PERFORMANCE METRICS AND TOOLS FOR WINTER MAINTENANCE OPERATIONS

J. Mewes
Iteris, Inc., United States
jmewes@iteris.com

ABSTRACT

The continued maturation of Maintenance Decision Support System (MDSS) technologies within the United States have enabled new approaches for near real-time evaluation of both the effectiveness and efficiency of winter maintenance operations. In general, MDSS utilize sophisticated road condition modeling techniques to integrate location-specific weather and road condition observations and forecasts, together with winter maintenance policies, practices and reported activities, to both track and predict how roads will respond to ongoing and pending / prescribed weather and maintenance activities. However, research being carried out in a fifteen-state Transportation Pooled Fund study has recently demonstrated that the underlying data tracking and simulation systems also hold substantial potential for supporting high-level evaluation of winter maintenance operations.

In one approach, weather data for each winter maintenance route are captured in real-time, archived, and then digested into various weather metrics that constitute the building blocks of the various winter severity indices already utilized by these agencies.

In another approach, this infrastructure is used to create detailed simulations of the road conditions resulting from the experienced weather conditions, and the maintenance activities that would have been required to treat those conditions. These simulations are highly customizable to localized environments, traffic, and maintenance policies and practices, thereby accounting for the unique situations that result in each location. This approach yields independent assessments of the justified maintenance resource utilization that can be compared against actual data. Thus, unlike approaches strictly based on weather, these approaches can account for variability in maintenance resource utilization owing to other localized factors.

For the purposes of evaluation, both approaches are being presented to managers in the respective agencies in a single graphical user interface. This interface provides various representations of the data relative to the agencies' road networks. An associated calculator tool permits the construction of multivariate equations based on these metrics, thereby permitting management personnel to e.g. track the severity of weather conditions using easily customizable weather severity indices supported by highly detailed weather information, or to assign costs to various aspects of the simulated winter maintenance activities so as to permit comparison against actual winter maintenance costs.

Over the course of the research, much has been learned on the strengths and weaknesses of these and related approaches to creating metrics against which maintenance operations can be evaluated. These findings, as well as examples of real-world utilization of these applications, will be presented.

1. BACKGROUND

The development of performance metrics for winter maintenance operations is a notoriously difficult problem. While measurement of the resources utilized in the practice of winter maintenance may be tracked in a number of different ways, evaluation of the effectiveness and efficiency of winter maintenance is hampered not only by variability in the weather, but also by variability in maintenance resource constraints and expected level of service.

Historically, agencies and other entities that undertake or are responsible for winter transportation maintenance activities have measured resource utilization in the performance in several ways. At the lowest level, deicer, abrasive, equipment, and labor usage are estimated and logged by individuals performing winter maintenance (perhaps using automated vehicle tracking technologies), or by their direct supervisors. At the highest level, an agency or entity may also track resource utilization through its procurement and/or payroll processes (e.g. the agency may have direct information as to the quantity of a particular resource it has purchased over a given timeframe).

In addition to tracking resource utilization, many agencies also define goals for the results of winter maintenance activities, and then attempt to measure the over- or under-achievement of these goals. This may be considered as an attempt to measure the 'effectiveness' of winter maintenance operations, and can be a far more difficult undertaking due to the inherent subjectivity involved in assessing road conditions, much less the difficulty of tracking changes to road conditions over time in response to maintenance activities that are in themselves addressing varying weather conditions.

Taken together, knowledge of winter maintenance resource utilization and winter maintenance effectiveness permit the determination of winter maintenance efficiency. There are inherent tradeoffs between resource utilization and the road conditions resulting from it, and efficiency measurement permits evaluation of these tradeoffs.

Complicating an efficiency measurement for winter maintenance activities is the variability of weather conditions. When comparing data from one area to another, or one storm or weather pattern to another, the variability of weather conditions makes it very difficult for winter maintenance managers to know whether the maintenance response was appropriate for the weather conditions being treated. This hinders management's ability to identify which practices and approaches are more effective or efficient, since it is difficult to ascertain whether any particular comparison over time, or between maintenance jurisdictions, is appropriate. Naturally, this impedes the ability of the agency or entity to identify and implement practices and policies which improve winter maintenance effectiveness and efficiency.

One traditional approach to addressing this problem is to develop a winter severity index, which is an attempt to quantify, often in a single figure, the impact of varying weather conditions on winter maintenance. There are, however, numerous problems with such an approach to quantification. One problem is that this approach is developed by drawing simplified and often statistical relationships between past weather conditions and historical agency resource utilization. Thus, such indices are typically simply a reflection of an agency's historical response to weather conditions, and thus not necessarily a reliable and independent metric. This is reflected in the fact that there are strikingly few instances of an agency successfully adopting and applying a winter severity index developed within another agency. Almost invariably, each agency will change the index, or develop a new index altogether, that better explains the relationship it has historically experienced between weather conditions and maintenance data.

This ad-hoc, agency-to-agency approach makes cross-jurisdictional comparisons of maintenance efficiency very difficult. Additionally, the value of winter severity indices is inherently limited because of the gross oversimplification of the underlying relationships. The same weather conditions may elicit an entirely different (yet still appropriate) winter maintenance response depending upon traffic patterns, maintenance policies and resources, and the characteristics of the ambient environment the roads are embedded in. None of these factors can be accounted for by a normalizing metric that is based upon weather alone.

2. MODEL-BASED APPROACHES TO QUANTIFYING WINTER SEVERITY

While winter severity indices have certainly proven useful to many agencies' efforts to evaluate winter maintenance efficiency, the aforementioned limitations continue to impede the industry's ability to reap the intended benefits. In response, a group of fifteen state transportation agencies have funded a fresh look at the problem under the U.S. Federal Highway Administration's (FHWA) "Maintenance Decision Support System" (MDSS) Transportation Pooled Fund Study (PFS) TPF-5(054) [1].

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 approach focuses on simulation of a 'dynamic layer' consisting of freeze point depressants, abrasives, and various forms of moisture (e.g., snow, ice, frost, liquid) residing atop the roadway. Analyses of past and present weather conditions are integrated with Road Weather Information System (RWIS) observations, as well as road condition and maintenance activities reports, to provide an ongoing assessment of the past and present states of the roadway. This ongoing assessment of the initial state of the dynamic layer is used in concert with weather forecast and available maintenance resources information to simulate the expected evolution of the dynamic layer, identify problematic conditions, and identify treatment options. Minimization techniques are used to find candidate maintenance actions that will maintain the required level of service in the most economical manner for the available human, equipment, and material resources.

In essence, the PFS MDSS therefore has the ability to simulate both the road conditions and winter maintenance activities required in response to interactions between weather, traffic, and environmental factors as well as the maintenance policy and resource constraints of the agency. While originally developed for real-time application, this capability opens the door to what may be called a "model-based approach" to normalizing winter maintenance data for varying situations [2]. Traditional approaches attempt to identify, based on historical data,the relationships between parameters that summarize the weather conditions over a given period of time and the corresponding utilization of maintenance resources. Conversely, a model-based approach provides the potential for direct simulation of the specific maintenance requirements of each and every unique situation. Utilization of a road condition model that simulates the relationships between weather conditions, traffic, road conditions, and maintenance activities is key to this class of approach.

Model-based approaches require complex and comprehensive simulation systems that have only recently become available. Such systems include the PFS MDSS, but also systems such as the Winter Model under development by the Swedish National Road and Transport Research Institute (VTI) [3]. The Winter Model consists of sub-models for assessing the state of the road (which is the key to all other models), the effects and their monetary value, and the optimization.

In the current MDSS-based approach, weather conditions are defined over a period of time at an hourly level, drawing upon a variety of meteorological data resources. The system then utilizes a road condition model to simulate road conditions over time, influenced by weather conditions, maintenance actions, traffic, environmental factors, etc. This requires simulation of processes such as radiation, heat and moisture exchanges between the atmosphere, the pavement, and its substrate; natural and chemically-induced phase changes; external factors such as the effects of traffic spray, splatter, and compaction on both road moisture and material residuals; and the actions of maintenance vehicles. The system can also ingest information regarding maintenance policies and resource constraints. This additional input data modulates the simulation of the road condition model with maintenance responses to weather conditions by applying either a rules-based model for a specific weather and road condition situation (e.g. based on an agency's 'standard practices'), or a dynamically-determined maintenance prescription based on available maintenance resources. The resulting weather, road condition, and maintenance data can then be applied in various data processing functions that explore the relationships between, for example, simulated and real-world costs and conditions.

From the perspective of a winter severity or maintenance demand index, one distinction offered by model-based approaches are that they yield an explicit simulation of the winter maintenance activities required to address the weather and road conditions, rather than attempting to draw expert-based or statistical relationships between simplified representations of the weather conditions and maintenance activities, based on historical actions which may or may not have been appropriate, or required, to meet the desired level of service. While the resulting data can be used as the basis for one or more specific indices intended to normalize specific aspects of winter maintenance resource utilization, the simulated data itself is the unique building block offered by this approach, as it removes the mystery from the relationships between weather, road conditions, and maintenance activities. The relationships between cause and effect become more clearly identifiable, as the (e.g.) hour-by-hour time-series of weather, road condition, and simulated maintenance activity requirements are directly available to support assessment of the actual operations of the agency for the selected time period. Further, the factors which impact how one agency prefers to react to a given weather situation can be explicitly accounted for by the simulation, permitting the tool to be applied across jurisdictional boundaries with confidence. For example, the effects of varying levels of service (road condition policies), traffic patterns, available deicers and their environmental limitations, crew and equipment availability, etc., can all be explicitly configured into and accommodated by the simulation process, providing a realistic basis for comparison of data across jurisdictional boundaries where these factors may differ, or even within different parts of the agencies' road networks where practical considerations necessitate different real-world responses to similar weather conditions.

3. QUANTIFICATION TOOLS

In order to facilitate evaluation and application of these potential new approaches to aiding performance measurement, an operational data collection and simulation system has been established over a large area maintained by the PFS MDSS member agencies. A block diagram of the system architecture is provided in Figure 1.

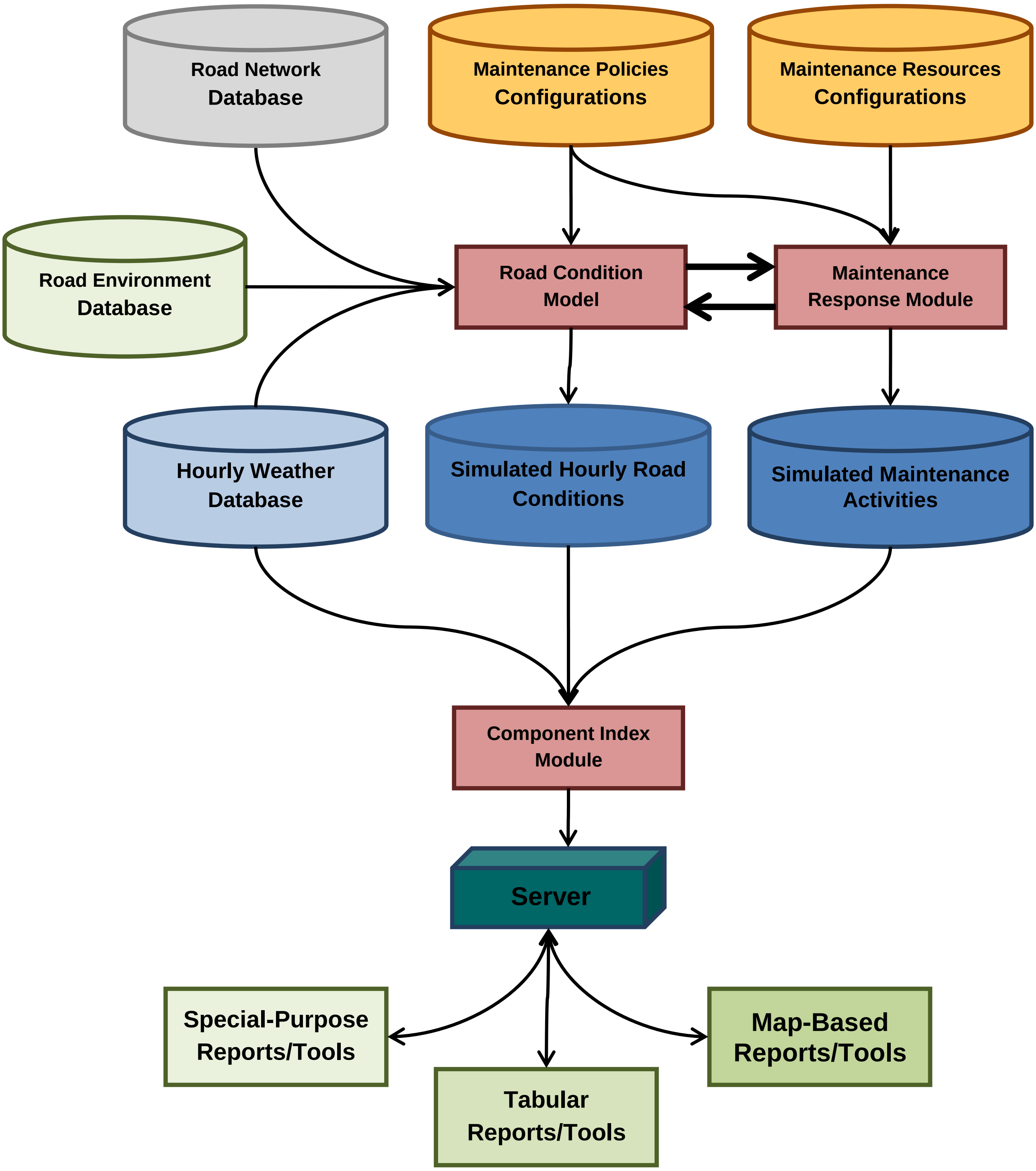


Figure 1: A block diagram of the winter maintenance simulation system architecture.

Additionally, a graphical user interface (GUI) has been developed by which agency personnel can visualize, manipulate and export the resulting data. The GUI permits the selection of a time period of interest, so that winter maintenance activities can be analyzed for a particular shift, weather pattern, day or storm, over an entire season, or from season-to-season, in a single display. Data are available in several forms, including graphical depictions of the time series of weather and simulated road and maintenance data for a particular segment of road over the selected timeframe (Figure 2), as well as map-based representations and export capabilities for aggregated data (Figure 3). In these latter spatially-oriented presentations, data are presented in the form of aggregate metrics that may be useful for quantifying conditions over the selected timeframe. These metrics are intended, in part, to serve as the building blocks for weather severity indices. These metrics may include, for example, averages, accumulations or durations of different aspects of the weather or types of weather conditions. Similar aggregate metrics are available for quantifying road conditions and simulated maintenance activities. The export capabilities are intended to permit external application of the data, such as in Maintenance Management Systems (MMS) that focus on higher-level asset management (e.g., time tracking, equipment purchasing/servicing, material procurement and allocation, etc. for winter maintenance).

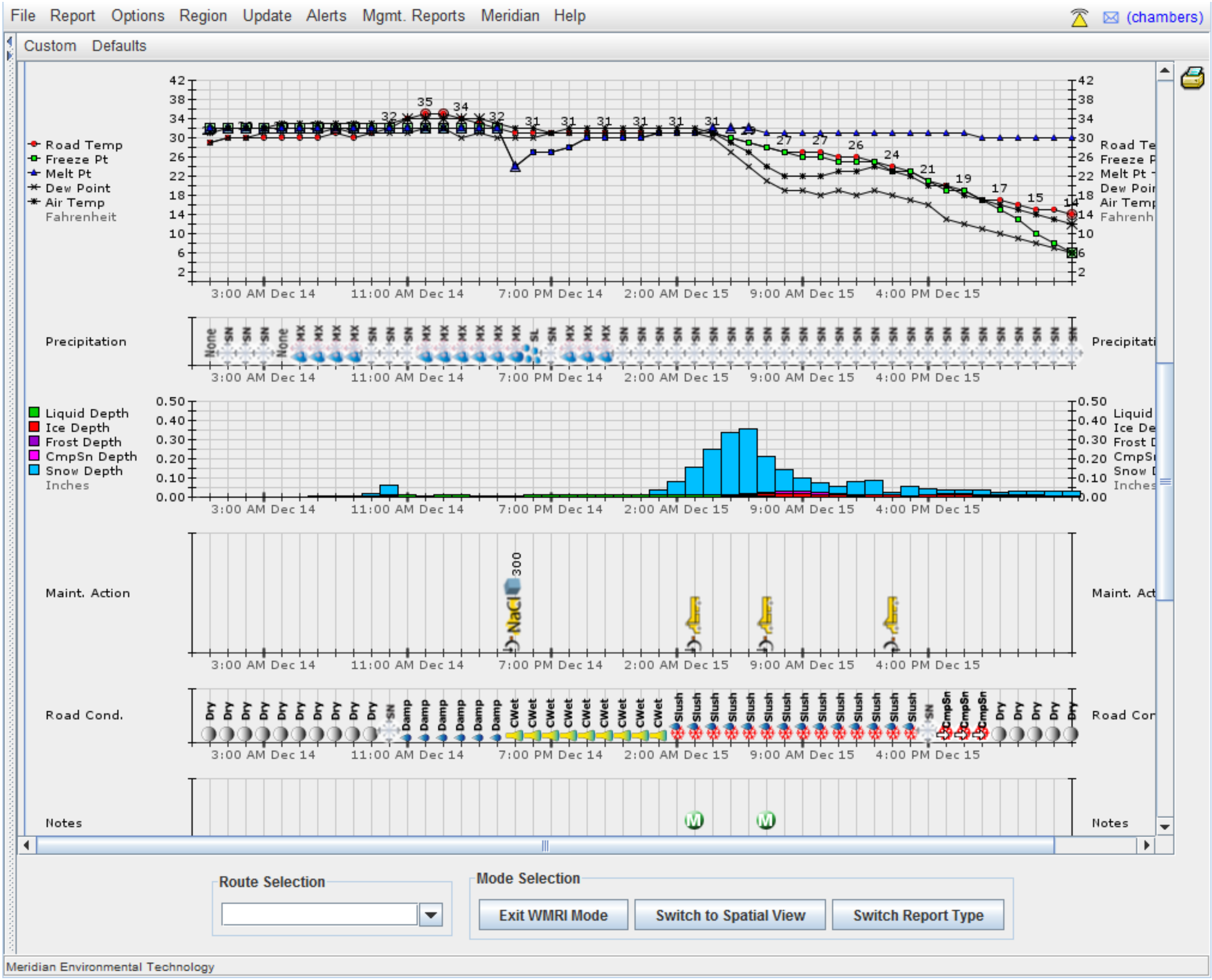


Figure 2: A graphical time-series presentation of data for a particular winter maintenance route, including weather conditions as well as the simulated road conditions and expected snowplow activities.

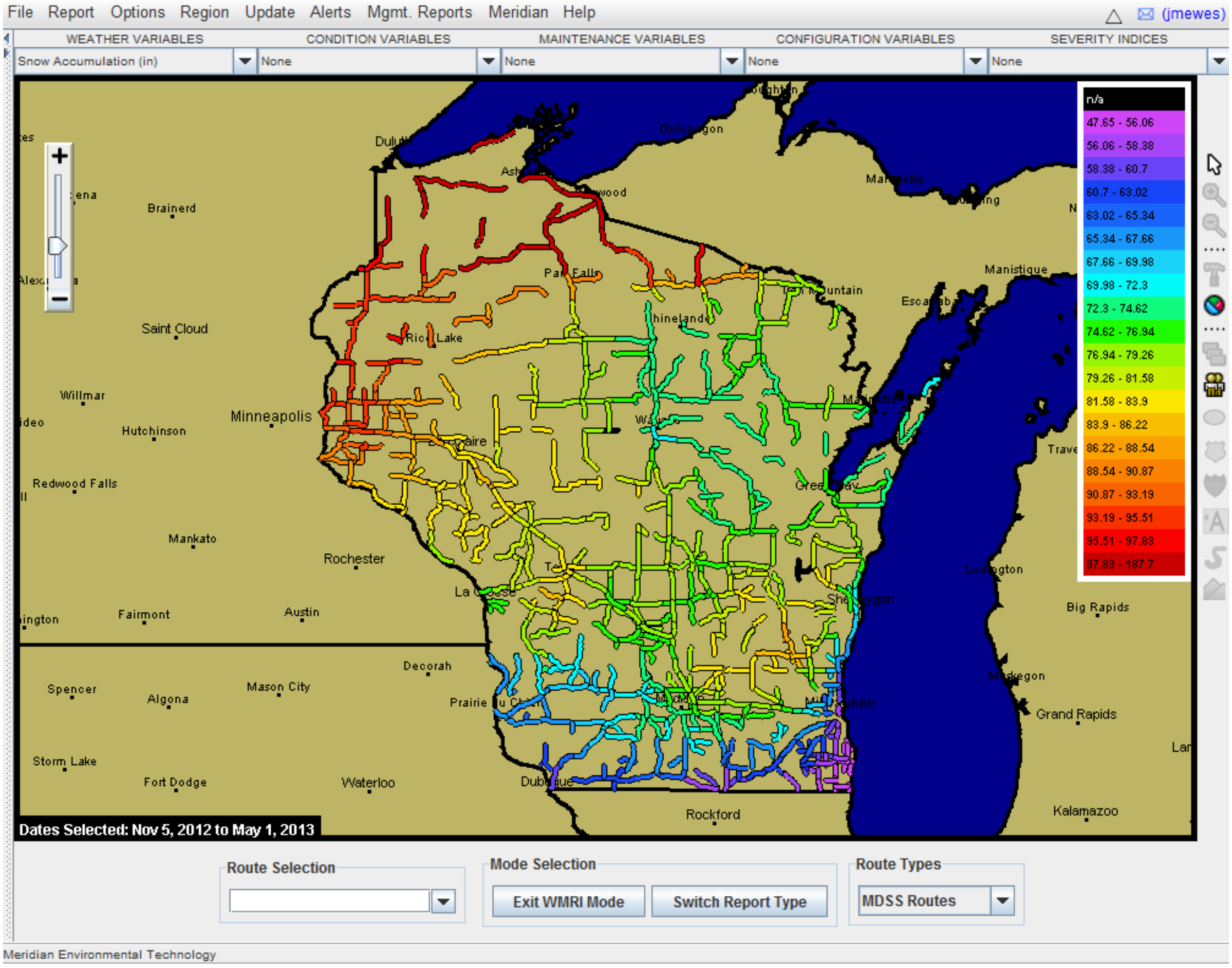
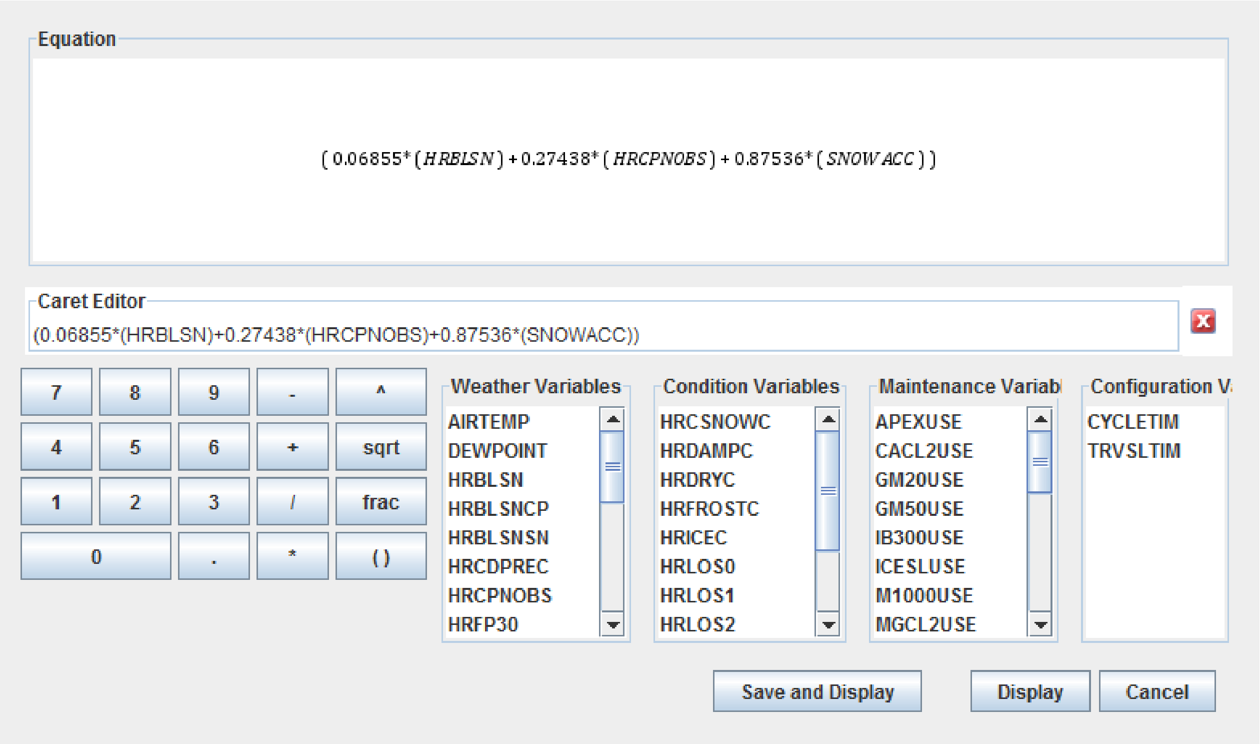

WEATHER VARIABLES: Snow Accumulation (in)
CONDITION VARIABLES: None
MAINTENANCE VARIABLES: None
CONFIGURATION VARIABLES: None
SEVERITY INDICES: None
Dates Selected: Nov 5, 2012 to May 1, 2013
Route Types: MDSS Routes

Figure 3: A map-based presentation of one of many available winter severity metrics, in this case the metric being total snow accumulation during the selected time period across the state of Wisconsin.

In order to facilitate broader application of the data, an equation editor is also made available to users (Figure 4). This equation editor permits users to create and display multivariate calculations based upon the aforementioned weather, road condition, and/or maintenance metrics. For example, a user may multiply the per-mile (or km) simulated quantity of a deicer by its associated unit cost, and then add the per-mile (or km) cost of operating the truck multiplied by the simulated number of maintenance actions, to arrive at an overall, simulated cost of winter maintenance per-mile (or km) for the selected time period. Alternatively, if a user desires to compare and contrast the simulated data with more traditional measures of winter severity, the tool can be used to specify the equation for the particular winter severity measure, at which point the underlying weather data are applied to calculate and display the desired winter severity measure. This provides transportation agencies with a convenient mechanism for comparing and contrasting various approaches and/or equations for quantifying winter severity.



$$(0.06855*(HRBLSN)+0.27438*(HRCPNOBS)+0.87536*(SNOWACC))$$

(0.06855*(HRBLSN)+0.27438*(HRCPNOBS)+0.87536*(SNOWACC))

Figure 4: An equation editor permits on-the-fly construction and visualization of multivariate winter severity measures based on a large number of available winter severity metrics, enabling users to apply preexisting equations for quantifying winter severity using a common underlying dataset.

4. OPERATIONAL EVALUATION

While research and development oriented toward improving both the toolset and the underlying data continue, the system has been used in both case study and operational settings by the transportation agencies that make up the MDSS Pooled Fund Study. The first such application was to aid a cost/benefit study for the MDSS system itself. In the analysis of potential benefits of MDSS, it was useful for the (independent) research team to have a long period of high-fidelity weather and road condition data upon which potential costs and benefits could be modeled [4]. Given that these data were not generally widely available from independent resources, the idea that the software underlying the MDSS system had the capacity to generate the desired data gained favor. Available historical weather, road condition and winter maintenance data for a selection of locations across the United States were acquired and used as control data against which the more complete simulated data could be compared. One of the datasets that falls out of this simulation process is the simulated salt usage and other maintenance resources (e.g., equipment and labor) over time. Comparisons of actual annual winter maintenance resource utilization against the simulated data strongly validated the idea that the appropriate winter maintenance response to weather conditions could be simulated. An example comparison of simulated and actual salt usage on a stretch of Interstate 93 in southern New Hampshire is provided in Figure 5. Multi-year correlations in various measures of resource utilization were generally found to range between 0.85 and 0.99 at the various locations across the country selected for study. In general, agreement between the simulated and actual data for a particular winter maintenance route often exceeded the level of agreement between actual data from adjacent maintenance routes.

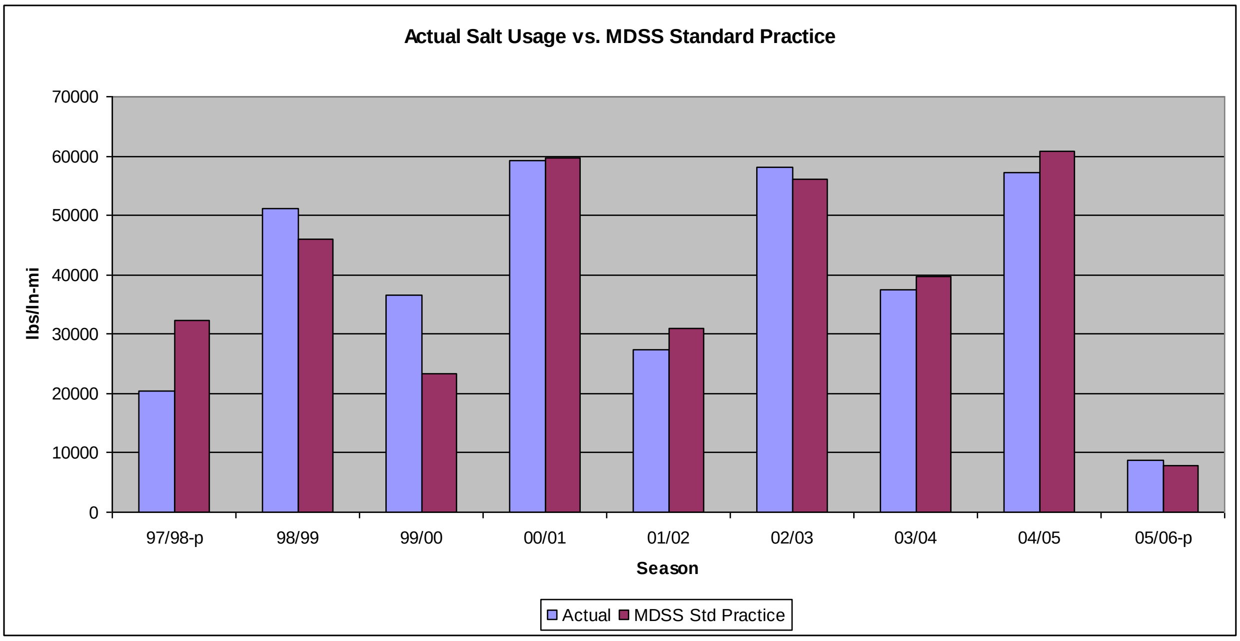
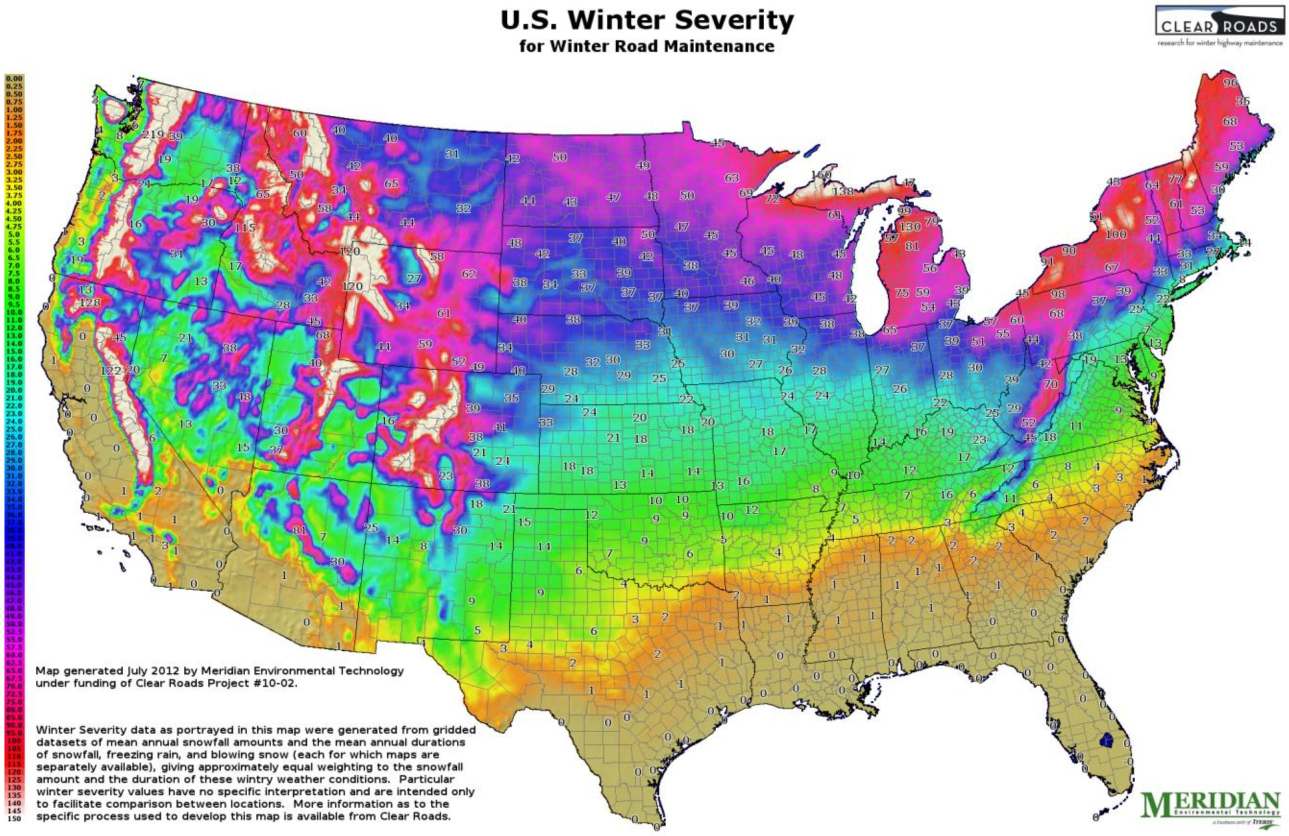


Figure 5: Simulated and actual salt usage on a high-volume winter maintenance route on I-93 in southern New Hampshire.

In spite of the initial success, further application of the system in an operational setting has revealed numerous, difficult obstacles to successful implementation of such a system. One problem is that the simulation system requires weather data that is not widely available, such as hourly snowfall amounts and downwelling radiation data. While special algorithms and multi-sensor approaches to assessing weather conditions permit construction of these data, research into the causes of irregularities in the simulated data have revealed very substantial differences in the sensitivity of different weather stations to similar conditions. While often inconspicuous in real-time, analysis of long periods of data from neighboring weather stations often tends to reveal disturbing differences in aggregate measures of weather conditions, particularly wintertime precipitation. The differences in e.g. the number of hours of snowfall during a winter season, as indicated by weather stations in close proximity to one another, are often of greater magnitude than what are believed to be the actual differences in weather conditions across much greater distances. This station-to-station variability makes reliable spatially-oriented comparison of weather conditions based on this data difficult to impossible.

In light of this issue, and in response to a request for the development of historical winter severity maps for the contiguous United States by the Clear Roads consortium, the same MDSS research team explored the potential for using data from weather forecast models as an additional resource in quantifying the severity of winter weather conditions [5]. While these computer-based forecasts do not always verify perfectly, they do provide two distinct advantages over weather observing networks: they produce scientifically-based weather data at a very high spatial resolution, and they produce a reasonably uniform response to similar weather conditions regardless of location or the availability of sensor networks. In this Clear Roads project, archived computer model data were loosely fit to available weather station records so as to produce high-resolution gridded weather data metrics that are grounded in reality (without being over-fit to station biases). Four separate datasets were generated for the project: annual snowfall amount, annual snowfall duration, annual duration of freezing rain, and annual duration of blowing/drifting snow. Using a simple equation, these datasets were then combined into one representative map of the overall severity of winter weather conditions from a winter maintenance perspective (Figure 6).

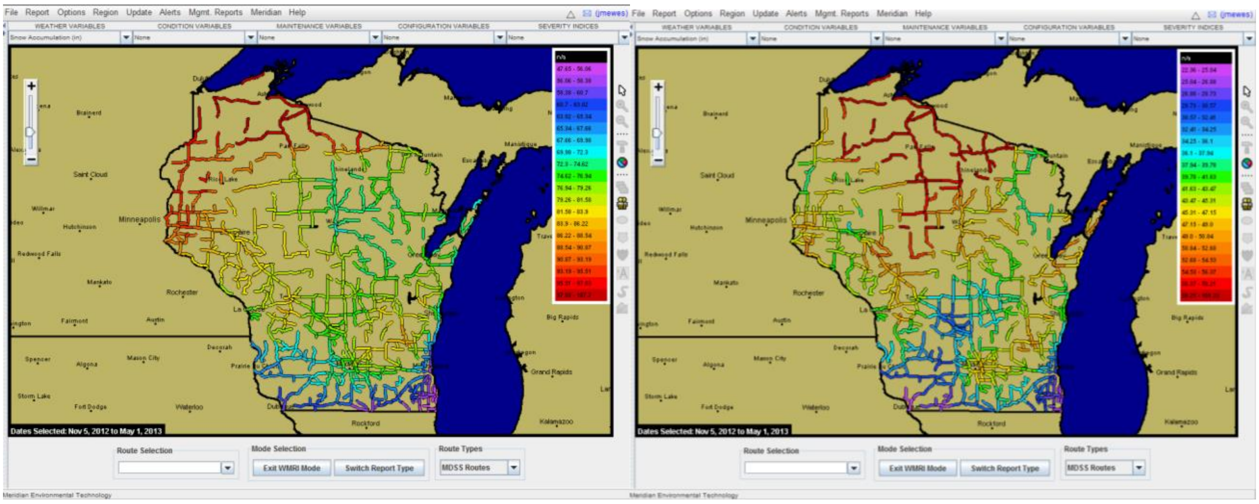


Map generated July 2012 by Meridian Environmental Technology under funding of Clear Roads Project #10-02.

Winter Severity data as portrayed in this map were generated from gridded datasets of mean annual snowfall amounts and the mean annual durations of snowfall, freezing rain, and blowing snow (each for which maps are separately available), giving approximately equal weighting to the snowfall amount and the duration of these wintry weather conditions. Particular winter severity values have no specific interpretation and are intended only to facilitate comparison between locations. More information as to the specific process used to develop this map is available from Clear Roads.

Figure 6: Winter severity map for the contiguous United States, based on a new approach that leveraged both observed and short-term forecasts of weather conditions.

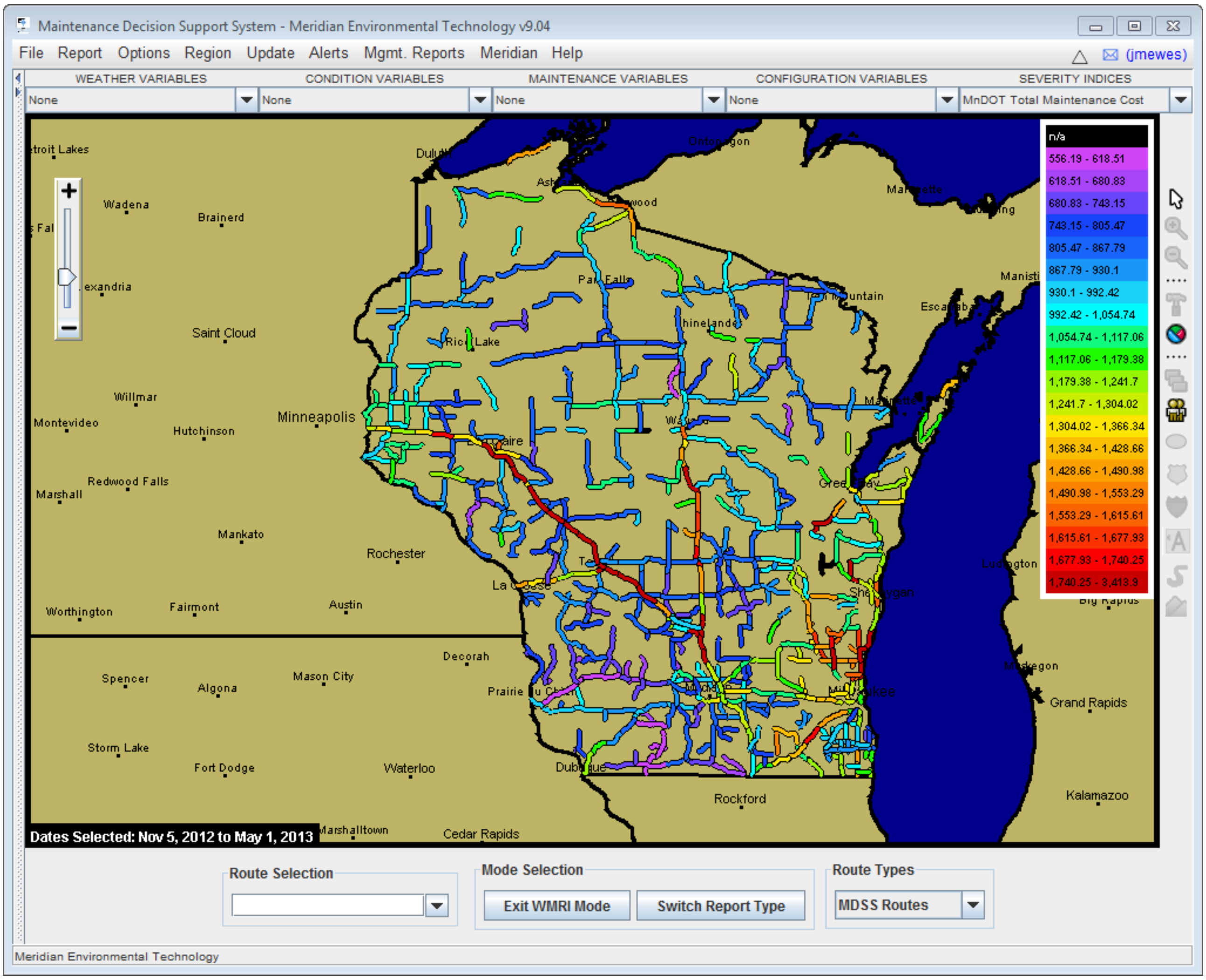
Following a similar approach, the operational system now tracks and utilizes data from two independent weather data resources: 'analyzed' weather and 'forecast' weather. The analyzed weather data is derived using multi-sensor approaches to assessing the weather conditions any particular maintenance route is exposed to. The forecast weather dataset is a concatenation of the shortest-term weather forecast data from all weather forecasts issued to the agency over the course of the winter season. (In the present case, these forecasts are gridded datasets containing ensemble computer weather model data, manipulated in real-time by meteorologists to match real-time trends in weather conditions.) While the two approaches yield similar information concerning many aspects of the weather, they can show substantial differences when a particular area is poorly observed, or represented by a weather station with a particularly egregious bias in the sensitivity of its precipitation sensors (see Figure 7).



Dates Selected: Nov 5, 2012 to May 1, 2013

Figure 7: Independent assessments of seasonal snowfall accumulation across the state of Wisconsin using a compilation of data from short-term forecasts of weather conditions (left) and a multi-sensor analysis of weather conditions (right). The forecast-based approach is subject to forecast errors, while the analysis-based approach is subject to sensor biases and other sensor network shortcomings. Agreement between the two datasets, or the lack thereof, can be used as an indicator of confidence in the patterns.

One of the potential benefits of the model-based approach is that it can reflect the influence of other localized factors, such as traffic volumes, roadway construction and/or environment, and local variations in winter maintenance practices or resource constraints. In many locales, it is common practice to expend an order of magnitude more resources in maintaining high-volume roads relative to lower-volume roads. This is a result of both the impact of traffic volume as well as the importance of maintaining a higher level of service on the roadways that carry the most traffic. These localized influences make comparison of the effectiveness and efficiency of winter maintenance activities between different jurisdictions difficult. Fortunately, the model-based approaches present the possibility of directly simulating the influence of these localized factors, such that the corresponding winter maintenance operations data can be normalized for these variations as well as varying weather conditions (compare, for example, the snowfall accumulations from Figure 7 with simulated per-lane-mile cost of winter maintenance over the same period in Figure 8).



WEATHER VARIABLES: None
CONDITION VARIABLES: None
MAINTENANCE VARIABLES: None
CONFIGURATION VARIABLES: None
SEVERITY INDICES: MnDOT Total Maintenance Cost

Dates Selected: Nov 5, 2012 to May 1, 2013

Route Types: MDSS Routes

Figure 8: A model-based approach offers the prospect of normalizing winter maintenance data for localized influences such as traffic volume, roadway environment, or local variations in winter maintenance practices, in addition to the weather-based normalization offered by more traditional approaches to quantifying weather severity.

As also discussed previously, another benefit of model-based approaches is that the relationship between weather conditions and the resulting simulations of the resource utilization justified by those conditions is much clearer. The simulation system provides detailed time series of road conditions and the maintenance activities that were required to address each situation (such as is shown in Figure 2), each of which are directly comparable to real-world data (such as in Figure 9).

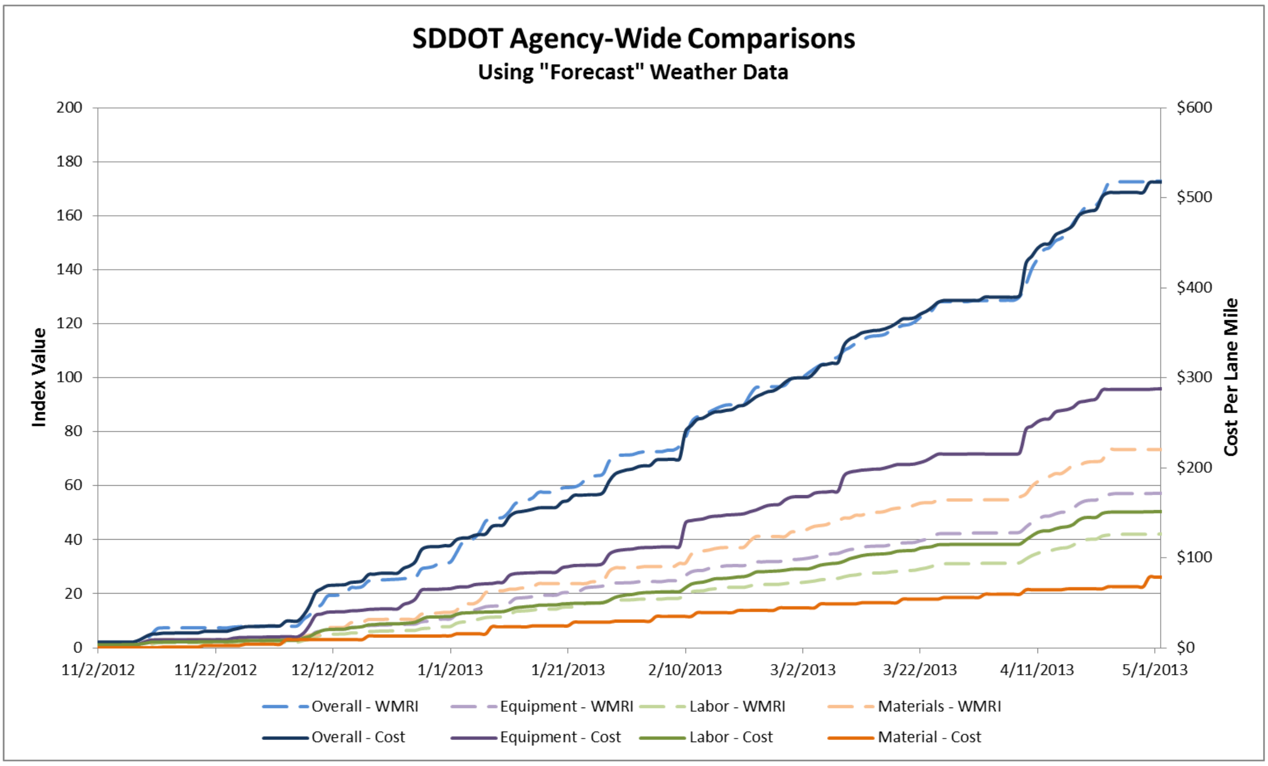


Figure 9: The model-based approach permits direct comparison between actual agency costs and simulated costs. In this variant, where the simulated data is represented as the “WMRI” fields, it is notable that the total cost of winter maintenance (per lane mile) across the state of South Dakota accrued at approximately the same rates and dates in both the actual and simulated cost data, but that the apportionment of those costs between materials and equipment (in particular) was substantially different. This is perhaps a reflection of an operations trade-off that is often considered by transportation agencies.

5. CONCLUSIONS

Modern weather data acquisition, integration and forecasting systems are providing a wealth of data that can be stored and utilized to track the severity of weather conditions as a means of facilitating performance evaluation for winter maintenance operations. Additionally, systems for simulating the interactions between weather, traffic, road conditions, and maintenance activities, such as MDSS, are providing further opportunities for better understanding the relationships between weather conditions and the use of maintenance resources.

Real-world applications to date have shown considerable promise for furthering the use of these systems to improve performance measurement in winter maintenance operations. At the same time, these applications have also revealed a number of obstacles that are easily missed or misunderstood if the data are blindly applied. In particular, the unpredictable biases of individual weather stations and the irregular distribution in coverage of weather sensor networks can obscure the signal in data owing to the true, underlying variations in the weather conditions themselves.

Further, while the additional layer of understanding the road condition and maintenance activity simulation systems can provide holds potential value, it also requires an understanding of what drives the simulation system to arrive at a particular solution. For instance, real-world decisions are made every day by maintenance personnel that impact the apportionment of costs between equipment, labor and materials, as well as the overall cost of maintenance, and these decisions may differ from how the model chooses to address a particular situation. Further, while the simulation system may be capable of simulating the impact of e.g. traffic and maintenance activities on road conditions, it is exceedingly difficult to validate how well these processes are being modeled, in part because of the difficulty associated with obtaining quantitative measurements of road conditions over time. As such, when differences are noted between simulated and actual maintenance resource utilization, it is difficult to know whether it is an indication of sub-optimal maintenance practices, or if it simply owes to inappropriate model configurations and/or shortcomings in the model itself.

Research to continue to better understand and address these and other issues is continuing under the Pooled Fund Study MDSS project.

6. ACKNOWLEDGEMENTS

This research has been funded in part under FHWA Transportation Pooled Fund Study TPF-5(054), Development of Maintenance Decision Support System, sponsored by the South Dakota Department of Transportation in partnership with 14 other state transportation agencies, the FHWA, and the Aurora consortium; under FHWA Transportation Pooled Fund Study TPF-5(218), Clear Roads Pooled Fund Study Project 10-02; and under South Dakota Department of Transportation Office of Research Project 2008-09.

7. REFERENCES

1. Mewes, J., R. Hart, L. Osborne, B. Hershey and D. Huft (2008): Maintenance Decision Support Systems: Research Progress and Continuing Needs. Preprints, American Meteorological Society 24th International Conference on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology. New Orleans, Louisiana, 2008.
2. Kuntz, J., L. Osborne, and J. Mewes (2008): Use of a Maintenance Decision Support System to Define Winter Severity Indices. Preprints, American Meteorological Society 24th International Conference onInteractive Information Processing Systems (IIPS) forMeteorology, Oceanography, and Hydrology. New Orleans, Louisiana, 2008.
3. Wallman, Carl Gustaf (2004): *The Winter Model: A Winter Maintenance Management System*. Transportation Research Circular E-C063, Transportation Research Board, National Research Council, Washington, D.C., pp. 83-94.
4. Ye, Z., Strong, C., Shi, X., Conger, S., and Huft, D. (2009): *Benefit-Cost Analysis of Maintenance Decision Support System*. Transportation Research Record 2009, 2107, 95-103. DOI: 10.3141/2107-10.
5. Mewes, John J. (2012): *Mapping Weather Severity Zones.* Clear Roads Pooled Fund Study TPF-5(218) Project 10-02 Final Report. http://www.clearroads.org/research-projects/10-02mapping-weather-severity-zones.html