THERMAL RESPONSE OF BRIDGES

Kynric M. Pell, John E. Nydahl, Vic A. Cundy, George Twitchell, and Mark Weber,
Department of Mechanical Engineering, University of Wyoming

Interest in the control of ice on highway structures has resulted in a number of demonstration projects to investigate the effectiveness of both active and passive techniques to control the problem. Few of these experiments have incorporated any preliminary thermal modeling in their feasibility studies and, as a result, have met with mixed success. Research was initiated to develop, verify, and document a thermal model applicable to highway structures. This program would allow the design engineer to conveniently estimate the thermal performance of proposed ice control devices in a specific environment. The thermal model was developed and verified by simulating the thermal response of an instrumented bridge to within a mean deviation of 2.1 F (1.2 C) over a 12-day period of severe winter weather. The model is general since standard heat-transfer correlations rather than inferred correlations from the data were used. The utility of the simulation is demonstrated in a study of the effect that insulation would have on the freezing characteristics of a bridge. Insulation would reduce the number of freeze-thaw cycles by 34 percent and the total time frozen by 15 percent. Experimental results indicated that modifying the surface radiative characteristics can induce even larger reductions for the site investigated.

•TEMPERATURE variations, particularly around the freezing point, can strongly influence the performance of highway structures. Elevated highway structures such as ramps, interchanges, and bridge decks exhibit a different thermal response to the environment than the remainder of the roadway exhibits, and this results in possible preferential icing where either the deck surface is iced and the roadway is not or vice versa. The former case presents a more obvious safety hazard for the motorist. In addition, it has been recognized that concrete bridge deck deterioration is related to freeze-thaw cycles and the time the deck is frozen. The total time frozen is an important parameter because a structure's icing characteristics and, therefore, the application of salt are related to it.

Interest in the thermal design of bridges to ameliorate safety problems and inhibit deterioration related to freezing has recently increased. Both active and passive techniques have been explored. Studies related to preferential icing have been primarily experimental, and the results were often inconclusive and proved to be site specific. The inconclusive results were primarily due to insufficient data; however, the results were site specific because heat transfer on bridges is an extremely nonlinear function of climatic environment and material properties.

In view of these difficulties, it seemed desirable to develop an accurate thermal simulation of structures that could use available historical weather data to predict the thermal performance of a structure. This would be particularly valuable in preliminary design studies to characterize the effectiveness of possible control techniques minimizing icing conditions. For the program to be broadly accepted, it would have to possess documented accuracy and broad applicability and be user oriented. A program exhibiting these characteristics could also be used to predict preferential icing by using regional weather forecasts. The objective of this research is to develop and document such a program.

BACKGROUND AND SCOPE

One obvious method to minimize freezing is to actively heat the structures, and this has been attempted on some bridges, roads, and runways, by using heat sources such as electrical, oil, and gas-fired boilers or hot springs. A comprehensive review of this literature is given elsewhere (1, 2). Typical heating systems have included resistive heating elements, convective tubes, and infrared and convective heaters placed either above or below the surface. These methods appear to have a limited application for extreme situations because of prohibitive capital expense and operating costs or large induced thermal stresses.

The limited use of the earth as a low-temperature heat source for a convective system to melt snow on pavement in a mild climiate has been successfully demonstrated (3), and the use of heat pipes in a related application has been investigated (4). A demonstration project using ammonia-charged, gravity-operated heat pipes has been conducted recently at the Federal Highway Administration research facility in Virginia (5). The development of design procedures for heat pipe systems for both retrofit and new construction on bridges to inhibit preferential icing is also being investigated by FHWA.

Passive methods involving the alteration of the thermal properties of bridges have also been studied; for example, the bottoms of bridges have been insulated to reduce the convective heat transfer (6, 7, 8, 9, 10), and surface radiative properties have been varied (9). Essentially, all of the investigations to date have been strictly experimental, and the results in Table 1 do not provide the basis for general criteria for use of these techniques.

Passive techniques can be effective in significantly altering the freezing characteristics of a bridge (Table 1) and the amount of alteration and whether it is beneficial or detrimental depends strongly on the location. It is evident that if thermal designs of structures are to be optimized they must be optimized for their local environment, especially when elaborate schemes, such as geothermal heating, are being considered.

The evaluation and optimization of proposed freeze-thaw and icing control devices for bridges, roads, or runways require either a well-instrumented engineering development facility or an accurate thermal simulation. Engineering development facilities are traditionally expensive and exhibit inherent inflexibility as is demonstrated by many of the experimental studies previously mentioned. These facts have led to an increasing use of simulation in all areas of engineering. In view of this need for an accurate thermal model of broad applicability, the current study was initiated (11, 12, 13).

Development of a basic computer code for heat transfer that was applicable to highway structures began in 1972. The simultaneous development of an experimental facility to provide input data and model verification was initiated by using financial resources, equipment, and personnel of both the University of Wyoming and the Wyoming Highway Department.

EXPERIMENTAL INVESTIGATIONS

Experimental Facility

The overpass bridges and adjacent roadway at the Cooper Cove interchange located 40 miles (64 km) west of Laramie, Wyoming, on Interstate 80 were chosen as the test site because of the severity and variety of the local micrometeorology and the proximity of the U.S. Forest Service and Wyoming Highway Department field test site at Cooper Cove. The westbound lane has an asphalt overlay that will permit direct comparison of the thermal response of two bridges that are similar except for surface radiation properties (concrete versus asphalt).

The installed instrumentation can be divided into two groups to measure (a) the local micrometeorology and (b) the actual thermal response of the bridge and roadway. The weather data supply the input for the numerical simulations, and the thermal response data permit simulation verification. Figure 1 shows the rack, containing most of the meteorological instrumentation, that was mounted on the rail of the eastbound bridge and that includes two anemometers, two wind vanes, aspirated ambient air temperature gauge, time-lapse camera, and two Eppley pyrheliometers. The pyrheliometers are mounted on a 10-ft (3-m) pole; one unit measures the incoming solar radiation and the other unit is shielded and sees only the bridge so that the reflected solar radiation can be measured. The solar radiation absorbed by the bridge deck as well as the surface condition can be deduced from these two measurements since the solar reflectivity varies with wetness, icing, and snowpack. In addition, some indication of cloud cover can be obtained from the upward facing Eppley pyrheliometer. Barometric pressure, humidity, and precipitation are also measured. The temperature distributions in the bridges and adjacent roadway are measured as a function of time by using thermistors embedded in the bridge decks and the adjacent roadway. All of the transducers (thermistors and weather instrumentation) are cabled to an instrumentation shed located under the bridge of the eastbound lane of I-80. The instrumentation shed houses the various instrumentation controllers and the magnetic-tape-based data acquisition system. The bridges were instrumented by potting the sensors in $^3/_8$-in.-diameter (9.5-mm) epoxy rods of varying lengths, which could be inserted into holes drilled from the bottom of the bridge deck. A schematic of this installation is shown in Figure 2. The locations of all the temperature sensors are shown in Figure 3. Three road cables were installed to measure the temperature distribution down to 10 ft (3 m) below the surface of the adjacent road.

The data acquisition system was originally developed with the cooperation of the Electrical Engineering Department of the University of Wyoming. It is capable of sequentially sampling, digitizing, and recording 100 channels of analog input signals in less than 4 sec. The entire system, consisting of a line voltage regulator, digital system, and digital recorder, is mounted in one instrumentation rack. The digital system consists of an electronic multiplexing switch, an amplifier, an A-D converter, a digital clock, and a logic module. These components are mounted in functional arrays on printed circuit boards. A rack mounting unit with appropriate card guides and terminal strips houses the complete digital system. Data in 100 channels can be sampled at a predetermined rate, and the signals are recorded on an incremental digital recorder in a format that is compatible with the equipment in the University of Wyoming's computer center.

Results

The data acquisition system went into operation on January 24, 1974, and data were taken on an almost continuous basis until June 16, 1974. Power failures and data acquisition failures caused the system to be closed down $7^1/_2$ days during this period. In addition, individual transducer malfunctions occurred during this period, but, because of the redundancy, these did not in general preclude simulation. On June 16, 1974, the data acquisition system failed because of overheating. Repair of the system and installation of an air-conditioning system were not completed until October 10, 1974, at which time the system started functioning continuously.

As long as the system is kept within operating temperature limits, it performs quite well, although noise on some of the instrumentation cables has been a consistent problem. The use of the isolation transformer to isolate the system from the power company ground has reduced this problem significantly. Throughout the program, the data acquisition system has been routinely subjected to calibration checks on all of the transducers.

An extensive computer-processing and data-reduction capability, providing a variety of tabular and graphical output formats, has been developed to provide convenient interpretation of the many parameters. All of the data processing is accomplished by using the program BRIDGEDATA, which incorporates 11 data-reduction modes. Input to the program includes the data tape generated in the field, a selection of the number of 1-min records that are to be averaged, and a specification of the particular mode to be executed.

Table 1. Passive techniques for control of icing on bridges.

Study	Time Observed (days)	Insulation Effects[a]		Surface Radiation Effects[a]	
		Freeze-Thaw Cycles	Total Time Frozen[b]	Freeze-Thaw Cycles	Total Time Frozen[b]
Nebraska (6)	80	-2	—	—	—
Texas (7)	41	+4	—[c]	—	—
New York (8)	147	-53	+2.6	—	—
Alabama (9)	245	+4	-7	+1[d]	-6
Missouri (10)	215	-15	+1	—	—
Wyoming	91	-34	-15	-37[e]	-36[e]

[a]Percentage reduction (-) or increase (+).
[b]Compared with control deck.
[c]2-hour reduction in duration of cycle.
[d]Dark epoxy covering on deck.
[e]Asphalt-overlaid deck.

Figure 1. Meteorological instrumentation rack and instrumentation shed at field site.

Figure 2. Thermistor installation on overlaid bridge.

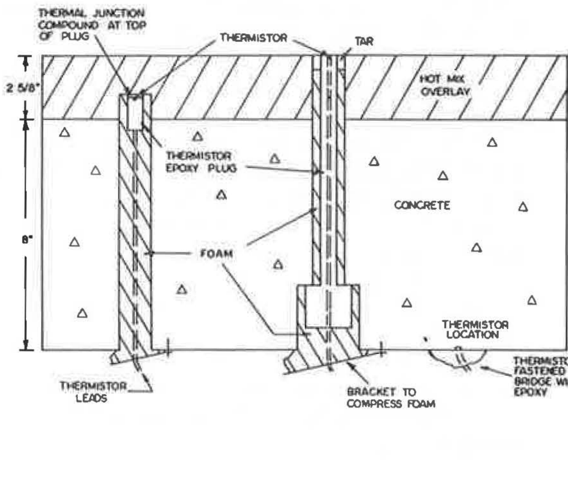
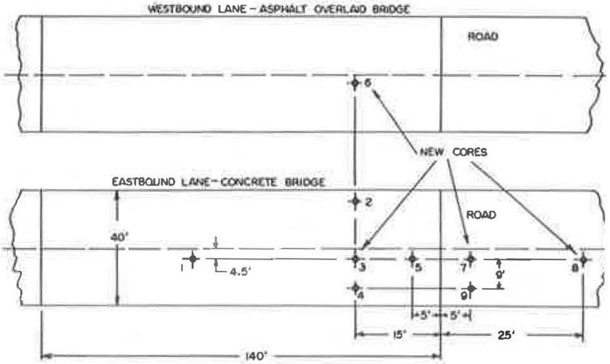


Figure 3. Thermistor locations in bridge decks and roadway.



A number of interesting results were obtained from a comprehensive data correlation study using BRIDGEDATA.

Over the 121-day period, a correlation between the surface temperatures measured at the five core locations on the concrete deck indicated that temperature differences of 3 F (1.67 C) could exist at the various locations. Location on the bridge does not appear to influence these temperatures with the exception of core 5, which appears to be warmed slightly by the proximity of the deck-road interface.

The asphalt-overlaid bridge deck is significantly warmer than the concrete bridge deck. During the period from February 1, 1974, when the asphalt bridge was instrumented, to June 15, 1974, there were 91 days when reliable comparisons could be made between the temperatures of the two decks. The surface temperatures were averaged for the day (6 a.m. to 6 p.m.) and for the night (6 p.m. to 6 a.m.). Since the tapes were generally changed around noon and the averaging was done on each tape as a unit, approximately 6 hours of data at the beginning and the end of each 8-day tape were neglected in the averaging process. These results showed that the concrete deck was 9.8 F (5.4 C) colder than the asphalt-overlaid deck during the day and 8.6 F (4.8 C) colder than the asphalt during the night for the 91-day period. A graphical representation of this data, along with air temperature, is shown in Figure 4. From the data averaged over the entire period, including that for both night and day, one can see that the asphalt-overlaid bridge was 9.2 F (5.1 C) warmer than the concrete deck. Graphic examples of this temperature difference are shown in Figure 5. A test of the effect of prevailing wind direction on this temperature difference did not result in any correlation. An additional test involving the simulated variation in internal thermal properties did not account for the observed differences. The difference in surface temperature of the two decks is therefore totally attributed to the difference in radiative properties of the two surfaces.

There was a positive indication that the number of freeze-thaw cycles was fewer and that the total time frozen (surface temperature) was significantly less for the asphalt-overlaid deck. Of the 91 days considered, the asphalt bridge experienced 18 freeze-thaw cycles, but the concrete deck experienced 40 freeze-thaw cycles. In addition, it is observed that the asphalt bridge was frozen an equivalent of 18 days, but the concrete bridge was frozen 26 days.

These results for the bridge can be contrasted with the roadway performance. During the 91 days when the surface temperature of the two bridges and the roadway could be compared, the roadway was 2 F (1.1 C) warmer than the concrete deck, and the asphalt deck was 7.2 F (4.0 C) warmer than the roadway. During the day, the concrete deck was an average of 1.5 F (0.8 C) colder than the adjacent road, and at night it was 2.5 F (1.4 C) colder. The observed range of variance for the ½-day averages was from 9.2 to -8.6 F (5.1 to -4.8 C). Similar data for the comparison of the asphalt deck with the roadway show that the asphalt bridge is an average of 8.3 F (4.6 C) warmer than the adjacent roadway during the day and 6.1 F (3.4 C) warmer during the night. In this case, the variance for the ½-day averages ranged from 16.4 to -2.5 F (9.1 to -1.4 C). Comparison of freeze-thaw performance indicates that the roadway exhibits 34 major freeze-thaw cycles during a 91-day period. This is significantly more than that experienced by the asphalt deck (24) but less than that experienced by the concrete deck (38). Table 1 gives some of these results.

The fact that the asphalt bridge is generally warmer than the adjacent roadway is surprising and contradictory to folklore. It is probably due to two factors. First, the temperature 10 ft (3 m) below the surface of the road varied from a low of 31 F (-0.56 C) to a high of 53 F (11.67 C) over the time interval studied. Obviously, this location is not below the frost line. Apparently the fill associated with the approach to the bridge [approximately 20-ft (6.1-m) elevation at the bridge] is subject to climatic variations to a much greater depth than the surrounding grade. As a result, the approach may be appreciably colder than the road at grade level. Second, note that, although the elevated structures may be expected to cool much faster than the roadway because of convection on the lower surface and their smaller thermal mass compared with that of the roadway, this smaller thermal mass also allows more rapid heating and, in fact, superheating with respect to the roadway.

Figure 4. Average ambient air temperature (top curve) and average temperature difference between the two bridge decks (bottom curve).

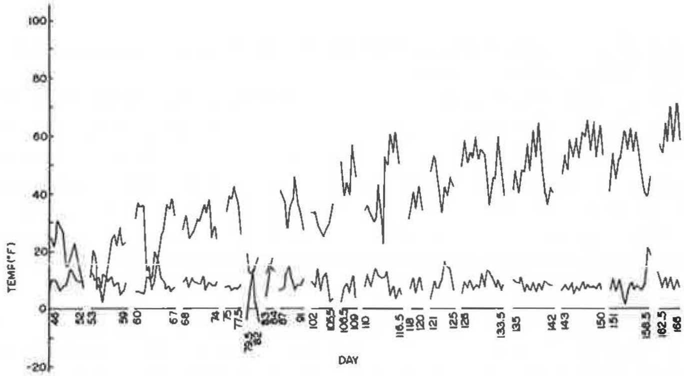


Figure 5. Comparison of surface temperature on asphalt and concrete bridge decks.

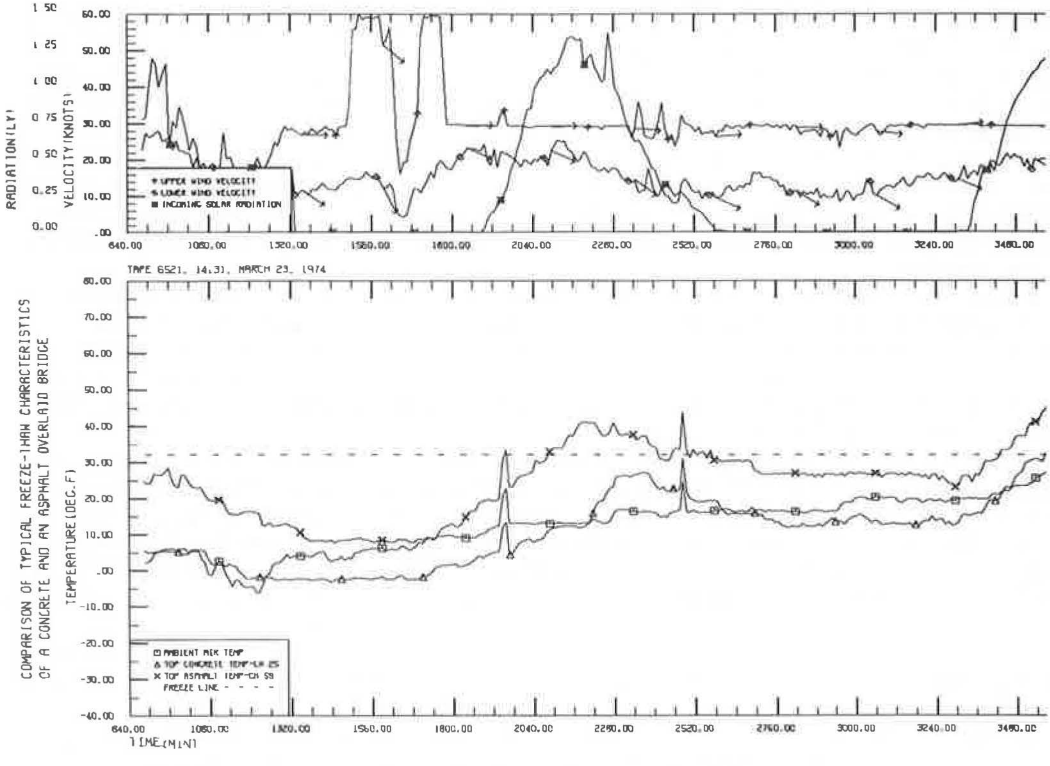
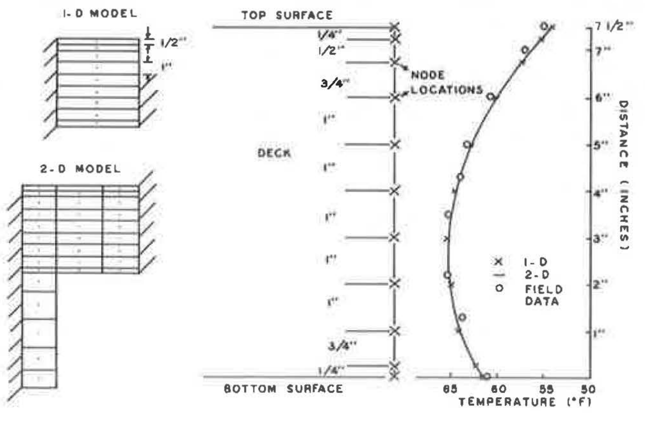


Figure 6. Temperature comparison of one- and two-dimensional models and experimental data.



LABORATORY EXPERIMENTS

A review of the literature indicated that the thermal conductivity of concrete can vary from 0.1 to 2.0 Btu/hour•ft•deg F (0.17 to 3.46 W/m•deg K) depending on the design of the mix. Similarly, the reported density and specific heat of concrete exhibit large variations. Investigations at the University of Wyoming confirmed these ranges of values (2, 14). It was found that the simulation was sensitive to the values used for these properties. This sensitivity necessitated that these properties be accurately determined for the actual materials found at the field site. A series of laboratory experiments were developed to evaluate the various properties.

The apparatus developed to measure thermal conductivity incorporates a guard heater, a specimen, a cooling reservoir, and the instrumentation for thermocouple temperature measurement. This standard arrangement provides a known heat flux through the specimen and allows a direct determination of the thermal conductivity from the temperature measurements. The value of thermal conductivity determined in this manner was combined with the known properties of steel to yield an effective value of thermal conductivity for the bridge. The values of the effective properties for concrete and asphalt are given below (1 Btu/lb•deg F = 4.18 kJ/kg•deg K; 1 Btu/hour•deg F = 1.7 W/m•deg K; and 1 lb/ft^3 = 1.6 kg/m^3):

Material	Heat Capacity (Btu/lb•deg F)	Conductivity (Btu/hour•ft•deg F)	Density (lb/ft^3)
Concrete	0.31	1.24	134.78
Asphalt	0.237	1.61	155.61

Density and specific heats of concrete and asphalt specimens were also measured by using standard techniques. These values were also combined with the known values for steel to obtain the values given above.

The comparison of the thermal response of the concrete and asphalt-overlaid decks presented previously indicates a strong dependence on the surface radiative properties. Generally these properties are a function of wavelength, and a wide range of values have been reported for the materials of interest (15). The short-wave (solar) radiative properties of the concrete deck have been characterized by using the Eppley pyrheliometers during the past year. There is no long-wave radiation instrumentation at the site; however, the excellent agreement between simulated and measured response of the concrete deck indicates that the models being used are probably adequate. In the case of the asphalt-overlaid deck, neither short-wave nor long-wave measurements have been made; as a result, the simulations suffer from this uncertainty.

SIMULATION

The simulation is based on a transient, three-dimensional, conductive heat transfer program developed by the Energy Research and Development Administration (16) and widely used by the National Aeronautics and Space Administration and industry. This program is now capable of handling inhomogeneous structures of arbitrary shapes, having internal heat generation that may differ at each internal node and vary with time. The heat transfer at the surface includes convection and radiation. The absorbed solar radiation was measured directly at the site, but the heat transfer between the atmosphere and the bridge surfaces was based on standard empirical correlations involving the measured environmental parameters.

The incident log-wave radiation from the atmosphere was calculated by using the empirical correlation (17, 18) for clear skies, which is based on air temperature and vapor pressure, as follows:

$$q_{L.W.} = \sigma T_a^4(a + b\sqrt{p}) \tag{1}$$

where

σ = Stefan-Boltzmann constant,
T_a = absolute air temperature at about 5 to 7 ft (1.5 to 2 m) above the surface,
a and b = constants, and
p = partial pressure of water vapor.

The long-wave radiation is also a strong function of cloud cover and cloud base height, but reasonable simulations were obtained if these parameters were ignored. Long-wave radiation emitted by the surface is calculated in the simulation by using the following equation:

$$q_{L.W.} = \epsilon_{L.W.}\sigma T_{surf}^4 \tag{2}$$

where

$\epsilon_{L.W.}$ = emissivity (0.80), and
T_{surf} = absolute temperature of the surface.

The long-wave radiation interchange between the ground and the bottom of the bridge deck was generally insignificant and was, therefore, ignored in the simple model presented here.

Calculation of the convective heat transfer depends on the flow structure around the bridge and is subject to large uncertainties. In spite of the fact that measurements indicate an appreciable difference between the mean flow velocities and directions above and below the bridge, parametric studies indicated that adequate simulations could be made without distinguishing between the upper and lower surface as far as convection is concerned. Both surfaces behave essentially as flat plates even though the bottom surface has a waffle structure. This is due to the very high Reynolds number of the turbulent flow. Kay's correlation for turbulent heat transfer from a flat plate was used in the simulation with good results (19):

$$q_{conv} = 131.6\rho c u Pr^{-0.4} Re_L^{-0.2}(T_{surf} - T_a) \tag{3}$$

where

u = free stream velocity in feet per second;
ρ = air density in pounds per cubic foot;
c = specific heat in British thermal units per pound·deg F;
Pr = Prandtl number; and
Re_L = Reynolds number based on L, the 40-ft (12-m) bridge width.

(If SI units are used in this equation, the numerical coefficient 746.8 should be used rather than 131.6.) Natural convection was incorporated in the simulation by using Vehrencamp's correlation (20):

$$q = 0.18(T_{surf} - T_a)^{1.3} \tag{4}$$

(For SI units, the numerical coefficient in this equation becomes 1.22.)

A study to determine the geometric complexity required for accurate simulation was undertaken to reduce the execution time of the computer simulations. One- and two-dimensional representations of the bridge were considered as shown in Figure 6. The two-dimensional model takes into account the web geometry below the concrete slab forming the deck, but the one-dimensional model represents just the deck slab. Results of the simulated temperature distribution for the one- and two-dimensional models and the measured temperature distribution are also shown in Figure 6. Although the data are for a particular time, they are typical of the results obtained throughout an 8-day simulation. It is apparent that a transient one-dimensional heat transfer model is sufficient for the type of investigations considered.

Most of the field data generated between January 24, 1974, and June 15, 1974, have been simulated by using the heat-transfer models previously described. This represents over 121 days of essentially continuous simulation including winter and spring environments. The mean deviation (based on absolute temperature difference) between the simulated and measured surface temperatures was only 2.1 F (1.2 C), in spite of the fact that this period encompassed many days when the upper surface was snowpacked, icy, or wet. It should be emphasized that the simulation does not treat these surface conditions explicitly but does directly incorporate into the program the fact that the solar radiation is absorbed.

Of a typical 8-day simulation, 1.5 days are shown in Figure 7. Mean deviation between the measured and simulated upper surface temperature for the full 8-day tape was 2 F (1.1 C); however, the mean deviation for the lower surface temperature was 2.2 F (1.2 C). Environmental conditions for the full tape included wind speeds of 60 knots (30.9 m/s) and ambient air temperatures below -10 F (-23.3 C). The upper surface, which was snowpacked for most of the 8 days, experienced five freeze-thaw cycles and was below freezing for 5.4 days. The first freeze-thaw cycle is included in Figure 7. It should be noted that the simulation accurately predicts the onset and termination of the freeze-thaw cycle. The excellent agreement between simulated and measured temperatures is surprising because the surface was snowpacked throughout most of the period.

Parametric studies were initiated to investigate the effect that an insulator, located at the bottom surface, would have on the freezing characteristics of the upper surface of the concrete deck. A perfect insulator was selected as the limiting case. The results of this study are given in Table 1, in which measured field site data are given for comparison. It was observed that insulation would be effective in reducing the number of freeze-thaw cycles (by 34 percent) and time frozen (by 15 percent) at this site under the prevalent environmental conditions and that the upper surface temperature was increased an average of about 1.92 F (1.1 C), and the lower surface temperature was increased 4.9 F (2.7 C). However, the average temperatures on both surfaces did decrease for one 8-day tape.

The results from part of a typical 8-day insulation study are graphically shown in Figure 8. Comparing the simulated temperature response of the insulated and uninsulated concrete decks for this 8-day period showed that the effect of insulation was to raise the average temperature of the upper surface by 2.1 F (1.2 C) and of the lower surface by 5.2 F (2.9 C). No reduction in freeze-thaw cycles occurred in this sample period. This result emphasizes the need to conduct comprehensive studies over extended periods of time. For this particular period of time, the average temperature of the bridge is well below freezing; therefore, a direct correlation can be made with the New York study (19). A result of this study indicates that the effect of insulation is minor during periods of hard freeze.

Insulation appears to be effective when the surface temperature is close to freezing and rapid alternate freezing and thawing cycles. In hard freeze or prolonged freeze situations, insulation is not effective in reducing the cycling. In Table 1, it may be seen that, at this site, asphalt overlaying is more effective in reducing freeze-thaw cycles and total time frozen than even a perfect insulator on the lower deck surface. It should be emphasized that these results for insulation should not be generalized to significantly different sites in view of the nonlinear dependence on geometry and environmental parameters.

Figure 7. Comparison of simulated and measured response of bridge with concrete deck.

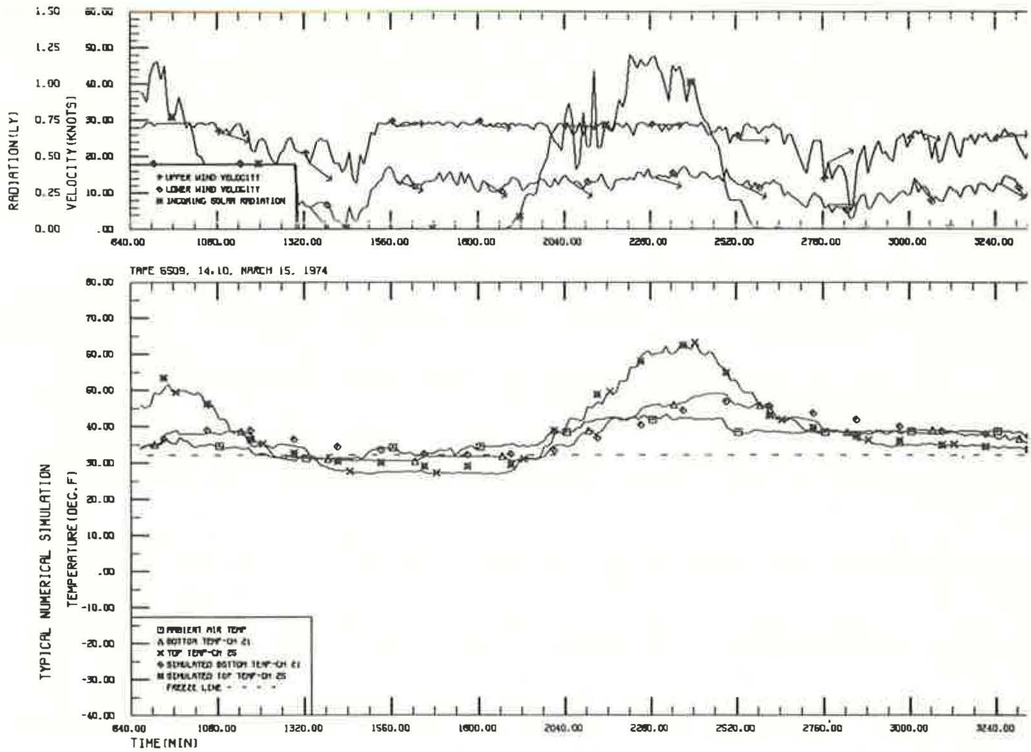
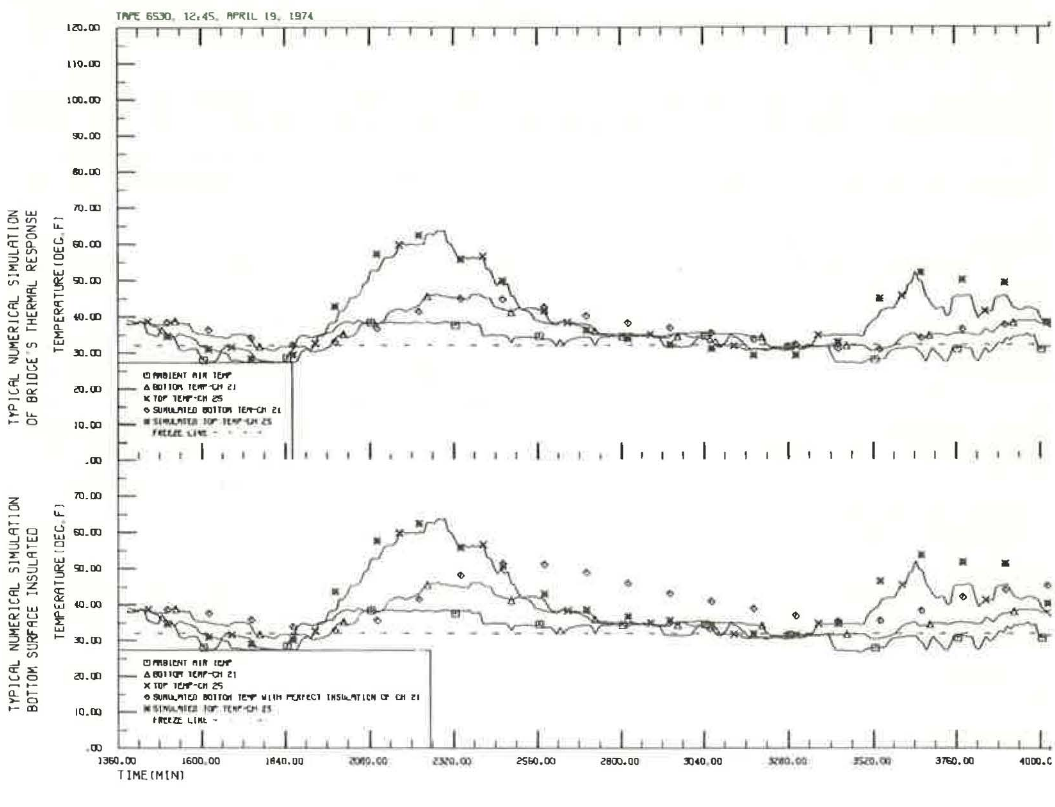


Figure 8. Comparison of bridge deck with and without insulation.



Parametric studies of the effect of modifying the surface radiative properties of the bridge were initiated by using the simulation. It was shown that large variations in the surface temperature can in principle be obtained by using this technique. This is qualitatively confirmed by the contrasting results obtained in the field site data for the concrete and asphalt-overlaid decks. In view of the uncertainty in the radiative properties previously noted, an exhaustive study was not pursued.

CONCLUSION

It has been demonstrated that accurate thermal simulations of highway structures can be obtained by using a relatively simple model. The environmental information needed for input (air temperature, wind speed, relative humidity, and solar radiation) is available for many regions in the form of a magnetic tape from the National Oceanographic and Atmospheric Administration.

The simulation has been verified by comparing simulation results to measured thermal response of a concrete bridge for 121 days. The mean deviation between measured and simulated temperatures was only 2.1 F (1.2 C) over the entire winter although this period encompassed many days when the upper surface was snowpacked, icy, or wet. In addition, the onset and termination of freeze-thaw cycles were accurately predicted.

Although the program was verified by using data obtained at a particular site, it incorporates correlations of standard heat transfer that should ensure applicability to other environments. Data obtained in Minnesota show that the response of bridges in rather large regions is similar inasmuch as all the bridges in a region exhibit icing at approximately the same time. This result indicates that the simulation used to study the parametric design of icing conditions could be based on regional historical weather data. The program, therefore, provides a convenient tool for optimizing the thermal design of highway structures for the local environment. Design alternatives that could be explored include radiative properties; insulation; material properties; composite structures; and active heating, including geothermal sources. Temperature distributions obtained from the program can also provide the basis for an analysis of thermal stress.

As an example of the utility of the simulation, a study was initiated to determine the effect that insulating the lower surface of the concrete bridge would have. Results indicate that the number of freeze-thaw cycles would be decreased by 34 percent and that the total time frozen would be decreased by 15 percent.

The experimental program to measure the thermal response of two bridge decks and the adjacent roadway as well as the local micrometeorological parameters has produced a number of important results in terms of contrasting thermal performance of various structures, in addition to providing the basis for development of the thermal simulation. Data obtained from January 24, 1974, through June 16, 1974, indicate that the asphalt-overlaid deck surface was generally warmer by 9 and 7 F (5 and 3.9 C) than either the concrete deck or the interfacing roadway respectively. The asphalt-overlaid deck was subject to 37 percent fewer major freeze-thaw cycles than the concrete deck and was below freezing for 36 percent less time than the concrete deck. In general, the concrete deck surface was 2 F (1.2 C) colder than the adjacent roadway surface.

A proposed icing control scheme for a particular site should be investigated by using a thermal simulation that incorporates historical weather data from the appropriate recording weather station even before a demonstration project is implemented.

ACKNOWLEDGMENT

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