Surface Transportation Weather Forecasting and Observations:
Assessment of Current Capabilities and Future Trends

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ABSTRACT

A significant increase in the awareness of the need for improved surface transportation weather services has occurred over the last five years. During this time, a coordinated national effort has been undertaken to highlight the unmet weather needs of the transportation community and identify research requirements and implementation strategies for improved weather services. The benefits of such technology improvements will include improved safety, efficiency, and capacity of the national surface transportation system. Because of the activities mentioned above, there will be an acceleration of research, development, and implementation of technologies focused on improving surface transportation weather services. In the next several years, the surface transportation system will move away from being primarily a reactive system to being 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 surface transportation weather services. Active participation by end users in defining surface transportation weather service needs will contribute to and help accelerate the development and implementation of new capabilities.

Key words: forecasting—modeling—observations—weather
ENVIRONMENTAL SENSOR SYSTEM MEASUREMENTS

Air Temperature, Dew Point, and Wind

Air temperature, dew point, wind speed and direction measurements are relatively mature, so there is little room for significant improvement. Air temperature measurement accuracy should be within 1 °F and dew point within 2° to 4° F. Wind speed measurement accuracy should be within 2 miles per hour and wind direction accuracy should be within 5 degrees (measurement range is from 0 to 360 degrees). When comparing these measurements, one should be aware that variations can exist over short distances (tens of feet) and with time (minutes). Differences can be expected over short distances due to local variations in terrain, elevation, shading, ground cover, and proximity to obstructions such as buildings and water bodies. 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.

Visibility

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.

Several factors 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 sight.

For road applications, it is more important to measure visibility below one 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 environmental sensor system (ESS) sites is encouraged, as they will provide a much needed data source for future surface visibility products.

Winter Precipitation

Winter precipitation (snow, ice, sleet) is difficult to measure accurately using automated systems. 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. Most of the gauges in operation today were developed for climatological analysis purposes.
The majority of precipitation gauges used today are not well-designed for measuring winter precipitation, particularly snow. 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-measurement of precipitation during the period when it is snowing, and a false over-measurement of precipitation when this snow melts and later falls into the gauge. 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. 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 improperly shielded gauges 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.

The National Weather Service (NWS) is currently replacing the tipping bucket gauges with improved 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 light-emitting diode weather identifier (LEDWI) at automated surface observing system (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. 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 sites 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.

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.
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 derive weather and road condition information automatically from video images. 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. The Federal Highway Administration (FHWA) began a research project in mid-2005 as part of the Clarus Initiative (Pisano, Alfelor, and Pol 2005) to develop algorithms to derive weather information from fixed video images. The Massachusetts Institute of Technology Lincoln Laboratory is leading this research effort.

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 (Aurora 2005). The study used temperature sensors attached to the surface of the pavement and compared the output with data from the sensors embedded in the pavement (e.g., pucks). Under ideal laboratory conditions, the average error of in-pavement sensors should be less than 2°F. During periods of rapidly changing conditions, including periods of high solar loading, the embedded pavement sensors are less accurate because the thermal properties of the sensors differ from the pavement and because the sensors are embedded below the pavement surface where heat and cold can be trapped. Under these conditions, temperature differences can easily exceed 10°F. These results are consistent with similar studies and indicate that great care must be taken when interpreting pavement temperature. The good news is that pavement temperatures should be more accurate during poor weather conditions (cloudy and wet), when solar effects are minimal.

Pavement temperature prediction models are generally configured to predict the surface conditions of the pavement (top 1/16th of an inch), while the pavement sensors are embedded in the pavement. 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.

It is important to measure the topmost layer of the pavement. This is one reason why thermistors, applied to the pavement surface, are often used to indicate “truth.” The accuracy of these devices, rapid response rates, and inexpensive costs make them very attractive pavement temperature sensors. It is anticipated that the use of inexpensive thermistor technologies will grow and be used to provide pavement temperature information between fully instrumented ESS locations.

Pavement Condition

A number of manufacturers 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. 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 the chemical that is contributing to the report; thus, there is uncertainty in the effectiveness (melting capacity) of the chemical. Devices that
measure chemical concentration using electrochemical conductivity techniques are considered passive. This means the device obtains information by reception and does not 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 (i.e., lowering the device temperature).

Active sensors provide a more accurate freeze point measurement 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 that may or may not be representative of the predominant condition of the roadway. Active sensors also produce waste heat as they cool. The waste heat has the potential to impact the accuracy of the pavement temperature measurement if the sensors are collocated in the same device.

There are some new sensors reaching the market that are based on optical and thermal characteristics of the pavement contaminant. These sensors measure thermal conductivity, electrochemical polarization, and surface capacitance to determine whether water, snow, or ice is on the pavement. These technologies are only now emerging in the road weather marketplace; 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 and other areas prone to icing). These devices hold promise for broader application, but additional testing is required to assess their performance.

WEATHER AND ROAD CONDITION PREDICTION CAPABILITIES

Weather Prediction Modeling

Predicting weather at road scales (a few miles to tens of miles resolution) pushes 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.

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 nation, the balloon sites are about 250 miles apart. These balloon data are sparse over unpopulated land areas, almost nonexistent over the oceans, and unreliable from undeveloped countries.

Given these limitations, it is obvious why weather models have traditionally had difficulty 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 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 years before the new data can be fully incorporated and utilized in weather modeling systems.
Another factor that limits weather forecasting skill is that traditional weather models, including operational models currently being used by the NWS, do not 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 conditions. The reasons for which models have traditionally started dry are complex and beyond the scope of this document, but the situation is improving. Techniques are being developed and tested in research models that allow models to begin with clouds and precipitation data based on observations. This is discussed in more detail later in this paper.

Weather models also need to make assumptions about the characteristics of the land, including vegetation type, greenness fraction, land use, snow cover, and soil moisture. This was traditionally determined using seasonally averaged data, and there was no daily feedback in the process. This means that if snow cover was not normal for a particular day, but it did snow the day before, the weather model would be initialized without the knowledge that snow was on the ground. The lack of updated land surface information reduces the forecast skill. The good news is that this problem is being mitigated, as land surface models are now being coupled with weather models. It is anticipated that most weather models will have this capability within the next two years.

Maintenance decision support system (MDSS) research (Mahoney and Myers 2003; Pisano, Stern, and Mahoney 2005) has shown that predicting weather and road conditions requires weather data at an 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 perform better, 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 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. Much 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 beyond 48 hours, the forecast skill drops. The most difficult
parameters to forecast are visibility and precipitation timing and amount, 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 predict conditions conducive to thunderstorms reasonably well, 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 updrafts and downdrafts are in each storm, they have difficulty evolving the structure forward in time.

Visibility is also difficult to predict because several factors 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 affect 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. However, 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 routinely be available to support high-resolution weather forecasting models.

**High-Resolution Models:** High-resolution models (also called meso-scale models) better predict 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 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 predict the weather with different skills. For example, some models are better with temperature, while others are better with precipitation. Some may be better with summer precipitation (thunderstorms), while others are better with 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 for the surface transportation community as part of the MDSS project.

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.

**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, 2) ensure that the model includes accurate road characteristic data, and 3) initialize the model with observed pavement surface and subsurface temperature data. 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.

Road temperature models that utilize direct and indirect solar radiation from the weather models perform better than models that use cloud coverage data from weather models. Road temperature prediction is highly sensitive to predictions of cloud amount and 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 course 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.

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 and some slightly warmer than the observations. The
differences are likely to be related to the different weather models used to drive the pavement models, 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, different 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.

**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-foot grid resolution) snow drift model. Local land characteristics (hills, valleys, road cuts, vegetation type and height, etc.) will have a major influence on 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 the models can identify the location and direction of drifting and estimate the amount of snow that will move.

**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 previously, one of the most difficult weather elements to predict is water vapor, which is reflected in surface dew point measurements. The complexities of predicting pavement temperature were also 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 prediction 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.
**SUMMARY**

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, FHWA, Intelligent Transportation Society of America, National Oceanic and Atmospheric Administration, National Science Foundation, national laboratories, Aurora Program, National Aeronautics and Space Administration, Transportation Research Board, 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. In the next few years, the surface transportation system will move away from being primarily a reactive system to being 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.
ACKNOWLEDGMENTS

The FHWA Office of Transportation Operations, Road Weather Management Program, sponsored this research. The contents of this paper 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.

The MDSS development team is grateful for the support and leadership provided by the FHWA, particularly Regina McElroy, Paul Pisano, Ray Murphy, and Andrew Stern of Mitretek.

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