THE USE OF METRO
(MODEL OF THE ENVIRONMENT AND TEMPERATURE OF THE ROADS) IN ROADWAY OPERATION DECISION SUPPORT SYSTEMS

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1 INTRODUCTION

Road maintenance operators face numerous challenges when making decisions about how to control snow and ice build up on the roadways during adverse winter weather. Over the last several decades, there have been numerous advancements that have helped mitigate some of the impacts weather has on road conditions such as the introduction of more effective treatment alternatives, new types of treatment strategies and improvement in the equipment used to service the roads. However, two of the most important factors related to optimizing treatment strategies are the ability to know the evolution of road weather conditions during a winter weather event and the understanding of how to employ this knowledge based on best practices for effective anti-icing and deicing. Until recently, the winter maintenance community has had to rely on conventional methods of acquiring, synthesizing, and applying road weather-related intelligence in the treatment decision process, which in some cases, can result in information overload and poor winter maintenance decisions (treatment types, timing, rates, and locations) (Petty et al. 2007).

In the late 1990s, the Federal Highway Administration (FHWA) Road Weather Management Program realized the need to address the challenges faced by the winter maintenance community in terms of effectively using road weather information in the maintenance decision making process. There were plenty of weather forecasts available to winter maintenance practitioners, and some companies even issued road-specific forecasts. However, there was no link between the road weather information and the decisions made by maintenance personnel. It was this disconnect between meteorology and surface transportation that became the genesis for the winter Maintenance Decision Support System (MDSS) (Pisano et al. 2005).

The MDSS is designed to provide winter maintenance managers and crews with objective guidance regarding the most appropriate treatment

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strategies to employ during adverse weather events. This guidance is based in large part on current and predicted weather and road conditions. The MDSS utilizes a pavement model to predict the state of the roadway, including road temperature and road conditions. In the past, the MDSS has used a one-dimensional mass and energy balance model called SNTHERM, which was developed by the U.S. Army Cold Regions Research and Environmental Laboratory (CRREL). Since SNTHERM is no longer being actively developed and supported, there was a need to implement a new pavement condition model. Through research and statistical evaluation of publicly available models, a Canadian model called the Model of the Environment and Temperature of the Roads (METRo) was identified as the leading replacement.

This paper describes the use of METRo within the MDSS framework. A brief summary of the MDSS is supplied. This is followed by an introduction to METRo. The remainder of the paper discusses the challenges and limitations of implementing METRo, as well as the benefits of using the model as part of a decision support system. Finally, a preliminary assessment of its performance under a variety of different weather conditions is provided.

2 BACKGROUND

In 2000, the concept of the Maintenance Decision Support System (MDSS) was conceived. FHWA's vision was an automated end-to-end decision support system that had the capacity to provide users with diagnostic and prognostic weather and road condition information, as well as guidance about how to treat roadways prior to and during winter weather events. In an effort to create a system that would fulfill this vision, the FHWA initiated the MDSS project. During the course of the project, five national research centers have contributed to the development of a prototype MDSS. The participating laboratories include the Army's Cold Regions Research and Engineering Laboratory (CRREL), National Center for Atmospheric Research (NCAR), Massachusetts Institute of Technology – Lincoln Laboratory (MIT/LL), National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL), and NOAA National Severe Storms Laboratory (NSSL).

An initial version of the FHWA MDSS Functional Prototype (FP) was developed and released for public use in 2002. Since that time, there has been a considerable amount of MDSS-related research and development, which has resulted in four subsequent prototype releases. The system has been demonstrated each winter over the state of Colorado since 2004.

The MDSS supplies end users with strategic information in the form of hourly forecasts of atmospheric and road conditions out to 48 hours at user-defined locations; forecasts are updated every three hours. Weather and road condition observations, along with radar and satellite products, present a source of tactical information. Atmospheric predictions include, but are not limited to, forecasts of ambient air temperature, dew point temperature, wind speed, and precipitation occurrence, type, and rate. The system also provides probabilities of precipitation and conditional probabilities of precipitation type. Forty-eight hour forecasts of road-related parameters such as road and bridge temperature, road mobility, and chemical concentration are also provided to decision makers. The prototype also combines predicted environmental and road condition information, along with standard practices for effective anti-icing and deicing, to derive route-specific treatment recommendations. Such treatments can be used by winter maintenance personnel as guidance as to what actions should be taken to maintain the highest level of service possible along each route of interest (Petty et al. 2007).

The MDSS is designed using a modular framework. This type of development model allows those responsible for setting up and operating the system to efficiently modify and update components without having to consistently augment other parts of the overall system. The modular framework also enables components to be easily added or removed, depending on the needs and requirements of the end user. The MDSS demonstrated in Colorado has utilized four primary components: 1) a numerical weather prediction system, 2) a road weather data forecast and data fusion system, 3) road condition and treatment module, and 4) a Java-based display system (Petty et al. 2007). Figure 1 shows a system overview of the MDSS, as it pertains to how the system has been set up and run for the most recent Colorado demonstration.
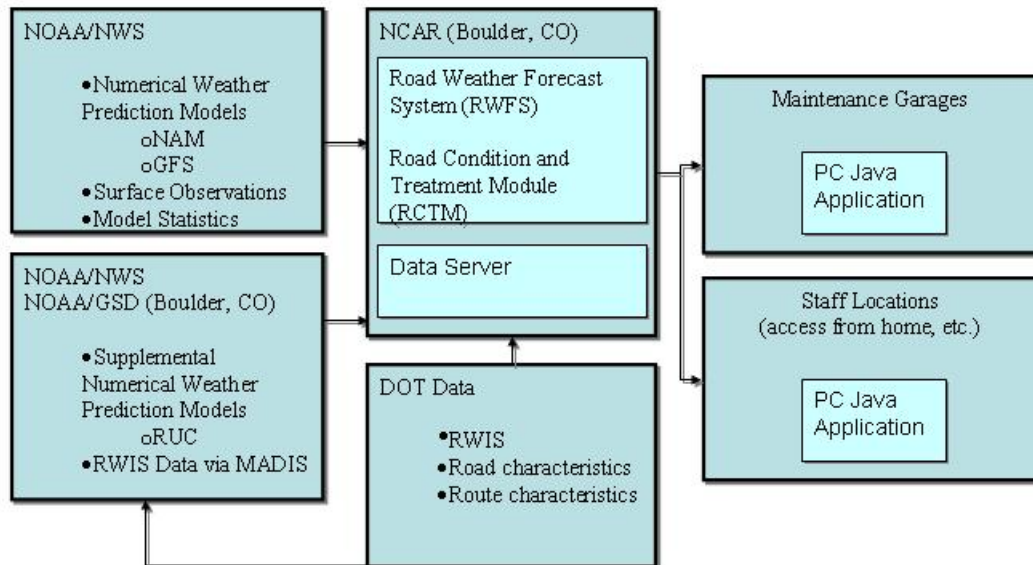

FIGURE 1. MDSS FP system overview.

The Road Condition and Treatment Module (RCTM) is considered to be the focal point of the MDSS, as its function is to produce road condition forecasts and treatment recommendations. A detailed depiction of the RCTM is provided in Figure 2. Note that the RCTM comprises several modules including a road temperature and snow depth module, net mobility module, rules of practice module, and chemical concentration module. Previous versions of the RCTM relied on SNTHERM to forecast pavement temperatures and road conditions. Recently, a rudimentary study was conducted to find a suitable replacement for SNTHERM. The investigation into a replacement model focused on several criteria including forecast performance, code stability, support, efficiency, and ease of use. In the end, the decision was made to incorporate METRo into the RCTM.
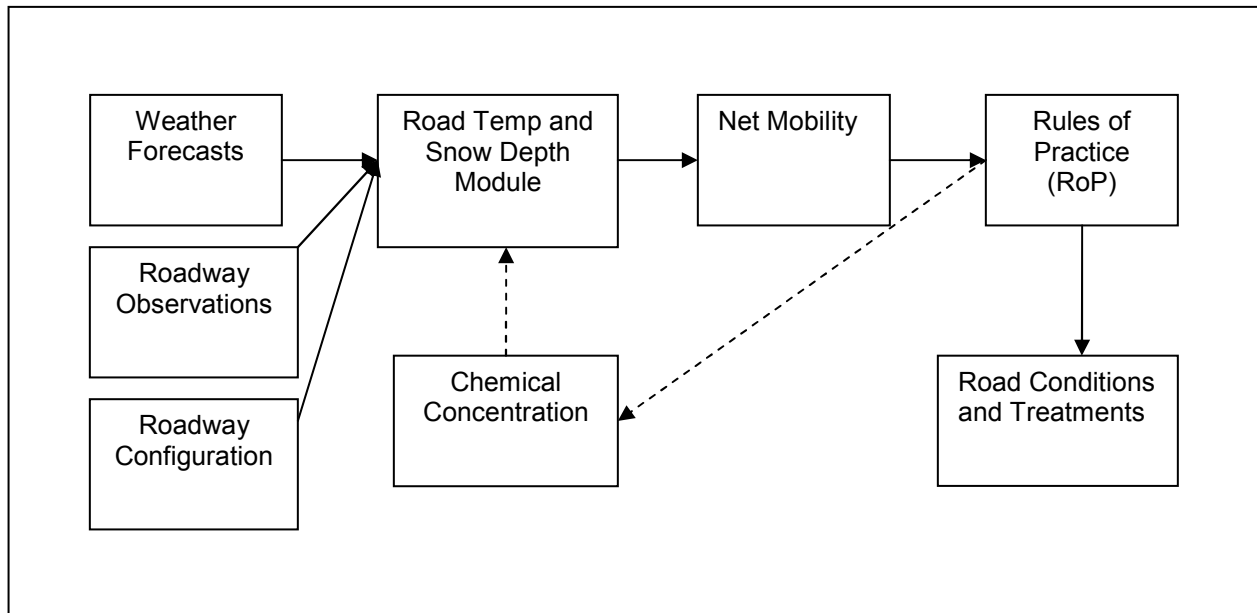

FIGURE 2. Road Condition and Treatment Module (RCTM) data flow diagram. Dashed lines indicate the data flow if the Rules of Practice module determines that a treatment is required.

3 METRo OVERVIEW

METRo is an operational model developed and used by the Meteorological Service of Canada, and it has been designed specifically to forecast local pavement temperatures (surface and subsurface) and road condition. METRo uses roads surface observations along with a weather forecast to predict the evolution of pavement temperatures and the accumulation of precipitation on the road (liquid and solid forms).

METRo is composed of three parts: an energy balance module for the road surface, a heat-conduction module for the road material, and a module to deal with water, snow and ice accumulation on the road. In determining the surface energy balance, METRo examines and computes short, longwave, and turbulent fluxes, as well as the flux related to the phase change of precipitating water. METRo also attempts to account for anthropogenic contributions such as the global effect of friction from automobile tires and heat released by the engines. A one-dimensional heat diffusion equation serves as the basis for computing the subsurface temperature profile, with key parameters being heat capacity and ground heat flux. METRo is capable of computing profiles for both roads and bridges. Finally, METRo has the capacity to simulate liquid water and snow or ice on the pavement surface by tracking and calculating key elements such as precipitation, evaporation, and runoff. The removal of snow resulting from the traffic can also be parameterized in the model (Crevier and Delage 2001).

METRo includes an observation assimilation mechanism to help initialize the forecast. This allows the system to be tuned to site-specific observations (Crevier and Delage 2001). The model requires at least some road surface and, if available, subsurface observations to initialize the road temperature profile.

This requirement will be discussed in more detail later in the paper.

4 CHALLENGES / LIMITATIONS

As with all forecast models, there are some challenges and limitations associated with using METRo. The issues described herein are related to implementing the model within the MDSS framework but may also pertain to running the model in a standalone mode.

METRo was developed for Linux platforms only. In order to use the model on other operating platforms (e.g., Windows), the code would need to be ported to those systems. This would not be too difficult, but it would be best accomplished in close collaboration with METRo developers, as this would ensure code integrity and functionality. METRo has modules written in three different software languages: C++, Python, and FORTRAN-77. It requires standard C++ and FORTRAN libraries. It also requires an external, publicly available library to interface between the various modules. Some of the internals would need to be redeveloped to interface with other operating systems.

As mentioned earlier, METRo requires an observational history of the road surface and, if available, the road subsurface. Using this history, METRo generates its own estimate of the current surface to subsurface temperature profile. At least a 1 hour history is required and 12 hours is preferred. Generating this history presents challenges at non-observing sites. In the MDSS, software was developed to create a history (or pseudo-history) from the combination of a previous forecast and observations to ensure that there would be an obs-history for all sites including non-observing sites.

Another potential drawback to using METRo is the time it takes to run. While SNTHERM takes approximately 0.2 seconds to generate a 48-hour forecast, METRo takes roughly 2 seconds. It is believed that this can be attributed to the fact that METRo uses the industry standard XML format, and the parsing of XML input files and/or writing the XML output files takes a significant amount of the processing time. It's estimated that METRo's input/output process takes up roughly 90% of the processing time. The run time is negligible for a few sites but can become problematic when running over a large number of sites in an operational system.

METRo uses specific weather forecast data to drive the road surface energy balance. Unlike SNTHERM, METRo does not use solar radiation, but instead it uses cloud cover in octants. Experience with SNTHERM has shown that providing forecast radiation data, instead of cloud cover data improved model performance, at least in the case of SNTHERM. METRo could be upgraded, with some minor caveats, to accept forecast radiation data directly. Even without radiation data, preliminary testing has revealed that METRo's performance is comparable to SNTHERM.

5 BENEFIETS

There are many attributes of METRo that make it a good fit for the MDSS and the technology transfer process. Aside from performing well under a number of disparate road weather conditions, which is discussed in more detail in the following section, METRo is also very easy to acquire and install, and the documentation appears to be complete. The documentation is also available in a wiki (http://documentation.wikia.com/wiki/METRo), which is a collaborative online document that is continuously updated by developers and users. As the community of METRo users expands, the wiki will facilitate information exchange ranging from system enhancement notifications to troubleshooting tips.

METRo is open source software distributed free of charge by Environment Canada, and since it is an operational model, the code has proven to be very stable. The METRo web site (http://home.gna.org/METRo/) describes any model changes/updates and has a Frequently Asked Questions (FAQ) section for new users. The authors had little difficulty installing and running the downloaded version of METRo.

Another advantage to using METRo is the support provided by the developers. The METRo development team is very responsive and open to suggestions. During this study, requests for assistance were made to METRo developers on multiple occasions. These exchanges included the need to address technical questions, as well as discussions regarding more complex integration issues. The developers were quick to analyze and resolve potential issues, including modifying and re-releasing code. While the METRo developers are not in a position to provide "operational" support to a large number of users, they have made a concerted effort to correct and rectify any problems with the code, and they have established the wiki as a way to provide answers to more basic questions regarding code acquisition, installation, and operation. METRo developers are genuinely open to feedback and eager to develop an understanding concerning how the code is being used or integrated with other systems.

6 PERFORMANCE ASSESMENT

The performance assessment is taken from a study that was conducted by NCAR (2007) to find a

suitable replacement model for SNTHERM. Two replacement models were examined: METRo and CRREL's new energy balance model called the Fast All-season Soil Strength (FASST) model. FASST was developed at CRREL to replace SNTHERM, with a significant portion of the code taken from SNTHERM (Frankenstein and Koenig 2004). In the assessment, SNTHERM is also included to serve as a baseline for performance.

Several case studies were performed to compare road temperature predictions from FASST, SNTHERM, and METRo to observed road temperatures for an Environmental Sensor Station (6th Parkway site) along E-470, a toll road east of the Denver metro area. The elevation of this Environmental Sensor Station (ESS) is approximately 5,535 feet. It supplies atmospheric data (e.g. air temperature, relative humidity, wind speed, and wind direction) and pavement temperature data (surface and subsurface).

For each case, two types of analyses were completed: one in which road temperature predictions were generated using forecast atmospheric data and another in which predictions were generated using actual observations (perfect prognosis [perfprog] approach). The forecast data were derived from the MDSS road weather forecast system (RWFS). For the perfprog analysis, the observation data, including insolation measurements, are primarily from the Vaisala (6th Parkway) ESS; however, since the ESS does not report precipitation or cloud cover, precipitation observations from a GEONOR gauge and cloud cover from the Automated Surface Observing System (ASOS) at Denver International Airport are used. Although these platforms provided the closest precipitation and cloud cover data, it should be noted that they are approximately 10 statute miles away from the 6th Parkway site; therefore, these data may not always be representative of the environmental conditions at the 6th Parkway ESS site. Three cases that exhibit a variety of weather are examined:

Warm, Clear (Day1), Cloudy (Day 2):
        08 November 2006
Warm Moderate Rain:
        07 July 2006
Moderate Snow (~ 5-6 inches):
        28 November 2006

The forecast figures show 48 hour forecasts generated at 12Z (0500 MST / 0600 MDT) and corresponding observations from the ESS road sensor. The x-axis displays lead time (hours out) from 12Z on the day indicated. For the forecast driven precipitation cases, times at which precipitation was forecasted and times when precipitation was observed are indicated on

the plots by the green and cyan circle, respectively. For the perfprog analyses, only observed precipitation is indicated.

For the comparison during the snow event, care should be exercised when attempting to draw definitive conclusions regarding model performance under these conditions. Forecasted pavement temperatures are plotted against actual observations in the perfprog charts, but it is unclear what, if any, winter maintenance activities took place during each snow event. The use of chemicals and plowing to control ice and snow will have an effect on the observed pavement temperatures. The models do not "know" what actions have been taken to treat the section of E-470 from which the pavement temperature observations are derived; therefore, the forecast may not conform to the observed values. However, it is reasonable to compare the models to one another during these events in an effort to investigate characteristics unique to each model.

It should also be noted that all pavement models are dependent upon a good weather forecast. The comparison between the forecast driven cases and perfprog cases highlight this point. A pavement model prediction is only as good as the weather forecast that drives it.

Clear Case: 8 November 2006

A record high temperature of 80°F occurred on 8 November 2006 followed by a weak cold front on 9 November. Figure 3 shows that for the forecast driven predictions on day one, METRo is the closest to the observed road temperatures. FASST and SNTHERM both under-predict the peak in road temperature, with FASST being about 5°C too cold. All three models are slightly out of phase with the peak in road temperatures on the first day. On day 2, all three models grossly over-predict the road temperatures as a result of an inaccurate weather forecast.

The perfprog analysis provides additional detail regarding the models' performance given an optimal forecast. Figure 4 shows that METRo closely matches the observations on day one and is by far the best forecast, as it not only captures the peak heating, but it does well to forecast the increase and decrease in pavement temperature during the morning and afternoon, respectively. SNTHERM and FASST both under-predict the road temperatures in the afternoon (lead times 6-15), with FASST being the worst of the two.

On day two, METRo has the better forecast overall, although differences in cloud cover used by METRo and what was observed at the Vaisala site are apparent. SNTHERM and FASST again under-predict the road temperatures on the second day. METRo and

FASST do reasonably well predicting the pavement temperatures on the first night but they are both too warm on the second night, while SNTHERM generally has a cold bias on both nights (lead times 18-27 and 39-48).
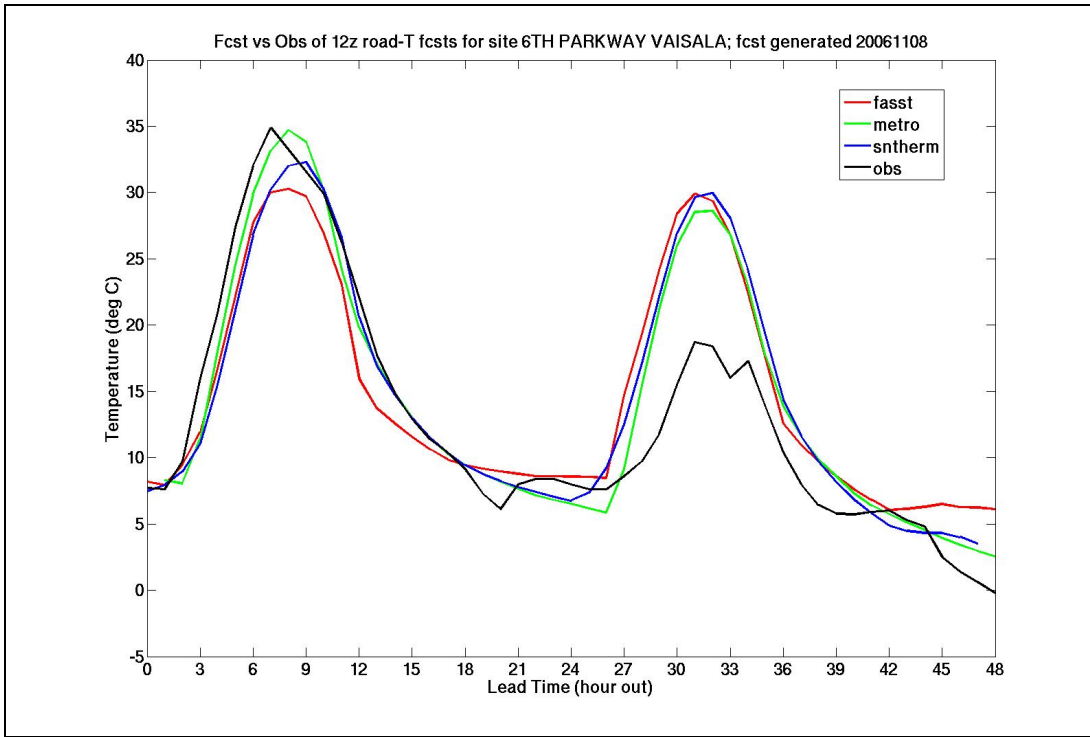

Figure 3. FASST, METRo, and SNTHERM road temperature forecasts based on RWFS output for 12Z on 08 November 2006.
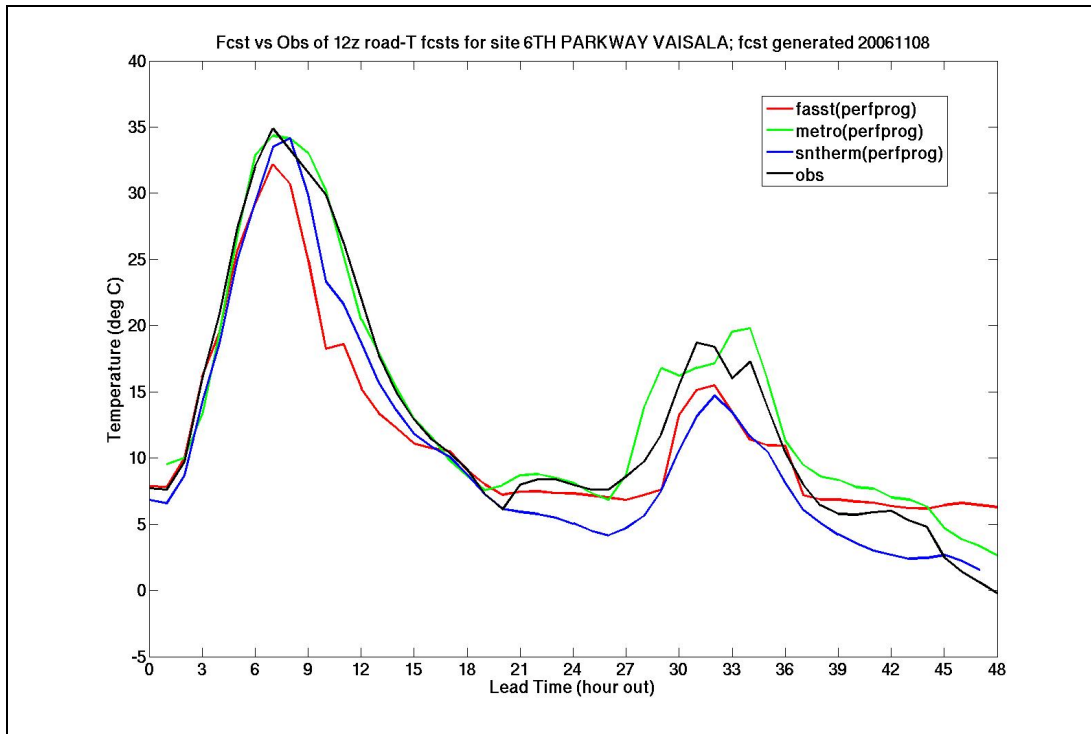
Figure 4. Perfect prognosis generated road temperature forecasts for 12Z on 08 November 2006.

Rain Case: 7 July 2006

On 7 July 2006, a summer cold front moved across the Colorado Front Range producing a prolonged period of moderate rain, dropping temperatures from the 80s into the 60s. Figure 5 indicates that for the forecast driven road temperatures, SNTHERM and FASST respond well to the reduction in solar insolation associated with the predicted onset of rain (lead times 6-15). The METRo forecast on the first day is an artifact of a clear cloud cover forecasts, and although it is closer to the peak road temperature compared to SNTHERM and FASST, it does not respond to the predicted rain. All three models are too warm overnight (lead times 15-24), with FASST being the warmest and METRo being the closest to observed values. By the morning of the second day (lead time 24), METRo is the closest to the observed road temperatures. All three models are out phase with the peak in observed road temperatures on the second day (lead times 24-39), and this can be attributed to

differences between the weather forecasts and the observed weather conditions.

For the perprog analysis, Figure 6 shows that METRo has the best overall road temperature forecast on the first day. SNTHERM and FASST under predict the peak in road temperatures (on the first day) using the observed radiation values. These models also show a notch pattern during the morning of the first day, which is not seen in the observed values. Overnight, METRo's forecast is the best, with SNTHERM a close second; FASST remains too warm. On the second day the differences between using observed cloud cover to derive solar radiation versus using observed radiation is apparent. SNTHERM does the best job of picking up on the sawtooth pattern observed in road temperatures, which is associated with the intermittent rain. Although METRo does not pick up on the details, it outperforms FASST and does well predicting the decrease in road temperature during the late afternoon on the second day.
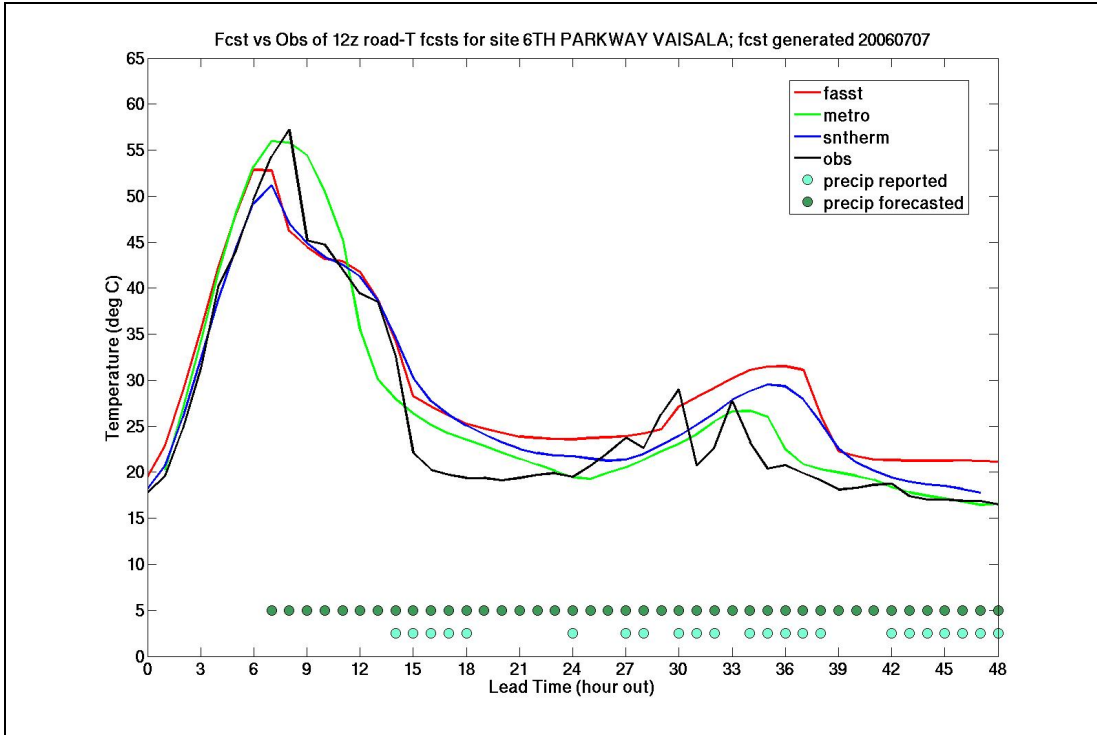
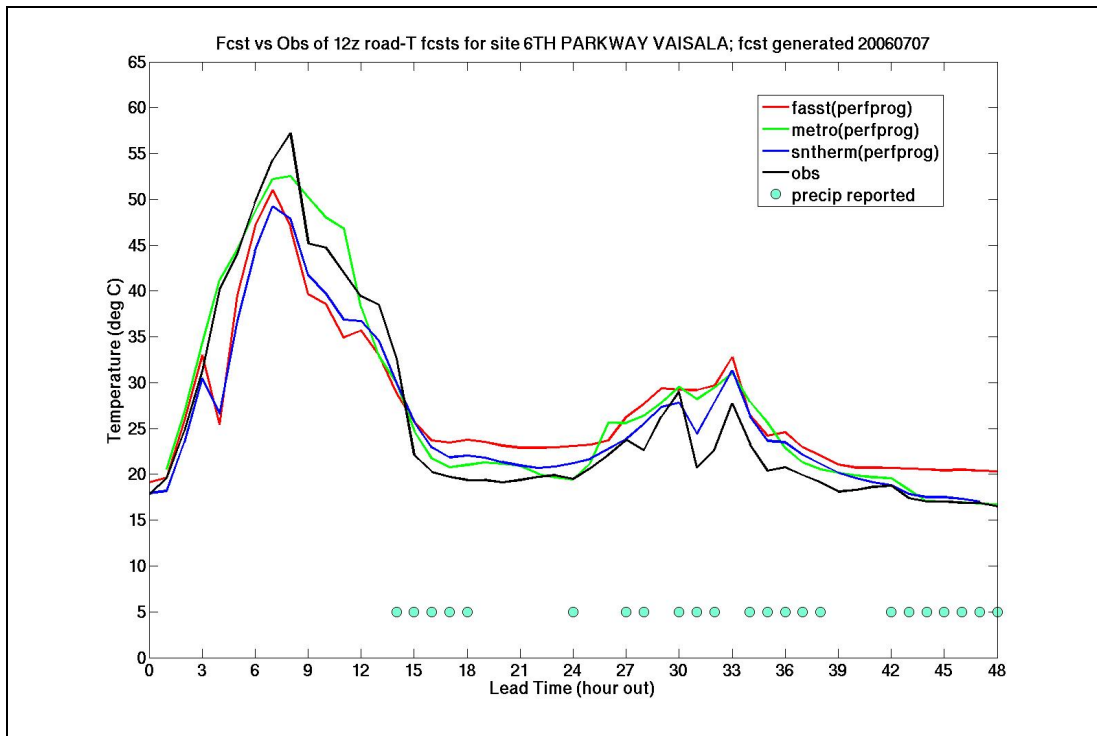**Figure 5.   As in Figure 1, except for 7 July 2006.**

Figure 6.   As in Figure 2, except for 7 July 2006.

Snow Case: 28 November 2006

The 28 November 2006 case is a prolonged moderate snow event with relatively warm air temperatures initially followed by much colder temperatures on 29 November. The event resulted in approximately 5 to 6 inches of snow at the 6th Parkway Vaisala site. Snow started at 5 p.m. on 28 November (lead time 12). Figure 7 shows that for the forecast driven output, all three models do well predicting road temperatures on the first day. Minor differences include the fact that FASST does a slightly better job of forecasting the increase in pavement temperatures during the first few hours of the day, but METRo's predictions are superior to FASST and SNTHERM during the afternoon.

After the predicted onset of snow (lead time 8), FASST is too warm through the rest of the forecast. The warm bias may be tied to the idea that FASST does not build up enough snow on the road. Initially SNTHERM responds well to the onset of snow and the forecast tracks well with the observations, but as the model builds up snow on the road the road, temperatures become damped and do not respond on the second day. METRo has the best overall forecast with just a slight cold bias on day 2 (lead times 27-36) and a slight warm bias through the second night (lead times 36-48). These biases may result from differences between the predicted cloud cover and precipitation and the actual observations.

The perfprog road temperature predictions for the 28 November case (Figure 8) show similar results to the forecast driven predictions. During day one, all three models under-predict the peak in observed road temperatures (lead times 6-9). METRo once again does well to forecast the decrease in temperature during the afternoon, while the decrease in pavement temperature noted by SNTHERM and FASST occurs too early. After the onset of snow (lead time 12) METRo has the best forecast, closely matching the observations throughout the evening and overnight period. During the night FASST predicts considerable colder temperatures compared to the actual observations, while the SNTHERM forecast remains too warm.

On the second day, METRo under-forecasts the increase in pavement temperature that occurs after sunrise, but its forecast remains substantially better than FASST and SNTHERM. Although FASST does forecast an increase in pavement temperature, its temperatures are much warmer than the observed values, and it continues to exhibit a very warm bias throughout the remainder of the forecast period. SNTHERM's forecast is damped due to the model's build up of snow on the road; as a result, the forecast is rather poor.
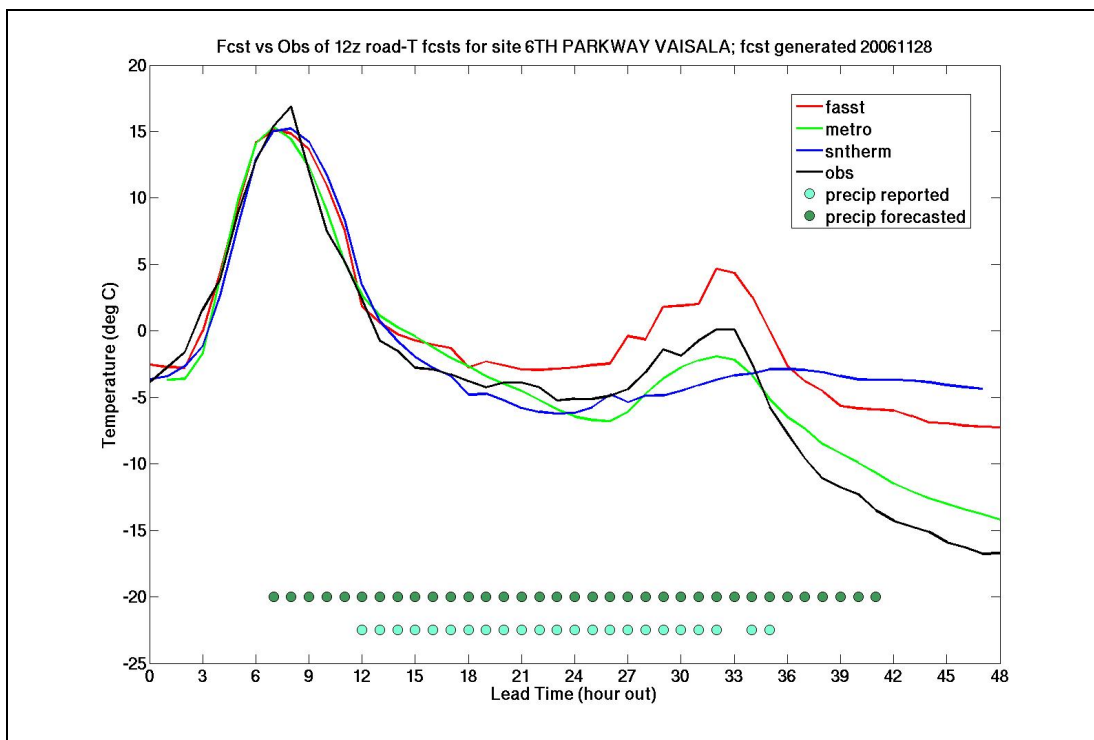

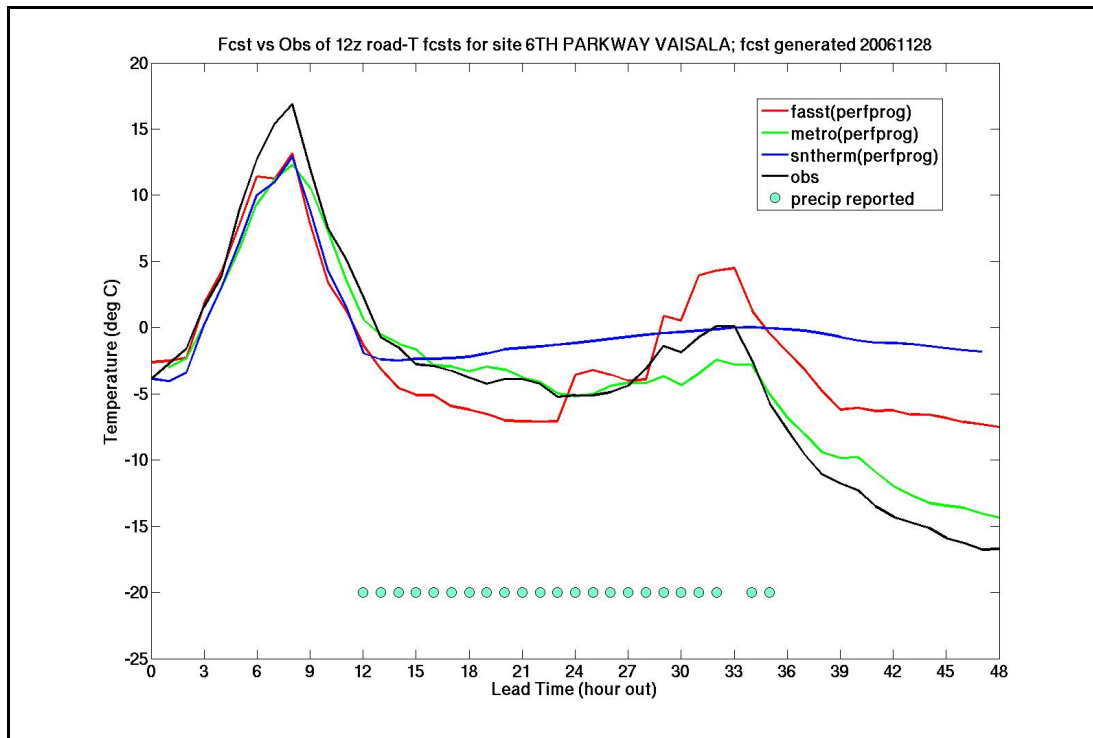**Figure 7.   As in Figure 1, except for 28 November 2006.**

Figure 8.   As in Figure 2, expect for 28 November 2006.

7 CONCLUSIONS

A maintenance decision support system such as the MDSS FP is dependent upon a reliable and accurate pavement conditions model. In the past the MDSS has relied on SNTHERM to predict pavement temperatures and road conditions but since this model is no longer actively developed and supported, there was the need to find a replacement. Through research and analysis of two publicly available models, METRo was identified as the best replacement for SNTHERM.

METRo is an energy balance model developed by the Meteorological Service of Canada. Like other models, METRo does have some weaknesses; two of the most notable are the amount of time it takes to run the model and the need for an observation history at each forecast site. Despite the fact that METRo has a few limitations, it possesses many traits that make it attractive for use in the MDSS, as well as other decision support systems. Not only has METRo performed well under a number of conditions, but experience has also shown that it is extremely easy to acquire, install and use, even for novice users. Moreover, the support provided by the developers, along with an expanding community of end users, will ensure that problems or issues that do arise can be addressed and corrected in a timely manner. As a result of these factors, METRo has been incorporated into the MDSS and it is

recommended that it be used in the development of other decision support systems targeting roadway maintenance and operations.

8 ACKNOWLEDGEMENTS

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