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MAINTENANCE DECISION SUPPORT SYSTEMS: RESEARCH PROGRESS AND CONTINUING NEEDS

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1. INTRODUCTION

Version 4.0 of the Pooled Fund Study (PFS) Maintenance Decision Support System (MDSS) was released to the 13 participating state transportation agencies during the fall of 2007. The PFS MDSS (Mewes et al, 2005) is a public / private venture into operational application of winter maintenance decision support technologies following the concept of the Federal Highway Administration's (FHWA) MDSS Functional Prototype (FP; Pisano et al, 2005) demonstration. The PFS MDSS integrates in-situ, remotely-sensed, and forecast weather information with data gathered from Road Weather Information Systems (RWIS), road condition reporting systems, and winter road maintenance activities data collection platforms to provide maintenance personnel with a suite of decision support tools.

The PFS MDSS has made significant strides in furthering the integration between the road and weather communities. Many new modules have been developed to simulate road weather processes that had not been previously addressed in a simulation framework. These modules have been developed on the basis of a relatively small but valuable pool of existing road weather research information and validated and refined using data collected in field case studies conducted during recent phases of the PFS MDSS project. This paper presents a brief overview of the PFS MDSS system and the accomplishments made to date, as well as an overview of valuable new research and observational needs identified during the PFS MDSS project that could be addressed by research organizations within the road weather community.

2. PFS MDSS APPROACH

The PFS MDSS approach focuses upon simulation of the 'dynamic layer' of liquid, snow, ice, de-icing agents and abrasives resident atop the pavement. Analyses of past weather conditions (including precipitation and radiation budgets) are integrated with RWIS observations as well as road condition and winter maintenance activities reports to provide an ongoing assessment of the past and present condition of the roadway. The information integration occurs within the HiCAPS[TM,1] pavement model and supporting MDSS libraries. HiCAPS[TM] is a mass and energy balance pavement model that simulates the evolution of the roadway and the overlying dynamic layer by modeling the combined effects of the individual fluxes and processes active upon that layer. Sensible and latent heat fluxes are modeled using bulk formulations, while ground heat flux is modeled using the unsteady heat flow equation. The HiCAPS[TM] latent heat flux module accounts for energy and mass exchanges due to precipitation, evaporation, sublimation, condensation, deposition, conduction, and phase changes.

The ongoing assessment of the initial state of the dynamic layer discussed in the preceding paragraph is used in concert with weather forecast and available maintenance resources information to construct an initial/boundary value problem. Standard minimization techniques are used to find candidate maintenance actions that will maintain the required level of service in the most economical manner given available human, equipment, and material resources. Resources and service level information is preconfigured for each maintenance route, but can be adjusted by the user as resource availability and practical maintenance limitations change during a storm situation. The system also supports dynamic layer simulation for user-defined maintenance actions in a 'what-if?' virtual scenario mode.

The PFS MDSS uses several new modules to simulate the effects of winter maintenance activities. The system supports application of the most commonly used freeze point depressant materials using new modules, allowing for parametric description of the eutectic properties of various chemicals. An iterative approach is used to solve for the complex eutectic properties of multiple freeze point depressants (each with different eutectic properties) working together within the mixture. During the simulation process a configurable amount of the applied material is assumed lost immediately upon application. The loss rate is left configurable based upon the form of the material (e.g., dry granular, prewet granular, or liquid) and the condition of the road to which the material is being applied. For simulated plowing operations, the system estimates the depth of snow and

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[1] HiCAPS is a trademark of Meridian Environmental Technology, Inc.

ice remaining behind the plow based upon plow type, road surface roughness and the depth of irremovable compacted snow and ice. Previously applied soluble / insoluble chemicals and grit are removed at the same fractional rate as the liquid / total moisture mass in the contaminant layer. Due to density considerations, liquid is assumed to preferentially reside near the bottom of the dynamic layer and is therefore generally removed at a lesser rate than frozen materials within the mixture. Moisture and maintenance materials are also removed by runoff, and by the effects of traffic.

Due to the lack of reliable and consistent research data on the cumulative effects of hundreds or thousands of vehicles upon the dynamic layer, the PFS MDSS instead employs a new approach where the effects of traffic are modeled on a more tractable vehicle-by-vehicle basis. Based upon average daily auto and truck traffic counts, the MDSS system distributes vehicles across the dynamic layer at a rate that varies according to a configurable pattern throughout the day. Each vehicle is assigned a random lane, track and vehicle width, and moisture within the tire tracks is splattered, sprayed, spread, suctioned or compacted depending upon the composition of the dynamic layer. Through this process moisture and materials are moved laterally atop the roadway, and are also removed from the roadway depending upon the splatter, spray, and spread widths relative to the distance of the tire track locations from the edge of the roadway (see Fig. 1).

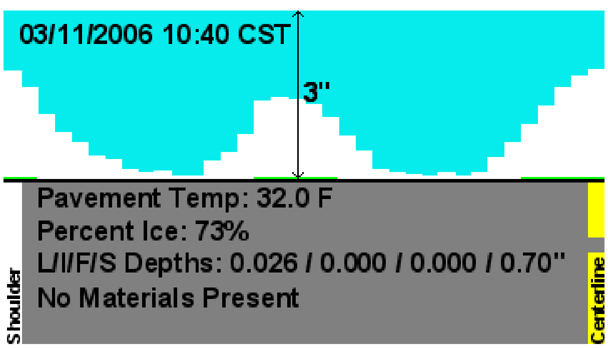

Figure 1: The impacts of traffic in the PFS MDSS are simulated on a vehicle-by-vehicle basis, where the underlying road condition model simulates the impact of each vehicle on a cross-sectional profile of liquid, ice and snow depths across each lane of roadway.

The inclusion of impacts of blowing snow into the HiCAPS™ core of the PFS MDSS system also required the development of new modules. These modules simulate the impact of wind and blowing / drifting snow on the dynamic layer, but keep with the philosophy of the PFS MDSS group that weather and blowing snow information should be inputs to the system rather than a part of the system itself. During the PFS MDSS project, predictions of blowing snow mass flux within the saltation layer provided by the University of North Dakota Surface Transportation Weather Research Center's (STWRC) Roadway Environment Blowing Snow (REBS; Osborne et al, 2006) model were used as the basis for determining the rate of blowing snow deposition onto the roadway. The rate of deposition is modulated depending upon the angle of incidence of the wind with the roadway. While resident atop the roadway the deposited blowing snow is subject to traffic processes in the system (even if slightly suspended), thereby allowing for creation of wheeltrack icing in certain situations. At the same time, the wind is also allowed to scour the deposited snow away. Scouring is approached as a fractional process so as to make processes self-limiting and therefore less sensitive to errors in the blowing snow mass flux estimates. The rate of scouring of deposited snow is a function of wind speed but is modulated by the presence of liquid and/or chemical residuals on the roadway, the road orientation relative to the wind, the density of the snowfall, and the depth of 'blowable' snow within the environment relative to the depth of snow deposited on the roadway (i.e., the scouring of deposited snow decreases as the environmental supply of blowable snow builds).

Decision support in the PFS MDSS is provided on a maintenance route, segment, and / or tile basis. A maintenance route is made up of one or more discrete segments of highway that are to be treated contiguously by a given maintenance vehicle. Each segment within a maintenance route possesses unique weather, construction, traffic, and/or environmental information. Maintenance needs within a single route can therefore vary considerably. However, the MDSS will only present maintenance action recommendations on the different segments of a given route that can be practiced with a single vehicle configuration and that can be performed at contiguous times with traversal, cycle, and dead times that are physically realistic. Note that although the materials recommended will be the same on all segments of a route, the recommended rates can vary substantially between segments based upon the modeled needs. Roadway information in the MDSS is generally displayed on a segment by segment basis. The smallest road subunit in the MDSS is the tile. A tile possesses no specific location within a segment, but is intended for modeling generalized variations in conditions along a segment (such as a sheltered area verses an open area). At this juncture information that is available at the tile level is hidden from the user

3. RESEARCH AND OBSERVATIONAL NEEDS

The preceding section highlights just a few of the accomplishments of the PFS MDSS project relative to simulating the roadway environment. In spite of these accomplishments there is still considerable room for improvement in the system if key pieces of research or observational support can be brought into place. These needs, identified throughout the course of the PFS MDSS project, are highlighted below.

3.a. WEATHER OBSERVATIONS

Reliable real-time observations of wintertime precipitation type and intensity are seriously lacking. Weather radar by itself isn't an adequate tool for supporting analysis of the condition of most transportation agency roads. Light precipitation, such as freezing drizzle, can create serious safety hazards without even being detected by weather radars. Overshooting problems are magnified in the winter months as precipitation often tends to fall from clouds with very limited vertical extent. Further, sub-cloud evaporation is a frequent occurrence during the winter months leading to an unacceptably high false alarm rate even while missing many other events altogether.

Due to the limitations of weather radar, Meridian has implemented a system within the PFS MDSS that uses ground-based weather observations, such as METAR reports and observations made by agency personnel and Road Weather Information System (RWIS) Environmental Sensing Stations (ESS), to supplement radar observations of precipitation. This supplemental data helps the PFS MDSS detect and assess the impact of many light precipitation events that would otherwise go undetected using weather radar alone. However, these data are of limited usefulness in reducing false alarms because of the relatively poor coverage of ground-based wintertime precipitation sensors in many areas of the United States. (This latter problem is compounded by the fact that many areas of virga detected in weather radar are relatively small in extent and therefore less likely to coincide with ground-truth precipitation sensors at any given time.) Even where present weather or precipitation sensors do exist, information on the accumulation rate of falling wintertime precipitation is typically unavailable or unreliable. A visibility-based system for estimating snowfall rates has been developed to support the PFS MDSS, but this system can falter when blowing snow or other obstructions to visibility are present. Sensors designed to directly measure wintertime precipitation rates are available for deployment, but field research carried out by Meridian and other University and Federal research laboratories over the course of the PFS and FP MDSS projects has shown serious problems with the reliability of information collected by many of these sensors. Resolving these wintertime precipitation observation issues will require both fundamental new research into methods for detecting and quantifying wintertime precipitation as well as a significant investment and commitment by State and Federal agencies to deploy networks with coverage sufficient to make the information collected operationally useful.

On the radiation front, downwelling long and short wave radiation play a key role in dictating the road temperature. As such, they also play a key role in dictating where sub-freezing road temperatures and potential snow and ice problems will develop. Case studies performed over the course of the PFS MDSS project have shown many instances where radiation appears to be playing a significant role in creating or eliminating problems on roadways. While the effects of short wave radiation on roads is often highly visible to road maintenance personnel, long wave radiation exchanges are arguably more important in evolving snow and ice situations. Small errors in parameterizations of the impacts of clouds on radiation budgets can lead to errant assessments or predictions of where and when snow, ice or frost will be a problem on road networks. Unfortunately, while the problem has been diagnosed during the PFS MDSS project using radiometers maintained at the UND/STWRC Road Weather Research Facility (RWRF; Osborne et al, 2006), reliable observations of short and especially long wave radiation are virtually nonexistent within the United States. This lack of observations makes it difficult to improve radiation assessment and forecasting processes that play a vital part in modulating the road temperature and condition.

3.b. BLOWING SNOW PROCESSES

Blowing snow is a primary problem of concern in many areas of the United States. Blowing and drifting snow creates travel problems in several ways: reduced visibility, snow drifts on roadways, and snow sticking to treated roads making anti-icing or de-icing winter maintenance operations impractical. Unfortunately, very little exists in the way of observational resources to support diagnosis and forecasting of blowing and (especially) drifting snow. While significant blowing snow may show up in weather observations, the vast majority of ground drifting typically goes unobserved by the weather community. Because of the lack of observations and the microscale variability of the problem it is generally necessary to approach blowing snow diagnosis and forecasting using models. Such models require detailed information on the extent and 'blowability' of the existing snowpack, as well as real-time updates to the character of this snowpack during storm situations. Detailed environmental data is also required in order to parameterize the microscale variability of blowing snow within these models (see Fig. 2 for example). None of this information is readily available operationally at this point in time.

Beyond diagnosis and prediction of its occurrence, blowing snow raises equally difficult considerations in how it interacts with roads. Among the areas needing more research are approaches for relating horizontal mass fluxes of blowing/drifting snow to road surface deposition rates. These relationships need to be defined in terms of road snow depth relative to the ambient 'blowable snow' depth, wind directions and speeds relative to road geometries, and the presence of de-icing chemicals and/or liquid moisture on the road. For example, it is well know by the winter maintenance community that chemical residues may collect drifting snow onto a road that might otherwise be blown clean, but the nature of this process and how conditions impact the propensity for the problem are not well understood. Likewise, it is also widely recognized by winter maintenance personnel that the propensity for drifting snow to accumulate on the roadway is related to the depth of fresh, blowable snow. The same horizontal mass flux of blowing/drifting snow can yield greatly increased roadway deposition rates as the ambient snow depth increases. The nature of this relationship is not well understood.

Figure 2: An example of drifting snow sticking to a roadway. Note that the road turns from icy to wet over a short stretch of distance into the photograph, as the blowing snow mass flux and road temperature both change in response to a small amount of wind sheltering by upstream trees. This image was captured during one of many case studies collected during the PFS MDSS project.

3.c. ROAD CONDITION MODELING

The PFS MDSS utilizes the HiCAPS™ pavement temperature and condition model to simulate the response of roadways to the combined impacts of weather, traffic, and winter maintenance activities. Numerous case studies have been performed during the PFS MDSS project to evaluate and refine the handling of certain road weather processes within this model. While significant strides have been made in improving the model's ability to accurately simulate processes at work on the road surface, many significant holes in the industry's collective understanding of basic processes still exist.

Contrary to popular public belief, it is generally not feasible to use de-icing chemicals to melt all snow from roadways. Rather, the goal of de-icing agents is generally to keep the dynamic layer atop the roadway adequately slushy to prevent bonding (thereby allowing the plow blade to remove it). One elusive parameter of critical importance to the process of making maintenance recommendations is a scientific description of the quantities that dictate the safety, mobility, and maintainability of a road (i.e., the quantitative scientific description of the road condition that winter maintenance activities are attempting to effect). The PFS MDSS presently uses multiple parameters, including measures of the cross-sectional depths of liquid, ice, frost, snow (both loose and compacted), and the slushiness of the mixture, to describe desired road conditions. Small variations in these quantities can have significant impacts on the recommended de-icing chemical application rates. As such the PFS MDSS' recommendations are sensitive to scientific parameters that are somewhat poorly understood at this point in time.

Further complicating the setting of these parameters is the fact that they vary substantially from one event and/or location to the next. The PFS MDSS researchers may assign numeric values to these parameters based upon descriptions of the desired road condition provided by local maintenance personnel. Unfortunately this is a highly subjective process. A maintainer might say they want to keep the road 'slushy'. This may mean that the composition atop the road be 20, 40% or 80% liquid (vs. frozen). However, all other processes aside, the amount of de-icing agent required to achieve those levels of slushiness increases linearly with the percentage (i.e., 40% liquid requires twice as much salt as 20% liquid). Due to budgetary and equipment constraints the goal for most maintenance routes is generally 25% liquid or less, but this is not always the case. Previous research has indicated that liquid / snow mixtures composed of 15-30% liquid will not bond with the pavement (Schaerer, 1970). Unfortunately 15-30% is a wide range, and it is not clear whether the same thresholds hold for other types of icing events. Maintainers have reported success in freezing rain situations during the PFS MDSS project while apparently only reaching lesser thresholds.

Yet another element of road temperature and condition prediction in need of further research is the relationship between sensible and latent heat fluxes in the road environment relative to the ambient environment. Using typical pavement texture depths and time series of pavement temperature and condition observations it is possible to work backward to arrive at latent heat flux exchange coefficients appropriate for application in bulk flux formulae (by calculating the coefficient required to fully evaporate moisture from the road within the observed amount of time). Unfortunately, while traditional theories would indicate that the sensible and latent heat flux exchange coefficients should be approximately equal, reality seems to indicate otherwise for the road surface. Heat flux exchange coefficients that provide for an adequate evaporation rate of moisture from the road surface generally yield far too tight of a coupling between atmospheric and road surface temperatures (i.e., road temperatures are held too close to the air temperatures, indicating an overestimate of the rate of sensible heat exchange). These observances appear to indicate that equality of these exchange coefficients is not a good assumption in the roadway environment. Previous research has already revealed that atmospheric profile observations in a roadway environment are systematically different from those predicted by similarity theory (Chen et al, 1999), but more research into the true nature of these relationships in the roadway environment is needed.

3.d. MODELING TRAFFIC IMPACTS

The impact of traffic is often oversimplified by the road modeling community. Traffic can be a maintainer's friend or enemy depending upon the situation. Cold, dry snowfalls or adequately slushy mixtures may be removed from the road though traffic processes (see Fig. 3 for example). On the other hand, traffic can quickly compress warmer snowfalls into ice. Research is needed to gain a better understanding of the factors that dictate the extent to which traffic will 'suction' snow off of roadways, and to gain a better understanding of the factors that affect the propensity for snow compaction and the factors that dictate the strength of the bond that develops between the compacted snow and the underlying roadway. Between the suction and compaction regimes lies a vast range of situations where the impacts of traffic vary according to traffic speed and the nature (especially the slushiness) of the mixture of snow, ice, liquid and de-icing agents present atop the road. Research is needed to gain a better understanding of the response of this dynamic mixture to the pass of a single vehicle tire (i.e., to parameterize the spray, splatter, spread, suction, and compaction processes) at various rates of speed and under varying road and weather conditions.

Figure 3: Traffic can act to clear snow and ice from roads in some situations while acting to create worsened conditions in others. The nature of the relationship between traffic, road, and weather conditions needs to be researched further. The image above, captured during a PFS MDSS case study, is from a case where the snow and ice mixture was adequately slushy for traffic to clear the slush rather than compacting it into ice. The corresponding simulated cross-section from the PFS MDSS pavement model is shown in Fig. 1.

3.e. WINTER MAINTENANCE MODELING

The effectiveness of available de-icing agents within the PFS MDSS is dictated by the eutectic curves (phase diagrams) of those chemicals as well as by the manner/form in which they are applied (i.e., dry granular, prewet granular, or as a liquid solution). Unfortunately, there is no standard means of measuring one of the most heavily marketed aspects of the performance of many de-icing agents: the agent's 'aggressiveness'. It is well known that e.g. prewetting salt with exothermic materials can significantly boost the effectiveness of the salt. While the ultimate melting capacity of the salt may not be significantly changed by the prewetting process, its effectiveness is nonetheless enhanced because more of the salt is able to go into solution quickly before traffic and/or subsequent maintenance activities can remove undissolved granular salt from the road. As such, the development of a means for quantifying the rate of melting expected with various de-icing agents under various conditions would improve MDSS' ability to discriminate between various agents' expected performance.

Another research item identified during the PFS MDSS project is the need for the development of relationships that better parameterize the loss of residual chemicals from the roadway as a result of traffic, especially in the post-storm environment where small amounts of residual can make the difference between a wet road and a refreeze situation. These loss rates are known to vary as a function of road condition, material form (e.g. granular vs. liquid, dry vs. prewet) and traffic volumes, speeds, and types (e.g. truck vs. automobile). There is also known to be a significant difference between the residual loss rates for dry chemicals that have and have not been previously dissolved into solution atop the roadway. While numerous research studies have provided qualitative results hinting at the nature of the underlying processes (e.g., Mitchell et al, 2003), a more quantitative research approach is required in order to develop formulas that can reliably estimate the amount of chemical residual present at any given time.

4. CONCLUSIONS

The PFS MDSS project has significantly advanced the state of the science of modeling the roadway environment. However, many significant research needs remain that can and should be addressed within the road weather research community if the science is to continue to advance.

5. ACKNOWLEDGMENTS

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