DEVELOPMENT OF AN EXPERT SYSTEM FOR FORECASTING FROST ON BRIDGES AND ROADWAYS IN IOWA

Final Report
Highway Research Advisory Board
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Highway Division
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DEVELOPMENT OF AN EXPERT SYSTEM FOR FORECASTING FROST ON BRIDGES AND ROADWAYS IN IOWA

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Final Report

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ABSTRACT

An expert system has been developed that provides 20-hour forecasts of roadway and bridge frost for locations in Iowa. The system is based on analysis of frost observations taken by highway maintenance personnel, analysis of conditions leading to frost as obtained from meteorologists with experience in forecasting bridge and roadway frost, and from fundamental physical principles of frost processes. The expert system requires the forecaster to enter information on recent maximum and minimum temperatures and forecasts of maximum and minimum air temperatures, dew-point temperatures, precipitation, cloudiness, and wind speed.

The system has been used operationally for the last two frost seasons by Freese-Notis Associates, who have been under contract with the Iowa DOT to supply frost forecasts. The operational meteorologists give the system their strong endorsement. They always consult the system before making a frost forecast unless conditions clearly indicate frost is not likely. In operational use, the system is run several times with different input values to test the sensitivity of frost formation on a particular day to various meteorological parameters. The users comment that the system helps them to consider all the factors relevant to frost formation and is regarded as an office companion for making frost forecasts.

I. Introduction

Under this research project we have done an in-depth study of the characteristics of frost and frost formation on roads and bridges in Iowa. We have used these frost formation characteristics as the basis for the development of an expert system for forecasting frost on bridges and roadways. The resulting expert system was tested in its initial version during the winter of 1989-90 by Freese-Notis Associates during their period of contract with the IDOT for frost forecasts. Results of the first year of operational use and additional data on frost formation led to a revised version that was used operationally by Freese-Notis during the winter of 1990-91. During this same winter season, the system was used independently by an Iowa State University meteorology faculty member on an episodic basis to provide an independent evaluation of the system performance during particularly difficult cases.

Reports of the results of this project have been made through oral presentations at the following conferences:

a) **Sixth International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology**, Anaheim California, February 1990.

b) **Fourth Workshop on Artificial Intelligence Research in Environmental Sciences,** Montreal, Canada, 24-27 September 1990

Written reports on project results have been published as follows:

a) Takle, E. S., and S. T. Hansen, Jr., 1990: Development and validation of an expert system for forecasting frost on bridges and roadways. **Preprints, Sixth International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology.** American Meteorological Society. 197-200.

b) Takle, E. S., 1990: Bridge and roadway frost: Occurrence and prediction by use of an expert system. **Journal of Applied Meteorology,** 29, 727-734.

c) Takle, E. S., 1990: An expert system for forecasting frost on bridges and roadways: Operational experience. **Abstracts of the Fourth AIRIES Workshop.** Montreal Canada.

Copies of these three reports are attached as the Appendix to this final report. In addition, the detailed summary of results of the survey of IDOT maintenance workers entitled "Bridge and Roadway Frost Survey" (June, 1988; 44 pages) was submitted to the IDOT as an appendix to the progress report in June 1988. The body of this final report will provide only an overview of project activities and results, and more details can be found in the reports in the appendix and the previously submitted survey summary.

II. Frost occurrences

Frost generally is more prevalent in the northwestern part of the state and least likely in the southeast. Sioux City, in the Missouri River Valley, reports by far the largest annual number of frost occurrences (58 on average) having 3 to 4 times as many occurrences as cities in southeastern Iowa. Scattered frost occurs about twice as frequently as widespread frost. The interannual variability of scattered frost also is about twice that of widespread frost. Maps of bridge and roadway frost occurrence over the state of Iowa are given in Figures 2 and 3 in the Appendix.

III. Development of the expert system

The characteristics of frost occurrence as determined from IDOT records, together with a survey of frost observations by IDOT maintenance workers and the frost forecasting experience of meteorologists were used as the basis for developing a set of rules and conditions for forecasting frost by means of an expert system, which is a form of artificial intelligence. A guiding principle in the development of the expert system was that it had to be practical and provide a forecast that conformed to the IDOT requirements placed on the consulting firm under contract with IDOT to supply frost forecasts. To be practical, the system could not use information not routinely or readily available to forecasters. For instance, soil temperatures would be quite valuable in determining potential for frost formation, but these are not readily available to forecasters on a timely basis. Furthermore, the IDOT requires that forecasts be made for its maintenance districts and not for specific locations, so if there is one occurrence of frost somewhere in the district, it is considered to be a frost event for the district.

The resulting expert system required the forecaster to enter information about recent maximum and minimum temperatures and forecasts of cloudiness, maximum and minimum temperatures, dewpoints, precipitation, and wind speed. Specific system inputs are listed in Table 7 of Appendix A.

IV. Operational results

The winter of 1989-90 provided the first opportunity to test the system in an operational setting. The system was installed on a computer at Freese-Notis Associates in Des Moines, and staff meteorologists were instructed in its use. The system was quickly adapted into the frost forecasting routine and became part of the frost forecasting procedure.

The system was used every day that a possibility of frost existed. Freese-Notis meteorologists reported that the system was overpredicting frost in the early part of the season, particularly November and December. This was not unexpected, because the system had been developed based primarily on frost occurrences from December, January and February, and early season residual bridge and roadway heat was not appropriately accounted for.

Changes to accommodate early season resistance to frost and cosmetic changes to streamline the system were made in preparation for the 1990-91 frost season. During this winter season, the system was again used by Freese-Notis Associates, but also was used on an episodic basis by an Iowa State University faculty member for the purpose of obtaining an independent evaluation of the system.

The operational meteorologists reported that the overprediction of frost in the early season seems to have been eliminated in the current version, although there were not as many marginal cases in the most recent winter to adequately test the changes. Another observation reported by the operational forecasters was that there seems to be excessive emphasis placed on the occurrence of southerly winds in prediction of frost. This change is easily made and can be done more accurately now with the enlarged data base.

The forecast meteorologists also raised a concern about the verification data. There are some maintenance residencies that almost never report frost even though nearby locations report frost very frequently. In cases when scattered frost is occurring, there will very likely be some frost-prone areas, but under cases of widespread frost all residencies would likely be reporting occurrences. It is the absence of frost observations under the latter conditions at some locations that leads the forecasters to conclude that there are differences in frost observing procedures at different residencies.

In spite of the minor inadequacies of the 1990-91 version of the expert system, the operational forecasters give the system their strong endorsement. They state that they never make a frost forecast in marginal situations without consulting the expert system. Two or three individual cases are usually run with different input values to test the sensitivity of frost formation to cloudiness, dew-point temperature, or minimum temperature. These "what if" tests help the forecasters to identify the most sensitive parameters for that particular day and to focus their attention of these high-priority items. They treat the system like any other forecast tool in that they use information from it in combination with other data and model results to come up with their final forecast.

The forecasters commented that the usefulness of the expert system goes beyond the answer (frost or no frost) that it gives; the questions that the system asks the forecaster causes the forecaster to consider in a systematic manner all parameters relevant to frost formation. This helps to organize the forecaster's approach to the frost forecast and ensures that all pertinent factors are considered. For example, in the early part of the frost season, the system asks for information about heat retention by the bridges but in the middle or latter part of the season this question is not asked.

Another advantage of the expert system as reported by the operational forecasters is that on weekends when the office is operating under a reduced staff, the meteorologist on duty treats the system as a colleague with whom he can test several ideas. Under such conditions the forecasters typically makes several runs with the system as a substitute for having another human forecaster for dialogue.

The Iowa State University faculty meteorologist that used the system on an episodic basis focused his attention on those situations when the system failed to forecast frost when frost actually occurred. He found that half of the missed frost forecasts were a result of the expert system missing the dew-point temperature by less than $1^{o}F$. For the frost events of 1990-91, a simple shift of the bias by $1^{o}F$ would significantly increase the "hit rate" without significantly increasing the "false alarm" rate. The ISU meteorologist observed that the hit rate for roadway frost was lower than for bridge frost but that the false alarm rate also was very low. This suggests that raising the threshold criterion for roadway frost also would improve the system performance. The ISU meteorologist also recommended that the role of fog formation in conjunction with frost formation be clarified. Under different conditions of when it develops, fog may either enhance or suppress frost formation. An additional rule clarifying the role of fog could lead to improved system performance under these condition.

An additional test performed by the ISU meteorologist was designed to evaluate the use of the overnight minimum temperature in place of the 7 AM temperature presently used by the system. For the 1990-91 frost season, this simple change significantly reduced overprediction of frost under conditions when the nighttime minimum temperature occurred well before sunrise. This change is easily made in the system and will be incorporated in the final version.

V. Summary and Conclusions

We have studied the physical and meteorological conditions under which frost forms on bridges and roadways in Iowa. We have used this information to develop an expert system to aid a forecaster in determining the likelihood of frost formation on bridges and roadways in Iowa. The system is considered to be a valued companion by operational forecasters for several reasons which we have listed above. They report that they definitely will use the system for assisting in frost forecasts during the next frost season. We intend to make modifications recommended by both the operational forecasters and the ISU meteorologist and deliver a final version to Freese-Notis Associates in advance of the 1991-92 frost season.

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Bridge and Roadway Frost: Occurrence and Prediction by Use of an Expert System

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ABSTRACT

A survey of the characteristics of frost occurrences on bridges and roadways derived from questionnaires completed by highway maintenance personnel and analysis of more than 4000 frost observations in Iowa reveal that bridge frost occurs up to 58 times annually in certain parts of the state and, roadway frost, as many as 35 times. Certain bridges or stretches of road seem frost-prone because of their location or because of adjacent features. An expert system designed to provide 20-h forecasts of roadway and bridge frost has been constructed from analysis of meteorological conditions and has been evaluated against human forecasters. The expert system, when supplied with perfect forecasts of commonly forecast meteorological variables, produced accuracy comparable to or higher than human forecasters. Human forecasters were observed to provide relatively unbiased forecasts for bridge frost but were highly biased toward reducing false alarms for roadway frost. The expert system, by contrast, is configured so that the decision threshold can be adjusted to give unbiased forecasts or forecasts that are biased in either direction without significant degradation of accuracy. A suggestion is made for the use of such a system as a management tool for separating forecast accuracy from (possibly nonmeteorological) decision-threshold criteria.

1. Introduction

Every winter, frost formation on bridges and roadways leads to considerable damage to vehicles, structures, and trees as well as occasional injury and loss of life due to motor vehicles going out of control on slippery surfaces. Materials and manpower for frost treatment on roads and bridges represent a significant expense to taxpayers. Highway maintenance agencies, in an attempt to increase the safety of highway travel within the constraints of annually budgeted funds, require more extensive information on the characteristics of frost formation. Some state, county, or city highway maintenance organizations contract for forecasts of frost to take preventive action or reduce the response time.

Frost occurrences on roads and bridges are not recorded by the National Weather Service, so there is no generally available climatology to be used as a statistical reference for forecasting. This brief note presents some results of a survey of the state highway department frost observing team and a limited climatology of frost occurrences in Iowa. A summary of some key factors in frost formation is presented, and some preliminary results are given from an expert system created for forecasting bridge and roadway frost.

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2. Frost occurrence and frost observations

Three conditions must exist for significant amounts of frost to accumulate on a surface

1. The surface temperature must be below freezing.
2. The surface temperature must be below the dewpoint temperature.
3. The dewpoint temperature must be near (even above) freezing or else well above the surface temperature for a significant period of time.

The first condition separates dew from frost, and the second guarantees supersaturation in the air just above the surface. The third condition ensures that either the deposition rate is high or the deposition period is long enough that frost accumulation will be sufficient to be hazardous to vehicular travel.

Frost on roads and bridges is not a routine observation of the National Weather Service or any agency except highway maintenance organizations. The highway maintenance-personnel in charge of observing and reporting frost generally have no formal training in meteorology to acquaint them with the process of frost formation and the differences between frost and other forms of ice-related meteorological processes. Nevertheless, because roadway maintenance personnel have been asked to observe and treat roadway and bridge frost for several years, they probably have a better sense of the commonalities and peculiarities of frost formation than most meteorologists.

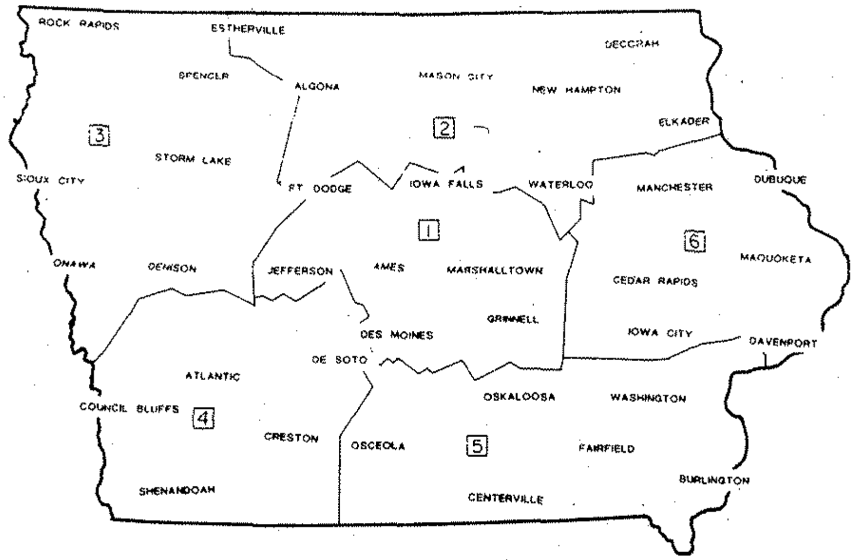


FIG. 1. Locations of Iowa Department of Transportation six maintenance districts (identified by number in squares) and cities for which road and weather conditions are reported.

3. Frost survey

In fall 1987, a questionnaire was developed by the author in consultation with Mr. Don East, Assistant Maintenance Engineer of the Iowa Department of Transportation (IDOT). The questionnaire was sent out by the IDOT to each of its maintenance garages in the state of Iowa. In Fig. 1 are shown the locations of the six maintenance districts and 37 cities in Iowa for which road and weather conditions are reported. All 125 surveys sent out were completed and returned. Our objective in the survey was to capture the practical knowledge of experienced frost observers to better understand frost formation as a possible aid in forecasting its occurrence.

a. Bridge frost

Maintenance personnel were asked whether there is one particular bridge in their area that is likely to be the first one (maybe the only one) to frost in the early morning. Sixty-three percent of the responses indicated that, indeed, there was a particular bridge more likely to be the first to frost. The responses to this question are summarized by district in Table 1. Observers in central and north-central Iowa (Districts 1 and 2) report a greater likelihood of a particular bridge being the first to frost, but those in western and southern Iowa (Districts 3 and 5) are more evenly divided on the question.

When asked to describe the characteristics of frost-prone bridges, respondents indicated that most such bridges span rivers or streams (43%) or railroad tracks (30%), with the remainder spanning roadways, and low-lying or other areas. The IDOT maintains more than 3000 bridges across the state, of which 79% cross waterways, 10% span roadways, 5% cross railroads, with the remaining 6% crossing other features. Therefore, the percentage of frost-prone bridges that span waterways is only about half of the percentage of total bridges that span waterways, and the percentage of frost-prone bridges that cross railroad tracks is six times the percentage of total bridges spanning railroad tracks. From the data reported by respondents, frost-prone bridges over waterways are about three times as long and 10% higher than frost-prone bridges over railroad tracks. We have no explanation for the unexpectedly high occurrence of frost on bridges spanning railroad tracks.

Sixty percent of the frost-prone bridges were of concrete construction, and 40% were steel. Of the total number of bridges in the state, 63% are concrete and 37% steel, so there seems to be no foundation for predicting frost on the basis of bridge construction type.

b. Roadway frost

Respondents were asked to indicate if, under conditions when roadways develop frost, there is a partic-

TABLE 1. Is there one particular bridge that is likely to be the first one (maybe even the only one) to frost in the early morning in your area?

District	Yes	No	No response
1	16	3	0
2	14	6	1
3	14	11	0
4	13	9	0
5	11	10	0
6	11	6	0
Total	79 (63%)	45 (36%)	1 (1%)

TABLE 2. When roadways frost, is there a particular stretch of road that seems likely to frost first?

District	Yes	No	No response
1	9	10	0
2	13	8	0
3	16	9	0
4	10	12	0
5	8	13	0
6	7	8	2
Total	63 (50%)	60 (48%)	2 (2%)

ular stretch of road that is most likely to frost first. For the total survey sample as shown in Table 2, observers were almost evenly divided on this question. However, Districts 2 and 3 reported "yes" by nearly a 2-to-1 margin, whereas District 5 and, to a lesser extent, District 4 reported a predominance of "no." This suggests that the northwestern part of the state, having generally colder surface temperatures and more frost occurrences, also may have stretches of roadway that are more consistently subject to frost. The southeastern part, by contrast, has higher surface temperatures, in general, and fewer total incidents of frost, which may contribute to the absence of portions of roadways that are consistently frost prone.

When asked to give any particular conditions about the stretch of roadway most likely to frost, respondents indicated by a wide margin that the stretch was sheltered or shaded (Table 3). In retrospect, the mention of this example in the survey question may have biased some observers toward reporting this answer. Several respondents did, however, add comments on the effect of sheltering in their areas. Some observers hold the idea that there are differences in the occurrence of frost over asphalt and concrete, but there is no consensus on which is more frost prone. More data on this are presented later. A variety of other reasons for a particular stretch being frost prone are given in Table 3.

Table 4 gives the responses to whether a roadway is less likely to frost the morning after a day when chemical treatment for frost was applied. A majority of observers in all districts reported "no" to this question, with District 6 having the widest margin. This suggests that the residual effect of previous frost treatment is minimally effective in suppressing a subsequent occurrence of frost.

An even wider margin of responses indicates that traffic volume does little to suppress frost formation, as shown in Table 5. This suggests that neither the crushing of ice crystal structures by compaction nor the heat from vehicle engines, exhaust, and tire contact are sufficient to alter frost formation. Kinosita and Akitaya (1970) report that the temperature of the rear (presumably the traction wheels) tires of a vehicle may be 6° to 27°C higher than the air temperature, depending on surface snow or ice condition and vehicle speed. From the survey, however, we conclude that normal vehicular traffic does not transfer a significant amount of this heat to the roadway to suppress frost formation.

Table 6 summarizes the responses to the question of whether asphalt or concrete might be more subject to frost formation. Also listed is the total number of lane miles of asphalt and concrete by district. This question drew a very mixed response with asphalt being observed to frost more frequently by 43 observers, concrete by 48, and 30 reported no difference. There seems to be the largest difference of opinion among districts on this question: In Districts 2 and 3, concrete seems to frost most often by a wide margin, whereas in Districts 4 and 5, asphalt roads seem to frost more frequently. Districts 1 and 6 are evenly divided. The latter two districts are centrally located in the north–south direction within the state and also have about half of their lane miles consisting of each surface type. The other four districts have about 60% asphalt roads. The northern districts, 2 and 3, report concrete more likely to frost even though their roadways are predominantly asphalt. In the southern part of the state, asphalt predominates both in lane miles and frost occurrence. It is tempting to speculate that concrete frosts more readily than asphalt under generally colder conditions. However, controlled physical tests would be much more conclusive than an opinion survey on this issue.

An overwhelming majority (89%) of the observers reports that age of the roadway has no bearing on whether or not it is more or less likely to frost.

TABLE 3. Compared with other roadways, is there anything peculiar about this section of roadway that would make it prone to frost (e.g., sheltered area)?

District	Asphalt	Concrete	Seal coat	Hilly	Sheltered/ shaded	Low-lying	River/ lake	Foam	Other
1	3	2	0	2	7	1	1	0	1
2	0	3	1	0	8	0	0	2	1
3	0	4	2	1	9	0	1	2	0
4	0	0	0	0	10	0	0	0	1
5	5	0	0	0	7	1	1	0	1
6	1	2	0	0	3	2	0	0	1
Total	9	11	3	3	44	4	3	4	5

TABLE 4. Is a treated roadway less likely to frost the next morning?

District	Yes	No	No response	No. of responses
1	8	9	2	19
2	8	12	1	21
3	10	14	1	25
4	5	16	1	22
5	8	13	—	21
6	4	12	1	17
Total	43	76	6	125

4. Frost climatology

The author is not aware of any published long-term observations of roadway or bridge frost. Observations systematically reported and filed by the Iowa Department of Transportation provide data for at least a limited climatology of such events for Iowa.

Data from mid-October through mid-April have been analyzed for the winters of 1985–86, 1986–87, 1987–88, and 1988–89. These data consist of observations made Monday through Friday except holidays in the vicinity of the cities shown in Fig. 1. For the period studied, there were 2608 observations of bridge frost and 1615 observations of roadway frost. Frost was reported as either "scattered" or "widespread" and was recorded as such for both bridges and roadways. Observations of both scattered and widespread frost have been totaled for the four seasons and then amplified by a factor equal to the total number of days in the frost season divided by the number of days observations were actually made; finally the result is divided by 4. This procedure approximately compensates for the lack of observations on weekends and holidays and therefore represents the estimated average number of occurrences of frost per frost season.

In Fig. 2 are shown contour plots of data for bridges. Frost generally is more prevalent in the northwestern part of the state and least likely in the southeast. Sioux City, in the Missouri River Valley, reports by far the largest number of frost occurrences (58), having 3 to 4 times as many occurrences as cities in southeastern Iowa.

Scattered frost occurs about twice as frequently as widespread frost. The interannual variability of scattered frost also is about twice that of widespread frost, with the ratios of standard deviation to mean being 0.30 and 0.16, respectively.

We have compared Fig. 2 with a map of Iowa showing the number of state-maintained bridges in each of the 99 counties (which are reasonably uniform in area). Counties having the highest number of bridges include Pottawattamie (212), Polk (212), Lynn (130), Scott ([illegible]0), Woodbury (95) and Blackhawk (86). These counties, respectively, include the cities of Council Bluffs, Des Moines, Cedar Rapids, Davenport, Sioux City, and Waterloo. Although Sioux City, having the highest frequency of bridge frost reports (Fig. 2), is among the residencies having a large number of bridges, there are other residencies of much higher bridge density, (e.g., Davenport) with much lower frost frequency. We conclude that the number density of bridges is not a dominant factor in determining the frost pattern of Fig. 2.

Comparable frost-frequency data for roadways are shown in Fig. 3. The overall pattern is similar to that for bridges, with frequency of occurrence increasing from southeast to northwest. Sioux City reported the state-maximum annual average of 35 events per year. As with bridges, scattered frost occurs on roadways about twice as often as widespread frost. The interannual variability, however, is comparable for both (ratios of standard deviation to mean being 0.28 and 0.34 for scattered and widespread, respectively) and compares with interannual variability of scattered frost on bridges.

Widespread roadway frost usually occurs as a result of moist advection over a cold roadway. Bridges, on the other hand, will more frequently develop widespread frost because of radiational cooling. The difference in interannual variability of widespread frost on bridges versus roadways may be due to more interannual variability in advection-induced frost compared with radiation-induced frost. A more detailed study of synoptic events is required to confirm this.

Frost occurrences are greatest in December and January, although there is a very slight tendency for roadway frost occurrences to peak slightly later in the season than bridge frost. A thoroughly cooled roadbed is a more likely candidate for frost under warm, moist advection.

The 30-year mean 0600 LST relative humidity for Des Moines for December, January, and February (peak frost months) are 79%; 75%; 77%, respectively. For the four-year period used in this study the average relative humidity values were 82%, 78%, and 80%, respectively, suggesting the period had a uniform 3% higher relative humidity than the long-term average. Mean monthly temperatures for this period were, on average, near normal for December and February but 4.3°C higher than normal for January. Both a higher January mean temperature and above-normal relative

TABLE 5. Does the volume of traffic affect the formation of frost?

District	Yes	No	No response	No. of responses
1	6	12	1	19
2	5	16	—	21
3	9	16	—	25
4	7	15	—	22
5	5	15	1	21
6	4	12	1	17
Total	36	86	3	125

TABLE 6. Road surface that frosts most frequently.

District	Asphalt	Concrete	No diff.	No response	No. of responses	Total lane miles Concrete	Total lane miles Asphalt
1	7	8	4	—	19	2231	2013
2	3	15	3	—	21	1512	2512
3	3	17	5	—	25	1556	2611
4	10	0	11	1	22	1725	2312
5	15	2	4	—	21	1568	2475
6	5	6	3	3	17	2127	2194
Total	43	48	30	4	125	10719	14117

humidity suggest the frost climatology herein reported may be slightly biased toward more occurrences when compared to the long-term average.

5. Prediction by use of an expert system

The conditions for significant accumulation of frost on bridges and roadways are quite specific and closely related to, but not identical with, routinely forecast meteorological variables. The success of forecasting frost on bridges and roadways is dependent on accumulated expertise not a part of conventional meteorological instruction programs. These facts suggest that this type of frost forecasting might be a suitable candidate for developing an expert system.

Under the sponsorship of the IDOT, we have developed such a system and have evaluated its *potential* performance. The system uses the Texas Instruments expert system shell PC+,[1] which is a backward-chaining system. The present system has 32 parameters and variables and 33 rules that use the three data items and seven forecast variables listed in Table 7.

As now configured, the system requires the forecaster to supply the items under category b of Table 7, but some or all of these could be supplied by numerical models, other expert systems, or add-on frames within the present system. Development of the system to the present state allows us to evaluate its potential accuracy, given perfect forecasts of the items in category b of Table 7. In an operational setting, the performance of the expert system will degrade in proportion to the errors incurred in forecasting the items in category b of Table 7.

From December, January, and February of the four frost seasons from 1985–89, we found a total of 247 days for which roadway and bridge frost data were available for the central district (District 1) of Iowa. We have used hourly observations from the Des Moines office of the National Weather Service, which is located at the southern edge of the central district, to provide data of Table 7 for each of these days for development of the expert system rules. The rules are used in combination to estimate the temperatures separately of the bridge and roadway, which are then compared with the forecast of dewpoint temperature.

Table 8 defines the terms used in the verification matrix. The original decision criterion was that frost would form if the estimated surface temperature was less than or equal to the dewpoint temperature. With the system configured in this manner, it is easy to change the decision criterion and examine the influence on hit rate and false alarm rate. By increasing the temperature threshold by 1°C, we are saying that frost will form somewhere in the district even if the surface temperature at the reference location is 1°C higher than the dewpoint temperature. In Fig. 4 are plotted the hit and false alarm rates for bridges and roadways as a function of threshold temperature. The general trend is for both hit and false alarm rates to rise as bias increases.

Mason (1982a) has proposed that signal detection theory (SDT) provides a method for analysis of the verification matrix that allows for separating forecast accuracy from the decision criterion. The SDT technique, outlined by Green and Swets (1974) and Swets (1973, 1986, 1988) allows for computations of indices d' and β, which are, respectively, the accuracy and decision criterion placement as determined from the likelihood ratio. This technique has been applied to

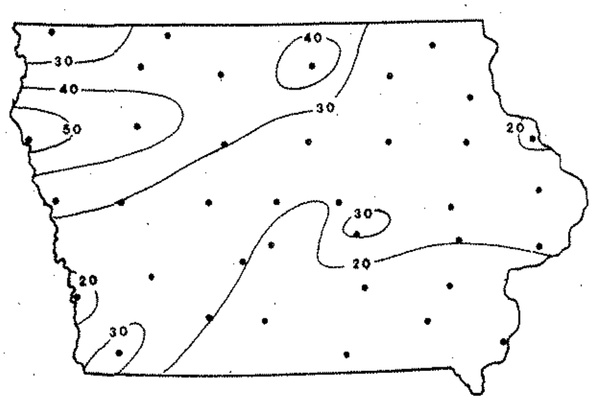


FIG. 2. Estimated number of total frost events per frost season for bridges.

[1] Mention of a particular commercially available product does not constitute endorsement of the product or the company by the author, Iowa State University or the IDOT.

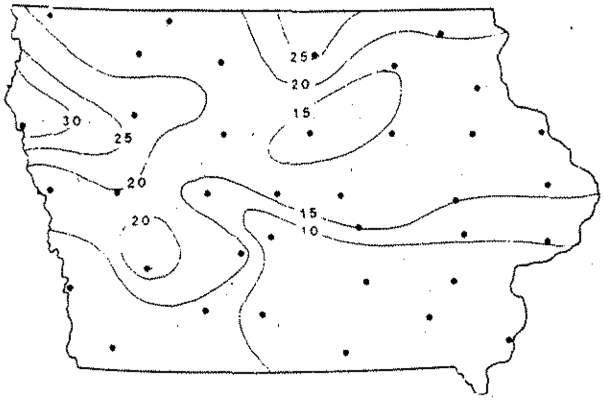


FIG. 3. Estimated number of total frost events per frost season for roadways.

TABLE 8. General verification matrix and definitions.

		Observed	
		No	Yes
Forecast	No	a	b
	Yes	c	d

Total number of events = $N = a + b + c + d$
Hit rate = $H = d/(b + d)$
False alarm rate = $F = c/(a + c)$
Miss rate = $M = b/(b + d)$
Correct nonoccurrence = $C' = a/(a + c)$
Sample relative frequency = $S = (b + d)/N$
Decision criterion = $x_c = P^{-1}(1 - F)$
Index of accuracy = $d' = x_c - P^{-1}(1 - H)$
Criterion placement = $\beta = \exp\{-0.5[d'(d' - 2x_c)]\}$
P^{-1} = inverse of normal probability distribution function

forecasts of a variety of weather variables (Mason 1982b; McCoy 1986).

The index of accuracy, d', is the number of standard deviations separating the means of the (assumed normal) distributions of decision variables preceding occurrence and preceding nonoccurrence. Thus, $d' = 0$ indicates no skill because the probabilities of hit and false alarm rate are equal. The β value is the likelihood ratio that the given data suggest occurrence over nonoccurrence. The criterion placement is considered unbiased if $\beta = 1$, biased toward maintaining a low false alarm rate at the expense of a lower hit rate if $\beta > 1$, and biased toward maintaining a high hit rate at the expense of a higher false alarm rate if $\beta < 1$.

Bridge values taken from Fig. 4 are plotted on the SDT relative operating characteristics (ROC) curve generated from Gaussian distributions (Mason 1982a; Swets 1986) as shown in Fig. 5. The range of threshold temperatures used does not span the entire range of hit and false alarms, but the limit cases must tend toward the points (0, 0) and (1, 1) in Fig. 5. By using these limits and the data points plotted we estimate by eye that the data define a constant d' of about 1.4. A comparable plot for roadways is shown in Fig. 6, where we estimate d' to be about 1.25.

TABLE 7. Information to be entered into the expert system.

a) *Data*
Minimum temperature yesterday
Maximum temperature yesterday
Minimum temperature this morning

b) *Forecasts*
Cl[illegible]er from sunset tonight to midnight tonight
Cl[illegible]ver from midnight tonight to sunrise tomorrow
Maximum temperature today
Min[illegible]um temperature tomorrow morning
[illegible]int temperature at 6 A.M. tomorrow
[illegible]tation from 9 P.M. tonight to 6 A.M. tomorrow (yes/
[illegible]
[illegible]ge wind speed and wind direction from midnight to 6 [illegible]. tomorrow

Some of the scatter about the constant d' lines likely would be reduced if more data were available. However, even with very large datasets, it is reasonable to expect that some systematic departures from constant accuracy (d') will exist in certain ranges of β, indicating that the system is more accurate for some ranges of bias than for others.

The accuracy of the system also is degraded because the input data from Table 7 refer to a fixed location (Des Moines), whereas the verification (as few as a single observation) may occur anywhere in the maintenance district. A smaller verification area or (in the limit) colocation of input data and verification would improve system accuracy.

For our original configuration (bias temperature = 0° Celsius), we calculate an accuracy value of 1.53 and a bias (2.32) toward minimizing false alarms. For roadways, the corresponding numbers are $d' = 1.33$ and $\beta = 1.90$, which suggests somewhat lower accuracy and a weaker bias toward minimizing false alarms than for bridges.

Another measure of accuracy, as suggested by Swets (1988), is the area under the ROC curve. If this area is A and if the expert system is presented a pair of randomly sampled weather conditions on successive trials—always having one condition leading to frost and the other not—the expert system can correctly distinguish between them A% of the time. Integration of the area under the data points given in Fig. 5 for bridges yields $A = 0.83$, and from Fig. 6 for roadways, $A = 0.81$. Swets considers A values below 0.70 to suggest insufficient accuracy for much practical value, and values between 0.70 and 0.9 to be useful for some purposes. By this criterion, the expert system potentially has practical value. Swets used ROC data published by Mason (1982b) to compute A values from 0.71 to 0.89 for forecasts of various meteorological variables. Even though the A value of forecasts made with our expert system will be reduced by uncertainty in the input, it has the potential to be of comparable skill compared with other forecast procedures.

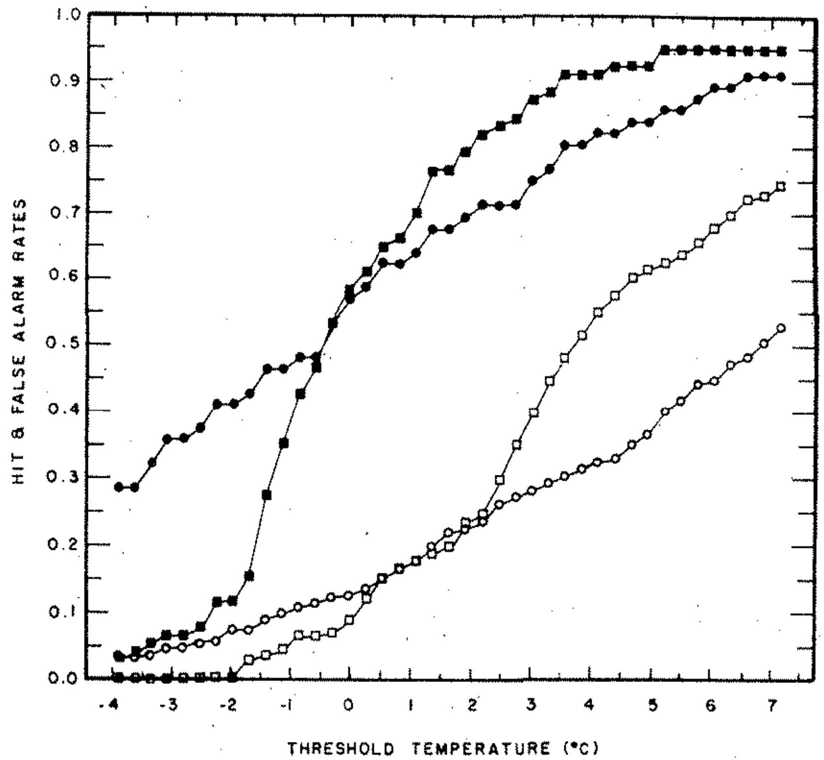
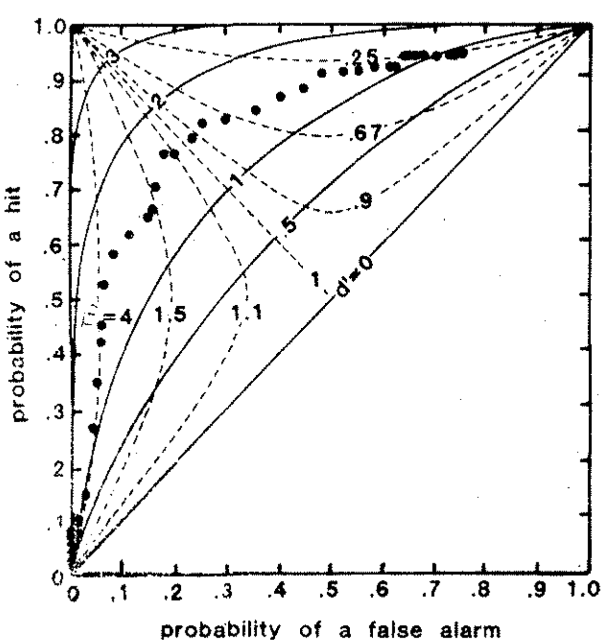


FIG. 4. Hit rate and false alarm rate for bridges and roadways for various values of expert system threshold temperature. Squares represent bridges and circles represent roadways, solid symbols represent hits, open symbols represent false alarms.



Values of criterion placement (β) and accuracy (d') for
ons of hit and false alarm rates taken from Fig. 4 for bridges.

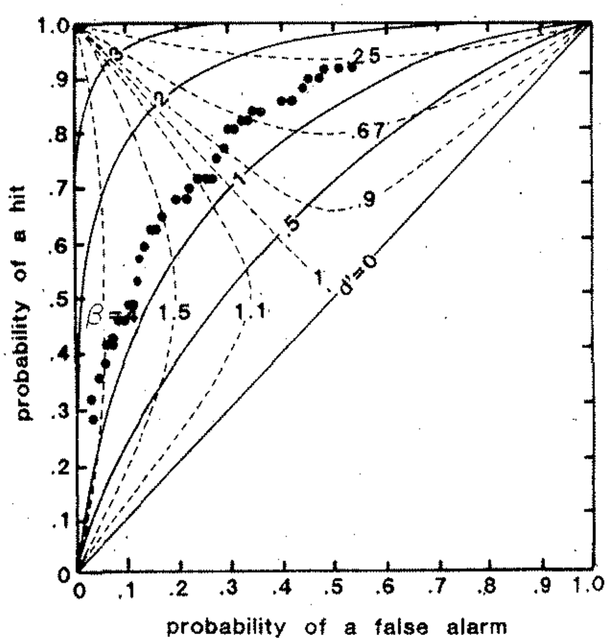


FIG. 6. Values of criterion placement (β) and accuracy (d') for combinations of hit and false alarm rates taken from Fig. 4 for roadways.

This procedure for configuring the expert system and evaluation by means of SDT has management implications in that decision criteria based on nonmeteorological considerations may be used to determine the optimum combination of hit rate and false alarm rate, with the attendant accuracy being given by the SDT curve. As an example, the consequences of a lawsuit arising from an accident on an untreated frosty bridge are greater, to a certain (management-determined) extent, than the consequences of sanding bridges when a false alarm is called. For the desired hit rate, the transportation manger can use the SDT plot to evaluate the expected false alarm rate and forecast accuracy and determine the bias (threshold temperature) of the expert system to optimize these three variables. Under the more general case in which decision criterion and accuracy are interrelated, the choice of system accuracy as well as decision criterion becomes a management choice. The expert system therefore allows management people to manage and forecasters to forecast, without excessive overlap.

6. Comparison with human forecasts

For December, January, and February of the 1986/87 and 1987/88 frost seasons, we found 69 days for which roadway and bridge data were available for both frost occurrences and frost forecasts by the private consulting meteorologists under contract with IDOT. We applied our expert system with zero threshold (as in Fig. 4) and with perfect forecasts of the items in Table 7b to these 69 days. The results (shown in Table 9) reveal that, for bridges, the forecaster and the expert system had comparable hit rates, but the expert system had a lower false alarm rate. This resulted in a higher accuracy (1.7 versus 1.2) for the expert system and a system bias (1.6) toward fewer false alarms, compared with a relatively unbiased (0.93) human. For roadways, the expert system had higher rates for both hits and false alarms but comparable accuracy compared with the human forecasts. The human forecasts of roadway frost were more highly biased toward reducing false alarms (2.1) than the expert system (1.4). We reemphasize that the performance of the system is at its potential best because we have used "perfect forecasts" of the variables in Table 7b.

TABLE 9. Comparison of forecast parameters produced by human forecasters with results from an expert system given perfect forecasts of items in Table 7.

	Bridges		Roadways	
	Human forecaster	Expert system	Human forecaster	Expert system
N	69	69	69	69
S	0.57	0.57	0.32	0.32
H	0.74	0.72	0.55	0.68
F	0.30	0.13	0.11	0.17
β	0.93	1.6	2.1	1.4
d'	1.2	1.7	1.4	1.4

7. Summary

This report gives a survey of the characteristics of frost occurrences on roadways and bridges in Iowa from the point of view of highway maintenance workers who routinely check for frost. A limited climatology of frost in Iowa based on data from four frost seasons is presented. These data show that the mean annual number of bridge frost occurrences ranges from about 12 to 58 and that the mean annual number of roadway frost events ranges from about 7 to 35 across the state of Iowa. Prediction of frost by use of an expert system is compared with predictions by human forecasters and is found to have the potential to be of comparable accuracy. A procedure is suggested for using an expert system as a tool by which management considerations can be used to establish the decision threshold criteria without adversely influencing accuracy if the system is properly configured. Under the more general case in which the decision criterion and accuracy are interrelated, the choice of system accuracy as well as the decision criterion becomes a management choice.

Acknowledgments. I acknowledge with much appreciation the assistance of Mr. Don East and the IDOT maintenance personnel for their assistance in providing the survey information, Ms. Sheri Mertz for tabulating the survey results and summarizing the data, Mr. Jeff Chapman for summarizing the frost occurrence and forecast information from IDOT records, and Mr. Stanley Hansen for the computer work including the development of the expert system. This research was funded by the Iowa Department of Transportation through the Iowa Highway Research Board research project HR-305. The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the Highway Division of the Iowa Department of Transportation.

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DEVELOPMENT AND VALIDATION OF AN EXPERT SYSTEM FOR *FORECASTING FROST ON BRIDGES AND ROADWAYS*

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1. INTRODUCTION

Frost formation on bridges and roadways during winter in cold climates leads to considerable damage to vehicles and structures as well as occasional injury and loss of life due to motor vehicles going out of control on slippery surfaces. Materials and manpower for frost treatment on roads and bridges represent a significant expense to taxpayers, and chemicals used for frost suppression can lead to unintended environmental consequences. Highway maintenance agencies, in an attempt to minimize chemical use and at the same time increase the safety of highway travel within the constraints of annually budgeted funds, require more precise information on the characteristics and timing of frost formation. Some state, county, or city highway maintenance organizations contract for forecasts of frost to more accurately target times and locations of occurrences and, hence, to formulate more efficient responses.

We have developed an expert system for forecasting frost formation on bridges and roadways for the central part of the State of Iowa. The system is based on rules derived from examination of meteorological conditions and Iowa Department of Transportation frost reports for central Iowa during a 4-year period and through discussions with professional forecasters with experience in forecasting bridge and roadway frost. An evaluation procedure adapted from signal detection theory is used to estimate the relative values of skill and decision criterion (i.e., bias) for the expert system. As we have it configured, our expert system has a tunable bias that can be independently established by management.

2. FROST OCCURRENCE AND OBSERVATIONS

Three conditions must exist for significant amounts of frost to accumulate on a surface

* the surface temperature must be below freezing
* the surface temperature must be below the dew-point temperature
* the dew-point temperature must be near (even above) freezing or else well above the surface temperature for a significant period of time.

The first condition separates dew from frost, and the second guarantees supersaturation in the air just above the surface. The third condition ensures that either the deposition rate is high or the deposition period is long enough that frost accumulation will be sufficient to affect vehicular travel.

In Iowa we can usually identify either advection or radiation as the primary cause of a frost event. Advection frost results from encroachment by air with water-vapor pressure exceeding the saturation vapor pressure corresponding to the temperature of the surface. Such events often are accompanied by cloudiness and sufficient wind to minimize orographic effects. These conditions, being of fairly large scale, are observable in the synoptic data and, therefore, are easier to forecast. Frost occurring because of radiant cooling of the surface is much more localized and, hence, more difficult to forecast.

For the past several years, the Iowa Department of Transportation (IDOT) has contracted with a private weather forecasting firm to provide yes/no forecasts of frost on bridges and roadways in each of six maintenance districts covering the state. Forecasts are required and observations made from mid-October through mid-April. Frost events usually occur near sunrise, so to allow sufficient preparation time, IDOT requires the frost forecast to be delivered before noon for the following morning (i.e., about an 18-hr forecast). If the forecast is "yes", trucks loaded with sand are deployed at 5:45 am to spread sand on bridges and to treat frost patches observed on roadways. Daily (Monday through Friday) reports by maintenance workers of frost observations were submitted to the state headquarters in Ames. There are 37 cities from which reports originate (i.e., about six per district). Although maintenance workers report frost as either "scattered" or "widespread," we consider either to qualify as a frost event. If there is a single observation of frost in a maintenance district, a "yes" forecast is considered a hit. Therefore, if frost had been forecast for both roads and bridges over the whole state and frost did cover the entire state, there would be 37 reports of bridge frost, 37 reports of roadway frost, and six hits each for bridges and roadways. Under current procedures IDOT does not receive forecasts of road frost. During the winter seasons of 1985-86, 1986-87, 1987-88, and 1988-89 there were 2608 observations of bridge frost and 1615 observations of roadway frost.

3. PREDICTION BY USE OF AN EXPERT SYSTEM

Under the sponsorship of the IDOT, we have developed an expert system that produces forecasts of frost separately for roads and bridges. The system uses the Texas Instruments expert system shell PC+[1], which is a backward-chaining system. The present system has 32 parameters and variables and 33 rules that use the 3 data items and 7 forecast variables listed in Table 1.

As presently configured, the system requires the forecaster to supply the items under category b of Table 1, but some or all of these could be supplied by numerical models, other expert systems, or add-on frames within the present system. Development of the system to the present state allows us to evaluate its potential accuracy, given perfect forecasts of the items in category b of Table 1. In an operational setting, the performance of the expert system will degrade in proportion to the errors incurred in forecasting the items in category b of Table 1.

Table 1. Information to be entered into the expert system

a) Data
- Minimum temperature yesterday
- Maximum temperature yesterday
- Minimum temperature this morning

b) Forecasts
- Cloud cover from sunset tonight to midnight tonight
- Cloud cover from midnight tonight to sunrise tomorrow
- Maximum temperature today
- Minimum temperature tomorrow morning
- Dew-point temperature at 6 a.m. tomorrow
- Precipitation from 9 p.m. tonight to 6 a.m. tomorrow (yes/no)
- Average wind speed and wind direction from midnight to 6 a.m. tomorrow

From December, January, and February of the four frost seasons from 1985-89, we found a total of 247 days for which roadway and bridge frost data were available for the central district (District 1) of Iowa. We have used hourly observations from the Des Moines office of the National Weather Service, which is located at the southern edge of the central district, to provide data of Table 1 for each of these days for development of the expert system rules. The rules are used in combination to estimate the temperatures separately of the bridge and roadway, which are then compared with the forecast of dew-point temperature.

Table 2 defines the terms used in the verification matrix. The original decision criterion was that frost would form if the estimated surface temperature was less than or equal to the dew-point temperature. With the system configured in this manner, it is easy to change the decision criterion and examine the influence on hit rate and false alarm rate. By increasing the temperature threshold by 1°F, we are saying that frost will form somewhere in the district even if the surface temperature at the reference location is 1°F higher than the dew-point temperature. In Fig. 1 are plotted the hit and false alarm rates for bridges and roadways as a function of threshold temperature. The general trend is for both hit and false alarm rates to rise as bias increases.

[1] Mention of a particular commercially available product does not constitute endorsement of the product or the company by the author or the IDOT.

Table 2. General verification matrix and definitions.

		Observed	
		No	Yes
Forecast	No	a	b
	Yes	c	d

total number of events = $N = a + b + c + d$

hit rate = $H = d/(b + d)$

false alarm rate = $F = c/(a + c)$

miss rate = $M = \frac{b}{b+d}$

correct nonoccurrence = $C = \frac{a}{a+c}$

sample relative frequency = $S = (b + d)/N$

decision criterion = $x_c = P^{-1}(1-F)$

index of accuracy = $d' = x_c - P^{-1}(1-H)$

criterion placement = $\beta =$

$\exp\{-0.5\,[d'(d' - 2x_c)]\}$

P^{-1} = inverse of normal probability distribution function.

Mason (1982a) has proposed that signal detection theory (SDT) provides a method for analysis of the verification matrix that allows for separating forecast accuracy from the decision criterion. The SDT technique, outlined by Green and Swets (1974) and Swets (1973, 1986, 1988) allows for computations of indices d' and β, which are, respectively, the accuracy and decision criterion placement as determined from the likelihood ratio. This technique has been applied to forecasts of a variety of weather variables (Mason, 1982b; McCoy, 1986).

The index of accuracy, d', is the number of standard deviations separating the means of the (assumed normal) distributions of decision variables preceding occurrence and preceding nonoccurrence. Thus, d' = 0 indicates no skill because the probabilities of hit and false alarm rate are equal. The β value is the likelihood ratio that the given data suggest occurrence over nonoccurrence. The criterion placement is considered unbiased if $\beta = 1$, biased toward maintaining a low false alarm rate at the expense of a lower hit rate if $\beta > 1$, and biased toward maintaining a high hit rate at the expense of a higher false alarm rate if $\beta < 1$.

Bridge values taken from Fig. 1 are plotted on the SDT relative operating characteristics (ROC) curve generated from Gaussian distributions (Mason, 1982a; Swets, 1986) as shown in Fig. 2. The range of threshold temperatures used does not span the entire range of hit and false alarms, but the limit cases must tend toward the points (0,0) and (1,1) in Fig. 2. By using these limits and the points plotted, we estimate by eye that the data define a d' of about 1.4. A comparable plot for roadways is shown in Fig. 3, where we estimate the d' to be about 1.25.

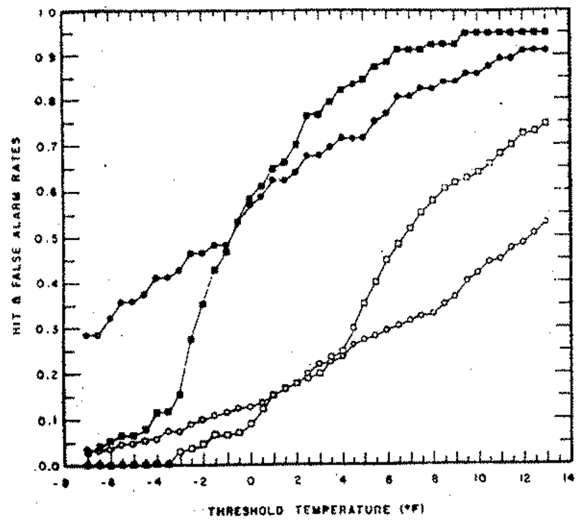

Fig. 1. Hit rate and false alarm rate for bridges and roadways for various values of expert system threshold (dew-point depression) temperature. Squares represent bridges and circles represent roadways; solid symbols represent hits, open symbols represent false alarms.

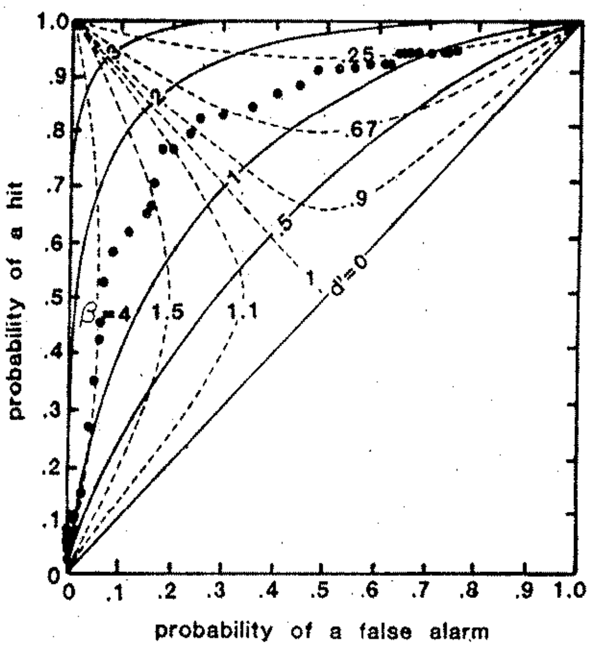

Fig. 2. Values of criterion placement (β) and accuracy (d') for combinations of hit and false alarm rates taken from Fig. 1 for bridges.

Some of the scatter about the constant d' lines likely would be reduced if more data were available. However, even with very large data sets, it is reasonable to expect that some systematic departures from constant accuracy (d') will exist in certain ranges of β, indicating that the system is more accurate for some ranges of bias than for others.

For our original configuration (bias temperature = 0 Fahrenheit degrees), we calculate an accuracy value of 1.53 and a bias (2.32) toward minimizing false alarms. For roadways, the corresponding numbers are d' = 1.33 and β = 1.90, which suggests somewhat lower accuracy and a weaker bias toward minimizing false alarms than for bridges.

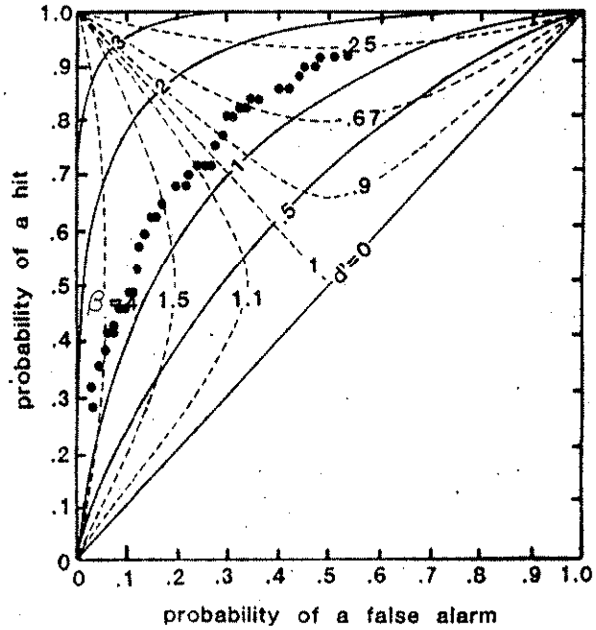

Fig. 3 Values of criterion placement (β) and accuracy (d') for combinations of hit and false alarm rates taken from Fig. 1 for roadways.

Another measure of accuracy, as suggested by Swets (1988), is the area under the ROC curve. If this area is A and if the expert system is presented a pair of randomly sampled weather conditions on successive trials -- always having one condition leading to frost and the other not -- the expert system can correctly distinguish between them A % of the time. Integration of the area under the data points given in Fig. 2 for bridges yields A = 0.83, and from Fig. 3 for roadways, A = 0.81. Swets considers A values below 0.70 to suggest insufficient accuracy for much practical value, and values between 0.70 and 0.9 to be useful for some purposes. By this criterion, the expert system potentially has practical value. Swets used ROC data published by Mason (1982b) to compute A values from 0.71 to 0.89 for forecasts of various meteorological variables. Even though the A value of forecasts made with our expert system will be reduced by uncertainty in the input, it has the potential to be of comparable skill compared with other forecast procedures.

4. COMPARISON WITH HUMAN FORECASTS

For December, January, and February of the 1986-87 and 1987-88 frost seasons, we found 69 days for which roadway and bridge data were available for both frost occurrences and frost forecasts by the private consulting meteorologists under contract with IDOT. We applied our expert system with zero threshold (as in Fig. 1) and with perfect forecasts of the items in Table 1b to these 69 days. The results (shown in Table 3) reveal that, for

Table 3. Comparison of forecast parameters produced by human forecasters with results from an expert system given perfect forecasts of items in Table 1.

	Bridges		Roadways	
	Human Forecaster	Expert System	Human Forecaster	Expert System
N	69	69	69	69
S	0.57	0.57	0.32	0.32
H	0.74	0.72	0.55	0.68
F	0.30	0.13	0.11	0.17
β	0.93	1.6	2.1	1.4
d'	1.2	1.7	1.4	1.4

bridges, the forecaster and the expert system had comparable hit rates, but the expert system had a lower false alarm rate. This resulted in a higher accuracy (1.7 vs 1.2) for the expert system and a system bias (1.6) toward fewer false alarms, compared with a relatively unbiased (0.93) human. For roadways, the expert system had higher rates for both hits and false alarms but comparable accuracy compared with the human forecasts. The human forecasts of roadway frost were more highly biased toward reducing false alarms (2.1) than the expert system (1.4).

We reemphasize that the performance of the system is at its potential best because we have used "perfect forecasts" of the variables in Table 1. The system is being tested operationally during the 1989-90 frost season by forecasters under contract to forecast frost in central Iowa for the Iowa Department of Transportation. Preliminary results of operational performance will be presented at the conference.

5. SUMMARY

Prediction of bridge and roadway frost by use of an expert system is found to have the potential to be of sufficient accuracy to be used as an operational tool. A procedure is suggested for using an expert system as a tool by which management considerations can be used to establish decision threshold criterion without adversely influencing accuracy. Configuring the expert system as we have and evaluation by means of SDT has management implications in that decision criteria based on nonmeteorological considerations may be used to determine the optimum combination of hit rate and false alarm rate, with the attendant accuracy being given by the SDT curve. As an example, the consequences of a lawsuit arising from an accident on an untreated frosty bridge are greater, to a certain (management-determined) extent, than the consequences of sanding bridges when a false alarm is called. For the desired hit rate, the transportation manager can use the SDT plot to evaluate the expected false alarm rate and forecast accuracy and determine the bias (threshold temperature) of the expert system to optimize these three variables. Under the more general case in which decision criterion and accuracy are interrelated, the choice of system accuracy as well as decision criterion becomes a management choice. The expert system therefore allows management people to manage and forecasters to forecast, without excessive overlap.

A more complete report of this study of bridge and roadway frost will be published elsewhere (Takle, 1990).

Acknowledgements

We acknowledge with much appreciation the assistance of Mr. Don East and the IDOT maintenance personnel for their assistance in providing the frost occurrence data, and Mr. Jeff Chapman for summarizing the frost occurrence and forecast information from IDOT records. This research was funded by the Iowa Department of Transportation through the Iowa Highway Research Board research project HR-305. The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the Highway Division of the Iowa Department of Transportation.

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An Expert System for Forecasting Frost on Bridges and Roadways: Operational Experience

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Abstract

We have developed an expert system for producing 20-hour forecasts of frost occurrence on bridges and roadways. The conditions for frost occurrence were determined by use of over 4000 observations of frost by state highway-maintenance personnel during 4 frost seasons, discussions with private forecasters who have experience in forecasting bridge and roadway frost, and meteorological observations at the nearby office of the National Weather Service. The expert system uses a commercially available Lisp-based, backward-chaining shell. The system has 32 parameters and variables and 33 rules that use 3 data items and 7 commonly forecast variables (e.g., max and min temperatures, dew point, cloud cover) to be supplied by a forecaster, a numerical model, or another expert system.

Roadway/bridge frost is an example of a class of forecasting problems where an end user (in this case a state highway-maintenance organization) imposes a management decision criterion on the forecaster. For example, the highway agency may put emphasis on having a high "hit" rate (correctly forecasting frost occurrence) at the expense of a correspondingly high "false-alarm" rate (calling for frost when none occurs). Our expert system is configured so that this decision criterion can be adjusted at the discretion of the highway-maintenance management without adversely affecting the forecast accuracy as determined by signal detection theory.

The system was supplied with perfect forecasts of the 7 required variables, and its frost forecasts were compared with those of human forecasters for a sample of 69 days. The accuracy (as measured by signal detection theory) of the expert system was comparable to or higher than the human forecaster. In real-time application, of course, the inaccuracy of the input variables will degrade the overall accuracy of the expert-system-based forecast. The human forecasters were observed to provide a relatively unbiased (favoring neither high hit rates nor low false-alarm rates) forecast for bridge frost but were highly biased toward reducing false alarms for roadway frost. The expert system, by contrast, is configured so that the decision threshold can be adjusted to give unbiased forecasts or forecasts that are biased toward emphasizing either a high hit rate or a low false alarm rate without significant degradation of accuracy.

The system was used operationally during the 1989-90 frost season. Forecasters typically ran the system 2-4 times with different forecast input in preparing the final frost forecast. System configuration allows multiple runs to be made quickly, with 2-4 runs requiring less than 10 minutes. Forecasters viewed the system as a consultant whose response they valued, particularly on weekends when a forecaster otherwise worked alone.