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Evaluation of a frost accumulation model

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Formation of frost on paved surfaces presents a potential hazard to the motoring public in cold climates. Temperatures of the paved surface are not measured routinely by the National Weather Service and are not part of public forecasts of winter conditions, yet highway maintenance personnel must make frost suppression and anti-icing decisions based on expectations of future paved-surface temperatures. The Road Weather Information System measures road surface, air and dew-point temperatures, road surface conditions, and wind data at numerous locations in the state of Iowa and reports the data in real-time to maintenance offices. A model based on simple concepts of moisture flux to the surface was developed that uses data from roadway weather stations or forecasts of dew-point temperature, air temperature, surface temperature and wind speed to calculate frost accumulation on bridge decks in Iowa. The analysis showed that the model has sufficient accuracy to be used as an operational tool for assessing frost accumulation on bridge decks. A logistical regression procedure was developed to determine the probability that a maintenance worker will observe frost for a given calculated frost depth.

1. Introduction

Frost frequently forms on paved surfaces in Iowa during the cold season (October–April), particularly in the early morning under conditions of radiational cooling or moisture advection. Takle (1990) reported that maintenance personnel tabulated 2608 bridge and 1615 roadway frost occurrences for the winters from 1985 to 1989 at 37 sites. He concluded that across Iowa each year the number of bridge frost events ranges from about 12 to 58, and that the number of roadway frost events varies from about 7 to 35. Frost accumulations may lead to hazardous conditions for motorists unless paved surfaces are treated with anti-icing solutions. However, treating bridge decks every time the surface temperature drops to the freezing point or below is not practical or economical. Furthermore, both automobile corrosion due to ice suppression chemicals on metal surfaces and contamination of nearby water bodies by fugitive chemicals (Shao & Lister 1996) are exacerbated by excess chemical use.

The Iowa Department of Transportation (IaDOT) chemically treats roadways and bridges for frost based on site-specific road weather forecasts (i.e. prevention) and real-time observations and Roadway Weather Information System (RWIS) data (i.e. mitigation). Accurate frost predictions promote effective anti-icing and de-icing procedures and minimise negative environmental impacts. Despite substantial improvements in understanding ice formation on roadways (Bogren & Gustavsson 1989; Gustavsson & Bogren 1990; Karlsson 2001), improved predictive models are needed.

One deficiency in existing models is the lack of acknowledgement of a difference between *roadway frost* and *roadway frost that is likely to be hazardous to motorists*. A highway maintenance policy that called for treating roadways every time the surface temperature was at or below the dew-point temperature and below freezing (conditions for frost to begin forming) would result in a waste of human and material resources, since these conditions frequently occur over periods that are too short to permit significant frost *accumulation*. Resources available to this project did not permit a correlation of measured friction with surface frost accumulation. In lieu of this limitation, we related frost accumulation (as calculated by our algorithm) to visual observation of frost – the conventional criterion for initiating frost suppression measures.

We developed a simple numerical algorithm to calculate the depth of frost accumulation on paved surfaces, which can be applied to bridges. The model uses current RWIS data to calculate current frost accumulation. Alternatively the model could use *forecasts* of dew-point temperature, air temperature, surface temperature and wind speed to produce *forecasts* of frost accumulation. Frost depths calculated by the model are compared with daily frost observations by IaDOT maintenance personnel. A relative operating characteristics (ROC) curve (Swets 1973) was used to evaluate the skill of the modelling procedure. Frost accumulations may be too small to be visible under standard IaDOT frost observation techniques. We used the frost accumulation model to calculate frost depths for those days on which frost observations were made. A linear logistic regression technique using these depths and concurrent yes/no frost observations was developed to determine the probability that a maintenance worker would observe frost at various calculated depths.

Crevier & Delage (2001) have recently reported a comprehensive numerical simulation model for forecasting roadway conditions in Canada. Their model includes prognostic equations for budgets of liquid and solid H_2O on paved surfaces and supporting equations for the energy balance at the surface. The algorithm we describe herein uses meteorological information from weather forecasts or RWIS observations to calculate the amount of frost that will accumulate consistent with the supplied data. The Crevier & Delage (2001) model includes frost as one of many ice/water conditions on the roadway surface. A practical consideration in the forecasting of frost is whether the amount deposited is (a) visible other than under microscopic observations, and (b) hazardous to motorists. We have used actual observations by department of transportation employees to establish a database of 'observed frost' (which is likely to be a subset of all frost that occurred during the observation period). Despite the fact that the model reported herein is much simpler than that of Crevier & Delage (2001) it goes one step further in discriminating potentially hazardous frost from all physically possible frost occurrences.

2. Data

2.1. RWIS data

RWIS installations are used throughout the world (Eriksson & Norrman 2001) for monitoring winter roadway conditions in areas likely to be hazardous to road transport. Sensor data from five automated RWIS sites in Iowa (Spencer, Mason City, Waterloo, southwest Des Moines, and Ames) were extracted from the IaDOT data archives. Locations of these five stations and information on their latitudes, longitudes, elevations and quality control are available from the Iowa Environmental Mesonet (2003). Site and aerial photos are also available. Care was taken to select sites that are not prone to strong urban influences, since these would not be applicable to conditions typically found in rural areas (Weller & Thornes 2001). Bridge deck surface temperatures, 5-m wind speeds, 2-m air temperatures and dew-point temperatures from the five RWIS sites for 21 winter-season months (1995–1998) were used as model input. Each automated RWIS site has four or five surface sensors embedded in the bridge decks. At each RWIS site, the bridge deck sensor that recorded paved surface temperatures with the least missing data was used in the model prediction procedure. Automated RWIS sensor reports are recorded at irregular intervals varying from 5 minutes to 3 hours. Values were interpolated to 1-minute intervals for use in the frost accumulation model.

Bogren et al. (2001) point out that under conditions when moisture is present on the paved surface large temperature differences can exist in the few centimetres above the roadway surface. In the current study we had no auxiliary measurements to correct for such possible differences between the RWIS measurement height and the near-field of the paved surface.

2.2. Paved surface frost observations

During the cold season, maintenance personnel record daily observations of the presence or absence of frost between 0500 LST and 0700 LST as viewed from inside a vehicle while making surveys of bridges. Frost observations are recorded and archived for litigation or research purposes. Although these observers lack scientific training, they usually have several years of experience in making daily observations of frost occurrences and are charged with the responsibility of treating surfaces when and where frost is found. Any frost, whether patchy or widespread, on the bridge was considered a frost event. The frost analysis for model verification used 462 frost observations for which corresponding RWIS data were available.

3. Frost accumulation model

Hewson & Gait (1992) showed that the meteorological conditions most conducive to rapid frost deposition include clear skies, a shallow layer of moist air in contact with the surface, high water-vapour content in that layer, a gentle but consistent breeze, recent cold weather, short day-length, and wind direction. According to Takle (1990) three conditions must exist for frost deposition of sufficient amount to be visible and to be hazardous to motorists:

- the temperature of the paved surface (T_p) must be at or below the melting point ($T_p \leq 273$ K);
- the temperature of the paved surface (T_p) must be less than the 2-m dew-point temperature (T_D) and the 2-m air temperature (T_A). ($T_A \geq T_D > T_p$)
- the 2-m dew-point temperature (T_D) must be near 273 K or well above the temperature of the paved surface (T_p) long enough for sufficient mass to accumulate to be visible.

The first condition ensures that when the paved surface temperature is at or below the melting point, any moisture deposited will be in the form of frost rather than dew. The second condition ensures that the moisture flux is towards the paved surface. The third condition ensures that a substantial amount of frost will be deposited.

The frost accumulation model (FAM2000) calculates the total depth of frost accumulated on bridge decks over time. The net flux of moisture, F_f, onto the paved surface (Rayer 1987; Barker & Davies 1990; Sass, 1992, 1997) is described by

$$F_f = \rho_d(\overline{w'q'_s})_s, \quad (1)$$

where ρ_d is the density of dry air, w' represents the turbulent vertical velocity, and q_s' is the turbulent specific humidity under saturated conditions at the surface. Using the transfer coefficient formulation (Stull 1988) to parameterise (1), we get

$$F_f = \rho_d C_E U(q_s(a) - q_s(g)) \quad (2)$$

where $q_s(a)$ is the specific humidity of air at 2 m and $q_s(g)$ is the specific humidity of air at the paved surface. The transfer coefficient, $C_E = 10^{-3}$ (see Stull 1988), is assumed to be constant. U is the 5-m RWIS wind speed ($m\,s^{-1}$). By use of Dalton's Law of partial pressures ($p = e + p_d$) and the ideal gas law, equation (2) becomes

$$F_f = \varepsilon R_d^{-1} C_E U(e - e_s(T_p))T_A^{-1} \quad (3)$$

which is similar to that used in Hewson & Gait (1992) where e is the actual vapour pressure at 2 m, $e_s(T_p)$ is the saturation vapour pressure of the paved surface temperature, and T_A is the 2-m RWIS air temperature. R_d is the gas constant for dry air with units of $J\,kg^{-1}\,K^{-1}$, and ε is the ratio of molecular weights between water and dry air. All temperatures have units of Kelvins. The difference in saturation vapour pressures, D, between the atmosphere and the paved surface is calculated using the Clausius-Clapeyron equation,

$$D = e_s(T_o)\{\exp[L_D/R_V(T_o^{-1} - T_D^{-1})] - \exp[L_D/R_V(T_o^{-1} - T_p^{-1})]\} \quad (4)$$

where L_D is the latent heat of deposition at the freezing point with units of $J\,kg^{-1}$. R_V is the gas constant for water vapour with units of $J\,kg^{-1}\,K^{-1}$, and $e_s(T_o)$ is the saturation vapour pressure at $T_o = 273.16$ K with units of Pascals. To allow for weak deposition when conditions are just saturated ($T_D = T_p$) a small adjustment to the 2-m RWIS dew-point temperature is performed,

$$T_D = T_p + 0.1. \quad (5)$$

The rate of growth in depth of frost as a function of time (in $m\,s^{-1}$) can be expressed as

$$R(t) = \rho_f^{-1}\varepsilon R_d^{-1} C_E U D T_A^{-1}, \quad (6)$$

by dividing equation (3) by an assumed constant density of frost ($\rho_f = 100\ kg\,m^{-3}$). Melting of frost is determined from the snow melt equation (SME) in the ETA model (National Center for Environmental Prediction) for $T_p > 273.16$ K, where the melt (SME) is

$$SME = (-10E(T_p - 273.16)(T_p^4 F + 1)T_p^{-1}). \quad (7)$$

SME has units of $m\,s^{-1}$, and $E = 1.0513 \times 10^{-8}\ m\,s^{-1}$ and $F = 6.48 \times 10^{-8}\ K^{-4}$ are constants. The model allows for a downward net flux of moisture (deposition) onto the paved surface, an upward net flux of moisture (evaporation or sublimation) from the paved surface, melting of frost with no deposition of moisture on the paved surface, and melting with simultaneous evaporation or sublimation of frost. Accumulation is updated at 1-minute intervals (Δt) based on linearly interpolated values of observed or forecast conditions supplied at longer (typically 20 minute) intervals. Finally, total frost depth (TFD) is the aggregate of incremental increases and decreases in frost depth as long as the sum is not negative:

$$TFD = \sum R(t)\,\Delta t. \quad (8)$$

4. Results

For the 462 frost observations, the model produced 88 cases of positive frost accumulations, ranging from a low of 10^{-5} mm to the largest value of approximately 0.07 mm. For those cases, highway maintenance personnel observed frost on paved surfaces 42 times (hits) and observed no frost 46 times (false alarms). In addition, frost was observed by maintenance personnel six times when no frost was calculated by the model (misses). For the remaining 368 observations the model produced no frost accumulations, and frost was not detected by IaDOT winter maintenance personnel (correct negative prediction).

All six missed events occurred in a span of two winter seasons between December 1995 and February 1997 in Waterloo. RWIS data in Waterloo were compared to data from surrounding locations which reported 2-m dew-point temperatures and the 2-m air temperatures less than the paved surface temperatures generally under overcast conditions. Consequently, the model calculation gave no frost accumulation. Radiational cooling and moisture advection were eliminated as possible causes for frost. As well as the possibility of human error, isolated snowfall or overnight re-freezing conditions may have led to the reported observations of frost.

From this we conclude that there may be a systematic discrepancy between modelled and observed frost for the Waterloo site for the two winter seasons. Resolution of this discrepancy could very well increase accuracy of the model beyond the level discussed in the following sections.

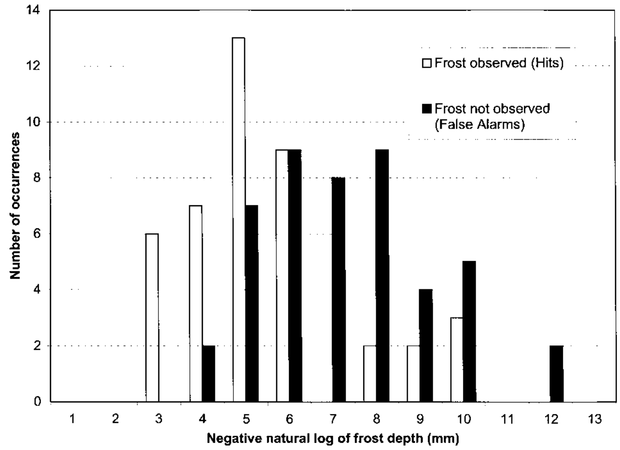

Figure 1. *Frequency distribution of (the log of) frost depths.*

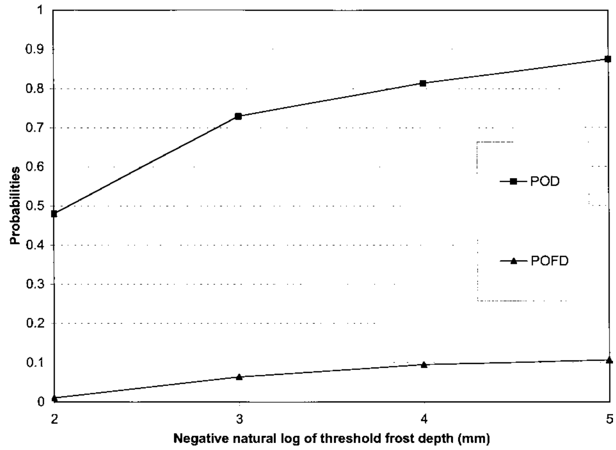

Figure 2. *Effect on POD and POFD of various thresholds.*

4.1. Verification

Model frost predictions and human frost observations were used to calculate probability of detection (POD) and probability of false detection (POFD) as given below:

$$\text{POD} = \text{hits}/(\text{hits} + \text{misses}) \quad (9)$$

$$\text{POFD} = \text{false alarms}/(\text{false alarms} + \text{correct negative prediction}) \quad (10)$$

The values of the probability of detection, POD = 0.875, and the probability of the false detection, POFD = 0.111, suggest that the model did detect frost events well.

The frequency of occurrence of (the log of) calculated frost depths is plotted in Figure 1 separately for days when frost was observed and days when no frost was observed. Both curves were tested for normality. The data for the observed frost days were determined to be non-normally distributed with a skewness towards larger calculated accumulations. However, accumulations calculated for the no-frost days were approximately normally distributed. The Wilcoxen Rank Sum hypothesis test was used to determine if the two separate curves have significantly different population means even if the curves are not necessarily normally distributed. The null hypothesis (that the two curves have the same population mean) failed, thus indicating that the two population means are significantly different. This provides at least some confidence that the frost model FAM2000 is capable, in a statistically significant sense, of distinguishing frost occurrences from the non-occurrences.

Frost must accumulate to some minimum (greater than zero) depth to be visible by humans. By moving the threshold value for observable frost from 0 mm to higher values (lower values of negative log), the probability of false detection decreases but the probability of detection also decreases (Figure 2). Table 1 shows the computed probabilities for the various thresholds.

We define the optimal threshold as the value that best discriminates between frost and no frost, i.e. the greatest difference between probability of detection and probability of false detection ($\Delta P = \text{POD} - \text{POFD}$). The best result, $\Delta P = 0.769$, occurred with a threshold depth of 10^{-5} mm.

4.2. Logistic regression model

We used logistic regression analysis (Agresti 1984; Hosmer & Lemenshow 1989) to investigate the relationship between the binary response (frost observations)

Table 1. *SDT calculations.*

Threshold depth (mm)	Probability of detection (POD)	Probability of false detection (POFD)	ΔP (POD-POFD)	Decision criterion (X_c)	Index of accuracy (d′)	Criterion placement (β)
0	0.875	0.111	0.764	1.22	2.37	1.08
10^{-5}	0.875	0.106	0.769	1.25	2.40	1.13
10^{-4}	0.813	0.094	0.719	1.32	2.21	1.61
0.000335	0.771	0.085	0.686	1.37	2.11	1.94
10^{-3}	0.729	0.063	0.667	1.53	2.14	2.68
0.002	0.729	0.043	0.686	1.72	2.14	4.02
0.007	0.542	0.022	0.520	2.01	2.12	7.49
0.018	0.271	0.005	0.266	2.57	1.96	22.56
			AVG	1.62	2.18	5.31

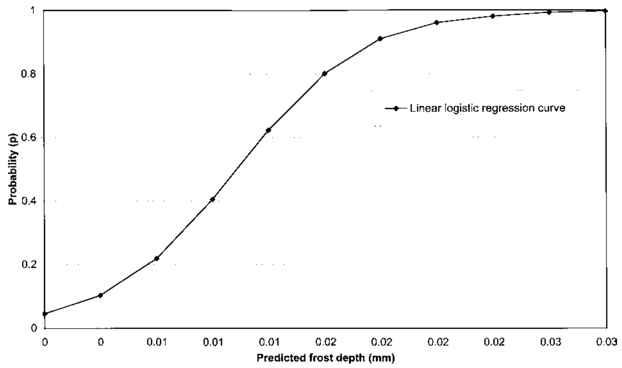

Figure 3. *The probability (p) that IaDOT personnel will see frost for a predicted frost depth.*

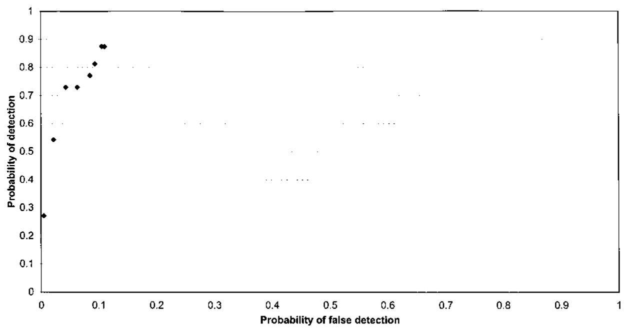

Figure 4. *The set of black dots defines the ROC curve using point estimates of POD and POFD for the various threshold frost depths.*

and the explanatory response (model-calculated frost depths) variables. Cox & Snell (1989) give a thorough discussion of binary response model methodology.

If **x** is the predicted frost depth (TFD in Eq. 8), and p is the probability of observed frost, then

$$\log(p/(1-p)) = \alpha + \beta \mathbf{x}. \tag{11}$$

By using maximum likelihood analysis (Aitchison & Silvey 1957; Ashford 1959), the intercept estimate, α, was calculated to be −3.0575, and the slope estimate, β, was 296.9. Solving for p gives

$$p = (1 + e^{-(\alpha+\beta \mathbf{x})})^{-1}, \tag{12}$$

the probability that an IaDOT employee will see frost under the predicted conditions. A plot of the probability of observing frost (p) as a function of predicted frost depths (**x** = TFD) (Figure 3) shows that a human observer following IaDOT procedures has a 50% probability of observing frost under conditions when the model gives a depth of 0.01 mm, which is at the upper end of the range (0.002–0.01 mm) of observable depths suggested by Hewson & Gait (1992).

5. Forecast accuracy and decision criterion

5.1. Signal detection theory

Signal detection theory (SDT), outlined in Mason (1982a), is a technique used to separate forecast accuracy from the decision criterion. Essentially, SDT is an extension of probabilistic forecasting using binary contingency table methodology. The SDT technique has been applied to forecasts of a variety of weather variables (Mason 1982b; McCoy 1986; Takle 1990; Buizza et al. 1999). SDT is used in this frost analysis in which the probabilistic forecast is a set of contingency tables where the probability of detection and probability of false detection were computed based on different threshold frost depths.

The SDT index of accuracy, d′, is defined as the number of standard deviations separating the means of the (assumed normal) distributions of the decision criterion preceding occurrence and preceding non-occurrence (Green & Swets 1974; Swets 1973, 1986, 1988). Thus, if the probabilities of detection and false detection are equal, $d' = 0$ which indicates no skill. Higher values of d′ indicate higher skill. The criterion placement, β, is the likelihood ratio that measures the occurrence against the non-occurrence. A high criterion placement value ($\beta > 1$) ensures a low probability of false detection at the expense of a lower probability of detection. A low criterion placement value ($\beta < 1$) suggests a bias towards maintaining a high probability of detection at the expense of a higher probability of false detection, and a value of $\beta = 1$ shows no bias towards either probability. The terms used to compute SDT values are given below:

- 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.

5.2. Relative operating characteristic curves

Data from Table 1 are used to plot the relative operating characteristic (ROC) curve (see Figure 4) generated from normal distributions (Mason 1982a; Swets 1986). The range of threshold frost depths observed in our study does not span the entire range of probabilities, but the limit cases must tend toward the points (0,0) and (1,1). Table 1 shows that the optimum threshold of 10^{-5} mm gives $d' = 2.40$ and $\beta = 1.13$ which indicates a slight tendency toward minimising false alarms.

Following Swets (1988), another measure of accuracy is defined by the area (AR) under the ROC curve. If AR = 1, the forecast is considered perfect, with accuracy decreasing with decreasing AR. AR = 0.5 gives a useless forecast system. Swets suggests that AR values less than 0.70 suggest insufficient accuracy to provide much practical value, while values between 0.70 and 0.90 define sufficient accuracy in the system. Buizza et al. (2000), Juras (2000) and Wilson (2000) caution against the use of arbitrarily defined areas for defining significance. For example, Juras (2000) argues that the limit value for AR should vary and depend on the variability of climatological frequencies of an event within a homogeneous region.

Integration of the area under the ROC curve given in Figure 4 for bridges yields a value AR = 0.91. Thus, using the qualitative threshold criterion range (0.70–0.90) from Swets (1988), the frost model (FAM2000) has potential practical value. This result indicates that FAM2000 has higher accuracy than the expert system reported in Takle (1990), which may have been hampered by a lack of RWIS-type information.

6. Summary

A model (FAM2000) based on simple mathematical description of moisture flux to the surface has been developed to calculate frost accumulation consistent with meteorological conditions provided by observations or forecast models. We supplied the model with RWIS data to calculate expected amounts of accumulated frost for occasions when IaDOT personnel made observations on these bridges. Results from the SDT and ROC analyses suggest that use of the frost accumulation model to distinguish visible and potentially hazardous frost from frost that is not visible has sufficient accuracy to be used as an operation tool; however, uncertainty of input information (i.e. forecasted or RWIS measured values) will correspondingly degrade the prediction of frost accumulation.

A key parameter determined was the 'threshold accumulated frost depth' calculated by the model that corresponds to the minimum observable frost seen by IaDOT maintenance personnel from inside a moving vehicle while making surveys of bridges. A logistic regression technique was used to determine the probability (p) that a maintenance worker will observe frost for a given calculated frost depth (TFD). Results indicated that a threshold depth of around 0.01 mm seems to be the minimal likely amount of frost accumulated on a bridge deck that is observable under IaDOT procedures.

Finally, some assumptions used in the simple model (e.g. use of neutral drag coefficient) and its application to an elevated surface (e.g. elevated bridge deck as opposed to a flat surface of infinite horizontal extent at the ground) might introduce biases into the model. Limitations of observations (e.g. frost occurring after the observer has completed his/her observation, or frost not forming due to residual frost-suppressing chemical) also may reduce accuracy of the model. A systematic comparison of model calculations with observations would allow evaluation of model accuracy and suggest ways of tuning for improvement.

The frost analysis focused on the prediction of frost on bridge decks based on RWIS temperature and wind speed data from five Iowa sites. When maintenance personnel are faced with the threat of nocturnal frost formation, they factor non-meteorological as well as meteorological information into their prevention plans. When considering all information available, IaDOT management can use the SDT procedure to determine the optimum combination of probability of detection and probability of false detection based on the established threshold frost depths. For example, when they receive a forecast frost accumulation, management can use the SDT procedure to evaluate the forecast accuracy in combination with available non-meteorological information (i.e. residual salt residue on paved surfaces, traffic volume or environmental issues). In addition, management can compare the results of the logistic regression probability of a forecasted maximum frost depth to internal frost prevention standards within the IaDOT.

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