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A DYNAMIC—STOCHASTIC APPROACH TO ROAD AND BRIDGE FROST FORECASTING

John J. Mewes* and Robert Hart
Meridian Environmental Technology, Inc.

1. INTRODUCTION

Forecasting frost development on roads or bridges at significant lead times is a notoriously difficult problem. The error magnitudes within the field of forecast meteorology at present are too large to provide for consistently reliable frost forecasts. Unfortunately the only way to improve the discrimination between frost and no-frost events in a forecast setting is to improve the accuracy of the underlying road or bridge and dew point temperature forecasts. These improvements will not be trivial to come by, making a reliable frost forecast system very difficult to construct within the near future.

In spite of these difficulties there are significant steps that can be taken to help agencies involved in winter road maintenance better understand and manage the risk of road or bridge frost on a daily basis. The purpose of the dynamic-stochastic approach presented here is to provide the winter maintenance community with a consistent and scientifically sound probability of road or bridge frost on a case-by-case basis. Given a stable and reliable system for arriving at these probabilities, winter maintenance personnel can begin to determine the probability thresholds that best balance the economics of pretreating for events that may not occur with the risk of not pretreating for some events that do occur and may lead to serious or fatal accidents. There is no single ‘correct’ probability threshold at which to initiate preventative maintenance actions for frost. The system presented here allows individuals involved in winter maintenance to find the probability threshold most appropriate for the economics and public roadway level of service expectations of the local community.

2. METHODOLOGY

This dynamic-stochastic approach to road and bridge frost forecasting requires a pavement surface condition model (hereafter, pavement model) to act as the dynamic core. In the present case Meridian’s proprietary Highway Condition Analysis and Prediction System (HiCAPS™) serves as the model. HiCAPS™ is a sophisticated pavement model developed to support Meridian’s winter forecasting requirements of its Department of Transportation customers. HiCAPS™ is a coupled mass and energy balance model. In the sense of pavement modeling, this means that additions or subtractions to the mass of moisture (in one or more forms) present upon the road surface are directly tied to the fluxes of energy into or out of the road surface. Modified bulk formulations are used for sensible and latent heat flux calculations in HiCAPS™. The processes of condensation, deposition, evaporation, sublimation, runoff, and snow removal are all treated within the model. The model also accounts for latent heat exchange associated with phase changes and the sensible heat exchange associated with precipitation at a different temperature than the pavement falling onto the roadway. Substrate temperatures at the lower boundary of the model are set to climatological deep-soil temperatures. HiCAPS™ uses the one-dimensional unsteady heat flow equation to model heat fluxes and storage within the pavement and its substrate. Meteorological forcing for HiCAPS™ is provided by Meridian’s meteorologists using tools provided by Meridian’s MPower™ forecast system. Downwelling solar and longwave radiation are calculated using three-dimensional atmospheric model forecast fields modified by the meteorologists via MPower™.

Given a history of forecasts from the pavement model and the corresponding road or bridge temperature observations from a Road Weather Information System (RWIS), it is possible to calculate the bias and error variance of the road or bridge surface temperature forecasts as a function of the time of day or lead time. The bias and error variance of dew point temperature forecasts can be calculated against available RWIS observations in a similar manner. Given the bias and error variance information and assuming a Gaussian distribution it is possible to construct probability density functions around the baseline road or bridge temperature and dew point temperature forecasts.

The probability of frost at a given time can be broken down into two independent probabilities: the probability that the pavement temperature will be below freezing and the probability that the dew point temperature will exceed the pavement temperature. Given a pavement forecast value T_P from the pavement model with bias B_P and error standard deviation σ_P, the probability P_F that the pavement temperature will actually fall below the freezing point T_F is given by:

$$P_F(T_P) = \frac{1}{2} - \frac{1}{2} erf\left(\frac{T_P - B_P - T_F}{\sigma_P \sqrt{2}}\right). \qquad (2.1)$$

Taking advantage of the fact that the errors in the pavement temperature and dew point temperature forecasts will generally be uncorrelated it is possible to show that the error variance of the difference between

Corresponding Author Address: John J. Mewes
Meridian Environmental Technology, Inc.
4324 University Ave., Grand Forks, ND 58203
e-mail: jmewes@meridian-enviro.com

the pavement temperature and dew point forecasts is given by:

$$\sigma_{P-Td}^2 = \sigma^2\left(T_P - T_d\right) = \sigma_P^2 + \sigma_{Td}^2 \qquad (2.2)$$

where T_d is the dew point temperature and σ_{P-Td} is the standard deviation of the error in the forecast difference between the pavement and dew point temperatures. In a similar fashion to (2.1), the probability P_M that the dew point temperature will exceed the pavement temperature and thus provide the moisture necessary for a frost situation is given by:

$$P_M(T_P - T_d) = \frac{1}{2} - \frac{1}{2} erf\left(\frac{(T_P - B_P) - (T_d - B_d)}{\sigma_{P-Td}\sqrt{2}}\right) \qquad (2.3)$$

where B_d is the calculated bias in the dew point temperature forecasts. Given the probability of the pavement temperature being below freezing (P_F) and the probability that atmospheric water vapor will be deposited on the road (P_M), the probability of frost P_{FR} is given by:

$$P_{FR} = P_F P_M \,. \qquad (2.4)$$

P_{FR} represents the true probability of frost occurring given a road or bridge temperature forecast T_P and a dew point forecast T_d and the error statistics associated with each.

3. FUTURE ENHANCMENTS

Although a step in the right direction, the technique still lacks several pieces of information that would make it far more robust to the user community. First, knowing the actual freezing point of a solution as it develops on the pavement is difficult, as it requires knowledge of previous maintenance actions and the processes that remove the associated ice-inhibiting materials from the roadway. A 0° C freezing point is a starting point, but may not be a good estimate in states with an active treatment program. A second process that is poorly represented in this formulation is adsorption of moisture onto the roadway by ice-inhibiting materials even while the dew point temperature is still below the pavement temperature. Finally, an enhancement that provides an indication of the probable depth of any frost that does form would be very useful. Scientific frost and road or bridge frost from a maintenance perspective are not one and the same. Some finite depth of frost buildup is required before it begins to significantly reduce the coefficient of friction between vehicles and the surface of the road or bridge. At present, little guidance information is available on which to base the differentiation between scientific and treatable frost.