Prediction of Preferential Icing Conditions on Highway Bridges

C. Birnie, Jr., and W. E. Meyer

Preferential icing of bridges, i.e., the freezing of bridges before the approaches do, involves the interaction of a number of variables such as location, weather conditions, thermal properties of the bridge structure, and traffic density. This paper reports on research undertaken to correlate these variables of weather, geographic location, and bridge deck thermal properties that lead to preferential icing. A bridge deck over a stream was instrumented to gather data on a continuous basis throughout the winter of 1969 and 1970. The field study was supplemented with a computer simulation of the heat flux in bridge decks and with measurements on a deck section in the cold room. With representative weather data and knowledge of the thermal characteristics of the bridge structure, it should be possible to construct a probabilistic model to predict the number of days per year that icing will occur. Such a model will be useful to the highway engineer in devising an economically justifiable countermeasure.

Preferential icing of bridge decks, a well-known safety hazard, refers to the formation of ice on a bridge deck at times when the approaches become merely wet or even remain dry. The existence of this hazard is well recognized, but its seriousness and frequency of occurrence for a given bridge have not been investigated systematically. The factors that lead to preferential icing have not been subjected to scientific study, and the possible means for preventing it have not received the attention they deserve. Although much work has been done on the control of ice and snow on elevated structures, this has been solely as part of the overall removal operations. This paper is concerned specifically with the situation in which measures are required in a district only for some bridges and not for other bridges or roads and streets.

To deal with the problem, we need methods for assessing the frequency and severity of preferential icing of a given bridge, and an assessment of the feasibility of countermeasures. This paper is in the nature of a progress report because we cannot yet offer final answers to all questions. It attempts to offer an analysis of the problem and reports research under way at the Pennsylvania State University.

GENERAL CONSIDERATIONS

Preferential icing is caused by the difference between the thermal response of an elevated highway structure and that of the approachways to the local meteorological conditions. Preferential icing will occur when (a) the bridge deck surface is below 32 F and the approachway is not, and (b) moisture is available in the form of high relative humidity, mist, fog, rain, sleet, snow, or runoff from a snow bank or other source.

Given a meteorological cycle, can we predict whether a bridge deck will freeze? We have taken 3 approaches to obtain an answer to this question: (a) a numerical solution for determining the time-temperature history of the bridge surface for a specified ambient temperature cycle; (b) exposing a test slab in a controlled temperature room, simulating a bridge deck undergoing changes in ambient temperature; and (c) instrumenting a highway bridge.

The last approach is the most obvious one, but suffers from the drawbacks that preferential icing is an extremely transient phenomenon and that the frequency of icing is very much a function of local conditions. To select a suitable bridge, we examined 14 different ones. We knew that there were no records on the frequency of icing, but we also found that subjective information was not of very much help. Accident records were examined, but the information recorded is too ambiguous and reported accidents are statistically too infrequent to provide guidance. Therefore, we had to make our choice on the basis of inferred thermal characteristics and meteorological conditions at the site.

The experience with this search for a bridge that would make a good experimental site emphasized the importance of the other 2 approaches. A computer simulation would be of considerable value because it would help to clarify the relation between thermal characteristics of a bridge and its environment. Similar simulations have, of course, been done before (1). Our first simulation was a relatively simple one because it seemed essential to get some initial guidance for the other phases of our work. There is a purely analytical solution with limited boundary conditions for the heat transfer problem in a slab (2). Because, however, the primary variable in the problem is the nature of the varying heat transfer conditions at the slab surfaces, a numerical approach was adopted. The computer program (SIMULATION I) solves the heat conduction equation

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho c}{k} \frac{\partial T}{\partial t}$$

for a one-dimensional slab with heat flow only in the direction perpendicular to the surfaces for the temperature distribution in the slab as a function of time.

LABORATORY EXPERIMENTS

We constructed a test slab to simulate a typical prestressed concrete bridge deck. Originally we intended to do this outside near our laboratory. This would, in effect, have brought a bridge to a location where observations and measurements could be made frequently, conveniently, and in comfort and safety. Although useful for many purposes, the test cycles would still have been largely dictated by nature. On the other hand, certain effects that influence preferential icing in the field would have been absent and difficult to simulate realistically, for instance, the residual effects of anti-icing agents. Therefore, we decided to place the slab in an available cold room and treat it purely as a laboratory tool, rather than as a substitute field experiment.

With the slab in the cold room, temperature, humidity, and precipitation can be controlled. Instrumentation can be checked out and, if necessary, put through repeated identical test cycles. This applies specifically to ice detection systems and methods. Eventually countermeasures can be evaluated with it before being incorporated in expensive field installations. In addition, the computer simulation can be validated with the slab.

Figure 1 shows a top view of the test slab in place. It is 3 by 4 ft with a thickness of 7.5 in., poured of Class AA concrete and insulated on its sides with Styrofoam to minimize end effects. Reinforcing rods were placed within the slab, their size and spacing approximating those in actual bridge decks. The thickness of the slab was selected to correspond to that of the bridge deck selected for the field experiment. Approximately 50 copper-constantan thermocouples were located at various points within the slab. Figure 2 shows a cross section of the slab and the location of these thermocouples. In addition, a wood plug 4 in. in diameter was placed in

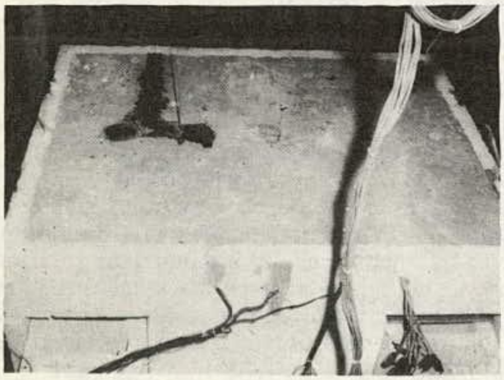

Figure 1. Top view of laboratory slab installed in cold room.

the slab when it was poured. It was subsequently replaced by a concrete cylinder containing thermocouples at ½ in. depth intervals. The slab was set up on concrete blocks to allow air to circulate over and under it. Styrofoam pads were placed between the blocks and the slab to thermally isolate it from the supports.

The thermocouples distributed through the slab provided the following information: There are no significant end effects; the reinforcing rods do not significantly affect the temperature field; and the couples in the core indicate the same vertical temperature gradients as couples elsewhere in the slab.

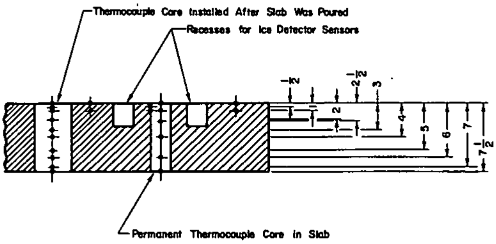

Figure 2. Cross section of laboratory slab showing location of thermocouples.

COMPUTER SIMULATION

The computer program (SIMULATION I) will be described in a forthcoming report (3). Figure 3 shows the computed and experimental values under identical thermal conditions. The agreement is good and was achieved by only manipulating the upper and lower surface film coefficients in the program. The actual values of the test slab coefficients are not known. This is significant in that it points out that if the computer simulation is to predict temperature distributions reliably, data on bridge deck surface film coefficients must be obtained. Williamson (4) has done some work in this area, but for our purposes more detailed information will be necessary than Williamson's work provides.

Another example of the usefulness of the program is shown in Figure 4 These results were obtained by first representing the ambient air temperature change by a polynomial that allowed the temperature to fall from an initial value of 77 to 10 F over a 4-hour period. The temperature in the slab was initially set at 77 F throughout. The program was run first allowing both the upper and lower ambient temperatures to fall as they would on a bridge deck, with both sides exposed to the same ambient conditions. The program was then rerun with identical initial conditions, but with the bottom surface held at 77 F, thus simulating an approachway receiving heat from the subbase. Several runs were made in these 2 modes but with varying surface film coefficients. Figure 4 shows that the lower the surface film coefficient, the longer the period of potential preferential icing will be.

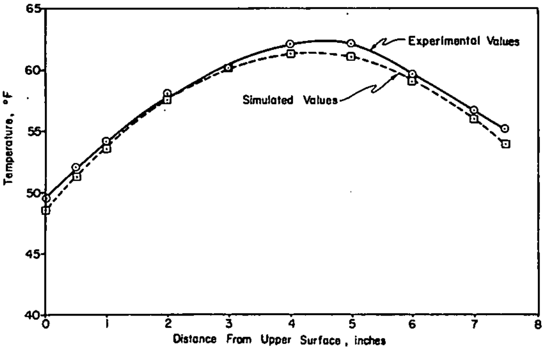

Figure 3. Comparison of temperature gradients in laboratory slab as measured and as computed by SIMULATION I.

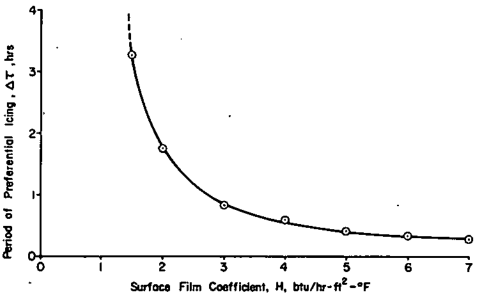

Figure 4. Period during which bridge deck is below freezing while approachway is not, as function of surface film coefficient (SIMULATION I).

The program is now being refined (SIMULATION II) to add simulation of multilayer decks and internal heat sources. The film coefficients are handled by a subprogram that will also take care of radiation heat losses or gains. The subprogram in effect controls the total heat fluxes at both surfaces. These heat fluxes are, of course, influenced by numerous variables. The experiments will serve to derive manageable functions.

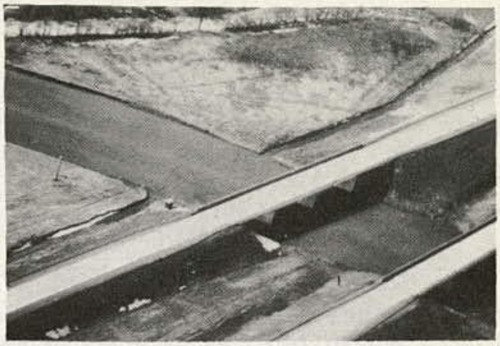

Figure 5. Aerial view of I-80 bridge over Bald Eagle Creek in Centre County. Upper deck is instrumented; instrument shack is on near creek bank just above bridge.

BRIDGE SURVEILLANCE

Interstate 80 bridge across Bald Eagle Creek in Centre County, Pennsylvania, was selected as the field test site (Fig. 5). The bridge is constructed of 7.5-in. thick slabs supported on concrete box beams. Installing thermocouples directly in the existing deck would have been extremely difficult. Because the experiments with the laboratory slab had shown that thermocouples in a removable core give temperature readings equivalent to those in the slab itself, a 4-in. diameter hole was cut into the deck and a core with thermocouples in place inserted into it (Fig. 6). This is a most convenient and economical method, particularly because surveillance would suffer only a brief interruption if one or more thermocouples should fail.

A similar core was installed in the approach to the bridge. The temperature profiles in both cores are recorded continuously. Moisture sensors were also installed in the deck to detect ice. A complete meteorological station was installed at the bridge site to monitor air temperature, wind speed and direction, precipitation rate, and absolute and relative humidity. The general arrangement of the instruments is shown in Figure 7. The recorders and auxiliary equipment are housed in a shack adjacent to the site. Figure 8 shows an inside view of the shack.

This installation will provide information on (a) the frequency and duration of the periods when the bridge surface is below 32 F but the approachway is not, (b) the ambient conditions during and preceding these periods, (c) the frequency with which moisture to cause preferential icing is available , and (d) the source of the moisture.

We have not yet found a method that is totally satisfactory for detecting the presence of ice on the road surface. We need to know when temperature and moisture combine anywhere on the bridge deck to form ice, and whether the ice constitutes a traffic hazard.

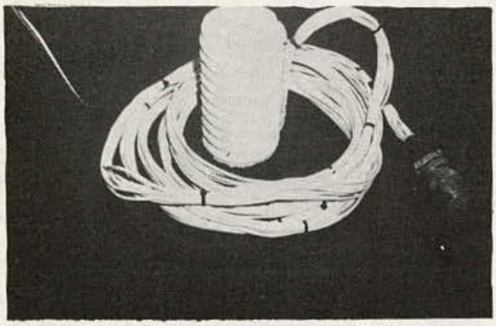

Figure 6. Core with thermocouples ready for installation in deck of bridge.

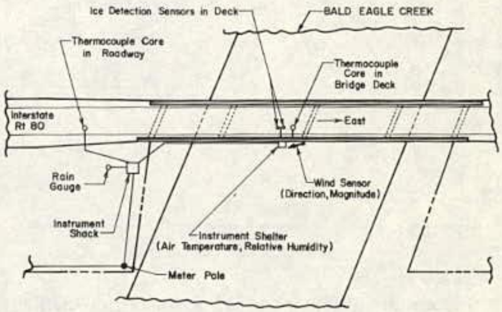

Figure 7. Plan view of instrumented bridge deck showing sensor locations.

ICE DETECTION METHODS

Detection methods can be grouped into 3 major categories:

1. Warning systems generate a suitable signal to warn traffic that ice is present on the bridge. When the condition ceases to exist, the signal will terminate.
2. Countermeasure actuation systems generate a signal that anticipates that ice will be forming sometime in the future. The length of lead time will depend on the type of countermeasure and may also depend on the specific weather conditions.
3. Monitoring systems monitor the functioning of the other 2 systems and contribute to research. Their accuracy must be high, and they should be capable of monitoring the entire test surface.

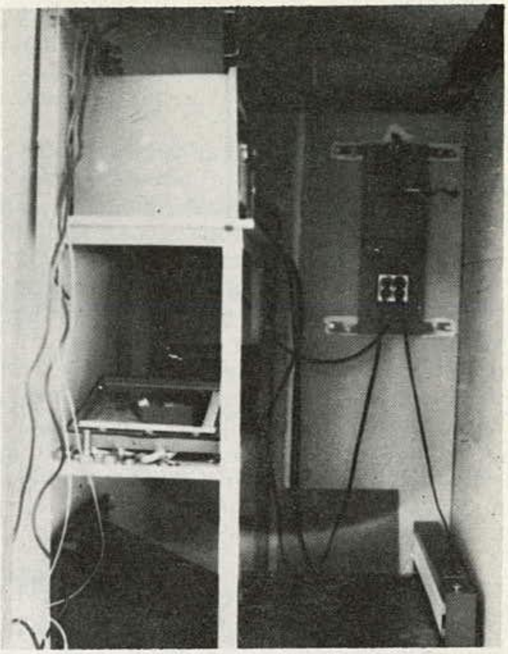

Figure 8. Inside of instrument shack.

Commercial systems are either the first or the second type. They monitor one or more of the variables, air temperature, road surface temperature, road surface moisture (liquid or frozen), and relative humidity. Those systems whose primary function is to anticipate icing conditions usually rely on the detection of air temperature and relative humidity because, when the air temperature approaches 32 F and the relative humidity is above 95 percent, the possibility of surface icing is high. The reliability of such systems has been shown to be doubtful (5). For example, such a method will not detect water resulting from melting snow or ice running across the road and about to refreeze.

Most of the current commercial systems do in fact monitor surface moisture in addition to air temperature and local relative humidity. Commonly 2 adjacent sensors measure electrical conductivity at the road surface. One of the sensors is heated. If the surface is dry, both sensors show high and equal resistance; if the surface is wet, both sensors have low and equal resistance. If there is ice on the pavement, the resistance of the unheated sensor will be high because it is covered with ice, which has high resistivity, while the heated sensor will melt the ice and low resistance will be indicated. Tests (5) indicate that this is a fairly reliable method, but conditions can exist under which it will generate a false signal. Figure 9 shows a laboratory experiment in which a thin film of ice was deposited on the test slab by a supersaturated atmosphere. An ice film has formed over the unheated sensor. The heated sensor, however, is dry. Evidently the energy input is great enough not only to melt the ice but also to evaporate all moisture from the sensor surface.

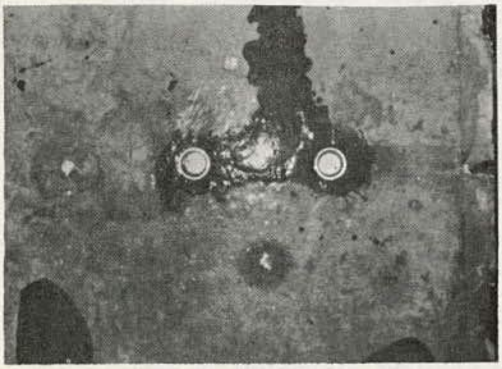

Figure 9. Ice detector sensors in laboratory slab when atmosphere is supersaturated. Left (unheated) sensor is covered with ice film, and right (heated) sensor is dry.

For practical applications, failure of a detecting system to deal with such subtleties may not be important, but for research purposes it is, because we must have accurate and reliable records of when ice formation began and when the ice disappeared. In addition, a research system should monitor not merely a small spot but the entire area under surveillance. Freezing meltwater may miss a spot sensor, and channeled traffic may melt the ice over the sensor while outside the wheelpaths ice may remain.

Another problem is the relation between the presence of ice and slipperiness. What we really are trying to eliminate is "preferential slipperiness." On the laboratory slab friction measurements were made at various ice thicknesses with a Keystone-Penn State drag tester (6). With films of ice not thick enough to obliterate the surface irregularities, the surface was not found to be especially slippery.

At present a conventional pavement ice detector is being used on the test bridge deck. The continuous on-off records from it are supplemented by daily reports from all highway maintenance personnel passing over the bridge. When icing conditions prevail, project personnel make an inspection whenever possible. We are, however, continuing our search for a fully automatic method that will give 100 percent coverage in time and space with as close to 100 percent accuracy as possible.

We have considered numerous detection schemes and tried out several, such as radiometric, light reflective scanning, and photography. We have also given thought to methods of automatically measuring slipperiness. So far all these solutions have been found to have serious shortcomings.

COUNTERMEASURES

Many methods for keeping roadways free of ice and snow have been investigated or used on a limited scale over the past 20 years. The prevention of preferential bridge icing could utilize this technology, except that the boundary conditions for its use are different. Melting a 6-in. snowfall competes economically with its removal by plowing. Control of preferential ice on bridges is in most cases an added service. On the other hand its accident potential is thought to be very high because it represents a local hazard that traffic encounters without warning under otherwise normal conditions.

Experience shows that the frequency with which bridges may freeze before roadway varies considerably. Obviously, economic considerations dictate different solutions when a countermeasure is likely to be used only once a year and when it is needed frequently, or when the skidding accident experience is high because of either traffic density or road geometry.

Operating cost is an important factor with snow melting schemes, but not with methods for the prevention of preferential icing because very low power levels are sufficient inasmuch as the object is only to prevent slippery conditions on the bridge when these do not exist on the adjoining roadway. Thus capital cost becomes extremely important.

THE PROBLEM OF PREDICTION

The crucial problem is to determine what level of service a particular bridge requires and how this service can be provided at acceptable cost. Although there are secondary factors, the requirements are functions of the thermal properties of the bridge and of its climatic environment. Rapid methods are needed to determine these 2 factors for a large number of bridges.

The thermal properties of a bridge are essentially constant and can therefore be determined at any time of the year. In essence this requires determining the effect of a known rate of input or subtraction of heat. There are numerous ways in which this can be done. We are currently using a vehicular-mounted radiometer to measure surface temperature while in motion. Knowing the surface temperature of the bridge deck and the adjoining roadway as well as the ambient temperature, we should at least be able to make a rough classification of bridges. Further measurements may be needed to characterize bridges that are subject to potential preferential icing.

The environmental characteristics are more difficult to quantify and describe. Macrometeorological data provide not much more than an envelope and a base line. Practical methods must be found for relating the microclimate at the bridge with the macroclimate reported by the U.S. Weather Bureau. The experience with our instrumented bridge should provide insight into the principles to be applied. We expect to find classifiable weather cycles for the near-freezing temperature range to which a limited set of rules can be applied for predicting at least the difference in the surface temperatures of bridge and approachway.

CONCLUSIONS

The problem of predicting when preferential icing of bridge decks will or will not occur is a complex one. Given a known environmental cycle, it is possible to predict the temperature differences between bridge deck and approachway provided the thermal characteristics of both are known. Possibilities have been indicated for obtaining these characteristics by routine methods. (Not mentioned was the prediction of the thermal characteristics of a bridge while in design, but guidance for a practical procedure for this purpose should be obtainable from the experience with existing bridges.)

The climatic conditions that can lead to preferential icing must be obtained by establishing a relationship between the macrometeorological histories that the U. S. Weather Bureau can provide and the microclimate at the bridge. At this time only speculations can be offered as to the type of data that must be collected at the bridge site and over what period. The instrumented test bridge is expected to furnish this type of information, at least for a single location.

Countermeasures will no doubt differ greatly, depending on the probable frequency with which preferential icing is likely to occur. Because different countermeasures require different phasing between actuating signal and arrival of the icing conditions, we must be able to predict from the ambient changes when icing is likely to occur.

ACKNOWLEDGMENTS

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Formal Discussion

W. D. Glauz and R. R. Blackburn

Birnie and Meyer are to be complimented on their many faceted approach to the examination of an illusive problem—detecting or predicting the occurrence of localized icy conditions on bridge decks. Their use of analytical and laboratory findings in conjunction with field work is commendable. However, there are certain features of bridge icing that, although alluded to, have been underestimated by the authors.

There are 2 major situations under which localized bridge icing might occur: (a) the freezing of some form of precipitation and (b) the occurrence of frost. In addition, bridge deck cooling is caused by both convection and radiation. The occurrence of frost is most often influenced by radiation cooling, whereas the freezing of precipitants can occur as a result of either type of cooling.

Let us first examine the icing condition studied by Birnie and Meyer—freezing precipitation in conjunction with convection cooling. We consider first the heat transfer behavior of the approach roadway. Heat can be lost from the upper surface to the adjacent air by the mechanism of convection, which is strongly dependent on surface winds that provide the movement of cooler air across the pavement. At the same time, heat is supplied to the pavement from below by conduction of heat from the warmer ground beneath the roadway. The net rate of temperature change, therefore, is dependent on the 2 heat-transfer rates.

A bridge, however, is not endowed with a heat source underneath. In fact, during a period involving cold winds, the bridge may lose heat by convection from both upper and lower surfaces. Thus, during a period of decreasing air temperatures, the bridge temperature is likely to be lower than the adjacent road temperature but warmer than the air temperature. If this occurs in conjunction with, or is followed by, a period of freezing rain, drizzle, sleet, or fog, quite likely the bridge will become icy whereas the approach roadway will only become wet. The temperature differential between bridge and approach roadway can be even greater if the neighboring terrain is such to enable higher wind velocities over the bridge; this is often the case because the bridge is elevated and thus less influenced by the earth's surface boundary layer.

The mechanism of bridge frosting is somewhat different and, in many locales, more prevalent than the phenomena just discussed. It requires the bridge deck temperature to be lower than the dew point temperature of the local atmosphere, which, in turn, is normally lower than the air temperature. In practice, a very high local relative humidity is also required—a common occurrence near rivers and other bodies of water. Under these conditions, the moisture in the air, when it comes in contact with the colder surface, will condense. If the deck temperature also happens to be below the freezing point, the condensation will be in the form of ice crystals.

The bridge deck-air temperature differential is occasioned by heat loss due to radiation. This generally occurs at night under clear skies when radiation can occur to the essentially absolute zero temperature of outer space. In this situation the bridge will tend to gain heat by convection from the warmer air, again depending on wind speeds. Here, then, a very calm atmosphere (lack of wind) will lead to lower deck temperatures. The approach roadway also radiates in the same fashion but is aided, again, by the warmer ground below.

The choice of surface film coefficients used by Birnie and Meyer, both for the analytical work as well as the chamber experiments, is therefore primarily dependent on wind speed when convection is being considered. Radiation heat losses, on the other hand, cannot be expressed in terms of a surface film coefficient. Thus their analytical model should not be expected to yield realistic, nonempirical results. Likewise, some difficulty might be experienced with the laboratory experiments because the simulation of winds may be a problem and the simulation of the radiation heat losses may be nearly impossible.

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The authors appreciate the comments made by Glauz and Blackburn. These are all valid and had been given some consideration although not specifically referred to in the paper.

The significance of the subgrade as a source of heat to the roadway is recognized. It is believed that this will be especially significant during the fall months when the average daily temperature is falling. Originally it was not planned to measure temperatures below the 7.5-in. level in the bridge approachway. However, at the time of thermocouple installation a probe was placed at a depth of 2 ft in order to monitor the subgrade temperature.

The possibility of frost formation as a source of slipperiness on the bridge was one of the major factors in the choice of the test site. The stream flowing under the bridge stays relatively warm all year because of the location of a power station about 2 miles upstream. We felt that this would furnish ideal conditions for frosting. However, the observations for one winter, which admittedly are limited, have not indicated any preferential frosting. On several occasions at very low air temperature, warm moist air was observed rising from the stream and forming hoar frost on surrounding vegetation and fences but not on the bridge deck. Furthermore, studies in the laboratory indicate that frost on a surface is not necessarily slippery unless it is quite heavy. Frost was allowed to form on the test slab by creating a supersaturated atmosphere and allowing it to condense. The slipperiness of the surface was then checked using a hand skid tester. Very little change in skid resistance was noted over that of a set surface. Apparently the surface disparities are great enough to nullify any effects of the frost when the layer is thin. More precise tests should be run to establish the correlation between frost layer thickness and skid resistance.

The net exchange of radiant energy between road surface and sky is important. Preliminary field data indicate that the surface emissivity has a major effect on the surface temperature. As expected this is most notable on clear days and nights. The radiant energy effect was also noted during laboratory tests when a strong light was used for illumination when taking pictures. It was noted that the ice in the region struck by the light rapidly melted. In developing the computer simulation, we included a term for radiant energy in the surface equations. At the time this paper was written, values had not been assigned to this parameter because we were uncertain as to what magnitude could be considered as reasonable. Consideration is also being given to placing instrumentation at the test site for measuring the net radiation exchange.