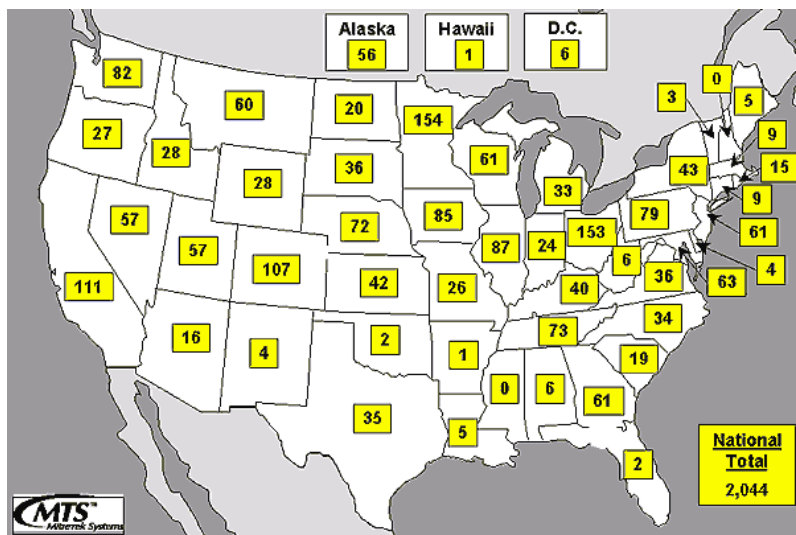


ROAD WEATHER FORECASTING AND OBSERVATIONS: ASSESSMENT OF CURRENT CAPABILITIES AND FUTURE TRENDS



Version Notes

Version Number	Date	Notes
Version 1.0	11 December 2004	Draft version prepared for the FHWA.

Cover Graphic: Graphic illustration of the total number and distribution of environmental sensors systems (ESS) deployed by state road operating agencies as of March 2004. Image courtesy of Mitretek Systems.

Questions and comments about this document should be directed to:

William Mahoney
Research Applications Laboratory
National Center for Atmospheric Research
P.O. Box 3000
Boulder, CO 80307
Ph: 303-497-8426
E-mail: mahoney@ucar.edu

Table of Contents

1. Purpose.....	5
2. Scope.....	5
3. Related Documents	5
4. Environmental Sensor System (ESS) Measurements	7
4.1 Air Temperature.....	7
4.2 Dew Point Temperature	7
4.3 Relative Humidity	7
4.4 Wind Speed and Direction	8
4.5 Visibility	8
4.6 Winter Precipitation.....	9
4.7 Snow Depth Sensors	11
4.8 Video Imaging	12
4.9 Pavement Temperature	12
4.10 Pavement Condition.....	13
5. Weather and Road Condition Prediction Capabilities	14
5.1 Weather Prediction Modeling.....	14
5.2 Road Temperature Prediction	18
5.3 Blowing and Drifting Snow Prediction	19
5.4 Road and Bridge Frost Prediction.....	20
6. Summary of Trends in Road Weather Services.....	21
7. Conclusion	22

Acronym Glossary

AGL – Above Ground Level
CONUS – Continental U.S.
CRREL – U.S. Army Cold Regions Research and Engineering Laboratory
DOT - Department of Transportation
DSS – Decision Support System
FAA – Federal Aviation Administration
FHWA – Federal Highway Administration
FSL – NOAA, Forecast Systems Laboratory
GUI – Graphical User Interface
IOC – Initial Operating Capability
ITSA – Intelligent Transportation Society of America
METAR – Meteorological Aviation Report (the acronym is French based)
MDSS - Maintenance Decision Support System
MIT/LL - Massachusetts Institute of Technology - Lincoln Laboratory
NASA – National Aeronautics and Space Administration
NCEP - National Centers for Environmental Prediction
NCHRP – National Cooperative Highway Research Program
NSF – National Science Foundation
NSSL – NOAA, National Severe Storms Laboratory
NOAA – National Oceanic and Atmospheric Administration
NCAR - National Center for Atmospheric Research
NWS – National Weather Service
OCD – Operational Concepts Description
RWM - Road Weather Management Program
STWDSR - Surface Transportation Weather Decision Support Requirements
TRB – Transportation Research Board
WMO – World Meteorological Organization

1. Purpose

This document is designed to provide guidance to State DOT maintenance administrators about current and near future weather observing and forecasting capabilities for surface transportation. The purpose is to provide information that helps separate fact from myth and hype with respect to road weather services.

2. Scope

This document provides a high level discussion of various weather observation and forecasting capabilities and attempts to present the information in a straightforward manner as an aid to State DOT personnel who often have to evaluate competing road weather observing and forecasting services. After reading this document, State DOT maintenance administrators should have a better understanding of what should and could be provided by commercial weather service providers.

A commercial product mentioned in this document or provided as an example or shown in illustrations does not represent an endorsement of the product.

3. Related Documents

For additional information on weather and road condition measurement and prediction capabilities, the reader is directed to the related documents listed in Table 1.

Table 1. Related Documents

Document and/or Web Sites	Primary Source
Best Practices for Road Weather Management – Version 2.0: Environmental Sensor Technologies http://www.ops.fhwa.dot.gov/weather/best_practices/1024x768/menu_environmental.htm	Federal Highway Administration
An Introduction to Standards for Road Weather Information Systems (RWIS) http://www.ops.fhwa.dot.gov/weather/best_practices/1024x768/transform_param2.asp?xmlns=pub.xml&xmlname=publications.xml&keyname=20	Federal Highway Administration
Automated Surface Observing System (ASOS) http://www.faa.gov/asos/faq.htm	Federal Aviation Administration (FAA)

Automated Weather Observing System (ASOS) http://www.faa.gov/asos/awosinfo.htm	Federal Aviation Administration (FAA)
ASOS User Guide http://www.nws.noaa.gov/om/brochures/asosbook.htm	National Weather Service
MDSS Technical Performance Report – Second Iowa Field Demonstration, Winter 2003-2004. http://www.rap.ucar.edu/projects/rdwx_mdss/documents/MDSS_Tech_Perf_Report_20Nov04.pdf	National Center for Atmospheric Research (NCAR)
Federal Meteorological Handbook (FMH-1), Surface Weather Observations and Reports, Office of Federal Coordinator for Meteorology, U.S. Department of Commerce, December 1995. http://www.ofcm.gov/fmh-1/fmh1.htm	U.S. Department of Commerce
ESS Owned by State Operating Agencies http://www.ops.fhwa.dot.gov/weather/mitigating_impacts/esmap.htm	Federal Highway Administration (FHWA)

4. Environmental Sensor System (ESS) Measurements

This section provides an overview description of weather measurements typically made as part of road weather observation systems and provides information about their capabilities and limitations.

4.1 Air Temperature

Air temperature is measured at all the Federal Aviation Administration (FAA) and National Weather Service (NWS) sites and at most Road Weather Information System (RWIS) sites. Sensors that measure air temperature are mature and they rarely fail. Air temperature measurement accuracy should be within 1 degree Fahrenheit (°F). When comparing air temperature differences between observation systems, one should be aware that variations can exist over short distances (10s of feet) and with time (minutes). Differences of several degrees can be expected over short distances due to local variations in terrain, elevation, shading, ground cover, and proximity to other obstructions such as buildings. Temperature differences can also vary over short time periods, especially during periods when temperatures typically change rapidly such as at dusk, dawn, during frontal passages, and periods of precipitation.

4.2 Dew Point Temperature

Dew point temperature is the surface temperature at which the air becomes saturated with moisture (100% relative humidity). Air can only hold a certain amount of water vapor at a given pressure, so when it cools to that temperature, condensation (dew) forms.

The dew point temperature is measured at all the Federal Aviation Administration (FAA) and National Weather Service (NWS) sites and at most Road Weather Information System (RWIS) sites. Sensors that measure dew point temperature are mature and although they rarely fail, they tend to fail more than temperature sensors. Dew point temperature measurement accuracy should be within 2 to 4 °F. Although an accuracy of 2 to 4 °F seems close, errors of even a fraction of a degree can impact fog and frost detections and predictions when the dew point and air temperatures are close (relative humidity near 100%). Because dew point accuracy is important, the sensors should be routinely calibrated as recommended by the manufacturer.

When comparing dew point temperature differences between observation systems, one should be aware that variations can exist over short distances (10s of feet) and with time (minutes). Differences of several degrees can be expected over short distances due to local variations in terrain, elevation, shading, ground cover, and proximity to water bodies and sources of water vapor such as manufacturing facilities and power companies. Dew point temperature differences can also vary over short time periods, especially during periods when moisture typically changes rapidly such as during frontal passages, and periods of precipitation.

4.3 Relative Humidity

Relative humidity is the ratio of the amount of water vapor (moisture) in the air compared to the total amount of water vapor that the air can hold at the same temperature. If the amount of water vapor in the air remains constant, but the temperature falls, the relative humidity will rise and vice versa. Relative humidity is a derived parameter that is calculated from the air temperature and dew point measurements; therefore its accuracy depends on the accuracy of the air temperature and dew point sensors. Relative humidity measurements should be accurate to within $\pm 2\%$. Although an accuracy of $\pm 2\%$ seems close, errors of even a fraction of a percent can impact fog and frost detection when the relative humidities are close to 100%. Differences of several percent can be expected over short distances due to local variations in terrain, elevation, shading, ground cover, and proximity to water bodies and sources of water vapor such as manufacturing facilities and power companies. Relative humidity differences can also vary over short time periods, especially during periods when moisture typically changes rapidly such as during frontal passages, and periods of precipitation. Because relative humidity accuracy is important, the sensors should be routinely calibrated as recommended by the manufacturer.

4.4 Wind Speed and Direction

Wind speed and direction is measured at all the Federal Aviation Administration (FAA) and National Weather Service (NWS) sites and at most Road Weather Information System (RWIS) sites. Sensor types that measure wind speed and direction vary between cup and vane style, propeller and tail style, and more recently sonic. These sensors rarely fail, but they do need routine maintenance to ensure that the systems are in proper working order. Propeller style systems may need new bearings once every year or two. Cup and vane systems also need bearing replacements every year or two and since they tend to be of lighter construction, they need to be checked to ensure none of the cups have broken off or been bent. Sonic anemometers tend to have the least maintenance, but should be checked to ensure nothing has contaminated the prongs (e.g., bird nests, etc.). In winter climates, all the systems are susceptible to icing and snow accumulation, so heated elements are recommended.



Photo of sonic anemometer

Wind speed measurement accuracy should be within 2 miles per hour (mph) and wind direction accuracy should be within 5 degrees (measurements range is 0 to 360 degrees). When comparing wind speed and direction differences between observation systems, one should be aware that variations can exist over short distances (10s of feet) and with time (minutes). Differences of several miles per hour and 10s of degrees can be expected over short distances due to local variations in terrain, sheltering due to local obstructions, elevation, and ground cover (trees versus grass). Wind speed and direction differences can also vary over short time periods, especially during periods when conditions can change rapidly such as during frontal passages, and periods of precipitation, especially thunderstorms.

4.5 Visibility

Visibility is measured at all major Federal Aviation Administration (FAA) airports and at most National Weather Service (NWS) sites. Visibility is measured at some roadway ESS sites,

particularly at sites prone to poor visibility conditions. Visibility is typically measured using an optical system that looks for light attenuation between a transmitter and receiver separated by 12 to 30 inches. An algorithm is used to correlate the amount of light attenuated and the visibility.

There are several factors that can impact visibility measurements. A dirty sensor lens and/or moisture on the lens can be misinterpreted as lowered visibility. A slowly failing transmitter (dimmer light source) can also be misinterpreted as lowered visibility. It is important to keep the lenses clean and follow the manufacturer's maintenance recommendations.

The most significant limitation of a visibility sensor is that it only measures the air between its transmitter and receiver. If visibility conditions vary greatly in the area, the reported visibility may not be representative of the conditions in a broader region. If a visibility sensor is being considered for a site that is prone to fog, care must be taken to site the instrument in the area most prone to fog. In addition, the sensor height should be close to the height of a truck cab (~6 feet) so that the visibility reported by the system corresponds to the condition in the driver's line of site.

Visibility sensor design varies between models and manufacturers as some are designed to measure visibility to several miles, while others are sensitive to closer ranges. For road applications, it is more important to measure visibility below 1 mile. Visibility sensors should be accurate to within 50 feet and many manufacturers indicate accuracy to within 35 feet.

Visibility measurements are critical for fog detection and diagnosis. The lack of visibility measurements is currently a major constraint on the development of high-resolution surface visibility products. The addition of visibility measurements at ESS sites is encouraged as they will provide a much needed data source for future surface visibility products.

4.6 Winter Precipitation

Winter precipitation is difficult to measure accurately. The standard method for observing precipitation is to use a gauge consisting of a collection container and a device or scale to determine the amount of precipitation that falls through the orifice. This technique has been employed for several hundred years and continues to be used today, although there have been distinct improvements in the instrumentation used to make the measurements. Today, there are numerous devices on the market designed to not only provide information on the amount of precipitation that has occurred, but the rate and time at which it fell and even the type of precipitation that occurred. However, most of the gauges in operation today were developed for climatological analysis purposes. There has been relatively little emphasis placed on the importance of viewing these data in real time. In addition, the vast majority of devices used today are not well designed for measuring winter precipitation, particularly snow.

The National Weather Service (NWS) makes observations of precipitation accumulation at its ASOS stations each minute, but only reports the accumulations typically once each hour as a part of the standard METAR report. Precipitation gauges have evolved considerably over the years and now offer the prospect of high-resolution measurements (0.001 inches) that are potentially

available in real time. While these gauges are commercially available, relatively few have been integrated into existing observing networks.

Winter precipitation is defined as frozen or freezing precipitation that occurs in the form of snow, sleet (ice pellets), snow pellets, graupel (spongy hail), freezing rain, or freezing drizzle. Various precipitation gauges have been developed over the years to measure rainfall accumulation and intensity. However, these same gauges perform poorly in snowfall. There are several reasons for this. The first is that snow tends to stick to the sidewalls of the gauge orifice rather than falling into the gauge as rain does. This results in a significant under measure of precipitation during the period when it is snowing, and a false over measure of precipitation when this snow melts and falls into the gauge at some later time. In extreme cases snow can actually “cap over” the opening of a gauge. The second reason that snow is more difficult to measure than rain is that snowflakes are generally less dense than raindrops and are affected more by the distortions in airflow around the gauge. When air encounters an object, such as a gauge, it tends to flow around the object. Snowflakes follow similar trajectories and flow around the gauge rather than going into the gauge. This results in an under measure of snowfall that increases as the wind speed increases. Adding wind shields around a gauge can reduce this problem. A considerable effort has gone into determining the most effective wind shield. Studies have shown that gauges that are improperly shielded may record less than 20% of the true precipitation when wind speeds are on the order of 20 miles per hour.

The accumulation of light snow is more difficult to observe because the precipitation rates for light snow are considerably less than for light rain, yet the reporting increment for the liquid-equivalent amount remains the same at 0.01 inches. Thus, light snow can fall for a considerable amount of time and never be reported. To eliminate this problem, gauges that can measure precipitation to a resolution of 0.001 inches are required. Researchers have been aware of these problems for many years and have tried to devise various solutions to improve a gauge’s ability to measure the snowfall. The World Meteorological Organization (WMO) has been very active in promoting intercomparison studies among gauges and wind shields used in countries around the world. The problem with these solutions is that a large wind shield is required, which is not practical for near roadway locations.

ASOS stations record precipitation accumulation using a tipping bucket gauge that is heated during the winter. The resolution of the measurement is 0.01 inches, but for reasons listed above, the measurements during winter are very poor. The NWS is currently replacing the tipping bucket gauges with improved systems (weighing gauges). These new gauges will be more sensitive to light precipitation and, because they don’t have to “tip” before they report new accumulations, they will provide better real-time information.

The NWS also uses an optical device called the LEDWI (light-emitting diode weather identifier) at ASOS sites to determine precipitation type. LEDWI is currently able to distinguish between rain and snow at precipitation rates greater than 0.01 inches, although during windy conditions (>25 knots) a vibration develops that causes rain to be reported as snow and snow to be reported as rain. The NWS is currently involved in a system procurement program to replace or upgrade the LEDWI systems.

ASOS stations also have icing sensors that are able to tell when freezing precipitation, freezing fog, or frost is occurring. Currently the NWS reports freezing rain when the icing sensor indicates icing and LEDWI says rain is occurring. However, freezing drizzle is not reported. ASOS does report freezing fog, but the report is not based on the observation that ice is detected on the icing sensor, but rather freezing fog is reported when the temperature is at or below freezing and the visibility is less than 5/8 mile. ASOS collects data each minute, but reports only hourly or when a change in conditions dictates that a “special” observation be reported. The lack of accurate, dependable precipitation detection has been a national issue since the NWS began its automation program; therefore care must be taken when interpreting these data.

During the past 10-15 years, state and local transportation departments have purchased and installed roadside environmental sensing systems and many include precipitation identification (yes/no) sensors. Some installations include precipitation type measurements using optical devices. Roadside ESS do not measure the liquid equivalent precipitation rate, which is critical for winter maintenance operations and could provide data important for assessing flooding and washout risks. Research conducted for the FAA and airlines concluded that liquid equivalent precipitation information is required for effective aircraft anti-icing as the water amount determines when chemical deicing material will fail due to dilution. Dilution of chemicals used for roadway winter maintenance is also a major factor for determining snow and ice control strategies, but little has been done to integrate real-time liquid equivalent information into the winter maintenance decision process. This is beginning to change as the [Aurora Program](#) is sponsoring a project to evaluate a new real-time winter precipitation gauge that may, because of its small size and low maintenance requirements, be a good candidate for future ESS sites.

There is considerable variation in the precipitation identification sensors used by various companies. At present little is known about the overall quality of these measurements, but most precipitation sensors do well except during critical periods of mixed precipitation, very light precipitation, and windy conditions.

4.7 Snow Depth Sensors

Measuring snow depth is difficult as the depth can vary significantly over short distances due to sheltering, exposure, and surface roughness. Human observers often take measurements at several locations near a site and report an average depth. Snow depth sensors have been developed that are designed to automatically report snow depth at a fixed site. Acoustic sensors measure the vertical distance downward to the snow surface and then calculate the snow depth beneath the sensor. Acoustic snow depth sensors are very accurate during calm conditions. However, on occasion hourly readings may be erroneously high during storms as the falling snowflakes can impede the distance measurement. The placement of acoustic sensors is critical as the location must be free from drifting and scouring to get a representative sample. Snow melt will also impact measurements. It would likely be difficult to find a suitable site for a snow depth sensor along a roadway as local obstructions, vehicle movement, and snow storage could reduce the accuracy of a sonic snow depth sensor.

4.8 Video Imaging

Video cameras are being installed along roadways at a rapid pace. Video data (still and streaming) are being utilized to observe traffic, incidents, weather, and road conditions. Research has been conducted and is accelerating on ways to develop image processing techniques designed to automatically derive weather and road condition information from video images. A good example of video imaging being used as a vehicle counter is the AutoScope® system. Fixed camera sites provide a better data set for post processing than adjustable sites (e.g., pan-tilt-zoom). In the future, it is likely that weather and road condition information will be derived from fixed camera images.

4.9 Pavement Temperature

Several studies of pavement temperature have been conducted over the last decade with varying results. The uncertainty in results prompted the Aurora Program to conduct a detailed evaluation of the accuracy of pavement temperature measurements. The Aurora Program completed the project in December 2004. Both laboratory and outdoor tests were performed. The project evaluated six in-pavement sensors and two mobile sensors. The report concluded that the accuracy of pavement sensors varies between vendor systems. Only an overview of the in-pavement sensors is provided in this section.

The Aurora Program study found that under ideal laboratory conditions, whereby the temperature of the test chamber was held steady, the average error of the in-pavement sensors was 0.8 °C (1.3 °F) and differences were found between sensors. Experiments simulating solar heating resulted in measurement errors of 4 to 5 °C (6.6 to 8.3 °F). Limited experiments of accuracy during periods of high nighttime cooling (clear, dry nights) were conducted and showed measurement errors of 1 to 2 °C (1.6 to 3.2 °F). Tests of sensor response time showed large differences between sensors with some taking up to 60 minutes to measure within 1 °C (1.6 °F) of the actual pavement surface temperature.

These results are consistent with other similar studies and indicate that great care must be taken when interpreting pavement temperature. The Aurora project found that the sensors tend to be more accurate when there is little solar influence, which generally corresponds to cloudy days and nighttime. So the good news is that the pavement temperatures should be more accurate during poor weather conditions (cloudy and wet).

Pavement models are generally configured to predict the surface (top 1/16th of an inch) of the pavement, while the pavement sensors are embedded in the pavement. The largest differences will occur during sunny periods when the pavement sensors generally read warmer than the pavement surface and during clear nights when the pavement sensors generally read cooler than the pavement surface.

Because of the uncertainty in pavement temperature accuracy, one must be very cautious about using the pavement data to rate or score pavement temperature forecasts. Pavement prediction accuracy should not be expected to be more accurate than the measurement accuracy.

4.10 Pavement Condition

In-Pavement Sensors: There are a number of manufacturers that provide pavement condition information. Road surface conditions reported by these in-pavement devices generally include dry, moist, wet, chemical wet, chemical concentration, frosty, snowy, and icy. The most common technique used to diagnose road condition and chemical concentration is to measure electrochemical conductivity. Chloride solutions are more conductive than water and the conductivity is proportional to the chemical concentration. A limiting factor of using this technique is that the type of chemical (NaCl, MgCl₂, CaCl₂, etc.) is not known, so when the system reports a certain chemical concentration, the user does not know from the device what chemical is contributing to the report and thus there is uncertainty in the effectiveness (melting capacity) of the chemical. This is not an issue if only one type of chemical is used for winter maintenance. Devices that measure chemical concentration using electrochemical conductivity techniques are considered *passive*. This means that the device obtains information by reception and it does not perform extra work to process the information.

The primary reason for measuring chemical concentration is to determine the freeze point temperature of the roadway. The freeze point temperature is a function of the chemical concentration on the road. Rather than diagnosing the freeze point temperature from chemical concentration measurements, it is better to directly measure the freeze point by lowering the temperature of the device and measuring when the solution freezes. Devices that directly measure the freeze point temperature are considered *active*. This means that the device obtains information by action (e.g., lowering the device temperature).

Active sensors provide a more accurate measurement of freeze point because it is measured directly. However, the sensor is still prone to problems as the sensor is in the pavement and can only take measurements in a small area, which may or may not be representative of the predominant condition of the roadway.

An Aurora project was conducted to assess the performance of chemical concentration measurements and found that the passive and active sensors have problems when the chemical concentration is near the full (saturated solutions) concentration. There are performance differences between active and passive sensors that are under investigation.

There are some new in-pavement sensors reaching the market that are based on optical characteristics of the pavement contaminant. These pavement sensors measure thermal conductivity, electrochemical polarization, and surface capacitance to determine if there is water, snow, or ice on the pavement. These measurements combined with pavement temperature and chemical concentrations are also used to diagnose freeze point temperature. The accuracy of these devices is now well known.

One of the most limiting factors of the in-pavement sensors is the fact that the measurements are only made at specific sites on the roadway, generally in or near the wheel tracks. Without additional confirming information, the user will not know if the data represent the predominant condition along the roadway or the local conditions on or near the sensor. The quality of the data reported by the sensor can also deteriorate with time as the roadway surface becomes worn. As the roadway ages, it often forms wheel tracks (depressed areas) and rough surfaces which can

impact the sensors by causing contaminants to become lodged in the device. For example, if water happens to pool on the sensor, it could report “wet” for several hours after the rest of the roadway has dried. In-pavement sensors should be inspected at least once annually to ensure that they and/or the pavement surrounding the sensor have not deteriorated.

Remote Sensors: Remote sensing of pavement condition is a new area of development. Remote sensing of pavement condition generally involves setting up a device above the roadway with a view of it. This allows a broader measurement and hence a better chance of detecting the predominant condition. Remote sensors include infrared imaging devices (scatterometers and spectrometers) such as the SurfaceWatch™ system that is designed to measure surface temperature, and road condition (e.g., wet, dry, ice), and laser based technologies such as the Goodrich IceHawk™. These technologies are only now emerging in the road weather marketplace and little is known about their overall skill and durability. They are also more expensive than in-pavement sensors, but the price is expected to drop as they become more widely used.

Because remote sensors measure a broader area of the roadway, they have great potential for diagnosing the predominant condition and should be considered for high risk sites (e.g. bridges, areas prone to icing, etc.). These devices hold promise for broader application, but additional testing is required to assess their performance.

5. Weather and Road Condition Prediction Capabilities

Section 4 describes many of the difficulties and measurement uncertainties that come with measuring and diagnosing various weather and road condition parameters. The complexity increases when predicting weather and road conditions. This section describes the current state of weather and road condition modeling, future trends, and opportunities.

5.1 Weather Prediction Modeling

Predicting weather at road scales (few miles to tens of miles resolution) is pushing the limits of weather predictability. While weather forecast models are becoming more sophisticated, the ability to know the current state of the atmosphere in three dimensions around the earth and predict future conditions remains a significant challenge. The primary shortcoming is the lack of global observations (surface and aloft) at the resolutions required to support new high resolution weather models.

Background: Weather models have come a long way over the last 30 years, but until recently they all depended almost entirely on data collected twice a day from balloons (called rawinsondes) released around the globe. Across the U.S. the balloon sites are about 250 miles apart (see figure below). These balloon data are sparse over unpopulated land areas, almost nonexistent over the oceans, and unreliable from third world countries.



Map of National Weather Service rawinsonde (balloon) network. Blue circles are upper air sites and red triangles are Global Climate Observing Sites.

Given these limitations, it is obvious why weather models have traditionally had a hard time predicting the weather. The models simply do not know very much about the state of the atmosphere over most of the earth and they have to guess at the weather conditions in-between observations. The situation is changing for the better thanks to faster computers, better observation systems, and more reliable communication technologies, but it will take several more years before the new data can be fully incorporated and utilized in weather modeling systems.

Another factor limiting weather forecast skill is that traditional weather models, including operational models currently being used by the NWS, do not start (initialize) with any clouds or precipitation. The models themselves generate clouds and precipitation and it takes a few hours of model run time for the clouds and precipitation to develop. This means that even at the start of the model run, there can be great differences between observed clouds and precipitation and the predicted condition. The reasons why models have traditionally started out “dry” are complex and beyond the scope of this document, but the situation is improving. Techniques are now being developed and tested in research models that allow models to begin with clouds and precipitation data based on observations. This is discussed further later in this document.

MDSS research has shown that predicting weather and road conditions requires weather data at hourly resolution to properly characterize rapidly changing conditions associated with sunrise, sunset, frontal passages, and precipitation episodes. Road temperature models are particularly sensitive to the solar cycle as road temperatures rise and fall quickly at dawn and dusk, respectively. The temporal resolution of weather model data provided by the NWS is only three hours. Therefore, anyone using the standard NWS models will only be able to provide forecast information at this temporal resolution. They may provide hourly output by interpolating, but the true resolution will remain three hours. It is likely that the NWS will eventually disseminate selected weather parameters at hourly resolution, but the timeframe for this is unclear.

Commercial weather providers that operate their own weather prediction models tend to have better performance as they have the flexibility to modify model characteristics to optimize the systems for specific applications including generating hourly output data.

New Data Sources: Data assimilation is the name of the process by which disparate data are gathered, processed, and readied for inclusion into weather models. The incoming data must be valid and incorporated into the models in a way that preserves the laws of physics. A lot of research is being conducted to develop methods and techniques that allow weather models to utilize high-resolution weather observation data sets such as radar and satellite data. These data, as well as data from global navigation satellites, ground observation systems, and buoys, have great potential to improve weather modeling, but these data have only recently been incorporated into research models; therefore it will be a few years before they are incorporated into the operational NWS models and the benefits are fully realized.

Forecast Skill: Short term forecasts (0-48 hours), have improved significantly over the last decade as operational and research weather models have improved, but the forecast skill drops beyond 48 hours. The most difficult parameters to forecast are precipitation timing and amount, and visibility, which are critical elements for surface transportation. When it comes to winter precipitation prediction, the forecast skill drops significantly after only 24 hours. For summer precipitation, namely thunderstorm prediction, weather prediction models have difficulty after only a few hours. The models do a reasonable job at predicting conditions conducive to thunderstorms, but they are still unable to predict exactly when precipitation will occur and how much precipitation will fall. This is mainly due to the fact that thunderstorms alter their immediate environment on very small scales by creating cold downdrafts and gust fronts, which change the stability structure around the storm. Because weather models do not know exactly where the up and downdrafts are in each storm, they have difficulty evolving the structure forward in time.

Visibility is also difficult to predict because there are several factors that influence visibility including sun angle, relative humidity, water droplet size and concentration, and precipitation type and rate. Local effects such as proximity to water bodies, hills and valleys, air pollution sources, and land use also effect visibility. Each of these factors is difficult to predict individually let alone combined into a visibility prediction.

Wind and temperature are probably the best predicted weather elements, particularly if statistical corrections are made to the data, but during periods of rapid changes, the timing of wind shifts and temperature changes can be incorrect.

Forecasting the amount and distribution of water vapor in the atmosphere remains a significant challenge as there are few observations of water vapor above the surface. The distribution of water vapor both horizontally and vertically has a major effect on the formation, evolution, and dissipation of clouds and precipitation. New data sets from weather satellites, global navigation satellites, aircraft, and surface based observations will improve the situation, but it will likely be a decade or two before a sufficient quantity of high resolution data sets around the earth will be routinely available to support high-resolution weather forecasting models.

High-Resolution Models: High resolution models do a better job of predicting the characteristics of a storm (e.g., whether the storm will be a single cell, multi-cell, line of cells, contain precipitation bands, etc.), but they still have difficulty on the timing and amount of precipitation. One must remember that high resolution models (also called meso-scale models) are initialized at the beginning of the forecast run using data from low resolution national-scale or global-scale models. If the larger-scale models are wrong, the high-resolution models will be wrong. If the larger-scale models are correct, the high-resolution models will generally provide better information about the structure of the weather systems.

Faster computers and the availability of new and more frequent observations allows models to be run more frequently, which provides opportunities for more frequent forecast updates and improved skill. The ability to provide more frequent updates will certainly aid decision makers.

Ensemble Modeling: It is well known in the weather community that different weather models have different skill at predicting the weather. For example, some models are better at temperature, while others are better at precipitation. Some may be better at summer precipitation (thunderstorms), while others are better at winter storms. Faster and less expensive computers have provided the opportunity for meteorologists to run multiple models at the same time and analyze the results. The resulting outputs from each model are blended to optimize the overall forecast and to assess the predictability of a particular weather situation. If multiple models are used and the data are intelligently blended, there is a higher probability that the overall forecast will be improved over any of the individual models. This technique was demonstrated as part of the MDSS project.

If on a particular day each of the models in the ensemble show similar results, then the weather pattern is probably more predictable than if there was a large spread in results. Methods and techniques are being developed and debated in the scientific community for extracting forecast confidence and/or probability information from model ensembles. Risk management decision makers that rely on weather information have expressed a strong interest in obtaining forecast confidence information. In what format the information is provided to users and how it is interpreted is another area of active research.

Model Post Processing: Post processing of model data general involves applying statistical techniques to forecast data that improve the accuracy of the predictions by taking advantage of observations. For example, local terrain characteristics, which are not typically captured by

weather models, may systematically influence wind and temperatures near a road corridor. If an observation system (e.g., ESS, NWS observation, etc.) was located along the route, data from the RWIS could be used to correct or tune the model data. Applying statistical corrections will, in general, improve the forecasts.

“Hot Start” Modeling Technique: As mentioned above, operational NWS models begin with a “dry” atmosphere. That means that they do not contain any clouds or precipitation at the initial time even though there may be clouds and storm systems in progress. Until recently, no techniques had been developed to integrate radar and satellite directly into weather models. Current operational weather models generate their own clouds and precipitation and this typically takes 2-3 forecast hours. This process is called the “spin up” time. This limits model skill for the first several hours of the forecast period.

The term “hot start” refers to a model initialization method that provides weather models with a starting point that includes clouds and precipitation based on actual observations. This is a new technique that shows significant promise in improving the prediction of precipitation (start, end, type, and rate), particularly in the first 6 hours of the forecast period.

5.2 Road Temperature Prediction

Numerous road temperature models have been developed and are utilized by the road weather community. Some of the models have been developed openly at universities and national labs, while others have been developed by the private sector and are proprietary. The majority of the models used operationally are heat balance models that predict the temperature profile from the pavement surface down several feet into the subsurface layer. The major differences are in how the models handle precipitation, snow and ice accumulation, and subsurface moisture. There is no simple way of judging the skill between the models, as there has not been any comprehensive scientific review of the available models, primarily due to the proprietary nature of the models used in the industry. A review of the literature suggests that, in general, the models’ performance is similar when given similar weather and road characteristic data.

The best ways to improve road temperature predictions are to; 1) provide the road temperature model with more accurate weather data, and 2) ensure that the model includes accurate road characteristic data. The second most important factor is the road characteristic data. Accurate data about pavement type and depth and subsurface type and depth should be part of the road temperature model configuration. Some vendors use “generic” road characteristics for their road temperature model while others incorporate actual “as-built” data. The use of “as-built” data is preferred.

Another result of road temperature modeling is that road temperature models utilizing direct and indirect solar radiation data directly from the weather models perform better than models that use cloud coverage data from weather models.

A survey of road temperature prediction results indicates that the skill varies greatly depending on the time of day and general weather conditions. All of the studies used in-pavement

temperature sensors as ground truth, which as described in section 4.9 have errors that are also dependent on time of day and weather conditions.

Road temperature prediction is highly sensitive to predictions of cloud amount, cloud depth, and the time of day the clouds appear. Because weather models are gridded, they can only generate cloud characteristics at each grid point. A coarse model grid (> 10 mile grid spacing) will smooth cloud characteristics. For example, the model cannot generate a single fair weather cloud or thunderstorm on scales less than 10 miles. A finer model grid (< 10 miles) will have a better chance of defining cloudy-clear boundaries, but smoothing will still take place. Because the prediction of individual clouds is difficult, road temperature predictions will be prone to errors during partly cloudy conditions both in the day and night.

Road temperature prediction accuracy is best during cloudy (widespread overcast) conditions and/or when precipitation is occurring. The predictions are worse during clear days when solar influences are greatest and clear nights when radiational cooling is strong. Because the in-pavement sensors are prone to errors during similar conditions, it is hard to state with confidence the absolute errors that can be expected with pavement temperature predictions. Another complicating factor is that the statistics used to report forecast errors differ between studies and vendors, making it hard to identify typical or expected errors.

With these issues in mind, some guidance is provided about the expected average temperature difference between the in-pavement sensor and the pavement temperature predictions. Without accurate ground truth data, it is not possible to state the absolute accuracy of road temperature predictions. The length of the forecast also impacts the skill. A 24 hour forecast will have, in general, more skill than a 36 hour forecast. During periods of rapidly changing weather, the predictions will be less accurate than periods of consistent weather.

During cloudy conditions the average difference between the measured pavement temperature and the prediction should be within 3 °F. During clear days, the average temperature difference should be within 10 °F with the highest difference near noon. There appears to be no consistent bias in pavement prediction as some models tend to be slightly colder than the observations and some slightly warmer. The differences are likely to be related to the different weather models used to drive the pavement models and the accuracy of the pavement characteristic data used by the pavement temperature model and the way the data are handled within the model. Of course difference pavement sensors will have different biases as well, which makes it difficult to determine the source of the error.

Road temperature prediction systems can be designed to minimize the difference between the observations and the predictions, but because of the measurement uncertainty of the in-pavement sensors, this technique may not result in the most accurate pavement surface prediction, only a good match between predictions and measurements. Strict pavement temperature quality control procedures must be implemented before any statistical corrections to pavement temperature models are made as poor quality data could degrade the output.

5.3 Blowing and Drifting Snow Prediction

As experienced winter maintenance personnel know, blowing and drifting snow have a major impact on winter maintenance operations. Weather models do not explicitly predict blowing and drifting snow, but do contain data that can be used to diagnose blowing and drifting snow conditions. Whenever it is snowing and there is wind, there will be blowing snow. For the sake of discussion, we will concentrate on conditions that cause snow to blow and drift after the precipitation has ended. Whether snow will blow around depends primarily on wind speed, the age of the snow, whether it has rained since it last snowed, whether the air temperature has risen above freezing since the last snow, the type of snow that originally fell (dry or wet), and the characteristics of the land surface that is holding the snow.



General alerts about blowing snow conditions can be generated using recent and predicted weather data, but it is very difficult to predict the amount of snow that will be moved without a very high resolution (< 30 feet grid resolution) snow drift model. Local land characteristics (hills, valleys, road cuts, vegetation type and height, etc.) will have a major influence in the amount of snow moved and these data are difficult to find and update in real-time prediction systems. Snow drift models are available, but they require a lot of pre-winter season configuration to ensure they have properly captured the local environment. Snow drift modeling should be considered for areas that are prone to drifting as they can identify the location and direction of drifting and an estimate of the amount of snow that will move.

5.4 Road and Bridge Frost Prediction

Whether or not road or bridge frost will form depends primarily on the pavement temperature and dew point temperature. In addition any residual chemical will reduce the likelihood of road frost. As mentioned in section 5.1, one of the most difficult weather elements to predict is water vapor, which is reflected in surface dew point measurements. In section 5.2, the complexities of predicting pavement temperature were described. As with most forecasts, near term forecasts will generally be more accurate than longer term forecasts; therefore there is hope that as weather and pavement predictions improve, so will road and bridge frost forecasts. In the meantime, care must be taken when interpreting frost forecasts as an error of only a fraction of a degree in either the pavement temperature or dew point temperature can make a large difference in the formation of frost.

Because of the uncertainty inherent in these predictions, a better approach would be to obtain information about frost potential in probabilistic or confidence terms rather than trying to explicitly attempt to determine the timing and amount of frost buildup.

6. Summary of Trends in Road Weather Services

There has been a significant increase in the awareness of the need for improved road weather services over the last five years. A coordinated national effort has occurred to highlight the unmet weather needs of the transportation community and identify research requirements and implementation strategies for improved weather services. The atmospheric science community is now actively engaged with the transportation community in a partnership that will accelerate technological improvements. Several key organizations are working together on road weather issues including the American Meteorological Society (AMS), FHWA, Intelligent Transportation Society of America (ITSA), National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), national laboratories, Aurora Program, National Aeronautics and Space Administration (NASA), Transportation Research Board (TRB), universities, and commercial weather providers. The benefits of the technology improvements will include improved safety, efficiency, and capacity of the national roadway system.

Because of the activities mentioned above, there will be an acceleration of research, development, and implementation of technologies that will improve road weather services. Department of transportation personnel should begin to see the following trends emerge from the transportation and weather communities:

- 1) The NWS and commercial weather providers will increase their use of high-resolution models and the resolution of those models will continue to increase.
- 2) The weather community will expand their use of model ensembles as a method to assess the predictability of particular forecast scenarios. The results will be used to generate probabilistic and/or confidence metrics for weather products.
- 3) Weather models will become more accurate in predicting and nowcasting short-term weather (0 to 6 hrs) by using “hot start” methods and blending actual observations into the forecast process.
- 4) The NWS will continue their modernization process to generate and distribute weather data in a digital (gridded) format. In addition, the NWS will refine the gridded products to better serve the public including the transportation community. The current product is called the [National Digital Forecast Database \(NDFD\)](#). A local digital database is under development that will have higher temporal and spatial resolution. Transportation departments and commercial weather service providers can take advantage of these new data.
- 5) The need for surface observations will increase as users demand more specific information. Surface observation data (e.g., RWIS) will be more fully utilized in decision support systems and in the weather forecast process.
- 6) The need to share surface observation data at a national level will increase as government and commercial weather providers develop data integration networks (e.g., [Clarus](#)) and other technologies that take advantage of the observations for the generation of products.

- 7) The need to digitize and distribute road condition information will increase as downstream information systems are developed that will require a national seamless dataset. Information systems will include 511, in-vehicle information systems, rest station kiosks, decision support systems for highway operations, etc.
- 8) The quality of the observations from the road weather information systems will get more scrutiny as the data become available to the broader user community. This will likely result in the development of new sensors and data processing methods, which will benefit all users.
- 9) The use of camera imagery will increase and imaging processing techniques will be employed that will derive weather and road condition parameters from the images.
- 10) Weather information and its presentation for surface transportation users will improve significantly and the need to seek out multiple sources of weather information will decrease as weather information providers tailor road weather information systems to specific end user categories (e.g., traffic, incident and emergency management, maintenance, traveling public, etc.).
- 11) Mobile communication systems will be used more often to provide field personnel with short-term information and alerts about weather and road condition hazards. This will allow users to adjust their field operations to account for the impact of weather on operations.

7. Conclusion

In the next few years, the surface transportation system will move away from being mainly a reactive system to a proactive system with respect to weather. The rapid rise in awareness of the impact of weather on the transportation system and the new relationships that are developing between the weather and transportation communities, provide a significant opportunity for improving road weather services. Active participation by end users in defining road weather service needs will contribute to and help accelerate the development and implementation of new capabilities.