupt weather changes that are not predictable by analyzing local observations.

MM5 version 3.4, run at Iowa State University, has been used as input for the BridgeT program during the months of November 2003 to March 2004. The Iowa State University MM5 has coarse grid resolution of 60 km and fine grid resolution of 20 km. It uses data from the National Centers for Environmental Prediction Eta model for initial and boundary conditions, the Oregon

State University Land Surface Model, the Cloud Radiation Scheme, Grell Cumulus Convection, planetary boundary layer (PBL) scheme of the Medium Range Forecast (MRF) model, and Dudhia Simple Ice. MM5 forecasts were issued two times a day, valid at 12 UTC (6:00 am LST) and 00 UTC (6:00 pm LST).

Observations used for comparison to the BridgeT model included RWIS bridge temperature observations, as well as early morning bridge frost and bridge temperature observations conducted by human observers on several overpasses in the Ames area.

Frost occurrence was observed for the 2001-02, 2002-03, and 2003-04 frost seasons. Observations were taken on the State Avenue Bridge over Highway 30 near Ames, IA during the 2001-02 winter. Verification of frost prediction used the first 24 h of the forecast run to minimize complication due to the possibility of multiple frost predictions in a single 48 h forecast. Verification also takes into account the ability of the IaDOT to use the forecast. For instance, a forecast with a 24-h lead time offers sufficient time for IaDOT to respond, whereas a 12-h lead time or less may not provide sufficient time for response.

Frost observations were made on 68 mornings during the winter of 2003-04. Frost was positively observed on five mornings. Since MM5 forecasts were available only twice a day, the 1200 UTC run must correctly predict frost occurrence because it determines the frost treatment for that work day. Performance of BridgeT is highly sensitive to the quality of its input. BridgeT is capable of producing accurate calculation of bridge surface temperature when supplied with accurate measurements of air temperature, wind speed, and radiation. Thus, overall model effectiveness is largely determined by the quality of the 1200 UTC run. When supplied with meteorological input from MM5, BridgeT frost prediction performance was reasonable but had a tendency for false alarms and partial hits. Improvements in weather forecast models will lead to overall improvements in BridgeT frost forecasts, since it was shown in sensitivity studies to be highly accurate when supplied accurate weather input.

Chapter 1
Introduction

Frost on roadways and bridges can present hazardous conditions to motorists, especially when it occurs in patches or on bridges when adjacent roadways are clear of frost.

The IaDOT chemically treats roadways and bridges to prevent frost formation to maintain safe driving conditions during the frost season. To minimize negative environmental impacts, vehicle corrosion, and materials cost, frost-suppression chemicals should be applied only when, where, and in amounts needed to maintain roadways in a safe condition for motorists. Accurate forecasts of frost onset times, frost intensity, and frost disappearance are needed to help roadway maintenance personnel decide when, where, and how much frost-suppression chemicals should be used.

Accurate frost forecasts rely on accurate forecasts of bridge surface temperature and ambient atmospheric conditions (i.e., air temperature, humidity, precipitation, and wind speed). All these factors, except bridge surface temperature, are routinely calculated by many weather forecast models. Although numerical weather models do not forecast bridge temperature, many models calculate the ambient parameters needed to derive the temperature of a bridge that is being influenced by the predicted weather.

Forecasting frost by use of weather forecast models presents a particularly difficult challenge for two reasons. Forecasting rare events like frost usually creates difficulty for forecast models because models frequently cannot resolve the weather scenario with enough detail to determine if the rare event will occur. Forecasting frost is doubly difficult because components of the surface water budget are highly nonlinear, often binary, and are highly heterogeneous in space. Furthermore, light precipitation, a key factor for frost non-occurrence, is highly dependent on particular cloud parameterizations used and may be subject to large errors (Gutowski et al. 2003).

Several roadway and bridge temperature prediction models have been developed in recent years to fulfill the need for accurate road or bridge temperature forecasts. Physically-based models such as The Roadway Conditions Model (Sass 1992, 1997), the German Weather Service (DWD) Version 3 model (Jacobs and Raatz 1996), and the Model of the Environment and Temperature of Roads (METRo) (Crevier and Delage 2001) forecast roadway or bridge temperature and conditions based on formulations of heat and vapor transfer between the atmosphere and the road or bridge. Statistical models such as the HS4Cast model (Hertl and Schaffar 1998) and the neural network described by Temeyer (2003) use statistics and pattern analysis rather than energy balances to predict road surface conditions.

Our goal was to simulate bridge surface temperature and frost accumulation by use of a simple module that could easily be incorporated into any weather forecast program. Our module (BridgeT) is a physically based finite-difference program that predicts bridge surface temperature by simulating vertical heat transfer in a bridge in response to evolving weather conditions produced by a forecast model. BridgeT outputs values of bridge deck temperature, frost depth and bridge condition (e.g., frosty, icy/snowy, dry).

BridgeT uses conduction and radiation calculations similar to METRo but with different formulations for latent heat and convection processes. Freezing and thawing of water on the bridge are instantaneous in METRo, but they can be gradual in BridgeT. METRo uses Monin-Obukhov similarity for convective parameterization, whereas BridgeT uses modified Reynolds similarity. BridgeT currently has no ability to simulate roadways.

Chapter 2
BridgeT Description

BridgeT simulates bridge surface temperatures by numerical (finite difference) solution of the one-dimensional heat diffusion equation. Details of the model formulation can be found in Greenfield (2004). Temperatures are calculated at 20 nodes throughout the bridge, including the top and bottom surfaces. BridgeT calculates heat fluxes due to natural and forced convection on the upper and lower surfaces, conduction through the bridge deck, long and short wave radiation, and latent heat processes due to phase changes of water on the top of the bridge deck. A vapor flux calculation uses the bridge surface temperature and concurrent meteorological variables from a weather forecast model to produce forecasts of incremental volume per unit area (i.e., depth) of frost deposited, melted, or sublimed and pavement condition. Initial temperatures are calculated using recent RWIS data. Output of BridgeT includes bridge-deck temperature, frost depth, and bridge condition (e.g., frosty, icy/snowy, dry).

Surface Energy Balance

Incoming fluxes at the top surface (Figure 2.1) include radioactive and latent heat fluxes, and convection. The bottom node experiences convection, but not latent heat or radiation because it is assumed that the bottom will stay dry, shielded from the sun, and in approximate long wave radioactive equilibrium with the surfaces directly under the bridge.

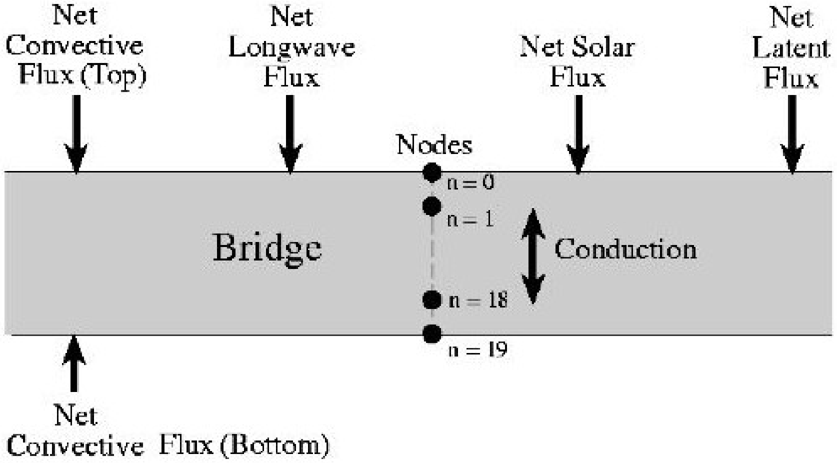

Figure 2.1. BridgeT fluxes and node assignment.
The surface node (n= 0) experiences conduction, convection, latent heating, and radiation. Interior nodes experience only conduction. The bottom node (n = 19) experiences conduction and convection.
Net fluexes into the slab are considered positive.

Convection. The convection calculations use Reynolds similarity which assumes that the wind column affected by the bridge is vertically uniform before encountering the bridge and that the air is incompressible. The surface convective coefficient is derived from the equations of the steady-state conservation of energy and motion for an incompressible fluid of constant properties. It was assumed that vertical velocity is independent of distance along the bridge, and that the change in velocity with height above the bridge is greater than changes along the bridge surface. The thermal gradient normal to the bridge surface is much greater than the gradient parallel to the surface, and heat generation due to viscous dissipation can be ignored.

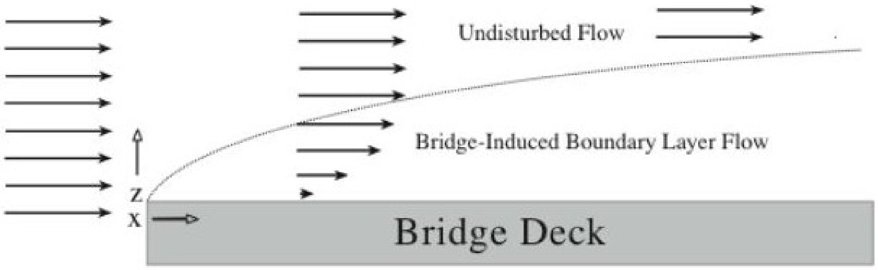

Figure 2.2. Bridge-induced boundary layer
and coordinates used in convective parameterization.

Natural convection suppresses mixing when the temperature profile is stable, and enhances mixing when the temperature profile is unstable. The dimensionless temperature gradient is calculated as if the flow over the entire bridge surface is turbulent using an experimentally derived relationship between the Reynolds Number and the Prandtl Number (Incropera and DeWitt 2002).

Precipitation. BridgeT incorporates latent heat effects of water on the bridge and calculates total frost depth by distinguishing between water phases and calculating water fluxes toward or away from the bridge. The maximum amount of water substance that accumulates on the bridge is truncated to a depth of 0.0011 m of liquid water and 0.00063 m (˘0.25 inches) of snow accumulation. Excess precipitation is assumed to be removed by runoff or plowing. These limitations will help keep unreasonably high amounts of latent heat effects from influencing the bridge.

The vapor flux toward the bridge (i.e., the condensation/evaporation rate) is positive for condensation or frost deposition and negative for evaporation or sublimation.

It is calculated by using the heat-mass transfer analogy that estimates the mass transfer coefficient using the convective heat transfer coefficient. BridgeT distinguishes between frozen and liquid precipitation by the temperature of the air. Precipitation is allowed to freeze, thaw, and evaporate from the bridge. The instantaneous equilibrium temperature between accumulated water and the top bridge node is calculated in all scenarios where precipitation accumulates on the bridge to allow heat fluxes between water substance and bridge.

Frost is allowed to accumulate when there is no existing precipitation or condensation on the bridge. Frost depth per unit area is calculated by dividing the accumulated frost mass by its density (assumed to be 0.1 times the density of water) and adding the result to the previous total. If frost or snow is assumed to be present on the bridge, the solar absorptive is decreased by a factor proportional to the depth of the ice to account for gradual increases in albedo through the development of frost or light snow accumulation.

Radiation. Radiation heat fluxes are determined using surface incident short wave and long wave radiation supplied directly by the forecast model. Long wave radiation lost from the bridge is computed by using the Stefan-Boltzmann relationship. Long wave radiation lost from the bridge and radiation reflected by the bridge are subtracted from the total incident radiation to find the net radiative flux toward the bridge.

Node temperature calculation. The equations for the nodes have been derived from the energy balance equation. Node temperatures are found by using the explicit finite-difference form of heat transfer equation (Greenfield 2004). Initial node temperatures are determined using previous RWIS surface temperature, air temperature, and wind speed observations (Greenfield 2004).

Chapter 3
Analysis

Input

Experiments were conducted with two different forecast model systems supplying input to BridgeT. Pennsylvania State University / National Center for Atmospheric Research Mesoscale Model (MM5) version 3.4, run at Iowa State University, has been used as input for the BridgeT program during the months of November 2003 to March 2004. MM5 forecasts were issued twice daily, valid at 12 UTC and 00 UTC.

The Road Weather Forecast System (RWFS) was designed by the National Center for Atmospheric Research for use with a winter road maintenance decision support system. RWFS is designed to maximize forecast accuracy by blending output from several numerical weather models (i.e., Eta, aviation, nested grid model) with surface observations and statistical regressions (Bernstein et al. 2004). It produces 48-h forecasts eight times daily (00, 03, 06, 09, 12, 15, 18, and 21 UTC). These model runs were available for the months of February, March, and 1-8 April 2003.

To evaluate the errors arising in BridgeT output from errors due to the forecast model, BridgeT was run with observations of radiation, temperature, humidity, precipitation, and wind speed. Observations of surface incident long wave and solar radiation were taken during the days 9 July 2002 and 11-19 July 2002. The radiation observations were taken over a soybean field southwest of Ames, IA, 19 km from the Ames RWIS station. These observations were combined with school-net precipitation observations (Iowa Environmental Mesonet 2004) and RWIS humidity, wind, and 2-m air temperature measurements and used to drive the BridgeT model.

Observation Datasets

Observations used for comparison with BridgeT model results included RWIS bridge temperature observations taken from the Interstate 35 overpass over 13th Street on the east side of Ames, IA, as well as early morning bridge frost and bridge temperature observations conducted by human observers on several overpasses in the Ames, IA area.

Frost occurrence was observed for the 2001-02, 2002-03, and 2003-04 frost seasons on several local bridges (Greenfield et al. 2004). The distances from the RWIS site to the observed bridges are approximately five to seven miles. The observer visited the bridges beginning at 500 LST and observed frost conditions both from the car and close-up on foot. While on the bridge on foot, the observers carefully examined the surface for frost and measured the temperature of the bridge surface with an infrared thermometer. The time, date, observations of bridge conditions, general weather conditions, frost characteristics, and surface temperature for each bridge were recorded. If frost was detected, the observer would return periodically until the frost dissipated for follow-up observations and measurements.

It is expected that this method of frost observation is very accurate. However, there may be situations (e.g., when frost is very light) where frost is present but not visually detected by the observer. These situations would lead to an increased false-alarm rate because some actual frost events may be recorded as no-frost events.

Validation Methods

Frost. Verification of frost prediction used the first 24 h of the forecast run. RWFS forecasts were updated eight times per day, and MM5 forecasts were updated twice a day. For this reason, it was possible to use many separate forecasts to predict frost for a specific observed frost event. To remove performance dependency on the frequency of newly issued runs, frost forecasts were analyzed according to whether that forecast would elicit an assumed response from the IaDOT. The assumed response for a frost forecast is chemical pretreatment to prevent the formation of frost on bridges. If no frost event was forecasted, bridges would not be pretreated. Pretreatment was assumed to be made only once a day, so multiple forecasts predicting frost for a particular morning are assumed to elicit only one treatment. If a subsequent run reverses a false forecasted frost event, the assumed pretreatment cannot be undone, so that frost forecast is still counted as a false alarm. A frost forecast/response was considered a success if frost was calculated to occur during a time period when frost was seen on any one of the observed bridges. A frost forecast was considered a “miss” when no frost was forecasted and no treatment is assumed to occur, but frost was observed on any of the bridges. A frost forecast is considered a “partial hit” if frost was forecast to occur in a run within 12 h of an observed frost event, but the previous runs did not forecast frost. A forecast like this has less (but still some) value because it would require the IaDOT to pretreat bridges at late hours and possibly within short time frames. Events lasting less than one half hour are considered “short events” which are counted as either partial hits or partial false alarms. These predictions are separated because they often do not have sufficient time to form deep frost or to be observed.

Conventional measures of forecast skill for binary events include false alarm rate (FAR), probability of detection (POD), miss rate (MISS), rate at which the model will correctly reject the possibility of frost (CR), and threat score (TS) (Greenfield 2004).

Average absolute error and bias of predicted frost start and end time were compiled for each frost event. Due to the method of observation, 500 LST was always the observed “start” time, although frost was usually present on the bridge by this time.

Temperature. Forecast bridge temperatures were analyzed by comparing RWIS observations to the BridgeT forecasts valid only at the time of the RWIS observation. Statistics (e.g., bias, root mean square error) are computed for each model run. Individual model runs were averaged to produce a summary measure of the model’s overall performance.

Chapter 4
Results

BridgeT Validation

The objective of BridgeT is to produce an accurate value of bridge deck temperature.
In operational applications BridgeT obtains its input from a weather forecast model, which has its own error characteristics. To evaluate errors produced by BridgeT alone we used weather observations taken near an RWIS site as input for BridgeT. Radiation observations were taken from a site located about 19 km from the RWIS site, so errors due to spatial separation are included in BridgeT's calculations.

For the observing period from 9 July 2002 and 11-19 July 2002. BridgeT surface temperatures (at approximately 25-min intervals) were on average 0.20 K cooler than RWIS temperatures with a root mean square error (RMSE) of 1.90 K (Figure 4.1). Errors frequently occurred during the peak daytime temperature range when the temperature is highly influenced by solar radiation. Small clouds episodically block a portion of the solar radiation from the RWIS bridge surface and radiometers at different times and for different durations due to the physical separation of the two observing sites. Daytime differences occasionally exceeded 5 K, with a peak difference of 7.75 K. The morning and evening temperature errors were typically small, thereby providing a measure of confidence in the ability of BridgeT to give accurate temperatures for times of the diurnal period when frost is likely.

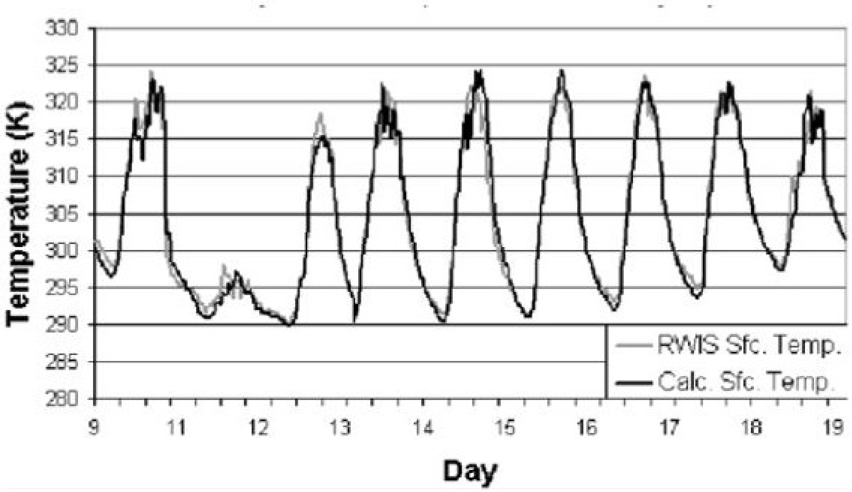

Figure 4.1 Observed (RWIS) and calculated bridge surface temperature for a 10-day period in July 2002.

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Calibration and Validation of Coupled Models

RWFS input. Four-hundred fifty five 48-h RWFS model runs (new run every 3 h) were used to drive BridgeT valid for the period from 3 February 2003 through 8 April 2003 for the Ames, IA RWIS site. RWFS-BridgeT produced forecasts that were cold-biased, evident especially through recurring errors in nighttime cooling rates. BridgeT was re-calibrated for use with this particular model to account for systematic biases in the model input. Corrections to the wind speed and long wave radiation yielded the most accurate calculations. Wind speed errors from the first 100 RWFS runs were used to calculate the wind speed correction to be used with RWFS runs. During the first 100 RWFS runs, the wind speed was on average 1.37 m/s higher than observed at the RWIS site. RWFS BridgeT forecasts improved when that bias was subtracted from all RWFS runs before convection calculations were performed, thus decreasing the convective fluxes. The long wave radiation values of the first 100 runs and all following runs were increased by a factor of 1.16 to help counterbalance steep nighttime cooling rates. Figure 4.2 shows a specific forecast before and after calibration.

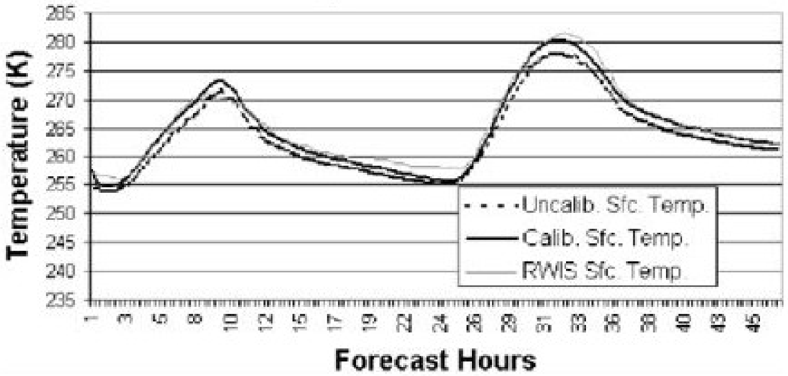

Figure 4.2. RWFS-BridgeT results before and after calibration compared to observed bridge temperature. Uncalibrated RSME was 2.28 K, calibrated RSMEwas1.17K.

Statistical analysis of 48-h forecasts of the RWFS-BridgeT model runs compared to Ames RWIS observations showed that the average bias and average RMSE of uncalibrated RWFS-BridgeT bridge temperatures for 48-h forecasts for the entire period were 2.03 K and 3.20 K, respectively. After calibration, the RWFS-BridgeT cold bias was 0.09 K with RMSE of 2.64 K.

The average error of the first 24 h of the calibrated RWFS-BridgeT runs was 0.03 K and the RMSE was 2.45 K. There were 122 forecast runs out of 455 where the calibrated calculation of bridge temperature was actually less accurate compared to its uncalibrated forecast. The average errors in the first 24 h were smaller than the average errors in the entire 48 h and the errors were reported to be less than 2 K over 60% of the time.

Bridge frost was observed twice during this period. RWFS-BridgeT correctly forecasted both events. When the forecast period was taken as the first 24 h of each run, RWFS-BridgeT correctly forecasted the only two observed frost events but predicted three false alarms for this period. There were two mornings where brief frost was predicted to occur one h after observations were concluded. Table 1 contains the frost performance indices for the RWFS-BridgeT runs. There were no partial hits. RWFS-BridgeT correctly predicted 86% of frost and no-frost mornings. Its high false alarm and prediction rate corresponds with RWFS-BridgeT's cold bias in early-morning bridge temperature. RWFS-BridgeT average frost start-time for those two events was 2 h and 10 min earlier than the first observation. Its end-times were on average 30 min different from what was observed, but had zero bias.

Table 4.1. RWFS-BridgeT frost performance during February and March 2003.

	FAR	POD	MISS	CR	POFD	TS
RWFS-BridgeT	0.60	1.00	0.00	0.86	0.14	0.40

MM5 input. One hundred ninety-eight 48-h MM5 model forecasts were used as input for BridgeT during the 2003-04 frost season from 11 November 2003 through 31 March 2004. Uncalibrated MM5-BridgeT surface temperature forecasts were on average 1.02 K too cool during this period and its RMSE was 2.73 K. The cold bias and RMSE improved with calibration for long wave radiation, similar to the long wave calibration used with RWFS. Best results were obtained when long wave radiation was increased by a factor of 1.13. Wind speed calibration was performed by subtracting the wind speed bias (0.96 m/s) of the first 50 runs from the wind speed before convection calculations were made. After calibration, the surface temperature bias was reduced to 0.16 K too warm and the RMSE was reduced to 2.64 K. Sixty-nine of 198 MM5-BridgeT forecast runs were actually less accurate after calibration. Figure 4.3 shows a specific MM5-BridgeT forecast before and after calibration.

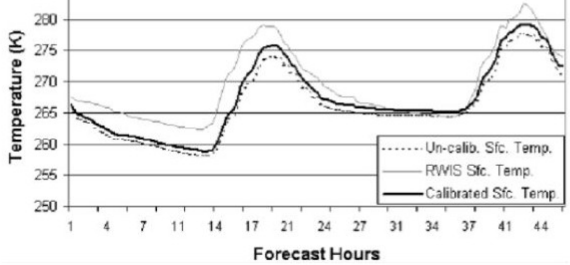

Figure 4.3 MM5-BridgeT results before and after calibration compared to observed bridge temperature. Uncalibrated RSME was 3.67 K, calibrated.

Analysis of the first 24 h of the runs showed MM5-BridgeT was on average 0.13 K too warm and had an RMSE of 2.40 K. Sixty percent of the 24-h MM5BridgeT surface temperature calculations possessed errors of less than 2 K.

Frost observations were made on 68 mornings during the winter of 2003-04. Frost was positively observed on five mornings. Since MM5 forecasts were available only twice a day, the 1200 UTC run must correctly predict frost occurrence because it determines the frost treatment for that work day. The 00 UTC run can only cause a partial hit because it is issued after the typical work day is concluded and will not influence treatment schedules except for emergency late-night treatment for the upcoming morning. Thus, overall model effectiveness is largely determined by the quality of the 1200 UTC run.

MM5-BridgeT frost prediction performance was reasonable but had a tendency for false alarms and partial hits. There were 6 false alarms, although one of which was predicted 24 h in advance due to missing forecasts and precipitation predictions during frost times in preceding forecasts. One frost event was not forecast at all due to the prediction of precipitation during that morning from all associated model forecasts. When light precipitation (< 0. 1 mm/h) was excluded in BridgeT, all frost events without missing model runs were predicted 24 h in advance. However, false alarms increased dramatically (20 false alarms). Figure 2.2 shows the performance for standard (light precipitation allowed) and calibrated (light precipitation excluded) BridgeT settings. Despite a poorer prediction rate with BridgeT's standard settings (i.e., light precipitation allowed), predictions of precipitation instead of frost may still cause some response (albeit for precipitation, not for frost) from the IaDOT.

Setting	Events Included	FAR	POD	MISS	CR	POFD	TS
-Precip.	No short events	0.79	1.00	0.00	0.69	0.31	0.21
-Precip.	Short events	0.80	1.00	0.00	0.67	0.33	0.20
Standard	No partial hits or short events	0.83	0.20	0.80	0.92	0.08	0.10
Standard	Partial hits and short events	0.60	0.80	0.20	0.90	0.10	0.36
Standard	Partial hits, no short events	0.56	0.80	0.20	0.92	0.08	0.40

Table 4.2. MM5-BridgeT frost prediction performance during winter 2003-04. The Standard setting includes light precipitation. The -Precip. setting excludes precipitation of less than 0.12 mm/h from BridgeT calculations. A short event is a predicted frost event lasting less than 10 min. A partial hit is a correct prediction of frost that was issued less than 24 h in advance

MM5-BridgeT predicted frost onset an average 3.9 h before observations began. Average frost demise was calculated to occur 23 min before observations ended.

Sensitivity

Sensitivity to forecast quality and bridge property specification. Input data quality is crucial for accurate surface temperature calculations. Accurate forecasts of bridge condition (e.g., dry, wet, frosty) requires not only accurate input for the calculation of bridge surface temperature, but also accurate meteorological conditions such as humidity and precipitation. Humidity forecasts are difficult for models to accurately produce and verification is difficult due to sensor accuracy or representativeness (Takle and Greenfield 2002).

Differences in bridge properties can be expected because of design differences, use of bridge materials having a range of thermal and radioactive properties, and variations due to differences in age, wear, and mixture composition. The bridge properties data required by BridgeT include solar absorptivity, long wave absorptivity, bridge thickness, density, specific heat, and thermal conductivity. From the range of plausible values, we found that the model performed best when we used the bridge properties listed in Table 4.3.

In principle, these properties may be specified for each individual bridge in a forecast region. It is important to note the impact these specifications have when varied within their usual ranges to investigate the possible effects of incorrect assignment of bridge characteristics, or how different bridges will react under identical weather conditions. Our sensitivity studies revealed that surface temperature calculations are particularly sensitive to the possible variations of solar reflectivity and thermal conductivity and are least sensitive to differences in long wave absorptivity and bridge thickness.

Bridge Property	Value
Bridge Thickness	0.21 m
Thermal Conductivity	1.401 W/m*K
Solar Absorptivity	0.74
Long Wave Absorptivity	0.88
Density	2300 kg/m^3
Thermal Diffusivity	6.922* 10^{-7} m^2/s
Specific Heat	880 J/kg*K

Table 4.3. Bridge properties used by BridgeT for this study.

Chapter 5
Summary

BridgeT was designed to help forecasters produce accurate forecasts of bridge frost and condition. BridgeT is a numerical model for heat transfer in a concrete bridge that takes atmospheric values from a weather forecast model and calculates bridge surface temperature, frost depth, and bridge conditions. It accounts for heat fluxes due to solar and long wave radiation, conduction through the bridge, convection on the top and bottom surfaces, and latent heat effects through explicit forward-difference numerical methods.

Comparisons of its results with measured surface temperatures from an RWIS station have demonstrated that BridgeT realistically represents early-morning low temperatures and temperature trends when run with input from observations of air temperature, wind speed, and radiation. Some of the error can be attributed to spatial separation (19 km) of the bridge temperature observation site and the radiation observation site.

BridgeT is capable of supplying surface temperatures within 1K of measured values over a 40-h forecast period if it is supplied with accurate weather forecasts. RWFS-BridgeT has shown reasonable skill in surface temperature and frost prediction although the nighttime cooling rate is typically too steep, likely due to RWFS long wave radiation errors. RWFS-BridgeT tends to over-predict frost but also has a high probability of predicting all frost events. These traits are consistent with the steep nighttime temperature trends associated with RWFS-BridgeT. MM5-BridgeT has shown slightly better skill in bridge temperature prediction; although calibration improved overall performance, calibration was not as effective at improving the forecast as was true for RWFS-BridgeT. Frost predictions were prone to false alarms and partial hits, largely due to humidity and precipitation errors from MM5.

Future improvements to BridgeT may include fine-tuning and testing its pavement condition forecasts, expanding BridgeT for roadway use, and incorporating treatment recommendations for predicted pavement conditions. Since BridgeT cannot improve upon the quality of its input, it remains vulnerable to failure through input errors. Improvements in mesoscale forecast quality, especially humidity and radiation accuracy, are necessary for significant improvements to BridgeT frost and surface temperature forecasts.

References

Bernstein, B.C., J.K. Wolff, and W. Myers, 2004: Verification of the road weather forecast system run during the 2003 demonstration at the Iowa Department of Transportation. Sixth Annual Symposium on Snow Removal and Ice Control Technology, Transportation Research Board, Spokane, WA, 109-126.

Crevier, L.-P., and Y. Delage, 2001: METRo: A new model for road-condition forecasting in Canada. *J. Appl. Meteor*., 40, 2026-2037.

Greenfield, T.M., 2004: Bridge frost prediction through heat and mass transfer methods. Master's thesis, Department of Geological and Atmospheric Sciences, Iowa State University, 116 pp.

Greenfield, T.M., E.S. Takle, B.J. Tentinger, J.J. Alamo, D. Burkheimer, and D. McCauley, 2004: Bridge frost occurrence and prediction. Sixth Annual Symposium on Snow Removal and Ice Control Technology, Transportation Research Board, Spokane, WA, 391-398.

Gutowski, W.J. Jr., S.G. Decker, R.A. Donavon, Z. Pan, R.W. Arritt, and E.S. Takle, 2003: Temporal scale of precipitation errors in central United States climate simulations. *J. Climate*, 16, 3841-3847.

Hertl, S., and G. Schaffar, 1998: An autonomous approach to road temperature prediction. *Meteor. Appl.*, 5, 227-238.

Incropera, F.P., and D. P. DeWitt, 2002: *Fundamentals of Heat and Mass Transfer*, 5th ed. John Wiley and Sons, Inc., 981 pp.

Iowa Environmental Mesonet, cited 2004: Iowa School Net precipitation data. Iowa State University. [Available online at http://mesonet.agron.iastate.edu/schoolnet/dl/]

Jacobs, W., and W.E. Raatz, 1996: Forecasting road-surface temperatures for different site characteristics. *Meteor. Appl*., 3, 243-256.

Sass, B.H., 1992: A numerical model for prediction of road temperature and ice. *J. Appl. Meteor.*, 31, 1499-1506.

Sass, B.H., 1997: A numerical forecasting system for the prediction of slippery roads. *J. Appl. Meteor*., 36, 801-817.

Takle, E.S., and T.M. Greenfield, 2002: Calculating accumulated frost by use of observed and forecast meteorological values. Final report to the Iowa Department of Transportation.

Temeyer, B.R., 2003: Use of an artificial neural network to predict air temperature, surface temperature, dew point, and wind speed for the prediction of frost. Master’s thesis, Department of Geological and Atmospheric Sciences, Iowa State University, 108 pp.