RELEASE NOTES

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<th>Version Number</th>
<th>Date</th>
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<td>Version 1.0</td>
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National Center for Atmospheric Research (NCAR):

Seth Linden     Bill Mahoney
Arnaud Dumont   Bill Myers
Jim Cowie       Kevin Petty
Jason Craig     Julie Prestopnik

Lincoln Laboratory (LL):

Robert Hallowell

Questions and comments about this document should be directed to the primary author of this report:

Mr. Seth Linden
Research Applications Laboratory
National Center for Atmospheric Research
P.O. Box 3000
Boulder, CO 80307
Ph: 303-497-8433
E-mail: linden@ucar.edu
ACRONYM GLOSSARY

AOTR – Agreement Officer’s Technical Representative
ASOS – Automated Surface Observing System (NWS)
AVN – National Weather Service Model (now called the GFS)
AWOS – Automated Weather Observing System (FAA)
CRREL – U.S. Army Cold Regions Research and Engineering Laboratory
C – Degrees Celsius
CDOT – Colorado Department of Transportation
DIA – Denver International Airport
DMOS – Dynamic Model Output Statistics
DOT - Department of Transportation
DOY – Day of the Year
DSS – Decision Support System
EMC – Environmental Modeling Center
EMFP - Ensemble Model Forecast Provider
ESRI – Environmental Systems Research Institute
ESS - Equitable Skill Score
Eta – National Weather Service Model (now called the NAM)
ETL – NOAA, Environmental Technology Laboratory
FAA – Federal Aviation Administration
FEC – Forward Error Correction
FHWA – Federal Highway Administration
FSL – NOAA, Forecast Systems Laboratory (now Global Systems Division)
FTP – File Transfer Protocol
GFS – Global Forecast System Weather Service Model (formerly called AVN)
GPS/AVL – Global Positioning System/Automated Vehicle Location
GRIB – Gridded Binary
GSD – NOAA, Global Systems Division (formerly called FSL)
HADS - Hydrometeorological Automated Data System of the NWS
HRDO – Office of Research and Development Operations (FHWA)
HOTO - Office of Transportation Operations
ITS – Intelligent Transportation System
JPO – Joint Program Office (FHWA)
LDM – Local Data Manager
MADIS – Meteorological Assimilation Data Ingest System (NOAA/FSL)
MAVMOS – Model Output Statistics from the NWS Aviation Model
MAE – Median Absolute Error
MDSS - Maintenance Decision Support System
MDSS FP - Maintenance Decision Support System – Functional Prototype
METAR – Meteorological Surface Observation including ASOS and AWOS sites
METRo – Model of the Environment and Temperature of Roads
MIT/LL - Massachusetts Institute of Technology - Lincoln Laboratory
MM5 – Mesoscale Model – Version 5 (NCAR & Penn State)
MOS – Model Output Statistics
NAM – North American Mesoscale Model (formerly called Eta)
NCEP - National Centers for Environmental Prediction
NEXRAD – NEXt generation RADar program
NSF – National Science Foundation
NSSL – NOAA, National Severe Storms Laboratory
NOAA – National Oceanic and Atmospheric Administration
NCAR - National Center for Atmospheric Research
NVD - Non-Verifiable Data
NWP – Numerical Weather Prediction
NWS – National Weather Service
QPE – Quantitative Precipitation Estimate
QPF – Quantitative Precipitation Forecast
RCTM – Road Condition & Treatment Module
RMSE – Root Mean Squared Error
ROP – Rules of Practice
RTVS – Real Time Verification System (RTVS)
RUC – Rapid Update Cycle (NWS weather prediction model)
RWFS – Road Weather Forecast System
RWIS – Road Weather Information System
RWMP - Road Weather Management Program
SNTHERM-RT – Heat balance model used to predict road temperatures
STWDSR - Surface Transportation Weather Decision Support Requirements
UTC – Universal Time Coordinated (same as Greenwich Mean Time)
VAMS - Value Added Meteorological Services
WIST-DSS - Weather Information for Surface Transportation Decision Support System
WMO – World Meteorological Organization
WRF – Weather Research & Forecasting Model
Z – Zulu time (same as Coordinated Universal Time/Greenwich Mean Time)
NOTICE

This document is disseminated under the sponsorship of the City and County of Denver in the interest of information exchange. The City and County of Denver assumes no liability for the use of the information contained in this document. This report does not constitute a standard, specification, or regulation.

The Federal Highway Administration (FHWA) Office of Transportation Operations, Road Weather Management Program, funded the development of the MDSS, and the City and County of Denver provided additional funding to support their operations. The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the U.S. Department of Transportation or the City and County of Denver.

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1 PURPOSE

The technical performance results of the prototype Maintenance Decision Support System (MDSS) from the winter 2006-2007 Colorado field demonstration are described in this document. Recommendations for future improvements are also highlighted throughout the document. The field demonstration officially started on 16 October 2006 and ended on 1 May 2007. Several different aspects of the MDSS are discussed including bulk statistics on its performance during the entire field demonstration and case studies of individual events, as they relate to the timing and onset of precipitation. Individual components of the system are evaluated, including the Road Weather Forecast System (RWFS) and mesoscale weather models.

2 INTENDED AUDIENCE

The intended audiences for this document are persons directly involved in the MDSS 2006-2007 field demonstration, including the Federal Highway Administration (FHWA), City and County of Denver, the E-470 Public Highway Authority, national laboratories, stakeholders with an interest in the MDSS project (private sector meteorological service providers, state Departments of Transportation (DOTs), and casual observers who wish to follow developments related to winter road maintenance technologies). It is recommended that the reader have a working knowledge of meteorological verification methods and statistical analysis metrics.

3 BACKGROUND

This MDSS Project is part of a federal procurement for research projects and deployment advocacy, which is funded primarily through the U.S. DOT Intelligent Transportation Systems (ITS) Joint Program Office (JPO).

It is anticipated that components of the prototype MDSS developed by this project will be enhanced, integrated with other operational components, and deployed by road operating agencies, including state DOTs, and generally supplied by commercial weather service providers.

Two national research centers participated in the MDSS 2006-2007 field demonstration. The participating national labs include:

- National Center for Atmospheric Research (NCAR)
- Massachusetts Institute of Technology - Lincoln Laboratory (MIT/LL)

4 RELATED DOCUMENTS

For additional information on the MDSS Project, the reader is directed to the related project documents and web sites listed in Table 4.1.
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5 METHODS

This document provides prototype MDSS results from the winter 2006-2007 MDSS field demonstration. Objective analyses of the weather forecasts were performed. In addition, analyses of the road temperature model and mesoscale weather model components are provided. Where possible, results are summarized and recommendations are provided as guidance for those planning to implement MDSS components or similar technologies.

Obtaining sufficient, high quality verification data, especially precipitation information, continues to be a challenge for this project and similar efforts. Issues related to verification data limitations are described throughout this document.

Surface weather observation quality from standard road weather information systems was assessed in 2003 via coincident observations of state and road parameters (Bernstein et. al. 2003). Differences apparent in the observations themselves set an acceptable threshold of deviation of the forecast from the observations, or a lower bound for the accuracy one can expect from the MDSS forecasts; for if the observations can only be measured within a certain tolerance, then differences between such observations and the MDSS forecasts are attributable to uncertainty in the observations themselves.

Objective verification is achieved via direct comparisons of MDSS forecasts and reliable observations from National Weather Service and roadside Environmental Sensor Stations. These results are presented through diagrams of root mean squared error (RMSE), median absolute error (MAE), and bias for state parameter fields (e.g. air temperature, dewpoint, and wind speed), as well as road and bridge temperatures. In an attempt to examine MDSS precipitation forecasts, several case studies are presented herein, including a number of different snow events with varying total snow depth accumulations.

6 MDSS VERIFICATION ROUTES

A total of 12 plow routes were configured in the MDSS for the 2006-2007 field demonstration. The plow routes include six along the entire E-470 corridor near Denver, Colorado, three on I-25 south of Denver, three on I-70 just west of Denver up to Floyd Hill, and three on I-70 in the mountains from Vail Pass to Wolcott, Colorado. The selected routes are shown in Figs. 6.1 and 6.2, and corresponding descriptions of the routes are provided in Table 6.1. Separate treatment plans were generated by the MDSS prototype for each of the plow routes.
Fig 6.1: Map of E-470 routes supported by the MDSS prototype during the winter of 2005-2006 Colorado field demonstration. Key observation sites are annotated. Note, there is no route C in the E-470 system.
Fig. 6.2: Map of CDOT routes configured in the MDSS prototype during the winter of 2005-2006 Colorado field demonstration. The camera icons represent locations of CDOT traffic cameras while the snowflakes represent locations of CDOT weather stations.
Table 6.1. Colorado Maintenance Routes for the MDSS Field Demonstration

<table>
<thead>
<tr>
<th>Region</th>
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7 MDSS SYSTEM CONFIGURATION

All of the MDSS core technical components (e.g., RWFS, RCTM, and data server) were operated centrally at NCAR in Boulder. A server at NCAR communicated (via the Internet) with local PCs running the display application at the City and County of Denver Department of Public Works Street Maintenance Division. E-470 and CDOT RWIS data were provided to NCAR via GSD as part of the Meteorological Assimilation Data Ingest System (MADIS) program. E-470 data were included in MADIS in late summer 2004 and CDOT RWIS data became available starting in late January 2005.

A simplified illustration of the MDSS prototype system configuration is provided in Fig. 7.1.
Fig. 7.1. Depiction of the prototype MDSS configuration for the winter 2005-2006 Colorado field demonstration. All network MDSS connections to the sites were via the internet.

The Road Weather Forecast System (RWFS) is tasked with ingesting reformatted meteorological data (observations, models, statistical data, climate data, etc.) and producing meteorological forecasts at user-defined forecast sites and forecast lead times. The forecast variables output by the RWFS are used by the Road Condition and Treatment Module (RCTM) to calculate the road surface temperature and to calculate a recommended treatment plan. In order to achieve this goal, the RWFS generates independent forecasts from each of the data sources using a variety of forecasting techniques.

A single consensus forecast from the set of individual forecasts is provided for each user-defined forecast site (e.g., plow route) based on a processing method that takes into account the recent skill of each forecast module. This consensus forecast is nearly always more skillful than any component forecast. The RWFS is designed to optimize itself using available observations near the routes (e.g., RWIS, METARS). The forecast modules that perform the best are given more weight over time. In addition, Dynamic Model Output Statistics (DMOS) are calculated weekly using observations and model output. The DMOS process is used to remove model biases. The optimization period of the RWFS is approximately 90-100 days. Observations and weather model data were collected well before the start of the demonstration period; thus, the system was fully
tuned, as it had an adequate learning period prior to the 16 October 2006 demonstration start date.

For more information on the RWFS as configured for the winter 2006-2007 demonstration, the reader is directed to Appendix A of the MDSS Prototype Release-4.0 Technical Description (see reference in Table 4.1).

8 DATA COLLECTION PROCESS

The first significant weather event occurred on 25 October 2006 and the last major weather event occurred on 29 March 2007. The demonstration officially began on 16 October 2006 and ended on 1 May 2007. During this period there were several winter weather events, which resulted in a very diverse season in terms of event snowfall amounts, duration, and large-scale characteristics. There were two major snowstorms during the 2006-07 winter season. Together these events resulted in more that 4 feet of snow across the Denver Metropolitan area. In total, there were nearly 15 snow events of 2 inches or greater within the Denver area during the demonstration period.

8.1 Data Sources: Weather Observations

The following weather observation data sources were used for verification and analysis:

- a) Colorado DOT and E-470 RWIS
- b) NWS ASOS/AWOS
- c) Local observer surface data
- d) Weather satellite
- e) Weather radar
- f) NWS storm summaries
- g) GEONOR precipitation gauge (Denver International Airport)
- h) Denver Urban Drainage and Flood Control District precipitation observations

8.2 Data Sources: Road Condition Observations

The following road condition data sources were used for verification and analysis:

- a) Colorado DOT and E-470 road temperature sensors
- b) NCAR personnel observations

9 MDSS ENHANCEMENTS FOR WINTER 2005-2006

Using the winter 2005-2006 post-demonstration evaluations from Colorado, technical performance results, and the lessons learned from meetings with area maintenance
personnel, limited system development activities were performed prior to and during the Colorado demonstration. Enhancements to the MDSS are listed below.

The MDSS utilizes a static weighting scheme for quantitative precipitation forecasts. On 16 February 2006, the weighting scheme was adjusted. For all forecast lead times, the weights were changed to 60% for the NAM, 30% for RUC, and 10% for the GFS. This was done in an attempt to improve the precipitation forecast during the 2005-2006 winter season. This change resulted in an improvement in precipitation forecast during the remainder of the 2005-06 winter season; however, during the 2006-07 demonstration period, additional adjustments were made to the system. On 1 December 2006, the quantitative precipitation forecast weights were changed from 60% for the NAM, 30% for RUC, and 10% for the GFS to 60% for the NAM, 20% for RUC, and 20% for the GFS.

Probability of Precipitation. During this demonstration period, additional adjustments were made to the threshold at which the system will declare precipitation. Within the RWFS there are set thresholds for hourly probability of precipitation (POP) and quantitative precipitation forecast (QPF) values that must be met before precipitation will be declared by the system. For the 2005-2006 winter field demonstration the POP threshold was set at 25% while the QPF threshold was 0.05 mm/hr. This past season, the POP was change to 20%. This change was based in part on feedback obtained from area maintenance personnel, which suggested that a more conservative forecast (e.g., earlier declaration of precipitation) would be more supportive of the winter maintenance operational environment.

Higher Resolution North American Mesoscale (NAM) model. On 27 October 2006, the MDSS began ingesting and using data from a higher resolution NAM model. Previously, the resolution of the data from this model was on the order of 18 kilometers (11.2 miles); the system is now using the 12 kilometer (7.5 miles) NAM data. This change was instituted in an effort to capture some of the more localized features associated with winter weather events.

10 OVERALL PERFORMANCE RESULTS

In this section, performance results are described for the entire winter 2006-2007 Colorado field demonstration for specific components of the MDSS. Bulk statistics based on the weighted average root mean square error (RMSE), median absolute error (MAE) and bias (forecast minus observation) are calculated. The statistics were calculated for 71 sites along the Colorado Front Range. The weighted average RMSE is calculated in the following manner: for each lead-time, RMSE is calculated for each site and then weighted based on the total number of valid errors for that site. The RMSE values (for each site) are then summed over all sites and divided by the sum of the errors for each site.
It should be noted that the statistics provided below included the latest upgrades to the MDSS, including those described in section 9.

10.1 RWFS Forecast Modules

The RWFS was configured to utilize and integrate four different forecast modules for the winter 2006-2007 demonstration. Numerical Models that were ingested into the RWFS included the NAM (the replacement for the Eta), GFS (formerly called the Aviation Model by the NWS) and RUC. Aviation Model Output Statistics (MAVMOS) were also used as input. Dynamic Model Output Statistics (DMOS) were calculated within the RWFS for each of the model inputs. The four weather forecast modules that were used to predict the weather parameters for each MDSS forecast point were:

1) NWS Aviation MOS (MAVMOS)
2) NAM DMOS
3) GFS DMOS
4) RUC DMOS

The RWFS integration process independently optimized the forecasts based on recent skill at each prediction site for each parameter and forecast lead time, except for precipitation. Forecast modules with the most skill get more weight in the RWFS integration process that generates the consensus forecast. Due to the lack of accurate winter precipitation measurements, the probability of precipitation (POP) and quantitative precipitation forecast (QPF) consensus output were calculated using fixed weights. The method chosen to select the weights for POP and QPF are described in section 11. Due to the lack of real-time insolation (incoming solar radiation) measurements, a fixed weighted blend of insolation values from selected forecast modules was also used, as described in section 12. More information on the RWFS can be found in the MDSS Technical Description (see Table 4.1 for reference information).

The RWFS also applied a Forward Error Correction (FEC), which is used to ensure that the forecasts produced by the RWFS more accurately reflect the current conditions in the near term. The forecasts valid at the current time are forced to match the available observations. Then, in the first forecast hours, the forecast time series is forced to trend toward and blend seamlessly into the RWFS consensus forecast.

10.2 Overall Performance of the Road Weather Forecast System

10.2.1 Performance Assessment of Meteorological Variables

The RWFS consensus forecast was compared to the forecasts from the individual models included in the ensemble in order to discern whether the RWFS statistical post processing methods and techniques added skill.

Error Analysis
Bulk statistics were computed for the four individual models listed in section 10.1 and the RWFS final consensus forecast for three meteorological variables (air temperature, dewpoint temperature and wind speed). The results are based on average RMSE and bias per lead time (out 48 hours) of forecasts initiated at 12 UTC for the entire season (1 October 2006 to 15 April 2007). As previously mentioned, and as will be the case for all the statistics in this section, the results are based on 71 sites along the Colorado Front Range.

For all three variables, the RWFS performed well with the consensus forecasts having lower RMSE values compared to the individual forecast module components for all lead times (Figs. 10.1-10.3). Forward Error Correction (FEC), which is applied to all the verifiable variables (variables that have corresponding observations), reduces the RMSE within the first six hours.

The reduction in forecast error due to FEC is less than what has been seen in previous years. At this time, it is not totally clear why the improvement is less pronounced this year as compared to past seasons, but it is possible that prolonged ESS data disruptions, as well as data latency resulting from the date change associated with Daylight Savings Time, may have played into the fact that there are higher errors during the first six hours of the forecast. It is also possible that the colder, snowier winter played a role. Nonetheless, there is notable improvement in forecast error during this period of the forecast, with the consensus forecast outperforming the individual forecast modules.

The reduction in overall error provided by the consensus forecast is most evident for air temperature and dewpoint temperature. In general, there is a more pronounced difference in skill (i.e. larger spread among the forecasts) between the final consensus forecast and its components for air temperature and dewpoint temperature than for wind speed (Figs. 10.1-10.2).
Fig. 10.1: Weighted average air temperature RMSE computed from the 12 UTC forecasts for the entire demonstration season (1 October 2006 – 15 April 2007). The consensus forecast (black line) and the individual forecast module components for the Colorado plains sites are shown.

Fig. 10.2: Weighted average dewpoint temperature RMSE computed from the 12 UTC forecasts for the entire demonstration season (1 October 2006 – 15 April 2007). The consensus forecast (black line) and the individual forecast module components for the Colorado plains sites are shown.
**Results Summary:** The statistical methods and techniques utilized by the RWFS do improve the predictions on average for all verifiable parameters. It is clear from the analyses that no single model performs better for all parameters; therefore, a blend of weather models will provide better results. FEC result in forecast improvements in the first six hours for all variables. It is unclear as to why FEC did not reduce the forecast errors in the first six hours as much as seen in years past. This may have been a result of latency in the observations or a colder and snowier winter than normal.

**Bias Analysis**

Bias was examined separately for the consensus forecast over every lead time and between the consensus and components forecasts over common lead times. Overall, the RWFS exhibits no significant bias for the three meteorological state variables examined (Figs. 10.4-10.6). There is a cold bias in air temperature during the late afternoon right before sundown. There is a slight wet bias in dewpoint and small positive bias in wind-speed although the magnitude of bias is very small.
Fig. 10.4: Weighted average air temperature bias computed from the 12 UTC RWFS output for the entire demonstration season (1 October 2006 – 15 April 2007) for the Colorado plains sites.

Fig. 10.5: Weighted average dewpoint temperature bias computed from the 12 UTC RWFS output for the entire demonstration season (1 October 2006 – 15 April 2007) for the Colorado plains sites.
In an effort to further investigate the small biases found in the consensus forecast, Figs. 10.7-10.9 have been included herein. These plots display the bias of the individual forecast components included in the final consensus forecast, as well as the consensus forecast bias. The most notable trend that is apparent from the plots is the fact that the MAVMOS forecasts exhibit the highest overall bias, independent of the forecast variable. This is consistent with previous studies. The MAVMOS has a cold bias in temperature for every lead time, but the bias becomes smaller during the warmest part of the day in the afternoon (Fig. 10.7). Although the MAVMOS has a large bias in air temperature it does not have the worst forecast skill (as indicated in Fig. 10.1). This may be the result of a colder than average winter. The MAVMOS also exhibits a dry bias for dewpoint (Fig. 10.8). The NAM has a slight warm bias in temperature. All of the modules have a small wet bias for dewpoint. The MAVMOS component consistently has the largest positive bias for wind speed. The NAM has a small positive bias for wind-speed, with the RUC and GFS showing no significant trend.

Fig. 10.6: Weighted average wind speed bias computed from the 12 UTC RWFS output for the entire demonstration season (1 October 2006 – 15 April 2007) for the Colorado plains sites.
Fig. 10.7: Weighted average air temperature BIAS computed from the 12 UTC forecasts for the entire demonstration season (1 October 2006 – 15 April 2007). The consensus forecast (maroon) and the individual forecast module components for the Colorado plains sites are shown.

Fig. 10.8: Weighted average dewpoint temperature BIAS computed from the 12 UTC forecasts for the entire demonstration season (1 October 2006 – 15 April 2007). The consensus forecast (maroon) and the individual forecast module components for the Colorado plains sites are shown.
Fig. 10.9: Weighted average wind speed BIAS computed from the 12 UTC forecasts for the entire demonstration season (1 October 2006 – 15 April 2007). The consensus forecast (maroon) and the individual forecast module components for the Colorado plains sites are shown.

Results Summary: The ensemble approach reduces bias from any one component. The RWFS exhibits no significant bias for the analyzed weather variables.

Given the errors and biases associated with the MAVMOS, it may be beneficial to exclude this forecast component in the future. Further investigation may be necessary.

10.3 Overall Performance of the Road Condition Treatment Module

10.3.2 Overall Performance of the Road and Bridge Temperature Forecasts from the RCTM

This section examines the road and bridge temperature forecasts using recommended treatments as determined within the MDSS Road Condition and Treatment Module (RCTM). Measurement differences between the predictions and pavement sensors were used to calculate median absolute error (MAE) and average bias (forecast minus observation) per lead time (out 48 hours) for 12 UTC forecasts generated over the entire season (1 October 2006 to 15 April 2007). Statistics were calculated for 9 road sites in the Denver area and 2 bridge sites along E-470.
The road temperature MAE ranges from around 1.0-1.5°C during the evening and overnight hours, but increases to a peak of about 4°C in the afternoon, which corresponds with the hours of maximum solar insolation (Fig. 10.10). There is a diurnal trend in the bias with a cold bias during the warmest part of the day followed by a warm bias shortly after sunset (Fig. 10.11). There is also a small cold bias during the middle of the night. This trend is indicative of the forecast being slightly out of phase with the observations.

![Median Absolute Error of 12h road-temperature forecasts from 20061001-20070415 for all CO plains sites](image)

**Fig. 10.10**: Road temperature MAE, computed based on 12 UTC forecasts from 1 October 2006 – 15 April 2007 for the Colorado plains sites. Local noon is at hours 7 and 31.
Fig. 10.11: Average road temperature bias from the 12 UTC forecasts for 1 October 2006 – 15 April 2007 for the Colorado plains sites. Local noon is at hours 7 and 31.

There is still some uncertainty as to whether part or all of the bias in the forecasted road temperatures is real or due to differences between the measurements made by the road temperature sensors (pucks), which have different thermal properties than the road surface, and the road temperature model, which was configured to predict the pavement skin temperature. Overall, there is a noticeable reduction in forecast error and bias compared to last year.

There are two bridge sites along E-470, one at Smoky Hill Road and another at the Platte River Bridge. Prior to this year, bridge road-temperature statistics were only calculated for the Platte River site because the puck at Smoky Hill was covered with pavement and shaded by the guardrail. The puck was relocated before the start of this year’s demonstration season and since it shows similar observations to the puck at Platte River (Figs. 10.12 and 10.13), both sites were used for verification. The bridge site at Vail Pass was not used for verification due to a lack of observations.

The diurnal trend in MAE for the bridge sites is similar to what is seen for the road sites but the magnitude of error is much greater during the afternoon with a peak of 4.5-5 °C (Fig. 10.14). Although the values at night are lower than those during the day there is an increase in MAE during the coldest part of the night, right before sunrise. The bias plot (Fig 10.15) shows that the forecast is too cold during the morning and too warm during the afternoon. This would suggest that the forecasts are a bit delayed in response during times of rapid warming and cooling.
Fig. 10.12: Bridge temperature forecast and observations from the 12 UTC forecast on 14 October 2007 for the Smoky Hill site. This now shows the normal diurnal change in observed bridge temperature.

Fig. 10.13: Bridge temperature forecast and observations from the 12 UTC forecast on 14 October 2006 for the Platte River Bridge site. This is an example of the normal diurnal change in observed bridge temperature.
Fig. 10.14: Bridge temperature MAE from the 12 UTC forecasts from 1 October 2006 – 15 April 2007 for the E470 bridge sites. Local noon is at hours 7 and 31.

Fig. 10.15: Average bridge temperature bias for the 12 UTC forecasts for 1 October 2006 – 15 April 2007 for the E470 bridge sites. Local noon is at hours 7 and 31.
10.3.3 Performance Assessment Based on Conditional Road Temperature and Bridge Temperature Forecasts

**Cloudy and Clear Conditions**

The cloud conditions were stratified by the observed cloud cover less than 20% (clear), 20%-50% (scattered), 50%-75% (broken), and greater than 75% (overcast). MAE calculated over all lead times (Figs. 10.16-10.17), labeled “no condition”, is included as a baseline comparison.

For the Colorado plains road sites, the largest difference in skill occurs during the hours of peak heating. The average error for partly, mostly and overcast conditions changes from day 1 (0-23 hours out) to day 2 (24-48 hours out). For day 1, the smallest errors are associated with overcast conditions with the largest errors occurring for clear to mostly cloudy conditions (Fig. 10.16). On day 2 the smallest errors are associated with partly and mostly cloudy conditions with larger errors occurring for overcast conditions and even larger errors for clear conditions. The sawtooth in MAE values under clear conditions is likely associated with pavement sensor being shaded at some of the sites. As noted on the plot (Fig. 10.16), forecast errors under overcast conditions dominate the statistics (i.e., these conditions exist more than other conditions). This would explain why there is a change in skill under overcast conditions with lead time. The difference between the conditional MAE values and the values under all conditions (indicated by the black line) is smaller than in years past. During the night, the difference in forecast skill under various sky conditions is negligible.

Bridge temperature forecasts show a similar trend to the road temperature forecasts in that there is a change in conditional error values from day 1 to day 2. On day 1, for most lead times, the smallest errors are associated with overcast conditions (Fig 10.17). On day 2, the smallest errors are associated with partly and mostly cloudy conditions with relatively larger errors for the overcast conditions. There is a large amount of variability in MAE during the middle of the day under clear conditions and this may be associated with pavement sensors shading issues at the two bridge sites. Again, the difference in conditional MAE and MAE under all conditions is smaller than in years past.

Pavement sensor shading, pavement skin temperature measurement errors, the inability of weather models to accurately predict mixed sky conditions (cloudy, scattered, broken, etc.), and simplified assumptions about pavement characteristics in the pavement heat balance models all contribute to errors in predicting pavement temperature.
Fig. 10.16: Average road temperature MAE from the 12 UTC forecasts for the entire demonstration season (1 October 2006 – 15 April 2007) during cloudy conditions for the Colorado plains sites.

Fig. 10.17: Average bridge temperature MAE from the 12 UTC forecasts for the entire demonstration season (1 October 2006 – 15 April 2007) during cloudy conditions for the E470 Bridge sites.
Results Summary: The results from the road temperature analyses show larger differences between the observations and predictions during the middle of the day when solar effects are the largest. The differences are likely due to several factors including errors in measuring pavement skin temperatures by embedded sensors (e.g., pucks), limitations in the ability of weather models to predict insolation accurately, and limitations of the pavement heat balance model, including simplified assumptions about pavement characteristics.

The results from the analyses performed during cloudy conditions indicate that several complex factors contribute to pavement prediction error. It is hard to accurately model changes in pavement temperature due to daily changes in cloud cover. Again, this highlights the issue that pavement temperature predictions are tied directly to accurate solar insolation predictions.

Overall, the road and bridge temperature forecast errors are lower than what was seen last year. This may be a combination of better model tuning and a cloudier than normal winter. During follow-on seasons, the MDSS will be using a new road temperature model. It is anticipated that this model will further reduce road and bridge temperature forecast errors.

11 QUANTITATIVE PRECIPITATION FORECASTS (QPF) CASE STUDIES

The concept behind the RWFS is based on having good observations near the forecast points that feed back into the system and tune each forecast parameter dynamically in order to optimize the contributions of each model in the ensemble on a run-to-run basis. However, forecasting any characteristic of precipitation (i.e. timing, rate, and phase) is very difficult in part due to problems in the forecasting process (model physics and knowing the state of the atmosphere), poor observation network, and the inability to verify actual precipitation amounts, particularly for winter precipitation (e.g., snow, sleet, etc.).

The lack of quality real-time winter precipitation observations prevents the RWFS from tuning itself for the QPF parameter\(^1\). Without quality, real-time quantitative precipitation observations (liquid equivalent), the RWFS quantitative precipitation prediction modules would end up at best being averaged (4-member average), and at worst being tuned incorrectly due to poor observation quality.

Due to this fact, it was necessary to modify the RWFS to fix the QPF weights across the four modules based on expert opinion. For this demonstration season the weights were fixed for all lead times. The weights for the QPF parameter are 60% NAM, 20% RUC, 20% GFS and 0% MAVMOS.

\(^1\) The lack of high quality, real-time quantitative precipitation information is a nationwide problem, and not just limited to Colorado.
Several case studies were performed to compare the consensus and individual model QPF to the actual liquid-equivalent precipitation collected by a GEONOR precipitation gauge that was installed at Denver International Airport by NCAR for a Federal Aviation Administration project. This precipitation gauge has a Double Fence Intercomparison Reference (DFIR) shield surrounding it in order to minimize the effects of the wind. A photo of the DFIR wind shield surrounding the GEONOR gauge at DIA is provided in Appendix B. According to Rasmussen et al. (2001), this snow gauge and wind shield combination measures within 5% of manual (ground truth) observations. A higher confidence is placed on the accuracy of the GEONOR liquid equivalent precipitation measurements than the hourly automated precipitation measurements made at ASOS sites.

Forecasts generated approximately 12 and 24 hours before the start of precipitation are used for verification. On the figures that follow, precipitation start time is indicated by a dashed line. Forecasts made for the DIA site were used for this analysis due to the location of the GEONOR, but the results should be applicable to the E-470 and Denver area CDOT sites.

The 2006-2007 winter was much colder and snowier than normal. There were more than 15 well-defined events during the season with 2 major blizzards. A summary of the weather events and system revisions made during the field season is provided in Appendix C. The total snowfall resulting from these events was significantly more than what is typically observed along Colorado’s Front Range and this provided numerous cases to choose from. The case studies described herein range from light to heavy, and they were chosen based on their certain unique characteristics. They include the following:

- Moderate Snow 26 October 2006
- Heavy Snow / Blizzard 20 December 2006
- Heavy Snow 28 December 2006
- Light Snow / Arctic Outbreak 1 February 2007

The event on 26 October 2006 was the result of an upper-level cut-off low that tracked across Colorado from northwest to southeast. Precipitation was generated by both upslope and upper-level dynamics. Snowfall around the region was generally between 4-8 inches, with the highest amounts in south Denver. The precipitation initially started out as rain at 04 UTC on the 26th and then switched over to snow at around 08 UTC (indicated by the dashed black line in Fig. 11.1).

In regards to the 09 UTC forecast from the 25th, which was generated approximately 24 hours prior to the event, all of the models were slightly too early with the onset of precipitation. Both the GFS and the MAVMOS were 4 hours too early with the NAM and consensus only about 1 hour early. The GFS has higher precipitation rates and total amount that what was observed. The MAVMOS and NAM forecasts are fairly close to the observed precipitation rate and total amount with both predicting slightly less than what was observed. The consensus forecast is the closest to the observed precipitation
rate and total amount. The actual total liquid accumulation for this event was 1.04 inches (26.31 mm) with the RWFS (consensus) predicting 1.02 inches (25.99 mm). The start time of this event was at the end of the RUC forecast lead times and thus it does indicate precipitation.

For the 21 UTC forecasts generated on the 25th all of the models except the MAVMOS do a better job predicting the start of the event (Fig. 11.2). All of the models are 6 hours late forecasting the end of the event. The GFS is too early with the onset of the heavy precipitation and over-predicts the total amount. The NAM forecast is late with the onset of heavy precipitation but is the closest to the observed total amount. The RUC and MAVMOS do well predicting the precipitation rate but over-predict the total amount. The consensus forecast reflects a blend of the components. It is slightly late with the onset of the heavy precipitation, does fairly well forecasting the precipitation rate but keeps the precipitation going for too long and ends up over-predicting the total amount. The RWFS (i.e., consensus) predicts 1.24 inches (31.37 mm) of liquid, which is 0.2 inches more than what was observed.

![Figure 11.1](image.png)

*Fig. 11.1:* 09 UTC 25 October 2006 RWFS run showing a liquid equivalent accumulation time-series plot comparing the DIA GEONOR measurements to the RWFS forecasts for the DIA site.
On 20 December 2006, Denver experienced a massive blizzard that ranked 7th biggest of all time. The event was characterized by a very large upper-level cut-off low that tracked across northern New Mexico into southeastern Colorado. Deep upslope and strong dynamics associated with the storm produced snow for over 30 hours. Snow started falling at 12 UTC on the 20th and ended at around 18 UTC on the 21st. Snowfall around the regions ranged from 30-36 inches in the western suburbs to 24 inches in downtown Denver and 21 inches at DIA.

With respect to the 12 UTC forecast generated on the 19th all of the models predict the onset of light snow long before the snow actually starts and are slow to ramp up the precipitation rate once the snow really does start (Fig. 11.3). As the storm system intensified, it also slowed down, making for a tough forecast. The GFS and MAVMOS forecasts are too low with the precipitation rate and thus show less accumulation than what was actually observed. Both the NAM and the RWFS are better predicting the precipitation rate and total accumulation. The RWFS forecast liquid amount matches the observed liquid amount of 1.04 inches (26.52 mm) for this period.

Fig 11.4 shows the 00 UTC runs from the 20th. Although all of the models do a better job predicting the start time of the event, there is a large spread in forecast precipitation rate and amount. The MAVMOS only predicts a total of 14 mm (0.55 inches) of liquid, whereas the NAM predicts in excess of 50mm (approx. 2 inches). The GFS is closer to what was observed but is still too low, predicting a total of 24mm (approx. 1 inch). The consensus forecast falls in between the GFS and NAM but is more heavily weighted towards the NAM and thus predicts a total liquid amount of 42mm (1.65 inches) which is still above the observed amount of 31.65mm (1.25 inches). The RUC is a little late with
the start of the heavier precipitation but accurately predicts the precipitation rate through the first part of the event. With so much spread among the model forecasts, this case highlights the benefit of an ensemble approach used by the RWFS.

![Graph showing liquid equivalent accumulation time-series plot comparing the DIA GEONOR measurements to the RWFS forecasts for the DIA site.](image)

**Fig. 11.3:** 12 UTC 19 December 2006 RWFS run showing a liquid equivalent accumulation time-series plot comparing the DIA GEONOR measurements to the RWFS forecasts for the DIA site.
On 28 December 2006, a second major snowstorm impacted the Denver area. This storm was the result of a digging upper-level trough that cut-off over the Great Basin and then tracked southeastward across southern New Mexico. Initial forecasts indicated that the storm would track farther north putting Denver under a prolonged period of snow. The forecast track changed leading up to the event with a southward progression from run to run. The change in storm track made for a difficult forecast. Snowfall was primarily generated by deep upslope associated with the approaching low. The snow started at 20 UTC on the 28th and ended at around 15 UTC on the 29th. Snowfall amounts ranged from 12-20 inches in the western suburbs to around 9 inches in downtown Denver and 5 inches at DIA.

Fig 11.5 shows forecasts generated approximately 24 hours before the start of the event. All of the models do a fairly good job predicting the start of the event and are only 1-3 hours too early. The GFS indicates higher precipitation rates and more total accumulation than what was observed. Initially, both the NAM and the consensus forecast predict lower precipitation rates than what was observed but then ramp the precipitation up too late, leading to higher total liquid amounts than what was observed. The MAVMOS most accurately predicts the overall trend in precipitation rate and amount. The observed liquid accumulation for this event was 13.89 mm (0.55 inches) with the RWFS predicting 17.53 mm (0.69 inches). The start-time of this event was beyond the RUC forecast lead times.
Fig 11.6 shows forecasts generated at 06 UTC on the 28th. Even at 12 hours out, the major NWS models (GFS and NAM) were still indicating a more northerly track and Denver getting a large amount of snow. This is evident by the much higher precipitation rates and total amounts predicted by the GFS, the NAM and subsequently the RWFS. The GFS is also too early with the start time by 5 hours, whereas the NAM, MAVMOS and RWFS are only about 2 hours early. The MAVMOS forecast accurately predicts the general trend in precipitation rate and total amount. The RUC does a good job predicting the start time as well as the precipitation rate through the first part of the event. For this run, the RWFS predicts a total of 30.73mm (1.21 inches) of liquid, which is well above the observed total of 13.89mm (0.55 inches).

![Diagram](image)

**Fig. 11.5:** 18 UTC 27 December 2006 RWFS run showing a liquid equivalent accumulation time-series plot comparing the DIA GEONOR measurements to the RWFS forecasts for the DIA site.
An Arctic outbreak occurred on 1 February 2007. A record low temperature of -18°F was recorded on the morning of the 2nd. This system was characterized by a digging shortwave that moved in from the north with an associated cold front at the surface. Eventually this system evolved into a big longwave trough over the central U.S., allowing arctic air to pour into the Front Range. Snowfall was generated by weak upslope and some upper-level dynamics associated with the leading shortwave. There was some light snow about 24 hours prior to the main event. Snow started falling in earnest at 22 UTC on the 1st and ended at about 06 UTC on the 2nd. Snowfall around the region ranged from 5-6 inches in the western suburbs to 3-4 inches around downtown Denver and 1-2 inches near DIA.

The plot of forecasts generated 24 hours before the start of the event show that all of the models are about 2 hours late with the onset of heavy precipitation (Fig. 11.7). The GFS, NAM and RWFS accurately predict the initial precipitation rate but keep the heavy snow going for 3 hours too long. All three over-predict the total amount of precipitation, with the NAM being the most overzealous. Since the RWFS precipitation forecast is heavily weighted towards the NAM, it closely resembles the NAM’s forecast. The MAVMOS under-predicts the precipitation rate and total amount. The observed total liquid accumulation for this event was 3.71mm (0.15 inches) with RWFS predicting 6.37mm (0.25 inches). The start of the event is beyond the RUC forecast lead times.

With respect to the 09 UTC forecast generated on the 1st, the NAM, GFS and the RWFS do a much better job predicting the start time of the event but miss the end time by 3-5 hours, and end up predicting more precipitation than what was observed (Fig. 11.8).
RUC and the MAVMOS are 2 hours late with the start of the event. The MAVMOS under-predicts the precipitation rate and total amount. The RUC does a good job predicting the precipitation rate through the first part of the event. For this run, the RWFS predicts a total of 0.17 inches (4.37mm) of liquid which is only 0.02 inches more than what was observed. Note that the total observed precipitation includes some light snow that fell 24 hours prior to the start of the main event.

![Diagram](image)

Fig. 11.7: 21 UTC 31 January 2007 RWFS run showing a liquid equivalent accumulation time-series plot comparing the DIA GEONOR measurements to the RWFS forecasts for the DIA site.
Results and Recommendation: Overall, the MAVMOS under-predicts precipitation and this supports the decision not to use it for QPF. For the lead times for which the RUC forecast was available, it seems to add benefit to the RWFS forecast.

The NAM’s QPF is too high and this was especially evident during the later part of the season (December – April). Since the RWFS QPF was heavily weighted towards the NAM, it may be beneficial to re-examine the weights and give more weight to the GFS and the RUC.

The ability of models to predict precipitation start and stop time and amount varies greatly between models. Care must be taken to ensure that the weights given to individual prediction modules are appropriate. If only low quality verification data are available, the weights should be fixed based on experience and/or expert opinion.

12 INSOLATION DATA

The following information is provided for reference. The statistics computed in this section are based on 2005-2006 forecasts.
It is well recognized that incoming solar radiation (insolation) is a critical parameter for predicting road temperature and thus very important in the RWFS process. For this demonstration season, short wave radiation data were available from the RUC, Eta and GFS models. Based on limitations in the GFS data it was predetermined to use the RUC and the Eta exclusively for predicting insolation. Listed below are descriptions of the issues that arose with the short wave radiation fields used in the MDSS.

**Eta Model:** The short wave radiation data from the Eta model is an instantaneous value given every 3 hours. The values are interpolated to produce hourly output, which can then be used by the RWFS.

**GFS Model:** The short wave radiation data from the GFS model is a time-averaged value over a 3 hour period. Because of the time averaging characteristic, it is not practical to use it as an input to a road temperature model.

**RUC Model:** The radiation data from RUC model provide instantaneous values and have an hourly temporal resolution. However, RUC insolation data is limited to a lead time of 21 hours.

Because of the nature of real-time shortwave radiation measurements, whereby values can change dramatically over short time periods (e.g., during partly cloudy conditions), and because real-time insolation measurements are not broadly available, it is not practical to use these data to forward error correct the RWFS insolation forecasts. Therefore, the weight blending values for insolation had to be fixed. The RWFS (consensus) was configured to use 50% RUC and 50% Eta insolation forecasts for near term forecasts (0-21 hr) and Eta insolation forecasts for the longer-term forecasts (21-48 hr).

The scatter plots show forecasts versus observations for all 12Z forecasts (for all lead times out to 24 hours) generated from 1 November 2005 to 31 March 2006. The forecasts are for the Vaisala site at 6th Avenue Parkway along E-470. Total average error has been calculated to get a sense of overall performance.

The observations used are from the pyronometer at the 6th Avenue Parkway (Vaisala) RWIS station and are ingested via the MADIS data stream. Quality control was done on the observations to ensure proper verification. Values greater than zero at night were set to zero.

The RWFS (consensus) forecast (Fig. 12.1) has lower average error and less outliers than the RUC (Fig. 12.2) and the ETA (Fig. 12.3) individually. All three seem to do a better job predicting values near peak heating (400 – 600 W/m²), but they struggle during the morning and late afternoon (100 – 400 W/m²). There is a positive bias in the RWFS forecasts during sunrise and sunset (less than 100 W/m²) and this can be attributed to the same bias in the ETA forecasts. Overall, all three forecasts show a positive bias during the morning and afternoon and a slight negative bias during peak heating. This would suggest that the forecasts are slightly out of phase with the observations.
Fig. 12.1: Scatter plot of the RWFS forecasted downward short-wave radiation from 12 UTC runs from 1 November 2005 to 31 March 2006 versus the observed solar radiation for the Vaisala site.

Fig. 12.2: Scatter plot of the RUC forecasted downward short-wave radiation from 12 UTC runs from 1 November 2005 to 31 March 2006 versus the observed solar radiation for the Vaisala site.
Results Summary: The ability of models to accurately predict insolation varies greatly between models and from day to day. By combining models a more consistent forecast can be achieved. The 50-50 combination of the RUC and ETA gives a better downward solar radiation forecast than any one component by itself.

13 ENHANCEMENTS FOR THE 2007-2008 WINTER SEASON

Road Condition Model

The Maintenance Decision Support System is designed to provide weather and road conditions forecasts, along with treatment recommendations, in support of winter maintenance operations. The treatment recommendations produced by the system are highly dependent on the predicted weather and its anticipated impact on pavement conditions. The prototype MDSS relies on several weather forecast models to create a consensus forecast of atmospheric conditions, while one surface energy balance model is used to generate forecasts of road temperature, as well as snow depth on the road. In conjunction with weather forecast data, these road condition forecasts are used to calculate the effects of actual and potential chemical applications on the road surface.
To date, the MDSS has used a road temperature model known as SNTHERM. SNTHERM is a one-dimensional energy and mass balanced model, developed at the U.S. Army Corps of Engineers, Cold Regions Research & Engineering Laboratory (CRREL) in the 1980s. This model is no longer being supported by CRREL. As a result, a study was conducted to evaluate potential replacement road temperature models. Criteria included forecast performance, code stability, support, efficiency, and ease of use. The assessment found that METRo, Model of the Environment and Temperature of Roads, provided the best forecast for the cases that were examined, which included a wide range of weather conditions. This model has been incorporated into the MDSS, and it has performed well under a number of disparate conditions. It is anticipated that the output from this energy balance model will lead to improved MDSS road temperature and road condition forecasts, as well as recommended treatments.

**Tactical Alerts for Frozen Precipitation and Freezing Roads**

The purpose of the Alert Generator is to generate notifications about important current or near-term events that might impact operations. They provide operators with a quick visual cue regarding near-term weather threats. The Alert Generator uses the most recent observation and forecast weather and road data to generate an alert status for a set of road segments. Weather and road conditions which result in an alert include the existence of frozen or freezing precipitation and wet roads with temperatures below freezing. Alerts are updated when new observation or forecast data are available.

Observations of current weather are obtained from METAR reports, which are used to examine whether frozen or freezing precipitation is occurring. If such precipitation exists at a METAR location close to a route, then a Weather Alert is generated for that route. One or more METARs may be assigned to each route so that the next METAR in the list can be checked if the first one is missing. For Road Alerts, the most recent road forecast is examined to determine if the road will be freezing with precipitation over the next 3 hours. Road Alerts are also generated based on a list of routes.

When an alert is active, it is displayed as a red flashing beacon on the display (Fig 13.1). Mousing over the alert beacon will show where the alert is valid (i.e., road segment).
Tactical Display Capacity

The MDSS display has been updated to include the capacity to view radar, satellite, and Automated Vehicle Location (AVL) data. Figs. 13.2 and 13.3 provide examples of AVL and radar data displayed in the MDSS client application, respectively. These real-time data will support the tactical decision process, as they will allow weather systems to be monitored and tracked. Additionally, AVL-related data from trucks in the field will provide information regarding the road condition, thus, allowing a more timely, accurate response to impacted road segments.
Fig. 13.2 MDSS with AVL data displayed.

Fig. 13.2 MDSS with radar reflectivity data displayed.
14 ADDITIONAL RESEARCH NEEDS

The section describes additional research needs that would result in improved atmospheric and road condition forecasts, as well as treatment recommendations. These topics are based on experience gained through field demonstrations, feedback from end-users, and analysis such as that presented herein. These topics have been highlighted in past performance assessment reports, and they are included here for continuity.

Numerical Weather Prediction

1) Land Surface Modeling: Additional research is required to couple weather prediction models with land surface models. This is a relatively new area of research and one that is critical for predicting the surface and near surface conditions.

2) Boundary Layer Meteorology: Research is required to better understand the atmospheric processes (e.g., surface fluxes, etc.) and their interactions with the land surface. Predicting phenomena such as drainage flows, fog formation, shallow fronts, road frost, blowing dust and smoke are all highly dependent on understanding the science of the near surface boundary layer.

3) Weather Model Configuration: Research is required to explore factors that could improve near surface weather prediction. Model configuration variables including the number and distribution of model levels and selection of physics packages to optimize skill during winter events need to be explored.

4) Data Assimilation: Additional research is required on the development of data assimilation techniques that can take advantage of current and emerging surface weather observations (e.g., vehicle based observations, short range radars, etc.) that have the potential for improving short range forecasts (0-12 hours). In addition, the performance of three- and four-dimensional variational analysis and four-dimensional data assimilation techniques need to be investigated.

5) Clouds and Insolation: Additional research is required to improve the prediction of clouds and insolation, as these parameters are critical for pavement temperature prediction. Pavement temperature predictions could be improved if insolation data from NWS models were provided hourly and all the models calculated the parameter in a similar manner (e.g., instantaneous versus average values).

Pavement Condition Detection and Prediction

1) Effect of Insolation: Additional research is required to understand how pavement temperature sensors (various models and brands) perform under varying insolation (direct and indirect radiation) conditions. Current results suggest that under conditions of strong solar loading, the accuracy of the pavement temperature sensors is reduced.
2) **Road Condition Sensing**: The accuracy of pavement chemical concentration and freezing temperature measurements is low and because of this poor performance, these data are not widely used by DOT personnel and not incorporated into systems such as the MDSS. Knowledge of the pavement chemical concentration and its incorporation into the MDSS would reduce the workload of DOT staff as they would not have to manually enter actual pavement condition information.

3) **Pavement Temperature Modeling**: Additional research is required to understand the interactions of differing chemical types with various forms of precipitation and the impact they have on pavement temperature. New pavement types such as porous asphalt also need to be studied so their temperature profile behavior can be properly modeled. The impact of traffic on pavement temperature and how traffic distributes chemicals needs to be studied.

4) **Utilization of Actual Treatment Data from Vehicles**: One of the largest deficiencies of the prototype MDSS is its inability to incorporate actual treatment data in near real time. Currently, DOT personnel must enter actual treatment data once operations have begun. In most cases, time does not permit the manual entry process to occur, and future MDSS treatment recommendations are not initialized properly and hence are inaccurate. Research is required to investigate optimal methods of incorporating GPS/AVL data from vehicles in near real time during winter events.

5) **Road/Bridge Frost**: Additional research is required to better understand the factors that influence the formation and dissipation of road and bridge frost. Improvements in bridge deck temperature prediction are needed and a better understanding of the gradients in air and dewpoint temperature near the pavement surface are also needed. In addition, the characteristics of long wave radiation, which are important for pavement temperature prediction, for bridges crossing varying surfaces (e.g., rivers, highways, valleys, railbeds, etc.) need to be understood to improve the prediction of bridge deck temperatures.

**General**

1) **Communication of Uncertainty**: The DOT users acknowledge that weather and road condition prediction is complex, particularly on road scales. They often requested that the information include terms of uncertainty (e.g., probability and/or confidence). The prototype MDSS included a graphical precipitation type product that indicated the conditional probability of precipitation type and the pooled fund MDSS includes confidence intervals for some parameters. Additional work is required to research and develop methods for calculating uncertainty and understanding the human factors issues involved in presenting this information to end users.
15 REFERENCES


The persons listed on this page are the primary technical leads on the MDSS software system and field verification data collection.

### MDSS Development Team

<table>
<thead>
<tr>
<th>Primary Responsibility</th>
<th>Technical Point of Contact</th>
<th>Telephone</th>
<th>E-mail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Lead</td>
<td>Jim Cowie, NCAR</td>
<td>303-497-2831</td>
<td><a href="mailto:cowie@ucar.edu">cowie@ucar.edu</a></td>
</tr>
<tr>
<td>MDSS Project Manager</td>
<td>Bill Mahoney, NCAR</td>
<td>303-497-8426</td>
<td><a href="mailto:mahoney@ucar.edu">mahoney@ucar.edu</a></td>
</tr>
<tr>
<td>Cell: 303-817-7975</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDSS Project Manager</td>
<td>Kevin Petty, NCAR</td>
<td>303-497-2705</td>
<td><a href="mailto:kpetty@ucar.edu">kpetty@ucar.edu</a></td>
</tr>
<tr>
<td>Lead Software Engineer</td>
<td>Bill Myers, NCAR</td>
<td>303-497-8412</td>
<td><a href="mailto:myers@ucar.edu">myers@ucar.edu</a></td>
</tr>
<tr>
<td>Rules of Practice</td>
<td>Robert Hallowell, Lincoln Laboratory</td>
<td>781-981-3645 Cell: 603-566-8457</td>
<td><a href="mailto:bobh@ll.mit.edu">bobh@ll.mit.edu</a></td>
</tr>
<tr>
<td>MDSS Display Application</td>
<td>Arnaud Dumont, NCAR</td>
<td>303-497-8434</td>
<td><a href="mailto:dumont@ucar.edu">dumont@ucar.edu</a></td>
</tr>
<tr>
<td>Verification Analysis</td>
<td>Seth Linden, NCAR</td>
<td>303-497-8433</td>
<td><a href="mailto:linden@ucar.edu">linden@ucar.edu</a></td>
</tr>
<tr>
<td>MDSS Program Support for the FHWA</td>
<td>Andy Stern, Mitretek</td>
<td>703-610-1754</td>
<td><a href="mailto:astern@mitretek.org">astern@mitretek.org</a></td>
</tr>
<tr>
<td>Road Weather Management Program</td>
<td>Paul Pisano, FHWA</td>
<td>202-366-1301</td>
<td><a href="mailto:Paul.pisano@fhwa.dot.gov">Paul.pisano@fhwa.dot.gov</a></td>
</tr>
</tbody>
</table>

### City and County of Denver

<table>
<thead>
<tr>
<th>Primary Responsibility</th>
<th>Technical Point of Contact</th>
<th>Telephone</th>
<th>E-mail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Senior Engineer</td>
<td>Pat Kennedy</td>
<td>720-865-6860</td>
<td><a href="mailto:william.kennedy@ci.denver.co.us">william.kennedy@ci.denver.co.us</a></td>
</tr>
<tr>
<td>Staff Engineer</td>
<td>Angela Hager</td>
<td>720-913-4562</td>
<td><a href="mailto:angela.hager@ci.denver.co.us">angela.hager@ci.denver.co.us</a></td>
</tr>
<tr>
<td>Administrative Manager</td>
<td>Kelly Duffy</td>
<td>720-865-6857</td>
<td><a href="mailto:kelly.duffy@ci.denver.co.us">kelly.duffy@ci.denver.co.us</a></td>
</tr>
<tr>
<td>Staff Engineer</td>
<td>Lindsey VanCleave</td>
<td>720-865-6851</td>
<td><a href="mailto:lindsey.vancleave@ci.denver.co.us">lindsey.vancleave@ci.denver.co.us</a></td>
</tr>
<tr>
<td>Senior Engineer</td>
<td>Brian Roecker</td>
<td>720-865-6869</td>
<td><a href="mailto:brian.roecker@ci.denver.co.us">brian.roecker@ci.denver.co.us</a></td>
</tr>
</tbody>
</table>

### E-470 Public Highway Authority

<table>
<thead>
<tr>
<th>Primary Responsibility</th>
<th>Technical Point of Contact</th>
<th>Telephone</th>
<th>E-mail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Director of Roadway and Land Management</td>
<td>Matt Alexander</td>
<td>303-537-3726</td>
<td><a href="mailto:matta@e-470.com">matta@e-470.com</a></td>
</tr>
<tr>
<td>Manager of Maintenance</td>
<td>Terry Gowen</td>
<td>303-537-3710</td>
<td><a href="mailto:tgowin@e-470.com">tgowin@e-470.com</a></td>
</tr>
<tr>
<td>Administrator</td>
<td>Micheli Watson</td>
<td>303-537-3747</td>
<td><a href="mailto:mwatson@e-470.com">mwatson@e-470.com</a></td>
</tr>
<tr>
<td>Maintenance Contractor T-P Enterprises, Inc.</td>
<td>Dave Pickrell</td>
<td>720-490-7214</td>
<td><a href="mailto:tpickrell@aol.com">tpickrell@aol.com</a></td>
</tr>
</tbody>
</table>

### Northwest Parkway

<table>
<thead>
<tr>
<th>Primary Responsibility</th>
<th>Technical Point of Contact</th>
<th>Telephone</th>
<th>E-mail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Administrator</td>
<td>Lina Kheng</td>
<td>303-533-1209</td>
<td><a href="mailto:LKheng@nwpy.org">LKheng@nwpy.org</a></td>
</tr>
</tbody>
</table>
APPENDIX B

GEONOR Precipitation Gauge located at Denver International Airport

Fig. B.1: GEONOR precipitation gauge with a DFIR shield.
<table>
<thead>
<tr>
<th>Event Date</th>
<th>Event Class</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 9-10, 2006</td>
<td>Light Rain Event</td>
<td>Event started as light rain on Monday Oct. 9. There was light drizzle during the previous night. Light drizzle was reported at DIA at 2 am. There was a change to rain around 11 am. The MDSS did not pick up on the drizzle but did an excellent job with the timing of the rain. The 1800 MDSS forecast (Oct 8) was predicting a transition to snow during the night of Oct. 9. This was consistent with all of the forecasts (TV, NWS, etc.). The 1800 MDSS forecast showed no transition-only rain, which is how the event verified. Overall, the MDSS did really well with the event.</td>
</tr>
<tr>
<td>Oct. 17-18</td>
<td>Snow event</td>
<td>MDSS predicted that this event would start as rain between noon and 3 pm and turn over to all snow around 7 pm. In some locations, the event did start as rain, but in most, it started as snow. In general, the event started about 3 hrs prior to the MDSS indication of precipitation. MDSS predicted 3, 5, and 4 inches of snow at NOAA, Sixth Ave, and Plaza A, respectively. Actual snowfall totals was on the order of 5 inches in Boulder, 3 inches at Sixth Ave, and 4 inches at Plaza A.</td>
</tr>
<tr>
<td>Oct. 20-21</td>
<td>Rain to snow</td>
<td>Event started as light rain and transitioned over to snow during the evening of the 20th. Approximately 5 to 6 inches of new snow was received in Boulder while 1 to 3 inches was recorded in the Denver Metro area. The MDSS indicated mainly rain in Boulder, and forecasted about ½ inch at Sixth Ave, and an inch at Plaza A.</td>
</tr>
<tr>
<td>Oct. 25-26</td>
<td>Rain to snow</td>
<td>Event was forecast as a potential major storm. Cutoff low over southern CO and northern NM. Event started as rain at midnight on the 25th, and changed over to all snow around 3 a.m. on the 26th. The 9 a.m. forecast (on the 25th) did a great job forecasting the start of the event, but the rain to snow transition was delayed in this forecast by about three hours. The 6 p.m. MDSS did excellent forecasting the start (midnight) and transition time (3 a.m.). The 9 a.m. forecast was predicting 3 to 5 inches of snow around the Denver area, but the 6 p.m. forecast indicated 5 to 8 inches. This may have something to do with the fact that the 21Z and 00Z RUC did not come in. I think this would have kept the forecasted amounts down some. Denver did receive 5 inches of snow in some areas (south and southeast along I70), but generally amounts were lower in downtown Denver. Louisville received about 5 inches. Snow ended about 1 p.m. on Oct. 26. MDSS was 2 – 3 hours late with the end time.</td>
</tr>
<tr>
<td>Oct 27</td>
<td>System Change</td>
<td>Went to the higher resolution NAM</td>
</tr>
<tr>
<td>Nov 12.</td>
<td>Snow (a little rain)</td>
<td>This was mainly a small snow event that began around 7:30 am on Sunday the 12th and ended in the late afternoon, with a period of clearing from about 11 am to 2:30 pm. MDSS picked up on the event and timing, but it forecasted mainly rain.</td>
</tr>
<tr>
<td>Nov 28-29</td>
<td>Extended light snow event</td>
<td>Light snow began at about 5 pm on Nov 28th. MDSS did not declare snow until the early morning on the 29th, but it did show 20% probability of snow around the start time. Once the snow started, the forward error correction helped to bring the MDSS more inline with the event.</td>
</tr>
</tbody>
</table>
Light snow continued throughout the night, with dropping temperatures into the upper teens by daybreak on Nov 29. Light snow continued through 2 pm on Wednesday.

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 1</td>
<td>System Change</td>
<td>Changed the QPF weights from 60% NAM, 30% RUC, and 10% GFS to 60% NAM, 20% RUC, and 20% GFS</td>
</tr>
<tr>
<td>Dec 20-21</td>
<td>Snow event</td>
<td>Major snow event occurred. Received about 24 inches in Denver and over 30 in Boulder. MDSS did well with the timing of the event, but it only forecast 14-16 inches in the Denver area (19 in Boulder). This may have something to do with liquid water conversion technique. Event began at about 5 am on the 20 and lasted until the early afternoon on the 21.</td>
</tr>
<tr>
<td>Dec 28-29</td>
<td>Snow event</td>
<td>Thursday (28th) evening heavy snow. By Friday morning 9 inches in Denver and about 12 inches in Boulder. System quickly died out in the afternoon. MDSS was picking up on this, but everyone else was forecasting more snow, which never happened.</td>
</tr>
<tr>
<td>Jan 4-5</td>
<td>Snow event</td>
<td>Snow began at midnight on Jan. 4 and lasted through the late afternoon hours on Jan. 5. MDSS was late with the start time by about 4 hours and under-predicted the snowfall amounts in Denver by a few inches, and by more that ½ foot in Boulder. MDSS end times were good.</td>
</tr>
<tr>
<td>Jan 21-22</td>
<td>Snow event</td>
<td>Light snow occurred on Jan 21, followed by a break overnight. On Jan 22, Denver received 4 to 6 inches of snow. This was not forecasted by the MDSS. MDSS had 2–3 inches of snow.</td>
</tr>
<tr>
<td>Jan 26</td>
<td>System Change</td>
<td>Reduced the POP threshold from 25% to 20%</td>
</tr>
<tr>
<td>Jan 27</td>
<td>Snow event</td>
<td>Snow started around 5 am on Saturday Jan. 27. This was about 6 hours earlier than MDSS forecast. This was consistent with other forecasts. MDSS did not show much in the way of precip. - less than ½ inch around Denver. Denver received about 2 inches.</td>
</tr>
<tr>
<td>Jan 31</td>
<td>Snow event</td>
<td>Undocumented.</td>
</tr>
<tr>
<td>Feb 1</td>
<td>Snow event</td>
<td>Snow started around 2-3 in the afternoon on Thursday. MDSS did well with the timing and amounts of this event. Denver received 2 to 3 inches of snow. Event ended early on Friday morning.</td>
</tr>
<tr>
<td>Feb 24</td>
<td>Snow event</td>
<td>Snow started around 4 a.m. in the morning on the east and southeast side of Denver. It ended at about 7 a.m. The MDSS showed less than an inch of snow for this event. Models had a very difficult time with this forecast. 18Z forecast dried up the moisture. Moisture came back in the 00Z forecasts. There was considerable variation in snow amounts. No snow in west Denver or Boulder. Almost 6 inches along E470.</td>
</tr>
<tr>
<td>March 29</td>
<td>Snow event</td>
<td>8 inches-Undocumented</td>
</tr>
<tr>
<td>April 12-13</td>
<td>Snow event</td>
<td>This event was forecast as a major snowstorm by the NWS and Media, but the system stayed too far to the south resulting in little or no snow accumulations. MDSS was the only system showing very little snow the night before.</td>
</tr>
<tr>
<td>April 27, 2007</td>
<td>System Change</td>
<td>Implemented new road temp model (METRo)</td>
</tr>
</tbody>
</table>